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MILITARY HANDBOOK

DESIGN OF COMBAT VEHICLES FOR FIRE SURVIVABILITY

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FOREWORD

1. This military handbook is approved for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendations, additions, and deletions) and any pertinent data that may be of use in improving this document should be addressed to Commander, US Army Tank-Automotive and Armaments Command, ATTN: AMSTA-TR-T, Warren, MI 48397-5000, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. This handbook was developed to provide guidance to the armored combat vehicle designer and program managers for the incorporation of fire survivability techniques early in the process and throughout the development of a vehicle. The application of these techniques should enhance the survivability of the combat vehicle and its crew. The design procedures and survivability techniques are also applicable to aircraft and naval vessels.

4. This handbook was developed under the auspices of the US Army Materiel Command's Engineering Design Handbook/Information Program, which is under the direction of the US Army Industrial Engineering Activity. Research Triangle Institute (RTI) was the prime contractor for this handbook under Contract No. DAAA09-86-D0009. This handbook was prepared at Southwest Research Institute (SwRI), a subcontractor to RTI, by a diverse team of experts under the direction of the principal investigator and author, Mr. Patrick H. Zabel. Mr. Zabel's dedication and attention to detail were crucial to the successful completion of this work. The development of this handbook was guided by a technical working group (TWG) chaired by Dr. James L. Thompson and composed of individuals from the Department of Defense. Mr. Steve McCormick of the US Army Tank/Automotive Research, Development, and Engineering Center deserves special recognition for his manuscript reviews and technical guidance to the principal investigator and the Engineering Handbook Office at RTI.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAV = amphibious assault vehicle
ABS = acrylonitrile butadiene styrene
AC = hydrogen cyanide
ACAV = armored cavalry assault vehicle
ACGIH = American Conference of Governmental Industrial Hygienists
ACV = armored combat vehicle
AEHA = US Army Environment Hygiene Agency
AEV = armored engineer vehicle
AFDSE = automatic fire detection and suppression equipment
AFES = automatic fire-extinguishing system
AFFF = aqueous film-forming foam
AFSSS = automatic fire-sensing and suppression system
AIT = autogenous ignition temperature
AP = armor piercing
APC = armored personnel carrier
APDS = armor-piercing, discarding sabot
APFSDS = armor-piercing, fin-stabilized, discarding sabot
APG = Aberdeen Proving Ground
APHEI = armor-piercing, high-explosive incendiary
API = armor-piercing incendiary
APIT = armor-piercing, incendiary tracer
APU = auxiliary power unit
AR/AAV = armored reconnaissance/airborne assault vehicle
ARV = armored reconnaissance vehicle
ASM = armored systems modernization
ASTB = Advanced Survivability Test Bed
ASTM = American Society for Testing and Materials
AT = antitank
AVLB = armored vehicle launch bridge
BDARP = Battle Damage Assessment and Repair Program
BDU = battle dress uniform
BFV = Bradley fighting vehicle
BITE = built-in test equipment
BMEP = brake mean-effective pressure
BMP = bronevaya maschina pickhota
BRDEC = US Army Belvoir Research, Development, and Engineering Center
BRL = US Army Ballistic Research Laboratory
CBV = cloth ballistic vest
BTR = brone transporter
CE = chemical energy
CEL = cumulative expected loss
CEV = combat engineer vehicle
CI = compression ignition
COIN = counterinsurgency
CONUS = continental United States
CPI = consumer price index
cps = counts per second
CRES = corrosion-resistant steel
CS = chloracetophenone solution
CST = cardiac sensitivity threshold
CTD = continuous thermal detector
CTFE = chlorotrifluoroethylene
CVC = combat vehicle crewman
DAN = document acquisition number
DF = diesel fuel
DIGL-RP = diglycol rocket propellant
DIVAD = division air defense
DoD = Department of Defense
DU = depleted uranium
EBW = exploding bridgewire
EMI = electromagnetic interference
emp = electromagnetic pulse
emr = electromagnetic radiation
EOD = Explosive Ordnance Disposal
EP = end point
EPA = Environmental Protection Agency
ETO = European Theater of Operations
F = fast
FAA = Federal Aviation Administration
FAASV = field artillery ammunition support vehicle
FAE = fuel-air explosive
FDES = fire detection and extinguishing system
FFES = fixed fire extinguisher system
FFFP = film-forming fluoroprotein
FMP = flight motor propellant
FoV = family of vehicles
FRF = fire-resistant fuels
FRH = fire-resistant hydraulic
FSES = fire survivability enhancement systems
FSI = Fire and Safety International
FY = fiscal year
GB = sarin
GD = soman
GFI = ground fault interrupters
GLT = grade G, low temperature
GWP = global warming potential
HC = hexachloroethane
HD = thickened mustard
HE = high explosive
HEAT = high-explosive antitank
HEAT-T-MP = high-explosive, antitank, tracer, multipurpose
HEF = high-expansion foam
HEI = high-explosive incendiary
HEIT = high-explosive incendiary tracer
HEP = high-explosive plastic
HESH = high-explosive squash head
HE-T = high-explosive tracer
HIPS = high-impact polystyrene
IBP = initial boiling point
IDLH = immediately dangerous to life or health
IFV = infantry fighting vehicle
IM = insensitive munitions

IR = infrared
ITP = intrathoracic pressure
JP = jet propellant
JTCG-AS = Joint Technical Coordinating Group for Aircraft Survivability
KE = kinetic energy
LANL = Los Alamos National Laboratory
LAV = light-armored vehicle
LAW = light antitank weapon
LEL = lower explosive limit
LFT = live-fire test
LGP = liquid gun propellant
LOI = limiting oxygen index
LOVA = low-vulnerability ammunition
LOX = liquid oxygen
LVTP = landing vehicle, tracked, personnel
MAP = monoammonium phosphate
MAW = medium antitank weapon
MBT = main battle tank
MDS = manual discharge system
MK = mark
MOGAS = motor gasoline
MOPP = mission-oriented protection posture
MRI = magnetic resonance imaging
MSEC = module, standard electrical control
NASA = National Aeronautics and Space Administration
NATO = North Atlantic Treaty Organization
NBC = nuclear, biological, and chemical
NFPA = National Fire Protection Association
NIST = National Institute of Standards and Technology
NWC = Naval Weapons Center
OCONUS = outside the continental United States
OD = outside diameter
ODP = ozone depletion potential
OFSA = optical fire sensor assembly
OVE = on-vehicle equipment
OVM = on-vehicle material
PARK AC = parked aircraft
PBI = polybenzimidazole
PBX = plastic bonded explosive
PETN = pentaerythritol tetranitrate
PG = propylene glycol
POL = petroleum, oils, and lubricants
ppm = parts per million
PTFE = polytetrafluoroethylene
PTS = permanent threshold shift
PVC = polyvinyl chloride
QPL = qualified products list
RAE = Royal Aircraft Establishment
RAF = Royal Air Force
REME = Royal Electrical and Mechanical Engineers
RHA = rolled homogeneous armor
RPG = rocket-propelled grenade
RPO = rocket-propelled flamethrower
RPO-A = rocket-propelled flamethrower-airborne
RR = recoilless rifles
RTD = resistance thermocouple detector
S = slow
SAE = Society of Automotive Engineers
SARS = Standard Army Refueling Systems
SAVA = Standard Army Vetronics Architecture
SBRC = Santa Barbara Research Center
SCR = silicon control rectifier
SEA = Southeast Asia
SG = specific gravity
SHF = single hydraulic fluid
SI = spark-ignition
SOP = standard operating procedure
SPH = self-propelled howitzer
STANAG = Standardization Agreement
STEL = short-term exposure limit
STLC = short-term lethal concentrations
S/R = subroutine
SURVIAC = Survivability/Vulnerability Information and Assessment Center
SUSV = small unit support vehicle
SWA = Southwest Asia
TACOM = US Army Tank-Automotive Command
TARADCOM = US Army Tank-Automotive Research and Development Command
TC = track commander
TCP = tricresyl phosphate
td = troland
TEA = triethylaluminum
TERA = Terminal Effects Research Activity
TLV = threshold limit value
TMB = trimethoxyboroxine
TNT = trinitrotoluene
TOW = tube launched, optically tracked, wire guided
TRADOC = US Army Training and Doctrine Command
TRV = tracked recovery vehicle
TTS = temporary threshold shift
TWA = Trans World Airlines
UF = ultrafast
UK = United Kingdom of England, Scotland, and Northern Ireland
US = United States
USAF = US Air Force
USASC = US Army Safety Center
USMC = US Marine Corps
USN = US Navy
USNSC = US Navy Safety Center
UUF = ultra ultrafast
UV = ultraviolet
VC = Viet Cong
VEESS = vehicle engine exhaust smoke system
W-P AFB = Wright-Patterson Air Force Base
WP = white phosphorus

CHAPTER 1
INTRODUCTION

The general purpose and objective of this handbook are stated. The scope and application of the handbook are also stated. The use of combat vehicles is reviewed, as are the threats to those vehicles. A design philosophy is given that can result in highly survivable combat vehicles. The contents of the remaining chapters are described.

1-0 LIST OF SYMBOLS

A = availability, i.e., probability that the vehicle is in a ready state at a random point in time, or operational readiness, dimensionless

C = capability, i.e., a measure of the ability of the vehicle to achieve its mission performance objectives, or design adequacy, dimensionless

CER = cost-effectiveness ratio, i.e., system effectiveness divided by vehicle cost, $\$US^{-1}$

P_{SF} = probability a sustained fire will result, dimensionless

$P_{SF_{EFC}}$ = probability a sustained fire will result when an external fuel cell is used, dimensionless

$P_{SF_{IFC}}$ = probability a sustained fire will result when an internal fuel cell is used, dimensionless

R = reliability, i.e., conditional probability that the vehicle can complete a defined mission under specific conditions, or dependability, dimensionless

SE = system effectiveness, dimensionless

VC = vehicle cost or cost of vehicle plus the fire survivability enhancement system (FSES) cost, \$US

1-1 PURPOSE

1-1.1 GENERAL PURPOSE

The purpose of this handbook is to provide information that can be used

1. By engineers to integrate fire survivability into the design of combat vehicles
2. By developers of fire prevention, detection, and suppression systems to understand the operational requirements and environments of combat vehicles
3. By vehicle project and product managers to obtain an overview of the available technology and of fire survivability problems
4. By military officers to obtain information to aid in establishing fire survivability requirements for future vehicles.

1-1.2 OBJECTIVE

The paramount objective of this handbook is to maximize the survivability and safety of the soldiers using combat vehicles from threat of fire. A secondary and complementary objective is reduction of acquisition, operating, and support costs through reduced fire damage to vehicles and equipment.

1-2 SCOPE

This handbook is intended to organize and consolidate documentation on technologies and techniques suitable to make combat vehicles more resistant to fire and to minimize the effects of fires on the vehicles and their crews.

This handbook contains data on

1. Materials used in combat vehicles with emphasis on their ignition and flammability characteristics
2. Available fire-reduction techniques and -extinguishing systems
3. Past experience with combat vehicle fires, materials, and components
4. Survivability enhancement testing
5. Computer models used to predict fire survivability performance.

Clothing can enhance the survivability of the crew. Combat vehicle designers, however, should not depend upon such clothing to meet the fire survivability design objectives.

Stowed munitions may detonate rather than burn or deflagrate given a ballistic impact. The design features needed to withstand the detonation are beyond the scope of this handbook.

1-3 APPLICATION

This handbook applies to all combat and tactical vehicles, which include tanks, fighting vehicles, armored personnel carriers, reconnaissance vehicles, combat engineer vehicles, self-propelled artillery, ammunition supply vehicles, recovery vehicles, amphibious landing vehicles, armored cars, and any other armored vehicles intended for use in the battle area in direct or indirect contact with hostile personnel. These vehicles can be either tracked, as is the main battle tank (MBT) M1, or wheeled, such as the light-armored vehicle (LAV) 25.

1-4 OVERVIEW

1-4.1 BACKGROUND

Most combat vehicles are armored to minimize the effects of hostile action on the occupants and internal equipment. The armor, however, can withstand only a given level of threat. The basic fire prevention design objective is to design the vehicle so that when the armor is overwhelmed or a slow-growth fire, which can occur in training, occurs, the occupants and internal equipment will not suffer catastrophic damage from fires or their effects. To accomplish this, the design and materials selected should be such that a fire is not ignited by an overmatching ballistic impact or, if a fire does start, to extinguish it before excessive damage or injury is incurred.

A fire-extinguishing system should be as simple as possible and consistent with the requirements for speed, effectiveness, and reliability. Any fire-extinguishing system for occupied compartments should be automatic because the occupants will probably be preoccupied when the system is needed. A fire-extinguishing system for the engine compartment should either be automatic or have a warning system to alert the driver and/or the vehicle commander when there is a fire in the compartment. Passive fire suppression techniques should be used to the utmost to reduce the probability of fire and/or to extinguish fires. Manual fire extinguishers are needed when the automatic system is off or does not trigger or when the fire is not extinguishable by the automatic system.

Fire extinguisher systems should not force the crew to leave the vehicle. Shaped-charge or kinetic energy (KE) projectile hits, which usually are the cause of ballistically induced fires, are usually from direct-fire weapons or bomblets. If the vehicle is unoccupiable, the personnel must choose either to leave the vehicle promptly and probably be exposed to other direct-fire weapons, such as machine guns, which are firing projectiles the vehicle armor could stop, or to remain inside and be overcome by fire or noxious gases. Personnel should be able to stay within the vehicle and, if it is operable, perform their duties for at least as long as is required for the vehicle to reach cover. Further, any ground fires resulting from jettisoned or drained fuel or other liquid combustibles should not bar personnel from operating or evacuating the vehicle.

The design philosophy for fire-extinguishing systems should be similar to that used by aircraft designers when they consider armor. First, they design components to withstand ballistic impacts, then they use the shielding provided by other aircraft components as much as possible to protect more critical components, and finally they use armor only as a last resort to protect what cannot otherwise be shielded. The abrogation of fire-extinguishing systems is not intended. The design concept is twofold:

1. Reduce the probability of ignition by selecting noncombustible materials, selecting materials that do not generate strong ignition sources when hit, or by preventing formation of combustible mixtures of fuel and oxygen.

2. Reduce the probability of sustained combustion by lowering the overall temperature of combustible materials, reducing the oxidizer available locally, or automatically releasing a fire extinguishant in the threatened region.

Once the armor is perforated, the ballistic penetrator cannot be prevented from killing people or destroying equipment, but a fire can be prevented, spall or secondary missiles can be minimized or stopped, and the generation of irritating, noxious, or toxic particulate or gaseous products can be minimized.

If a vehicle were made to be indestructible by fire, to destroy the vehicle to prevent it from falling into hostile hands in the event of local defeat or encirclement would be almost impossible for the crew. To have vehicle destruction a problem is the true goal of this handbook.

1-4.1.1 Review of Combat Vehicle Use

Combat vehicles are used to protect and carry fighting personnel* to a location at which those personnel can use their weapons effectively against an enemy. In ancient times rams used to batter castle or city gates were armored with wood and ox hides to protect warriors within from arrows, javelins, rocks, hot oil or water, and fire. These rams were the ancient and medieval equivalent of our modern combat vehicles. In World War I the coupling of the internal combustion engine with the endless track developed for farm tractors produced the first effective cross-country combat vehicle. These early combat vehicles were armored to protect their crew from the caliber .30 rifle and machine gun ball bullet and were designed to pass through barbed wire entanglements and over trenches to enable the crewmen to use vehicular machine guns against enemy infantry or vehicular cannon against enemy weapons. These tanks still proved vulnerable to small arms armor-piercing bullets, which could penetrate the armor, perforate fuel cells, and ignite gasoline vapors, and to direct-fire, high-explosive artillery shells (Ref. 1). From that day to this the history of tanks and other combat vehicles is one of developing better armor to resist the weapons used against the combat vehicles and then developing better weapons to defeat the combat vehicle armor. Shortly before they jumped into Sicily in 1943, General George Patton told the men of the 505th Airborne Infantry, "Now I want you to remember that no sonuvabitch ever won a war by dying for his country. He won it by making the other poor dumb sonuvabitch die for his country." (Ref. 2). Eventually the armor will be penetrated; therefore, the combat vehicle must be designed to continue to protect its occupants after the armor is penetrated so that our troops can win any war they have to fight.

Because combat vehicles must carry fuel for their internal combustion engines and carry propellants and explosives for use in their weapons, the occupants and internal components of these vehicles are highly vulnerable to fire and/or explosion when a threat penetrates the armor. The burning or explosion of the contents of the vehicle usually kills or injures the crewmen and destroys the vehicle. Throughout

*US military vehicles are designed for 5th percentile size females through 95th percentile size males.

the history of combat vehicles, the solution has been to improve the armor; however, designers are now seeking ways to enhance the survivability of crew and vehicle by reducing the probability of fire or explosion given a perforation of the armor or by reducing the vulnerability of crew and vehicle given the ignition of fire or the initiation of explosion.

Since the first tanks appeared in World War I, many variations of combat vehicles have been developed. There are still tanks, but there are also armored personnel carriers, infantry fighting vehicles, self-propelled artillery, combat engineer vehicles, recovery vehicles, and many other special purpose vehicles that are intended to protect the crewmen while they are performing their mission or engaging an enemy. Combat vehicles can be best categorized by their cross-country mobility and armor protection against threats that would inhibit dismounted infantry or other operations by unprotected soldiers.

The British designed the Mark I tank in 1916 to protect infantrymen from machine-gun fire and shrapnel while traveling across open terrain between trench systems. These tanks had to be able to negotiate shell craters, trenches, and barbed wire entanglements. These British tanks were vulnerable to direct hits by artillery, but the machine gun and magazine rifles forced the towed artillery to move into defilade. Thus artillery pieces were not often encountered by tanks during their assault of the forward trenches. Besides, the artillery pieces were not designed to track and engage moving targets. Against machine-gun fire, particularly after the Germans had introduced the 7.92-mm armor-piercing (AP) bullet, the British tanks were found to be vulnerable to fuel fires. These early Mark I, II, and III tanks had the fuel cells installed within the vehicle. There was only one compartment, which contained the engine, the mobility fuel, and the crew. To simplify the internal hardware further, the engine was supplied fuel by gravity feed. Thus the fuel cell was located over the engine, and when a bullet penetrated the armor or entered through a hole or slit and perforated this fuel cell, the fuel would dribble onto the hot engine where it would usually ignite. This situation was remedied in the design of the Mark IV tank by emplacing the fuel cell low, outside, and in the rear of the vehicle and by armoring it (Ref. 1). Note in Fig. 1-1 that the steel fuel cell box is across the rear of the vehicle between the tracks. After the shooting stopped in 1918, later tank designers forgot why that change had been made, and the fuel cell was moved back inside the next model tank.

In World War II the fire survivability of combat vehicles received much less consideration than did mass-producing, arming and armoring, and providing them the capability to move. The only fire survivability feature considered in US tanks was to provide protection for stowed ammunition, which consisted of metal jackets for ready ammunition in the turret, and at the request of the British, water jackets surrounded the ammunition storage on some of the M4 tanks.

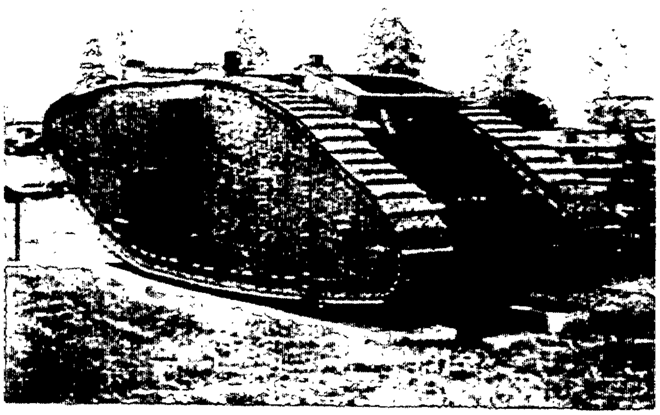

Figure 1-1. British Mark IV Tank Viewed From Left Rear

All British and German tanks and most American tanks were gasoline fueled. The Russian tanks and some of the American M4 tanks used diesel engines, but the only reason these American tanks had diesel engines was that there were not enough gasoline engines available. Also the Americans preferred to carry more ammunition, so water jackets were often removed from ammunition magazines and/or more ammunition was stowed within the vehicle than the water-jacketed magazines could hold. Fire was accepted as one of the phenomena that could happen to someone else's tank. The Russians used design features that improved vehicular fire survivability more than did the Americans, Germans, or British. These features included the use of diesel fuel and the incorporation of fixed, manually actuated water, and later carbon dioxide, fire extinguishers. The Americans and British did provide hardened holders for some of the stowed ammunition in order to reduce the incidence of ammunition propellant explosions given fragment or spall impacts. Most of the major powers started using steel cartridge cases, but the reason was usually to conserve brass rather than to have a more fragment-resistant cartridge case. In World War II most warfare was conducted with known battlefronts with enemies in somewhat fixed locations. There were a few more fluid situations, such as in North Africa, but usually the locations of the enemy were known and armored vehicles could be used facing their opponents. Also the use of small, shoulder-fired antitank grenades began to threaten tanks from any direction. The Russians used Stormavik aircraft to attack tanks from above with cannon fire.

After World War II, a little more attention was given to fire survivability features for combat vehicles. Russians, and later the Americans, placed fixed fire-extinguishing systems in the engine compartments of their vehicles and usually used carbon dioxide for a fire extinguishant. The British also used carbon dioxide fire-extinguishing systems and kept water jackets on their ammunition magazines; these water jackets were not removed until the Challenger MBT was made. The Americans switched to diesel fuel primarily to reduce the incidence of fires but then used the diesel fuel to cool some engine parts. Some of this heated fuel was returned to the fuel cell and thus heated the remaining fuel—sometimes above its flash point. This practice almost negates the value of using diesel fuel as a less easily ignitable fuel and increases the magnitude of the hazard because the volumetric energy content of diesel fuel is higher than that of gasoline. The Americans began to incorporate fire suppression systems using Halon in their crew and engine compartments. Similar systems have been developed and improved upon by the Israelis, British, and Germans. Starting with the T-55, the Russians have used Halon-type fire extinguishers in both engine and crew compartments. The Americans use rear-mounted external fuel cells, armored against small arms, on some vehicles, and the Israelis have incorporated this feature in their latest MBT, the Merkava III. The Americans now use a fire-retardant hydraulic fluid, but this fluid can be ignited and does burn, especially in mist or spray form. Also it has too great a viscosity at low temperature to be used in gun recoil systems. The Americans have incorporated separate, vented ammunition compartments (magazines), which can protect the occupants from ballistically initiated gun propellant.

Many of these fire survivability enhancements have been incorporated because of the increasing need to repair damaged vehicles rather than to depend upon receipt of new vehicles—a burned out vehicle is usually irreparable—and the need to conserve trained crews.

1-4.1.2 Review of Threats

1-4.1.2.1 Direct-Fire Threats

A continuously improving inventory of KE and chemical energy (CE) weapons are designed to destroy combat vehicles. The armor of combat vehicles is designed to protect the occupants and internal components from selected threats attacking from specific directions. When combined with weight, size, and other requirements, the protection requirements result in combat vehicles that usually are heavily armored in the front, less heavily armored on the sides, and lightly armored on the rear, top, and bottom. Since threat capabilities improve and hostile tactical scenarios change, direct-fire antitank weapons can be assumed to be capable of defeating combat vehicle armor almost anywhere. A direct hit by a high-explosive artillery projectile of 100-mm caliber or greater on a lightly armored combat vehicle or on the side or rear of a heavily armored vehicle will usually damage or at least immobilize the vehicle.

Currently, even small, shoulder-fired rockets, such as light antitank weapons (LAWs) or rocket-propelled grenades (RPGs) -7 or -16, can penetrate the rears or tops of even the most heavily armored vehicles. And in urban terrain infantrymen can attack the tops of armored vehicles. Combat vehicles lighter than first-line MBTs can usually be defeated by the larger rocket-propelled antitank missiles, such as the tube-launched, optically tracked, wire-guided (TOW), or Sagger, missiles, even through their heaviest armor. The slug of a shaped charge can cause significant damage within a lighter combat vehicle and possibly is hot enough to ignite diesel fuel spray. The shaped-charge jet can pass completely through both sides of a light combat vehicle and eject spall and molten particles into the vehicle from both the exit side of the wall initially impacted and the entry side of the far wall. This spall and splash back can be a major ignition source for fuel spray and exposed propellant. A shaped-charge jet passing through solid propellant will ignite the propellant and usually result in deflagration. A shaped-charge jet passing through high explosive will usually cause detonation. A shaped-charge jet passing through the fuel in a fuel cell usually will generate a high-pressure hydraulic ram against the fuel cell walls. When the fuel cell ruptures, the fuel usually is sprayed into the adjacent compartment. The jet will not ignite the liquid hydrocarbon fuel inside the fuel cell, but the jet will draw some of the fuel behind in its wake in the form of a mist, which can be readily ignited by the spall or molten splash generated by the jet. This fuel mist usually spreads radially and will burn in a fireball along the trajectory of the jet. Once fuel starts to burn, it liberates heat that vaporizes other liquid fuel, which then burns. This fuel fire ignition process takes only milliseconds.

Diesel fuel spray is slightly more difficult to ignite than is gasoline fuel spray. Gasoline vaporizes more readily than diesel fuel at normal ambient temperatures; therefore, a small gasoline leak is more dangerous than a small diesel fuel leak. The vapors mix with air to form combustible mixtures, and gasoline emits more vapors than diesel fuel at normal operating temperatures. When heated, diesel fuel can provide highly flammable vapors. As the temperature of diesel fuel reaches its flash point, it becomes as flammable as gasoline. Similarly, hydraulic fluid burns readily in spray or mist form. Hydraulic fluid is particularly susceptible to forming a spray or mist because it is used at higher pressure than is the mobility fuel. Such hydraulic fluid sprays are almost as flammable as diesel fuel sprays. These include fire-resistant hydraulic fluid. A noncombustible hydraulic fluid has not yet been used because of the high cost of such fluid, even though the noncombustible hydraulic fluid is much less expensive than the combat vehicle that can be lost because of the combustible hydraulic fluid. Because ballistic impacts often result in hydrocarbon fluid sprays that are subject to ignition without regard to specific mixture ratio, a fuel spray is generally more hazardous than a fuel vapor-air mixture, which is more temperature dependent for ignition.

Once mobility fuel, solid propellant, or hydraulic fluid starts to burn, it produces a great amount of heat. Items that would otherwise smolder or melt burn readily with the extra heat. These items include rubber, plastics, wood, and fabric.

Solid gun propellants also burn more readily with increased pressure.

Some ignition sources are present before the ballistic impact disperses fuel. Hot spots, such as turbine combustor housings or turbochargers, readily ignite sprays of liquid fuel or hydraulic fluid. Electrical shorts caused by abrasion of insulation or ballistic impact ignite materials that are much less flammable than hydrocarbon fluids. With ignition sources such as these, any action that causes a fuel spray or fuel vapor in air usually will result in a fire.

1-4.1.2.2 Overhead and Underneath Threats

Not even the gods could make a warrior completely invulnerable—Achilles had his heel. Similarly, present-day combat vehicle designers have to save weight somewhere, so they have chosen to place less armor on the tops and bottoms of the vehicles than on the fronts and sides. The vehicle rears are also left a little weaker than the fronts and sides on the theory that tanks will usually be facing the enemy. As Lucas Phillips (Ref. 3) explains, however, sometimes the enemy will get behind friendly vehicles and shoot from there. This situation can occur in meeting engagements and where the enemy has infiltrated into our rear areas. This technique is favored by the former Soviets (Ref. 4) and Chinese and was used against US forces in Vietnam. But the tops and bottoms of combat vehicles remain their weakest parts.

To attack the top surfaces of combat vehicles, two basic approaches have been followed. The first is to use cluster warheads with many small shaped-charge bomblets that fall upon the vehicle or a shaped-charge warhead missile attack from above. A variation of this approach is to use explosively formed penetrators instead of shaped-charge jets. The second approach is to have a rapid-fire cannon mounted on an aircraft fire an armor-piercing projectile from above. In World War II armor-piercing bullets were used; more recently, long rod penetrators of a hard, dense material have been used. Therefore, the vehicles have to be designed so that both KE penetrators and CE (shaped-charge) warheads are considered.

To attack the bottom surface, the principal fire threat is a shaped-charge-type land mine. The shaped charge could either form a jet or launch a flyer plate. The mine could be fuzed with a tilt rod or a magnetic proximity device.

1-4.1.2.3 Incendiary Threats

In addition to the CE and KE penetration weapons and antitank mines that are currently fielded, the former Soviet forces reportedly used several incendiary weapons in Afghanistan that could pose a significant threat to our combat vehicles. These are the family of rocket-propelled infantry flamethrowers, i.e., the rocket-propelled flamethrower (RPO) and rocket-propelled flamethrower-airborne (RPO-A). (Refs. 5 and 6) These weapons are similar to the 3.5-in. rocket launcher.

Also two aerial-dispensed incendiaries were reportedly used by the Soviets in Afghanistan. One was a black, tar-like substance (Ref. 6), dispensed from container bombs that spread the incendiary in large droplets, which ignited when stepped on by personnel or when driven on by vehicles. The second incendiary consisted of brown droplets (Ref. 7) dispensed by a cluster bomb and accompanied by small antipersonnel charges. These droplets are reputed to ignite on contact by foot, wheel, or track. These incendiary weapons are more fully described in par. 2-3.1.3.

These incendiary weapons are threats that should be considered in designing combat vehicles. In urban or heavily wooded terrain there is the threat of the Molotov cocktail, a gasoline-filled glass bottle with a burning wick, which was successfully used by the Finns against Russian tanks in 1940. The RPO and RPO-A present the threat of an improved Molotov cocktail projected from a distance in either urban or rural terrain. The aerial-dispensed incendiaries present a threat on a road, trail, or open area, each of which can become a pool fire under a vehicle.

1-4.1.3 Review of Survivability Enhancement Techniques

Most designers, when faced with the need to counter a fire, install a fire extinguisher in the vehicle, but fires are difficult to start and maintain when they are wanted and are difficult to extinguish when they are not wanted. Also fires can destroy both personnel and equipment even when promptly extinguished. For these reasons, preventing fires is preferable to extinguishing them. Fire extinguisher systems should not be eliminated. There will always be instances in which fires cannot be precluded. Fire extinguisher systems, however, should not be the only, or even the primary, protection against fires.

The simplest way to prevent a fire is to delete one of the three elements needed for combustion to occur. The three elements are (1) a fuel in a combustible state, (2) sufficient oxidizer in intimate contact with the fuel, and (3) an ignition source in contact with both fuel and oxidizer that can raise the temperatures of the two to their kindling state. Thus a fire can be prevented by removing the fuel, assuring that the fuel is not in a combustible state or form, reducing the amount of oxidizer present, or eliminating or reducing the probability of ignition sources. All of these are described in this handbook. Control of these elements is also used to extinguish fires. Fires are extinguished (1) by placing a barrier between the fuel and oxidizer, e.g., light water foam, (2) by diluting the oxygen until there is not enough present to support combustion, e.g., diluting the air with carbon dioxide, (3) by cooling the fuel and surrounding objects below their kindling temperatures, e.g., by cooling with water, (4) through chemical inhibition of the combustion process, e.g., with Halons or potassium bicarbonate, or (5) by a combination of these techniques.

Flammable fluids, in fact, almost all combustible materials, burn only in the gaseous state and then only within a rather narrow range of fuel-vapor-to-air mixture ratios. A fuel-vapor-to-air mixture can be too fuel rich or too fuel lean to burn. Designers should not depend upon maintaining a mixture that is too fuel rich because as that mixture spreads away from the fuel source, more air is available to assure that somewhere the mixture will be combustible. Once a fire starts, the heat increases fuel vaporization, and air convection makes more of the mixture combustible. The more volatile the fuel, the more probable the presence of a combustible mixture. Gasoline is more hazardous than diesel fuel because it is in vapor form at normal operating temperatures. When diesel fuel is heated, however, it can become almost as volatile as gasoline. This is the reason it is poor policy to use diesel fuel as an injector coolant unless the fuel is injected into the engine and burned immediately after it is heated. Recirculating heated diesel fuel to the fuel cell increases the fire hazard.

The energy required to ignite a combustible fuel-vapor-air mixture is one-tenth of a millijoule, which is a miniscule amount of energy. Mists or sprays of flammable liquids in air can be ignited below the lean limit and above the rich limit of the fuel-vapor-air mixtures given somewhat more ignition energy than that required to ignite the vapor-air mixture but much less than the energy available in a ballistic impact. Thus mists or sprays in air present a greater hazard than does a vapor-air mixture. Prevention of the release of mists or sprays can eliminate the most hazardous of the fuel forms. Diesel fuel mists or sprays normally occur when the fuel cell is pressurized locally by hydraulic ram resulting from ballistic impact and when the spray is released from failures in the fuel cell. These failures can be significantly reduced through fuel cell design, fuel cell material selection, and/or fuel cell confinement or reinforcement. The release of fuel sprays in critical locations can also be significantly reduced by proper fuel cell location or by compartmentation. Because antitank gunners normally aim at the center of the presented area of the target, the probability of a fuel cell impact can be reduced by locating the fuel cell as far from the normal aim point as possible. Fuel cells can be located either low in the vehicle or in the rear. The probability of diesel fuel spray from a fuel line can be reduced by lowering the pressure in the fuel line. If atmospheric pressure is used to force the fuel to flow, there is a much smaller probability of a fuel spray given fuel line puncture by a ballistic impact. Hydraulic fluid lines, on the other hand, are usually more highly pressurized than fuel lines, and they are located throughout the vehicle. Therefore, the hydraulic power system of a vehicle can be more hazardous than a properly designed fuel system unless a truly nonflammable hydraulic fluid is used. Electric drives can be used to eliminate the hydraulic fluid. Alternatively, a fire extinguisher or inerting system can be used to extinguish combustion or reduce the probability of a hydrocarbon fuel fire in a given compartment. A fixed fire extinguisher system in one compartment, however, cannot affect a fire in another compartment, and some extinguisher systems must direct the extinguishant at the fire to be effective. Also use of gaseous extinguishants, such as many Halons or carbon dioxide, makes the effect time dependent since hot spots will not be cooled and the gaseous extinguishant will be diluted by airflow through the compartment with passage of time. This dilution makes the compartments thereby protected subject to reignition after more air has mixed with the atmosphere of the compartment.

Solid rocket propellants and to a lesser degree high explosives contain most of the oxidizer as well as the fuel needed for combustion. Solid gun propellants burn more rapidly when pressurized, and a cartridge case prevents the rapid dispersion of products and results in pressure buildup. For these reasons, solid propellant or explosive fires are more difficult to preclude than are liquid fuel fires. Solid rocket propellants are usually closer to a stoichiometric oxidizer-to-fuel mixture than are high explosives; therefore, they are more susceptible to reacting violently given a ballistic impact. Once ignited, solid rocket propellants can be extinguished only by being cooled below the kindling temperature, preferably with a water deluge. When these propellants are cased, either with a metallic or combustible case, or are in a solid mass as are caseless charges, the coolant cannot reach the propellant in time to prevent chemical reaction. Cooling of gun propellant has proved feasible only with exposed propellant grains. This is fine for ammunition loading plants but does not help in combat vehicles unless a device is used to inject the liquid through the cartridge case. Methods for enhancing crew and vehicle survivability given solid propellant or high-explosive initiation due to ballistic impact usually focus on containment and redirection of the explosion effects away from critical areas of the vehicle.

By critical examination of the combustion phenomena for each combustible and of the failure modes of the equipment, the equipment can be modified either to preclude fire or explosion or to assure that the fire or explosion effects will be directed away from the crew and critical components of the vehicle.

1-4.2 DESIGN PHILOSOPHY

1-4.2.1 Basic Combat Vehicle Design Philosophy

History has shown that every armor system fielded has been followed by the fielding of an antiarmor system capable of overcoming the armor, which has in turn been followed by the fielding of a newer armor system capable of withstanding the new antiarmor system, and that design, development, manufacture, and fielding of the newer armor system have taken twice as much time as they did for the newer antiarmor system (Ref. 8). Therefore, sooner or later armor will be overcome by some threat. The combat vehicle should be constructed so that when the armor is defeated, the crew will not be burned and the vehicle will not be damaged beyond recovery by fire.

In designing a combat vehicle, the priority for protection is

1. Personnel
2. The vehicle
3. Equipment within the vehicle
4. Material stowed within the vehicle.

The approach used in designing a combat vehicle should be to use passive fire protection techniques to

1. Eliminate, reduce, or confine combustible materials.
2. Reduce the probability of ignition of these combustible materials.
3. Reduce the probability of having sustained combustion of these materials.
4. Reduce the generation or liberation of toxic, noxious, or irritating products that would drive personnel out of the vehicle.
5. Provide some means for the crew to extinguish whatever combustion does occur.

Specific techniques that can be used are to

1. Locate hazardous items so that if they burn or explode, the personnel will not be killed or injured and the vehicle will not be destroyed. If possible, render these items nonhazardous by preventing severe reactions, e.g., by providing an extinguishant which will be released by the same threat that caused the reaction.
2. Assure that a damaged combat vehicle provides protection for its occupants. The vehicle must remain habitable and, if possible, operable after being hit, which includes preventing the entrance of flame, fire, and noxious products into the occupied compartments.
3. Realize that if a combat vehicle is hit once, it is subject to being hit more times, particularly if the vehicle can no longer move; therefore, care must be taken to design the vehicle so that the early hits do not render the vehicle more susceptible to potential fires by subsequent hits.

1-4.2.2 Incorporation of Fire Survivability Concepts

General George S. Patton, Jr., has been quoted as saying, "There is only one tactical principle, which is not subject to change. It is to use the means at hand to inflict the maximum amount of wounds, death and destruction on the enemy in the minimum amount of time." (Ref. 9). The job of vehicle designers, program managers, equipment manufacturers, and planners is to make certain that US troops have at hand, now and in the future, the most fire survivable and effective combat vehicles in order for them to wound, kill, and destroy the enemy.

There are basically three times during the life of military equipment when fire survivability enhancement devices can be incorporated into combat vehicles. These three times are when the vehicles are

1. Already issued to troops
2. Currently being produced
3. To be designed for future use.

Where combat vehicles are currently vulnerable to fire, these vehicles should be modified and the fire survivability concepts must be designed for economic incorporation. Fire survivability concepts for retrofit on existing vehicles may not be as fully effective, as economical, as light, or use as small a volume as a complete vehicle redesign would provide, but these design modifications can provide significant survivability enhancement. When incorporating modifications into existing vehicles, maintenance personnel can more easily replace specific components, such as an existing single-walled fuel cell with a double-walled fuel cell, which will fit into the same space, or install an added component, such as a reinforcing wall over an exposed portion of a fuel cell, than tear out the internal components and rebuild, relocate, and replace all or most of these. This also means modifications that can be performed at the organizational or direct support level of maintenance are preferable to those that require depot or fabricator rework. Field teams from the depots or fabricator should be sent to advise the organizational or direct support maintenance personnel to assure proper modification.

Modifications that can be incorporated during production should be planned in order to minimize disruption in the production schedule. Again, these modifications may not be as effective as those incorporated in a completely new design, but they will be better than no design modification and should be more effective and less expensive than modifications that would be made after the vehicle is completed.

When incorporating fire survivability concepts into designs of future vehicles, the designers have more freedom to select materials, locations, and techniques than they do when modifying existing vehicles or changing designs already in production. The same goals can be achieved using different means. Some hazards can be precluded by more reasonable material selection or component location. In general, however, a single, optimum design will not be achieved since there are design tradeoffs and continued changes in threats, required contents, and operational requirements that will make today's defense tomorrow's hazard. Some thought should be given to providing designs that can accommodate the future modifications which will undoubtedly become necessary.

Note that when fire survivability enhancements are incorporated early in the design and development of a combat vehicle, better protection is provided at a lower cost with similar weight and volume penalties. For example, it costs more money to provide less protection on older and current combat vehicles than to design future systems that include these enhancements. In general, the current designs will be used by troops now and for several years. The future designs will be used for combat vehicles sometime in the future and for many years after they are issued to troops.

1-5 COST ANALYSIS

Inevitably, when a modification to a combat vehicle is proposed, the first question asked is what is the cost, or what am I buying for the cost? There is no existing computer model that can be used to predict this cost or to establish whether the modification will be cost-effective. Documents that could assist in the preparation of such a computer model are the cost and effectiveness analyses of modifications to the M113 family of vehicles (FoV) and the M60 MBT by Douglas Hackenbruch (Ref. 10 and 11), the cost comparison of nine alternate fire-extinguishing systems for the Field Artillery Ammunition Support Vehicle (FAASV) by John Karas (Ref. 12), and a means to estimate the life cycle costs of incorporating survivability enhancement concepts for fuel systems in aircraft (Ref. 13) in an unpublished report by P. H. Zabel and N. W. Blaylock.

1-5.1 COST-EFFECTIVENESS STUDIES CONDUCTED AT THE US ARMY TANK-AUTOMOTIVE RESEARCH AND DEVELOPMENT COMMAND (TARADCOM) [NOW US ARMY TANK-AUTOMOTIVE COMMAND (TACOM)]

The cost-effectiveness of fire survivability enhancement systems (FSES) was evaluated for two different vehicles. The use of external fuel cells was evaluated for the M113 FoV (Ref. 10), and the use of automatic fire detection and suppression equipment (AFDSE) was evaluated for the M60 MBT (Ref. 11). The basic evaluation technique was the same in both cases, but the methods used to calculate the system effectiveness *SE* differed. In both cases combat damage data from Southeast Asia (SEA) were considered, and for the M60 MBT data from the Yom Kippur War were reviewed. In both cases, the Dehn fuel fire model (Ref. 14) was used to establish the probability a sustained fire could exist; this model description was supplemented by Wright and Slack (Ref. 15).

1-5.1.1 External Fuel Cell for M113 FoV

In the analysis of the M113 FoV, the use of external fuel cells was deemed 100% effective preventing a sustained diesel fuel fire within an M113-type vehicle. This followed the Dehn fuel fire model, which states that four consecutive events must occur for a sustained fuel fire to develop. These four events are (1) a fuel spray must form, (2) the spray must be ignited, (3) the ignited spray must ignite a fuel pool, and (4) the extinguishing system must fail. Hackenbruch assumed that with external fuel cells the probability of a fuel spray forming and the probability of a fuel pool forming inside an armored personnel carrier (APC) were near zero. As a corollary, the system effectiveness of the FSES was assumed to be equal to the complement of the probability of having a sustained fire P_{SF} or

$$SE = 1 - P_{SF}, \text{ dimensionless.} \qquad (1\text{-}1)$$

For P_{SF} Hackenbruch evaluated the combat loss data from SEA for fiscal year (FY) 1969 to obtain the probability of a sustained fire resulting when an internal fuel cell is used $P_{SF_{IFC}}$ for the M113 FoV. He assumed that P_{SF} equaled the number of incidents of sustained fires causing complete losses divided by the total number of vehicles hit. He then estimated how many vehicles would not have been lost if these vehicles had had external fuel cells to obtain the probability of a sustained fire resulting when an external fuel cell is used $P_{SF_{EFC}}$ by deleting the number of vehicles that had fires start from hits on the fuel cell from the sustained fire subtotal.

The cost-effectiveness ratio *CER* was determined for the M113 FoV by dividing the *SE* by the vehicle cost *VC* or

$$CER = SE/VC, \ \$\mathrm{US}^{-1}. \qquad (1\text{-}2)$$

The vehicle cost used was the cost to acquire the vehicle. This *CER* was determined for the vehicle as manufactured, i.e., with an internal fuel cell, and for the vehicle with external fuel cells. The incremental cost of the external fuel cells was estimated by Government personnel.

The *CER* with the FSES was compared to the *CER* without the FSES to determine whether the FSES was cost-effective. These *CER*s and their constituent *SE*s and *VC*s were then compared to establish the break-even cost of the FSES and alternatively the break-even cost of repairing damaged vehicles.

1-5.1.2 AFDSE for M60 Series MBT

Regarding evaluating the cost-effectiveness of incorporating AFDSE into the M60 series MBT, the difference in the evaluation was the method used to establish the system effectiveness. The SEA data available were for the M48A3 MBT and the Yom Kippur War data for M60 MBTs. These data were not sufficiently detailed to permit assumption of the validity of Eq. 1-1; therefore, the expression recognized by the Department of Defense (DoD) for *SE* was used. This *SE* is

$$SE = A \cdot R \cdot C, \text{ dimensionless} \qquad (1\text{-}3)$$

where

- A = availability, i.e., probability that the vehicle is in a ready state at a random point in time, or operational readiness, dimensionless
- R = reliability, i.e., conditional probability that the vehicle can complete a defined mission under specific conditions, or dependability, dimensionless
- C = capability, i.e., a measure of the ability of the vehicle to achieve its mission performance objectives, or design adequacy, dimensionless.

Hackenbruch (Ref. 11) determined *A*, *R*, and *C* for the vehicle, with and without the AFDSE, by using a combination of the available combat damage data and vulnerability assessments provided by TACOME3. TACOME3 (Ref. 16) is a computer model with which the probability of kill of a combat vehicle can be computed given shotlines of either KE or CE projectiles through the armor and then internal components. Using TACOME3 techniques and inputs, Hackenbruch computed values of *SE* for the vehicle with and without AFDSE. Using these values of *SE* and costs of the vehicle and AFDSE, which were determined in the same manner as those for the M113 FoV and its FSES, he calculated the CERs and analyzed cost-effectiveness, break-even AFDSE cost, and break-even vehicle repair cost in the same manner described for the M113.

1-5.2 COST ANALYSIS FOR FAASV PREPARED BY TACOM

Nine fire-extinguishing system alternatives for the M992 FAASV were compared for combat effectiveness and cost-effectiveness for protecting against fires ignited by shaped-charge warhead perforations (Ref. 12). A shotline generation program was run that passed an array of shotlines through each one-inch square of the area presented by the vehicle and recorded the incidents on ammunition, diesel fuel, and hydraulic fluid. This shotline generation program was repeated for horizontal and vertical aspects 30 deg apart. These shotlines were assumed to be hits by shaped-charge warheads that would overwhelm the vehicle armor. The assumption was made that a hit on any ammunition would result in an explosion which would cause the loss of the vehicle and its contents. Hits on diesel fuel or hydraulic fluid containers would result in vehicle loss due to a sustained fire unless these were protected by some fire-extinguishing system in the same compartment as the container. The assumed effectiveness of each fire-extinguishing system considered is given in Table 1-1. The cost associated with a hit is the vehicle cost times the probability of an explosion or a sustained fire. The probability of a sustained fire is the complement of the probable effectiveness of the fire extinguisher to extinguish a fire listed in Table 1-1. These fire extinguisher systems were not assumed effective against explosion of ammunition.

A combat analysis was performed to generate the cumulative probability of survival and cumulative expected loss (CEL) for each alternative by round. The methodology used to compare the alternatives was CEL after the vehicle was hit by one, two, and three penetrating munitions. For two or more hits redundancy of extinguisher systems either in added bottles or in discriminating sensors reduced the CEL. A break-even analysis and an incremental analysis were performed to examine systems, cost, survivability, and expected loss.

1-5.3 METHODOLOGY TO ESTIMATE LIFE CYCLE COSTS OF AIRCRAFT FUEL SYSTEM SURVIVABILITY ENHANCEMENT CONCEPTS

Zabel and Blaylock (Ref. 13) prepared a methodology to estimate life cycle costs of incorporating and using several alternative survivability enhancement devices for aircraft fuel systems. The items treated were the overall system and specific subsystems, such as self-sealing fuel cells, ullage filler materials (reticulated foam, fiber mats, and metal mesh), void space fillers, powder packs, fire-extinguishing systems, on-board nitrogen generators, and some other devices. The costs included both those normally contracted and those incurred in a Government depot. The life cycle costs included the cost of engineering plans for incorporating the modifications, the cost of the hardware to be added including the cost of qualification testing if necessary, the costs of disassembling existing aircraft as necessary and reassembling the aircraft as modified or the additional costs of using these new devices over the existing hardware if the aircraft had not yet been assembled, and the additional costs to operate, maintain, and support these devices through the operational life of the aircraft including additional units needed for potential battle damage repair.

The cost elements were based upon combinations of estimates by suppliers or fabricators of the materials, components and subsystems and of costs realized by some prime

TABLE 1-1. ESTIMATED EXTINGUISHER SYSTEM EFFECTIVENESS (Ref. 12)

EXTINGUISHER TYPE*	EFFECTIVENESS**, %
Portable	1
Fixed fire extinguisher system (FFES), manual activation, no automatic warning system	30
FFES, manual activation with automatic warning system	90
Dry chemical passive panel	90
Automatic fire extinguisher system using Halon 1301	99

*Deployed in either crew or engine compartment
**Effectiveness estimates to extinguish a fire in a given compartment based upon discussions with personnel from Human Engineering Laboratory and the Systems Integration Branch of Light Combat Vehicle Program Manager's Office

contractors and Government agencies or depots in obtaining components for original assembly or replacement items needed for maintenance operations. Component costs were obtained from records of Government purchases for stockage of repair parts and tracked from 1970 to 1981; these costs were found normally to escalate with the consumer price index (CPI). These components were made by originally qualified vendors of the products who became "locked in" for future procurements. Another example is shown as Fig. 1-2 in which a combination of Government-owned drawings and specifications plus a generic qualification and procurement competition resulted in a decrease in price over the same time period. For the initial procurement the relative cost was 2 and the CPI approximately 1.3. The data were furnished by a prime contractor for the same type of

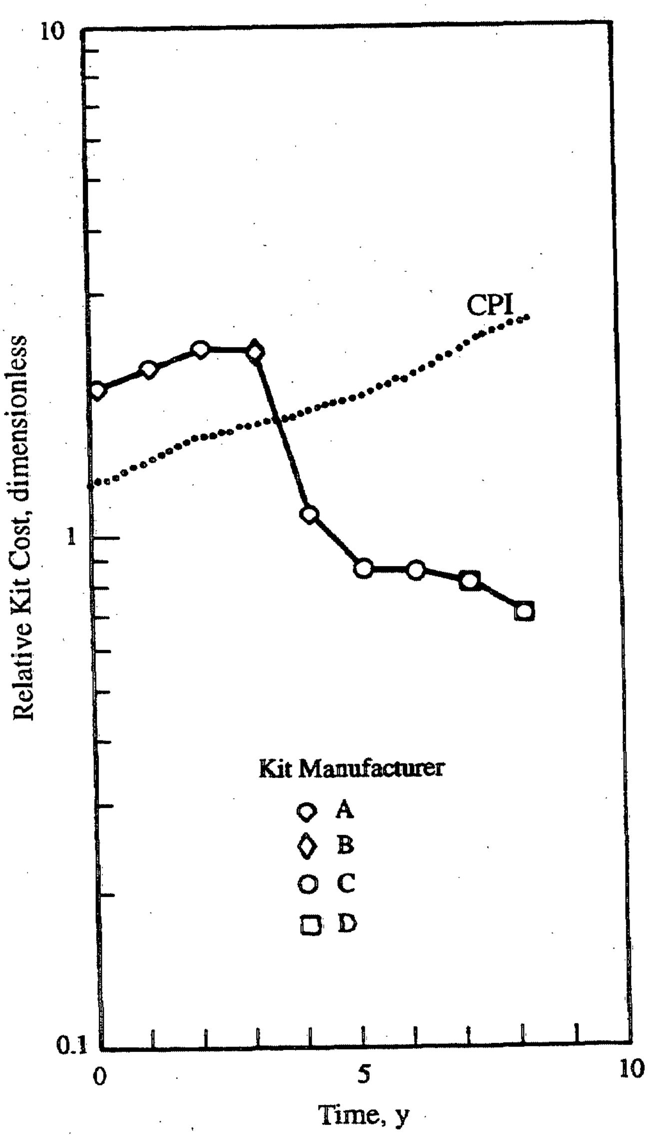

Figure 1-2. Reduction in Reticulated Foam Kit Cost Resulting From Simplification and Competition (Ref. 13)

component. In estimating unit costs the effects of procurement quantity, unit complexity, and fabrication and assembly "learning" were factored into the estimates.

Estimations of the effectiveness of these survivability enhancement concepts were beyond the scope of the cost estimator effort; however, Zabel *et al.* (Ref. 17) developed effectiveness factors for many of these items based upon test results.

1-6 CONTENT OF HANDBOOK

This handbook covers the types of combat vehicle fires, how these fires are initiated, what flammable materials are present, and what hazards the fires present to the crew and their vehicle.

The combustible materials present are described in detail with emphasis on the properties that enhance or degrade ignitability and fire sustainability or create special hazards. The combustible materials include fuels; hydraulic fluids; other mobility fuels, oils, and lubricants; munitions; and other combustibles, such as electrical wiring insulation, rubber and plastics, seat covers and cushions, paints and coatings, and items used or stowed in or on the vehicle. The clothing worn by the crew is not considered as either protection or as a combustible; however, spare clothing and bedding stowed by the crew within or on the vehicle are treated as combustibles.

Fire prevention that can be gained by engine selection or engine design features is discussed. Fuel, hydraulic, and electrical system design features that affect fire prevention are described and discussed. Munitions types and stowage features that affect fire prevention are covered. General guidance on material selection for fire reduction is provided. System design features that enhance fire prevention or inhibit fire propagation are covered.

Crew survival criteria are covered and include the types and extents of thermal injury and ear, lung, and eye injury. The potential for asphyxiation or toxic gas poisoning is discussed. The potential effects on human performance from these types of injuries are discussed.

Fire detection systems and their components are described and their characteristics given.

Fire-extinguishing agents and systems are described and discussed. Both active and passive systems are covered, as are manual fire extinguishers.

Techniques used to test and evaluate design verification are described and discussed. Means of measuring performance parameters that can be tested are described. The techniques used to model crew incapacitation, equipment damage, and fire initiation, growth, extinguishment, and prevention as functions of ballistic impacts or other ignition causes are described. Existing computer models are described. If these are lacking, the elements needed for such models are given.

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CHAPTER 2
CATEGORIZATION OF FIRES

This chapter identifies broad categories of fires that occur in combat vehicles. Fire types are defined and grouped on the basis of propagation rate. The type of combustible material, ignition source, fire location, and other details that affect the growth rate of fires and hence the survivability of combat vehicles are discussed.

2-0 LIST OF SYMBOLS

D_{dd} = fuel droplet diameter, μm
D_{sd} = sphere diameter, mm
E_a = apparent activation energy, kcal/mole
T_{ig} = temperature of sphere that results in fluid ignition, K
β = fuel droplet evaporation factor, $\mu m^2/ms$
τ = fuel droplet evaporation time, ms

2-1 INTRODUCTION

Fires in combat vehicles can be categorized by rate of growth, by means of initiation, by fuel types, and by location. The rate of growth of a fire can vary from a deflagration, i.e., a low order explosion occurring in milliseconds, to a smolder, e.g., the burning of coals. Normally the rate of growth of a fire varies as different combustible materials are reached or released, as the heat generated builds up, or as the quantity of oxidizer present changes. The state or form of the combustible material, or fuel, also affects the rate of growth. Thus the potential rate of growth of a fire can influence the selection of the fire suppression system. For example, an automatic system would be needed to suppress a deflagration.

The definitions that follow are useful in considering the state or form of combustibles:

1. *Vapor*. Any substance in the gaseous state; thought of with some reference to the liquid or solid state. Vapor is molecular in size and usually formed by heating a liquid so that molecules leave the liquid bulk.

2. *Fog*. Vapor condensed into fine droplets large enough to scatter light and to obscure vision. The droplets in a fog range in size from 0.25 to 1.0 μm and remain suspended in air by the effects of Brownian motion.

3. *Mist*. Liquid droplets greater in size than 1.0 μm and extending up to about 5 μm in diameter. For droplets in this size range, the gravitational force is relatively small compared to the viscous draft force. These droplets are not permanently airborne by Brownian motion; they will eventually settle unless buoyed up by gas convection or circulation. Sloshing of fuel in a cell can cause a mist to form in the ullage of the fuel cell.

4. *Spray*. A distribution of droplet sizes generally greater than 5.0 μm in diameter. In the area of combustion, sprays are produced by shear forces acting on a liquid fuel jet that impinges on the surrounding air. The liquid is dispersed and forms sheaths followed by ligaments, which, because of surface tension forces, break up into droplets. A ballistic impact through a liquid fuel or rupture of a high-pressure hydraulic fluid line can result in a spray.

5. *Dust*. A mist-like suspension in which the material is in the solid state rather than liquid.

The means of initiation of fires include munition initiation, electrical discharge, hot surfaces, and exothermic reactions. The jet from a shaped charge can initiate gun propellants directly or can disperse liquid hydrocarbon fuel in the form of vapors and spray and can project high-temperature particles of aluminum or steel, which can ignite the hydrocarbon fuel. High-velocity, kinetic energy (KE) projectiles can do the same. Armor-piercing incendiary or tracer projectiles can introduce a burning material into an internal, vehicular compartment as well as disperse fuel. Armor-piercing, high-explosive incendiary projectiles can introduce a detonating warhead into a lightly armored vehicle. Thus there are many means by which to disperse fuel in flammable forms and provide many ignition sources from threat munitions. Electrical discharges can occur where insulation is destroyed through abrasion during normal vehicle operation or is ruptured and removed by munition effects. Unless the electrical circuit is broken, the electrical discharge can continue for a considerable time. Hot surfaces can ignite hydrocarbon fluids that are sprayed thereon. If the temperature of the hot surface is high enough, heavy hydrocarbon fluids can be cracked to produce more easily ignited, lighter fluids. Exothermic reactions can provide heat to melt and boil and then ignite combustibles. Exothermic reactions include the spontaneous combustion of oily rags, a smoldering cigarette butt, and a slow-burning fire, which by itself might not be dangerous. High-temperature exothermic reactions, such as burning metals, can convert extinguishants into fuels and oxidizers. The means of initiation of a fire is an important consideration in selecting the details of the extinguishant and fire suppression system.

All combustible materials are considered to be types of fuel. These fuels include hydrocarbon fluids, gun propellants, high explosives, electric wire insulation, paint, plastics, rubber, seat covers, axe handles, maps, clothing, magnesium/aluminum alloy road wheels, and lithium battery plates. The fuel type is a determinant for the extinguishant to be used as well as the type of fire suppression system. In addition to fuels oxidizers also should be considered. For example, armored maintenance or recovery vehicles, or armored personnel carriers used for medical evacuation, may be required to carry bottled oxygen. Release of the oxygen could increase the probability of ignition and contribute to the severity of a fire in this type of vehicle.

Fires can occur within, on, or below combat vehicles. Potential fire locations are important in positioning fire suppression systems and in designing other survivability enhancement features. Most current combat vehicles have separate engine and personnel compartments. Munitions are often carried within personnel compartments for accessibility. Some combat vehicles, however, have separate compartments for the stowage of munitions and other hazardous items. Fuel can be carried in cells located within vehicles, either in the engine compartment or the crew compartment, or in external cells. An individual fire-extinguishing system is normally effective only for a single compartment.

2-2 DEFINITION OF FIRES

Fire is a chemical reaction that involves the rapid oxidation of a combustible material. Combustion is an exothermic process: Heat is liberated. A combustible material ignites when an ignition source raises its temperature above its kindling point for a time in excess of the ignition delay period. This chemical reaction occurs at the junction of the combustible material and the oxidizer. For most solid or liquid materials, combustion occurs at or near the surface. For gaseous materials combustion occurs in the volume in which a flammable mixture of combustible gases, e.g., fuel vapor and air, exists. For solid propellants for which the oxidizer in solid form is mixed intimately with the fuel, which is also in solid form, combustion will start at the place of ignition and travel through the propellant at a rate affected by the surrounding pressure.

Flaming combustion occurs when the combustible material is in the gaseous state. Most combustible materials burn in the gaseous state; this is true for hydrocarbon fuel (liquid), magnesium (solid), and the volatiles in wood. Solids decompose, sublimate, or melt and then vaporize to burn. A liquid vaporizes to burn. The volatiles in wood decompose to burn as gases; then the remaining carbon burns as a glowing solid.

Smoldering or glowing combustion occurs when the combustible material is in the solid state. Carbon, such as coke or charcoal—coal or wood after the volatiles have been boiled out, burns in two stages as a glowing mass. In the first stage the solid carbon combines with atmospheric oxygen to form carbon monoxide. In the second stage the gaseous carbon monoxide combines with atmospheric oxygen to form carbon dioxide.

Combat vehicle fires can be categorized by rate of growth, means of ignition, fuel type, and fuel location. Such fires may be internal, external, or on the ground. Each category of fire is defined and described in the paragraphs that follow. These definitions include both fast-growth and slow-growth fires and describe the fuel involved and probable mode of ignition.

Fires are the observable effects that result from rapid chemical reactions between an oxidizing medium (such as air) and oxidizable (combustible) materials. Combustion reactions are accompanied by the release of heat, light, and oxidation products. The rapidity at which fires burn varies—they can be slow smoldering; they can have a gradual flame spread; or they can be an explosion, a nearly instantaneous total involvement of exposed materials. Explosions vary in rate of reaction from a deflagration to a detonation. A deflagration, i.e., a reaction occurring in milliseconds, is a rapid fire, whereas a detonation, i.e., a reaction occurring in microseconds, is a chemical reaction that is not categorized as a fire. The products of these two reactions differ. Normally in a fire the products are more thoroughly oxidized than they are in a detonation.

The ignition and propagation of fires require the simultaneous presence of three key ingredients, fuel, oxidizer, and heat. Heat energy is required to achieve ignition and to sustain combustion. Initially, it must be provided by an external source and for sustained combustion is supplied or supplemented by energy released by combustion reactions. The oxidizer may be atmospheric oxygen or it may be an oxidizing substance present in, or derived from, materials containing fuel-oxidizer mixtures. The fuel can be any combustible material within or around the vehicle or of the vehicle itself.

2-2.1 IGNITION

Ignition is dependent upon the state of the combustible material. To have a fast-growth fire when the oxidizer is primarily atmospheric oxygen, the fuel must be a vapor, mist, or dust. A very minute quantity of heat energy can cause ignition of vapor, but greater quantities of heat energy are needed to ignite mist or dust. When the combustible material is in large globules, pools or bodies of liquid, or in large particles or objects of solid matter, a slow-growth fire is more probable unless a great quantity of energy is involved. Ignition is described for both fluid and solid combustibles. Solid combustibles that contain oxidizers, e.g., solid propellant, burn at a rate dependent upon the surrounding pressure. They burn slowly at atmospheric pressure and more rapidly as the pressure increases.

2-2.1.1 Fluid Combustibles

The presence of gaseous fuel, oxidizer, and an ignition source is not sufficient to assure that ignition will occur. If the fuel-oxidizer mixture is lean in fuel, ignition will not occur even if the amount of energy injected by the ignition source is enormous. The same is true within limits if the fuel-oxidizer mixture is extremely rich in fuel. At an extremely high temperature, such as that achieved by the burning of combustible metals, some materials present can be altered to provide more easily ignitable ones, e.g., water can disassociate into hydrogen and oxygen. As illustrated in Fig. 2-1, there is a limited range of fuel-air mixtures in which ignition can occur. This figure shows the existence of a lower limit of flammability and an upper limit of flammability between which ignition can occur. Between these limits lies the optimum concentration at which the least amount of energy is required to achieve ignition. For combustible vapors and atmospheric oxygen this optimum concentration is near the stoichiometric ratio.

2-2.1.1.1 Ignition of Fuel Vapors

For vaporizable liquid fuels flammability characteristics may be represented graphically, as shown in Fig. 2-2. This figure illustrates the volatility and flammability characteristics of common military mobility fuels, i.e., motor gasoline (MOGAS), jet propellant (JP)-4, JP-8, diesel fuel (DF)-1, DF-A, JP-5, and DF-2. This graphical portrayal was developed specifically for use in this handbook by using established estimation procedures to extend existing data from Refs. 3, 4, 5, 6, 7, and 8. In Fig. 2-2 the centrally located vapor pressure curve separates liquid fuel on the left from vaporized fuel on the right. The flammable vapor range for each of the illustrated fuels lies within the shaded areas, between the lean limit (lower boundary) and the rich limit (upper boundary), to the right of the vapor pressure curve. The intersection of the lower limit boundary with the vapor pressure curve corresponds to the theoretical flash point of each fuel, i.e., the lowest temperature at which the surface of a liquid fuel can support combustion. The vapor pressure data for each of the fuels correspond to the in-solution volatility of the most volatile constituents of the fuel. This concept is consistent with the observed effects of mixing a volatile fuel with a relatively nonvolatile fuel. For example, if a small quantity of JP-4 is mixed with JP-8, the most volatile JP-4 components will dominate the vapor pressure and surface vapor concentration, as shown in Fig. 2-3. The theoretical flash points of these fuels at their flammability limits are presented in Fig. 2-4. The flash point of JP-4 is not controlled by the military specification and can vary through the values shown in Figs. 2-2, 2-3, and 2-4.

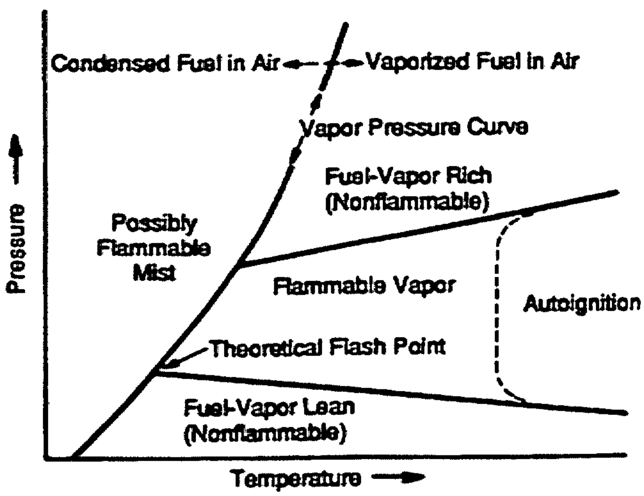
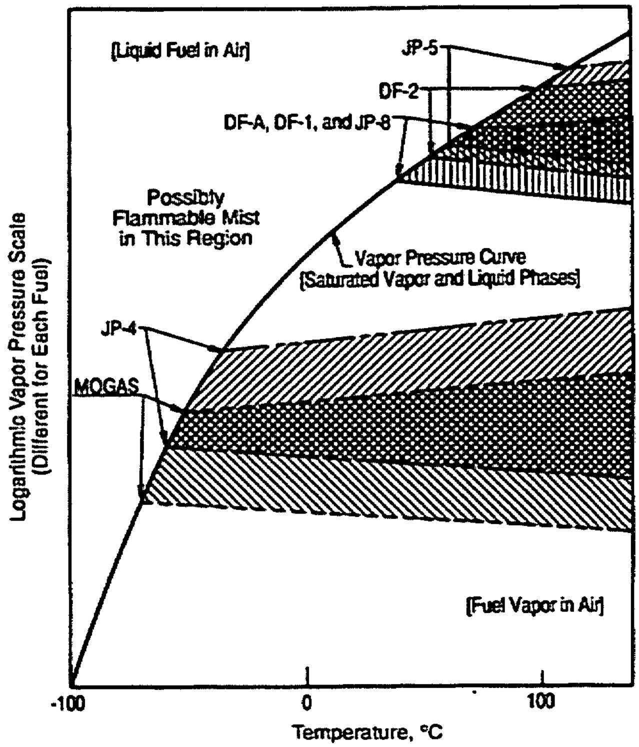


Figure 2-1. Fuel Flammability Ranges (Ref. 1)



NOTE: Shaded Areas Signify Flammable Regions

Figure 2-2. Qualitative Representation of Flammability Limits on Military Mobility Fuels (Ref. 2)

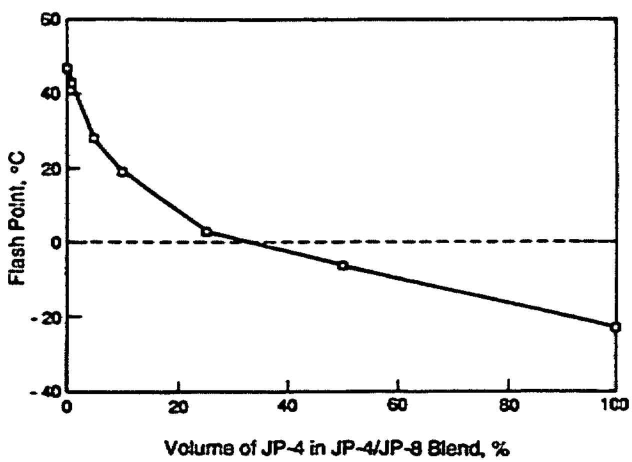


Figure 2-3. Blends of Fuels With Widely Differing Volatile Synergistic Flash Point Effects (Ref. 1)

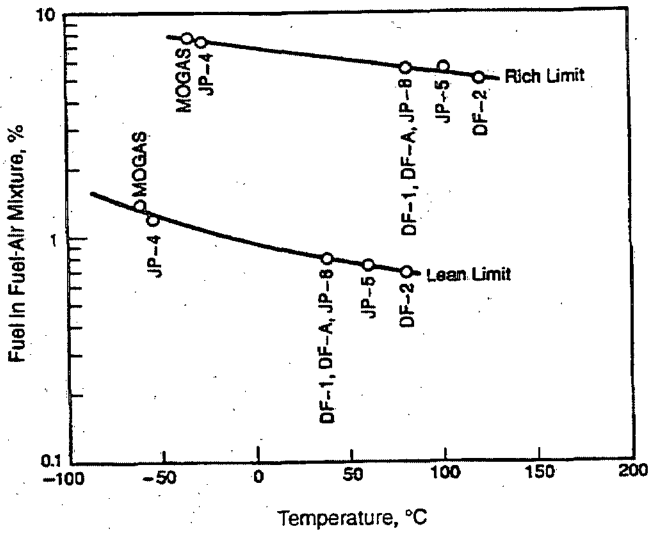


Figure 2-4. Correlation of Theoretical Flash Points With the Flammability Limit Compositions for Standard Military Mobility Fuels (Ref. 2)

Volatile fuels, such as MOGAS and JP-4, whose vapor compositions are above the rich flammability limit, are not nonflammable. Because of their high volatility, such fuels generate vapors that can diffuse or be carried into the air in surrounding regions with compositions ranging from over-rich at the liquid surface to zero at sufficient distances from the source liquid. Hence the compositions pass through the flammable range as the vapors travel from the fuel source into the surroundings. Moreover, because of their mobility, such vapors can encounter ignition sources remote from the liquid fuel source.

2-2.1.1.2 Ignition of Fuel Mist

Diesel fuel mist or spray requires slightly more energy to ignite than does gasoline mist or spray. Hydraulic fluid mist or spray requires slightly more energy to ignite than does diesel fuel mist or spray. These mists or sprays, however, are still easily ignited, especially since ballistic impacts create strong ignition sources.

Liquid fuel *must* vaporize before it will burn. The process of combustion consists of three steps: (1) fuel evaporation, (2) mixing of fuel vapors in air, and (3) oxidation reactions. The rate of flame propagation and heat release will always be limited by one of these processes. For example, if fuel evaporation and mixing are relatively slow, the burning rate will be limited because fuel must vaporize and mix with air before it will burn.

The droplet evaporation rate is strongly dependent on the droplet diameter. According to Godsave's Law (Ref. 9), the droplet evaporation time τ in milliseconds can be expressed as

$$\tau \propto \frac{D_{dd}^2}{\beta}, \text{ ms} \tag{2-1}$$

where

D_{dd} = fuel droplet diameter, µm
β = fuel droplet evaporation factor, µm^2/ms.

For example, the time required to evaporate a 100-µm droplet at flame temperatures of approximately 1927°C (3500°F) is about 25 ms, and a 10-µm droplet would evaporate in about 0.25 ms. When droplets in a combustible mixture are less than 20 µm, a flame can propagate through the mixture at up to twice the rate that would exist if the fuel had been completely vaporized. With larger droplet size this flame propagation rate decreases. Therefore, flame propagations through fuel vapors, fogs, and mists all occur at almost the same rate. Large convective currents are present when fuel vapors, fogs, and mists are formed due to ballistic attack. These currents result in a significant increase in flame speed.

There are basically two types of mixing processes. The first is simple diffusion, sometimes accompanied by mild convection. This is found in relatively quiescent fuel/air interfaces. Because the mixing is relatively slow, the burning process is also slow. The second form of mixing is turbulent mixing; it is much faster than simple diffusion because the fuel and air are carried together by fast-moving eddies. Turbulent mixing is the dominant mixing process of most practical combustion systems and of rapid-growth fires.

In this discussion the concern is the combustion of a cloud of atomized fuel formed by the impact of a high-speed penetrator upon a fuel cell. In this case, the cloud of atomized liquid fuel is very dense and there is only a limited supply of air within the cloud. As the fuel droplets evaporate, the fuel-air mixture becomes very rich, and the cloud will not burn because the fuel concentration has exceeded the rich flammability limit. Consequently, combustion is possible only near the periphery of the cloud where there is a substantial supply of oxygen. When an ignition source, such as a spark or a burning incendiary, is present at the fuel cloud/air interface, a diffusion flame quickly envelopes the cloud. In a diffusion flame the fuel is not initially mixed with air, so mixing is the rate-controlling step in the burning process. When the fuel cloud is produced by a high-energy penetration of a liquid fuel source, the turbulence in the fuel cloud and the surrounding air is such that they mix at a rate much faster than in still air. This increased rate of mixing of the fuel vapors and air increases the burning rate and consequently the heat release rate until the turbulence produced by only the burning fuel creates a self-sustaining mixing of the fuel and air, especially when the droplet diameters are larger, i.e., 50 µm or greater. Fuel mists or sprays are produced when a ballistic penetrator punctures a high-pressure line or a nonpressurized vessel that is then pressurized through hydraulic ram. A small puncture in a high-pressure line is worse than complete severance because the small puncture creates a spray, whereas severance produces a stream.

If the release of these mists or sprays can be prevented, the most hazardous of the hydrocarbon fuel forms can be eliminated. Diesel fuel mists or sprays normally occur when the fuel cell is pressurized locally by hydraulic ram that results from ballistic impact, and the spray is released at failures in the fuel cell. These fuel cell failures include the perforation made by the projectile or jet, the rupture of seams, and the tearing out of bosses or other attachments. These failures can be precluded by proper fuel cell design and fuel cell material selection or by fuel cell confinement or reinforcement.

Also, as indicated in Fig. 2-2 for vaporizable liquid fuels, ignition and combustion can occur in the region to the left of the vapor pressure curve if the liquid phase is dispersed as a spray or mist in air. Thus, the flammable range cannot be indicated on the graph because it is determined by complex interactions among variables involving the nature of the mist, its environment, and the type of ignition source. A discussion of the major difference between flame propagation in suspensions of liquid droplets in air and in mixtures of fuel vapor in air follows.

The lower flammability limit for a mist on a weight basis in some cases may be less than that of the same fuel dispersed as a vapor-air mixture. It is partly because of this phenomenon that the fire or explosion hazards posed by fuel mists are substantial even though the energy required to ignite a mist is substantially greater than that for a gaseous mixture. Fig. 2-5 illustrates the minimum energy required to achieve spark ignition of JP-4, JP-8, and JP-5 sprays or mists and the effects of temperature on the minimum ignition energy (Ref. 10).

Mobility fuels are blends of many hydrocarbon fluids. Ignitability of a blend depends primarily upon the lighter—gaged by molecular weight—hydrocarbon fluids (Ref. 11). The simpler of these fluids are described in Table 2-1, and the energy required to ignite the vapor of the lighter of these is shown in Fig. 2-6. There is not a great difference in the minimum ignition energy for any of these vapors, but both the vapor-air mixture ratio at which the minimum energy is effective and the overall mixture ratio ignitability range increase with an increase in fluid molecular weight. These lighter hydrocarbon fluids are present in mobility fuels to a varying degree. More are present in fuels with a lower flash point, e.g., JP-4, than in a fuel with a higher flash point, e.g., JP-5. Since these lighter fluids, e.g., methane, ethane, or propane, are more volatile than the heavier ones, e.g., decane, tridecane, or cetane, the lighter fluids, which are present in freshly refined fuels, are basically absorbed by

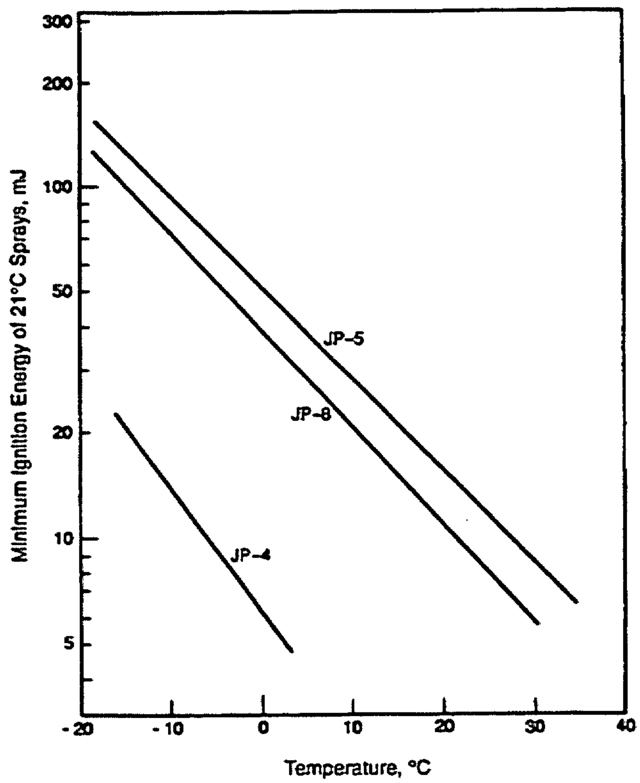


Figure 2-5. Minimum Energy to Ignite Selected Military Fuels in Spray Form (Ref. 10)

the heavier fluids and are lost from the blend as it "ages" or "weathers". DF-2 has been crudely described as a blend of decane 19%, cetane 57%, docosane 14%, C_2-benzenes 5%, and C_2-naphthalenes 5% (Ref. 13). This is a simplification of the composition of DF-2.

Mists may be highly flammable, even when the temperature of the droplets is substantially lower than the flash point of the fuel. In addition, flame propagation rates and the resulting blast overpressures in mists can be greater than in gases, depending on the properties of the mist and the composition of the liquid fuel. In view of the unique characteristics of flammable mists, their importance relative to combat vehicle fire safety cannot be overstated.

2-2.1.1.3 Geometry Effects

The ability of an ignition source to achieve ignition in the presence of a flammable fuel-air mixture depends not only on the temperature or energy content of the ignition source but also on its geometry. As shown in Fig. 2-7, the source temperature required for ignition increases as the surface area of the ignition source decreases. The greatest temperature or energy content is required for electrical sparks.

TABLE 2-1. PROPERTIES OF SIMPLE HYDROCARBONS (Ref. 12)

FLUID	FORMULA	MOLECULAR WEIGHT	SPECIFIC GRAVITY DIMENSIONLESS, AT °C	BOILING POINT, °C AT ATMOSPHERIC PRESSURE
Methane	CH_4	16.04	0.466 @ –164	–164
Ethane	C_2H_6	30.07	0.572 @ –100	–88.6
Propane	C_3H_8	44.11	0.5853 @ –45	–42.1
Butane	C_4H_{10}	58.11	0.6012 @ 0	–0.5
Pentane	C_5H_{12}	72.15	0.6262 @ 20	36.1
Hexane	C_6H_{14}	86.18	0.6603 @ 20	69.0
Heptane	C_7H_{16}	100.21	0.6837 @ 20	98.4
Octane	C_8H_{18}	114.23	0.7025 @ 20	114.23
Nonane	C_9H_{20}	128.26	0.7176 @ 20	150.8
Decane	$C_{10}H_{22}$	142.29	0.7300 @ 20	174.1
Tridecane	$C_{13}H_{28}$	184.37	0.7564 @ 20	235.4
Cetane*	$C_{16}H_{34}$	226.45	0.7733 @ 20	287
Docosane	$C_{22}H_{46}$	310.61	0.7944 @ 20	368.6

*or hexadecane

2-2.1.1.4 Ignition of Vapors by an Exploding Charge

An example of the ignition of an explosive JP-4 vapor-air mixture by the products of detonation from a 23-mm high-explosive incendiary tracer (HEIT) projectile impacting at 472 m/s (1548 ft/s) is shown in Fig. 2-8. This figure illustrates a sequence of events after a 23-mm HEIT projectile* detonated on the outside surface of a fuel cell containing JP-4 near –7°C (20°F). An explosive mixture of fuel vapors and air formed within the ullage. A high-frame-rate motion picture camera recorded events within the ullage through a transparent top of 3.2-mm (0.125-in.) thick acrylic. Fig. 2-8(A) shows products of the detonation of an aluminized explosive following fragments that perforated a crashworthy, caliber (cal) .50 self-sealing panel, which was along one wall of the fuel cell. Figs. 2-8(B) through 2-8(I) show this cloud of detonation products traversing the ullage to a similar crashworthy, cal .50 self-sealing panel on the opposite wall. Note that this cloud of detonation products, which contained numerous glowing particles of aluminum that were the probable source of the light photographed, did not

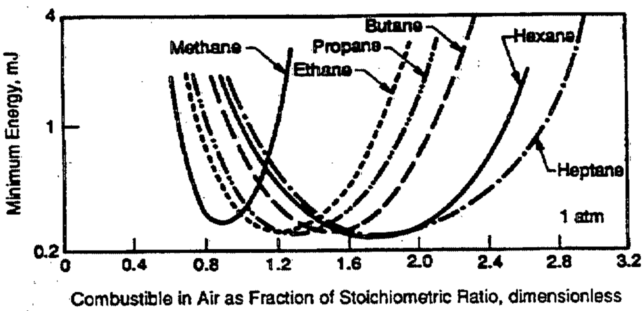


Figure 2-6. Spark Ignition Energy vs Fuel-Air Composition for Various Straight Chain Saturated Hydrocarbons in Vapor State (Ref. 3)

*The MG-25 fuze of this projectile had been modified to produce an almost super quick function rather than the normal delay function.

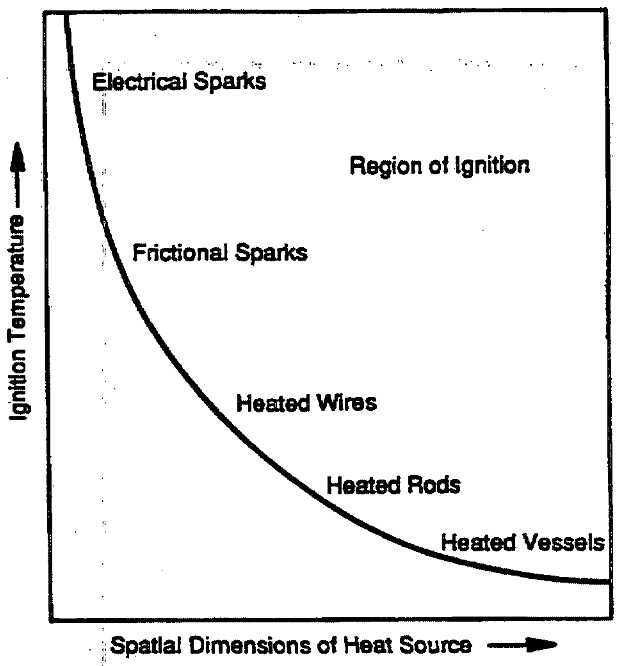


Figure 2-7. Relative Ignition Temperatures of Heat Sources (Ref. 14)

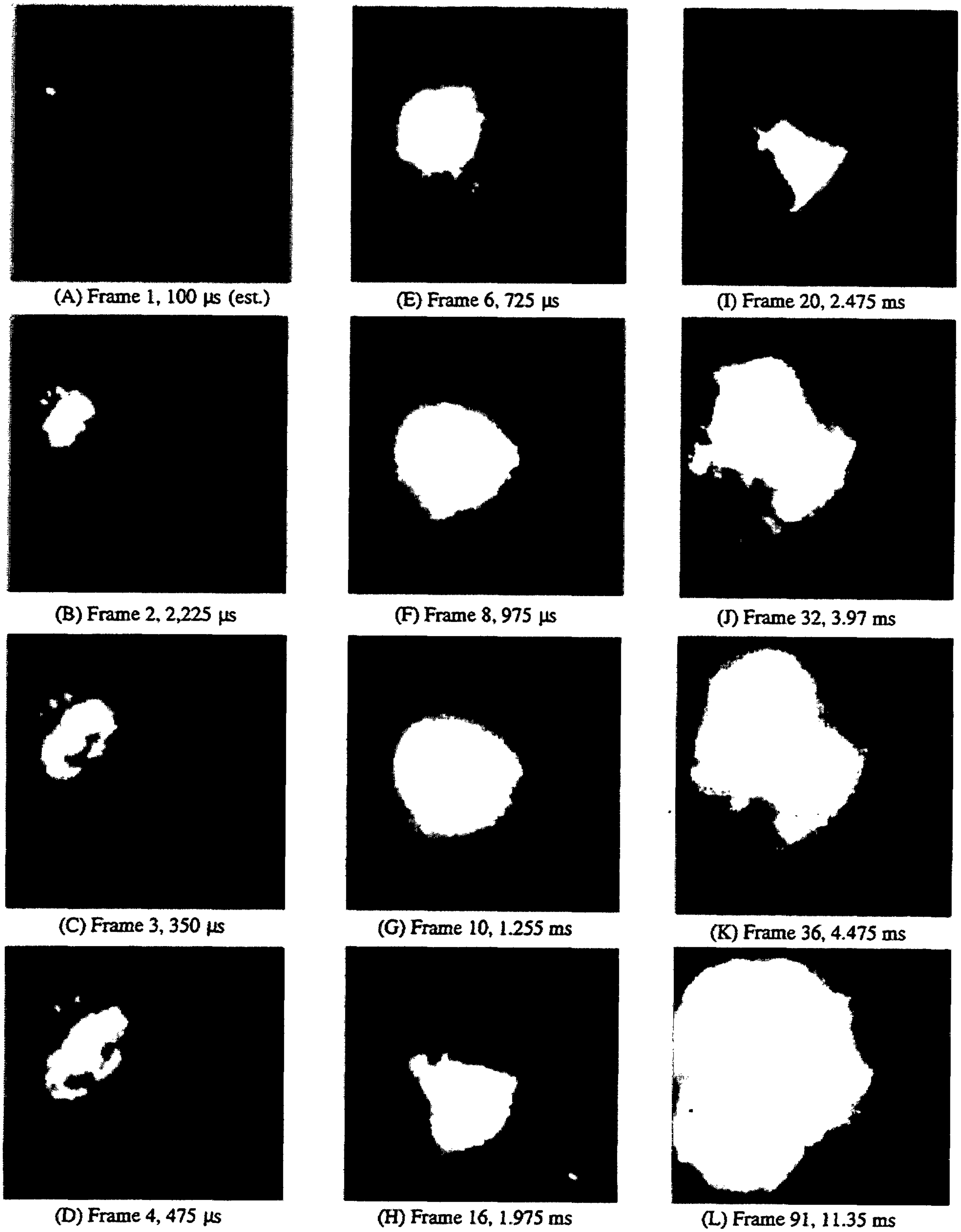


Figure 2-8. Time Sequence From 23-mm HEIT Detonation to Ullage Vapor Combustion (Ref. 15)

ignite the explosive mixture and were either cooling or collecting on that far wall until approximately the time of Fig. 2-8(I) when the vapors in the ullage ignited. At the time of Fig. 2-8(L), the transparent top of the test fixture began to rupture (Ref. 15).

2-2.1.1.5 Ignition of a Spray by a Heated Surface

When heated surfaces ignite a fuel spray, ignition temperatures exhibit an apparent inverse volatility effect. The surface temperatures required to achieve ignition of a hydrocarbon fuel spray increase with increasing fuel volatility, even though the minimum autoignition temperatures remain about the same (Refs. 4 and 14). Similar effects have been observed for hot-surface ignition of low-volatility hydrocarbon oils. An explanation of this effect could be in the rates of fuel vapor evolution when the liquid fuel impinges on the heated surface; these rates would increase with increasing fuel volatility. With a more volatile fuel, the location of the vapor-air mixture containing the composition required for ignition under the existing conditions would be pushed farther from the hot surface than it would for a less volatile fuel because the rate of vapor evolution increases with fuel volatility. Since the temperature gradient within the vapor adjacent to the hot surface would be about the same for different hydrocarbons and if all other physical conditions are the same, the surface temperature required for ignition of the mixture would be correspondingly higher if the mixture were farther from the surface. Obviously, these inverse effects do not imply that hot-surface fire safety should increase with increasing fuel volatility. In fact, the coincident increase in the evolution of flammable fumes would represent a decrease in fire safety.

2-2.1.1.6 Ignition by Hot Particles

Finnerty and Schuckler (Ref. 16) explored the ignition of military fuels by hot particles. Their work concerned the situation in which a small, hot particle came in contact with liquid fuel. This could occur where hot spall or a shaped-charge slug could come to rest in a puddle of fuel on or in a combat vehicle. Stainless steel spheres were used for the particles. DF-2 and MOGAS were used to test both low- and high-volatility fuels. The spheres were heated and then dropped into fuel in a container. The size of the sphere and the depth of the fuel were adjusted so that approximately a third of the sphere would protrude above the fuel surface unless complete immersion of the sphere was desired. A sustained fire was adjudged only when the entire fuel surface burned; otherwise, the result was judged to be no ignition.

The conclusions were

1. Diesel fuel can be ignited by partially submerged hot particles as long as the fuel temperature is 30°C (86°F) or higher.
2. Fully submerged particles can ignite diesel fuel at or above its flash point.
3. The lowest temperature T_{ig} in K at which a partially submerged steel sphere can ignite diesel fuel near its flash point is

$$T_{ig} = 1338 \exp(-0.00736 D_{sd}), \text{K} \quad (2\text{-}2)$$

where

D_{sd} = sphere diameter, mm.

4. The apparent activation energy E_a, i.e., the energy needed to ignite the fuel, for diesel fuel is 32 kcal/mole.
5. Gasoline was ignitable by hot steel spheres at fuel temperatures of –78°C (–108°F) and 0°C (32°F), but the gasoline vapors formed were too fuel rich to be ignited at 25°C (77°F).

2-2.1.1.7 Environmental Effects

In addition to the foregoing effects of variables on flammability, both the ignition energy, or ignition temperature, requirements and the flammability limits may be altered by environmental effects, such as the flow of fuel-air mixtures past the ignition source. Such influences are shown in Figs. 2-9 and 2-10.

2-2.1.2 Solid Combustibles

Solid combustibles that are dependent upon external oxidizers generally require more heat energy to ignite than do combustible vapors (Ref 18). If these solids are in the form of dust, ignition can occur at lower energy levels than it can for larger combustible particles, and the combustion can achieve a very rapid growth, as is demonstrated by dust explosions in grain elevators. In combat vehicles, such dust clouds can be formed on a small scale by the ballistic pene-

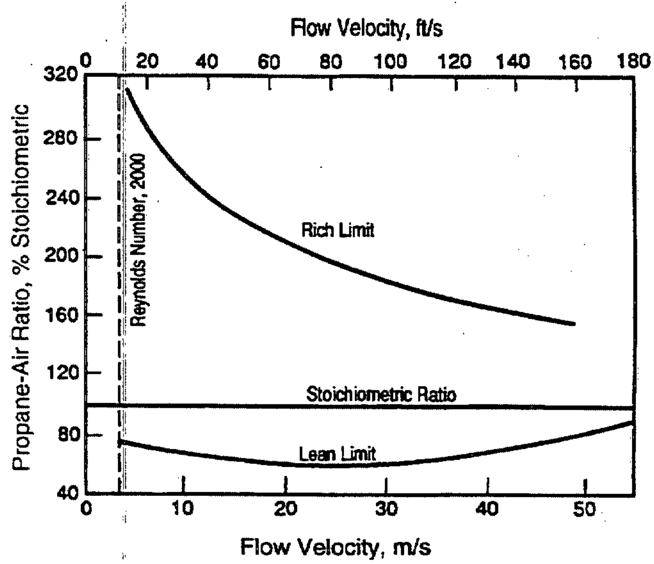
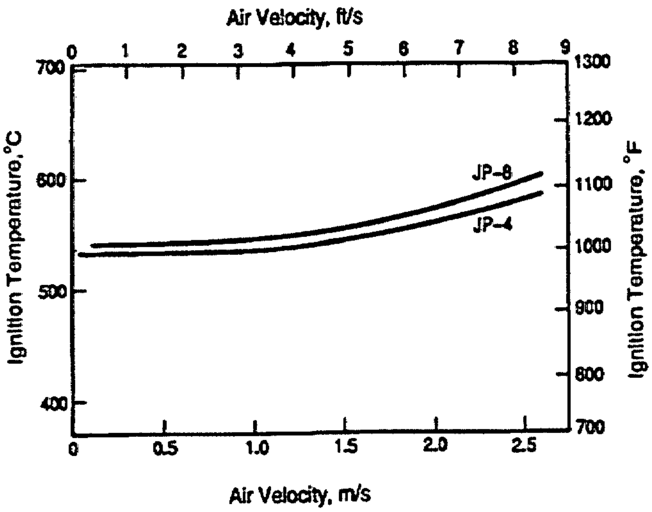


Figure 2-9. Effect of Airflow Upon Flame Propagation (Ref. 4)



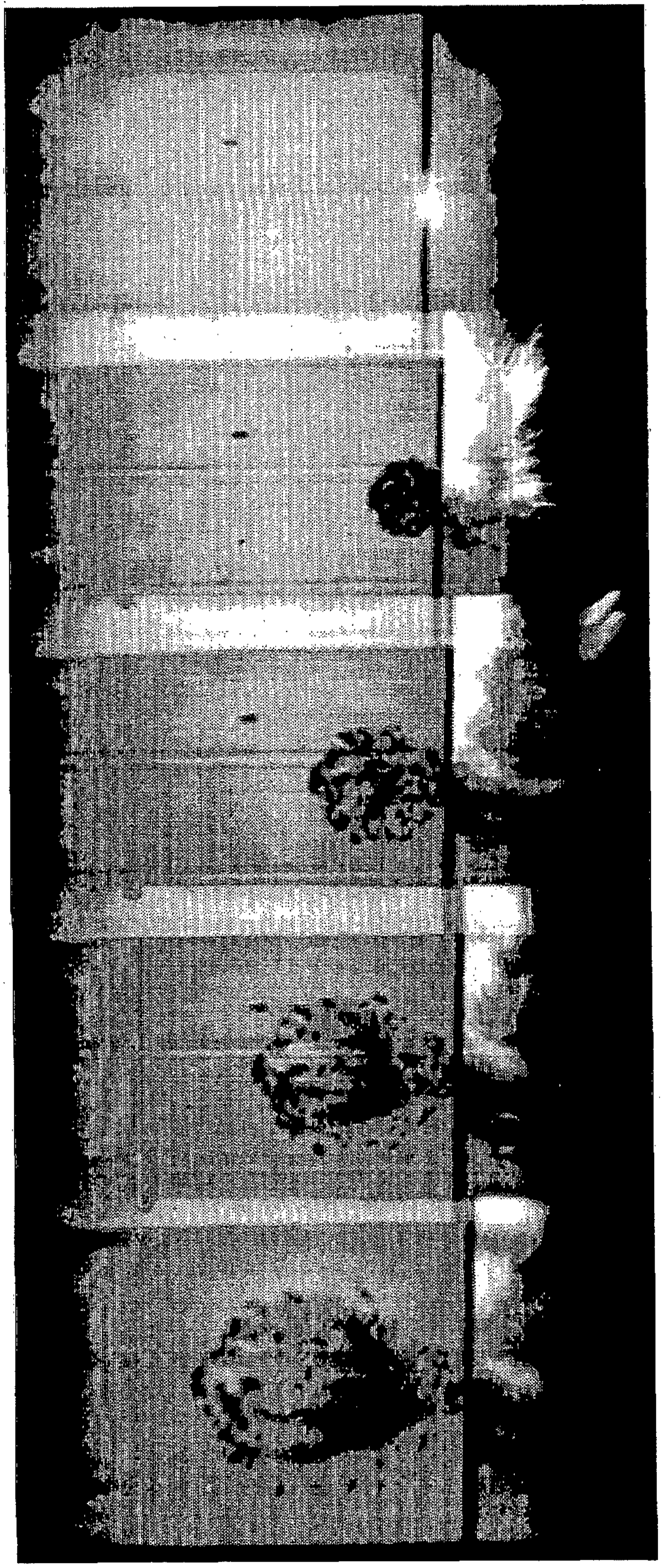
NOTE: Air Temperature, 177°C (350°F)

Figure 2-10. Comparison of Ignition Temperatures of Two Aircraft Fuels With a Heated 51-mm (2-in.) Diameter by 610-mm (24-in.) Long Steel Target (Ref. 17)

tration of a solid material layer by a fragment, a kinetic energy penetrator, or a shaped-charge jet. An image converter was used to obtain a series of five photographs taken at 20-μs intervals to establish the terminal effect of steel fragments fired into thin targets in order to obtain penetration data. Fig. 2-11 shows such a series of photographs in which a steel fragment, traveling from right to left at 1754 m/s (5753 ft/s), impacts a thin aluminum sheet. This impact occurred after the first frame (top) but before the second frame. Note the flash or splash-back, which appears to the right of the target sheet. Note also the cloud of particles of shattered fragment and spall, which appears to the left of the target sheet. This cloud of particles and spall was accompanied by a strong flash from small pieces of spall that combusted in the air. Fig. 2-12 is of a similar test in which the steel fragment impacted a titanium sheet at 1861 m/s (6106 ft/s). In this test the top frame was taken shortly after impact. The flash was stronger than the one emitted by the aluminum sheet in the previous figure. In a program to establish the effectiveness of external fuel cells to enhance the survivability of a combat vehicle given a small shaped-charge impact (Ref. 19), tests were performed to establish the characteristics of the flash generated when the shaped-charge jet perforated a simulated vehicle wall. Fig. 2-13 shows the test installation just after the shaped-charge jet passed through 6.25-mm (0.25-in.) thick steel on both sides of the fixture. This frame, taken from the real-time motion picture, shows the warhead detonation fireball escaping through the small annular space between the fragment trap and the entry face of the fixture, the jet flash (i.e., a combination of ionized air from the jet passage and flash from the

US Air Force Photograph.

Figure 2-11. Front Face Splash Emitted by Aluminum 2024T81 Sheet When Impacted by a Steel Fragment



US Air Force Photograph.

Figure 2-12. Front Face Splash Emitted by a Titanium 6Al 4V Sheet When Impacted by a Steel Fragment

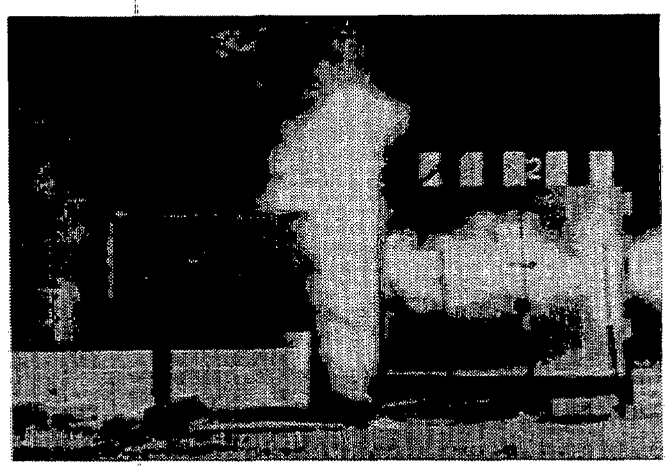
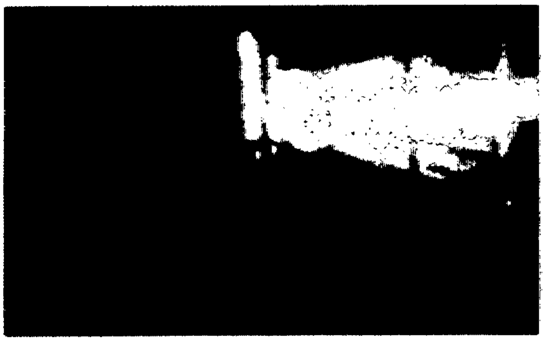


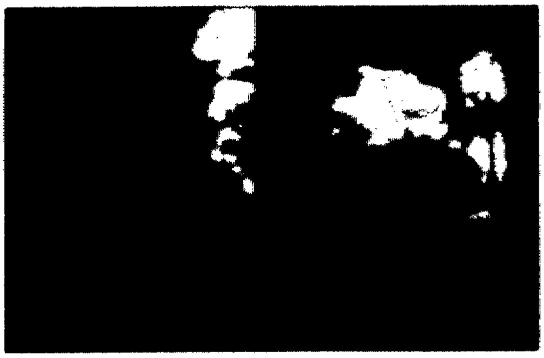
Figure 2-13. Shaped-Charge Jet Perforating Steel Plates on Both Sides of a Test Fixture (Ref. 19)

steel spall), the splash from the rear face, and the rear face jet and spall flash. In one test, shown in Fig. 2-14, the simulated vehicle wall was 6.25-mm (0.25-in.) thick rolled homogeneous armor (RHA) steel. In another test, shown in Fig. 2-15, the simulated vehicle wall was 25.4-mm (1.0-in.) thick Aluminum 5083. In both figures, the jet traveled from left to right. The flash, which is seen to the left of the test fixture wall, is a fireball from the shaped-charge detonation. Note that the shaped-charge fireball persisted for over 20 ms in both tests, but the RHA flash had vanished within 10 ms, as seen in Fig. 2-14(C). Actually all light within the test fixture was gone in 9 ms. The aluminum flash was still visible after 20 ms as seen in Fig. 2-14(D), and all light within the test fixture was gone in 28 ms. This aluminum flash was both more brilliant (Note how Frames 1 and 4 are "washed out" in Figs. 2-15(A) and (B) compared to the same frames for Fig. 2-14.) and had a longer duration—over three times—than the RHA flash. As with the steel fragment impacts shown in Figs. 2-11 and 2-12, the flash appears at both the impacted face of the target and at the exit face. In all of these cases the perforation flash, although not a hazardous fire itself, is an ignition source that can ignite liquid fuel mists caused by a ballistic penetrator that perforates a fuel or hydraulic system component.

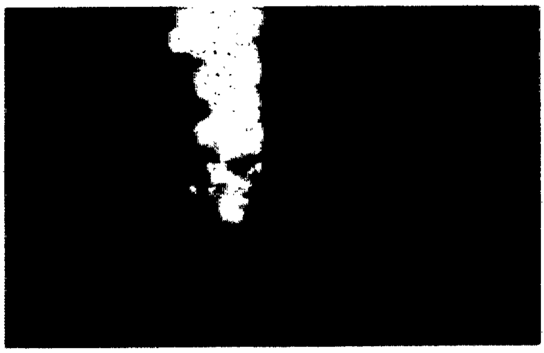
Combustible metals, such as magnesium and lithium, pose a peculiar problem. Many fire extinguishants cannot be used because of the high burning temperature of these combustible metals. These temperatures are high enough to break down some extinguishants. Halons containing chlorine, e.g., 1211, can produce phosgene, a toxic gas, when exposed to high heat levels. Water will disassociate into oxygen and hydrogen, which later can explode upon recombination. In addition, high-temperature engine parts can cause diesel fuel or hydraulic fluid to break down into more volatile hydrocarbon fluids that are more readily ignited. Because of the danger involved when the more commonly



(A) Frame 1, $t = 0$



(B) Frame 4, $t = 3$ ms



(C) Frame 11, $t = 10$ ms

(D) Frame 21, $t = 20$ ms

Figure 2-14. Flash Emitted by RHA Steel Target (Ref. 19)

(A) Frame 1, $t = 0$

(B) Frame 4, $t = 3$ ms

(C) Frame 11, $t = 10$ ms

(D) Frame 21, $t = 20$ ms

Figure 2-15. Flash Emitted by Aluminum Target (Ref. 19)

used fire extinguishants encounter burning combustible metals, the National Fire Protection Association (NFPA) has established a separate classification, Class D, for combustible metal fires (Ref. 20).

When there is a gross release of energy, as in the detonation of a high explosive, pieces of moderately combustible materials, such as polyethylene or aluminum tubing surrounding the explosive, can deflagrate in air (Refs. 21 and 22). This deflagration probably occurs because the detonation and ensuing outward expansion of detonation products can pulverize and heat the surrounding materials and drive them outward to contact atmospheric oxygen and thus promote combustion.

2-2.1.3 Solid Combustible-Oxidizer Mixture

Gun propellants are examples of solid combustible-oxidizer mixtures. Such mixtures can be initiated by heat, hot particles, impact by a shaped-charge jet or hypervelocity projectile, and severe deformation or crushing. The heat can be from a fire and be added rather slowly to the propellant itself or to the casing that encloses the propellant. The hot particles can be from a primer composition or from the ballistic perforation of the cartridge case by a fragment or projectile. In a test program that evaluated the use of selected fire extinguishants to mitigate the deflagration of the propellant charge of a 105-mm cartridge (Ref. 23), the baseline test demonstrated how the propellant charge reacted to perforation by the jet from a US Army Ballistics Research Laboratory (BRL) 81-mm precision shaped-charge warhead. In these tests the 105-mm cartridge was placed within a 0.76-m (30-in.) diameter steel pipe, a tank hull was simulated by steel plates, and the shaped charge was detonated so that the jet perforated the simulated hull and then the cartridge. The reaction of the gun propellant to perforation by the shaped-charge jet is shown in Fig. 2-16. This violent reaction was a deflagration, as was shown by examination of the remnants of the cartridge case. (The even more violent reaction, seen to the right of the pipe, is the detonation of the shaped charge. The rod of light seen to the left of the pipe is the reaction of the air to the passage of the shaped-charge jet.)

2-2.2 GROWTH

The growth of fires following ignition is affected by availability of fuel and oxidizer, by the addition of heat, and

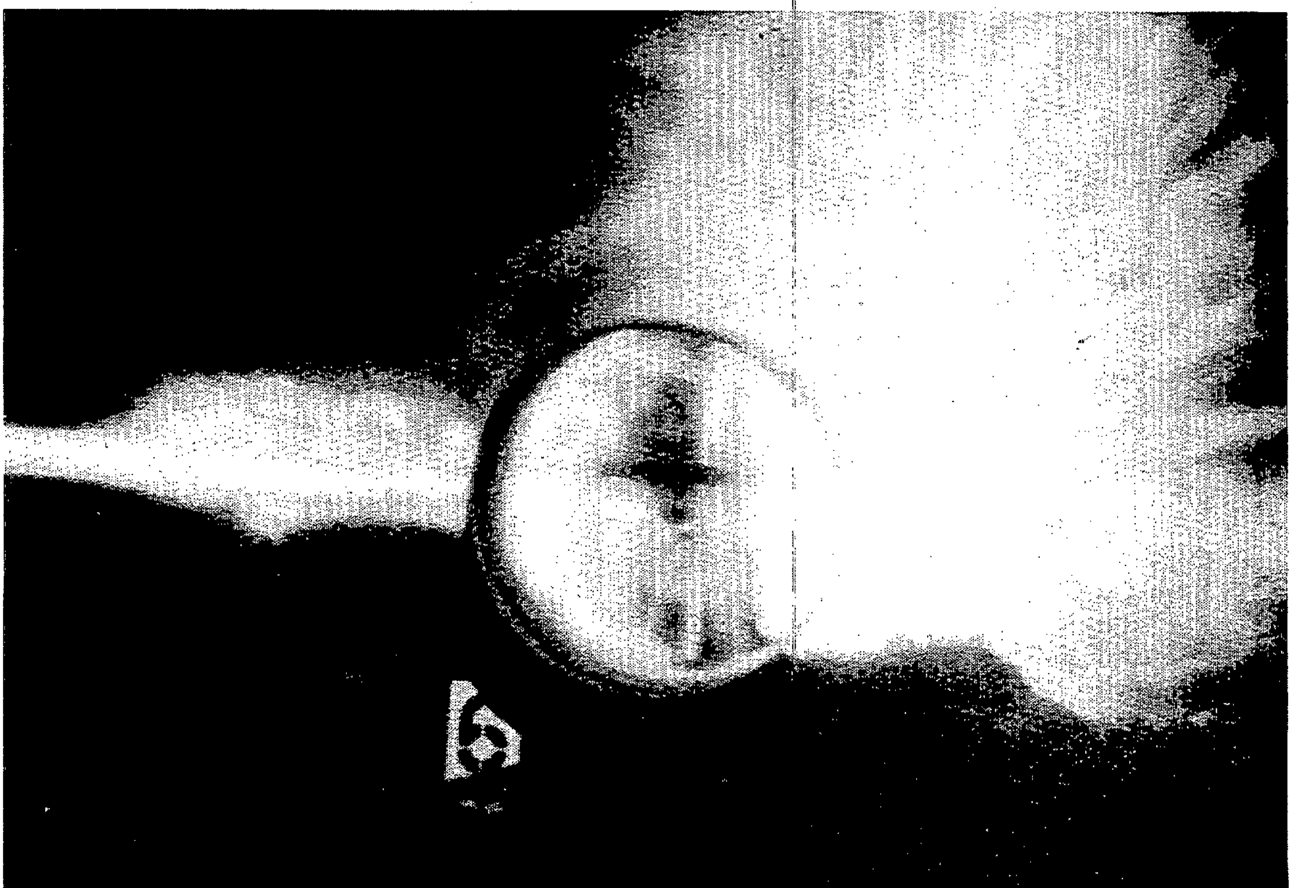


Figure 2-16. Reaction of Gun Propellant in 105-mm Cartridge to Perforation by a Shaped-Charge Jet (Ref. 23)

by location of the fire. Both fuel and oxidizer must be present for a fire to sustain itself, let alone grow.

The addition of heat makes combustible materials more flammable. Liquid fuels vaporize with the addition of heat. Solids melt and then vaporize with more heat, or the volatiles in solids boil out with the addition of heat. On the other hand, when heat is removed, the growth of a fire slows down or stops, or the fire dies down and can be extinguished.

The location of a fire affects fire growth primarily as a function of where the heat is applied to the fuel. The addition of heat makes air expand. The hotter air, being less dense, rises and carries the heat and flames upward. Fuel that is above the fire becomes hot more quickly than fuel that is alongside or below the fire, so the fire travels upward quickly. Fire can travel laterally or downward but at a much lesser rate.

If the combustible is an intimate mixture of fuel and oxidizer, e.g., gun propellant, the fire moves through the material. Gun propellants are known to burn more rapidly when in a confined space because an increase in pressure causes an increase in the rate of combustion.

From the standpoint of the survivability of combat vehicles, fires can be categorized as "rapid-growth fires" and "slow-growth fires". These are described and discussed in the paragraphs that follow.

2-3 RAPID-GROWTH FIRES

Fires in combat vehicles can result in the destruction of the vehicle and loss of the crew. Combat vehicles contain flammable hydrocarbon fluids and explosives. When a vehicle is struck by a fragment or projectile that interacts with either of these energetic materials, a rapid-growth fire can result. This rapid-growth fire can be a low-order explosion, i.e., a deflagration. Rapid-growth fires are characterized by being too fast for the vehicle occupants to react; therefore, any fire prevention system must be automatic, i.e., not dependent upon personnel to activate or direct its employment. Rapid-growth fires are often initiated by munitions, but such a fire can start from other causes, such as a hydraulic fitting failure that sprays fuel or hydraulic fluid onto an engine hot spot.

2-3.1 MUNITION INITIATION

Combat vehicles can be attacked from any direction. Some of the weapons employed will not be as serious a threat to the combat vehicle as others. Lightly armored combat vehicles can be seriously damaged by weapons to which a heavily armored vehicle is almost invulnerable.

Currently, we can expect to have the following types of weapons used against our combat vehicles:

1. KE penetrators including armor-piercing projectiles, long rod penetrators fired at very high velocity, pyrophoric penetrators, and explosively formed penetrators
2. Shaped charges including high-explosive antitank (HEAT) projectiles fired from guns and warheads of rocket-propelled missiles or shoulder-fired rockets like the light antitank weapon (LAW) and rocket-propelled grenade (RPG)
3. Armor-piercing, high-explosive incendiary (APHEI) or armor-piercing, incendiary tracer (APIT) projectiles
4. Incendiary threats, such as Molotov cocktails as well as the rocket-propelled flamethrower (RPO) and rocket-propelled flamethrower-airborne (RPO-A), or similar incendiary mixtures dispensed from aircraft
5. Fragments from high-explosive projectiles
6. Land and beach mines including those with explosively formed penetrators and some type of shaped charge.

One combat vehicle threat left off this list is a fuel-air explosive (FAE) weapon, which would probably not involve combustion of other materials as a damage mechanism.

The assumption that the threat overwhelms or bypasses the vehicular armor is used. Throughout the history of combat vehicles, armor and antiarmor threats have been in competition—first with the armor superior and then with the antiarmor threat superior. Currently, combat vehicles include rather lightly armored ones, such as armored personnel carriers or fighting vehicles, as well as the heavily armored main battle tanks (MBT). Also these MBTs are not armored all over to the same degree. The 60-deg frontal arc has the heaviest armor, the sides are less heavily armored, and the rear, top, and bottom are even less armored. Therefore, even the best-armored vehicle is vulnerable somewhere. Combat vehicles should be designed so that if the armor is defeated, a catastrophic failure will not occur. A catastrophic failure as considered here is an explosion or a fast-growth fire.

2-3.1.1 Kinetic Energy Threats

There are many types of KE penetrators that can pose a threat to combat vehicles. The armor-piercing (AP) bullet of World War I is still available. The tank and antitank gun AP projectiles of 2 1/2 to 3 calibers in length used in World War II are still around, although they are no longer the principal antitank threat. The newer KE projectiles are the long rod penetrators. These long rod penetrators can be made of hardened steel, tungsten, or depleted uranium; are from 10 to 12 calibers in length; and are launched using sabots, which drop off after the projectile leaves the muzzle. Many of the long rod penetrators, e.g., armor-piercing, fin-stabilized, discarding sabot (APFSDS) have fins, unlike the earlier armor-piercing, discarding sabot (APDS) projectiles of 3 to 4 calibers in length, which depended upon spin alone for stabilization.

Penetrators often break up during penetration, particularly if they impact at a sufficiently large angle of obliquity or encounter successive surfaces that are at different angles of obliquity. Where the target is overwhelmed, the breakup can result in damage to fuel system components, stowed munitions, and other items by multiple projectile pieces. These KE penetrators, intact or in pieces, can rupture fuel cells and cause a spray of fuel within a vehicular compartment. Impact of these fragments could initiate the propellant in a rocket motor.

When passing through a material, kinetic energy penetrators produce a flash and spall similar to those shown in Figs. 2-11 and 2-12. Flashes in these figures appear on both the impacted faces of the targets and the exit faces. Also the flash emitted by titanium in Fig. 2-12 is more intense than that from aluminum shown in Fig. 2-11. These flashes are strong ignition sources that can ignite a fuel mist resulting from a penetration.

Depleted uranium penetrators not only cause extremely strong flashes but are in essence pyrophoric, i.e., produce sparks when they strike steel or ignite spontaneously in air when in a finely divided state.

Another kinetic energy threat is from fragments from high-explosive-filled projectiles. Fragments would produce the same effects after penetrating the armor as would the AP penetrators. Some of the older AP penetrators contained a small quantity of high explosive, which was initiated by a delay fuze. These would produce fragments as well as a small blast within the vehicle after penetrating.

2-3.1.2 Chemical Energy Threats

HEAT warheads were first fielded during World War II by the U.S., England, and Germany. These warheads employ focused chemical energy and are frequently referred to as shaped charges. This round in its simplest form consists of a cylinder of high explosive with a conical cavity at one end. The cavity is lined with a thin metallic liner. When the explosive charge is initiated, the liner collapses to form a stream or jet of high-velocity, high-density material. The jet is followed by a relatively slow-moving slug. The jet is capable of penetrating homogeneous metal armors having thicknesses equivalent to several times the cone diameter of the warhead.

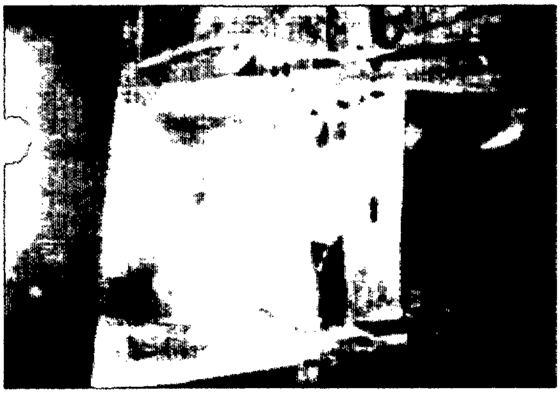
A shaped charge is presumed to detonate at nominal warhead standoff on contact with the outer surface of the vehicle. Most fin-stabilized, rocket-propelled HEAT projectiles are traveling at a relatively low velocity at impact, e.g., the velocity of the Russian RPG-7 is approximately 294 m/s (965 ft/s) (Ref. 24). Hence the greatest warhead effect against the vehicle is obtained from the jet formed by the shaped charge. The tip of this jet has a velocity of approximately 7620 m/s (25,000 ft/s). Obviously, the velocity of the shaped-charge jet is primarily due to the chemical energy of the warhead; the residual velocity of the projectile has only a minor contribution to the velocity of the jet with respect to the target vehicle. Even when a HEAT projectile is fired from a tank gun, the velocity at impact is in the vicinity of 914 m/s (3000 ft/s) and is still a minor contributor to the jet velocity with respect to the target.

The fragmentation from the shaped-charge projectile body would have a primary velocity directed sideward. At zero degree obliquity, only where projectile impact velocity approaches 914 m/s (3000 ft/s) would any casing fragments impact near the hole in the target surface created by the jet. These casing fragments would most probably be from the base of the projectile, would have a comparatively low forward velocity (This velocity would be the difference between the projectile velocity at impact and the velocity imparted by the charge detonation.) and a comparatively large size (much larger than the hole produced by the jet), and would probably be unable to penetrate through the vehicle armor. The other projectile casing fragments, which would probably be lighter but have a higher velocity, would most probably not penetrate through the vehicle armor either. Thus the behind-the-armor effects would be produced by the jet and the slug (if it also passes through the jet hole). This jet would probably produce a comparatively small diameter hole in steel armor but a larger hole in aluminum armor. Where a fuel system component is intersected, this jet would probably perforate the fuel system component and the fuel and most internal components of the vehicle in its path and may exit the vehicle through the opposite side. This action has been demonstrated repeatedly in tests. These tests showed that a small amount of fuel vapor followed the jet through the hole in the inside wall of the fuel cell and burned in a fireball inside the vehicle. In many tests the bulk of the fuel in the vehicle compartment leaked from open seams of the fuel cell.

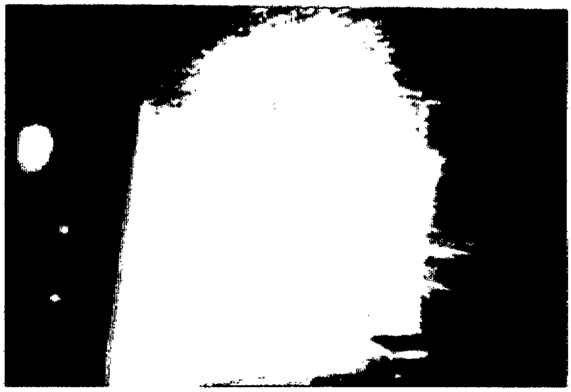
In a series of tests of a thin-walled, welded, metal fuel cell, which was mounted on the inside surface of a combat vehicle, the shaped-charge jet pressurized the fuel through the hydraulic ram effect. The welded seams ruptured, and the liquid contents sprayed into the vehicle. Fig. 2-17 shows frames taken from the high frame rate motion picture—1000 frames per second—from the test in which the fuel cell was filled with water. These frames show the generation of incandescent particles, which can cause ignition of a fuel spray. In Fig. 2-17(A) the jet has already traveled from right to left. A puff of mist has emerged from the hole through which the jet passed, and the seam in the fuel cell has opened almost 2/3 of its length. Sprays of mist can be seen that have emerged through similar splits in the front seam of the fuel cell. In Fig. 2-17(B) the mist from the jet exit hole is dispersing and that the seam has opened farther. Also the mist sprays from the front seam split(s) have dispersed. In Fig. 2-17(C) a heavy mist spray is emerging from the split seam. Also "sparklers", probably from the impact of the jet on the far vehicle wall, are coming into view enroute to the locations of the mist sprays. In Fig. 2-17(D) the sparklers from the jet perforation are contacting the outer limits of the spray mist. In Fig. 2-17(E) the sparklers have continued toward the entry wall. The sparklers and mist are well

(A) Frame 1

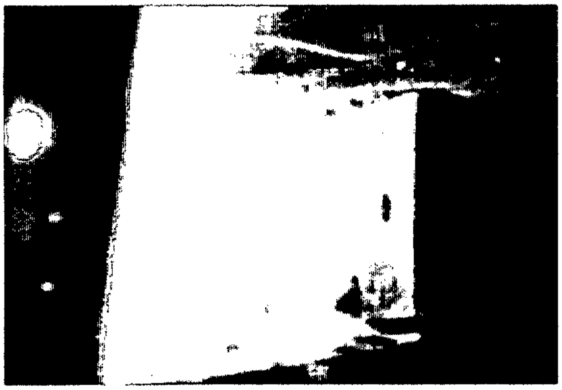
(D) Frame 4



(B) Frame 2



(E) Frame 5



(C) Frame 3

(F) Frame 6

Figure 2-17. Response of Water-Filled Fuel Tank to a Shaped-Charge Jet (Ref. 25)

mixed in Fig. 2-17(F). In a similar test, but with DF-2 in the fuel cell instead of water, the DF-2 ignited shortly after the sparklers reached the mist.

Where a fuel cell is ruptured, the fuel spray enters the vehicle compartment in the form of a mist unless special antimisting additives are placed in the fuel (Ref. 26). This mist is readily ignitable, but the strongest ignition source is apparently produced by the subsequent impacts of the jet with components within the compartment including the far vehicle wall. Ignition of this fuel mist and/or vapor and the air within the compartment results in a fireball; the heat from which can severely injure the occupants. Additional fuel can flow into the compartment through the jet perforation hole and ruptures, if any, in the fuel cell walls or seams. This fuel can vaporize from the heat of the earlier fireball. If air is being continuously introduced into the compartment, the resulting combustion can be sustained. The liquid fuel can collect in the bilge, and given sufficient air and heat and an uncovered bilge, a pool fire can result.

If this jet impacts an explosive-filled object, a chemical reaction can be initiated, as shown in Fig. 2-16. If the explosive is a propellant, a deflagration can occur or, with the stronger rocket propellants, a detonation. The reaction of a high explosive is less predictable; the result could be anything from a detonation to a mechanical rupture of the casing with no reaction from the explosive. Pyrotechnics would probably burn, but less sensitive or energetic materials would probably not react other than mechanically.

Some land mines are shaped charges directed upward. These charges can be finely focused to produce a jet or broadly focused to project a flyer plate, i.e., the Misznay-Schardin effect. The jet or plate is directed into the bottom of the hull of the vehicle, which is less protected than the rest of the vehicle. Otherwise, the effects are similar.

2-3.1.3 Incendiary Threats

In 1917 the Germans attacked British Mark IV tanks with flamethrowers. In 1940 the Finns used Molotov cocktails—a gasoline-filled glass bottle with a burning wick—with great success against Russian tanks. (The Finns named this simple, expedient weapon to indicate how they planned to extend their hospitality to these emissaries of the Soviet Foreign Minister, Vyacheslav Molotov.)

Soviet forces reportedly used several incendiary weapons in Afghanistan. These weapons can pose a significant threat to our combat vehicles. One of these is the family of rocket-propelled infantry flamethrowers, RPO and RPO-A (Ref. 27). These weapons are similar in appearance and function to the US 3.5-in. rocket launcher. The RPO launcher has a rated tube life of 100 rounds, whereas the RPO-A launcher is a plastic one-shot device.

The RPO round is a rocket-propelled incendiary charge. The filler consists of four liters of an incendiary mixture, and the complete round weighs 9.25 kg (20.4 lb). The RPO has a maximum range of 400 m and a maximum effective range of 190 m. The charge is ignited on firing, burns in flight, and after exploding on impact, produces a fireball 30 to 40 m deep and 3 to 4 m wide.

The RPO-A has been used by airborne and helicopter-borne troops. The complete assembly, launcher plus missile, weighs approximately 11 kg and has a filler charge in the warhead approximately one-half of that of the RPO. The RPO-A has a maximum range of 800 to 1200 m and a maximum effective range of 400 to 600 m. The accuracy of the RPO-A is two to three times better than that of the RPO. The incendiary used is a brown liquid, which ignites when droplets hit an object. The same launcher was reportedly used in Afghanistan for warheads filled with white phosphorus (WP) and with shrapnel warheads (Ref. 27). Later information (Ref. 28) indicates that this infantry rocket flamethrower, known as the Schmel, is actually a fuel-air explosive (FAE) weapon that is used against light armored vehicles, fortifications, and troops. (The Soviets used Afghanistan as a testing ground for weapons and tactics. Reports of Soviet activities in Afghanistan were often confusing or contradictory.)

Another incendiary reportedly used by the Soviets in Afghanistan (Ref. 29) was a black, tar-like substance dispensed from container bombs that spread the incendiary in large droplets, which ignited when stepped on or when driven on. The droplets emit flames that shoot upward. These droplets continued burning and emitted sickening fumes. Trucks driven onto these droplets have burned completely. These black droplets were difficult to detect on asphalt roads.

Bombs reportedly used in Afghanistan contained another form of this "liquid fire" (Ref. 30). The incendiary was described as a "brown" liquid, which was less viscous than the black, tar-like substance and more easily ignited. This incendiary was used in conjunction with small antipersonnel charges. The brown droplets dispensed by the bomb were reputed to ignite on impact; hence this may have been the same incendiary described for the RPO-A.

These incendiary weapons are threats that should be considered in the design of combat vehicles. In urban terrain there is the threat of the Molotov cocktail. The RPO and RPO-A present the threat of an improved Molotov cocktail or a fuel-air explosive device projected from a distance in either urban or rural terrain. The "liquid fire" presents a threat of a pool fire being created under a vehicle on a road, trail, or open area.

2-3.1.4 Blast Threats

Blast threats include high-explosive plastic (HEP)—called high-explosive squash head (HESH) by the British—and FAE.

HEP warheads crush on the outer surface of an armored target before detonating. This intimate contact enables the shock wave from the detonation to pass into the armor.

When this shock wave reflects from the opposite surface of the armor and meets a secondary stress wave traveling from the originally shocked surface, the metal fails and sends spall into the vehicle. This effect is felt by the outer armor layer only, so only monolithic armor is affected. Spaced armor can withstand this type of warhead provided the outside layer does not fail catastrophically.

A fuel-air explosion is the deflagration of an explosive fuel-air mixture. When such an explosion occurs outside a vehicle, the outer vehicle surface receives significant impulsive loading. Light armored vehicles receive significant damage.

Both the HEP and FAE or their secondary effects could damage armored vehicles and injure crew members, but neither induces fire as a primary effect.

2-3.2 FUEL

The types of engine fuels that may be exposed to fire ignition situations in combat vehicles can be categorized in general terms of volatility, source, and purpose. Military fuel types include (in the order of decreasing volatility): (1) gasoline motor fuel (MOGAS), (2) gasoline-type aviation turbine engine fuel (JP-4), (3) kerosene-type aviation turbine engine fuel (JP-8), arctic-grade diesel engine fuel (DF-A), and winter-grade diesel engine fuel (DF-1), (4) regular-grade diesel fuel (DF-2), and (5) high-flash-point kerosene-type aviation turbine engine fuel (JP-5). Other fuel types include commercial diesel engine fuels, foreign diesel engine fuels, field expedient mixtures, and fire-resistant fuels. Detailed properties and characteristics of such fuels are presented in par. 3-2.

2-3.2.1 Locations

Primary factors in combat vehicle fire survivability are the positioning and size of fuel storage cells. The type, number, and location of fuel cells are largely determined by the purpose of the vehicle. Historically, primary design consideration has been given to meeting the range requirement of the vehicle. This, in turn, has dictated the fuel volume requirement. The purpose of the vehicle then determined to what extent the fuel had to compete for volume with other mission-essential materiel, e.g., weapons, ammunition, etc. Consequently, resulting fuel cell arrangements range from a single cell system to a multiple cell system with fuel management controls.

Fuel cells in many combat vehicles are in or near the troop compartment; this location, given projectile penetration, can diminish crew survivability. Other vehicles have fuel cells located in the engine compartment or externally mounted, usually in the rear. Fuel transfer lines that service the engine are often contained within the engine compartment but must travel to the fuel cell. Auxiliary fuel lines service smoke generators in the engine compartment or exhaust or small personnel heater units in the troop area. Heater fuel lines extend into the troop compartment and are typically controlled by manual valves. External auxiliary fuel stowage in small quantities is also common and is generally used to fuel auxiliary generators. Detailed descriptions of fuel storage and handling systems are presented in par. 4-3.

2-3.2.2 Hazards

Combat vehicles are subject to various hazards that could initiate catastrophic rapid-growth fires. These include nonhostile events such as accidental fuel spillage and impingement of leaking pressurized hydraulic fluid or lubricating oil on hot engine-related surfaces. Hazards resulting from hostile actions include fuel spillage due to ballistic fuel cell rupture, fuel spray caused by projectile penetration of the fuel cell or fuel line, impingement of leaking pressurized hydraulic fluid or lubricating oil on hot engine-related surfaces, and ignition of stowed ammunition by ballistic effects.

In the case of ballistic penetration of the combat vehicle crew compartment, several specific situations can be defined to represent the possible hazardous conditions. These situations are described in Table 2-2 in terms of the sequence of objects the penetrator encounters as it passes through the vehicle, the fuel forms, and the primary ignition sources, e.g., sparklers from portions of the vehicle that are impacted. The spurt of fuel may be interspersed with or surrounded by mist and/or vapor, which can ignite and be a secondary ignition source and thereby behave as a "flamethrower".

In fuel-release incidents the extent of the rapid-growth fire hazard differs with the type of fuel involved. Generally, the more volatile the fuel being used, the greater the hazard. The amount of the other contributors to combustion, however, in a given design or situation, can modify the hazard. Highly volatile fuels, such as MOGAS or JP-4, at the standard sea level temperature of 15°C (59°F) or higher may not support combustion within a fuel cell because of insufficient air (The fuel-air mixture would be too fuel rich for ignition.), whereas outside the cell these fuel vapors, subjected to the same ignition source, would burn. On the other hand, depending on the extent of ventilation available, less volatile fuels, such as DF-2, lubricating oils, or hydraulic fluids, could support extensive pool burning inside the vehicle. Pool burning, in turn, could lead to ignition of stowed Class A (e.g., cloth, wood, and paper) combustibles or to cook-off of other combustibles such as lubricating oil, hydraulic fluid, or stowed ammunition.

The relative hazards posed by mists or sprays of military mobility fuels depend upon the nature and severity of the ignition source, the fuel temperature relative to its flash point, and the droplet size involved. In the case of spark ignition, Fig. 2-5 illustrates that a mist or spray of a volatile fuel, such as JP-4, can be ignited by sparks that are about an

TABLE 2-2. PENETRATOR OR JET TRAJECTORY, FUEL FORM, AND PRIMARY IGNITION SOURCE

SITUATION	OBJECTS ALONG TRAJECTORY	FUEL FORM	PRIMARY IGNITION SOURCE
1	Hull, Fuel Cell, Crew Compartment, Hull	Spray Spurt	Hull at jet exit Spray fireball
2	Hull, Crew Compartment, Fuel Cell, Hull	Spray Spurt	Hull at jet entry Fuel cell at entry
3	Fuel Cell, Hull, Crew Compartment, Hull	Spray Spurt	Hull at both entry and exit Spray fireball
4	Hull, Crew Compartment, Hull, Fuel Cell	Spray Spurt	Hull at exit Hull at both entry and exit
5	Hull, Crew Compartment, Deck, Fuel Cell or Bilge, Hull	Spray Spurt	Deck Deck

order of magnitude weaker than those required to ignite mists of nonvolatile fuels, such as JP-8 or JP-5 (Ref. 10).

2-3.3 HYDRAULIC FLUID

Hydraulic power is transmitted by the pressure and flow of liquids. For many years petroleum oils were the most common hydraulic fluids; however, use of synthetic fluids is becoming widespread. Most hydraulic fluids used today are flammable or at best "fire-resistant". The term fire-resistant can be misleading, however, and depends upon the state and form of the fluid when subjected to an ignition source. Refer to Chapter 3 for fluid properties.

2-3.3.1 Locations

The functioning of combat vehicles is dependent on sustained operation of all vehicular subsystems. The vulnerability of hydraulic systems is doubly critical because their damage can lead not only to fires but to system and, therefore, vehicular, failure. For example, hydraulic systems in tanks provide power to operate the turret and the gun mechanisms, as well as other secondary functions such as the operation of magazine doors. The hydraulic fluid system schematic in Fig. 2-18 shows the hydraulic power supply and distribution system for the gun elevation, turret direction, and the magazine door of the M1 tank (Ref. 31).

The M1 hydraulic system provides 37 kW (50 horsepower) for the operating demands of the gun and turret drive system and the turret ammunition door actuation system. The total capacity of the hydraulic system is 72 L (19 gal), which includes 68 L (18 gal) in the reservoir and 3.8 L (1 gal) in the lines. A variable-displacement, pressure-compensated pump is interfaced directly to the turbine engine accessory drive unit. This 11.03-MPa (1600-psig) pump is electrically depressurized during the engine starting cycle. Hydraulic power redundancy is provided with a 746-W (one-horsepower) electric auxiliary pump to provide power for the gun/turret drive system during engine off and emergency operations.

The turret ammunition door actuation system employs a linear actuator that is hydraulically decelerated at each end of the door travel. The controls include a solenoid-operated directional valve that is actuated by the loader's knee switch. A pressure-compensated flow-control valve limits and controls the actuating speed of the door. Cross pilot-operated check valves are used to lock the actuator and door hydraulically.

An accumulator, precharged with nitrogen, supplements the hydraulic flow in excess of the system output for main gun deck clearance during rapid turret traversing.

A filter manifold and reservoir are fully integrated with vehicle layout and are readily accessible for ease of maintenance. Filter elements require service only when self-contained differential pressure indicators pop out to alert the crew visually of the maintenance requirements. Fluid is not spilled during filter changes because of built-in poppet valves that stop incidental flow. Quick disconnects are used for easy uncoupling of hydraulic lines to service components or remove the engine. Tubing for the system is stainless steel, MIL-T-8808 (Ref. 32), a high-performance tubing. Stainless steel ferrules are brazed on tubes, and flareless-type fittings conforming to military specifications are employed to provide reliable, leak-tight hydraulic connections.

Thermal stability of the system is maintained with the use of a simple tube-finned crossflow heat exchanger, which is integrated with the vehicle cooling system. A shield is provided to isolate the hydraulic reservoir from the crew.

The main and auxiliary hydraulic systems provide the gun/turret drive and control systems with adequate power for all mission and emergency operations.

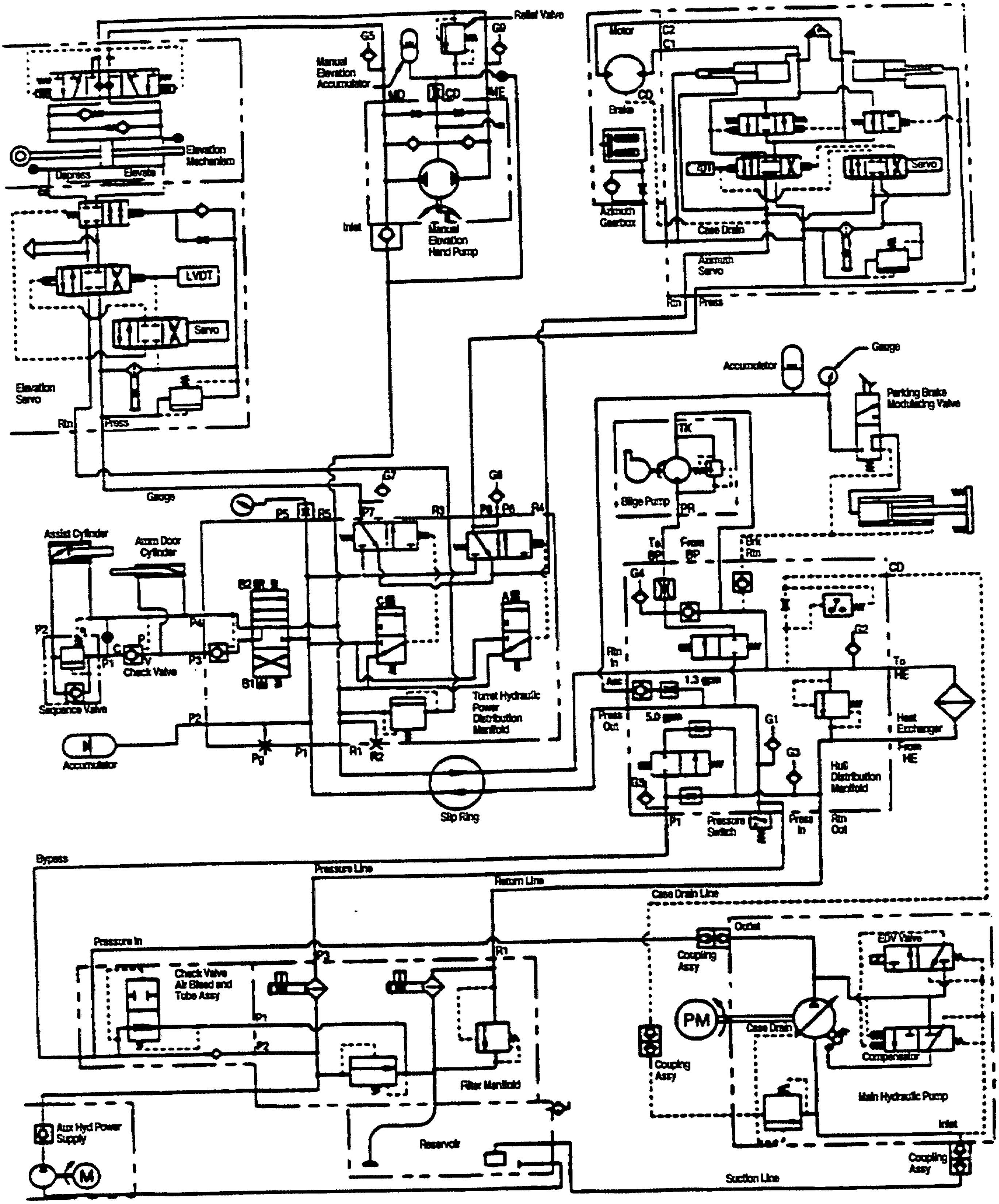


Figure 2-18. Hydraulic Power Supply and Distribution, M1 MBT (Ref. 31)

NOTE: The following abbreviations are used in Fig. 2-18.

Acc = accumulator
Amm = ammunition
Assy = assembly
Aux Hyd = auxiliary hydraulic
BP = bilge pump
Brk Rtn = brake return
CD = case drain
EDV = electrical depressurization valve
HE = heat exchanger
LVDT = linear variable-displacement transducer
MD = manual depress
ME = manual elevate
Press = pressure
Rtn = return
Servo = servovalve

2-3.3.2 Hazards

Oral reports from members of the Israeli Defense Force to US Army representatives after the Yom Kippur War (1973) disclosed the hazard to tank crewmen of burning hydraulic fluid sprays following ballistic impact. The potential for this hazard was verified by tests conducted at Aberdeen Proving Ground (Ref. 33).

2-3.4 MUNITIONS

In the design of future armored combat vehicles and the modifications to or update of older armored vehicles, consideration must be given to the probability that these vehicles will be subjected to an overmatching threat. This has been true through history and will continue to be true in the future because of the rapid progress being made in the designs of kinetic and chemical energy projectiles and of the development of high-velocity and/or hypervelocity guns capable of defeating current defensive armor systems. Means must be found to enhance survivability, to simplify repairability, and to promote future modifications. Modern combat vehicles frequently carry a significant volume of munitions, and much of this volume consists of propellants and may include explosives. Any rocket or smoke systems and propellants associated with the primary and often the secondary weapon system munitions have enough energy to incapacitate the crew completely and destroy the vehicle. The propellant presents a severe threat of explosion primarily from a deflagration of the propellant that can be followed by burning of other combustibles and finally detonation of the high explosive. During World War II, the Vietnam War, and the Arab-Israeli Wars, most irreparably damaged armored combat vehicles revealed evidence of catastrophic fire.

2-3.4.1 Locations

Although ammunition stowage locations differ among vehicles, small and large caliber ammunition stowage can be found in almost every available area, including the ready rack and bustle of the turret. Additional storage is provided in compartments or boxes attached to external surfaces. Some survivability enhancement designs place cartridges in storage racks. Cartridges are spaced and shielding materials are placed between the rounds to reduce the probability of blast and fragment initiation of propellant in contiguous rounds.

2-3.4.2 Hazards

The hazard presented by munitions is that they are extremely sensitive to ballistic impact or to fire. Munitions usually contain components that either explode or burn when impacted. If rounds are perforated and the propellant is initiated, it is desirable that the explosion or hot gases and debris not injure the crew. Stowage designs now exist that will contain or direct away the fire, blast, and debris not only from the crew but also from adjacent ammunition.

2-4 SLOW-GROWTH FIRES

Slow-growth fires can be as destructive as rapid-growth fires. In fact, a slow-growth fire can ignite and burn undetected for a considerable period before it grows to a conflagration. Most slow-growth fires in crew compartments, however, can be detected in time for crew members to react before excessive damage has been caused.

2-4.1 IGNITION SOURCES

2-4.1.1 Electricity

Historically, electrical system failures have been a primary ignition source for slow-growth fires, particularly on tracked vehicles. Most electrical fires within the engine or the crew compartment, including the turret, are caused by electrical shorts and are maintenance or crew related. In addition, almost all of these are related to some type of material failure. In general, electrical fires involve both the metallic conductors and the insulating materials. Therefore, particular attention must be given to conditions that can cause insulation degradation, excessive resistance heating and arcing, and connector integrity and function failure. Care must be taken to prevent sparking and arcing of electric components, particularly in areas with potential leakage of liquid flammables or in oxygen-rich areas that contain combustibles such as electrical insulation, fabrics, or other potentially flammable materials.

The opening of a mechanical switch or the mechanical breaking of a current-carrying wire may cause an arc to jump across the separating conductors. This action could cause ignition of the insulation or of any combustible gas mixtures present. Even when protected, all electric components and wires with sufficient energy to ignite flammables should be considered potential ignition sources. Incandescent carbon wear particles, i.e., hot surface ignition sources, can be produced by brushes in electrical motors.

2-4.1.2 Hot Surfaces

The majority of nonmunition-initiated fires in combat vehicles occur in the engine compartment, are started by hot surface ignition, and are petroleum, oil, and lubricants (POL) related. Since hot surfaces will exist on and within vehicles, care must be taken to reduce their potential as ignition sources for fires and explosions.

Even with very minor leakage during operation or minor spillage during maintenance, combustible masses can easily form on or near hot surfaces by the gradual accumulation of solid residues produced by severe oxidation and decomposition of lubricating oils or hydraulic fluids. For example, a thin film of almost any mineral oil exposed to air at atmospheric pressure at 149°C (300°F) will reduce to a coke-like mass in a short time, and the process will accelerate with increased temperature and the presence of catalytic particles, such as rust. The accumulation of deposits, dust, and debris on engine and component surfaces also progressively reduces local heat transfer so that ultimately, as the buildup continues and the temperature continues to rise, a potential hot spot ignition source steadily develops.

2-4.1.3 Exothermic Reactions

Exothermic reactions, i.e., reactions that generate heat, can lead to fires and explosions in a rapid or long-term fashion. Thus the direct contact of potential exothermic reactants should be avoided. Care must be taken to prevent fuels or other combustible fluids from leaking into munitions compartments and from contacting reactive paints, plastics, metals, or other component materials because such contact could promote smoldering or ignition. Fluid contamination and mixing should be avoided to reduce the risk of fluid instability, decomposition, or autoignition. Lubricant decomposition (on hot surfaces) can lead to the formation of carbon deposits, which, because they contain the "carbon/oxygen complex", can become highly exothermic, and once the exothermic reaction is initiated, combustion of oil films and/or carbon deposits can proceed rapidly. Even very small accumulations can become a problem because they can rapidly build in size in the presence of oil vapors or mists. The process is self-perpetuating. As the accumulation grows, it further reduces heat conduction from the area while it increases the surface area available for the capture of more vapor so that the enlarged deposit quickly becomes oil soaked. In this state, the liquid film temporarily retards oxidation by reducing the amount of oxygen that can enter the deposit; however, since convective cooling is also reduced, the temperature of the deposit gradually increases as it "dries out" by slow oxidation. Upon further decomposition a critical point is reached at which sufficient oxygen can reenter the developing porous structure to allow oxidation to continue at an ever-increasing rate. This process repeats until the particle reaches a critical size and temperature at which more heat is produced than can be carried away. At this point the reaction rates steadily increase. Additional heat is generated, part of which is absorbed by self-heating and part of which is lost to the cooler surroundings through convection and conduction. Since the rate of heat production is an exponential function of temperature, whereas the rate of heat dissipation is substantially linear, the oxidation process (depending on surrounding conditions) can quickly lead to temperatures that exceed the spontaneous ignition temperature of the residual carbon deposit. This situation may cause the particle itself to ignite, or if a combustible vapor is present, an immediate fire or explosion may result. When the temperature reaches the kindling point of dry carbon, the deposits may start to glow and give off heat, which causes other pieces of carbon to smolder. Hoses or other combustible materials in contact with or in the vicinity of these smoldering particles may become involved. In some cases the hot carbon deposits may break loose and become ignition sources as they travel through or lodge in some other part of the engine compartment and thereby create either an immediate or impending hazard. If these incandescent particles encounter a combustible mixture directly, an immediate fire or explosion may occur. If the particles lodge in an oil-soaked area, their heat may form and then ignite a combustible mixture or they may experience sufficient heat transfer to be temporarily cooled below the immediate danger point. Further accumulations, however, will increase the likelihood of a fire.

2-4.2 COMBUSTIBLES

2-4.2.1 Fuel

The ignition and development of slow-growth fires may be categorized in terms of fuel type and the presence of coexisting flammable materials. The types of fuel subject to ignition as slow-growth fires include kerosene-type mobility fuels, hydraulic fluids and lubricating oils, and Class A combustibles. Class A combustibles consist of materials either stowed within the vehicle, such as paper or cloth products, or used in its construction, such as electrical insulation and rubber-like elastomers. Such fires may be initiated by spontaneous ignition of contaminated Class A combustibles; by incendiary ballistic effects; by burning engine fuel, lubricating oil, or hydraulic fluid; or by electrical malfunctions. Such slow-growth fires may lead to catastrophic destruction of the vehicle as the fire spreads to other fuels and to stowed ammunition. The ignition of vehicle parts made of a Class D combustible, i.e., combustible metals, as described in par. 2-4.2.4, by incendiary ballistic effects represents a separate type of slow-growth, but highly sustained, fire.

Kerosene-type mobility fuels, hydraulic fluids, and lubricating oils may fuel slow-growth fires when spilled as pools. Following ignition of a fuel pool, flame will spread across the liquid surface at a rate determined by the temperature of the fuel. This rate is about 20 mm/s (0.8 in./s) when the hydrocarbon liquid temperature is below the flash point. The pool ahead of the advancing flame front, however, is warmed by convection and thermal radiation from the flame, and as the liquid temperature approaches the flash point, the flame speed increases rapidly and levels out at about 1.25 m/s (4.1 ft/s) at temperatures above the flash point (Ref. 3). This difference in flame speed reflects the difference between flame propagation where liquid vaporization is the controlling factor and flame propagation where a preexisting vapor phase exists.

The below-the-flash-point case represents one type of slow-growth fire because the time required for the entire pool to become involved in the conflagration can be long enough to allow crew action either to extinguish the fire or to evacuate. Additionally, the rate of energy release in pool fires is substantially slower than in vapor or mist deflagrations. Table 2-3 indicates how slow this burning rate is and shows the influence of temperature on the flame propagation and the rate at which the pool surface drops as fuel is consumed.

2-4.2.2 Hydraulic Fluids

Flame spread rates of hydraulic fluids are controlled by chemical and physical characteristics of the fluid and the systemic parameters, such as operating temperatures and surface temperatures. Table 2-4 shows some typical values for the hydraulic fluids used in the flame propagation tests (Ref. 36). It is readily apparent that there are great differences in flash points among the various fluids. The flash point is not an important flammability consideration in mist ignition, but it is a very important property that affects continued burning and flame propagation rates. It is important to remember that if the system operating temperature is much over 100°C (212°F), the MIL-H-5606 (Ref. 37) and MIL-H-6083 (Ref. 38) fluids would exhibit flame propagation rates more near rapid growth than slow growth. In contrast, at the same operating temperatures, MIL-H-83282 (Ref. 39) and MIL-H-46170 (Ref. 40) fluids exhibit slow-growth characteristics. Under these conditions, continued flame involvement may occur only as a result of wicking action. When wick burning occurs, the flame may or may not propagate from the flame source, depending on the surface temperature.

2-4.2.3 Oil and Lubricants

The conventional lubricants used in diesel engines generally are formulated to meet the MIL-L-2104 (Ref. 41), MIL-L-9000 (Ref. 42) or MIL-L-46167 (Ref. 43) (arctic) specifications. In these classes of lubricants, generally a base oil will be blended with antioxidants, antiwear additives, and

TABLE 2-3. FLAME PROPAGATION RATES IN FUELS AT VARIOUS TEMPERATURES (Ref. 34 and 35)

FUEL	CLOSED CUP FLASH POINT, °C (°F)	FUEL TEMPERATURE AT TEST START, °C (°F)	PROPAGATION RATE		
			ALONG SURFACE*, mm/s (in./s)	ALONG STRING**, mm/s (in./s)	VERTICAL†, mm/min (in./min)
Jet A-1	45 (113)	24 (75)	33.0 (1.3)	6.1 (0.24)	
JP-5	63 (146)	24 (75)	Did not propagate	4.3 (0.17)	
DF-2	64 (148)	24 (75)	Did not propagate	3.6 (0.14)	
Jet A-1	45 (113)	51 (125)	63.5 (2.5)		
JP-5	63 (146)	51 (125)	Did not propagate		
DF-2	64 (148)	51 (125)	Did not propagate		
Jet A-1	45 (113)	77 (170)	Instantaneous††		
JP-5	63 (146)	77 (170)	63.5 (2.5)		
DF-2	64 (148)	77 (170)	25.9 (1.02)		
JP-5	63 (146)	96 (205)	406.4 (16.0)		
DF-2	64 (148)	96 (205)	25.4 (1.0)		
AvGas	Unknown	Unknown			6.0 (0.24)
JP-4	Unknown	Unknown			5.0 (0.20)
JP-5	Unknown	Unknown			4.4 (0.17)

*Along the surface of fuel in a channel. See Ref. 34 for a description of the test.
**Along a fuel-wetted string. See Ref. 34 for a description of the test.
†Vertical rate of drop of pool surface as fuel is consumed. See Ref. 35.
††Too fast to establish with video. Probably rate of flame front in vapor. The maximum flame speed through hydrocarbon fuel vapor in air is in a slightly richer than stoichiometric mixture and is approximately 400 mm/s (15.7 in./s).

TABLE 2-4. INSPECTION DATA FOR SELECTED HYDRAULIC FLUIDS (Ref. 36)

FLUID	VISCOSITY, mm^2/s or cSt at 37.8°C (100°F)	VISCOSITY, mm^2/s or cSt at 99°C (210°F)	FLASH POINT, °C (°F)	FIRE POINT, °C (°F)
MIL-H-5606**	12.74	4.27	103 (217)	113 (235)
MIL-H-6083**	13.43	3.86	102 (215)	113 (235)
MIL-H-83282A†	16.52	3.75	225 (437)	251 (483)
MIL-H-46170	15.85	3.62	244 (435)	244 (480)
Skydrol 300 (Phosphate Ester)	11.73	3.89	193 (380)	207 (405)
MS-5 (Silicone)	40.54	11.35	249 (480)	324 (615)
MIL-H-13919B† (Discontinued)	38.71	10.75	141 (285)	154 (310)
MIL-B-46176†† Source A	34.19	8.18	282 (540)	316 (600)
MIL-B-46176†† Source B	16.63	4.79	252 (485)	271 (520)

	AUTOIGNITION TEMPERATURE, °C (°F)	AMERICAN PETROLEUM INSTITUTE (API) GRAVITY AT 15.6°C (60°F)	POUR POINT*, °C (°F)
MIL-H-5606**	238 (460)	31.1	< –68 (–90)
MIL-H-6083**	238 (460)	33.0	< –68 (–90)
MIL-H-83282A†	407 (765)	33.1	< –68 (–90)
MIL-H-46170	410 (770)	32.7	< –68 (–90)
Skydrol 300 (Phosphate Ester)	566 (1050)	1.6	< –68 (–90)
MS-5 (Silicone)	363 (685)	1.09	< –66 (–87)
MIL-H-13919B† (Discontinued)	346 (655)	30.6	< –64 (–83)
MIL-B-46176†† Source A	435 (815)	27.7	< –66 (–87)
MIL-B-46176†† Source B	396 (745)	30.8	< –67 (–87)

*The "less than" symbol (<) means that the pour point is at a lower temperature than that shown.
**Revision number not stated
†Revision number in effect at time of property determination
††Tested prior to product approval, but met the basic specification requirements

detergent dispersants. The finished product is normally a very viscous—compared to fuels—fluid that operates in a very low-pressure environment and thereby produces only drips and leaks, which require an overwhelming ignition source to sustain burning. Instances in recent years in which oil leaks came in contact with heated surfaces resulted in sustained burning that was difficult to control with conventional suppression systems. These fluids normally have a flash point in excess of 200°C (392°F) and ignite at surface temperatures in the 400 to 500°C (752 to 932°F) range. Lubricating oil is not normally considered hazardous; however, wick burning or heated surfaces readily act to ignite leaks or spills of these fluids. At high operating temperatures the viscosity of lubricating oil becomes significantly lower and thus renders the oil more hazardous.

2-4.2.4 Others

Slow-growth fires result from the ignition of plastics, elastomers, composites, wire insulations, pipe insulations, paints, coatings, textiles, woods, books, journals, manuals, and certain metals. Ignition may occur from exposure to faster growth combustibles such as torching from fuels, incendiaries, pyrotechnics, electrical shorts, explosives, pyrophoric penetrators, or incendiary projectiles. Clothing, spall curtains, rags, texts, manuals, and other utilitarian items including plastic canisters, paper or plastic dinnerware, containers, fluid cells, and upholstery represent potential slow-growth fire combustibles that are in close proximity to personnel. Painted surfaces and composite structures, such as fluid cells, bulkheads, storage compartments, and decorative panels, pose a less proximate personnel hazard. Electrical and refrigerant insulation, ductwork, etc., pose even a lesser hazard.

Hoses, insulation, and electrical jacketing located in and around engine compartments are vulnerable to ignition by burning fuels from leaking or ruptured cells or lines ignited by assault weapons, projectiles, incendiaries, explosives, or electrical shorts.

Coatings and paints represent a minor source of fire hazard but can be damaged by exposure to heat and flame and can be instrumental in the spread of fires, as can clothing, upholstery, etc. Coatings and paints, as well as most synthetic materials, may produce toxic or noxious fumes when they burn.

Metals burn because they are powerful reducing agents, and as a rule, they oxidize at room temperature to a limited degree, i.e., the outer exposed surface forms an oxide fairly readily. This oxide layer, in turn, often protects the base material from subsequent and continuous oxidation or corrosion—a condition that depends upon the continuity of the oxide and the chemical potential of the metal below. Each metal has a specific chemical potential related, in a sense, to its electromotive series position, which is really a definition of its chemical reactivity or chemical proclivity toward combining with other materials.

Uranium becomes pyrophoric when finely divided, warmed, or heated as a solid. When it is used as a projectile, the heat of friction upon impact induces ignition. Uranium is listed as a dangerous fire hazard in the form of a solid or dust when exposed to heat or flame and is a moderate explosion hazard in the form of dust when exposed to flame (Ref. 44). It is also an alpha particle emitter, which makes the material highly toxic when ingested.

Lithium metal—used in high-power batteries—is less reactive with water and oxygen than the other alkali metals (cesium, potassium, rubidium, sodium, etc.) but forms nitrides with moist nitrogen unlike the other alkali metals. When heated in air, lithium does burn and can burn violently. It reacts slowly with cold water and does not ignite the liberated hydrogen. If the water is heated, the lithium reacts more rapidly and generates enough hydrogen at a high enough temperature to become explosive. Lithium is considered a dangerous fire hazard and would easily be ignited by the kinetic energy of an impinging projectile, as would uranium.

Small aluminum particles will ignite and burn in atmospheric oxygen (e.g., flash powder and nuclear flash simulators), but larger pieces or plates will not sustain combustion. If oxygen-rich materials, such as propellants, however, are burning very close to aluminum, they supply the heat and additional oxygen required to sustain combustion of larger pieces of aluminum. This fact was demonstrated by the burning of the *HMS Sheffield* during the Falkland Islands conflict. Similarly, iron filings and fine steel wool will burn in atmospheric oxygen, but larger pieces will not. (Fine steel wool will ignite from a spark from a flint and steel.) Given that these metals burn at very high temperatures, the powdered metals produced by a ballistic penetration are formidable ignition sources, but the metals themselves are not usually hazardous combustibles.

The kinetic energy of impacting projectiles on metals increases with the mass (linearly) and velocity (by the square) of the projectile, and hence its ability to ignite targets increases accordingly. Magnesium and its alloys with aluminum are subject to ignition in air by impinging projectiles; steels normally are not. At elevated temperatures or in an oxygen-enriched atmosphere, spall from most target metals ignites when impacted with sufficient kinetic energy. Lithium, aluminum, and magnesium in small particles are vulnerable to ignition as elements in air. Uranium, plutonium, and thorium, among others, are also vulnerable to varied degrees.

Active metals, such as magnesium, ignite very easily and burn very rapidly, whereas inactive metals, such as titanium, may or may not ignite and burn. Mercury and lead are very slow to react, as are copper, gold, silver, and platinum. These metals are virtually impossible to ignite and cannot sustain combustion without the use of pure oxygen and very high temperatures. Their chemical potential is much lower than that of magnesium. In between active and inactive metals are an assortment of materials that have their own inherent chemical potential. An important consideration in addition to chemical potential is surface area. Almost any metal finely divided and exposed to a strong ignition source will burn explosively, whereas monolithic bulk metal is difficult to ignite and would burn relatively slowly under normal conditions. Surface area, mass, and chemical potential all figure significantly in the endothermic reaction required for ignition and in the exothermic reaction that is generated and dictates the rate at which the metal will burn and the amount of heat generated.

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CHAPTER 3
MATERIALS AND HAZARDS

Combustible materials located within or on combat vehicles are described. The properties of the materials that relate to ignition and sustained combustion are presented. Hazards resulting from the combustion of these materials are described.

3-1 INTRODUCTION

This chapter provides detailed descriptions of the combustible materials located within or on combat vehicles. The properties of each combustible material that affect ignition and sustained combustion are presented. The hazards presented by each combustible material are also presented. Flammability characteristics, which are peculiar to a given material, are described. The conditions under which the combustibility of these materials is affected are described.

The combustible materials described are

1. Mobility fuels, such as diesel fuel, turbine fuel, and gasoline
2. Hydraulic fluids
3. Other petroleum products, oils, and lubricants
4. Munitions
5. Other combustibles such as electric wiring insulation, spall and radiation liners, seats, on-vehicle equipment (OVE), paints and coatings, and miscellaneous combustibles including plastics and elastomers, textiles, and other items that can burn.

3-2 MOBILITY FUELS

Military mobility fuels are derived from petroleum and comprise complex mixtures of indefinite numbers of hydrocarbon molecules. Differences among the various fuels are from the composition (hydrocarbon type and size) of the constituent molecules. In general, these fuels are distinguished by distillation characteristics, such as initial boiling point (IBP), boiling point distribution versus percent distilled, and final boiling point, i.e., end point (EP) (Ref. 1).

Specific fuels are additionally defined by other properties required by the end application of the fuel. For example, the chemical structure of the hydrocarbon molecules present in spark-ignition engine fuels is significantly different from those present in diesel engine fuels. This difference is required to assure optimum ignition quality since spark-ignition engines require fuel-ignition properties essentially opposite those required by the compression-ignition mechanisms of diesel engines.

As an additional illustration, a very important property of turbine engine fuels is the amount of thermal radiation emitted during their combustion since this radiation is detrimental to the turbine engine parts. Consequently, turbine fuels should not contain substantial quantities of hydrocarbon molecules that produce excessive thermal radiation. Other properties, such as energy content (heating value), vapor pressure, viscosity, pour point, melting point, and density, vary with the type and size of hydrocarbon molecules. Therefore, such properties of a mobility fuel may be tailored by the appropriate hydrocarbon compositional adjustments.

Further examples of engine-performance-related hydrocarbon composition tailoring of fuels are provided by composition adjustments made to optimize pumpability and filterability in low-temperature applications, to minimize carbon deposition, to assure adequate fuel vapor for ignition, and to minimize evaporation losses.

Several fuel-related factors govern the nature and extent of the hazards with regard to fire safety and survivability. In a particular fire exposure situation, the physical, chemical, and flammability properties of the fuel, the quantity of fuel, the fuel environmental conditions, and the extent of involvement with other combustible materials are important. Such factors determine whether the resulting fire develops slowly or rapidly and whether it remains trivial or becomes catastrophic.

In addition to performance requirements, logistics and safety requirements may be considered in the selection of the mobility fuels to be used in combat vehicles. As the temperature of a liquid fuel—such as jet propellant (JP)-8, diesel fuel (DF)-2, DF-1, or DF-A—increases, the vapor pressure increases until it eventually corresponds to the lean-limit composition of fuel vapor in air at the theoretical flash point of the specific fuel. This fact is shown for United States (US) military fuels in Fig. 2-2 and described in subpar. 2-2.1.1. At the flash point, vapor above the surface of the bulk liquid ignites when subjected to an adequate ignition source. On the other hand, if the liquid fuel is dispersed as a spray (or mist), the dispersion can achieve ignition at lower than flash point temperatures if sufficient ignition energy is provided, as is indicated in Fig. 2-5. At temperatures above the flash point, the liquid surface is covered with enough fuel vapor to generate a flammable mixture with air. Temperatures substantially above the flash point, however, are required to generate enough vapors to form a mixture that is too fuel rich to sustain combustion. In the case of the gasoline-type fuels, e.g., motor gasoline (MOGAS) and JP-4, within a small, confined space (the ullage of a fuel cell), sufficient vapor pressure may exist at temperatures below the normal operating temperature to exceed the rich limit of flammability (Ref. 2). Designers cannot, however, rely upon this fact to provide fire protection because dilution with air at the outer edge of the fuel vapor provides a combustible mixture.

The foregoing discussion illustrates the need for knowledge of the fuel properties, most of which are described in Ref. 3, to assure successful use of military mobility fuels. In addition, such knowledge is quite important to optimizing vehicle fire survivability (Refs. 4 and 5).

In 1987 the Department of Defense (DoD) initiated implementation of a "one fuel forward" concept, which involves the use of a single fuel in diesel-fuel-consuming and turbine-fuel-consuming ground equipment and aircraft. Preceding this action, US aircraft in Europe had been converted from JP-4 to JP-8. The North Atlantic Treaty Organization (NATO) allies have concurred with this concept; therefore, diesel engines being constructed in the future must be able to operate on JP-5 and JP-8 as well as DF-2. JP-5 meets DF-2 requirements for flash point and has been used successfully in both diesel and turbine engines. JP-8 has a flash point equal to that of DF-1 and DF-A and is an efficient diesel fuel, but it has other characteristics to meet aviation needs. At the time this handbook was written, all US Army and US Air Force organizations assigned to NATO had converted to JP-8, and US Army organizations in the continental United States were in the process of converting from DF-2 to JP-8.

The properties described are those related to the potential for ignition and those that would be used to establish the effects of fire. The two parameters by which the flammability of liquids can be determined are the flash point and the initial boiling temperature. These will be described and related to those of JP-8. The other parameters of interest relevant to fire are the fire point, autoignition temperature, viscosity, heat of combustion, thermal conductivity, specific heat, density, and vapor pressure versus temperature.

3-2.1 DF-2: DIESEL FUEL

Diesel fuel is used in compression-ignition engines. DF-2 is normally used where cold-starting and cold-fuel handling are not severe problems. It is intended for use in all automotive high-speed diesel engines and in medium-speed applications in areas in which the ambient temperatures are above –18°C (0°F).

The properties of DF-2 are defined in Federal Specification VV-F-800, *Fuel Oil, Diesel* (Ref. 6). Typical properties pertinent to flammability and combustion obtained from tests are summarized in Table 3-1. DF-2 is not as volatile as gasoline at normal room* temperatures, but when heated to or above its flash point, DF-2 can be as flammable as gasoline (Ref. 5).

DF-2 comes in two grades: the first is for the continental United States (CONUS)** and the second is for use outside the continental United States (OCONUS). The CONUS grade has a minimum flash point of 51.7°C (125°F), whereas the OCONUS grade has a minimum flash point of 56°C (133°F). Thus DF-2 obtained in the U.S. can ignite at a slightly lower temperature than can the DF-2 obtained elsewhere. DF-2 has a higher minimum flash point than JP-8 (38°C (100°F)) and is less volatile.

*The temperature most often used for the design of air-conditioning equipment as the most comfortable set point is 24°C (75°F).
**The continental United States includes Alaska and Hawaii.

3-2.2 DF-1 WINTER-GRADE DIESEL ENGINE FUEL

DF-1 diesel fuel is intended for use at ambient temperatures as low as –32°C (–25.6°F).

The properties of DF-1 are defined by Federal Specification VV-F-800 (Ref. 6). Properties related to ignition and combustion are summarized in Table 3-1. Data in Ref. 7 indicate that commercial diesel 1-D should meet the flash point requirements for either DF-1 or DF-A.

3-2.3 DF-A ARCTIC DIESEL ENGINE FUEL

Arctic diesel fuel, as its name implies, is intended to be used to power diesel engines in arctic-type frigid environments. DF-A has the same flash point as DF-1 and JP-8.

The properties of DF-A are defined by Federal Specification VV-F-800. There is enough overlap in the specifications for DF-A and DF-1 for a given lot of diesel fuel to meet both grade requirements. Because there is so little use of DF-A, there is little likelihood that a refinery would make a special production run of a diesel fuel that would meet DF-A requirements but not DF-1 requirements. Therefore, combat vehicle designers should assume that DF-A and DF-1 would react similarly as far as fire survivability is concerned.

3-2.4 JP-8 KEROSENE-TYPE AVIATION TURBINE ENGINE FUEL

JP-8, per MIL-T-83133 (Ref. 14), is a kerosene-type aviation turbine engine fuel that has replaced JP-4 in combat aircraft and is replacing diesel fuels—DF-2, DF-1, and DF-A—in ground combat and tactical vehicles in NATO areas. JP-8 is functionally the same as Jet A-1—the fuel used by commercial aircraft worldwide; however, JP-8 has some icing-, corrosion-, and static-inhibiting additives that Jet A-1 lacks. JP-8 has a higher minimum flash point than JP-4 and a lower minimum flash point than DF-2, but these points are essentially the same as those for DF-1 and DF-A. DF-1 or DF-A is no longer needed in NATO areas in winter or in the arctic because JP-8 meets the winter and arctic requirements (Refs. 6 and 15). The initial boiling point of 91 samples of JP-8, supplied by 15 sources worldwide, was 144°C (291°F) minimum, 174°C (345°F) maximum, with a 157.5°C (316°F) average (Ref. 15). Pertinent properties and flammability characteristics are tabulated in Table 3-2.

JP-8 is specified as having a specific gravity between 0.775 and 0.840 and a minimum net heat of combustion of 42.8 MJ/kg. (A typical sample of DF-2 was tested and

TABLE 3-1. DIESEL FUEL PARAMETERS FROM TESTS (Refs. 7-13)

PROPERTY	MILITARY			COMMERCIAL	
	DF-1	DF-2 CONUS	DF-2 OCONUS	GRADE 1-D	GRADE 2-D
Specific Gravity at 15°C (60°F), dimensionless	0.8338	0.8493	0.845	0.811-0.825	0.863-0.865
Flash Point, °C (°F)	66 (150)	70 (158)	66 (151)	54-59 (130-138)	66-74 (151-166)
Fire Point, °C (°F)		115 (235)			
Kinematic Viscosity at 40°C (104°F), mm^2/s or cSt	1.86	2.5-3.1 1.22 @ 100°C (212°F)	3.2	1.63	2.80
Net Heat of Combustion at 40°C (104°F), MJ/(kg·°C) (Btu/(lbm·°F))	42.556 (18,295)	42.556 (18,295-18,450)			
Thermal Conductivity at 40°C (104°F), W/(m·°C)	0.09205	0.07699			
Specific Heat, J/(kg·°C)	2134	2259			
Autoignition Temperature Vapor in Air, °C (°F)		250 ± 3 (482 ± 5)			
Latent Heat of Vaporization, J/kg	203	258			
Autoignition Temperature Hot Manifold, °C (°F)		649 ± 17 (1200 ± 25)			
Distillation IBP, °C (°F)	188 (370)	188 (370)		176-177 (349-351)	182-188 (360-371)
Distillation 10%, °C (°F)	214 (417)	214 (417)		196-198 (386-389)	224-227 (435-440)
Distillation 50%, °C (°F)	238 (461)	258 (496)	281 (538)	218-225 (425-438)	267-271 (513-520)
Distillation 90%, °C (°F)	314 (598)	314 (598)	340 (644)	249-255 (480-492)	315-321 (599-610)
Distillation EP, °C (°F)	343 (650)	343 (650)	370 (698)	271-293 (520-560)	343-349 (650-660)
Cetane Number, dimensionless	44	44	47		

found to have a specific gravity of 0.8577 and a net heat of combustion of 42.305 MJ/kg.) Therefore, concern has been expressed that there is an energy per unit volume decrease of approximately 4% for JP-8 versus DF-2, which may result in slower acceleration, less available power, and shorter travel range for the vehicle when JP-8 is used. Both laboratory and field tests, as well as experiences in Southwest Asia (SWA), have shown that either the fuel metering system will automatically adjust or can be adjusted for the differences in the fuels to provide the power needed. There can be a slight loss in vehicle acceleration, and there probably will be a loss in the travel distance (Refs. 20-26). Of the vehicles tested, which included the M1 and M60 main battle tanks (MBTs), Bradley fighting vehicles (BFVs), M113A3 armored personnel carriers (APCs), M88 tracked recovery vehicles (TRVs), and tactical and administrative vehicles, only the M88 TRV continued to exhibit degraded performance with JP-8, and this performance was deemed to be vehicle-peculiar (Ref. 27).

JP-8 has another failing relative to DF-2: It cannot produce smoke from the vehicle engine exhaust smoke system (VEESS). The smoke results when the larger molecules of high boiling point fluids form mist droplets. Note on Fig. 3-1 that fog oil and DF-2 have greater portions of high boiling point fluids (the larger or heavier molecules) than does JP-4, JP-8, or Jet A-1. For this reason, combat vehi-

TABLE 3-2. AIRCRAFT TURBINE FUEL PARAMETERS FROM TEST (Refs. 9–13 and 15–19)

PROPERTY	AT °C (°F)	FUEL							
		JP-4	JP-5	JP-8	JET A	JET A-1	KEROSENE	AV GAS 100-130	AV GAS 115-145
Specific Gravity, dimensionless	15°C (60°F)	0.762-0.78	0.817-0.83	0.800-0.819	0.805-0.816	0.805	0.8-0.83	0.7	
Flash Point, °C (°F)		–18 (0)	62-66 (144-150)	45.6-46 (114-115)	41-60 (105-140)	43-54 (109-130)	50-52 (122-125)		–43 (–45)
Fire Point, °C (°F)			77 (170)			57 (135)			
Autoignition Temperature (AIT) Vapor in Air, °C (°F)		229-246 (445-475)	224-248 (435-478)	224-240 (435-465)	224-238 (435-460)	250 ± 3 (482 ± 5)	149 (480)	441-565 (825-1050)	471 (880)
AIT Liquid Stream, °C (°F)		704 (1300)	704 (1300)	649 (1200)		649 ± 14 (1200 ± 25)			
Kinematic Viscosity, mm^2/s or cSt	–20 (–4)		5.75-5.84	4.09	5.58	1.48			
	40 (104)		1.50	1.10-1.25		1.07-1.21			
	70 (158)		1.02	0.88		0.77-1.04			
	100 (212)					0.58			
Net Heat of Combustion, MJ/(kg·°C) (Btu/(lbm·°F))		42.8-43.5 (18,412-18,723)	42.6-43.0 (18,312-18,514)	42.5-43.0 (18,325-18,506)	42.8-43.3 (18,412-18,628)	42.7-43.1 (18,377-18,508)	43.2 (18,000)	44.2 (19,000)	
Thermal Conductivity, W/(m·°C) [Btu/(ft·h·°F)]	40°C (104°)	0.1364 (0.0788)		0.0946 (0.05467)				0.1364 (0.0788)	
Specific Heat, J/(kg·°C) [Btu/(lbm·°F)]	40°C (104°)			1715.4 (0.41)					
Latent Heat of Vaporization, J/kg, (Btu/lbm)				0.02072 (48.16)					
Vapor Pressure, kPa (lb/in.^{2})	16°C (60°F)	8.96 (1.3)						19.99 (2.9)	
Distillation IBP, °C (°F)		59 (138)	180 (356)	150-157.5 (305-316)	163 (325)	149-167 (300-333)	177 (350)		
Distillation 10%, °C (°F)		90-99 (194-210)	193-196 (380-385)	176-188 (359-370)	192 (377)	170-173 (338-343)	193-196 (380-385)	60 (140)	
Distillation 50%, °C (°F)		143 (289)	212-215 (414-419)	200-209 (392-426)	203 (397)	194-196 (381-385)	221 (430)		
Distillation 90%, °C (°F)		199-209 (390-409)	238-242 (460-468)	235-256 (456-493)	247-249 (476-480)	228-234 (442-453)	254 (490)	116 (240)	
Distillation EP, °C (°F)			261 (502)	258-284 (496-543)	271 (520)	247-276 (477-529)	274 (525)	159 (319)	
Cetane Number, dimensionless		23	42	45		45.0-49.1			

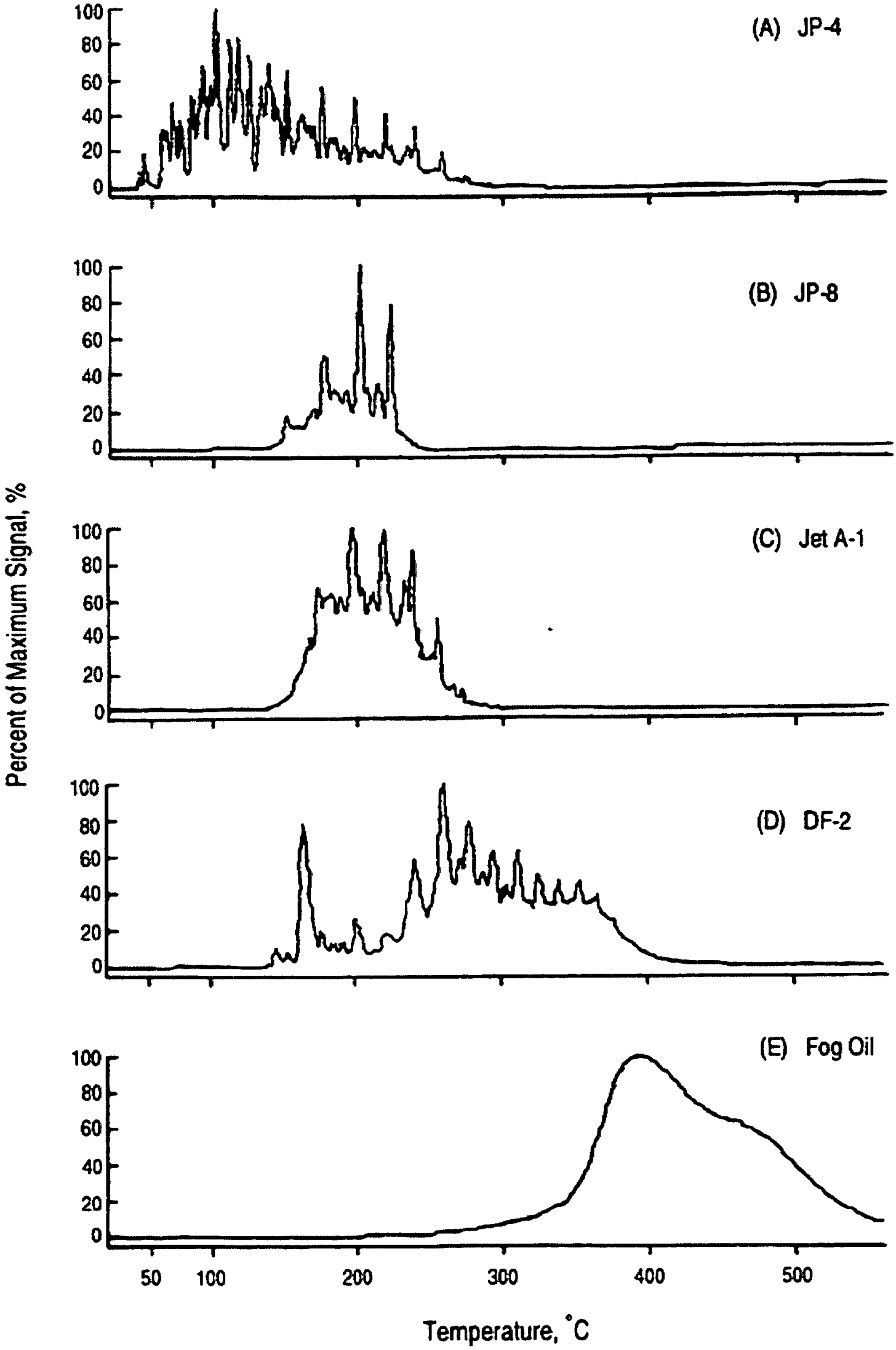

Figure 3-1. Typical Chromatograph Distillation Traces of JP-4, JP-8, Jet A-1, DF-2, and Fog Oil (Refs. 13 and 19)

cles using JP-8, Jet A-1, or Jet A fuel will have to carry fog oil. There is more information on fog oil and the VEESS in Ref. 28 and par. 3-4.3. Jet A and Jet A-1 are made to the same specification and have the same properties except for the maximum freezing point, which is –40°C for Jet A and –47°C for Jet A-1.

JP-8 is procured per military specification MIL-T-83133. The alternate fuel for JP-8 is Jet A-1, which is described in American Society for Testing and Materials Standard ASTM D 1655 (Ref. 29). Note on Fig. 3-1 that the samples of JP-8 and Jet A-1 show similar temperature ranges and therefore are from the same "narrow cut" of hydrocarbon fuels. This alternate fuel was used in the 1991 operations in SWA (Ref. 11). In SWA some organizations using Jet A-1 in lieu of DF-2 complained of lack of lubricity. In JP-8 lubricity is supplied by one of three additives used to convert Jet A-1 to JP-8; this lubricity-adding material is a dimeric organic acid, usually dilinoleaic acid, which is intended to provide an anticorrosion feature.

3-2.5 OTHER FUELS

3-2.5.1 JP-4 Gasoline-Type Aviation Turbine Engine Fuel

JP-4 is a gasoline-type fuel comprised of mixtures of gasoline and kerosene and is used as a jet engine fuel in military aircraft. The properties of JP-4 are defined in Military Specification MIL-T-5624, *Turbine Fuel, Aviation Grades JP-4, JP-5, and JP-5/JP-8 St* (Ref. 30). Its pertinent properties are summarized in Table 3-2.

JP-4 exhibits significant vapor pressure but not as much as MOGAS, and it contains heavier hydrocarbons than MOGAS, which cause slower overall evaporation rates. In gasoline-type fuels sufficient vapor pressure exists at subroom temperatures to exceed the rich limit of flammability. The flash point of JP-4 is not specified in MIL-T-5624, but tests of JP-4 samples indicate that a flash point of approximately –18°C (0°F) can be expected. This flash point is significantly lower than that of JP-8. JP-4 has a marginal cetane number; 23 is a typical value. Therefore, it is used only as an emergency fuel in compression-ignition engines.

3-2.5.2 JP-5 High-Flash-Point, Kerosene-Type Aviation Turbine Engine Fuel

JP-5 fuel is intended for use in naval aircraft because volatile fumes of lower flash point fuels could pose a flammability hazard in shipboard applications, specifically aircraft carriers and helicopter-bearing ships.

The properties of JP-5 are defined by Military Specification MIL-T-5624 (Ref. 30). Typical properties are summarized on Table 3-2. JP-5 is within the distillation patterns of JP-8 and Jet A-1 on Fig. 3-1; therefore, JP-5 would not produce smoke using the VEESS.

Evaluation of data in Ref. 15, which is based upon evaluation of flash points of 63 samples from 15 sources, indicates that JP-5 should ignite less readily than JP-8. Thus a combustible vapor layer should form over JP-8 at a lower temperature than it does over JP-5. The average flash point of JP-5 is 62°C (144°F), whereas that of JP-8 is 46°C (115°F), which indicates that JP-8 vapor would ignite at a lower temperature than would JP-5 vapor. The average heat of combustion of JP-5 is 42.929 MJ/kg (18,456 Btu/lbm), whereas that of JP-8 is 43.019 MJ/kg (18,495 Btu/lbm). It can be assumed that there is no essential difference in the heat output of these two fuels.

3-2.5.3 Automotive Gasoline

Gasoline is a multicomponent blend of petroleum-derived hydrocarbons with appropriate additives and is used in spark-ignition engines. Several grades are formulated with different antiknock indices. Volatility is established during production to obtain gasoline in five classes; gasoline is processed by US refineries in the appropriate volatility class for the geographic location and the month of use. The US Army uses three specifications for procuring gasoline: ASTM D 4814 (Ref. 31), MIL-G-3056 (Ref. 32), and MIL-G-53006 (Ref. 33). In 1959 the US Army started converting to diesel fuel from gasoline for ground combat vehicles. Now the primary use of gasoline by the US Army is for passenger and/or administrative automobiles.

Commercial automotive gasoline is procured under ASTM D 4814, and there are five volatility classes for both leaded and unleaded blends of neat gasoline or blends of gasolines and oxygenates (gasohol), such as alcohols or methyl tert-butyl ether, for use in CONUS. Commercial gasoline is usually available in one antiknock index for leaded and three antiknock indices for unleaded gasolines. The properties of gasoline vary according to classes and indices, which are selected for geographic location and climate.

Gasoline for combat automotive vehicles can be procured according to MIL-G-3056 for OCONUS use. Two types of unleaded gasoline are procured under this specification: Type I is an all-purpose gasoline that meets NATO Code No. F-46, and Type II is a low-temperature, all-purpose gasoline. This gasoline is intended for use in automotive, stationary, and marine spark-ignition engines; vehicle and personnel heaters; and cooking units. This gasoline is *not* to be used within CONUS.

Selected properties of aviation gasoline are given in Table 3-2. In general, gasoline is much more volatile at lower temperatures than diesel fuels or JP-8 and could form combustible fuel-air mixtures at relatively low ambient temperatures. This vulnerability of gasoline-fueled vehicles is the principal reason gasoline has been removed from use by the US Army.

3-2.5.4 Gasohol

Gasohol is a blend of gasoline and 10% by volume of denatured ethyl alcohol. Leaded or unleaded automotive gasohol is procured per ASTM D 4814 or MIL-G-53006 (Ref. 33). Gasohol is supplied in five volatility classes, five water miscibility classes, and 14 different antiknock grades. The volatility and water miscibility classes are selected as functions of the month and geographic location of use. The antiknock index is selected by the procuring agency from six levels of limited grade, six levels of regular grade, or two levels of premium grade gasohol. The procuring agency also selects whether the gasohol will be leaded or unleaded.

3-2.5.5 Commercial Diesel Fuels

The properties of commercial diesel fuels are defined by ASTM D 975, *Standard Specification for Diesel Fuel Oils* (Ref. 34). Pertinent properties are summarized in Table 3-1. Note that both of the commercial diesel fuels listed—1-D and 2-D—have higher flash points than the minimum for JP-8.

3-2.5.6 Foreign Diesel Fuels

3-2.5.6.1 NATO Diesel Fuel F-54

The principal foreign diesel fuel used by the US Army is NATO diesel fuel F-54, which is analogous to DF-2 (OCONUS). NATO F-54 has a minimum flash point of 56°C (133°F). DF-2 (OCONUS), intended for entry into the Central European Pipeline System, has a minimum flash point of 58°C (136°F).

The properties of NATO F-54 are defined by NATO Standardization Agreement (STANAG) 2754. Pertinent properties are equivalent to OCONUS DF-2 in Table 3-1. NATO fuel codes are given in Table 3-3.

3-2.5.6.2 Russian Diesel Fuels

The requirements for diesel fuels meeting Russian Specification GOST 305-82 are shown in Table 3-4. The Russians

TABLE 3-3. NATO FUEL DESIGNATIONS AND US EQUIVALENT SPECIFICATIONS/STANDARDS (Ref. 12)

NATO CODE NO.	NATO TITLE	MILITARY/FEDERAL SPECIFICATION	INDUSTRY EQUIVALENT STANDARD
F-18	Gasoline, Aviation, Grade 100/130	ASTM D 910 Aviation Gasoline	ASTM D 910 Aviation Gasoline
F-46	Gasoline, Auto, Military (91 RON)	—	—
F-57	Gasoline, Auto, Low Lead (98 RON)	STANAG 2845	CEN EN-228
F-67	Gasoline, Auto, Unleaded (95 RON)	STANAG 2845	CEN EN-228
—	—	ASTM D 4814 S-I Engine Fuel	ASTM D 4814 S-I Engine Fuel
—	—	MIL-G-53006 Gasohol	—
—	—	MIL-G-3056 Gasoline	—
F-40	Turbine Fuel, Aviation, Widecut Type + FSII(S-748/S-1745)	MIL-T-5624 Turbine Fuel, Aviation, Grade JP-4	—
F-34	Turbine Fuel, Aviation, Kerosene + FSII(S-748/S-1745)	MIL-T-83133 Turbine Fuel, Aviation, Grade JP-8	—
F-35	Turbine Fuel, Aviation, Kerosene	MIL-T-83133 Turbine Fuel, Aviation	ASTM D 1655 Aviation Turbine Fuel, Jet A-1
F-44	Turbine Fuel, Aviation, High-Flash Type + FSII(S-1745)	MIL-T-5624 Turbine Fuel, Aviation, Grade JP-5	—
F-54	Diesel Fuel, Military	VV-F-800 Fuel Oil, Diesel Grade DF-2 (OCONUS)	—
F-65	Low-Temperature Diesel Fuel Blend	1:1 Mix F-54 With F-34/F-35	—
—	—	VV-F-800 Fuel Oil, Diesel Grades DF-A, DF-1, 7 DF-2 (CONUS)	ASTM D 975 Diesel Fuel, Grades 1-D and 2-D
F-75	Fuel, Naval Distillate, Low Pour Point	—	—
F-76	Fuel, Naval Distillate	MIL-F-16884 Fuel, Naval Distillate	—
S-748	Fuel System Icing Inhibitor (FSII)	MIL-I-27686 Inhibitor, Icing Fuel System	ASTM D 4171 Fuel System Icing Inhibitors
S-1745	Fuel System Icing Inhibitor (FSII) High-Flash-Point Type	MIL-I-85470 Inhibitor, Icing Fuel System, High Flash	—

CEN = Comite Europeen de Normalisation
RON = Research Octane Number

TABLE 3-4. RUSSIAN GOST 305 AUTO DIESEL FUELS (Ref. 35)

	SOVIET-TYPE DIESEL FUEL			
	SUMMER	WINTER	NORTHERN WINTER	ARCTIC
PHYSICOCHEMICAL PROPERTIES	L	Z	ZS	A
Cetane No. (min)	45	45	45	45
Pour Point, °C (max)	−10	−35	−45	−55
Cloud Point, °C (max)	−5	−25	−35	−45
Flash Point, °C (min)	40	35	35	30
Viscosity at 20°C, mm^2/s or cSt	3.0-6.0	1.8-5.0	1.8-3.2	1.5
Specific Gravity, dimensionless at 20°C (max)	0.860	0.840	0.830	0.830
Fractional Composition at the Maximum Temperature in °C Indicated:				
50% Distills	280	280	280	240
90% Distills	360	340	340	330
End Point	369	340	340	330

use type L fuel as the U.S. uses DF-2. Types Z and ZS compare to DF-1, and Type A to DF-A (Ref. 35).

3-2.5.6.3 Foreign Commercial Diesel Fuels

In a survey (Ref. 8) conducted to establish how well foreign sources of commercial diesel fuel would meet the requirements of OCONUS DF-2 per VV-F-800C, a total of 78 samples of commercially available diesel fuel from at least 27 countries were found to have an average flash point of 66°C (151°F), with a maximum of 88°C (190°F) and a minimum of 21°C (70°F). Thirteen of the samples had flash points below the specification value of 56°C (133°F) minimum, and ten of those were from a single country (from which a total of eleven samples had been received). These undesirably low sample flash points ranged from 21 to 55°C (70 to 131°F). Seven of these 13 were below the specified minimum flash point of JP-8, i.e., 38°C (100°F), which means that the potential for ignition could be greater in some instances than it would if JP-8 were used.

3-2.5.7 Primary, Alternate, and Emergency Fuels

For every vehicle a primary fuel is designated that permits full design performance. Alternate fuels are designated that provide acceptable operational performance, i.e., a level of performance that meets the minimum requirements defined in the vehicle specification. Emergency fuels are also designated for use when the primary or alternate fuels are not available. Performance may be degraded, but emergency fuels should not materially degrade the design operating life of the vehicle (Ref. 36). The primary, alternate, and emergency fuels for US Army materiel are given in Table 3-5.

3-2.5.7.1 Field-Expedient Mixtures

Field-expedient mixtures include alternate fuels, blends of one specification fuel with another, and adulterated specification fuels.

In Europe, NATO units have used a 50/50 mixture of JP-8 and DF-2—NATO Code No. F-65—as a winter diesel fuel. When one fuel is blended with another, the blend will have all the flammability characteristics of both constituents, and it will be flammable over the entire range between those of the constituents. An example is the blend of JP-8 and DF-2; it would be flammable from the lean limit of flammability of JP-8, seen on Fig. 2-2, through the rich limit of flammability of DF-2. Consequently, such blends represent a greater fire and/or explosion hazard than would either constituent alone.

3-2.5.7.2 Comparison of Fuel Types

The principal fuel characteristic of concern in this handbook is flammability, and the fuels of major concern are those that are or may be used in combat vehicles. These include DF-2, JP-8, JP-5, and others. If flammability is to be gaged by flash points alone, then commercial diesel 2-D would meet CONUS DF-2 requirements, as is shown in Ref. 7 in which samples from throughout the U.S., taken in 1990 and 1991, had a minimum flash point of 56°C (132°F). Worldwide samples described in Ref. 8, however, failed to meet the OCONUS DF-2 standard of a minimum flash point of 56°C (133°F) in 13 of 76 cases. There is no indication that only the foreign equivalent of commercial diesel 2-D was included in the samples. The sample from Scotland obtained in March with a flash point of 51°C (124°F) could

TABLE 3-5. FUELS USED IN ARMY MATERIEL (Ref. 12)

ITEM	PRIMARY FUEL	ALTERNATE FUEL (See Note 1)	EMERGENCY FUEL
Ground gasoline-consuming materiel: OCONUS environments	MIL-G-3056 (MOGAS)	F-57 (Gasoline) F-67 (Gasoline) F-18 (AVGAS)	—
CONUS environments	ASTM D 4814 (S-I Fuel) (See Note 2)	MIL-G-53006 (Gasohol) ASTM D 910 (AVGAS)	—
Ground diesel-fuel-consuming materiel: OCONUS environments	VV-F-800 (Diesel), F-54 (See Note 3)	MIL-T-83133 (JP-8), F-34 MIL-T-5624 (JP-5), F-44 MIL-F-16884, F-76* F-75 (Navy Distillate)* ASTM D 1655 (Jet A-1) (See Note 4) F-65 (Diesel Blend)	MIL-G-3056 (MOGAS) F-57 (Gasoline) F-67 (Gasoline) F-18 (AVGAS) MIL-T-5624 (JP-4), F-40
CONUS environments	VV-F-800 (Diesel)	ASTM D 975 (Diesel) ASTM D 1655 (Jet A) (See Note 4) ASTM D 396 (FO1 & FO2)	ASTM D 4814 (S-I Fuel) ASTM D 910 (AVGAS) MIL-T-5624 (JP-4), F-40
Aviation materiel: Gasoline-consuming	ASTM D 910 (AVGAS), F-18	F-18 (AVGAS)	ASTM D 4814 (S-I Fuel)
Turbine-fuel-consuming	MIL-T-83133 (JP-8), F-34	MIL-T-5624 (JP-5), F-44 MIL-T-5624 (JP-4), F-40 ASTM 1655 (JetA/A-1) ASTM 1655 (Jet B)	—

NOTES:
1. Environmental conditions may limit use of certain alternate fuels designated with an asterisk (*).
2. ASTM D 4814 a spark-ignition engine fuel (S-I fuel) that allows use of oxygenates to enhance its antiknock quality.
3. Although VV-F-800 is shown as the primary fuel, MIL-T-83133 (JP-8) or MIL-T-5624 (JP-5) will be used as the primary fuel in those theaters in which the single fuel on the battlefield is implemented in accordance with DoD Directive 4140.25 and, more recently, with US ratification of STANAG 4362.
4. Jet A-1/F-35 or Jet A is acceptable for continuous use in environments with cold to moderate temperatures. For moderate to high temperatures, Jet A-1/F-35 or Jet A is not recommended and should be replaced with JP-8/F-34.

well have been the equivalent of winter diesel and would have met the DF-1 criteria, i.e., a flash point 37.8°C (100°F) minimum. Also two of the 13 samples failed to meet the OCONUS DF-2 flash point requirement but would have met the CONUS DF-2 flash point requirement, and another three would have met the DF-A/DF-1 flash point requirement. The user of commercially available foreign diesel fuel cannot rely upon meeting fuel specifications but should test the fuel to ascertain its quality, as was done in SWA (Ref. 11).

3-2.5.7.3 Single Fuel on the Battlefield

In recent operations one mobility fuel was designated to be the primary fuel used in both aerial and ground vehicles. In Operation Just Cause—Panama, 1989—JP-5 was so designated. In Operations Desert Shield and Desert Storm—SWA, 1990 to 1991—Jet A-1 was so designated and is still used for organizations in Kuwait in 1993. In Operation Restore Hope—Somalia, 1992 to 1993—JP-5 was designated the primary fuel.

In Operation Desert Storm concern was expressed that the Jet A-1 fuel did not have sufficient lubricity and that the lower flash point would present a fire hazard. The lesser lubricity did not present a problem, and the greater fire hazard did not materialize (Ref. 11). In some instances, organizations added engine oil or hydraulic fluid to "improve" the lubricity, but this action added contaminants to the fuel, which increased filter clogging. There was a problem with filters clogging in older vehicles that had been using DF-2, but this was the same problem that had been encountered earlier at Fort Bliss in a program to establish the feasibility of using JP-8 in diesel-engined equipment. (Refs. 25 and 26) JP-8 or Jet A-1 cleans the DF-2 sludge out of the system and thus overloads the filters until the fuel system is clean. The one deficiency presented by JP-8 or Jet A-1 is the failure to produce smoke in the VEESS. For this reason, some major commands chose to use DF-M, i.e., DF-2 that meets the requirements of MIL-F-16884, instead of Jet A-1 in Operation Desert Storm (Ref. 11). VEESS fuel usage is discussed in par. 3-4.3.

3-2.5.8 Fire-Resistant Fuels

Extensive research and development have been conducted by the US Army to reduce fire vulnerability and increase fire survivability of mobility equipment by modifying the flammability characteristics of the mobility fuels, particularly diesel fuel. Following several preliminary generations of experimental formulations (Ref. 37), a fire-resistant diesel fuel formulation has been proposed (Refs. 38 and 39). This fuel contains 10% by volume of added water dispersed with 12% by volume of emulsifier premix (equal parts of surfactant and aromatic concentrate) as a clear-to-hazy, aqueous microemulsion. The fuel displays an appearance and properties similar to those of the base fuel from which it is made, and its use in diesel engines does not adversely affect engine durability.

These fuels are not ready to be fielded. Various fire-resistant fuel formulations were tried and did not meet all of the fuel handling system and environmental performance requirements specified by the potential military users.

The volumetric net heat of combustion of the fire-resistant fuel formulation is less than that of its base fuel by approximately the amount of dilution with water. The viscosity of fire-resistant fuel is somewhat greater than that of its base fuel and is substantially greater at low temperatures.

Fire-resistant fuel enhances fuel fire safety by decreasing ignition susceptibility, by retarding flame spreading rates, and by self-extinguishing if ignited when spilled. It is effective for starting, idling, and running diesel engines as well as turbine combustors. On the other hand, it burns readily when dispersed as a spray or mist.

The partial vapor pressure of water above fire-resistant-fuel-type microemulsions has been experimentally determined to be significantly less than that of pure water (Ref. 40). It has been determined also that sufficient amounts of water vapor exist (approximately 24% by volume) in otherwise flammable fuel-air mixtures (approximately 2 to 3% fuel by volume) ahead of an advancing flame to prevent sustained combustion above the bulk liquid. Hence the flame on the surface of the fire-resistant fuel liquid is self-extinguishing.

Conversely, when the fire-resistant fuel is dispersed as a spray or mist, the amount of water vapor formed by the totally vaporizing droplets is of the same order of magnitude on a volume basis as the fuel vapor formed. Thus the water vapor concentration in the fuel-air-water mixture formed from a mist of fire-resistant fuel is about an order of magnitude less than that required to prevent sustained combustion. The combustion characteristics are comparable to those of a mist formed from only the base fuel; therefore, a fuel fireball usually occurs when a shaped-charge jet perforates a fuel cell containing fire-resistant fuel.

3-3 HYDRAULIC FLUIDS

As the use of hydraulics and fluid power systems has increased, the number and types of hydraulic fluids available have also increased. Descriptions of the more common types of hydraulic fluids are presented with a brief summary of those properties pertinent to ignition and/or flammability. Hydraulic fluids currently in use are described in MIL-HDBK-113 (Ref. 41); hydraulic fluids and their usage are covered in MIL-HDBK-118 (Ref. 42).

Because of the wide and vastly different areas of application, it is not surprising that hydraulic fluids have been classified by many different systems based on various characteristics, such as physical properties, chemical types, operating characteristics, utility, or specific applications. Although none of these groupings fully describe the properties of a hydraulic fluid, they are still employed and assist in selecting fluids for use in specific areas. In this handbook hydraulic fluids are classified by fire resistance.

Hydraulic fluids can be classed as flammable, fire-resistant, or nonflammable. A flammable hydraulic fluid can burn almost as well as a fuel does. The fire-resistant classification is somewhat arbitrary because the degree of flammability depends on both the specific fluid and the definition of "flammability". Generally, flammability has been gaged by whether or not a sustained fire results within an enclosure. However, because fireballs of sufficient strength and duration can injure personnel, flammability can be evaluated based upon the fireballs produced when a shaped-charge jet or a high-explosive projectile encounters a fluid. Other gages of flammability are whether a flame results when a liquid stream or spray encounters a hot object and whether the flame is on the hot object only or also encompasses the liquid or spray. Usually fire-resistant hydraulic fluids are of three types: synthetic fluids, water-based fluids, and aqueous emulsions. Fire-resistant synthetic fluids are fire-resistant because of their chemical nature and include phosphate esters, chlorinated hydrocarbons, halogen-containing compounds, organophosphorus derivatives, and mixtures of similar materials. The water-based fluids are solutions of various natural or synthetic materials in water and depend upon their water content for fire resistance. Glycols, polyglycols, and mixtures containing additives are the most common hydraulic fluids of this type. Aqueous-emulsion-type hydraulic fluids also depend upon water content for fire resistance and are water-in-oil mixtures made from petroleum hydrocarbons, but they may contain various additives to provide other desirable properties. A nonflammable hydraulic fluid will not burn under most conditions.

3-3.1 FIRE-RESISTANT HYDRAULIC FLUID

Fire-resistant hydraulic (FRH) fluid normally refers to a synthetic fluid (compared to a petroleum-based fluid) and contains an additive package developed for a specific application. The synthetic base stocks are normally polyalphaolefins or esters, such as phosphate esters. The following fluids are those normally used by DoD service groups. Pertinent data on parameters related to flammability are given in Table 3-6.

TABLE 3-6. HYDRAULIC FLUIDS PARAMETERS (Refs. 43-50)

PROPERTY	FLUID						
	MIL-H-5606	MIL-H-6083	MIL-H-46170	MIL-83282	MIL-H-53119 (CTFE)	MIL-B-46176	MIL-H-19457
Flash Point, °C (°F)	91-103 (195-217)	102-124 (215-255)	224 (435)	196-226 (385-437)		252-282 (485-540)	
Fire Point, °C (°F)	107-112 (225-235)	112 (235)	250-254 (480-489)	252-254 (486-489)		271-313 (520-600)	
Autoignition Temperature (AIT), Vapor in Air, °C (°F)	225-238 (437-461)	238-243 (460-470)	368-410 (694-770)	347-407 (656-765)	630-646 (1165-1195)	396-436 (745-815)	560 (1040)
AIT Liquid Stream, °C (°F)	388 (730)	524 (975)	400 (750)	322-400 (630-750)	927 (1700)		
AIT, Spray, °C(°F)	721 (1330)	730 (1350)	504-730 (939-1350)	677-730 (1250-1350)	>927 (>1700)		
Net Heat of Combustion, MJ/kg (Btu/lbm)	42.07-42.40 (18,100-18,240)	42.13 (18,126)	41.20 (17,726)	41.14-41.54 (17,700-17,870)	560 (2390)		
Coefficient of Thermal Vol. Exp. $m^3/m^3/°C$ ($in.^3/in.^3/°F$)	2.222×10^{-4} (4.0×10^{-4})			2.556×10^{-4} (4.5×10^{-4})	2.778×10^{-6} (5.0×10^{-6})		
Specific Heat, J/(kg·°C) [Btu/(lbm·°F)]	2052 (0.49)	1970 (0.47)	2100 (0.50)	2093 (0.50)	980-1005 (0.234-0.24)		
Latent Heat of Vaporization, kJ/kg		247	205				
Surface Tension, dynes/cm		28.99	20.97				
Linear Flame Speed, mm/s			1.7				

(cont'd on next page)

TABLE 3-6. (cont'd)

PROPERTY	At °C (°F)	FLUID						
		MIL-H-5606	MIL-H-6083	MIL-H-46170	MIL-83282	MIL-H-53119 (CTFE)	MIL-B-46176	MIL-H-19457
Specific Gravity, dimensionless	15 (60)	0.860-0.865	0.860	0.862	0.84-0.860		0.877-0.889	
Kinematic Viscosity mm^3/s or cSt	−54 (−65)	2050			10,250	881		
	24 (76)		21.30	27.37				
	37.8 (100)	12.73	13.43	15.85	16.52	156 at −40°C (−40°F)	16.63-34.19	
	99 (210)	4.27	3.86	3.62	3.75	2.87 at 40°C (104°F)	4.79-8.18	
	116 (240)	2.9			2.1			
	149 (300)	2.1			1.5			
Absolute Viscosity, MPa or cP	−54 (−65)	2050			10250	4870		
	116 (240)	2.9			2.1	3.1		
	199 (300)	2.1			1.5	2.1		
Thermal Conductivity, W/(m·K) [Btu/(h·ft·°F)]	38 (100)	0.1350 (0.078)			0.1678 (0.097)	0.0744 (0.043)		
	93 (200)	0.1026 (0.0593)				0.0675 (0.039)		
Bulk Modulus, MPa (lb/ft^2)	25 (77)*	1.884 (273,300)			1.891 (274,200)	1.680 (240,700)		
Vapor Pressure, Pa (mm_{Hg})	99 (210)	1267 (9.5)			467 (3.5)	1267 (6)		
	116 (240)	2533 (19)			667 (5.0)	2000 (15)		
	149 (300)	7466 (56)			1133 (8.5)	9466 (71)		

* also at 20.68 MPa (3000 psi)

3-3.1.1 MIL-H-46170, *Hydraulic Fluid, Rust-Inhibited, Fire-Resistant, Synthetic Hydrocarbon-Base* (Military Symbol FRH, NATO Symbol H-544)

Although MIL-H-46170 (Ref. 51) hydraulic fluid is the fire-resistant version of MIL-H-6083 (Ref. 52), it will still produce a fireball when a shaped-charge jet passes through. MIL-H-46170 can be mixed with MIL-H-6083, and the mixture will produce fireballs given a shaped-charge jet impact because the mixture has the worst characteristics of each constituent over the temperature range of each constituent and any temperature inbetween. Pertinent data relative to MIL-H-46170 hydraulic fluid follow:

1. *Intended Use*. Type I is intended for use in recoil mechanisms and battle tank turret hydraulic systems. This fluid has superior fire-resistance characteristics compared to MIL-H-6083 fluids, and it has been evaluated and found satisfactory for use in the M1, M60, and M48 series tanks. If it is to be used in other combat vehicles, a study should be made to determine its applicability, particularly with respect to seal compatibility and low-temperature operability, in such systems. Since this fluid is rust inhibited, it may be used as a preservative medium for hydraulic systems and components. Type II is a preservative fluid for aircraft hydraulic systems and components. Type I is natural straw-yellow in color, but Type II is dyed red for identification purposes.
2. *Limitations*. For retrofit of hydraulic systems containing MIL-H-6083, MIL-H-6083 should be drained as completely as possible. Contamination of MIL-H-46170 with MIL-H-6083 or MIL-H-5606 (Ref. 53) seriously affects the fire-resistance characteristics of this fluid. This fluid cannot be used in the recoil system of self-propelled artillery because its low-temperature viscosity is too high; MIL-H-6083 hydraulic fluid is used instead.
3. *Constituent Materials*. This fluid consists of a synthetic hydrocarbon (alphaolefin polymer) base stock and additives to meet the technical requirements of the finished product.

3-3.1.2 MIL-H-83282, *Hydraulic Fluid, Fire-Resistant, Synthetic Hydrocarbon-Base, Aircraft, Metric, NATO Symbol H-537*

This US Air Force (USAF)-specified hydraulic fluid, per MIL-H-83282 (Ref. 54), is the fire-retardant version of MIL-H-5606. Pertinent data relative to this hydraulic fluid follow:

1. *Intended Use*. This fluid is intended for use in automatic pilots, shock absorbers, air compressor gearboxes, brakes, flap control mechanisms, missile hydraulic servo-controlled systems, and other hydraulic systems using synthetic sealing materials. The recommended operating temperature range is from –40 to 204°C (–40 to 400°F). Although designed for aircraft use, this fluid has applications in ground equipment.
2. *Limitations*. This fluid is not rust inhibited. Contamination of this fluid with MIL-H-5606 results in a significant loss of its fire-resistance properties.
3. *Constituent Materials*. This fluid consists of a synthetic hydrocarbon base stock and additives to meet the technical requirements.

3-3.1.3 Proposed Single Hydraulic Fluid

The Belvoir Research, Development, and Engineering Center (BRDEC) has proposed a single hydraulic fluid (SHF) to replace the MIL-H-5606, MIL-H-6083, and MIL-H-46170 hydraulic fluids currently used in Army equipment. This single fluid is to be a fire-resistant fluid that will not sustain a pool fire; it is to be usable at temperatures to –20°C or lower, including use as a recoil fluid in large caliber guns; it is to provide improved lubricity and corrosion protection for the equipment; and it is to be compatible with the seals and metallurgy of existing equipment. Toxic and environmentally hazardous constituents are to be eliminated. The flash point of the SHF is to be 192°C (378°F) (Ref. 55).

3-3.2 NONFLAMMABLE HYDRAULIC FLUIDS

A program was initiated by the Air Force to develop a MIL-H-5606 replacement without the restrictions imposed by requiring compatibility with hydraulic systems that use MIL-H-5606. This fluid was to be nonflammable in situations in which a threat produces a flash and a spray, which normally result in a fireball with both petroleum-based and fire-retardant hydraulic fluids. This situation is the sense in which the term "nonflammable" is used. Very few fluids are totally nonflammable, but the resistance of these fluids to ignition and subsequent burning is so far superior to that of existing fluids defined as fire-resistant that the use of the term nonflammable is justified. The operational properties of MIL-H-5606 hydraulic fluid, except density and system material compatibility, were used as target requirements for this nonflammable fluid. No separate efforts were made to develop nonflammable hydraulic fluids for ground vehicle systems. This fluid has been adopted by the Army as MIL-H-53119(ME) (Ref. 56). Pertinent properties of this fluid are tabulated in Table 3-6.

MIL-H-53119 is a commercially available chlorofluorocarbon fluid based on chlorotrifluoroethylene (CTFE). CTFE has no flash point, but it does have an allowable heat of combustion of 11.51 MJ/kg (2748 Btu/lbm) maximum. Thus there could be some combustion involved, particularly if the fluid is tested with the compression-ignition test used for the water-based catapult hydraulic fluid, MIL-H-22072 (Ref. 57).

3-3.3 PETROLEUM-BASED FLUIDS

The petroleum-based fluids that follow are still used for some applications in hydraulic systems of all the branches of service, especially low-temperature applications.

3-3.3.1 MIL-H-6083, *Hydraulic Fluid, Petroleum-Base for Preservation and Operation* (Military Symbol OHT, NATO Symbol C-635)

Pertinent data relative to MIL-H-6083 (Ref. 52) hydraulic fluid follow:

1. *Intended Use*. This hydraulic fluid is intended primarily for use as a preservative for aircraft hydraulic systems and components in which MIL-H-5606 is used as an operational fluid and for use as an operational preservative fluid for all tactical and support ordnance equipment for which a determination has been made that MIL-H-46170 (FRH) cannot be used. Examples of ordnance use are recoil mechanisms and hydraulic systems for rotating weapons or aiming devices. The fluid is dyed red for identification purposes. The operating temperature range is –54 to 135°C (–65 to 275°F). This hydraulic fluid has a rather high rate of evaporation and should not be used as a general-purpose, high-temperature lubricant.

2. *Limitations*. The rust-preventive additive somewhat increases the viscosity of this fluid and also limits its high-temperature capability. Consequently, it is not generally a suitable aircraft hydraulic fluid except in those systems specifically designed for this fluid. It is not interchangeable with any other type or grade of hydraulic fluid.

3. *Constituent Materials*. This hydraulic fluid consists of light petroleum fractions, a viscosity index improver, an oxidation inhibitor, and tricresyl phosphate (TCP) antiwear agents.

3-3.3.2 MIL-H-5606, *Hydraulic Fluid, Petroleum-Base, Aircraft, Missile, and Ordnance* (Military Symbol OHA, NATO Symbol H-515)

Pertinent data relative to USAF-specified MIL-H-5606 (Ref. 53) follow:

1. *Intended Use*. The primary intended use of this fluid is in aircraft applications, such as automatic pilots, shock absorbers, brakes, flap control mechanisms, missile hydraulic servo-controlled systems, and other hydraulic systems using synthetic sealing material. This fluid has limited use in ground equipment since it does not provide any rust protection. This oil is dyed red for identification purposes. The recommended operating temperature ranges are –54 to 71°C (–65 to 160°F) in open systems and –54 to 135°C (–65 to 275°F) in closed systems. For sealed systems pressurized with inert gas, a maximum operating oil temperature of 260°C (500°F) can be tolerated for short periods (not to exceed 15 min).

2. *Limitations*. MIL-H-5606 has a rather high rate of evaporation and should not be used as a general-purpose, high-temperature lubricant. Shipment and storage of systems filled with this fluid require draining and refilling with MIL-H-6083 for preservation and testing. This fluid is not interchangeable with any other type or grade of hydraulic fluid.

3. *Constituent Materials*. MIL-H-5606 consists of light petroleum fractions, a viscosity index improver, an oxidation inhibitor, and TCP antiwear agents.

3-3.3.3 MIL-H-19457, *Hydraulic Fluid, Fire-Resistant, Nonneurotoxic*

MIL-H-19457 (Ref. 58) is a fire-resistant fluid for hydraulic systems that are accumulator loaded and generate pressures above 4.14 MPa (600 psi) gage. This fluid was compounded for use in submarines and must be a stable, homogeneous formulation of tertiary butylated triphenyl phosphate and other ingredients. Its fire resistance is 42:1 minimum when tested using the compression ratio test by which the cetane rating is determined. This fluid would be hazardous to personnel if it were released in air and breathed.

3-3.3.4 MIL-B-46176, *Brake Fluid, Silicone, Automotive, All-Weather, Operational and Preservative, Metric* (Military Symbol BFS, NATO Code No. H-547)

This silicone-based hydraulic brake fluid, MIL-B-46176 (Ref. 59), is for use in brake systems operating at ambient temperatures ranging from –55 to +55°C (–67 to +131°F). The flash point of this fluid is not less than 204°C (399°F).

3-3.4 HYDRAULIC FLUID HAZARDS

3-3.4.1 Ignition and Combustion of a Spray

When a high-pressure line is ruptured either by direct penetration or by being jarred loose as a result of impact, various combinations of events can occur. Initially, of course, a mist or spray would develop, and depending upon the size of the rupture, this spray could become more of a stream than a mist.

In 1972 Noonan (Ref. 60) conducted some tests of incendiary bullets impacting either a pressurized hydraulic fluid line or a plate covering a hydraulic fluid spray to establish whether there were benefits to be obtained by using MIL-H-83282 rather than MIL-H-5606. In all of his firings into pressurized hydraulic lines with both MIL-H-83282 and MIL-H-5606, fireballs were obtained that had mean durations of approximately 1.61 s unless the fires became sustained. In 6 of 28 tests with MIL-H-5606, the fires were sustained, whereas in none of the 20 tests with MIL-H-83282 was the fire sustained. Clearly then there was a slight advantage to using MIL-H-83282 instead of MIL-H-5606.

In Noonan's tests in which the incendiary bullets were fired through a striker plate into a hydraulic fluid spray, there was a less clear differentiation. With MIL-H-5606 eight of 10 tests resulted in fires, all of which were sustained. With MIL-H-83282 17 of 18 tests resulted in fires, 13 of which were sustained. Although MIL-H-83282 was better than MIL-H-5606, it was only marginally better. Also tested was a proprietary hydraulic fluid under evaluation by the USAF, known as AEROSAFE 2300, which produced fires in all 37 tests, all of which self-extinguished. A missile hydraulic fluid, MIL-H-46004* (Ref. 61), was also tested, but in nine tests six fires resulted, all of which had to be extinguished.

In 1974 Noonan (Ref. 62) conducted another series of tests to compare MIL-H-6083 to MIL-H-83282 for relative fire survivability of the M60 MBT. This time he performed a fluid spray test for the vast majority of specimens. He made two changes to his test procedure, both of which were unfortunate. First, for these tests he changed from the oil burner nozzle he used in the earlier test series to a nozzle that better met the federal standard called for in MIL-H-83282. This nozzle change resulted in a narrower spray, which had different ignition and combustion characteristics. It was more difficult to have the flash from the incendiary bullet coincide with the spray, and the fires that did ignite tended to self-extinguish. Second, to obtain more positive ignition, he substituted a small flame produced by burning an oil-soaked cloth for the incendiary bullet flash. This replacement igniter produced much less heat over a much smaller space but for a longer time than did the incendiary bullet. The results for 123 tests with MIL-H-6083 and for 165 tests with MIL-H-83282 were all the same: All produced fires that self-extinguished. The MIL-H-6083 fires had a median duration of 1.04 s and the MIL-H-83282 fires had a median duration of 0.83 s. Similar tests using the oil burner nozzle produced different results. The MIL-H-6083 fluid produced sustained fires in all 23 tests. The MIL-H-83282 fluid produced only 31 sustained fires in 104 tests, and the other 73 fires self-extinguished with a median duration of 3.49 s. Four tests were performed with MIL-H-83282 fluid using the oil burner nozzle and incendiary bullets for igniters, and all four tests resulted in sustained fires. Some cup flammability tests** were performed with both MIL-H-6083 and MIL-H-83282. In these tests the fluid was preheated to 27°C (80°F), 104°C (220°F), or 177°C (350°F). For all three fluid temperatures MIL-H-6083 produced sustained fires. MIL-H-83282, however, self-extinguished when tested at the two lower fluid temperatures and produced a sustained fire at only the highest fluid temperature.

Because a better definition was needed for the fluid spray ignition test, a program was conducted by Kanakia *et al.* (Ref. 50) to establish the effects of fluid spray pattern and droplet size upon ignition in order to produce a standardized method for hydraulic fluid flammability assessment. From this program it was concluded that the air velocity through the nozzle was the most critical parameter to obtaining reproducible results. The temperature of the fluid being tested is also critical but can easily be measured. The pressure at the nozzle is important but can be adjusted and measured. The nozzle must be standardized in terms of type and manufacturer and must be tested and preselected to maintain uniformity among laboratories. These nozzles must obtain a consistent pattern and droplet size. Finely dispersed fuel droplets are a serious flammability hazard in the presence of a proper ignition source; however, experiments have shown that once the ignition source is removed, the flame may not be sustained, as shown in Table 3-7.

*MIL-H-46004 was cancelled 19 July 1982 and replaced by MIL-H-5606.

**The fluid was placed in a cup and heated to one of three specified temperatures. An open, wide-mouthed Bunsen burner flame was applied to the fluid surface for three seconds and then removed. If the fire in the cup self-extinguished upon withdrawal of the flame, the fluid was considered to be capable of producing only a nonsustained fire. The three initial bulk fluid temperatures represented: 27°C—an unoperating hydraulic system, 104°C—a hydraulic system after frequent operations, and 177°C—a gun recoil system after many rapidly fired rounds.

TABLE 3-7. RESPONSE OF VARIOUS HYDRAULIC FLUIDS TO HIGH-PRESSURE SPRAY IGNITION (Federal Test Standard 791B, Method 6052) (Ref. 48)

FLUID	RESULTS
MIL-H-5606**	Ignition at pilot, self-extinguishing flame
MIL-H-6083**	Ignition at pilot, self-extinguishing flame
MIL-H-83282A*	Ignition at pilot, self-extinguishing flame
MIL-H-46170*	Ignition at pilot, self-extinguishing flame
MIL-H-13919B*	Ignition at pilot, self-extinguishing flame
MS-5	Ignition at pilot, self-extinguishing flame
Skydrol 300 (Phosphate Ester)	No ignition at 152, 305, or 457 mm (6, 12, or 18 in.)
MIL-B-46176* Source A	Ignition at pilot, self-extinguishing flame
MIL-B-46176* Source B	Ignition at pilot, self-extinguishing flame

NOTE: Properties of materials are given in Table 2-4.
*The change letters apply to the materials tested or test methods used.
**Change letter not known

Finnerty *et al.* (Ref. 63) demonstrated that MIL-H-46170 FRH fluid would ignite and burn in mist form when exposed to a strong ignition source. The FRH fluid, at a working temperature of 77°C (170°F) and contained in 6-mm (0.25-in.) outside diameter, 0.9-mm (0.035-in.) thick corrosion-resistant steel (CRES) 304 tubing (which simulates the hydraulic fluid tubing used in US combat vehicles) and pressurized to 10.35 MPa (1500 psi), sprayed when the tubing was hit by one or more explosively launched steel cubes. The cubes had a mass of 0.13 g (2 gr), 1.04 g (16 gr), or 6.48 g (100 gr) and a velocity of approximately 300 to 800 m/s (984 to 2625 ft/s), which simulates behind armor debris from a kinetic energy penetrator. These tests demonstrated that these fragment impacts could result in breaks in the steel tubing, that the FRH fluid could escape through the breaks and form a mist, and that the FRH fluid mist could be ignited by a strong ignition source—an ethyl alcohol fire—even when the FRH fluid is well below its flash point.

This ignition of hydraulic fluid in mist form was again demonstrated in another program conducted in 1970. In that program a silicate ester hydraulic fluid (Oronite 8515) had an initial bulk fluid temperature of approximately 21°C (70°F) and a flash point of 202°C (395°F). The ballistic impact produced a spray, ignition of which resulted in an explosion. (This incident is further described in par. 4-4.4.1.)

There is strong evidence that a flame front will pass through a mist more rapidly than through a vapor-air mixture. Burgoyne (Ref. 64) measured the burning velocity of tetralin ($C_{10}H_{12}$) mist in air as a function of the mist droplet size, as is shown on Fig. 3-2. Note that the flame front speed in vapor is approximately 280 mm/s but that the speed with droplets of 0.015 mm or greater is approximately 605 mm/s. Burgoyne indicated that tetralin, which has a boiling point of 207°C (404°F), has a lower limit of flammability in air as a vapor of 100°C (212°F) but has a lower limit of flammability in air as a mist of 29°C (84°F).

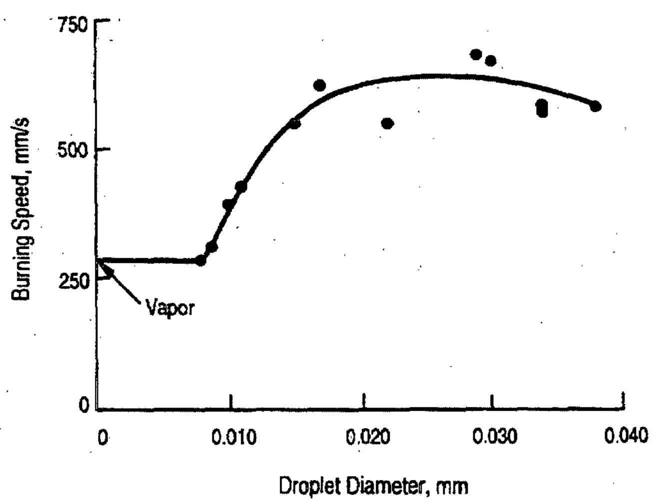

Figure 3-2. Effect of Mist Droplet Size on Burning Speed of Monodispersed Tetralin-Air Suspension (Ref. 64)

In a more recent ballistic test program conducted by Wright-Patterson Air Force Base (Ref. 65), a 20.68-MPa (3000-psi) hydraulic system was installed within a simulated aircraft dry bay, and a Russian 23-mm high-explosive incendiary tracer (HEIT) projectile was fired into it while an airflow of 0 m/s (0 knot) or 244 m/s (475 knots) passed over the simulated aircraft. With an airflow of 0 m/s MIL-H-5606 had 32 sustained fires in 32 tests, and MIL-H-83282 had 32 self-extinguishing fires with a mean duration of 7.31 s. With a 244-m/s airflow MIL-H-5606 had no fire in 10 tests and 22 self-extinguishing fires with a mean duration of 3.07 s, and MIL-H-83282 had no fire in five tests and 27 self-extinguishing fires with a mean duration of 8.44 s. These results indicate that under high-speed airflow conditions, MIL-H-83282 can experience more combustion than MIL-H-5606. This difference would be important for combat vehicles only when there is a marked excess of oxygen present, such as is provided by a high-speed airflow or rupture of an oxygen bottle.

3-3.4.2 Ballistic Rupture of a Vessel

When an incendiary round penetrates a hydraulic fluid reservoir or line, there are several possible results. The parameters affecting these results are the volume and temperature of the fluid and the duration and intensity of the incendiary exposure. With ballistic impact there is sufficient energy over sufficient time to create a flammable mist and to ignite it. Results of ballistic tests using a pressurized hydraulic cylinder and 20-mm HEIT projectiles, shown in Table 3-8, indicate that some fluids produce self-sustaining fires. The petroleum-based fluids (MIL-H-5606 and MIL-H-6083) produced a large fireball and sustained burning of the remainder of the fluid when subjected to these ballistic tests. Results obtained with other fluids, however, generally showed a fireball (of various sizes) but no residual burning. Finnerty (Ref. 63) demonstrated that a shaped-charge jet ruptures a hydraulic fluid container, broadcasts the fluid, and ignites it. In tests in which shaped-charge jets perforated steel reservoirs containing either MIL-H-6083 or fire-resistant MIL-H-46170 that had no fire protection, both hydraulic fluids ignited and burned (Ref. 67). See par. 7-3.2.1.3 for hydraulic fluid reservoir protection techniques.

3-3.4.3 Combustion of a Pool

In a hydraulic system that is under pressure during normal combat vehicle operation, the operating temperature can be approximately 104°C (220°F). The temperature of the fluid in a gun recoil mechanism may be substantially higher; one estimate is 177°C (350°F). Therefore, the normal operating temperature is near the flash point of the petroleum-based fluids that have been in use. Flame propagation studies have shown that once this fluid is ignited, the

TABLE 3-8. RESPONSE OF VARIOUS HYDRAULIC FLUIDS TO BALLISTIC IMPACT OF 20-mm HEIT AMMUNITION (Ref. 66)

FLUID	TEST FUEL TEMPERATURE AMBIENT 21°C (70°F)	TEST FUEL TEMPERATURE 77°C (171°F)	REMARKS
MIL-H-5606**	X	X	Impact fireball, sustained burning
MIL-H-6083**	X	X	Impact fireball, sustained burning
MIL-H-83282A*	X	X	Impact fireball
MIL-H-46170*	X	X	Impact fireball; 0.803-s duration
MIL-H-13919B*	X	X	Impact fireball, some sustained burning at 77°C tests
MS-5	X	X	Small impact fireball
Skydrol 300 (Phosphate Ester)	X	X	Small impact fireball
MIL-B-46176* Source A	X	X	Small impact fireball; 0.349-s duration
MIL-B-46176* Source B	X	X	Impact fireball; 0.667-s duration

NOTE: Properties of materials are given in Table 2-4.
*Change letter applies to material used.
**Change letter not known

flame should spread until total pool involvement has occurred. Flame propagation, however, occurs only after the temperature at the surface of the bulk liquid is near the flash point of the fluid. It is improbable that the bulk temperature could be maintained at or near 200°C (or even reached) until ignition occurs. Hence it is unlikely that bulk liquid involvement could ever occur with the newer fire-resistant hydraulic fluids. This fact is further indicated by the ballistics tests described in Ref. 66, which showed residual burning with the petroleum fluids and no residual burning with the other fluids (Ref. 48). It is interesting to note that another petroleum-based fluid, MIL-H-13919*, which had a significantly higher flash point than that of MIL-H-5606, showed less extensive residual burning than MIL-H-5606. Again a relationship exists between flash point and bulk liquid fire involvement. It should be emphasized, however, that the mist flammability characteristics are not directly related to flash point. MIL-B-46176 has a still higher minimum flash point, 204°C (399°F), but also produced a fireball from the 20-mm HEIT impact that was, however, of a shorter duration than the one produced by MIL-H-46170. When a liquid container is in contact with the detonation of a high-explosive projectile, the detonation undoubtedly will simultaneously form a mist and, if the fluid is combustible, ignite it (Ref. 68). Flame propagation studies of bulk fluid have shown that the fluid has to be heated to near its flash point before even a wick will stay ignited or certainly before a flame will propagate.

*MIL-H-13919 is now obsolete.

3-3.4.4 Ignition and Combustion on a Hot Surface

In an effort to relate fire vulnerability to hot-surface ignition, it was determined that mist from petroleum-based fluids—flash point of approximately 100°C (212°F)—would not ignite when sprayed onto surfaces heated to 730°C (1350°F), i.e., glowing red. The same result was obtained with fire-resistant fluids. This result was entirely unexpected, so further experiments were conducted to explain it. The procedure used was a combination of a high-pressure spray apparatus (Fed. Test Std. 791B, Method 6052) and the hot manifold (Fed. Test Std. 791B, Method 6053). Table 3-9 shows that the degree of atomization greatly influences the surface temperature required for ignition.

To better understand those situations in which the fine mist would not ignite on the glowing red surface, various methods of mist generation were attempted. The standard procedure of Method 6052 used a 0.4-mm (0.014-in.) square-edged orifice and 6.9 MPa (1000 psi) nitrogen pressure. It was thought that perhaps the mist formed by this method produced an overrich situation at the heated surface and that forced dilution with air might produce a fuel-air mixture in the flammable range. Therefore, in one series of experiments mist generation was accomplished by using a smooth-bore fuel-delivery tube; the mist was formed by three intersecting air jets that caused the fuel stream to break up into very fine droplets. The mist formed using this procedure of air impingement also would not ignite at surface temperatures up to 730°C (1350°F).

TABLE 3-9. EFFECT OF ATOMIZING PRESSURE ON MIST FLAMMABILITY (Ref. 48)

FLUID	MANIFOLD SURFACE TEMPERATURE REQUIRED FOR IGNITION, °C (°F) HIGH PRESSURE, 6.9 MPa	LOW PRESSURE, 0.69 MPa
MIL-H-6083*	No fire up to 730 (1350)	524 (975)**
MIL-H-83282A***	No fire up to 730 (1350)	400 (750)
MIL-H-46170***	No fire up to 730 (1350)	400 (750)
Skydrol 300 (Phosphate Ester)	No fire up to 730 (1350)	677 (1250)
MS-5	649 (1200)	454 (850)
MIL-G-13919B***	No fire up to 730 (1350)	482 (900)

*Change letter of material used not known
**Temperature given bulk fluid temperature of 14°C (25°F)
***Change letter applies to material used

Further studies were conducted with mists formed by a standard nozzle from a T-63 turbine engine. These results showed that the mists formed by this procedure ignited instantly upon coming into contact with the hot surface, the temperature of which was greater than 730°C (1350°F). The same results were obtained with two petroleum-based fluids; thus once again the relationship is to particle size rather than volatility.

When a low-pressure (nonmisting) spray impinged on the same hot surface, the ignition temperatures were entirely different. It is interesting to note in Table 3-9 that an increase in hot-surface ignition temperatures of MIL-H-6083, relative to those of MIL-H-83282 or MIL-H-46170, is observed (relative to the minimum AIT) in the low-pressure spray procedure. It would seem, therefore, that a low-pressure or dripping leak would be very hazardous due to the low temperature required for ignition.

3-4 OTHER PETROLEUM, OILS, AND LUBRICANTS (POL)

3-4.1 TRANSMISSION FLUIDS, ENGINE OILS, AND LUBRICANTS

A goal of the DoD is to limit the number of POL products required. Therefore, certain classes of fluids are used to service more than a single requirement. A number of research programs are currently underway to evaluate multiuse of fluids in order to reduce the number of fluids required to be stocked and to prevent the required use of proprietary products. The paragraphs that follow list the specifications currently being used and present the only available property concerned with flammability, the flash point. If other pertinent information is available, it is included. Other properties are given in MIL-HDBK-113 (Ref. 41).

3-4.1.1 MIL-L-2104, *Lubricating Oil, Internal Combustion Engine, Combat/Tactical Service*

The US Army lubricating oil used in the crankcase of both spark- and compression-ignition internal combustion engines and in other applications, such as power transmissions and power systems, is specified in MIL-L-2104 (Ref. 69) and comes in four grades: 10W, 30, 40, and 15W-40. The specified minimum flash points of these four grades are 205°C (401°F), 220°C (428°F), 225°C (437°F), and 215°C (419°F), respectively. The specified kinematic viscosities, i.e., minimum and maximum values in cSt at 100°C (212°F), for these four grades are (5.6, <7.4), (9.3, <12.5), (12.5, <16.3), and (12.5, <6.3), respectively. Some measured values for these parameters are in Table 3-10.

3-4.1.2 MIL-L-2105, *Lubricating Oil, Gear, Multipurpose*

Multipurpose gear oil for the US Army is specified in MIL-L-2105 (Ref. 71) and comes in three grades: 75W, 80W-90, and 85W-140. The specific minimum flash points for these three grades are 150°C (302°F), 165°C (329°F), and 180°C (356°F), respectively. The specified kinematic viscosities, i.e., minimum and maximum values in cSt at 100°C (212°F), for these three grades are 4.1, no requirement; 13.5, <24.0; and 24.0, <41.0.

3-4.1.3 MIL-L-7808, *Lubricating Oil, Aircraft Turbine Engine, Synthetic-Base, NATO Code No. 0-148*

This aircraft lubricating oil for gas turbine engines is specified in MIL-L-7808 (Ref. 72) and is available in a single grade. The specified minimum flash point of this fluid is

TABLE 3-10. TYPICAL PROPERTIES OF SELECTED LUBRICANTS (Refs. 10, 44, 45, 50, and 70)

PROPERTY	MIL-L-2104				MIL-L-7808	MIL-L-23699	MIL-L-46152				MIL-L-46167
	10W	30	40	15W-40			30	5W-30	10W-30	15W-40	
Specific Gravity, dimensionless	0.883	0.891	0.893	0.886	0.92	0.99			0.894	0.886	
Flash Point, °C (°F)	204-214 (399-417)	218-220 (424-428)	225 (437)	204-211 (399-412)	207-225 (405-437)	227 (440)	216-247 (421-477)	209 (408)	204-235 (400-455)	218 (424)	200-218 (392-424)
Latent Heat of Vaporization, kJ/kg	154										
Heat of Combustion, MJ/(kg·K) [Btu/(lbm·°F)]	35.383 (15,211)				34.40-35.78 (14,790-15,383)	30.36-33.04 (13,060-14,215)					
Specific Heat at Constant Pressure, kJ/(kg·K)	2.10										
Autoignition Temperature, °C (°F) Vapor in Air	350	372		363	387-412 (728-755)	384-415 (725-778)					364-368 (687-694)
Minimum Ignition Temperature, °C (°F) Stream on Hot Manifold					704 (1300)	621 (1150)					
Minimum Ignition Temperature, °C (°F) Spray on Hot Manifold	720	680		705	834 (1533)	>816 (≥1500)					685-690 (1265-1274)
Fire Point, °C (°F)	236	241		238	238 (460)						243-247 (469-477)
Surface Tension, dynes/cm	32.71										
Flame Propagation on Liquid Surface, mm/s	1.98	1.47		1.39							1.48-1.75
Kinematic Viscosity, mm^2/s or cSt, at 100°C (212°F)	6.7	11.8-12.1	14.8-15.3	14.3	3.1-3.3		10.50-12.28	12.17	9.58-11.92	14.3-15.19	
at 40°C (104°F)		107	152				78.64-115.2	78.42	46.83-92.88	112.05	
at 38°C (100°F)					12.1-12.58						
at 24°C (76°F)	89.67										
Pour Point, °C (°F)	−33 (−27)	−18 (0)	−15 (5)	−24 (−11)					−35 (−31)	−24 (−11)	

210°C (410°F). The specified kinematic viscosity of this fluid is at –53.9°C (–65°F) 17,000 cSt maximum and minimum at 100°C (212°F) 3.0 cSt. Some typical property values are given in Table 3-10.

3-4.1.4 MIL-L-9000, *Lubricating Oil, Shipboard Internal Combustion Engine, High-Output Diesel*

This US-Navy-prepared specification for lubricating oil for high-output diesel engines is specified in MIL-L-9000 (Ref. 73) and is available in a single grade. The specified minimum flash point is 199°C (390°F) and the specified kinematic viscosity range is 12.5 to 16.5 cSt at 100°C (212°F).

3-4.1.5 MIL-L-21260, *Lubricating Oil, Internal Combustion Engine, Preservative and Break-in*

This US-Army-prepared specification for lubricating oil, which is intended for preservation and breaking in engines and transmissions, is specified in MIL-L-21260 (Ref. 74) and is available in four grades: 10W, 30, 40, and 15W-40. The specified minimum flash points and kinematic viscosities at 100°C (212°F) are the same as those for MIL-L-2104.

3-4.1.6 MIL-L-23699, *Lubricating Oil, Aircraft Turbine Engine, Synthetic Base*

This US-Navy-prepared specification for aircraft turbine lubricating oil, intended for use in gas turbine engines, helicopter transmissions, and other aircraft gear boxes, is specified in MIL-L-23699 (Ref. 75) and is available in a single grade. The specified minimum flash point is 246°C (475°F). The specified kinematic viscosity is 5.5 cSt at 98.9°C (210°F). The maximum value is 13,000 cSt at –55°C (–67°F), and this should not change more than ±6% after 72 h ±5 min of soaking at that same temperature. At 37.8°C (100°F) the viscosity should be 25 mm^2/s (cSt), and at 98.9°C (210°F) the viscosity range should be 5.00 to 5.50 mm^2/s (cSt). Some typical properties of this lubricant are given in Table 3-10.

3-4.1.7 MIL-L-46152, *Lubricating Oil, Internal Combustion Engine, Administrative Service*

This US-Army-prepared specification, MIL-L-46152 (Ref. 76)*, is for the purchase of engine lubricating oil for use in noncombat, administration vehicles. It covers five grades: 10W, 30, 5W-30, 10W-30, and 15W-40. The specified minimum flash points of these grades are 205°C (401°F), 220°C (428°F), 200°C (362°F), 205°C (401°F), and 215°C (419°F), respectively. Some typical properties of these fluids are given in Table 3-10.

In an evaluation of commercially available, rebranded lubricants, 5 of 16 samples of SAE 30 and 2 of 24 samples of SAE 10W-30 were below the specified flash points (Ref. 70).

3-4.1.8 MIL-L-46167, *Lubricating Oil, Internal Combustion Engine, Arctic*

Specification MIL-L-46167 (Ref. 77) was prepared by the US Army for one grade of lubricating oil to be used in internal combustion engines, both spark- and compression-ignition types, when the ambient air temperature is in the range of –55 to 5°C (–67 to 41°F) and to be used in arctic regions as an all-weather power transmission fluid. The minimum flash point is 220°C (428°F). The specified kinematic viscosity is 5.6 cSt minimum at 100°C (212°F), 8,800 mm^2/s (cSt) maximum at –40°C (–40°F), and 75,000 mm^2/s (cSt) maximum at –55°C (–67°F).

3-4.1.9 VV-L-765, *Lubricant, Enclosed Gear, Non-extreme Pressure*

The federal specification, VV-L-765 (Ref. 78), covers four grades of enclosed gear oil for nonextreme conditions. These grades are 80, 90, 140, and 250, and their respective flash points are 177°C (350°F), 191°C (375°F), 204°C (400°F), and 204°C (400°F).

3-4.2 ANTIFREEZE COMPOUNDS

Most antifreeze compounds use mixtures of water, glycol, and an additive package. Therefore, flammability considerations are not usually given to these products. A flammability hazard could occur if the water concentration were reduced substantially, e.g., by evaporation. Mist flammability would begin to occur with glycol concentrations estimated around 60% by volume, and sustained flame propagation would occur with a glycol concentration estimated greater than 90% by volume. The effects of this phenomenon were illustrated in two tests of a double-walled fuel cell in which the interstitial space contained either water with 25% aqueous film-forming foam (AFFF) or water with 25% AFFF and 50% propylene glycol (PG), and the fuel tank contained commercial diesel fuel. (Propylene glycol was used rather than ethylene glycol, which is generally used in automotive applications, because the latter is toxic.) The fireballs—produced when the jet from an M28A2 rocket warhead perforated the fuel cell—lasted for 0.041 s with the water-25% AFFF mixture and for 1.000 s with the 25% water, 25% AFFF, and 50% PG mixture (Ref. 79). These tests indicated that the propylene glycol provided a flammable fuel and thus increased the duration and size of the diesel fuel fireball. The following specification products are generally used to lower the freeze point of water in combat vehicles.

*MIL-L-46152 has been superceded by A-A-52039, *Lubricating Oil, Automotive Engine, API Service SG*, 31 October 1991.

3-4.2.1 MIL-A-11755, *Antifreeze, Arctic-Type*

Pertinent data relative to MIL-A-11755 antifreeze (Ref. 80) follow:

1. *Intended Use.* Arctic-type antifreeze is intended for use in the cooling system of liquid-cooled internal combustion engines to protect against freezing where the ambient temperature remains close to –40°C (–40°F) for extended periods of time but may drop as low as –68°C (–90°F). This material may also be used as a heat transfer liquid for military applications where low temperatures are encountered.
2. *Limitations.* This material is designed to be used as packaged and should never be diluted with water.
3. *Constituent Material.* This compound is a premixed arctic grade antifreeze that consists of ethylene glycol, water, various glycol ethers, and inhibitors.

3-4.2.2 MIL-A-46153, *Antifreeze, Ethylene Glycol, Inhibited, Heavy-Duty, Single Package*

Pertinent data relative to MIL-A-46153 antifreeze (Ref. 81) follow:

1. *Intended Use.* Inhibited ethylene glycol antifreeze is intended for use in the cooling system of liquid-cooled internal combustion engines other than aircraft to protect against freezing in ambient temperatures as low as –48°C (–55°F) when diluted to 60% by adding water.
2. *Limitations.* This material should not be used under arctic conditions and should not be packaged in metal containers.
3. *Constituent Material.* This is a conventional antifreeze concentrate that contains ethylene glycol, water, and inhibitors.

3-4.2.3 Other Freeze Point Suppressants

Currently most freeze point suppressants used by the US Army are ethylene glycol based. Ethylene glycol is both toxic and flammable and has a flash point of 111°C (232°F) and a net heat of combustion of 17.06 MJ/(kg·K) (7340 Btu/(lbm·°F)). Ethylene glycol has an autogenous ignition temperature (AIT) of 458°C (856°F); a 50% solution of ethylene glycol in water has an AIT of 484°C (903°F). Because it is nontoxic, propylene glycol was selected as the freeze point suppressant, but its flash point is 99°C (210°F), its AIT is 446°C (835°F), and its net heat of combustion is 21.73 MJ/(kg·K) (9350 Btu/(lbm·°F)) (Ref. 82).

In World War II some German artillery pieces had a solution of water and potassium lactate as the recoil fluid (Ref. 83). At present, the US Air Force is experimenting with calcium chloride as a freeze point suppressant in water used in a fire extinguisher (Ref. 84). Another freeze point suppressant that is currently used in a water-based airport runway deicer and as a heat transfer fluid for ground source heat pumps is potassium acetate. Cryotech E36™ Liquid Runway Deicer* (Ref. 85) has been modified not to affect the aluminum of aircraft, and the heat transfer fluid, GS4* (Ref. 86), has been modified not to affect carbon steel, aluminum, or brass. Both of these fluids are nominally 50% by weight potassium acetate plus corrosion inhibitors, and both have nominal specific gravities of 1.275 at 20°C (68°F). Their freezing points at their nominal composition are less than –50°C (–58°F). The runway deicer has an absolute viscosity of 10 mPa·s (cP) at 20°C (68°F) and an absolute viscosity of 20 mPa·s (cP) at 0°C (32°F). The heat transfer fluid, GS4™, has a typical absolute viscosity of 6.4 mPa·s (cP) at 20°C (68°F) and of 12.3 mPa·s (cP) at 0°C (32°F). The E36™ Liquid Runway Deicer has been subjected to a spray test on a hot manifold; the solution produced no fire (Ref. 87).

3-4.3 FOG OIL

With the change from DF-2 diesel fuel to JP-8 turbine fuel in combat vehicles, the need for a special fluid in the VEESS of combat vehicles arose. These systems are used in the M1 MBT family, the BFVs, and the M60 MBT/M88 TRV family. When used with the VEESS, DF-2 produces excellent smoke; JP-8, JP-5, and Jet A-1 do not. To date, the best smoke-generating performance has come from fog oil per MIL-F-12070 (Ref. 88). Fog oil was compounded for use in US Army field smoke generators, which are used to obscure large terrain features, e.g., to reduce observation by the enemy in a valley during a river crossing. Both the smoke generator and the VEESS meter a spray of fog oil into a hot, flowing gas so that the fog oil vaporizes. This fog oil condenses into a fog shortly after leaving the smoke generator or the VEESS and becomes a dense, white cloud, that persists near the ground for two or three minutes. Smoke is formed from the heavier ends of the fuel blend, which can be estimated from the distillation breakdown. (See Fig. 3-1.) JP-8 has an end point of 258 to 284°C but does not generate smoke. CONUS DF-2 has an end point of 370°C and produces approximately 74.8% of the smoke of an equal volume of fog oil (Ref. 28). Fog oil starts near the end of the DF-2 distillation trace, as shown on Fig. 3-1. The smoke produced by a mixture of fog oil and JP-8 was proportionate to the amount of fog oil in the mixture, i.e., the fuel added nothing to the smoke produced. Therefore, the VEESS was redesigned to be separate from the fuel system of the vehicle. A proposed system for the M1 MBT would have one 39-L (10-gal) tank containing fog oil mounted in the right rear of the engine compartment.

Fog oil consists of overhead petroleum fractions (hydrocarbons extracted during the initial distillation as opposed to

*Use of the trade name does not mean that the Government is endorsing the product.

other late processes such as cracking) without additives; rerefined oils are prohibited. Fog oil has a minimum flash point of 160°C (320°F), a minimum kinematic viscosity of 3.40 mm^2/s or cSt at 40°C (104°F) to a maximum of 4.17 mm^2/s or cSt at 100°C (212°F), and a pour point of –40°C (–40°F) maximum (Ref. 19).

3-5 MUNITIONS

Munitions that are carried on combat vehicles are identified and the properties, flammability characteristics, and hazards are described in the following paragraphs. These munitions are described in terms of their energetic contents, i.e., propellants used in guns or in solid rocket motors; high explosives used in projectiles, charges, or other items; and other materials such as smoke, incendiaries, or flares.

If the main weapon is a high-velocity gun, the ammunition will usually be a fixed cartridge. The propellant charge is normally loose grains of propellant in a metallic—brass or steel—case or in a combustible case (e.g., the 152-mm M409 high-explosive, antitank, tracer, multipurpose (HEAT-T-MP) cartridge), or the charge can be a compact mass adhered to the projectile (referred to as "caseless"). The metal-cased cartridge is usually the most rugged.

A lower velocity weapon, such as a howitzer, usually uses either a semifixed cartridge or separate loading ammunition. A semifixed cartridge has a projectile that can be removed from the case to enable a cannoneer to modify the charge by removing or adding bags of propellant. The use of separate loading ammunition involves loading a projectile, a propellant charge, and a primer instead of a cartridge. There is no case, but the propellant charge is usually transported within a metal tube.

If the main weapon is a mortar, the round consists of a projectile with a propellant charge attached either as multilayered wafers or in bags. This round comes in a travel pack and is removed shortly before firing. The travel pack can be a cardboard or steel tube or a metal box. The charge is varied by removal of some of the wafers or bags.

If the main weapon is a missile launcher, the ammunition is rocket-propelled. These rocket-propelled missiles usually present the greatest challenge for nonhazardous stowage design.

All of these types of rounds must be readily available for use in the weapon, and they must be stowed to minimize the hazard presented. The warheads can contain explosives, pyrophoric chemicals (such as white phosphorus or triethylaluminum), other chemicals (such as flares or smoke-generating mixtures), or can be inert.

Secondary weapons are usually machine guns or automatic cannon. The ammunition for these weapons is normally fixed. Most of these use metal-cased cartridges, but some use caseless cartridges. Some vehicles have small caliber mortars or automatic grenade launchers. Secondary weapons are operated from within the vehicle. Ammunition should be readily available to the gunner.

Almost all armored vehicles now mount grenade launchers for quick-reaction smoke screens. These grenade launchers are usually mounted on the turret or superstructure of the vehicle. The ammunition for these grenade launchers is usually located near the launchers.

Ammunition for the crew's individual weapons is also stowed within the combat vehicle. Most of these individual weapons are used when the crewmen dismount to travel or fight on foot, but some vehicles have firing ports to permit the firing of these weapons from within the vehicle. Although most of these individual weapons use fixed cartridges, there can be hand grenades, light antitank weapons (LAWs), medium antitank weapons (MAWs) such as the Dragon, and mines (such as the Claymore). Hand grenades and weapon-launched grenades have high-explosive (HE) or chemical fillers. Mines are usually HE filled. LAWs and MAWs have both solid propellant rocket motors and high-explosive antitank (HEAT) warheads. On some occasions bulk explosives are carried on or in the vehicle. These weapons and ammunition should be available to the crewmen when they dismount.

The hazard presented by the energetic materials used in the munitions is primarily the potential for fire or explosion. Also these materials can emit noxious or toxic fumes. It is generally acknowledged that most armored vehicles destroyed beyond recovery are those in which internal fires have caused the stowed munitions to explode.

Most combat vehicles carry as many munitions as can be stowed within and/or without. These munitions often contain both a low explosive for launching the projectile and a high explosive for obtaining the desired terminal effects. The low explosive is either a gun propellant or a solid rocket motor propellant. The rocket motor propellants are usually near-stoichiometric mixtures of fuels and oxidizers and are usually quite sensitive to either ballistic impact or heat. The high explosives are much more fuel-rich, and most are less sensitive to kinetic energy impact or heat than are the low explosives. A small number of the high explosives are sensitive to ballistic impact or heat; these are the primary explosives used to initiate the explosive trains in the warheads or projectiles. These primary explosives, e.g., mercury fulminate, lead azide, and lead styphnate, are used to convert a mechanical movement or an electric current flow into an explosion. Fortunately, these primary explosives occupy a very small volume and are usually embedded within the projectile. Explosion of the primary explosives may have to be amplified by a less sensitive explosive, such as pentaerythritol tetranitrate (PETN) or Composition A5, in a booster to assure initiation of the main charge. The principles of explosive behavior are covered in detail in AMCP 706-180 (Ref. 89) and explosive trains are covered in AMCP 706-179 (Ref. 90). For the purposes of this handbook, it must be realized that there are both low and high explosives within or on combat vehicles and that these explosives are capable of being ignited or initiated by either ballistic impact or heat.

Low explosives are designed to function by burning at controlled rates. It is possible, however, for low explosives to burn at a much higher than desired rate, i.e., to deflagrate, and some of these low explosives may even detonate. When such chemical reactions occur, the strength of the container for the explosive can be exceeded, sometimes catastrophically. On the other hand, high explosives are intended to detonate but can also burn slowly. The containers for these high explosives usually are designed to fragment so that they cause maximum damage to nearby personnel and/or equipment. In some ballistic impacts the low explosives tend to deflagrate, whereas the high explosives often tend either not to react or simply to burn slowly. High explosives can burn initially and later deflagrate and then detonate; consequently, the designer should always design for the worst case, i.e., detonation.

Some of the energetic materials carried in combat vehicles are pyrotechnics. Since some pyrotechnics contain both oxidizer and fuel in a near-stoichiometric mixture, a strong ballistic impact can result in combustion.

3-5.1 GUN AND SOLID ROCKET PROPELLANTS

Gun propellants used in munitions employed in combat vehicle gun systems such as armor piercing (AP), HE, rocket-assisted projectiles, and small arms ammunition for crewmen's individual and crew-served weapons are of three general types. The propellants are single-base, double-base, and triple-base—a classification based on the number of explosive ingredients used in their formulation. Single-base propellants in general contain nitrocellulose as an explosive ingredient, double-base propellants contain nitrocellulose and nitroglycerin, and triple-base propellants contain nitrocellulose, nitroglycerin, and nitroguanidine. Usually triple-base propellants are less susceptible to thermal, compressional, and shock initiation than single- or double-base propellants. Additives control characteristics such as burning rate, flame temperature, energy release rate, gas evolution, deterioration as a function of temperature and time, vulnerability, and ignition. Most solid propellants burn more rapidly when confined, i.e., higher pressure increases the burn rate.

Gun ammunition can be handled as either fixed or semifixed cartridges or as separate loading components. Fixed cartridges are those in which the propellant charge usually has loose grains, is standardized, and cannot be changed for a single round. Examples of fixed cartridges are small arms cartridges and combat vehicle gun cartridges up to 152 mm or the combat engineer vehicle high-explosive plastic cartridge of 165 mm. Most often these cartridges have the projectile crimped or otherwise firmly fixed to the cartridge case. Semifixed ammunition, such as that for the 105-mm howitzer, has the projectile loosely inserted in the cartridge case so that the projectile can be easily removed and the propellant charge, which is in a number of bags, can be altered (zoned) for each specific round. After adjustment of the propellant charge, the projectile is replaced. Separate loading ammunition has three components: a projectile, a propellant charge that often consists of several bags of propellant, and a primer. These items are loaded individually into the weapon.

Brass, aluminum, or steel cases protect the propellant from minor ignition sources. The steel case is slightly more resistant to spall or fragment impact than the brass case, and both are more resistant than the aluminum case. Given a shaped-charge jet impact that will probably cause the propellant to deflagrate, however, the cartridge case can provide a number of large, rapidly moving fragments, as shown on Fig. 3-3. On the other hand, when a shaped-charge jet perforated an ammunition can containing loose, brass-cased, 5.56-mm cartridges, only the cartridges that were struck by the jet exploded (Ref. 92).

There have been several efforts to reduce cartridge weight and handling problems. The 152-mm gun/launcher used on the M551 Sheridan has fixed cartridges with a combustible case. The propellant is of loose grains within the case. This cartridge has a number of problems. Initially, the case left burning residue in the chamber, but this problem was solved. A rubber cover had to be placed over the case to protect it from high humidity in Southeast Asia, and the case is prone to rupture when roughly handled and spill propellant grains in the vehicle.

A combustible case cartridge reduces cartridge weight and eliminates the problem of a fired case cluttering the crew space. The partially combustible-cased, 120-mm tank gun cartridges for the M1A1 MBT illustrate improved characteristics; in these cartridges the problems that plague the 152-mm cartridge have been solved. These cartridges consist of a metal case base and a combustible sidewall. The

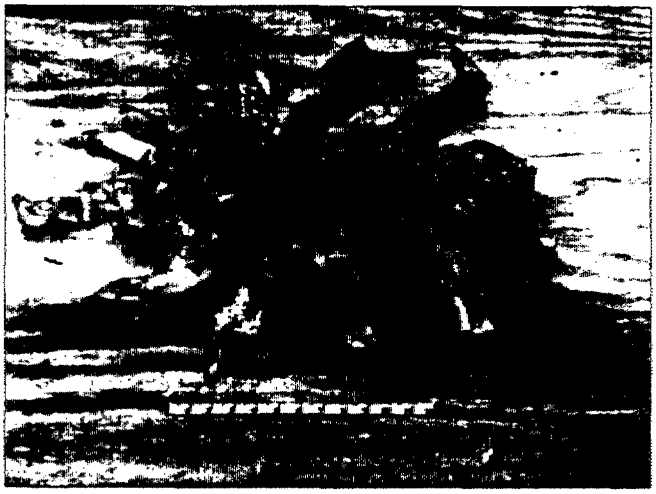

Figure 3-3. 105-mm Cartridge Case After Deflagration of Solid Propellant Filler Penetrated by a Shaped Charge (Ref. 91)

propellant for kinetic energy (KE) projectiles is granular and for HEAT projectiles is stick.

Another concept still not fully developed is the caseless cartridges and the weapons to use them. The propellant of a caseless cartridge is molded solidly around the projectile. The binder on the outside of the propellant block is intended to protect the propellant from moisture. This concept would eliminate the combustible case itself and the potential problem of spilling loose propellant grains in the vehicle.

A third concept is to use a low-vulnerability propellant. This propellant could be either an insensitive solid propellant or an insensitive liquid gun propellant in which the charge needed for a particular round is metered into the breech by the gun computer. The insensitive solid propellant, probably a plastic-bonded type, would be used as solid propellant is now. The liquid gun propellant would be carried in a special container with appropriate plumbing to the gun. This system would be particularly effective for the current semifixed- or separate-loading-type weapons because it would eliminate having unused bags of propellant cluttering the vehicle or gun site and would reduce the current large tonnage and volumetric requirements placed on the logistic system. The liquid gun propellant currently being considered by the US Army has been insensitive to a shaped-charge jet perforation as long as the storage container has a less than critical diameter. Plastic-bonded solid propellant has been much less sensitive to impact than explosive-bonded propellant. Both of these subjects are discussed in par. 4-6.3.

Initially, rocket propellants were similar to gun propellants, and the rocket motors were designed to operate at approximately 24 MPa (3500 psi) (Ref. 93). As performance requirements increased and the volume allowed for motors decreased, however, more energetic propellants were formulated. In general, the more energetic the propellant, the more sensitive it is to thermal and shock effects (Ref. 94). These types of propellants, sometimes referred to as composite propellants, are cast in place or extruded in a single, large grain. The grain has a synthetic rubber-based or plastic binder.

Pertinent properties of typical propellants are given in Table 3-11. M1 is a single-base, M2 is a double-base, and M15 and M30 are triple-base solid gun propellants. JA-2 and diglycol rocket propellant (DIGL-RP) are German propellants used in the cartridges for the smoothbore 120-mm tank gun. JA-2 is for the KE cartridge and DIGL-RP is for the HEAT cartridge, even though it was initially a rocket propellant. Both cartridges have combustible cases with a metallic base. T5 and T8 are the older US rocket- or jet-assisted takeoff bottle propellants, and M7 launch motor and the flight motor propellants (FMP) are newer US rocket propellants. Note that M7 and FMP are primarily high explosives with a low-explosive binder.

The vulnerability or ignitability of propellants by external sources is dependent on their ignition sensitivity. Basically, propellants can be ignited by heating them above their kindling temperature; propellants can also be ignited by explosive shock. Ignitions of these types in armored vehicles are usually caused by ballistic attack involving projectile, fragment, spall, or shaped-charge jet impact. In these instances, the impacting projectile, fragment, or jet perforates the stowage compartment, containers, cartridge cases, and propellant charge. The extent of the openings caused by these impacts determines whether the propellant is confined, semiconfined, or unconfined. The pressure and rate of burning generated by the burning propellant are directly proportional to the degree of confinement. Some unconfined propellants burn slowly and can self-extinguish. Confined propellant can explode. Once a propellant that is a near-stoichiometric mixture of fuel and oxidizer is ignited, it is not easily extinguished. There has been considerable searching for low-vulnerability propellants.

As previously mentioned, ignition occurs when the temperature of the propellant at any point is raised to or above its autoignition temperature. The converse is also true: The fire is extinguished when the temperature of the burning propellant is reduced below its ignition temperature. This extinguishment has been accomplished by Vargas et al (Ref. 100), who used a water deluge system, and by Finnerty (Ref. 101), who used explosively launched water. The water deluge system requires an enormous quantity of water, and onboard vehicle stowage of this water would cause an intolerable weight and volume penalty. Both Vargas and Finnerty were extinguishing fires in exposed propellant, not cased propellant. Ball (Ref. 102) more recently investigated a water injection system intended for the 120-mm rounds of the Leopard MBT. Ball's system would use considerably less water and would extinguish cased propellant fires.

3-5.2 HIGH EXPLOSIVES

In modern combat vehicles explosives can be found in HE warheads stowed externally in boxes or internally in bustles and ready racks. The HE warheads vary in size from 20-mm projectiles to 165-mm engineer demolition projectiles or 203-mm HE projectiles. The quantity of HE for an individual warhead or projectile ranges from 0.01 kg of aluminized RDX to greater than 16.5 kg of Composition B. The various warheads use HE to produce fragments, blast, and metallic jets for the defeat of armor systems, operating systems, and personnel. Explosives are also used in reactive armor systems fastened externally to combat vehicles, e.g., Israeli Blazer armor. This reactive armor has proven vulnerable to a strong incendiary (Ref. 103).

Both kinetic energy and chemical energy threats can perforate the armor of combat vehicles and the casings of high-explosive-filled warheads stowed either internally or externally and can result in burning, deflagration, or detonation of these warhead fillers. If either detonation or deflagration

TABLE 3-11. PERTINENT PROPERTIES OF SELECTED PROPELLANTS (Refs. 93, 95-99)

PROPERTY	M1	M2	M15	M30	JA-2	DIGL-RP	T5	T8	FMP	M7
Specific Gravity, dimensionless	1.57	1.65	1.66	1.66	1.57	1.55				
Isobaric Flame Temperature, °C (°F)	2144 (3891)	3046 (5515)	2321 (4108)	2767 (5013)	3092 (5598)	2868 (5194)				
Heat of Combustion, MJ/kg (Btu/lbm)	12.45 (5354)	9.52 (4094)								
Heat of Explosion, MJ/kg (Btu/lbm)	2.93-3.11 (1260-1337)	4.51-4.76 (1939-2047)	3.33-3.35 (1432-1441)	4.08 (1754)	4.69 (2017)	4.29 (1845)	5.27 (2266)	3.15 (1355)	4.82 (1806)	5.25 (1967)
COMPOSITION										
Nitrocellulose, %	84.2	75.55	20.0	28.0	59.5	62.5	57.5	58.0	35.0	
Nitroglycerin, %		19.95	19.0	22.5	14.9		39.2	22.5		
Nitroguanidine, %			54.7	47.7						
RDX, %									62.0	
Oxidizer(s), %		2.5			0.05	0.05			1.5	
Binder/Stabilizer, %		1.75			25.55	37.45			1.0	
Other, %	15.8	0.25	6.3	1.8			3.3	19.5	0.5	

occurs, the end result could be disabling or catastrophic damage to the vehicle and crew. Also the HE in nearby rounds could be initiated through "cook-off" by fires of the HE or other flammable fluids and solids. If warheads are perforated and combustion occurs, serious fires, i.e., those that last from milliseconds to minutes and produce high thermal flux, fumes, blast, and noise, are the normal result. In addition, fragments produced by detonation can cause fratricide of other munitions through ignition of propellant charges or initiation of the projectile HE fillers.

Pertinent properties of selected high explosives are given in Table 3-12. The properties are those associated with fire or explosion. The explosives are

1. Trinitrotoluene (TNT), Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and Composition B (a mixture of 60% RDX and 40% TNT), which represent the explosives used in many HE warheads
2. Octol (a mixture of 75% octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) and 25% TNT) and LX-14 (a mixture of 95.5% HMX and 4.5% Estane® 5702-F1, a polyurethane solution), which represent the fillers of some shaped-charge warheads
3. PBX 9404 (a plastic-bonded explosive (PBX) consisting of 94% HMX, 3% nitrocellulose, and 3% tris-β-chloroethyl phosphate), DATB (1,3-diamino-2,4,6-trinitrobenzene), and TATB (1,3,5-triamino-2,4,6-trinitrobenzene), which are representative of the newer impact- and temperature-resistant explosives being developed in the insensitive munitions programs.

In addition to the thermal properties of selected high explosives, Table 3-12 also contains some data by which the relative sensitivities to heat and impact or shock may be gaged. For the older explosives, such as TNT, Composition B, RDX, and HMX, Ref. 90 presents the temperature that would cause an explosion after a 5-s bake. Ref. 104 contains an illustration from which the temperatures that would cause an explosion after a 100-s bake at each temperature can be estimated. While making these estimates, the author of this handbook assumed that LX-14 would have the same reaction to temperature as does LX-10 (Both contain approximately 95.5% HMX and 4.5% of a plastic binder, e.g., Viton A for LX-10 and Estane® 5702-F1 for LX-14.) and that the reaction temperature of DATB would be approximately one-third of the way between those of TNT and TATB and would be closer to that of TNT.

The relative impact sensitivities of the explosives mentioned may be gaged for the older explosives by the rifle bullet test results (Ref. 90) and for all of them by the Los Alamos National Laboratory (LANL) small-scale gap test results (Ref. 104). The rifle bullet test consists of firing a caliber .30 ball M2 bullet at 853 m/s (2800 ft/s) into 76-mm (3-in.) long, capped, steel pipes (51-mm (2-in.) inside diameter and 1.59 mm (0.0625 in.) thick), containing the explosive, and monitoring the reaction of the explosion. The LANL small-scale gap test consists of detonating a standard charge (the donor) against a variable stack of spacers (the gap) to initiate the explosive being tested (the acceptor), which is abutted against a witness plate. The detonation of the acceptor is ascertained by the dent in the witness plate. The sensitivity of the acceptor explosive is inversely proportional to the thickness of the gap, i.e., the thicker the gap, the more sensitive the explosive.

3-5.3 OTHER MUNITIONS

The primary munitions carried by combat vehicles include antitank cartridges for the main guns, antitank missiles such as the tube-launched, optically tracked, wire-guided (TOW) missile, high-explosive artillery projectiles and propellant charges, and engineer demolition charges fired from a 165-mm launcher. The antitank munitions can be either kinetic energy or chemical energy. In addition to these primary munitions, other types of munitions are carried in or on combat vehicles. These other munitions can be special purpose rounds for the main armament such as smoke, incendiary, flares, or antipersonnel rounds; munitions for individuals such as small arms cartridges, hand grenades (including those for riot control), or LAWs; and other items such as antitank or antipersonnel mines, smoke projector cartridges, distress flares, demolition charges, or incendiary grenades for materiel destruction. The United States had some triethylaluminum (TEA)-filled 66-mm rockets for use against bunkers in Vietnam, which could be carried in combat vehicles if used again.

Most of these munitions contain propellant, either gun or rocket, and/or high-explosive charges that, if hit, would react similarly to the primary munitions previously discussed. There are, however, other munition fillers that must be considered. These fillers include pyrotechnics, combustible metals or mixtures, toxic chemicals, and pyrophoric materials.

The pyrotechnics include smokes, flares, and incendiaries. The most common smoke used in munitions is white phosphorus (WP) loaded into large shells and hand grenades. White phosphorus is pyrophoric and is a signaling or screening agent; it causes casualties by burning and can ignite combustibles. WP-filled shells must be stowed vertically in a vehicle since WP melts at 44.1°C; the shell filler could melt and resolidify with an asymmetric shape that would affect exterior ballistics. The other smokes are used for screening and signaling. Screening smoke, such as white or red phosphorus, burns to produce phosphorus pentoxide, which becomes droplets of phosphoric acid in moist air. These smoke fillers are progressive burning solids that do not require added or atmospheric oxygen. Hexachloroethane (HC) smoke produces an aerosol of zinc chloride. The HC smoke mixture is sensitive to an electrical spark, is moderately impact sensitive, but is insensitive to friction and the mild shock of a Number 8 blasting cap (Ref. 106). The reaction of HC smoke being struck by a shaped-charge jet is not recorded, but an interesting result was obtained in

TABLE 3-12. PERTINENT PROPERTIES OF EXPLOSIVES (Refs. 90, 93, 104, and 105)

PARAMETERS		TNT	COMPOSITION B-3 (60% RDX 40% TNT)	RDX	OCTOL (75% HMX 25% TNT)	LX-14 (95.5% HMX 4.5% Estane®)	PBX 9404	DATB	TATB
Density, TMD SG		1.654	1.75	1.806	1.843	1.849	1.865	1.837	1.938
As Loaded SG		Cast 1.5-1.6	1.72		1.80-1.82	1.83	1.83-1.84	1.79	1.88
Method		Pressed 1.63-1.64							
Melt Point, °C (°F)		80.9 (178)	79-80 (174-176)	205 (401)*	79-80 (174-176)	>270 (>518)*	>250 (>482)*	286 (547)	>325 (>617)*
Heat of Combustion, MJ/kg (Btu/lbm)		15.02-15.15 (6462-6516)	11.67**-11.8† (5022-5076)	9.56**-9.65† (4113-4152)	11.20** (4817)				
Heat of Explosion,	MJ/kg (calculated) (Btu/lbm)	4.52-5.9 (1944-2533)	5.19-6.44 (2232-2771)	5.36-6.78 (2304-2917)	6.57 (2826)	6.59 (2835)	6.53 (2809)	5.27 (2267)	5.02 (2160)
	MJ/kg (experimental)	4.56	5.02	6.32			5.77	4.10	
Specific Heat, kJ/(kg·K)		1.37 at 20°C	1.25 at 25°C	1.126 at 25°C	1.13 at 20°C††		1.13 at 20°C††	0.962 at 20°C**	
Thermal Conductivity, W/(m·°C)		0.260 at 18-45°C	0.262 at 25°C	0.106		0.439 at 25°C	0.432 at 21°C	0.251	0.536 at 38°C
Temperature Causing Explosion After 5s (Cook-off), °C (°F)		475 (887)	278 (532)	260 (500)	350 (662)				
Temperature Causing Explosion After 100s Bake, °C (°F)		280 (536)	197 (387)	207 (405)	257 (484)	255 (491) (LX-10)		290 (554)††	310 (590)
Rifle Bullet Test,	Exploded	40%	3%	100%	70%				
	Partially Exploded		13%						
	Burned		4%						
	Unaffected	60%	80%		30%				
Small-Scale Gap Test (LANL), mm		0.33	1.1-1.4	4.8-5.6	0.56-0.71	1.5-2.0	2.97	0.36	0.13

*decomposes
**experimental
†calculated
††estimated

TMD SG = Theoretical maximum density specific gravity
LANL = Los Alamas National Laboratory
SG = specific gravity

Vietnam when a shaped-charge jet entered a smoke grenade but did not exit.

Colored signal smokes are produced by heating a mixture to vaporize its components. A dye is included in the components to color the cloud formed. The heat produced is relatively low since the smoke agent should sublimate below 300°C (572°F). Currently, most combat vehicles carry smoke grenades that are launched from tube arrays mounted on the turret or equivalent and can provide a quick "smoke screen" to reduce the accuracy of hostile, direct-fire weapons. The grenades are small screening smoke grenades, and the grenade cartridges contain a small amount of propellant. Two types of grenades are currently used: a red phosphorus grenade for visible obscuration (The red phosphorus is pyrophoric and produces white smoke.) and a brass flake grenade for infrared (IR) obscuration. A third type of grenade is being developed that will combine these two types of obscuration; the filler is a combination of brass flakes and carbon filaments (Ref. 107).

Flares carried on or in combat vehicles include illumination rounds (such as those fired from self-propelled artillery and mortars), signal flares, and road flares. In addition, some vehicles may carry small trip or antipersonnel flares used to protect positions at night. These flares are pyrotechnic devices that burn for a comparatively long time, i.e., seconds, and emit considerable light and heat. The predominant fuel for flares is magnesium, but aluminum has also been used. The flare mixture contains sufficient oxidizer to consume the fuel.

An incendiary device that could be found within a combat vehicle is a thermite grenade, which could be used to destroy the engine, gun, or some other critical component to prevent capture of combatworthy equipment. Such incendiary devices could be ignited or initiated by ballistic impact and could serve as ignition sources or could burn or melt their way downward through the vehicle. Thermite grenades cannot be extinguished.

Antipersonnel rounds, such as the canister or flechette (beehive), would not have energetic contents more hazardous than the propellant. Small arms cartridges are not excessively hazardous when they are in brass, steel, or aluminum cases, but many caseless small arms cartridges packed together without flame barriers between them could present an explosion hazard. Grenades are liable to explode when subjected to a sustained external fire. LAWs react to ballistic impact, as do larger rocket-propelled munitions, such as TOW missiles. Explosive charges or explosive-containing devices similar to the Claymore, antitank, or antipersonnel mines would react similarly to other high-explosive-filled munitions. Also pyrotechnic-filled devices, such as smoke projector cartridges or distress flares or fusees, would react similarly to larger pyrotechnic-filled munitions. A TEA-filled warhead would react similarly to the pyrophoric WP-filled warhead, i.e., when the case is ruptured, the contents ignite and burn.

3-6 OTHER COMBUSTIBLES

The other combustibles found on or in combat vehicles include

1. Electric wiring insulation
2. Spall and radiation liners
3. Seats
4. On-vehicle equipment (the impedimenta carried by the vehicle crews and needed to maintain the vehicle and to enable the crewmen to live in the field)
5. Paints and coatings
6. Miscellaneous combustibles, such as plastic or elastic components, bedrolls, camouflage nets, maps, documents, rations, combustible metal parts, and other items.

These other combustibles are usually more difficult to ignite than hydrocarbon fluids or explosives and are more difficult to extinguish than combustible fluids. Once ignited, these items can smolder for a long time before flaming and, while smoldering, often emit toxic gases. A smoldering material is not extinguished by smothering with gaseous extinguishing agents; it has to be cooled below the kindling temperature.

Also included as other combustibles are combustible metal items. Combustible metals, such as magnesium and lithium, present a very different problem. They are difficult to extinguish because the extinguishants used for other fires will not extinguish these metals. The burning temperature of these metals is so high that the normal extinguishants decompose before extinguishing the fire. Further, the decomposition products of the extinguishants used on the metals can be hazardous. These products can combust, even explode, or are toxic. A different type of fire extinguisher is needed for these Class D combustibles that would not otherwise be installed on a combat vehicle.

3-6.1 ELECTRIC WIRING INSULATION

The combustible components in an electrical wiring system are the dielectric element (insulation) used to isolate electrically the conductor from its surroundings, the paper wraps used in most multiconductor power cables, and the jacketing in grouped cables. In most vehicles that require a run of bunched, jacketed cables, wrap material is not used and therefore is not discussed.

Synthetic elastomers are used extensively as insulation and jacketing components in electrical wiring systems. Most elastomers burn easily when not fire-retarded. Ethylene-propylene copolymers, chlorosulfonated polyethylene, and silicones are widely used elastomers for electric wire insulation. The incorporation of halogens either as an additive or as a part of a molecule has been used to decrease the flammability of elastomers. As a result, materials such as polychloroprene (neoprene), chlorinated polyolefins, epichlorohydrin rubbers, fluoro and chlorofluoro elastomers, halogen-containing polyurethanes, and various compositions incorporating halogenated additives are found in electric wire insulation material. These fire-retardant additives unfortunately are deficient in overall safety characteristics because they emit smoke and toxic halogen-containing vapors, such as hydrochloric and hydrofluoric acid and/or phosgene, when burned or exposed to intense heat.

Phosphorous compounds have also been used to decrease the flammability of wire insulation. In electric wire insulation elastomers the use of these compounds is limited to plasticized polyvinyl chloride and polyurethanes. Materials that contain phosphorus as a fire retardant have slower flame propagation and are more difficult to ignite by small ignition sources, but they show little advantage over other retardants when exposed to a higher heat flux. Phosphorus-containing elastomers also produce toxic organophosphorus decomposition products when pyrolyzed.

The incorporation of inorganic elements as part of the polymer structure also significantly reduces the flame and smoke characteristics of the resulting elastomer. Silicone elastomers and developmental phosphonitrilic elastomers are examples of these materials. Fire retardancy is also achieved by incorporating large amounts of inorganic filler into the elastomer. This additive reduces the fuel value of the composition. Most filled elastomers contain in excess of 50% inorganic particulates.

3-6.1.1 Elastomer Types

The fire safety characteristics of elastomers generally used for electrical insulation applications are largely determined by their composition and may be classified into specific categories:

1. *Chlorine-Containing Elastomers*. This group contains polychloroprene, chlorinated ethylene polymers and copolymers, and epichlorohydrin rubbers. These materials have significantly better fire retardancy than the purely hydrocarbon rubber; however, they generate large amounts of black smoke and hydrogen chloride (hydrochloric acid, HCl) gas and possibly phosgene gas when exposed to large fires.

2. *Fluorocarbon Elastomers*. These elastomers are usually difficult to ignite and resist flame propagation. They generate significant toxic hazards, such as hydrofluoric acid, when exposed to intense fires.

3. *Silicone Elastomers*. Silicone elastomers generate relatively little smoke, are fire-retardant, have a low fuel value, and do not contain halogens. They are somewhat deficient because their mechanical properties are marginal.

3-6.1.2 Thermoplastic Types

Thermoplastic resins are also extensively used in wiring insulation and jacketing. The predominantly used thermoplastics in these applications are polyolefins, polyvinyl chloride (PVC), and types of polyethylene described as follows:

1. *Polyolefins*. The major polyolefins used in electrical insulation are high-density polyethylene, ethylene-propylene copolymer, and cross-linked polyolefins. Additive systems based on a combination of halogen compounds and antimony oxide have been effective in reducing flammability. These compositions do, however, burn readily in fully developed fires and emit toxic smoke, halogen acid fumes, and phosgene.

2. *Polyvinyl chloride (PVC)*. Polyvinyl chloride does not burn under most normal conditions. When exposed to flame or excessive heat, however, PVC emits hydrogen chloride at a relatively low temperature in a highly endothermic reaction. This characteristic accounts for the intrinsic low flammability of the uncompounded polymer. Chlorinated and phosphorus-based fire-retardant additives are used to reduce the flammability of the plasticized composition. The phosphorus-containing composition produces toxic organophosphorus decomposition products upon pyrolysis.

3. *Chlorinated and Chlorosulfonated Polyethylene (Hypalon)*. The flammability of this resin decreases directly with its chlorine content. Compositions containing up to 67% chlorine have been prepared. Antimony oxide reduces the amount of chlorine necessary to achieve the desired fire retardancy. The flammability characteristics closely resemble those of PVC, and hydrogen chloride is the major combustion product along with toxic antimony-containing smoke and possibly phosgene.

A list of insulations with their National Electrical Code®* designation and application provisions is given in Table 3-13.

Electrical installations in bilges, intercompartmental passages, and ventilation or air-handling ducts should be made so that the spread of fire or combustion products is not substantially enhanced. Openings around electrical penetrations through fire-resistant bulkheads should be fire-stopped by using approved methods.

3-6.1.3 Toxic Effects

It is doubtful that the total mass of insulation present in vehicle wiring would constitute a significant fire hazard with respect to the heat released from its combustion. The presence of toxic gases emitted due to fire, smoldering, or pyrolysis effects, however, could cause considerable discomfort.

3-6.2 SPALL AND RADIATION LINERS

Spall liners are used to capture particles of armor that break free and are projected within a combat vehicle by a penetrator such as a KE projectile or a shaped-charge jet, or by the shock from a detonating warhead such as a high-explosive plastic (HEP), or by a nonarmor-perforating KE

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TABLE 3-13. CONDUCTOR APPLICATION AND INSULATIONS (Ref. 108)

TYPE OF INSULATION	TYPE CODE	MAXIMUM OPERATING TEMPERATURE	APPLICATION PROVISIONS	INSULATION	OUTER COVERING, IF ANY
Fluorinated ethylene propylene (FEP)	FEP or FEPB	90°C (194°F)	Dry and damp locations	Fluorinated ethylene propylene	None
		200°C (392°F)	Dry locations—special applications*	Fluorinated ethylene propylene	Glass braid, asbestos, or other suitable braid material
Mineral insulation (Metal sheathed)	MI	90°C (194°F) 250°C (482°F)	Dry and wet locations For special application*	Magnesium oxide	Copper or alloy steel
Moisture-, heat-, and oil-resistant thermoplastic	MTW††	60°C (140°F) 90°C (194°F)	Machine tool wiring in wet locations as permitted in NFPA 79** Machine tool wiring in dry locations as permitted in NFPA 79**	Flame-retardant, moisture-, heat-, and oil-resistant thermoplastic	(A) None (B) Nylon jacket equivalent
Paper		85°C (185°F)	For underground service conductors or by special permission	Paper	Lead sheath
Perfluoroalkoxy	PFA	90°C (194°F) 200°C (392°F)	Dry and damp locations Dry locations—special applications*	Perfluoroalkoxy	None
Perfluoroalkoxy	PFAH	250°C (482°F)	Dry locations only. Only for leads within apparatus or within raceways connected to apparatus. (Nickel or nickel-coated copper only)	Perfluoroalkoxy	None
Heat-resistant or cross-linked synthetic polymer	RH	75°C (167°F)	Dry and damp locations	Heat-resistant or cross-linked synthetic polymer	Moisture-resistant, flame-retardant, non-metallic covering†
Heat-resistant or cross-linked synthetic polymer	RHH††	90°C (194°F)	Dry and damp locations		
Moisture- and heat-resistant or cross-linked, synthetic polymer	RHW††,†††	75°C (167°F)	Dry and wet locations. Where over 2000V, insulation shall be ozone-resistant	Moisture- and heat-resistant or cross-linked synthetic polymer	Moisture-resistant, flame-retardant, non-metallic covering†

*Where environmental conditions require maximum conductor operating temperatures above 90°C
**National Fire Protection Association Publication 79. See Article 670, Ref. 108.
†Some rubber insulations do not require an outer covering.
††Insulation and outer coverings that meet the requirements of flame-retardant and limited smoke and are so listed shall be permitted to be designated limited smoke with the suffix "/LS" after the code type designation.
†††Listed wire types designated with the suffix "-2", such as RHW-2, shall be permitted to be used at a continuous 90°C-operating temperature, wet or dry.

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TABLE 3-13. (cont'd)

TYPE OF INSULATION	TYPE CODE	MAXIMUM OPERATING TEMPERATURE	APPLICATION PROVISIONS	INSULATION	OUTER COVERING, IF ANY
Moisture- and heat-resistant or cross-linked, synthetic polymer	RHW-2	90°C (194°F)	Dry and wet locations	Moisture- and heat-resistant or cross-linked synthetic polymer	Moisture-resistant, flame-retardant, non-metallic covering†
Silicone-asbestos	SA	90°C (194°F) 125°C (257°F)	Dry and damp locations For special application*	Silicone rubber	Asbestos, glass, or other suitable braid material
Synthetic, heat-resistant	SIS††	90°C (194°F)	Switchboard wiring only	Heat-resistant, cross-linked, synthetic polymer	None
Thermoplastic and asbestos	TA	90°C (194°F)	Switchboard wiring only	Thermoplastic and asbestos	Flame-retardant, nonmetallic covering
Thermoplastic and fibrous outer braid	TBS	90°C (194°F)	Switchboard wiring only	Thermoplastic	Flame-retardant, nonmetallic covering
Extended polytetrafluoro-ethylene	TFE	250°C (482°F)	Dry locations only. Only for leads within apparatus or within raceways connected to apparatus or as open wiring. (Nickel or nickel-coated copper only)	Extruded polytetrafluoro-ethylene	None
Heat-resistant thermoplastic	THHN††	90°C (194°F)	Dry and damp locations	Flame-retardant, heat-resistant thermoplastic	Nylon jacket or equivalent
Moisture- and heat-resistant thermoplastic	THHW	75°C (167°F) 90°C (194°F)	Wet location Dry location	Flame-retardant, moisture- and heat-resistant thermoplastic	None
Moisture- and heat-resistant thermoplastic	THW††,†††	75°C (167°F) 90°C (194°F)	Dry and wet locations Special applications within electric discharge lighting equipment. Limited to 1000 open-circuit volts or less. (One size only, see Ref. 108)	Flame-retardant, moisture- and heat-resistant thermomplastic	None

*Where environmental conditions require maximum conductor operating temperatures above 90°C
†Some rubber insulations do not require an outer covering.
††Insulation and outer coverings that meet the requirements of flame-retardant and limited smoke and are so listed shall be permitted to be designated limited smoke with the suffix "/LS" after the code type designation.
†††Listed wire types designated with the suffix "-2", such as RHW-2, shall be permitted to be used at a continuous 90°C-operating temperature, wet or dry.

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TABLE 3-13. (cont'd)

TYPE OF INSULATION	TYPE CODE	MAXIMUM OPERATING TEMPERATURE	APPLICATION PROVISIONS	INSULATION	OUTER COVERING, IF ANY
Moisture- and heat-resistant thermoplastic	THWN†† ,†††	75°C (167°F)	Dry and wet locations	Flame-retardant, moisture- and heat-resistant thermoplastic	Nylon jacket or equivalent
Moisture-resistant thermoplastic	TW††	60°C (140°F)	Dry and wet locations	Flame-retardant, moisture-resistant thermoplastic	None
Underground feeder and branch-circuit cable—single conductor (For Type UF cable employing more than one conductor, see Article 339 of Ref. 108.)	UF	60°C (140°F) 75°C (167°F**)	See Article 339 of Ref. 108.	Moisture-resistant Moisture- and heat-resistant	Integral with insulation
Underground service-entrance cable—single conductor (For Type USE cable employing more than one conductor, see Article 338 of Ref. 108.)	USE†††	75°C (167°F)	See Article 338 of Ref. 108.	Heat- and moisture-resistant	Moisture-resistant nonmetallic covering (See Section 338-1 (b) of Ref. 108.)
Heat-resistant, cross-linked, synthetic polymer	XHH††	90°C (194°F)	Dry and damp locations	Flame-retardant, cross-linked, synthetic polymer	None
Moisture- and heat-resistant, cross-linked, synthetic polymer	XHHW†† ,†††	90°C (194°F) 75°C (167°F)	Dry and damp locations Wet locations	Flame-retardant, cross-linked, synthetic polymer	None

** For ampacity limitation, see Section 339-5 of Ref. 108.
†† Insulation and outer coverings that meet the requirements of flame-retardant and limited smoke and are so listed shall be permitted to be designated limited smoke with the suffix "/LS" after the code type designation.
††† Listed wire types designated with the suffix "-2", such as RHW-2, shall be permitted to be used at a continuous 90°C-operating temperature, wet or dry.

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TABLE 3-13. (cont'd)

TYPE OF INSULATION	TYPE CODE	MAXIMUM OPERATING TEMPERATURE	APPLICATION PROVISIONS	INSULATION	OUTER COVERING, IF ANY
Moisture- and heat-resistant, cross-linked, synthetic polymer	XHHW-2	90°C (194°F)	Dry and wet locations	Flame-retardant, cross-linked, synthetic polymer	None
Modified ethylene tetrafluoroethylene	Z	90°C (194°F) 150°C (302°F)	Dry and damp locations Dry locations—special applications*	Modified ethylene tetrafluoroethylene	None
Modified ethylene tetrafluoroethylene	ZW†	75°C (167°F) 90°C (194°F) 150°C (302°F)	Wet locations Dry and damp locations Dry locations—special applications*	Modified ethylene tetrafluoroethylene	None

*Where environmental conditions require maximum conductor operating temperatures above 90°C
†Listed wire types designated with the suffix "-2", such as RHW-2, shall be permitted to be used at a continuous 90°C-operating temperature, wet or dry.

projectile. This spall liner could be an unbonded ballistic fabric curtain, such as the Israelis use in the Merkava, or a bonded ballistic fabric panel, such as is used in the M113A3 APC and the M2A2 and M3A2 BFVs. These spall liners also capture residual penetrator fragments after the initial penetration and thus prevent their ricochet within the vehicle. These liners must be able to stop the spall, and if the liner is used for another purpose, it must have the properties and strength needed for that task. Materials that can be used for spall curtains include Kevlar®, ballistic nylon, and other such fabrics. The binder materials include phenolic, polyethylene, and polyurethane. The penetrator will undoubtedly perforate the spall liner at the initial entrance location. The liner, either in the form of curtains or panels, should be spaced at least 102 mm (4 in.) from the wall that can emit spall or preferably farther. This spacing allows the spall to travel away from the penetrator trajectory so that the spall will not pass through the hole the penetrator makes in the liner.

Radiation liners are used to reduce the number of fast neutrons and amount of gamma radiation from a nuclear detonation. Radiation liners contain materials that can slow fast neutrons and then trap them without generating more neutrons or gamma radiation. Materials used to slow fast neutrons are those with a large number of hydrogen atoms, such as water, polyethylene, and polyurethane. The materials that excel at absorbing gamma radiation and/or slowing thermal neutrons are hydrogen, lithium, boron, zirconium, cadmium, lead, and some rare earth elements. These absorbing materials are usually embedded in the material used to slow the fast neutrons, and the mixture is applied to the inside surface of the armor or skin of the vehicle (Ref. 109). This liner may be 5- to 76-mm (0.20- to 3.0-in.) thick and may be bonded to the armor.

The hazards and problems associated with radiation liner materials are related to the reactions of these materials to fast neutron impact, the combustibility or toxicity, and the mechanical properties of these materials. For example, metallic lithium and zirconium burn readily. Lithium, boron, and cadmium are toxic. Cadmium emits gamma radiation when impacted by fast neutrons. The rare earth elements are expensive. Polyethylene does not bond readily and burns easily. Lead absorbs gamma radiation but passes thermal neutrons.

Where a thick, dense, elastic layer of material is applied to the inside surface of a monolithic armor, spall generation is inhibited. Thus a radiation liner may also serve as a spall liner with resulting savings in space or volume. Care must be taken to assure that the radiation liner does not "focus" the spall particles into a tighter pattern, i.e., act like the choke on a shotgun. Care must also be taken to ensure that the materials are not in a toxic form and that they do not provide additional easily combustible materials or strong ignition sources.

3-6.3 SEATS

Seat materials in a combat vehicle are among the most significant of the "other" combustibles present. Furthermore, the covering and the interior foam or batting of the seats is more easily ignited than many other materials inside the vehicle. Once ignited, seat materials may burn rapidly and produce heat, toxic products, and smoke. Seat materials are also more difficult to extinguish than many other materials.

Seats are a composite product. They are composed of an exterior fabric covering and an interior mass comprised of flexible foam or batting or both. The composition of the exterior fabric is the main determinant of the relative flammability of the overall composite. Thus a selected seat foam material covered by heavy PVC is less likely to ignite and spread flame than that same material covered by cotton, rayon, or polyester fabric. If the seat covering is ruptured and the interior is exposed, however, the flammability of the interior material may dominate the fire.

The nature of the ignition source is critical to whether or not a given seat composite will ignite and burn. Possible ignition sources include electrical shorts, hot surfaces (including cigarettes and metal fragments), slowly burning fuels (including any flammable liquids), other burning combustibles (including debris, paper, and fabrics), and rapid-burning combustibles such as hydrocarbon fluid sprays and munitions.

Fabric coverings and interior foam or batting materials may each be classified into three categories based on their response to heat or flame: (1) those that melt, (2) those that char, and (3) those that are highly resistant to ignition and generally do not melt. Each of these categories must be considered in view of the most likely ignition sources. Table 3-14 summarizes the behavior of the various types of fabric coverings and interior seat materials when presented with the ignition sources indicated.

Examples of fabrics and interior materials that melt are polyester, polyolefin, and polyurethane. Polyurethane foam is widely used as a cushioning material in residential and commercial furniture. Although not readily ignited by smoldering cigarettes, polyurethane foam ignites easily when exposed to open flame. Its open cellular structure provides enormous surface area for combustion, and its chemical components liberate approximately 40% more heat than cellulosic materials like wood, paper, or cotton. Fabrics and interior materials that char include cotton, wool, and polyisocyanate. Fabrics and paddings that are more fire-resistant include polyimide, neoprene foam, and polyvinyl chloride. The presence of a fire-blocking layer between the fabric and interior of a seat composite adds measurably to the fire resistance of the entire composite. When used as a fire-blocking layer, flame-retardant cotton or a fabric backed with aluminum foil can markedly improve resistance to cigarettes and small, open flames. Flame retardants applied to polyurethane cushioning can provide significant protection against small flame sources such as matches. Such retardants, however, may evaporate over time and thus would be less effective. In a large fire, retardants may be cooked out and produce disabling irritants and/or increase smoke. Addition of a flame retardant to an ordinarily flammable material is often insufficient to classify that material as "highly resistant" to ignition.

In the presence of electrical shorts or hot surface ignition sources, fabric coverings that melt away from the heat will generally not ignite. (See Table 3-14.) The interior material, however, is then exposed to the ignition source. If the interior material is also prone to melting, smoldering combustion, i.e., self-propagating thermal decomposition, may occur. Although smoldering is less immediately life threatening than flaming, it can produce toxic fumes and is very difficult to extinguish. Furthermore, continued smoldering in the interior of a foam or batting may lead to sudden flaming combustion.

Fabrics that char may smolder when in contact with electrical shorts or hot surface ignition sources. This charring may protect the interior materials for a short time better than melting fabrics; however, continued smoldering, e.g., cotton

TABLE 3-14. FIRE HAZARD OF SEATS

CHARACTERISTIC RESPONSE TO FIRE	IGNITION SOURCE		
	ELECTRICAL OR HOT SURFACE	FUEL OR OTHER COMBUSTIBLES	RAPID (EXPLOSIVE)
Fabrics that			
Melt	Melt, no ignition	Melt, burn	Burn, spread
Char	Smolder	Burn slowly	Less spread, postsmolder
Resist fires	Should not ignite	Burn if ignition source hot enough	Least spread
Interior materials that			
Melt	Smolder	Burn, melt and flow	Burn, spread molten drops
Char	Smolder	Burn more slowly	Less spread, smolder
Resist fires	Acceptable if smolder resistant	Acceptable if resistant to open flame	Least spread

fabrics, may result in flaming combustion. Interior materials that char will also smolder. Char-forming materials often evolve carbon monoxide, an odorless, toxic gas.

Generally, fabrics that are highly fire-resistant will not ignite from electrical shorts or hot surfaces. Similarly, interior materials that are fire-resistant will generally not ignite as a result of these ignition sources. Smoldering combustion, however, can continue for very long periods even in fire-resistant materials, unless they are designed to be smolder resistant.

Fires due to fuels or other combustibles have similar effects on seat composites; these fires differ only in the relative intensity of the fire as an ignition source. As fabrics melt, they withdraw from these ignition sources and expose the interior material. If the fabric melts and flows into the region of the initial fire, however, the molten material contributes substantially to the fire. Interior materials that melt will likely burn and spread the fire even beyond the original source.

Char-forming fabrics and highly flame-resistant fabrics may offer some protection to seat composites from flaming ignition sources and are less likely to expose the interior material. In the same manner, char-forming and highly fire-resistant interior materials may be less likely to ignite and contribute to the fire. Most materials will burn, however, if the intensity of the ignition source is sufficiently high.

In the case of rapid ignition, possibly with explosive force, the materials that melt would create the greatest hazard because they would ignite and spread the fire with flaming, molten droplets. The char-forming materials would have less tendency to spread, but they may continue to smolder long after the initial ignition source is extinguished.

3-6.4 ON-VEHICLE EQUIPMENT (OVE)

In general, much of the OVE in combat vehicles is metal, e.g., tools or combat weapons, and therefore is not subject to the usual concerns about fire safety. Items that should be considered possible contributors to a fire include, but are not to be limited to, maintenance and repair tools with wooden or plastic handles, canvas or nylon straps, plastic instrument cases, plastic ammunition boxes, nonmetal brushes, tarpaulin and camouflage nets, books (manuals) and papers (e.g., drawings), sleeping bags, field packs, and cloth flags. These items do not constitute a major portion of the possible flammable items onboard a vehicle. Furthermore, they are not easily ignited nor do they readily burn. If glowing, they could provide long-term ignition sources and serve to reignite more combustible items.

Illustrations of the items carried in and on a typical combat vehicle are shown on Fig. 3-4. Note that the individual weapons and stowed ammunition are included.

3-6.5 PAINTS AND COATINGS

One of the oldest methods used to protect the underlying substrate from corrosion, wear, or, in the case of flammable substrates, from reaching ignition temperature is paints and coatings. Combat vehicles are also painted to provide camouflage and chemical warfare agent resistance. The most common fire-retardant coatings are intumescent (i.e., swells and chars when exposed to flame) or fire-retardant, nonintumescent types.

3-6.5.1 Nonintumescent Coatings

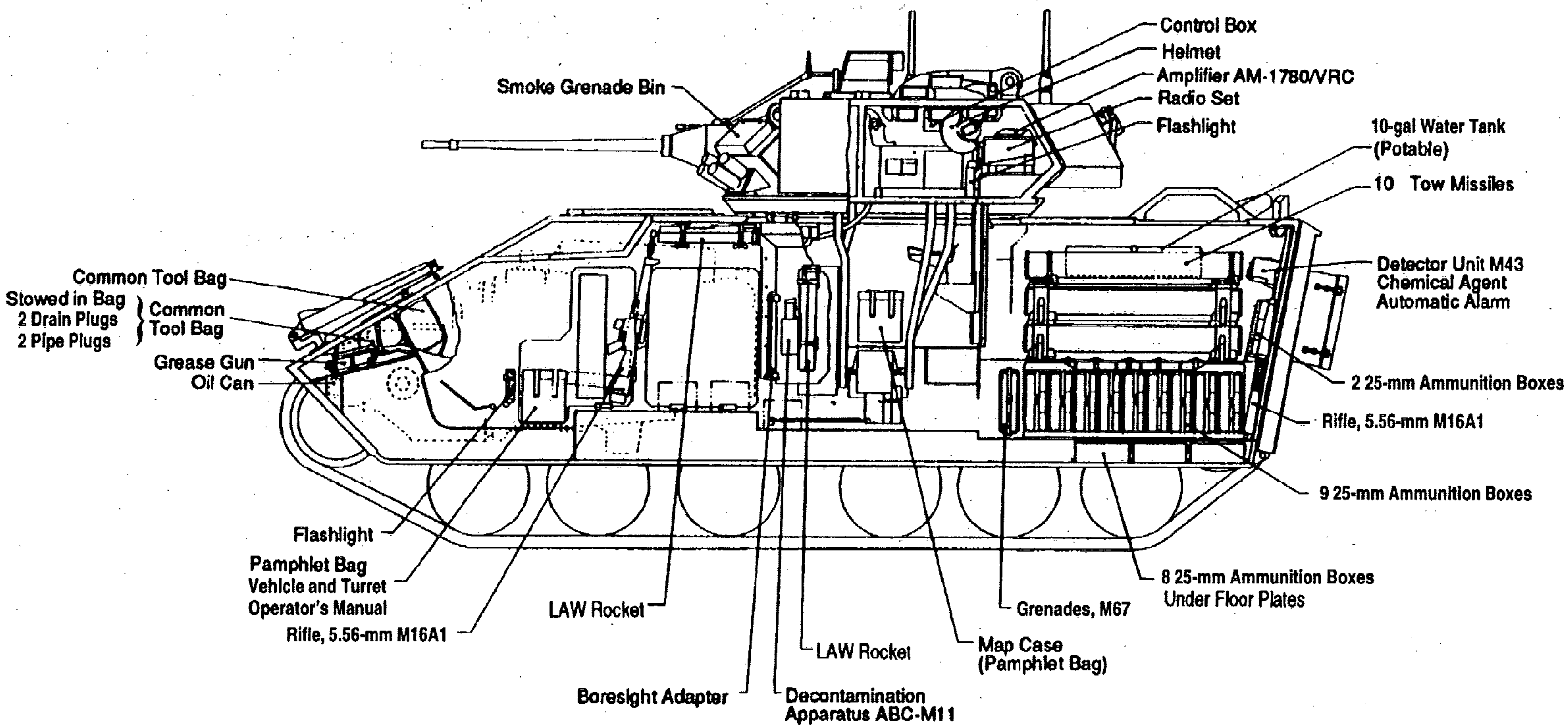
Although fire-retardant, nonintumescent coatings do not provide the same degree of fire protection to the underlying surface as intumescent coatings, they are useful in vehicles that are repeatedly painted to provide protection to the surface or to enhance or camouflage their appearance. The paints constitute a fire hazard regardless of the nature of the underlying surface as layers of conventional paints build up. Fire-retardant coatings are formulated to resist flaming even when heavy layers of paint are exposed to fire. Flame-retardant additives do not render these coatings nonflammable; they raise the kindling temperature (the temperature at which solids will ignite). Once the flame-retardant coating does ignite, it can burn hotter and usually emits more toxic or noxious fumes than the same coating without the flame-retardant additive. A description of these coatings follows:

1. *Alkyd Coatings*. The most commonly used fire-resistant paints are based on chlorinated alkyds. These paints use chlorinated diacids or anhydrides. Halogenated additives have been used in fire-retardant coatings because of their low cost and minimal effect on the basic paint properties when used in conjunction with metal oxides. Inert mineral fillers are also used to reduce the flammability of the coating. The percentage of fillers in the paint must be high in order to raise the ignition point of the organic material in the paint to desired levels.

2. *Other Polymers*. Coatings based on epoxy resins and urethane are widely used on US combat vehicles because of the chemical agent resistance they provide. Coatings based on melamine/formaldehyde and phenol/formaldehyde resins are used as somewhat ablative, char-forming coatings.

3-6.5.2 Intumescent Coatings

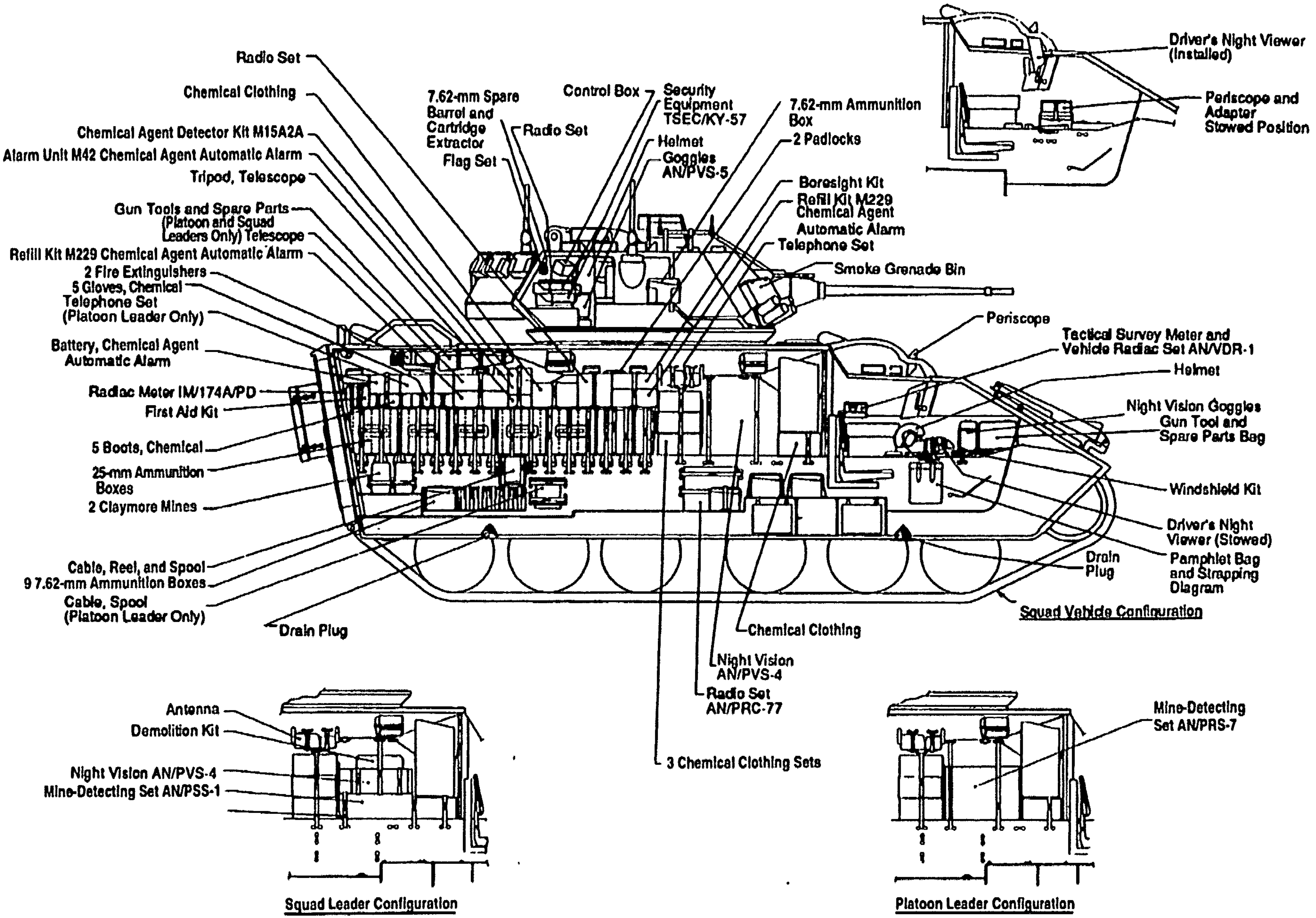
When subjected to a significant level of heat, intumescent coatings undergo charring and expand from a thin paint film to a thick, puffy coating with a low thermal conductivity. The resultant puffy coating can insulate the underlying substrate from heat, exclude oxygen from the substrate, produce diluent nonflammable gases, and reduce the production of flammable combustion products. The expanded coating retains its effectiveness until it is broken up by extremely high heat or erosion. These coatings protect nonflammable substrates, such as metals, by reducing the transfer of heat to them. The char does not resist abrasion. A successful fire survivability enhancement application of intumescent coating is described in subpar. 4-8.4.2.



(A) Right Interior Stowage

Figure 3-4. CFV M3A0 Stowage Diagram

(cont'd on next page)



(B) Left Interior Stowage

Figure 3-4. (cont'd)

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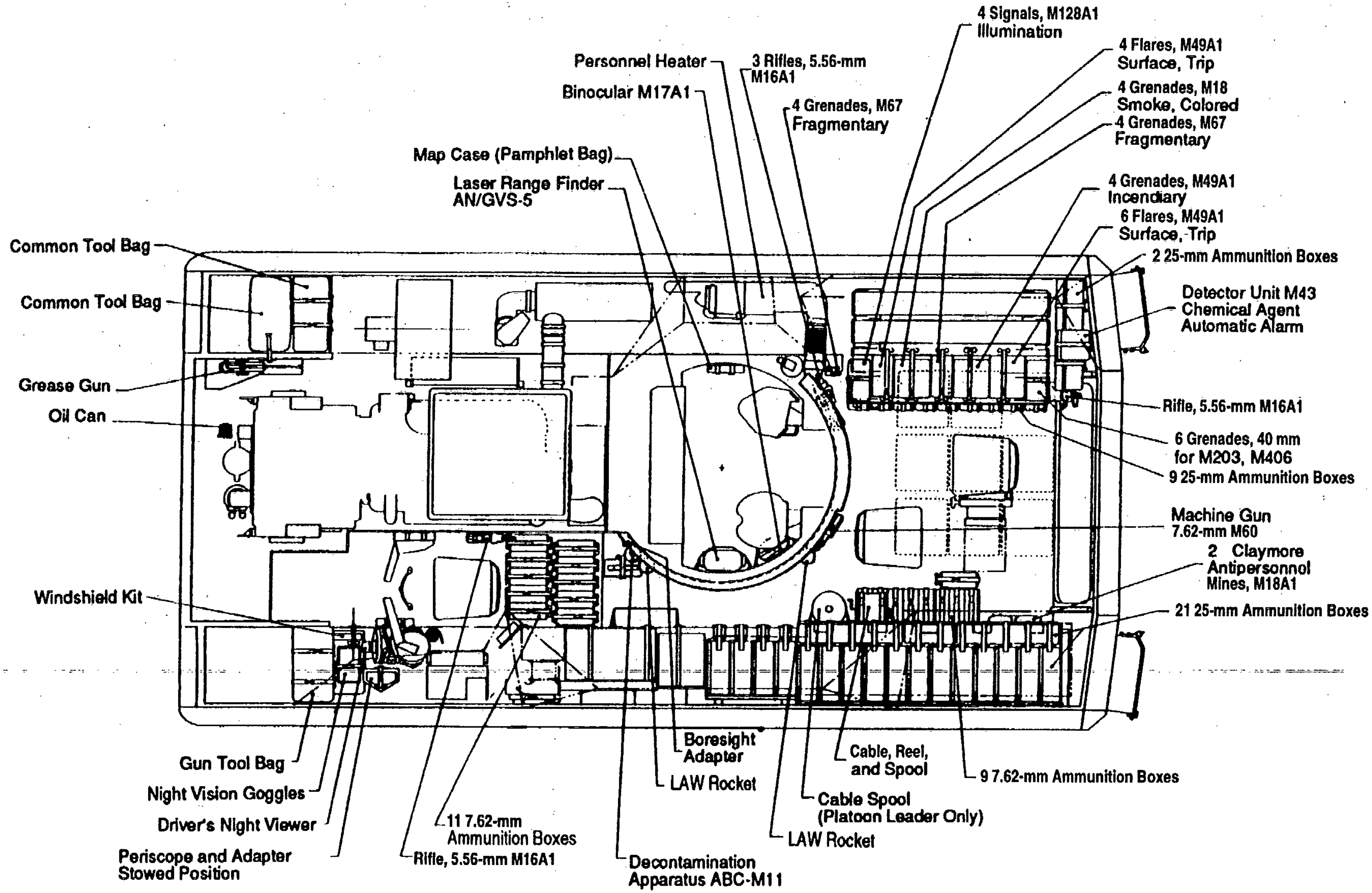

(C) Top View, Interior Stowage

Figure 3-4. (cont'd)

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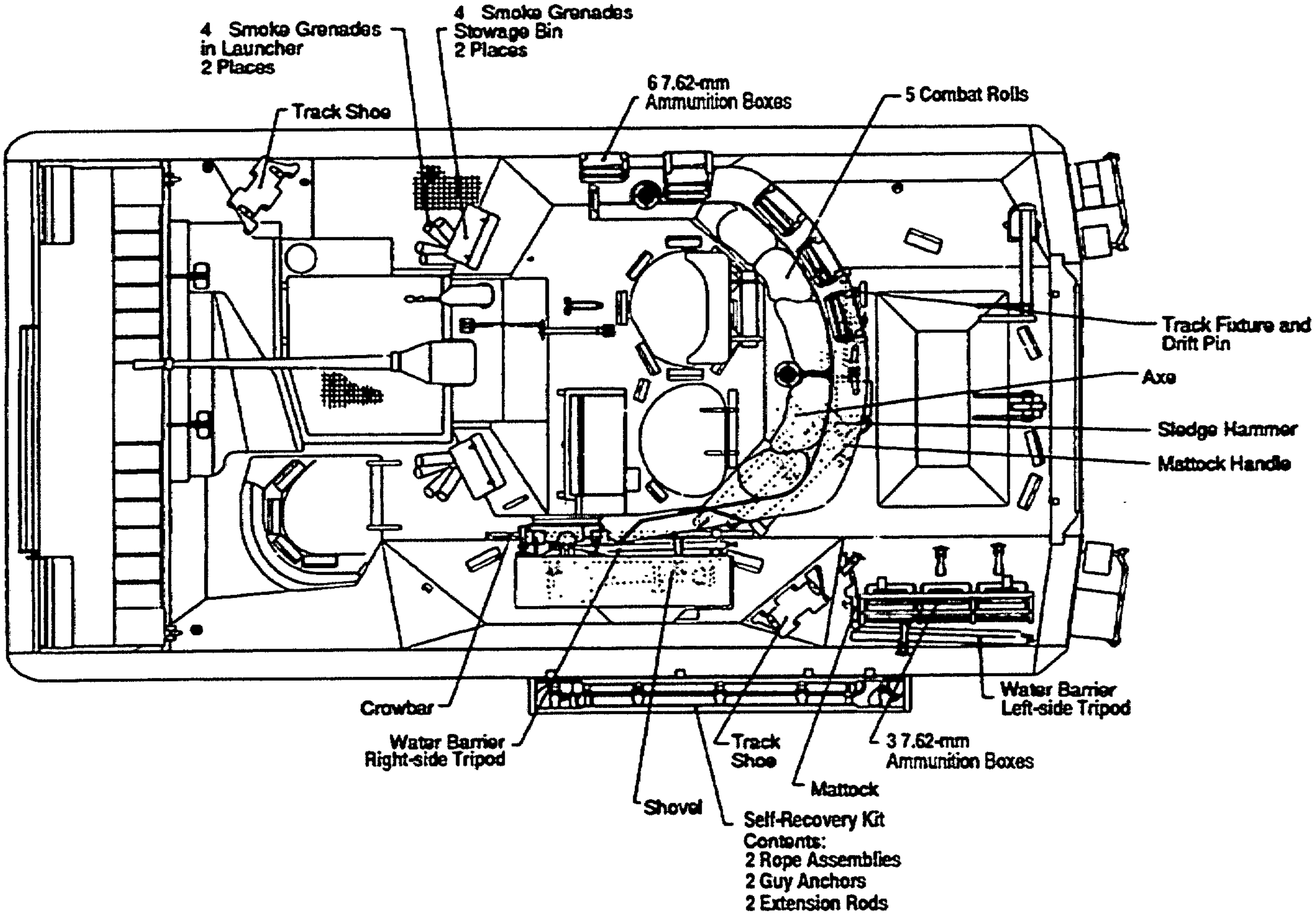
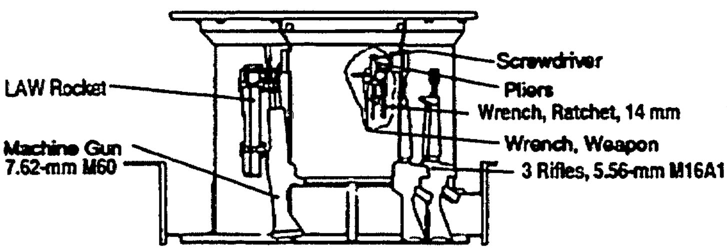


(D) Top View, Exterior Stowage



(E) Rear View of Turret Shield and Partial View
of Turret Interior

Figure 3-4. (cont'd)

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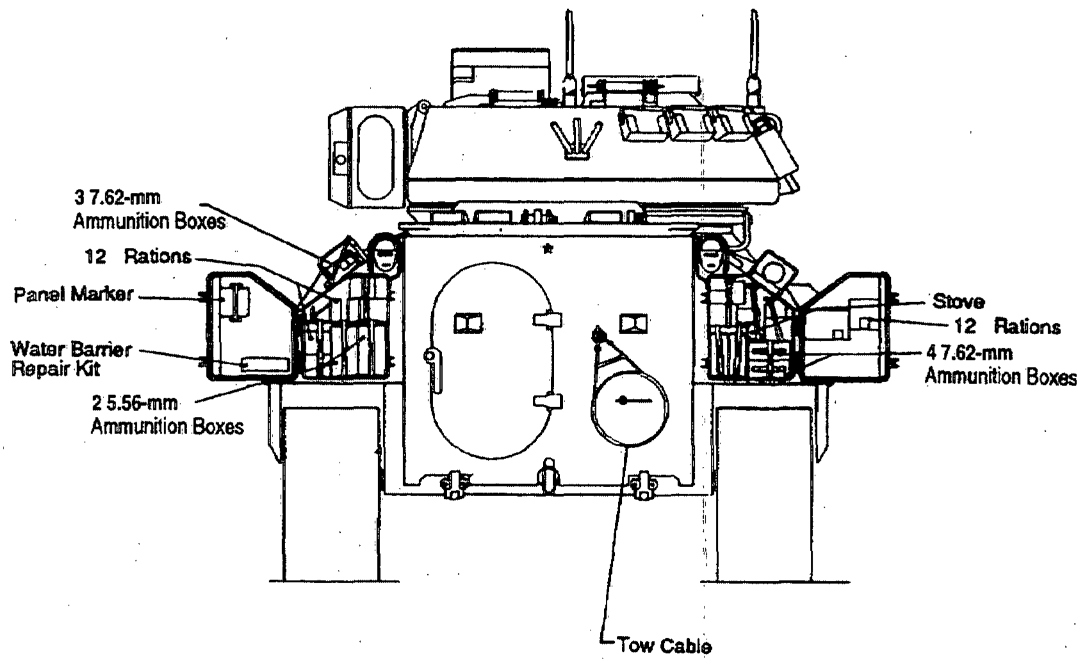

(F) Rear View

Courtesy of FMC Corporation

Figure 3-4. (cont'd)

Intumescent coatings contain several ingredients necessary to cause intumescent action. A catalyst is used to trigger the first of several reactions occurring in the coating. A carbon-forming compound reacts with the catalyst to form a carbon residue. A gas-forming compound decomposes and causes the carbon char to foam into a protective layer. A resin binder forms a skin over the foam and traps the gases in the char layer. Many intumescent coatings have drawbacks such as poor aging, poor humidity resistance, lack of flexibility, and high cost. Intumescent coatings release more noxious fumes than most nonintumescent coatings. Intumescent coatings are normally used in unoccupied compartments.

The amount of fuel in paints and coatings is relatively small. The ability of a finish material to resist the spread of flame is determined by the ASTM E 84 test. (Ref. 110) A flame spread rating of 25 or less is desirable. An assessment of the toxic effect of the smoke developed from exposure of a paint or coating to fire must be supplied by the manufacturer of the material upon request.

3-6.6 MISCELLANEOUS COMBUSTIBLES

Miscellaneous combustibles include plastics, elastomers, textiles, paper, trash, debris, combustible metals, and any other item not already covered that is located on or in a combat vehicle and can burn.

3-6.6.1 Elastomers, Plastics, Fire-Retardant Additives, and Fillers

Plastics and elastomers are widely used in military vehicles. These polymeric synthetic materials and natural rubber pose a serious health hazard when they burn in a vehicular fire. Some materials are more hazardous than others when burned. Fire-retardant additives can be incorporated within the polymeric matrix of the material to reduce the ignitability of the mixture. These fire retardants increase the specific heat of the mixture and thus increase the amount of heat necessary to raise the temperature of the mixture to the kindling temperature of the combustible component. These fire retardants can also pose a serious health hazard when the material burns. Some fire retardants can release toxic products when the base material burns. Others can break down into toxic components when subjected to heat. Fillers and extenders are also normally incorporated into the polymeric matrix. These fillers can be released into the atmosphere as the polymer burns and the resultant char is disturbed. Some of the fillers are combustible and most are harmful upon inhalation. A list of the properties of the combustible materials, including some noncombustible fillers used in military vehicles, is given in Table 3-15.

TABLE 3-15. PROPERTIES OF PLASTIC AND ELASTIC MATERIALS INCLUDING FILLERS AND FIRE-RETARDANT ADDITIVES (Refs. 111-116)

MATERIALS	SPECIFIC GRAVITY, dimensionless	THERMAL CONDUCTIVITY, W/(m·K) [Btu/(h·ft²·°F/ft)]	COEFFICIENT OF THERMAL EXPANSION, 10^{-5} m/m·K (10^{-5} in./in.·°F)	SPECIFIC HEAT, J/kg·K (Btu/lbm·°F)	FLAMMABILITY ASTM D 635, mm/min	(in./min)	AUTOIGNITION TEMPERATURE, °C (°F)
PLASTICS							
Acetal	1.4-1.5	0.22 (0.13)	3.61-8.1 (2.0-4.5)	1465 (0.35)	27.9	(1.1)	232 (450)
Acrylic	1.18	0.21 (0.12)	8.1 (4.5)	1465 (0.35)	13.0-55.9	(0.51-2.2)	293 (560)
Alkyd	2.50-2.15	0.05-0.10 (0.03-0.06)	1.8-5.4 (1.0-3.0)	1047 (0.25)	self-ext*	self-ext	260 (500)
Allyl Ester	1.32	0.21 (0.12)	10.8 (6.0)	1256 (0.3)	8.9	(0.35)	260 (500)
Cellulose Ester	1.3	0.17-0.35 (0.1-0.2)	7.7-15.5 (4.3-8.6)	1256-1758 (0.3-0.42)	13.0-50.8	(0.51-2.0)	143 (290)
Chlorinated Polyalkene Ester	1.4	0.14 (0.08)	11.9 (6.6)	1047 (0.25)	self-ext	self-ext	260 (500)
Cyanates/Cyanimides	1.4	0.21 (0.12)	3.6 (2.0)	1675 (0.4)	slow burn	slow burn	232 (450)
Epoxy (Expoximide)	1.15	0.69 (0.4)	11.2 (6.2)	1675 (0.4)	variable	variable	232-288 (450-550)
Epoxy (Brominated Cyclonalphatic)	1.22	0.21 (0.12)	3.1-5.4 (1.7-3.0)	1465 (0.35)	self-ext	slow to self-ext	260 (500)
Furan	1.2	0.21(0.12)	5.4 (3.0)	1675 (0.4)	slow	slow	260 (500)
Melamine	1.48	0.21 (0.12)	3.6 (2.0)	1675 (0.4)	self-ext	self-ext	327-341 (620-645)
Ureaform Aldehyde	1.5	0.35 (0.20)	2.7 (1.5)	1675 (0.4)	self-ext	self-ext	149 (300)
Casein	1.2	0.21 (0.12)	3.6 (2.0)	1675 (0.4)	slow to self-ext	slow to self-ext	177 (350)
Poly (bis-maleimide)	1.4	0.35 (0.20)	5.4 (3.0)	1130 (0.27)	self-ext	self-ext	260 (500)
Polyalkene Ethers	0.9	0.17 (0.10)	11.7 (6.5)	1968 (0.47)	7.9-13.0	(0.31-0.51)	204 (400)
Polyamide	1.14	0.17 (0.10)	8.6 (4.8)	1675 (0.40)	self-ext	self-ext	218-282 (425-540)
Polyarylene Ether	1.0	0.17 (0.10)	3.6 (2.0)	1675 (0.4)	9.4-24.9	(0.37-0.98)	204 (400)
Polybutadiene	1.1	0.21 (0.12)	5.4 (3.0)	1675 (0.4)	24.9-38.1	(0.98-1.5)	243 (470)
Polybutylene	0.91	0.22 (0.13)	12.8 (7.1)	1675 (0.4)	24.9-38.1	(0.98-1.5)	204 (400)
Polycarbonate	1.20	0.19 (0.11)	6.8 (3.8)	1256 (0.30)	self-ext	self-ext	271 (520)
Polyester (saturated)	1.31	0.17 (0.10)	9.5 (5.3)	1675-2512 (0.4-0.6)	slow	slow	249 (480)
Polyester (unsaturated)	1.12-1.46	0.19 (0.11)	6.8-10.6 (3.8-5.9)	1382-2303 (0.33-0.55)	self-ext-22.9	(self-ext-0.9)	249 (480)
Polyethylene (C-1)	0.91-0.93	0.35 (0.20)	16.0-19.6 (8.9-10.9)	2219-2303 (0.53-0.55)	63.5	(2.5)	177 (350)
Polyfluorocarbon FGR	2.14-2.17	0.21 (0.12)	15.1-18.9 (8.4-10.5)	1172 (0.28)	INF†	INF	288 (550)
Perfluoroalkoxy (PFA)	2.14-2.17	0.26 (0.15)	23.4 (13.0)	1047 (0.25)	INF	INF	288 (550)

*ext = extinguish
†INF = inflammable

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TABLE 3-15. (cont'd)

MATERIALS	SPECIFIC GRAVITY, dimensionless	THERMAL CONDUCTIVITY, W/(m·K) [Btu/(h·ft²·°F/ft)]	COEFFICIENT OF THERMAL EXPANSION, 10^{-5} m/m·K (10^{-5} in./in.·°F)	SPECIFIC HEAT, J/kg·K (Btu/lbm·°F)	FLAMMABILITY ASTM D 635, mm/min (in./min)	AUTOIGNITION TEMPERATURE, °C (°F)
PLASTICS (continued)						
Polytrifluoro chloroethylene (PTFCE)	2.10-2.15	0.26 (0.15)	7.0 (3.9)	921 (0.22)	INF† INF	288 (550)
Polytetrafluoroethylene (PTFE)	2.10-2.30	0.24 (0.14)	9.9 (5.5)	1047 (0.25)	INF INF	277 (530)
Polyvinylidene Fluoride (PVF)	1.78	0.17 (0.10)	12.1 (6.7)	963 (0.23)	self-ext self-ext	288 (550)
Polyvinylidene Fluoride (PVF_2)	1.77	0.24 (0.14)	15.3 (8.5)	1382 (0.33)	INF INF	288 (550)
Polyimide	1.42	0.35 (0.20)	5.0 (2.8)	1130 (0.27)	self-ext self-ext	>343 (>650)
Polyphenylene Sulfide	1.90	0.35 (0.20)	1.8-3.6 (1.0-2.0)	1465 (0.35)	self-ext self-ext	288 (550)
Casein-Aldehyde	1.1	0.21 (0.12)	3.6 (2.0)	1675 (0.4)	slow slow	149 (300)
Phenolics	1.36	0.21 (0.12)	3.1-4.7 (1.7-2.6)	1465 (0.35)	self-ext self-ext	271 (520)
Polypropylene	0.9-0.91	0.17-0.19 (0.10-0.11)	6.8-10.4 (3.8-5.8)	1884 (.45)	18.0-25.4 (0.71-1.0)	199-210 (390-410)
Polystryrene	1.04	0.10-0.17 (0.06-0.10)	5.9-8.6 (3.3-4.8)	1256-1465 (0.30-0.35)	25.4-38.1 (1.0-1.5)	254 (490)
Polysulfone	1.24	7.4 (4.3)	5.6 (3.1)	1005 (0.24)	self-ext self-ext	232 (450)
Polyurethane	1.12-1.22	0.24 (0.14)	16.9 (9.4)	1717 (0.41)		216 (420)
Polyvinylacetate	1.19	0.14 (0.8)	14.2 (7.9)	1675 (0.4)		232 (450)
Polyvinyl Chloride (PVC)	1.2-1.55	0.12-0.17 (0.07-0.10)	16.2 (9.0)	1256 (0.3)	self-ext self-ext	235 (455)
PVC-Vinyldene Chloride	1.68-1.75	0.10 (0.06)	16.0 (8.9)	1340 (0.32)	self-ext self-ext	>277 (>530)
ELASTOMERS						
Natural Rubber	0.93	0.14 (0.08)	66.6 (37.0)	1675 (0.4)	25.4-76.2 (1.0-3.0)	
Butyl R††	0.90	0.10 (0.06)	57.6 (32.0)	1675 (0.4)	25.4-76.2 (1.0-3.0)	
Nitrile R	0.98	0.24 (0.14)	70.2 (39.0)	1465 (0.35)	12.7-38.1 (0.5-1.5)	
Styrene Butadiene R	0.94	0.24 (0.14)	66.6 (37.0)	1675 (0.4)	25.4-50.8 (1.0-2.0)	
Polyurethane R	1.25	0.22 (0.13)	36.0 (20.0)	1675 (0.4)	25.4-50.8 (1.0-2.0)	216 (420)
Acrylic R	1.09	0.22 (0.13)	36.0 (20.0)	1675 (0.4)	25.4-50.8 (1.0-2.0)	
Silicone R	1.1-1.6	0.22 (0.13)	81.0 (45.0)	1675 (0.4)	2.5-12.7 (0.1-0.5)	288-296 (550-565)
Polyester R	1.16-1.27	0.24 (0.14)	36.0 (20.0)	2093 (0.5)	25.4-38.1 (1.0-1.5)	
Ethylene Propylene R	0.90	0.22 (0.13)	36.0 (20.0)	1675 (0.4)	25.4-76.2 (1.0-3.0)	
EPDM R	0.86	0.22 (0.13)	36.0 (20.0)	1675 (0.4)	25.4-76.2 (1.0-3.0)	
Isoprene R	0.93	0.22 (0.13)	66.6 (37.0)	1675 (0.4)	25.4-76.2 (1.0-3.0)	
Polysulfide R	1.35	0.22 (0.13)	36.0 (20.0)	1675 (0.4)	12.7-38.1 (0.5-1.5)	

†INF = inflammable
††R = rubber

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TABLE 3-15. (cont'd)

MATERIALS	SPECIFIC GRAVITY, dimensionless	THERMAL CONDUCTIVITY, W/(m·K) [Btu/(h·ft^2·°F/ft)]	COEFFICIENT OF THERMAL EXPANSION, 10^{-5} m/m·K (10^{-5} in./in.·°F)	SPECIFIC HEAT, J/kg·K (Btu/lbm·°F)	FLAMMABILITY ASTM D 635, mm/min (in./min)	AUTOIGNITION TEMPERATURE, °C (°F)
<u>FILLERS</u>						
Silica (SiO_2)	2.2-2.6	12.1 (7.0)	0.05 (0.03)	837-1256 (0.2-0.3)		
Silicates	2.1-2.5	4.3-6.9 (2.5-4.0)	0.34-0.41 (0.19-0.23)	837 (0.2)		
Calcite (CaO)	2.7	7.1 (4.1)	1.4 (0.76)	837 (0.2)		
Gypsum	2.97	6.9 (4.0)	1.1-1.4 (0.6-0.8)	837 (0.2)		
Titanium Oxide (TiO_2)	3.9-4.2	6.9-10.4 (4.0-6.0)	0.02 (0.01)	754-879 (0.18-0.21)		
Talc	2.7-2.8	2.6-3.3 (1.5-1.9)	0.58-0.72 (0.32-0.40)	837-921 (0.2-0.22)		
Clay	2.0-2.5	6.1 (3.5)	48.6-57.6 (27.0-32.0)	754-837 (0.18-0.20)		
Alumina (Al_2O_3)	3.4-3.9	23.0-36.9 (13.3-21.3)	0.36-0.41 (0.20-0.23)	837 (0.2)		
Aluminates	3.7-4.1	10.4-13.8 (6.0-8.0)	<0.02 (<.01)	1047 (0.25)		
Fly Ash	2.5-4.0	10.4-13.8 (6.0-8.0)	<0.36 (<0.2)	837-1256 (0.2-0.3)		
Rice Hull Ash	2.5-4.0	10.4-13.8 (6.0-8.0)	<0.36 (<0.2)	837-1256 (0.2-0.3)		
Carbon Black	1.8-2.1	5.2-8.7 (3.0-5.0)	0.23-0.29 (0.13-0.16)	754 (0.18)	7.6-25.4 (0.3-1.0)	
Graphite	2.0-2.3	112.5-164.4 (65.0-95.0)	0.13-0.31 (0.07-0.17)	754 (0.18)	7.6-25.4 (0.3-1.0)	
Asbestos	2.2-2.5	2.1-2.9 (1.2-1.7)	0.54-0.79 (0.30-0.44)	837 (0.2)		
Fiberglass	2.2	3.5-12.1 (2.0-7.0)	0.32-0.36 (0.18-0.20)	837-1256 (0.2-0.3)		
Graphite Fiber	1.5-1.9	3.5-86.5 (2.0-50.0)	0.36-0.74 (0.2-0.41)	837 (0.2)	7.6-25.4 (0.3-1.0)	
Ceramic Fiber	3.0-3.3	5.2-6.1 (3.0-3.5)	<0.02 (<0.01)	837 (0.2)		
Nylon Fiber	1.14	0.17 (0.10)	8.6 (4.8)	1675 (0.40)	7.6-25.4 (0.3-1.0)	
Alkyd Fiber	2.1	0.52-1.0 (0.3-0.6)	1.8-5.4 (1.0-3.0)	1047 (0.25)	12.7-50.8 (0.5-2.0)	
Imide Fiber	1.4	0.35 (0.20)	3.6 (2.0)	1130 (0.27)	12.7-25.4 (0.5-1.0)	
Iron	7.9	60.6 (35.0)	1.4 (0.75)	461 (0.11)		
Aluminum	2.7	233.6 (135.0)	2.2-2.5 (1.2-1.4)	963 (0.23)		
<u>FIRE-RETARDANT ADDITIVES</u>						
Aluminum Hydroxide	2.42			1193 (0.28)	0	
Antimony Trioxide	5.2-5.7			347 (0.08)	0	
Sodium Borate Decahydrate	1.73			1611 (0.038)	0	
Sodium Borate Pentahydrate	1.815				0	
Zinc Borate	3.1-3.64				0	

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TABLE 3-15. (cont'd)

MATERIALS	SPECIFIC GRAVITY, dimensionless	THERMAL CONDUCTIVITY, W/(m·K) [Btu/(h·ft^2·°F/ft)]	COEFFICIENT OF THERMAL EXPANSION, 10^{-5} m/m·K (10^{-5} in./in.·°F)	SPECIFIC HEAT, J/kg·K (Btu/lbm·°F)	FLAMMABILITY ASTM D 635, mm/min (in./min)	AUTOIGNITION TEMPERATURE, °C (°F)
<u>FIRE-RETARDANT ADDITIVES</u> (continued)						
Disodium Phosphate	1.5-2.0				0	
Sodium Silicate Hydrate					0	
Magnesium Phosphate	1.73				0	
Magnesium Silicate					0	
Dibromoneopentyl Glycol					0	
Tetrabromophthalic Acid Ester					0	
Chlorendic Anhydride	1.73				0	
Tricresyl Phosphate	1.16				0	
Ammonium Fluoroborate	1.87				0	
Hexachlorocyclopentadiene	1.7-2.4				0	

3-6.6.1.1 Plastics

Most plastics in use today will burn. Even those materials classified as nonflammable or self-extinguishing decompose and evolve potentially hazardous gases if subjected to a sustained flame. Those materials classified as slow burning can still evolve significant amounts of toxic fumes over a short period of time if the burning material has a high surface area, which creates greater contact with atmospheric oxygen.

Some of the more flammable of the combustible plastics are certain epoxies, cellulosic compounds, acrylics, acetals, polyacrylene ethers, polybutylene, polybutadiene, polyester (unsaturated polyurethane), polyethylene, polypropylene, and polystyrene. Examples of slow-burning plastics are furans, acetals, cyanates/cyanimides, and caseins. Self-extinguishing materials are plastics such as alkyds, chlorinated ethers, polyvinyl chlorides, melamines, ureaformaldehydes, phenolics, polyamides, polycarbonate, polyimides, polyphenylene sulfide, and polysulfane. The very heavily halogenated plastics, e.g., polyfluorocarbons and chlorofluorocarbons, are nonflammable.

Plastics are organic and can emit hazardous gas when burned. If any organic material is burned without sufficient oxygen present, carbon monoxide is formed. The chlorinated resins are particularly hazardous when burned because phosgene can be produced. Materials that can produce phosgene when burned are PVC, PVC-vinylidene chloride, chlorinated polyalkene ethers, and the chlorofluorocarbons. Phosgene is formed even in the presence of sufficient oxygen for complete combustion of the materials. The chlorinated resins will also emit hydrogen chloride (HCl) gas when burned. The fluorocarbons emit hydrogen fluoride (HF) when burned. Both HCl and HF are toxic when inhaled. The cyanates/cyanimides emit hydrogen cyanide (HCN) upon burning. HCN is a highly toxic and flammable gas. Upon burning the sulfurous resins, such as polysulfone and polyphenylene sulfide, emit hydrogen sulfide and produce sulfuric acid if sufficient moisture is present.

3-6.6.1.2 Elastomers

The elastomeric materials used in military vehicles are flammable. Flammability is reduced somewhat by the halogenation of the polymeric resin. Chloroprene and halogenated silicone are examples of elastomers with reduced flammability. Chloroprene will burn even though halogenated. The halogenated silicones are considered nonflammable, and the unhalogenated silicones are considered combustible. When silicone burns, the residue contains silica, which can be a potentially harmful irritant when inhaled in powder form.

All of the elastomers are organic and when incompletely burned, will emit carbon monoxide. The chlorinated elastomers can produce phosgene when burned. The polysulfide elastomers have a high sulfur content and when burned can emit sulfur dioxide and/or hydrogen sulfide and produce sulfuric acid if moisture is present.

Natural rubbers are highly combustible. The carbon black in tires or track pads, for example, burns at a high temperature and produces glowing coals that are difficult to extinguish.

3-6.6.1.3 Fire-Retardant Additives

Both organic and inorganic materials are used as fire retardants. Some of the inorganic fire retardants are nontoxic but can be respiratory irritants. Magnesium silicate, disodium phosphate, sodium borate, and antimony trioxide are all considered toxic. Antimony trioxide is also a suspected carcinogen.

The organic fire retardants are normally highly halogenated and when heated to a given temperature can generate toxic products. Those fire retardants that contain bromine emit hydrogen bromide gas when heated to decomposition temperature. Those retardants containing chlorine can emit phosgene and hydrogen chloride. Organic fire retardants also produce carbon monoxide when incompletely burned. The organic fire-retardant chemicals are considered toxic, but when incorporated into a plastic or elastomeric matrix, the chemicals are effectively encapsulated so the polymeric materials are safe to handle.

Fire retardants inhibit burning by several mechanisms. Some retardants alter decomposition and combustion reactions, so any evolved gases either are noncombustible and act as diluents or possess sufficiently high heat capacities to serve as heat sinks. Either effect reduces chemical reaction rates and hence heat release rates in the burning evolved gases. Water, carbon dioxide, and halogenated compounds operate via this gas-generating mechanism. Phosphorus- and boron-containing compounds increase the amount of carbonaceous char and thereby reduce the amount of flammable gas evolved from a burning material and reduce the available heat of combustion. Halogenated compound additives also may inhibit free radical chain reactions as the burning plastic decomposes into combustible gases. Antimony trioxide works synergistically with the halogenated retardants.

3-6.6.1.4 Fillers

Fillers and extenders are commonly mixed with plastic and elastomeric resins to improve certain physical and chemical properties of those resins and to reduce the cost of the resultant mixture. Most of the fillers are harmful to inhale and are classed as respiratory irritants. Prolonged inhalation of crystalline silica can lead to silicosis, a serious lung disease. Asbestos is a widely suspected carcinogen, and great care must be taken not to inhale any asbestos particles. Because of its carcinogenicity, asbestos is not normally used.

Fillers containing carbon are flammable. Examples of combustible organic fillers are graphite and carbon black.

Finely divided metal fillers, such as aluminum and iron, are highly flammable and are used in pyrotechnics. These materials burn at high temperatures. Airborne graphite and carbon fillers and fibers can also damage electrical equipment by causing it to short out and malfunction.

Filler and reinforcing fibers help to maintain the physical integrity of the unburned material and the burned char. Maintaining the integrity of the outer char reduces the exposed surface area of unburned substrate. Some fillers have a high specific heat and thermal conductivity and absorb or dissipate the available heat—characteristics that prevent the polymeric material from being heated to ignition temperatures. Hydrated fillers absorb heat energy as they dehydrate. See Table 3-15 for properties of typical filled and fiber-reinforced plastics.

3-6.6.2 Textiles

Fabric items such as NBC protective garments, canvas sacks, tarpaulins, camouflage nets, and sleeping bags pose a most significant fire threat. Upon ignition, these items will burn and may be difficult to extinguish because of deep-seated smoldering combustion. Ignition may occur from any of several sources, e.g., hot metal, fuels or other combustibles, and munitions. Ignition of canvas due to hot metal fragments would be a particularly insidious fire that could potentially smolder for a long time prior to ignition. Smoldering combustion, although it is not an apparent fire, may produce toxic gases.

Equipment such as tarpaulins, camouflage nets, fabric camping gear, or sleeping bags stored on the outside of a vehicle may pose an unusual fire hazard in the case of ignition of spilled fuel or a Molotov cocktail external to the vehicle. Such equipment would likely ignite and possibly sustain flaming combustion long after the fuel has burned off. This fire hazard on the outside of a combat vehicle could generate smoke, potentially make the inside of the vehicle untenable due to heat, or cause continued burning of items on or inside the vehicle.

Clothing, including chemical protective garments, stowed within the vehicle would probably be made of nylon, cotton, nomex, Kevlar®, fiberglass, wool, rubber, and/or the chemical protective carbon-impregnated coatings. Sleeping bags would probably be made of fiber- or down-filled nylon. Individual tents are made of nylon; troop tents are made of canvas. Camouflage nets are made of nylon with synthetic streamers providing the colored fills. Manila rope is often used.

There are too many materials in use today to describe the composition of each and the range of possible combustion products that could result. Table 3-16, however, contains some pertinent properties of natural and synthetic materials. All materials containing carbon are likely to evolve carbon monoxide and/or carbon dioxide during combustion. The amount of air present at the site of combustion influences the ratio of carbon monoxide (highly toxic) to carbon dioxide (asphyxiant). Also a wide variety of polymer decomposition products evolve as simple hydrocarbons (e.g., methane and propane), partially oxidized species (e.g., acetaldehyde and acrolein), and more complex compounds (e.g., polynuclear aromatics).

Many of the materials in combat vehicles, either natural or synthetic, contain nitrogen, sulfur, and halogens, in addition to carbon and hydrogen. See Table 3-16. When these materials burn, hydrogen cyanide (HCN), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ammonia (NH_3), and halogen acids (HCl, HBr, and HF) may form. Also isocyanates, nitriles, and other polymer decomposition products may be present.

Some of the other textile materials mentioned that are not specifically identified in Table 3-16 fall within the general polymer groups. Canvas is generally linen, hemp (natural plant fiber), or cotton. Burlap is usually jute (also a natural plant fiber) or hemp. Both of these would fall under the general category of "sisal" in Table 3-16. Manila rope, made of manila hemp, is used because it is resistant to stretching. Down would probably fall in the same category as silk (fibroin or protein). Fiberglass and rock wool are used as insulation and would have relatively little burnable mass; however, there is some resin to hold it together. This small amount of burnable mass does not necessarily mean that the combustion products are nonhazardous. Fiberglass as a fabric or construction material probably contains at least 50% polyester or epoxy resin, which would be in the category of polymethylmethacrylate (PMMA) for the purposes of identifying elemental composition. (PMMA is also used in monobloc form for aircraft canopies and is referred to as stretched acrylic.)

Studies involving the analysis of atmospheres in real fires have been conducted by the use of portable smoke-sampling devices carried by firemen in actual fire environments. In these studies samples of the fire atmospheres were analyzed for selected toxic combustion gases. The results of the analyses confirm that combustion products can be produced by materials in real fires in sufficient concentration to create environments that are toxicologically hazardous to the occupants as well as to the firemen engaged in fire-fighting operations. A brief review of the toxicological effects of exposure to the major fire gases is presented in Table 3-17.

3-6.6.3 Other

Other items located in or on combat vehicles that can burn or support combustion and that can present a hazard include

1. Paper items, such as maps, documents, and message pads
2. Rations
3. Trash and debris
4. Bottled oxygen and acetylene

TABLE 3-16. PERTINENT PROPERTIES OF FIBERS, PAPER, AND LEATHER (Refs. 117-119)

MATERIAL	SPECIFIC GRAVITY, dimensionless	HEAT OF COMBUSTION, MJ/kg	SPECIFIC HEAT, kJ/kg·°C	AUTOIGNITION TEMPERATURE, °C (°F), IN FLASK	AUTOIGNITION TEMPERATURE, °C (°F), HOT PLATE	THERMAL CONDUCTIVITY, W/m·K	LATENT HEAT OF VAPORIZATION, MJ/kg
Cotton	0.080	16.5-20.4	0.267-0.312	385 (725)	465 (869)	0.005-0.042	
Leather	0.86-1.00	18.2-19.8	0.310			0.060-0.159	
Silk	0.058-0.101		0.284			0.019-0.045	
Wool	0.136	20.7-26.6	0.339	540 (1004)		0.020-0.036	
Paper, brown	0.7-1.53	16.3-17.9		400 (752)	470 (878)	0.045-0.130	2.2
Cellulose Acetate, $C_3H_{12}O_6$	1.27-1.34	17.8-18.4	1.26-1.76	550 (992)			3.5
Polyamide (Nomex®)		27.0-28.7		515 (954)			
Nylon 6/6	1.13-1.15	31.6-31.7	1.67-1.70				2.3
Rayon		13.6-19.5					
Fiberglass	2.55 (E Glass)		0.186	467 (873)*		1.57	1.7-2.2
Polyamide (Kevlar®)	1.44			427 (800) starts to carbonize			
Polyethylene (Spectra®)	0.97		2.30	488 (910)*			1.5-2.7
Sisal		15.9					
Linen						0.030-0.087	

*Test method is not described.

TABLE 3-17. TOXICOLOGICAL EFFECTS OF FIRE GASES (Ref. 120)

TOXICANT	SOURCES	TOXICOLOGICAL EFFECTS	ESTIMATE OF SHORT-TERM (10-min) LETHAL CONCENTRATION, ppm
Hydrogen Cyanide (HCN)	From combustion of wool, silk polyacrylonitrile, nylon, polyurethane, and paper	A rapidly fatal asphyxiant poison	350*
Nitrogen Dioxide (NO_2) and Other Oxides of Nitrogen	Produced in small quantities from fabrics and in larger quantities from cellulose nitrate and celluloid	Strong pulmonary irritant capable of causing immediate death as well as delayed injury	>200
Ammonia (NH_3)	Produced in combustion of wool, silk, nylon, and melamine; concentrations generally low in ordinary building	Pungent, unbearable odor; irritant to eyes and nose	>1000
Hydrogen Chloride (HCl)	From combustion of polyvinyl chloride (PVC) and some fire-retardant-treated materials	Respiratory irritant; potential toxicity of HCl coated on particulate may be greater than that for an equivalent amount of gaseous HCl.	>500, if particulate is absent
Other Halogen Acid Gases (HF and HBr)	From combustion of fluorinated resins or films and some fire-retardant materials containing bromine	Respiratory irritants	HF $\approx$ 400 HBR > 500
Sulfur Dioxide (SO_2)	From materials containing sulfur	A strong irritant; intolerable well below lethal concentrations	>500
Isocyanates	From urethane polymers; pyrolysis products, such as toluene-2, 4-diisocyanate (TDI), have been reported in small-scale laboratory studies; their significance in actual fires is undefined.	Potent respiratory irritants; believed to be the major irritants in smoke of isocyanate-based urethanes	$\approx$100 (TDI)
Acrolein	From pyrolysis of polyolefins and cellulosics at lower temperatures ($\approx$400°C)	Potent respiratory irritant	30 to 100

*Some investigators believe that 350 ppm would require at least 30 min to cause lethality.

5. Void filler materials, such as reticulated foam
6. Combustible metal components.

Paper items kept within combat vehicles include maps, message pads, manuals, records, and many other documents. These can become saturated with fuel, oil, or other hydrocarbon fluids if the liquids are sprayed onto the paper items. The paper can be ignited by a fuel or gun propellant fire, by electrical shorts, or by a hot metal fragment or a shaped-charge slug lodged within or on the paper item. The paper can burn by either flaming or glowing.

Rations are normally difficult to ignite but would provide additional fuel in a strong fire.

Trash includes wastepaper, cleaning rags, used filter elements, old fuel or hydraulic fluid hose, cigarette butts, and many other combustible items that collect in vehicles. Debris includes leaves, twigs, small branches, and other combustible matter that fall into or are blown or tracked into vehicles and collect in the bilge, corners, or other out-of-the-way places in vehicles. Many of these items become saturated with motor fuel or oil and can be ignited by electrical discharges, vehicular hot spots, hot metal pieces from ballistic impacts, or the combustion of more easily ignited items. Once ignited, these items can smolder until fire suppressants have become diluted and fires can reignite.

Bottled oxygen can be found in combat vehicles that are used for medical evacuation or for maintenance or recovery of immobile vehicles. In the latter case, bottled acetylene will probably be present also. If an oxygen bottle is ruptured or oxygen can otherwise escape, the probability of ignition and of achieving flaming combustion of combustible items is greatly increased. Freed acetylene would present a potential explosion hazard.

If placed within a combat vehicle, void filler material, such as reticulated foam, would provide another combustible item. Normally this polyester or polyether foam would be somewhat difficult to ignite, but given a strong fire, it would burn.

Combustible metals include lithium, magnesium, and titanium. Lithium is used in the newer, heavy-duty batteries. Given a ballistic impact that ruptures the battery case, the lithium plates could be exposed to air. Lithium combines with either oxygen or nitrogen and produces a high quantity of heat while combusting. This characteristic makes extinguishing a lithium fire difficult. Magnesium and high magnesium-aluminum alloys burn in air once ignited.

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CHAPTER 4
FIRE PREVENTION

The components and systems of combat vehicles that render the vehicles and crew vulnerable to fire are described, and techniques are given that enhance vehicular survivability by preventing the ignition of fires. The components and systems that contribute most to vehicular and crew vulnerability are the on-board munitions, the engine, the fuel system, the hydraulic system, and the electrical system. Material selection criteria and system integration are also discussed.

4-1 INTRODUCTION

When presented with the problem of eliminating an unwanted fire, most designers of combat vehicles would incorporate a fire extinguisher into the design of the vehicle. However, fire extinguisher systems should not be the only or even the primary protection. At the very least, fire can force the crew to evacuate and will destroy needed items. A better protection technique is to incorporate fire prevention measures into the design of the vehicle and its components in order to minimize the possibility of a fire being ignited or, once started, of propagating. Fire prevention can be accomplished by (1) keeping fuel from an oxidizer-rich region, (2) reducing the oxidizer available to fuel that is plentiful, (3) keeping ignition sources from flammable fuel vapor-air mixtures, (4) providing a heat sink to transfer heat energy away from potential fuels and thereby keeping their temperatures below their kindling points, (5) introducing nonflammable gases to dilute the existing fuel and oxidizer mixture below flammable levels, (6) releasing gases with a higher probability of uniting with free radicals, (7) providing a low thermal conductivity layer, which reduces the rate of heat transfer to combustible materials, and/or (8) providing a material that absorbs heat innocuously—i.e., evaporates or becomes hotter, as does aluminum oxide—and thus reduces the quantity of heat available to raise the temperature of any fuels present.

The fire-critical systems or components of combat vehicles are covered in the paragraphs that follow and include the engine, the fuel system, the hydraulic system, the electrical system, and munitions. A paragraph on material selection and another on system integration complete this chapter.

Armored combat vehicles provide mobility, protection, and firepower. All three attributes are essential. These vehicles must operate in the field for long periods while moving frequently. In training, soldiers use combat vehicles in much the same manner they would in combat; therefore, a review of reports of fires that have occurred during peacetime operations can provide insight into vehicle weaknesses that would be exacerbated in combat operations.

There are four categories of combat vehicles:

1. Fighting vehicles, such as main battle tanks (MBT) M1, M60, and M48; Bradley fighting vehicles (BFV) infantry M2 and cavalry M3; the light-armored vehicle (LAV) 25; and the armored reconnaissance/airborne assault vehicle (AR/AAV) M551
2. Personnel carriers, such as the armored personnel carrier (APC) M113 and its variants—the armored command post M577, the cargo carrier M548, and others that are more properly combat vehicles, such as the improved tube-launched, optically tracked, wire-guided (TOW) missile antitank vehicle M901, or combat support vehicles like the armored self-propelled 107-mm mortar carrier M106. There is also the amphibious assault vehicle (AAV) 7.
3. Combat support vehicles, such as self-propelled howitzers (SPH) M109 and M110, combat engineer vehicle (CEV) M728, and division air defense (DIVAD) vehicle M247 (Sgt York)*
4. Service support vehicles, such as the field artillery ammunition supply vehicle (FAASV) M992, the armored vehicle launch bridge (AVLB), and the tracked recovery vehicle (TRV) M88.

There are two databases that can provide information on design needs. The US Army Safety Center (USASC) collects and collates reports of fires involving Army equipment. The bulk of these reports concerns operations during peacetime, i.e., noncombat fire incidents. These reports are referred to as the USASC database. The second database is data collected during the Battle Damage Assessment and Repair Program (BDARP) conducted in Southeast Asia (SEA) during the late 1960s and early 1970s. This database is maintained at the Survivability/Vulnerability Information and Assessment Center (SURVIAC) at Wright-Patterson Air Force Base (W-P AFB), OH. This database is referred to as the SEA BDARP database. These databases are described in subpars. 4-1.1 and 4-1.2. Recommendations for design considerations are in subparagraphs in this chapter on the fuel system, ancillary power, electrical systems, ammunition, materials selection, and systems integration or in Chapter 7, "Extinguishing Agents and Systems".

*The air defense vehicle (Sgt York) was never fielded by the US Army. It is included here because there are some data on it and it represents a type of vehicle that may be fielded in the future.

4-1.1 TRAINING-INDUCED FIRES

Records of fire incidents are collected by the USASC, Fort Rucker, AL. Extracts of these records for the period fiscal year (FY) 1983 through FY87 from US Army organizations and from the US Navy Safety Center (USNSC) for the period October 1985 through September 1986 were reviewed for this handbook. Many of the USNSC reports were of the same incidents reported by the Army, but they were from the fire departments because all service fire departments report incidents to the USNSC. The US Army tactical and training organizations, even those in Germany, submit fire reports to the USASC. Often, details missing in a report from one source are given in the report from another source. The USASC issued two reports summarizing fires prior to 1984 (Refs. 1 and 2), but these summaries lacked the details required to analyze the design features that either resulted in fires or helped to extinguish fires.

A tabular summary of vehicle fire survivability statistics is given in Table 4-1. Table 4-1 is divided into four sections: (A) ignition source, (B) fire location, (C) combustible materials, and (D) extinguisher used for final suppression of fire.

There were 39 reports involving M1 tank fires from FY83 through FY87. The vast majority of reported fires (33 of 39) were engine related and located in the engine compartment. Of the remainder four were in the personnel compartment and two were external fires. The primary combustibles included fuel, oil, and hydraulic fluids, which were usually ignited by contact with heated surfaces. Less frequent cases involved the electrical short circuit of major wiring harnesses (6 of 39) or the explosion of heated aerosol cans (2 of 39). Fire department equipment using copious quantities of water was required to extinguish the blaze in at least eight of the reported cases, whereas on-board equipment extinguished 29 fires. Other evaluations are given in later paragraphs.

A very limited data set exists on the M2 and M3. Only nine fires were reported during the time period. Six of the reported fires were located in the personnel compartment, and half of these were due to the troop compartment heating unit.

The largest data set, containing 88 reported fires from FY83 through FY87, exists on the M60 tank. Sixty-eight of the incidents occurred in the engine compartment of the tank and involved burning of electrical wiring harnesses, electrical ignition of leaking fuel, or ignition of fuel, oil, or hydraulic fluid on heated surfaces. Nineteen of the 20 remaining incidents occurred in the personnel compartment and consisted largely of fires related to the personnel heating units or the ignition of soft items—camouflage nets, sleeping bags, clothing and personal items, sandbags, tarpaulins, upholstery—and stowed munitions. The majority of reported fires were extinguishable by on-board means; 28 had to be extinguished by fire departments.

The smallest data set was obtained for the M48 tank, which is no longer in wide usage. Only five reports were obtained for review, and the majority of the problems resulted from the location of the munition storage racks.

The M113 series vehicles had 40 reported fires during the time period. Many of these cases involved electrical arcs that ignited fuel in the engine compartment. Sometimes soft items, such as clothing and camouflage netting, burned and the fires spread to on-board ammunition. Fire departments had to extinguish many of these fires. Some of the vehicles burned uncontrolled and were completely destroyed.

The data set on the M88 TRV had 38 reports. Almost all reported fires, 35 of 38, occurred in the engine compartment and usually involved the ignition of fuel or oil on a heated surface. Some wiring harness electrical fires were reported. Twenty-three of the fires were extinguished with on-board equipment—14 of them with fixed fire extinguisher systems (FFESs), and nine with portable extinguishers—and 13 by fire departments.

The M60 AVLB, M728 CEV, and M247 (Sgt. York) DIVAD had a total of only eight reported fires. All occurred in the engine compartment and all but one involved the ignition of oil or fuel on a heated surface. The remaining fire was caused by an electrical short. Half of the fires had to be extinguished by fire departments.

The M109 and M110 self-propelled howitzers had six reported fires. The fires varied and half were in the crew compartment. Two electrical fires were reported, one in an engine compartment and one in a turret. Both were extinguished with portable equipment. Another involved gloves that ignited when placed on the personnel heater. A fire started when a mechanic cut a filled hydraulic line with a torch. Two others were caused by munitions effects while firing the main gun.

An overall examination of these fire statistics reveals that the engine compartment was the principal location for these noncombat fires (163 of 233). These fires typically involved either electrical or heated-surface ignition of fuel, oil, or hydraulic fluid or the burning of electrical components (172 of 233). The next largest contributor was personnel heaters in the troop compartment, which comprised 25 of the reported fires. These fires were caused by fuel from unpurged heaters, explosion of aerosol cans left on top of an operating heater, or other combustible items placed on or near these heaters. Munitions effects caused few of the fires, although ammunition was involved as a combustible in 12 of the noncombat fires.

4-1.2 BATTLE-INDUCED FIRES

4-1.2.1 Battle Damage Assessment and Repair Program Database

In the mid-1960s, the US Air Force and the US Army each had a BDARP in which teams were sent to SEA to obtain descriptions of the battle damage sustained by equipment, both aircraft and ground vehicles, and of the efforts

TABLE 4-1. SUMMARY OF VEHICLE FIRE SURVIVABILITY STATISTICS (Ref. 3)

VEHICLE	NUMBER OF INCIDENTS	(A) IGNITION SOURCE				
		HEATED SURFACE	ELECTRICAL	MUNITIONS	PERSONNEL HEATER	OTHER
M1 Tank	39	28	6	0	2	3
M2 and M3 BFVs	9	2	4	0	3	0
M60 Tank	88	30	35	1	10	12
M48 Tank	5	1	3	0	0	1
M113 APC	40	6	16	4	7	7
M88 TRV	38	21	10	0	2	5
AVLB, CEV, and DIVAD	8	7	1	0	0	0
M109 and M110 SPH	6	0	2	2	1	1
	233	95	77	7	25	29

VEHICLE	NUMBER OF INCIDENTS	(B) FIRE LOCATION		
		ENGINE COMPARTMENT	PERSONNEL COMPARTMENT	EXTERNAL TO HULL
M1 Tank	39	33	4	2
M2 and M3 BFVs	9	3	6	0
M60 Tank	88	68	19	1
M48 Tank	5	2	3	0
M113 APC	40	13	21	6
M88 TRV	38	35	2	1
AVLB, CEV, and DIVAD	8	8	0	0
M109 and M110 SPH	6	1	3	2
	233	163	58	12

(cont'd on next page)

TABLE 4-1. (cont'd)

VEHICLE	NUMBER OF INCIDENTS	(C) COMBUSTIBLE MATERIALS							
		WIRING HARNESSES, etc.	FUEL	OIL	HYDRAULIC FLUIDS	MUNITIONS	PERSONAL GEAR, SOFT ITEMS, AND CLOTHING	EXTERNAL	NOT REPORTED
M1 Tank	39	2	24	0	6	1	2	1	3
M2 and M3 BFVs	9	2	7	0	0	0	0	0	0
M60 Tank	88	14	36	24	1	2	3	0	8
M48 Tank	5	1	0	0	0	3	0	0	1
M113 APC	40	6	16	0	0	5	10	3	0
M88 TRV	38	7	12	13	0	0	1	2	3
AVLB, CEV, and DIVAD	8	1	3	4	0	0	0	0	0
M109 and M110 SPH	6	2	0	0	1	1	2	0	0
	233	35	98	41	8	12	18	6	15

VEHICLE	NUMBER OF INCIDENTS	(D) EXTINGUISHER USED FOR FINAL SUPPRESSION OF FIRE							
		SELF-EXTINGUISHING	FIXED FIRE EXTINGUISHER		PORTABLE	OTHER	FIRE DEPARTMENT	VEHICLE DESTROYED	NOT REPORTED
			AUTOMATIC	MANUAL					
M1 Tank	39	1	8	5	16	0	8	0	1
M2 and M3 BFVs	9	0	0	1	5	0	1	0	2
M60 Tank	88	3	*	13	37	0	28	0	6
M48 Tank	5	0	*	0	1	0	1	0	3
M113 APC	40	7	*	1	7	1	16	4	4
M88 TRV	38	0	*	14	9	0	13	0	2
AVLB, CEV, and DIVAD	8	0	*	2	1	1	4	0	0
M109 and M110 SPH	6	1	*	0	4	1	0	0	0
	233	12	8	36	80	3	71	4	18
			124 total using onboard fire-extinguishing equipment						

no automatic fixed fire extinguisher system necessary to repair that damage. The records involving combat vehicles hit by shaped-charge warheads were examined to obtain a measure of the damage these vehicles sustained. The vehicles for which data exist include the M48A3 MBT, the M551 AR/AAV, and the armored cavalry assault vehicle (ACAV), which was a field-modified variant of the M113A1 APC. All of these are diesel powered. Either the BDARP did not start until after the gasoline-fueled vehicles were replaced, or the BDARP effort did not include organizations with gasoline-fueled vehicles. The hostile weapons used against these vehicles included the rocket-propelled grenades (RPG) RPG-2 and RPG-7 and the 57-mm and 75-mm recoilless rifles (RR). No large caliber kinetic energy (KE) projectile data are included in the database. The data reviewed are summarized in Ref. 4. Insights presented in this handbook are based upon the BDARP database, upon several test programs, and upon reports and accounts of events in conflicts.

The data described in Ref. 4 include all incidents involving high-explosive antitank (HEAT) impacts on ground combat vehicles in the BDARP database. Incidents in which fire and/or explosion resulted are further described in Table 4-2, which is divided into three sections: (A) incidents resulting in fire or explosion, (B) highly combustible items hit by jet without a fire resulting, and (C) fire extinguisher system or extinguishant hit by jet. All of these incidents are referenced back to a Document Acquisition Number (DAN), which is the data element identifier used at SURVIAC, the repository for these records. Although not covered in this handbook, there are numerous reports of mine damage in the BDARP database.

4-1.2.2 Vehicles, Situations, Threats, and Combustibles

The data available (Ref. 6) for the M113 family of vehicles (FoV) consist of that for 43 ACAVs, one APC M113A1, one 107-mm mortar carrier M106, one 81-mm mortar carrier M125, and one cargo carrier M548. These vehicles were diesel-powered and had a manually activated, fixed CO_2 fire extinguisher system in the engine compartment and only a portable CO_2 extinguisher in the crew compartment. The ACAVs, Fig. 4-1, were used as fighting vehicles by armored cavalry, armored infantry, and combat engineers (Refs. 7 and 8). Therefore, they were exposed to hostile direct-fire antitank weapons; all 47 data points included were for damage due to direct-fire antitank weapons. The cupola of the ACAV was similar to that of the APC M113A3, Fig. 4-2.

*The ACAVs were APC M113A1s modified in field depots in SEA. Records of the modifications are not available at either the prime contractor, FMC Corporation, or the US Army Tank-Automotive Command (TACOM). FMC Corporation probably furnished some of the track commanders' (TC) cupolas (Ref. 5). The BDARP records do not differentiate between ACAV and unaltered APC M113A1. The author was able to differentiate by data given in each DAN.

These ACAVs had the same fire suppression system as the M113A1. A 4.8-mm (0.188-in.) thick aluminum wall separated the crew compartment from the engine compartment. The fixed fire extinguishing system for the engine compartment had one 2.3-kg (5-lb) CO_2 bottle and could be activated manually by use of a handle located beside the driver or by use of another handle within the troop compartment. No fire detection system was provided. One 2.3-kg (5-lb) portable CO_2 fire extinguisher was provided for the troop compartment. It was located on the inside surface of the right rear vehicle wall opposite the aluminum or steel fuel cell, which was located against the left rear vehicle wall.

Many land mines were encountered in SEA. These mines so overwhelmed the armored vehicles used—the ACAV, other M113-based vehicles, the MBT M48A3, and the AR/AAV M551—that these vehicles were modified to improve their countermine resistance. First, sandbags or other items were placed on the lower deck. Later, some of the M113-based vehicles had an additional layer of titanium armor bolted on the forward half of their bellies. Crewmen often rode on top rather than within the vehicle. Finally, in some M113-based vehicles extensions were added to the driving controls to allow the driver to sit on top of the vehicle.

Combat vehicles in SEA were often attacked with shaped-charge weapons while the crewmen were exposed on top. This crew exposure skewed the combat injury data toward more wounds from bullets or fragments than wounds from behind armor effects, such as from the shaped-charge jet, from spall, or from blast, which are expected for combat vehicle crewmen.

The three main combustibles for battle-induced fires are the mobility fuel, the munitions (particularly the solid propellant), and the hydraulic fluid. Other combustibles burn, but not as rapidly, and do not liberate as much heat energy. A hit with either a shaped-charge jet or a high-velocity kinetic energy penetrator both disperses the fuel or the gun propellant and ignites it. Hydraulic fluid is usually at a high pressure and sprays when a hydraulic line or a hydraulic fluid container is punctured. Further, the jet or penetrator creates many ignition sources.

4-1.2.3 Hits: Number and Locations

Vehicles are often hit more than once in a single engagement. Gunners usually continue to fire on a target until they see visible evidence that they have killed the target, particularly when that target has the capability to attack the gunner. The following quotations, based upon World War II experience, are taken from War Department Pamphlet 20-17, *Lessons Learned and Expedients Used in Combat* (Ref. 9):

> "*466. Disabled Tanks.* Crews should stay with immobilized tanks, manning their guns as long as possible. However, if the situation changes, the crew must be notified and they must be resupplied with ammuni-

TABLE 4-2. FIRE AND NONFIRE INCIDENTS (Ref. 4)

(A) INCIDENTS RESULTING IN FIRE OR EXPLOSION

DAN	VEHICLE	INITIAL COMBUSTIBLES	FIRE LOCATION	FIRE SUPPRESSION SYSTEM: FFES USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: PORTABLE EXTINGUISHER USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: OTHER USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: REASON	CREW EVACUATION: TIME AVAILABLE	CREW EVACUATION: NUMBER EVACUATED	REMARKS
157	M48A3	Main gun propellant	CC	N	N		No time	N	2	Blown out by explosion
169	M48A3	Oil in filter	EC	N	N	SE	Fire not detected		0	
1839	M48A3	Unknown	CC	N	N			Y	3	Propellant explosion 10-15 min after fire
153	M48A3	CS grenade	Turret	N	N			Y	3	Crew killed or wounded by small arms fire
310	M551	Propellant	Turret	N	N		No time	Y	4	Flash fire of one round
463	M551	Wire insulation	Turret	Y-N	N			Y	3	Sustained fire of wiring insulation in turret; vehicle abandoned for fear of explosion of on-board ammunition
632	M551	Wire insulation	EC	N	N	Burned out	Fire not detected		0	In battery box
670	M551	Wire insulation	CC	(Prob. No)	Y-Y			Y	2	
1532	M551	Fuel	EC	Y-?	Y-Y			Y	4	
1550	M551	Propellant	CC	N	N		No time	N	0	4 killed by propellant explosion
228	M113A1	Fuel	EC, CC	N	Y-N		Under fire by enemy	Y	4	
381	M113A1	Fuel	CC	N	Y-N			Y	5	

Notes: CC = crew compartment; EC = engine compartment; FFES = fixed fire extinguisher system; CS = a tear gas; Y = yes; N = no; SE = self-extinguished; RPG = rocket-propelled grenade

(cont'd on next page)

TABLE 4-2. (cont'd)

(A) INCIDENTS RESULTING IN FIRE OR EXPLOSION

DAN	VEHICLE	INITIAL COMBUSTIBLES	FIRE LOCATION	FIRE SUPPRESSION SYSTEM: FFES USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: PORTABLE EXTINGUISHER USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: OTHER USED-EFFECTIVE	FIRE SUPPRESSION SYSTEM: REASON	CREW EVACUATION: TIME AVAILABLE	CREW EVACUATION: NUMBER EVACUATED	REMARKS
383	M113A1	Fuel	CC	N	N			Y	4	
385	M113A1	Fuel	CC	N	?			Y	4	
432	M113A1	Grease	Driver compartment	N	N	Wool blanket-Y		Y	4	
607	M113A1	Diesel-soaked waste	CC	—	Y-Y			Y	0	
671	M113A1	Wire insulation	Driver compartment	—	Y-Y			Y	0	
672	M113A1	Fuel	CC	N	N		No time	Y	2	
728	M113A1	Small arms ammunition	CC		Y-Y			Y	0	
756	M113A1	Fuel	CC	N	N	SE		Y	3	Hit at fuel level
1666	M113A1	Paper	CC		N	Water-Y		Y	0	
1668	M113A1	Clothing	CC		N	Water-Y		Y	0	
1682	M113A1	Cans of oil	CC		N	SE		Y	3	
117	M106	Wire insulation	Battery box	—	N	Burned out	Fire not detected			A second RPG-7 penetrated through an ammunition storage box but did not cause an explosion or fire
301	M125	Two white phosphorus warheads	CC	—	Y-N			N	1	Other ammunition did not explode
1709	M548	Fuel, ammunition	Cargo hold	—	Y-N	Dirt-Y				107-mm rocket hit vehicle in cargo hold

(cont'd on next page)

TABLE 4-2. (cont'd)

(B) HIGHLY COMBUSTIBLE ITEMS HIT BY JET WITHOUT A FIRE RESULTING

DAN	VEHICLE	ITEM HIT BY JET
30	M48A3	Gun recoil cylinder; no fire; hit probably in nitrogen portion of reservoir
36	M48A3	Jet deflected into a 90-mm round; round fired from gun soon afterward
213	M48A3	Fuel tank hit in ullage
312	M113A1	Fuel lines and hydraulic line in bilge while vehicle was moving
388	M113A1	Fuel and hydraulic lines cut in bilge while vehicle was parked
435	M113A1	Fuel cell in ullage
1696	M551	Smoke grenade launcher on side of turret; minor damage to turret skin after exiting grenade launcher

(C) FIRE EXTINGUISHER SYSTEM OR EXTINGUISHANT HIT BY JET

DAN	VEHICLE	ITEM HIT BY JET
336	M113A1	Fire extinguisher bottle; jet did not pass beyond fire extinguisher bottle
360	M113A1	Water-filled radiator in engine compartment; jet did not exit radiator
333	M551	Marmite can, then water can; did not exit water can

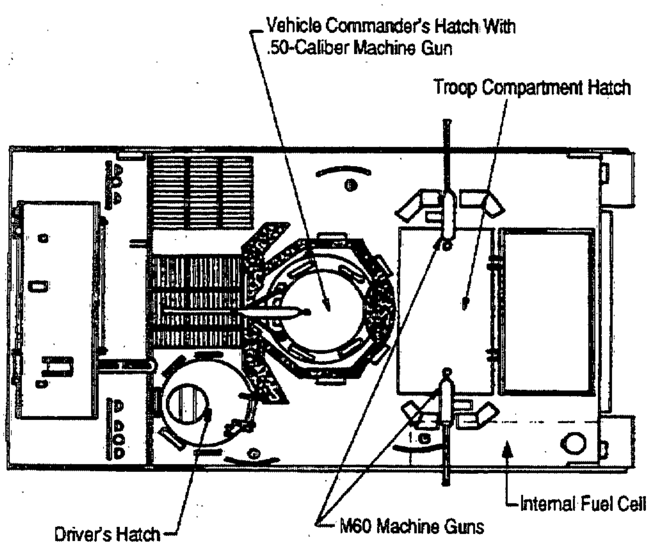
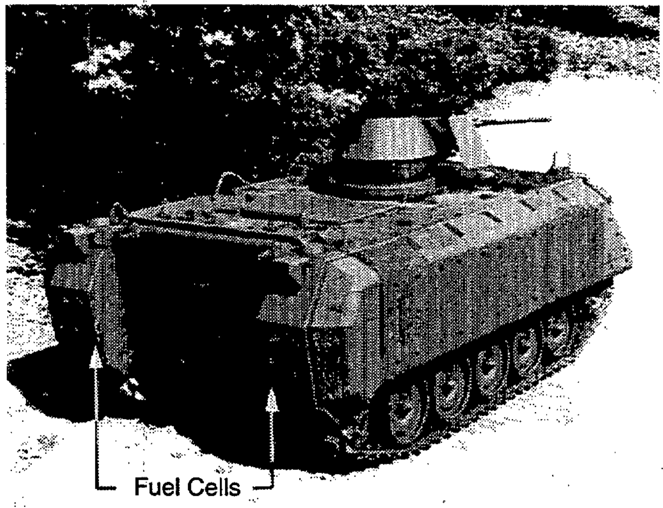


Figure 4-1. Armored Cavalry Assault Vehicle (ACAV) (Ref. 7)



Courtesy of FMC Corporation.

Figure 4-2. M113A3 Showing the Cupola for the .50 Caliber Machine Gun

tion. When contact is impossible, chances of retrieving the tank are gone; the crews should destroy their tanks and infiltrate back to our lines. [European Theater of Operations] (ETO)"

This excerpt shows that the U.S., as well as the Russians*, continued to man immobilized tanks as long as they were effective in engaging the enemy.

"*409. Gunnery.* In training tank crews, too much practice in acquiring speed in gun manipulation cannot be given. We make it [standard operating procedure] SOP to fire into all tall buildings, as they invariably contain snipers and machine gunners. We continue to fire at an enemy tank until it catches fire, to prevent its repair or use as a pillbox. (ETO)"

This excerpt indicates that we recognized that immobilized tanks were still dangerous and should be fired on until we know they are no longer dangerous. Therefore, we can assume that a disabled tank can be hit several times. Thus to be truly survivable, it must not catch fire on subsequent hits, and it should be able to move to cover or to a safe place. Multiple hits on vehicles were seen in SEA (Ref. 4).

Installing a manually activated flame and smoke emitter, a device used by naval ships in the past, on a combat vehicle would provide the crew a means to give the appearance of a vehicle having suffered catastrophic damage and might preclude the vehicle from receiving additional hits.

There has been much discussion on the most probable impact location of an antitank projectile on a combat vehicle. Most antitank gunners aim at the center of the presented

*A single immobilized Russian Klementi Voroshilov (KV)-2 heavy tank held up the advance of strong elements of the 6th Panzer Division on a road through a forest for 48 h on 23-24 June 1941 (Ref. 10).

area. Impact locations of RPGs on the APC M113 series, the MBT M48A3, and the AR/AAV M551 were obtained from the BDARP data. These hits were made in daylight or at night, with the gunners either attacking or defending, while the vehicles were moving or stationary, and with no apparent impact pattern for any set of conditions (Ref. 4). The 57 hits scored on the 46 M113 series APCs are plotted on Fig. 4-3. Most of these vehicles were ACAVs. The people firing at these vehicles were not aiming at defenseless targets; they were engaging fighting vehicles. Note that there are 17 hits on the front of the vehicle, 18 hits on the right side, 16 hits on the left side, and 6 hits on the rear. In all four profiles the hits are best described as scattered, and these hits were at a great variety of obliquities. Hits all over the target are readily understandable because the antitank gunner is not often given the opportunity for a pure side-on, head-on, or rear-on shot. Twenty-five hits were during night attacks. One RPG even detonated on an attacker, but the jet passed through him and hit the vehicle. Several shots were fired in heavily vegetated areas in which the lower portions of the vehicles were not visible to the firers. Ten shots were fired from ambush at vehicles in convoys or with reaction forces.

The 23 hits on the M48A3 MBT are shown on Fig. 4-4 together with the 16 hits on the M551 AR/AAV. The pat-

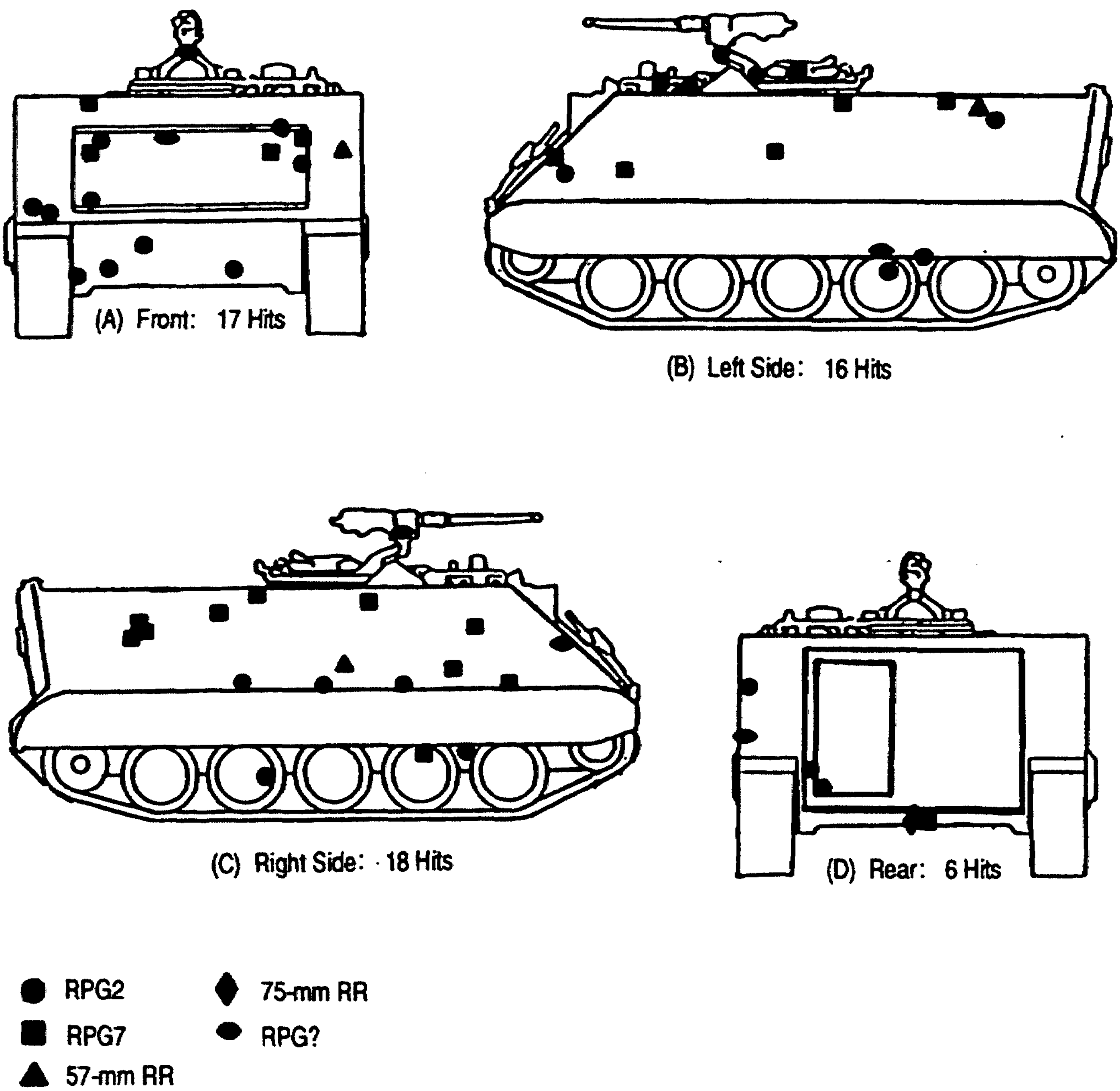


Figure 4-3. M113A1 APC Hit Pattern, Southeast Asia (Ref. 4)

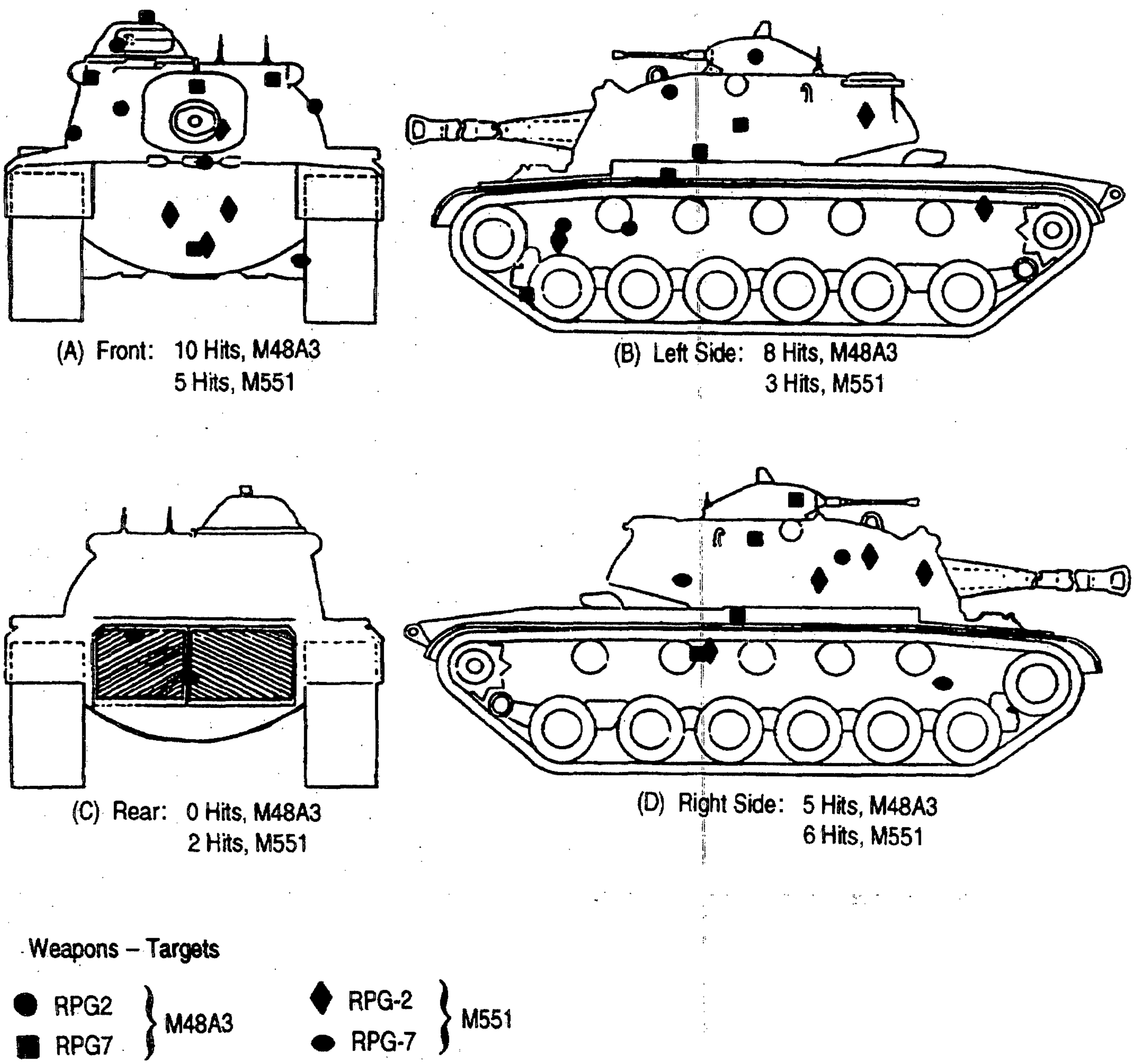


Figure 4-4. M48A3 MBT and M551 AR/AAV Hit Pattern, Southeast Asia (Ref. 4)

terns of these 39 hits are not essentially different from the hits on the M113A1 APC, and the conclusions are the same. The hits are likely to be anywhere on the presented area of the vehicle. The front and the right and left sides are almost equally apt to be hit, but the rear is less apt to be hit. These conclusions, however, should not be extrapolated beyond shoulder-fired, rocket-propelled antitank weapons.

4-2 ENGINE TYPES

Fire safety of military vehicles could be increased tremendously by simply removing the prime mover (engine) and its fuel system. The vehicle would then become a pillbox, a past use for some immobilized tanks. Today ground combat forces depend more on mobility for effective fighting than any ground force in history. Much of this increase in mobility comes from high-powered, compact engines. The first practical engines used in combat vehicles were the spark-ignition, or gasoline, type. Then compression-ignition, or diesel, engines were used. Lately turbine engines have been placed in the US M1 MBT and the Russian T80 MBT. The Russians have since returned to a diesel engine for the T80, and there is some talk of later versions of the M1 having a diesel engine, primarily to conserve fuel. This paragraph describes those engines that have been used, are being used, or will probably be used to power military ground vehicles in the near future.

There have been few major developments in military engines for ground vehicles in the past few decades, and "revolutionary" power plants are unlikely in the foreseeable future. The guidelines presented in this handbook will be appropriate for some time to come. All engines do much the same task, i.e., convert a combustible fuel to usable work. As long as the nature of this task remains the same, danger due to fires will exist.

The engine types included are compression ignition, spark ignition, and turbine. The characteristics of each type are described. Specific details of the fuel system are listed as well as potential areas for hot-surface ignition. Differences from commercial vehicle practices are explained.

4-2.1 COMPRESSION IGNITION

The compression-ignition (CI), or "diesel", engine is the primary power plant for current combat and tactical vehicles. This development is due to some very good reasons:

1. *Reduced Fire Hazard*. Due to its wide fuel tolerance, the diesel engine can burn fuels with a much higher flash point than a spark-ignition engine. This is the primary reason for using CI engines in military equipment and was the basis for "dieselization" of the ground vehicle fleet in 1959. In 1987, in order to reduce further the number of fuels provided in a combat zone, the Department of Defense (DoD) selected JP-8 to be the fuel for both aircraft and ground vehicles. JP-8 has a lower flash point, 38°C (100°F), than DF-2, 60°C (140°F). Therefore, it may be more readily ignitable given a spray or leakage resulting from perforation or rupture of fuel containers due to ballistic or accidental damage or wear-out of fuel lines or fittings.

2. *High Thermal Efficiency*. The CI engine enjoys good thermal efficiency for three reasons: lean combustion, high compression ratio, and low pumping work. Due to the nature of the CI engine, it can run with no lean misfire limit of the fuel and air mixture. Thus the combustion can occur with very lean mixtures. The leaner the combustion, the higher the thermal efficiency. Lean combustion is the primary reason that diesel engines are more fuel efficient than gasoline engines. The compression ratio can be much higher than it can for a spark-ignition engine. This also has a direct effect in raising engine thermal efficiency. The diesel engine does not have a throttle to restrict airflow into the engine, and this lack of pumping work reduces energy losses due to friction.

3. *Wide Fuel Tolerance*. Because the CI engine is not as explosion limited as the spark-ignition engine, the fuel requirements are somewhat relaxed. Fuels for CI engines have a cetane number requirement rather than an octane number (Ref. 11). The band of fuels that can possibly operate in diesel engines is wide. Although the most commonly used fuels in CI engines are distillates, or kerosene, under some limited circumstances this type of engine can burn fuels similar to naphtha or residual products. These depend on engine size, load cycle, starting requirements, and desired performance.

4. *High Reliability*. CI engines have a reputation for high reliability, and in most cases this reputation has been well earned. The CI-type engine eliminates the need for an ignition system—a factor that is a primary cause of spark-ignition engine degradation and poor operation. By eliminating this sensitive electrical system, overall engine reliability is improved and a major ignition source for fires is eliminated. There is another reason for high reliability in diesel engines. Because the combustion event is very severe, diesel engines must be very rigid in order to withstand the high combustion pressures. The rigid engine structure aids in engine durability and reliability by keeping cylinder bores and bearing surfaces concentric for reduced engine wear.

The heart of the CI engine is the fuel injection system. It must do three things very well and very quickly, i.e.,

1. Meter the proper amount of fuel into the chamber
2. Inject fuel at sufficient pressures to provide atomization and sufficient mixing of the fuel and the air
3. Initiate the combustion event by proper timing of the injection.

The equipment comprising the fuel injection system must have very close tolerances due to the high pressures involved. Consequently, the diesel fuel injection pump is normally the most costly component of a diesel engine. Because of these close tolerances, the fuel must have lubricity, and the fuel injection pump must be protected from dirt, water, or other contaminants that may be present in the fuel. Some of the Jet A-1 fuel used in Southwest Asia (SWA) in early 1991 is believed to have been lacking in lubricity. It was, but other factors were found to be the causes of degraded engine performance. "Quick fixes", such as adding a lubricant to the fuel, resulted in more severe problems (Ref. 12).

A typical diesel fuel injection system is supported by a fuel-water separator, a primary fuel filter, and a secondary fuel filter. The fuel-water separator acts as its name implies—it separates water from the fuel. These devices use centrifugal force and coalescing materials to provide good separation. A primary filter catches the largest contaminant particles. Many primary filters use a depth-type medium and filter down to 70 µm. The secondary fuel filter is in series with the primary filter and emplaced just before the injection pump. These filters normally use barrier-type media and filter to 10 µm.

The specific layout of these components varies from one make of engine to another and in many cases from one vehicle to another, but all components have a common function. They must provide clean fuel to the injection pump at adequate flows and pressures. This function normally requires additional pumps to push the fuel through the filter system.

Sometimes fuel heaters are included to aid in cold weather operation by preventing fuel waxing, and often a fuel-burning intake heater is used to aid cold starting.

There are several features that distinguish combat diesel engines from commercial diesel engines. Engines of combat vehicles must be protected from ballistic impacts. This protection leads to armoring and placing the engine in a rather small compartment and thereby reduces heat transfer to the atmosphere. This heat transfer provides the bulk of the cooling of commercial engines. Fans are used to increase the heat transfer to the forced-air coolant. Usually very high output is required from a small package for combat vehicles. To reach this output, most engines are modified for increased power output with sacrifice in engine life. Normally, this means the engine is operated at higher brake mean effective pressure (BMEP)—a term for thermal loading—and at higher piston speeds. Both factors have a detrimental effect on engine life, the extent of which is determined by individual engine designs. Since the combat diesel is operating under higher power than a commercial diesel, it will normally have higher component temperatures. A diesel engine for a commercial truck can be expected to last from 8000 to 12,000 h, whereas the specifications for future combat diesels are for 2000 h. This is a very strenuous requirement based upon the power output required.

Since the US Army has a mission to operate in all theaters of the world, the engines and their support systems are designed to operate under a wide variety of environmental conditions. These engines must start unaided at –32°C (–25°F) within five minutes and be able to operate with sufficient cooling at full power to 52°C (125°F). The dirty environment encountered in many locations places a great deal of emphasis on air filtration equipment.

The capability of US equipment to perform well under adverse conditions was amply demonstrated in Operation Desert Storm. Combat and tactical vehicles designed and prepared for use in Central Europe were shipped to Southwest Asia and without major modifications for acclimation were used in a major combat operation with no massive breakdown of vehicles. This major operation included a sweep through extremely hostile terrain by a highly mechanized force, and the following comment was made:

> "Throughout the theater, there appeared to be an above average amount of engine fires. The extended use of the vehicles, the heat and sand, all probably contributed to those fires." (Operations Officer, First Armored Division Artillery, Ref. 13)

The tremendous amount of dust undoubtedly contributed to engine overheating because this dust would coat the engine and reduce heat transfer to the surrounding air. Another officer from the same organization stated that because the dust almost clogged the radiators and filters, the crew were required to clean dust from these components every time the vehicles stopped (Ref. 14).

4-2.1.1 Fuel Feed

The components of the fuel feed system were previously mentioned. Briefly, (1) the fuel cell stores fuel, (2) the fuel transfer pump pushes fuel through the fuel-water separators and filters to an injection pump, (3) the injection pump times, measures, and delivers fuel under pressure to the cylinders through injection nozzles, which atomize and spray fuel into the cylinders, and (4) when an excess fuel flow is needed for heat transfer or other reasons, plumbing is provided by which the uninjected fuel is returned back to the fuel cell. In addition, there may be other fuel transfer pumps used to relocate fuel within or between fuel cells.

Obviously, at a junction of each of these components with the fuel feed lines, there is a potential for leaks. The following are reasons why this is an important concern in combat vehicles:

1. There is severe vibration in combat vehicles (particularly tracked vehicles) due to the operating environment and the drive train.
2. Because the components are enclosed in an armored hull, it is much more difficult to detect leaks, and the leaked fuel tends to collect within the vehicle rather than drain overboard.

These difficulties are true not only of the lines as they attach to each of these components but also with the removable components, particularly the fuel filters.

In a typical 560-kW (750-hp) diesel engine used to power some main battle tanks, the engine burns approximately 136 kg/h (300 lb/h), or 163 L/h (43 gal/h), of fuel. Some diesel fuel injection systems, however, require as much as 2.5 to 9 times as much fuel as the engine burns to be circulated through the pump for cooling—a factor largely dependent upon injector type and engine make. The problem occurs when the fuel used for cooling is returned to the fuel cell and heats up the fuel stored in the cell. In many instances, the bulk fuel in the storage cell can reach temperatures higher than the flash point of the fuel. At the flash point the fuel vapors form combustible mixtures that can be ignited by an external source, such as ballistic impact or an electrical spark. When the fuel cell, e.g., the cell of the APC M113A3, is exposed to hostile observation, the heated fuel cell can be much more readily detected by hostile observers' infrared sensors than a heated fuel cell buried within the vehicle. Some of these infrared sensors, however, are sensitive enough to detect a vehicle with buried heated components. For this reason, consideration has been given to using a cooler in the return line to reduce the temperature of stored fuel. This procedure, incidentally, would be counter to the desires of diesel engine designers because some diesel engines perform better when the fuel is injected at a temperature of 54°C (130°F); therefore, diesel engineers welcome warm diesel fuel.

The nominal pressure through the fuel filters is approximately 345 to 689 kPa (50 to 100 psi). This again is dependent on engine design and vehicle configuration, but it does offer possibility of leakage. The high-pressure injection lines, as found in some engines, carry fuel at approximately 103 MPa (15,000 psi). The fuel return, or leak-back, lines then operate anywhere from 0 to 276 kPa (0 to 40 psi).

Three fuel injector types used in US combat vehicles follow:

1. Jerk pump, or pump-line-nozzle, system
2. Unit injector system
3. Common rail system.

The jerk pump, or pump-line-nozzle, system is used on a variety of both combat and tactical vehicles. In combat vehicles the primary example is the AVDS-1790 engine used in the M60 series and in the diesel-powered M48A3 and A5 main battle tanks. In the jerk pump there is a plunger that pumps fuel through individual high-pressure lines to a fuel injection nozzle at each cylinder. This system has the disadvantage of more areas for potential fuel leakage due to the multitude of high-pressure injection lines. An advantage, though, is that sometimes engine control is better due to the governing and advance features built into this type of fuel injection pump. This system has the even greater advantage of having no need to cool the injector head. Therefore, a much smaller quantity of slightly heated diesel fuel is returned to fuel cells, and overall vehicle fire survivability is greatly enhanced.

The unit injector has the advantage of incorporating several components of the pump-line-nozzle system into one unit. In this case, there is an individual metering pump that is part of the injector itself for each cylinder located in the cylinder head. This compact arrangement eliminates the need for high-pressure injection lines and therefore eliminates areas for potential leakage. This type of system is used on the 8V-71T Detroit Diesel engines found in the M109 and M110 self-propelled howitzers and the 6V-53 engines used in the M113 family of vehicles and the light-armored vehicle (LAV) 25. This type of engine is also used in many tactical support vehicles. One disadvantage of the unit injector is the high flow rate of fuel required through the cylinder head. This results in increased heat rejection to the fuel and thus increased fuel cell heating.

Common rail systems use a constant-pressure feed line to supply individual injectors at each cylinder with a constant flow rate. There is a timing device (in most cases, a rocker arm and plunger) at each cylinder to increase the pressure of the fuel and time its injection into the combustion chamber. The components are machined to close clearances; hence they are less tolerant to uneven heating and require more cooling than the jerk pump system. The VTA-903 Cummins engine used in the M2/M3 Bradley Fighting Vehicle System uses this type of common rail injector system. This system incorporates many of the advantages and disadvantages of the unit injection system. It eliminates the high-pressure feed lines yet has high heat rejection to the return fuel.

A test was conducted using the APC M113A3, which uses the 6V-53T engine, to establish how high the temperature in the fuel return system could become (Ref. 15). This test, conducted with a lightly loaded vehicle on a flat track and on a cool day, showed that the return fuel temperature can reach the flash point of DF-2 and can exceed the flash point of JP-8 at least somewhere within the fuel system.

4-2.1.2 Hot-Surface Ignition

The potential for hot-surface ignition of leaking fuel is very high in combat vehicles. Since the engines run at very high load, many of the components operate at higher temperatures than their commercial counterparts. Heat that commercial vehicles would lose to the environment is trapped in combat vehicles and increases the need for cooling air and the power required to supply that air. The confining armor and the close packing of components within the combat vehicle limit air movement through the vehicle to cool these components. To minimize the weight of the encompassing armor, space in combat vehicles is also minimized. A major requirement in combat vehicle design is to reduce overall vehicle volume; thus the compartments of the engine propulsion system are very compact. The air requirements for these combat vehicles are extremely high, e.g., the MBT M60 uses more than 706 std m^3/min (20,000 scf/min) at high rpm. Because any air that enters the compartment must be forced through ballistic grills, the power required to move air through the engine compartment is increased over that required for commercial vehicles.

Two major areas for hot-surface ignition are the turbocharger casing and the exhaust manifold. Exhaust gases of combat diesel engines reach temperatures as high as approximately 649°C (1200°F). A fuel leak onto surfaces at this temperature can easily result in a fire. However, this fire need not be started by fuel alone. Engine lubricating oil in combat vehicles runs as hot as 121° to 132°C (250° to 270°F), and transmission oil reaches a high temperature of 149°C (300°F). This oil moves through coolers, which are sometimes integral to the engine. At each of these coolers are junctions that are potential leakage paths. A vehicle fire can start by ignition of oil and then spread to the fuel tank area. In some vehicles hydraulic fluid lines are located in the engine area. These lines provide another source of combustible fluids.

A significant consideration in the design and material selection of engine compartment components is that the highest temperatures are experienced after the engine has been shut off by the master switch. This effect results from the sudden cessation of forced air cooling. If the master switch simultaneously disengages the automatic fire-extinguishing system, a fire resulting from poor design or material selection could produce severe damage. For proper fire survivability the fire suppression system should remain engaged at least until the engine has cooled off and preferably should be in an alert standby condition at all times.

4-2.2 SPARK IGNITION

Although the spark-ignition (SI), or "gasoline", engine has the advantages of increased power-to-weight ratio and power-to-volume ratio over the diesel, it has one key feature that prompted its removal from combat vehicles. Its combustion system requires a volatile fuel for proper operation. This fact and the desire of the Army to reduce logistical burden by supplying a single fuel have prompted the US Army to eliminate gasoline-fueled vehicles from current and future combat, tactical, and support vehicle fleets. The engine is discussed here, though, for completeness, historical value, and the potential for use in specialized situations.

The four-stroke spark-ignition engine operates similarly to the four-stroke diesel engine. During the intake stroke, a mixture of fuel and air is drawn into the combustion chamber. This mixture is compressed to high pressures; at an appropriate time in the cycle, the fuel-air charge is ignited by a spark plug. The combustion of this fuel-air mixture causes hot gas to expand and pushes the piston downward on a power stroke. The combustion products are then exhausted from the combustion chamber.

There are limiting factors for this combustion system:

1. The fuel-air mixture must be held within a narrow range of flammability limits for adequate combustion.
2. The fuel must have specific properties (high octane number) to prevent self-ignition (knock) that can quickly destroy the engine.

4-2.2.1 Fuel Feed

The components of the fuel feed system in gasoline engines are much simpler than those in diesels. The extreme level of fuel cleanliness necessary because of the close tolerances in the diesel fuel injection pump are not required of gasoline engines. Although the magnitudes of fuel flow rates are only slightly higher than those in diesel engines, the pressures in fuel lines are in many cases two orders of magnitude less than those in diesel engines. The temperature of the fuel is generally near ambient condition because the fuel is usually not used to cool any engine components.

Carburetors or fuel injection systems are used to introduce the fuel into the combustion airstream. These devices have three functions, namely,

1. To meter the fuel accurately according to the airflow to maintain the fuel-air mixture within a narrow margin
2. To mix this fuel with the air and vaporize it
3. To control the quantity of fuel-air mixture entering the engine and thus control the load.

Carburetors are relatively simple and generally use a venturi principle to determine engine airflow. A float bowl, or diaphragm chamber, normally is used to store fuel prior to its introduction into the combustion chamber.

Fuel injection systems are generally much more sophisticated than carburetors. Fuel injection systems have the capability to measure the air into the cylinder, then meter the fuel into that cylinder by controlling the injection pressure, the time of valve opening, and the time of valve closing. This control can assure that the proper quantity of fuel is injected at the optimum time with the proper pressure to assure correct atomization. Fuel injection systems as used in combat vehicles should not be confused with current electronic fuel injection systems used for automobiles. The automobile systems have been developed primarily to meet emissions and fuel economy requirements and in some cases to improve performance. Their operation depends heavily on electronics and is much different from the mechanically based systems previously used on combat engines.

Of particular concern in gasoline engines is routing the fuel supply line. The fuel line must be routed away from hot components not only due to the possibility of fire but also to prevent "vapor lock", which occurs when fuel boils in the feed line and stops flow to the engine.

4-2.2.2 Hot-Surface Ignition

Hot-surface ignition is a greater problem with spark-ignition engines than with compression-ignition engines. The primary reason is high relative temperatures. Because the SI engine operates with a very narrow fuel-air ratio band and this band is near the stoichiometric condition, the exhaust gas temperature is higher. Exhaust gas temperatures of 816°C (1500°F) are easily reached. Thus exhaust system components, such as manifolds and in some cases turbocharger turbine casings, achieve much higher temperatures, and these temperatures offer greater potential for fire hazard. The autoignition temperature of gasoline, however, is higher than that of diesel or turbine fuel.

Another area to be considered in reducing hot surface areas is the engine structure itself. Many of the previously fielded military gasoline engines were air-cooled. Air-cooled engines generally have higher surface temperatures than water-cooled engines; thus the engine surface creates a potential hot source for fuel ignition and vaporization. A significant consideration in the design of and material selection for engine compartments is that the highest temperatures are experienced after the engine has been shut off. This effect results from the sudden cessation of forced air cooling.

4-2.3 TURBINE

With the fielding of the M1 Abrams MBT, the US Army took a significant departure from traditional combat vehicle power plants. The turbine engine used in this tank offers several advantages over the previously used diesel and SI engines. Although the final determination for the "best" tank power plant has not been made, the turbine engine shows several advantages, such as increased power-to-weight ratio, increased power-to-volume ratio, potential for quieter operation, less vibration, and decreased fuel sensitivity.

These advantages, however, are accompanied by some disadvantages. Fuel economy of turbine engines is generally poor, particularly under light loads and especially at idle. The engines generally operate poorly under variable speed and load conditions, which are required in ground vehicles. These engines are sensitive to the torsional vibrations of the drive train caused by high rotational speeds, although there are ways to overcome these. The turbine engine requires much greater quantities of air for combustion and internal cooling. Large quantities of clean air in a combat environment are difficult to obtain, and when contaminated with fuel or oil, the large air filters can become combustion chambers. Finally, the turbine combustion cans are hot spots without equal for igniting spilled fuel, lubricating oil, or hydraulic fluid.

Turbine engine operation is very simple. A compressor, sometimes multistage axial or centrifugal, compresses a constant flow of air. This air enters a combustion can or chamber into which fuel is injected. This continuous combustion process with hot, expanding exhaust products drives a series of turbines that power both the compressor and the output shaft.

There are some differences in turbines used in ground vehicles from the gas turbines typically used to power aircraft. One of the main differences is the incorporation of a recuperator or regenerator in the ground vehicle. This device is used to increase fuel economy by taking part of the waste heat in the exhaust and adding it to the air before combustion. This component is expensive, bulky, and operates at a high temperature, so it constitutes another hot surface area for possible ignition of spilled or sprayed combustible fluids.

One of the primary differences between the turbine and the piston engines is the nature of the combustion process. Combustion in both the CI and SI engines takes place within the cylinders of the engines, whereas combustion in the turbine engine takes place within a special chamber, the combustor can. Because combustion is continuous in the turbine engine, peak combustion temperatures must be held much lower than in piston engines. Since there is no cooling system, the temperatures are controlled by using excess air through the combustion process. In other words, the turbine engine operates at approximately a 50:1 air-to-fuel vapor mass ratio as compared to 25:1 for the diesel and 15:1 for the gasoline engine. Therefore, an increased volume of air is needed to maintain the same power as in other engines. For this increased quantity of air, large air cleaners are added in the M1 MBT. These air cleaners are in a compartment partially separated from the engine. Combustible fluids can collect, so the air cleaners are subject to fires. (See subpar. 4-2.3.2.) The air cleaner compartment is not protected by the fixed fire extinguisher system; hence a fire in the air cleaner compartment requires manual extinguishment.

There are also some differences in the way a turbine engine starts and stops. Failed cold starts represent a potential fire hazard when excess fuel collects within the combustor can and ignition does not start when intended. The potential problem of excess fuel in the combustor can is even more dangerous under a hot restart condition. Fuel puddling within the turbine compartment is vaporized by hot surface components and can ignite quickly. Ignition of fuel vapors within the engine compartment also occurs during flameouts, because if the engine is operated through a transient situation and the combustion rate does not keep up with the airflow rate, a flameout causes excess fuel to be trapped within the engine.

4-2.3.1 Fuel Feed

The components of the turbine fuel system are very similar to those of a diesel. The necessary components include feed pumps, fuel/water separators, fuel filters, and an injection system. Thus the areas of potential leakage are essentially the same as in a diesel engine. The primary differences in the fuel system are the constant flow process required versus the intermittent injection in the diesel engine and the fact that injection pressures are normally an order of magnitude lower than for diesels.

Another difference in the fuel feed system for the turbine engine is that the combustor can is so hot during normal operation that it can bake the rubber fuel hose into a ceramic-like state so that the hose can fracture from normal shock and/or vibration. This provides a leakage path for the fuel to spray on the combustor can. The fuel ignites upon contact with the combustor can, as is described in subpar. 4-2.3.2.

Some typical flow rates follow. A gas turbine engine of 1120 kW (1500 hp) flows approximately 306 kg/h (675 lb/h) of fuel. With most turbine engines there is no fuel return. Pressures in the fuel line are on the order of megapascals.

Some turbine engines have other uses for pressurized fuel. The AGT-1500 gas turbine engine in the M1 MBT uses fuel pressure to control inlet guide vanes and power turbine stators. These movable devices in the engine airflow tract help the engine run efficiently over a wider speed/load range; however, they also require more fittings and seals and thus offer more areas of potential leakage.

There are significant differences in the combat vehicle gas turbine operating in a ground vehicle environment from the gas turbine in aircraft practice. Engine vibration is much more severe in the ground environment. It is due not only to torsional vibrations on the drive train but also to vehicular vibrations caused by a tracked vehicle operating in an off-road environment. These vibrations must be considered not only from engine design and structural standpoints but also with regard to the possibility of vibrating loose fuel fittings, filters, or other components around which a leak could occur. Not only is there more potential for leakage, but also maintenance is much more difficult. The combat vehicles must be maintained "in the field", in mud, snow, dust, and other poor conditions. The engine is enclosed in an armored compartment, so parts are difficult to access for inspection and maintenance. The potential for undetected fuel leaks increases as the components are covered with dirt and reside in difficult-to-access places.

4-2.3.2 Hot-Surface Ignition

Potential areas for hot-surface ignition on gas turbine engines include the combustor can, recuperator, and the exhaust ducting system. Although temperatures of the components, other than the combustor can, are slightly less than those of a diesel, the size of these components makes shielding difficult. For example, a 559-kW (750-hp) diesel exhaust system produces approximately 4220 kg/h (9300 lb/h) of hot exhaust products. By comparison, the 1120-kW (1500-hp) gas turbine engine produces 15,615 kg/h (34,425 lb/h) of exhaust products. The size of the duct must be larger for a turbine engine; thus routing it away from fuel system components is more difficult. Since the amount of ducting is high and recuperator size is large, the stored energy in these components adds to engine heating after shutdown and provides hot surface areas for fuel ignition, as is described in subpar. 4-2.1.2. In the M1 series MBT the heat from the combustor can is so intense that it has ignited or melted the rubberized-fabric-covered, steel-braid-protected, polyethylene fuel line when the line was mounted improperly. The rubberized fabric ignited and the fuel line ignited or melted and allowed the diesel fuel to spray onto the combustor can. This fuel promptly ignited and resulted in an engine compartment fire. This fire also spread in the air cleaner compartment. The tank crew extinguished the air cleaner compartment fire by pouring water from a 19-L (5-gal) can through the grill to the air cleaner (Ref. 16).

4-3 FUEL SYSTEM

Most fires, even of mobility fuels, can be precluded. Flammable fluids, in fact, almost all combustible materials, burn only in the gaseous state and then only within a rather narrow range of fuel vapor to air mixture ratios. A fuel vapor to air mixture ratio can be too fuel rich or too fuel lean to burn. A designer should not depend upon keeping a mixture ratio too fuel rich because as that mixture spreads away from the fuel source, more air is available; this additional air assures that somewhere the mixture will be combustible. Once a fire starts, the heat increases convection; thus the mixture becomes more combustible. The more volatile the fuel, the more probable the presence of a combustible vapor mixture somewhere in a vehicle. This is the reason gasoline is more hazardous than diesel fuel. When diesel fuel is heated, however, it can become almost as volatile as gasoline. Therefore, it is not safe to use diesel fuel as an injector coolant unless the fuel is injected into the engine and burned directly after it is heated. Recirculating heated diesel fuel to a fuel cell is a poor practice from a survivability point of view.

The fuel system consists of one or more fuel cells, a transfer subsystem, and the fuel lines, which connect the fuel cells to the engine. The vulnerability of the fuel system of armored vehicles has been documented for both World War II and more recent conflicts. "The petrol [gasoline] carried on the [BroneTRansporter] BTR-60 makes it liable to 'brew up' [burn] if hit. This has earned it the nickname 'wheeled coffin' (kolesniy grab) in Afghanistan. White phosphorus shells can ignite fuel, especially in external tanks." (Ref. 17). The BTR-60, Fig. 4-5, has two 145-L (38.3-gal) fuel cells located on the floor of the troop compartment, one on each side of the vehicle in the rear. The general design of the fuel system is shown on Fig. 4-6. This wheeled vehicle often caught fire when it initiated a land mine in Afghanistan.

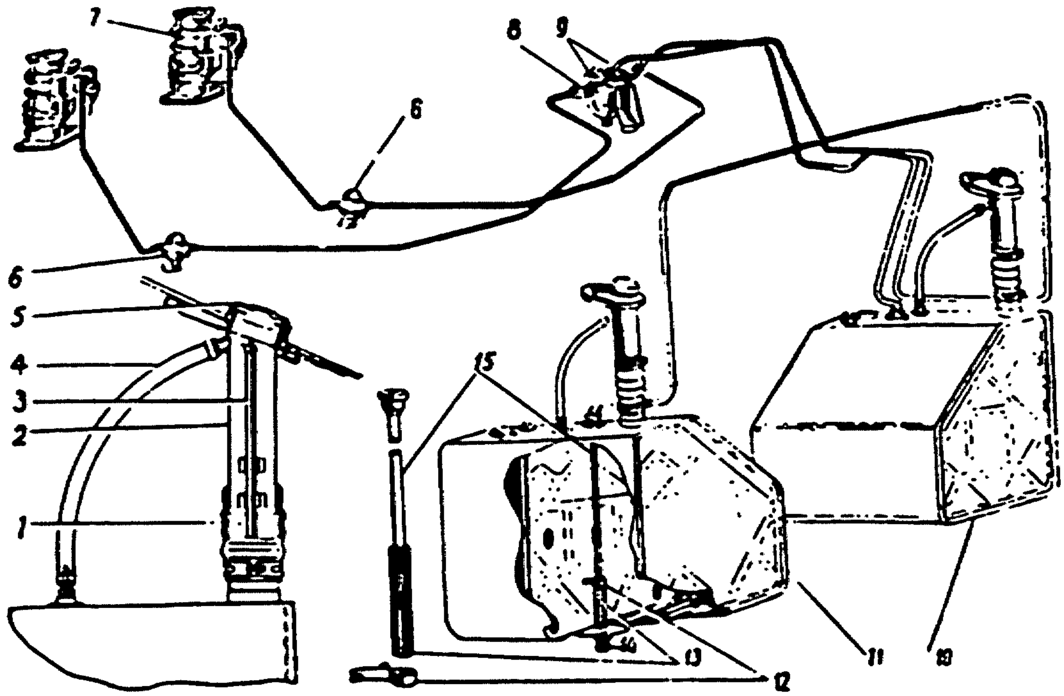
A similar vulnerability to fire was shown by Russian tracked APCs. The Bronevaya Maschina Pickhota (BMP) series of vehicles is tracked and diesel powered. These BMPs have a total fuel capacity of 460 L (121.5 gal), 55 or 70 L (14 or 18 gal) of which is carried in each of two integral fuel cells, which are in the rear doors of the crew compartment, as shown in Fig. 4-7. The remaining fuel is carried in a fuel cell located between the seats in the passenger compartment, as in Fig. 4-8. This vehicle is equipped with the fire extinguisher system described in subpar. 7-5.1.3.4.2. In the Middle East and Afghanistan these BMPs were reported to have a propensity to burn or explode when hit, particularly by HEAT warheads, due to the dense packing of ammunition and to the fuel-filled rear doors (Ref. 17) and internal fuel cells, which form the benches on which the passengers sit.

4-3.1 FUEL STORAGE

All combat vehicles use hydrocarbon fuel. This fuel, i.e., gasoline, diesel, or turbine fuel, is liquid and is stored in a cell*. These fuel cells have been made of steel, aluminum,

Figure 4-5. Rear View of BTR-60

*In this handbook the fuel container of a vehicle is referred to as a "cell"; the term "tank" is reserved for a heavily armed and armored combat vehicle.



1	Crimped Hose	9	Stopcock
2	Fill Pipe	10	Gasoline Fuel Cell
3	Gasoline Level Index Rod (dipstick)	11	Gasoline Fuel Cell
4	Air Vent	12	Filter Holder (clamp)
5	Fill Cap	13	Filter
6	Gasoline Pump	14	Drain Plug
7	Carburetor	15	Gasoline (Fuel) Line
8	Gasoline Sediment Pump		

Figure 4-6. BTR-60 Fuel System Schematic

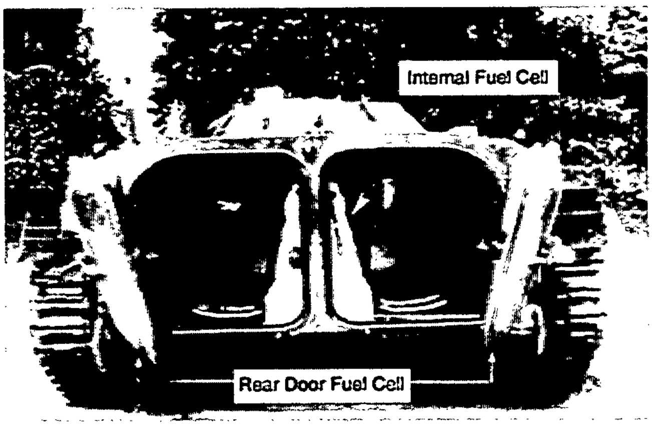
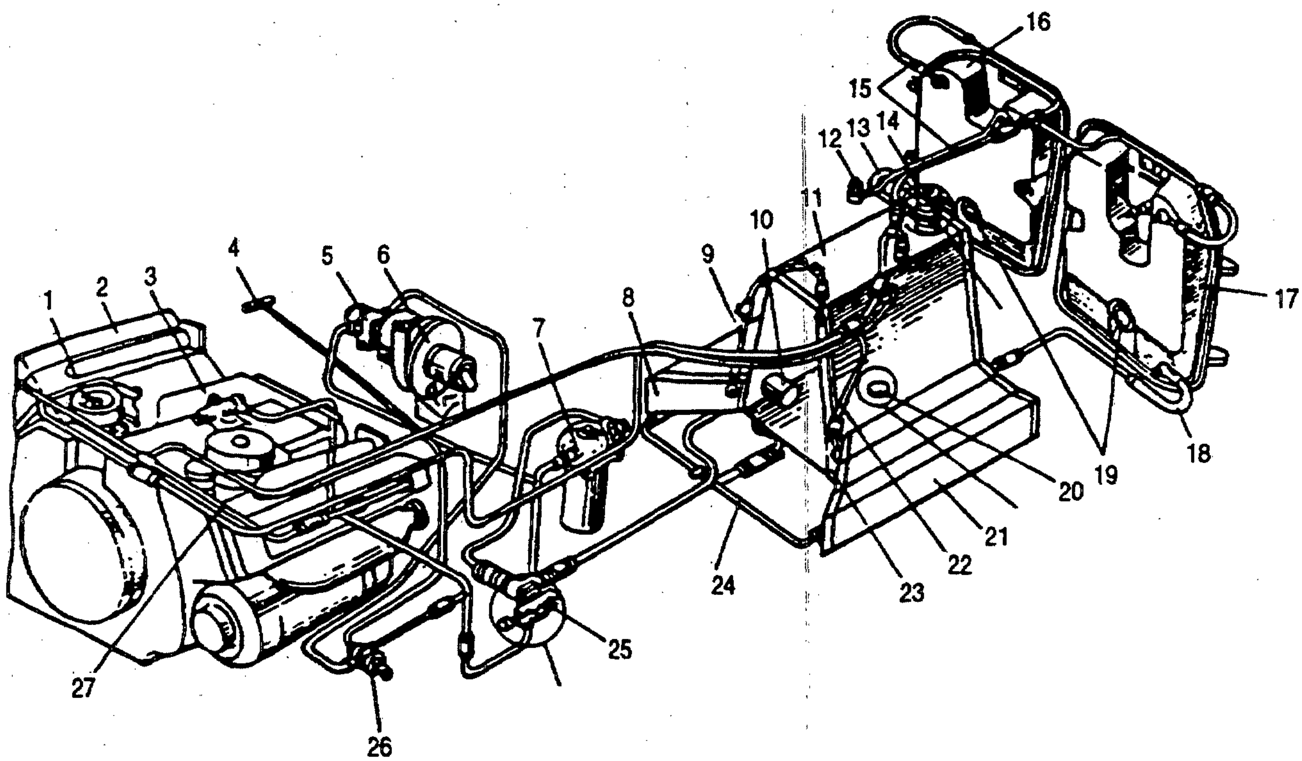


Figure 4-7. Rear View of BMP-2

fiberglass, rubberized fabric, or plastic. A combat vehicle may contain one or more fuel cells located anywhere within or on the vehicle. These fuel cells are usually vented but may be pressurized. The primary fuel cells are fixed within or to the vehicle, but the Russians have used supplementary jettisonable fuel drums, primarily to extend the range of the vehicles for movement to the battle area.

4-3.1.1 Current US Fuel Cell Design

All current US combat vehicles use a kerosene-type diesel fuel or jet propellant. The M1 series MBTs have six internal fuel cells made of high-density polyethylene—two forward (one on each side of the driver) and four to the rear. There are an upper and lower rear fuel cell on each side of the engine. The two forward and two upper rear sponson cells are compartmented, whereas the two lower rear cells are in the engine compartment. The M113A2 APC and the AAV7A1 have one welded, light-gage aluminum fuel cell high on the left rear side of the troop compartment. The M113A3 APC has two heavy aluminum external fuel cells—one at each side in the rear, above and behind the tracks, as shown on Fig. 4-2. The M60 MBT has two welded, light-gage aluminum fuel cells within the engine compartment. The M2 infantry and M3 cavalry fighting vehicles have two internal fuel cells made of rotary-molded nylon 6. The upper cell is centered high on the right side, and the lower cell is on the hull floor in the center of the vehicle. Both cells are in the troop compartment. Carbon steel fuel cells were used from World War I (US heavy tank



1.	Fine Fuel Filter	15	Drain Pipes
2	Engine	16	Right Door Fuel Tank
3	Engine Fuel Feed Pump	17	Left Door Fuel Tank
4	Injector	18	Pipeline
5	Preheater Fuel Pump	19	Fuel Tank Access Hole Cover
6	Preheater Pump Unit	20	Plug
7	Coarse Fuel Filter	21	Left-Hand Bench Fuel Tank
8	Right-Hand Bench Fuel Tank	22	Drain Pipe
9	Drain Pipe	23	Fuel Level Indicator
10	Fuel Feed Pump	24	Pipe
11	Fuel Tank	25	Fuel Valve
12	Drain Valve	26	Preheater Fuel Valve
13	Pipeline	27	Injector Fuel Return Pipes
14	Fuel Filler Neck		

Figure 4-8. BMP-2 Fuel System

Mark VIII) until the US Army switched from gasoline-fueled to diesel-fueled engines about 1959. The Landing Vehicle, Tracked, Personnel (LVTP)5 is an example of a vehicle using rubberized-fabric fuel cells (Ref. 18). US Army helicopters and counterinsurgency (COIN) aircraft use crashworthy, self-sealing fuel cells, per MIL-T-27422 (Ref. 19), which were originally developed for racing cars. Self-sealing fuel cells are often considered for use in US combat vehicles but are not adopted because of their ineffectiveness against antitank projectiles.

4-3.1.2 Fuel Cell Design Criteria

For maximum performance and safety the fuel cell should be considered an integral part of the vehicle rather than an add-on component; hence fuel cell requirements should be considered during vehicle design. The integrity of the fuel cell is a major concern with respect to fire safety and survivability. Fuel cells should be designed to withstand the pressure surges and impingement forces associated with rapid refueling—up to 38 L/s (600 gpm)—and to withstand an internal overpressurization of 14 kPa gage (2 psig) without permanent deformation. It is advisable for fuel cells to be able to withstand the explosion of ullage vapors. This feature is currently a requirement for external aircraft fuel cells, particularly the composite, filament-wound ones. Fuel cells should be provided with baffles to reduce fuel sloshing and aeration, and the LVTP5 and the M110 SPH both have reticulated foam in their fuel cells to do this. Both of these vehicles use the early Type I, reticulated, 10-pores-per-inch (ppi) orange foam. The latest versions of this foam—MIL-B-83054 (Ref. 20), Type VI, 10-ppi, dark beige, and Type VII, 25-ppi, light beige—have a much longer life, which is estimated at 20 years, and are conductive, which prevents buildup of a static electric charge during high-speed refueling.

A plastic lining on the interior walls of the fuel cell may be used to reduce seam leakage and fire hazard in the event of a rupture. Bottom fittings and valves should be installed in a flange or spud designed to accommodate them, should not extend more than 19 mm (0.75 in.) below the lowest part of the fuel cell or sump, and should be protected against damage. The fuel cell should be clean and not prone to rust or corrosion. Coatings, if used, should cover the interior surface of the entire fuel cell, should not deteriorate in the fuel, and should not degrade or contaminate the fuel in any way.

Joints of a metal fuel cell body should be closed by arc-, gas-, seam-, or spot-welding, by brazing, by silver soldering, or by techniques that may provide heat resistance and mechanical securement at least equal to those specifically named. Joints should not be closed solely by crimping or by soldering with a lead-based or other soft solder.

Each fuel cell should be equipped with a nonspill operational vent that adequately permits the passage of air and other gases during operation and that is protected against the entry of dirt, water, and other debris. The vent should be adequate to vent gases and air without creating back pressure. Each fuel cell should also have a safety venting system, which in the event the cell is subjected to fire, will prevent internal cell pressure from rupturing the body of the cell or body openings (if any). The safety venting system should activate before the internal pressure in the cell exceeds 345 kPa gage (50 psig) or 50% of the rated burst pressure, and thereafter the internal pressure should not exceed the pressure at which the system is activated by more than 34.5 kPa gage (5 psig), despite any further increase in the temperature of the fuel. Any venting of liquid fuel should be overboard and, if possible, not underneath the vehicle.

The cell and other fuel system components must be designed to operate throughout the range of vehicle attitudes. The design and construction must assure that the cell cannot be filled in a normal filling operation with a quantity of fuel that exceeds 95% of the liquid capacity of the cell and that, when filled, normal expansion of the fuel will not cause fuel spillage or interfere with cell venting.

Metal cells and metal fittings of nonmetal cells should be grounded to the vehicle main frame or chassis by electrical conductors to prevent buildup of static charges.

4-3.1.3 Fuel Cell Location

Much time and effort has been expended to locate fuel cells where they are less likely to be hit. In selecting the location for the fuel cell(s), the following should be kept in mind:

1. An antitank gunner will normally aim at the center of the presented area of the target vehicle, but that target vehicle may be at any attitude or partially obscured by dust, fog, or underbrush and probably will be visible for only a very short time. Usually the gunner will have little choice of where the munition will hit the target. This fact has been borne out by the impact patterns on M48A3 MBTs, M551 AR/AAVs, and M113A1 APCs, Figs. 4-3 and 4-4, from the SEA BDARP data and is also discussed in subpar. 4-6.2.1. The only difference for terminally guided missiles is that they are directed toward the strongest signature on which the seeker guides, such as the source of infrared (IR) radiation for a heat-seeking missile.

2. Antivehicular mines can penetrate the bottoms of armored vehicles, as was shown in other SEA BDARP data and in tests of the LVTP5 (Ref. 18). Tilt rod fuzed mines, such as the Russian TKM-2 or AKS, the Hungarian UKA-63, or the Czech and Slovak plate charge mines with a side-mounted tilt rod, are directed at the bottom of the hull (Ref. 21). Therefore, no place in an armored combat vehicle is truly "safe" for locating fuel cells.

A better approach is to locate or design the fuel cell so that when it is perforated, fuel is not sprayed or dumped within the vehicle. Any spilled fuel is directed overboard or into a relatively safe sump such as a closed bilge (Ref. 22) so that ignition within the vehicle of this spilled or sprayed fuel is improbable. Examples of such designs are given in subpars. 4-8.1.3 and 4-8.3.1.

4-3.1.4 Hydraulic Ram Loads

When a fuel cell is pierced by a shaped-charge jet or high-velocity KE penetrator, extremely high hydraulic ram pressures are generated. In a series of tests described in Ref. 22, the hydraulic ram pressures were measured. These pressures provide an indication of the magnitudes that can be expected. In one case, a jet from a US Army Ballistic Research Laboratory (BRL) 81-mm, precision shaped charge generated a peak hydraulic ram pressure of approximately 49.1 MPa (7126 psi) in a plastic fuel cell when the slug from the shaped charge was stopped in the simulated vehicular armor. In a second case, the same type of shaped charge generated a peak pressure of approximately 64.9 MPa (9408 psi) when the shaped-charge slug passed through the armor into the plastic fuel cell. Impulsive pressure loads like these can rupture many fuel cells. Similar tests with the warhead from an 89-mm (3.5-in.) M28A2 rocket resulted in damage to a welded 6.4-mm (0.25-in.) thick Al 6061 fuel cell shown on Figs. 4-9 and 4-10. These figures show that the weldments were the principal failures of the aluminum Advanced Survivability Test Bed (ASTB) engine compartment fuel cell. A weld expert examined these failures and stated that the welds lacked penetration

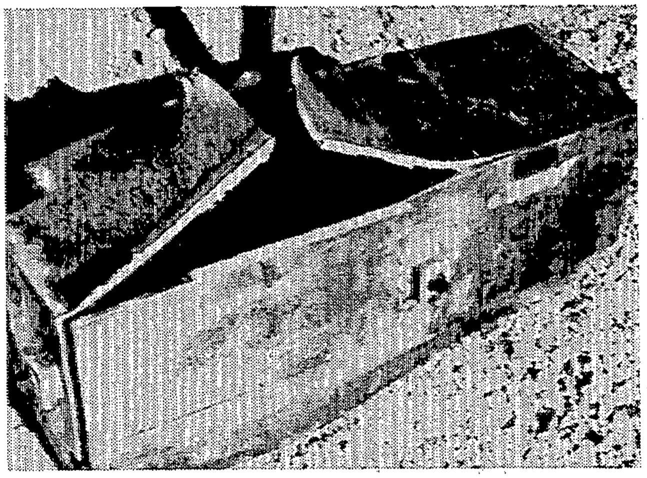


Figure 4-9. View of Aluminum ASTB Engine Compartment Fuel Cell Bottom and Rear Showing Weld Failures (Ref. 23)

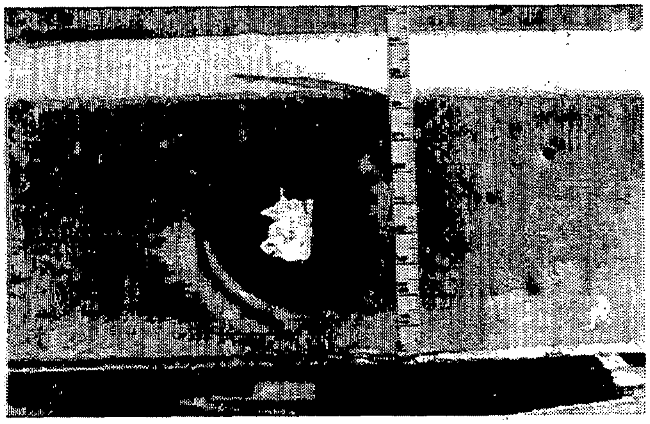


Figure 4-10. Front View of Aluminum ASTB Engine Compartment Fuel Cell Showing Weld Failure at Seam Between Front and Bottom Faces (Ref. 23)

into the base material of the faces. This illustrates that welds of metallic fuel cells must be complete and must have the maximum strength possible. There were large holes at both the entry and exit points, and the aluminum was not able to withstand the blast and hydraulic ram forces. A similar cell made of 12-gage (2.67-mm or 0.105-in. thick) corrosion-resistant steel (CRES) 304 sustained the damage shown in Fig. 4-11. Note that the welds held; damage was due only to the jet punctures.

4-3.1.5 Fuel Cell Survivability Enhancement

Where gross fuel cell ruptures occur without fire prevention devices, a conflagration normally ensues. Plastic fuel cells have also been known to rupture, as shown in Fig. 4-12. Crashworthy, self-sealing fuel cell constructions per

Figure 4-11. Stainless Steel Engine Compartment Fuel Cell After Penetration by a Shaped-Charge Jet From an M28A2 Warhead (Ref. 24)

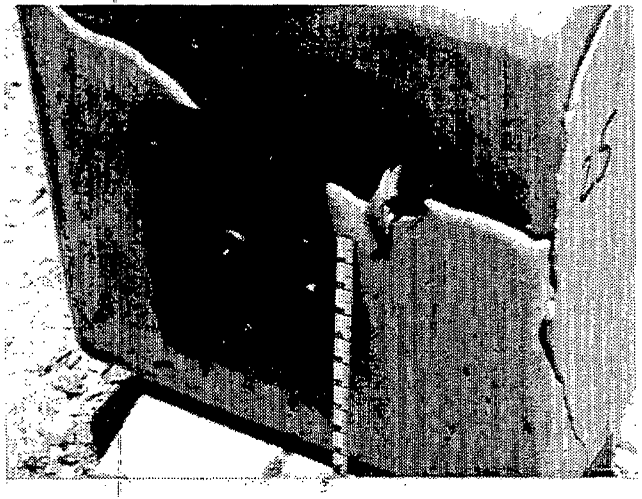
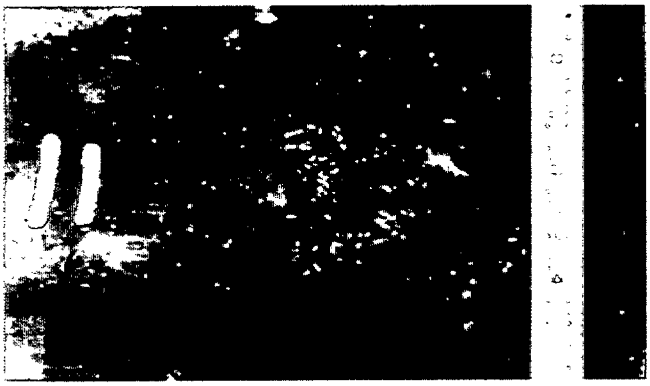


Figure 4-12. Ruptures in a Plastic (Nylon 6) Fuel Cell After Penetration by a Shaped-Charge Jet From an 81-mm BRL Precision Warhead (Ref. 22)

MIL-T-27422 (Ref. 19) are cored* by shaped-charge jets, illustrated in Fig. 4-13, and hence do not necessarily provide a seal. These observations indicate some of the problems encountered during selection of a fuel cell material and configuration. Some fuel cell designs that have sustained a shaped-charge jet perforation without a conflagration are described in Refs. 22 through 24. These designs include the use of a double wall, as shown in Fig. 4-14, and the confining of a cell to prevent gross rupture, as shown in Fig. 4-15.

*When a sharp-edged penetrator or a shaped-charge jet perforates a self-sealing construction, some of the material is removed, as a corer removes the core of an apple. This action mechanically removes material required for formation of a mechanical seal.



(A) Exit Hole

(B) Entry Hole

Figure 4-13. A Crashworthy Caliber .50 Fuel Cell Penetrated by a Jet From an 81-mm BRL Precision Shaped Charge (Ref. 22)

The value of this confinement was illustrated in two tests with actual vehicular fuel cells. In one test without the confinement, the fuel cell failed at the access port, illustrated in Fig. 4-16, and a catastrophic fire ensued; in another test with confinement, the fuel cell failed near the access port, illustrated in Fig. 4-17, but no sustained fire ensued, i.e., the fireball self-extinguished in 64 ms.

In a series of tests involving external fuel cells for armored combat vehicles, use of a barrier between the fuel cell and the vehicle provided the protection needed to prevent injection of the fuel into the vehicle. In tests in which the fuel cell was fastened directly to the external surface of the hull of the simulated vehicle, the fuel spewed into the vehicle through the hole perforated by the shaped-charge jet in the hull. This result occurred (1) when the jet passed through the fuel cell, the hull, and into the vehicle compartment and (2) when the jet passed through the hull, the vehicle compartment, the hull, and into the fuel cell. This spewing of fuel into the vehicle compartment did not occur when a spacer, or barrier, containing gravel was emplaced between the hull and the fuel cell. The shaped-charge jet still passed through the array of hull, vehicle compartment,

Figure 4-14. Exit Holes in Jacket and Fuel Cell Wall After Penetration by the Jet of an M28A2 Warhead (Ref. 24)

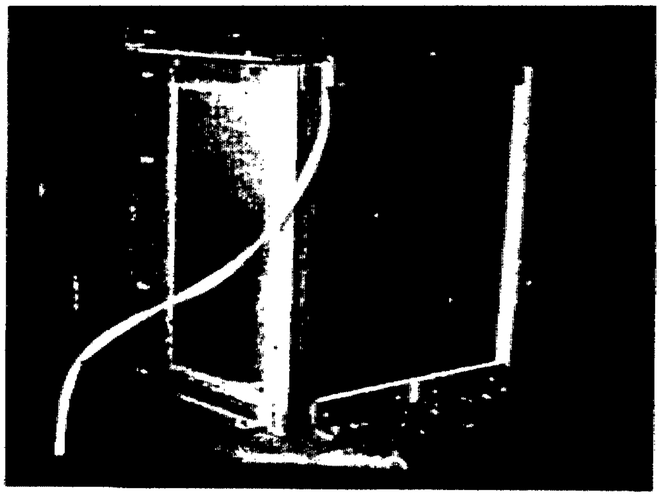


Figure 4-15. Confinement Box Used With Test Cells (Ref. 22)

hull, spacer, and fuel cell, as in Fig. 4-18*, but the fuel, which had been pressurized by hydraulic ram, impinged on the gravel and then poured out through drain holes in the bottom of the spacer, illustrated in Fig. 4-19. It did not spew into the compartment (Ref. 23). Thus external fuel cells with fuel barriers have been shown to provide "safe" storage.

A shaped-charge jet can damage fuel cells severely and cause a fuel spray that is ignitable by hot particles coming from impacts of the penetrator on other vehicular components. Fig. 4-20 illustrates the severe damage KE penetrators can cause to fuel cells that also results in fire.

*Fig. 4-18 shows the incandescent glow resulting when a shaped-charge jet passes through a vehicle hull, a 1.8-m (6-ft) wide compartment, and another vehicle hull. Note that the jet entered the fuel cell, which contained No. 2 diesel fuel, but did not exit it.

Figure 4-16. Fuel Cell Failure at Access Plate (Ref. 22)

Figure 4-17. Fuel Cell Failure Near Access Plate

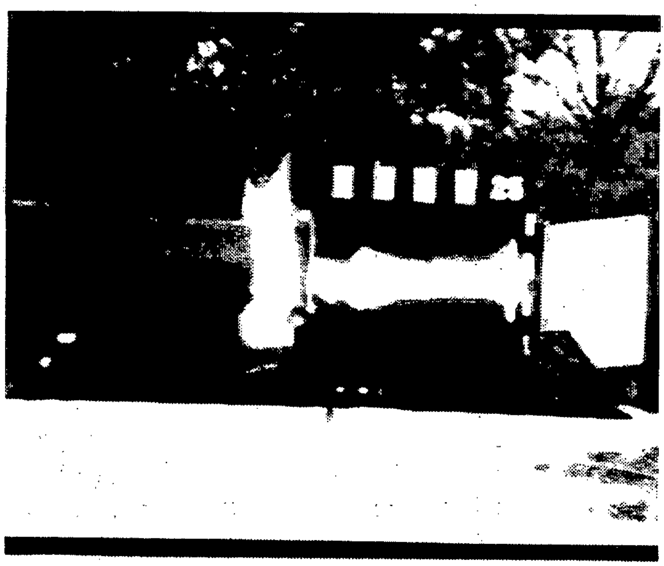


Figure 4-18. Jet Penetration Through Simulated Vehicle Armor, Crew Compartment, and Fuel Barrier Into Fuel Cell (Ref. 23)

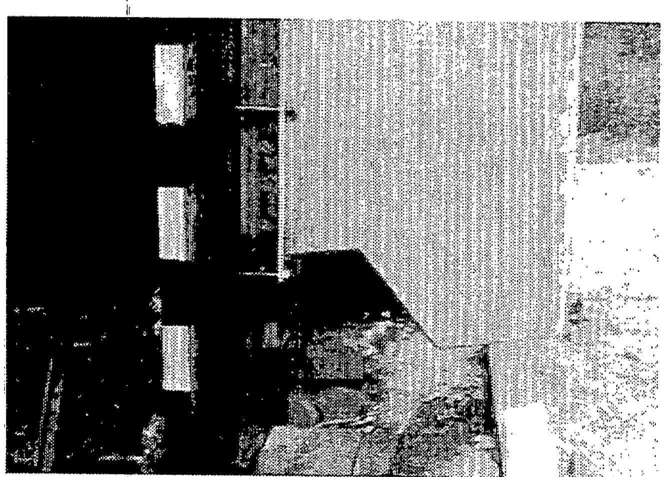


Figure 4-19. Fuel Drainage From Fuel Barrier (Ref. 23)

(A) Example A

(B) Example B

Figure 4-20. Two Examples of an Aluminum Engine Compartment Fuel Cell Hit by a Kinetic Energy Penetrator After the Penetrator Passed Through the Vehicle Hull (Ref. 25)

The survivability enhancement criteria for fuel cells that should be used by designers are the following:

1. Assure that the fuel cell will not suffer gross rupture upon ballistic impact, or if the cell does rupture grossly, assure that the fuel will not spray into an occupied or engine compartment.

2. Assure that there is a safe collection location for the fuel and that the fuel has a path by which it can flow to the collection location or overboard drain.

3. Assure either that the fuel cell cannot be pressurized and then spray fuel into an occupied compartment or that sprayed fuel cannot reach an occupied compartment.

4. Assure that the fuel cell is strong enough to withstand explosion of ullage vapor/air mixture.

4-3.1.6 Comments on Fuel Cell Design

The following observations apply to the design and location of fuel cells:

1. A fuel cell incorporated into the wall of or within a compartment occupied by personnel presents a hazard to those personnel.

2. Location alone cannot be depended upon to "protect" a fuel cell because vehicles can be hit from any direction by direct-fire weapons; the probability of being hit from the rear is somewhat less than it is from the front or sides. Although the bottom of a vehicle is not often exposed to direct fire, it is exposed to mines. The top of the vehicle is exposed to bomblets and to attack from above.

3. External fuel cells should not be detectable by thermal sensors. Hot fuel should not be recycled into exposed external fuel cells because hostile personnel using IR detectors can easily locate these vehicles.

4. Upon ballistic penetration, a double-walled fuel cell incurs significantly less damage to the wall in contact with the fuel than a single-walled fuel cell (Ref. 24).

5. The bilge, if covered to preclude free entry of air, is a relatively safe collection location for fuel (Ref. 22).

6. A plastic fuel cell with an intact containment wall will not spray fuel into an internal compartment, even though the wall is perforated and the cell fails grossly (Ref. 22).

7. A fuel cell should not be adjacent to an air-filled compartment containing a strong ignition source because a threat could perforate through both the fuel cell and the compartment wall and provide a passage by which fuel could reach the ignition source. An example of such an undesirable design is a vehicle that had its muffler compartment separated from a fuel cell by a 19-mm (0.75-in.) aluminum wall at one location and had a cutout in the plastic fuel cell containing a fuel-fired space heater within a 3.12-mm (0.125-in.) thick aluminum box at another location (Ref. 22).

8. Fuel cells should not be pressurized or allowed to pressurize.

9. If a fuel cell is mounted on the external surface of an occupied compartment, a baffle should be emplaced between the fuel cell and the hull to prevent fuel from passing into the occupied compartment through a hole made in the hull by a penetrator (Ref. 23).

10. Designers of light-armored vehicles must consider the effect of the shaped-charge slug within the vehicle, as well as the jet. (Heavy armor usually traps the slug, but light armor does not.) The slug is relatively massive (170 g was the mean mass of 43 copper slugs from M28 HEAT warheads.), is hot enough to ignite DF-2, and travels approximately 244 m/s (800 ft/s) (Refs. 22, 23, 24, 26, and 27).

4-3.2 FUEL TRANSFER SUBSYSTEM

The fuel transfer subsystem generally is defined as all of the components required to transfer fuel from the onboard fuel cells to the engine. These include the fuel transfer pumps, strainers, filters, fuel-water separators, fuel heaters, and fuel lines (tubing, hoses, fittings, crossovers, and vents) but do not include the fuel injection pump or carburetor or other nonengine, fuel-consuming equipment, such as smoke generators, starting aids, or personnel compartment heaters. These latter items interface with the fuel transfer system, and if not properly designed and maintained, they can have a significant impact on overall fire safety. With respect to the fuel transfer subsystem, the major areas of concern are connector and fitting compatibility, line routing and material, and fuel demand and duty cycle requirements. Performance and environmental specifications for these items should consider fire safety and fire survivability by emphasizing leakage resistance upon rupture or puncture and resistance to heat, particularly when the component is to be located near an intense heat source.

The location and placement of fuel system components are important from both functional and fire safety points of view. Subpars. 4-2.1.2 and 4-2.3.2 state that particular care must be taken when routing fuel lines through the engine compartment or when lines are located near exhaust components or other heat transfer surfaces. Fuel cell filling ports should be easily accessible and located so that spilled fuel will not contact any part of the exhaust system, manifolding, electrical components, or other hot, or potentially hot, surfaces or sparking locations. This fact applies to other fuel system components as well, particularly filters and fuel-water separators, which require access for element replacement and drainage. If these items are located above wiring harnesses or other electrical equipment, care should be taken to shield or isolate the electrical components since fuel spilled during element servicing could permanently damage electrical insulation and present a fire hazard.

Normally no part of the fuel system should extend beyond the widest part of the vehicle nor should fuel lines be outside the armor envelope. If external fuel cells are used, ingress for the fuel lines must be provided through the armor. Lines or components extending below the bottom on the sides, the rear, or the deck of the vehicle must be protected from impact. Sturdy shrouding or guards must be provided where fuel lines or components are exposed to stones thrown by vehicle wheels or tracks or where they can be stepped on by operating personnel. Electrical wiring and connectors must also be protected to prevent abrasion and breakage, which, in addition to negating the circuit, could become a source of ignition.

The probability of diesel fuel spray from a fuel line can be decreased by reducing the pressure in the fuel line. If atmospheric pressure is used to force the fuel to flow, there is a much smaller probability of fuel spraying out following a ballistic impact. Fuel system components should be designed and packaged, e.g., in a single casing, insofar as possible to reduce the number of connection points so that the number of potential leakage points can be decreased. Components should also be designed to produce the minimum pressure drop attainable. Suction or low-pressure fuel systems are preferred because they are less likely to leak fuel or rupture during operation. In most cases, suction and low-pressure fuel are possible from the fuel cell to the fuel injection pump.

Locating fuel lines and hydraulic lines in the bilge is a less vulnerable solution than routing them through the crew compartment. Any spray would most probably be deposited on the walls, top, or bottom of the bilge; however, the bilge is less likely to promote a sustained fire (Ref. 22). If, however, a pressurized line is used from the fuel cell to the engine or if a suction line could result in siphoning, an automatic fuel line shutoff that responds to significant pressure changes should be provided. Such an automatic shutoff system, i.e., one that senses pressure in the return side of a fuel system, is not recommended because it would immediately cripple the mobility of a vehicle that otherwise would be able to move to safety to effect repairs.

The design and use of fuel system heaters require careful attention because they introduce energy into the fuel system and can bring electrical components into close proximity to the fuel. Three types of fuel system heaters—in-fuel cell, in-line, and filter—are commonly used to assure adequate fuel flow during cold weather operation. In-fuel cell and filter heaters are used mainly to assure fuel flow during engine start-up, whereas in-line heaters are used to maintain fuel temperature during engine operation. In-fuel cell and filter heaters are usually electrically operated; in-line heaters may be all-electric, all-coolant, or combined electric plus coolant. Electrical units often start to heat fuel the instant the ignition is turned on. All coolant units rely on heat transfer from the coolant and therefore require an operating engine. Electrical units should automatically switch on or off as the fuel temperature passes through preset limits. They should have integral circuit breakers with a reset switch to prevent overheating in the power assembly in case of an electrical short. All electrical components must be physically isolated from the fuel-carrying components under all operating conditions and temperatures.

Guidelines for the design of the compression-ignition engine and gas turbine fuel systems used in military vehicles are given in the *Fuel System Design Handbook for Military Vehicles Applicable to Standard Army Refueling Systems (SARS) Compatible Vehicles* (Ref. 28).

4-3.3 FUEL LINE CONSTRUCTION AND ROUTING

Fuel lines and other fuel-carrying or -containing components should, in most cases, be isolated from hot surfaces. The exception is the primary fuel filter that is often located in the engine compartment as close to the engine as possible so it will benefit from the radiant heat emitted by the engine during cold weather operation.

Fuel lines can be either first-quality steel tubing (preferred) or flexible hose and should be designed for two times or more pressure than is expected in normal operation. Copper and copper alloys should not be used. Flexible hose, if used, must have a fuel-resistant synthetic rubber inner tube, reinforcing inner braid, and a cover resistant to fuel, lubricating oils, mildew, and abrasion. As a minimum requirement, the flexible hose must be able to withstand a suction of 67.7 kPa (20 in. Hg) without collapsing, a working pressure of 1.7 MPa (250 psi), and temperatures between −51°C (−60°F) and 121°C (250°F), although some applications may require withstanding wider temperature ranges. The hose should not crimp due to bending and should be resistant to bending. When steel tubing is used, short pieces of flexible hose often provide the relative motion of various elements of the fuel system. Flexible hose is often used at the inlet to the injection pump to serve as a surge damper to smooth out pressure pulsations. Careful routing of fuel lines cannot be overemphasized. Lines should be routed where they are protected from damage due to hazards or heat and where the fuel will not spray onto hot spots after accidental or ballistic puncture of the line. Care must be taken, however, to keep the number of bends and fittings to a minimum. The tubing or hoses should be secured to the vehicle at regular intervals to prevent failure due to excessive load and vibration and to avoid shifting while in service. Flexible fuel hose per MIL-H-13444 Type 3 (Ref. 29) has proven quite spall resistant. In fact, it has withstood the impact of a shaped-charge slug (Ref. 22), but the fuel line couplings are not self-sealing as was demonstrated in a test, shown in Fig. 4-21. Fuel line fittings should be of top quality, and all connections should be capable of withstanding a pressure of 1.7 MPa (250 psi).

Fuel system components should be readily accessible for inspection and maintenance. Fuel system design should carefully consider the need for fuel line redundancy, a feature that can work for or against vehicle fire survivability. Although redundancy can be a strategy to increase fuel sys-

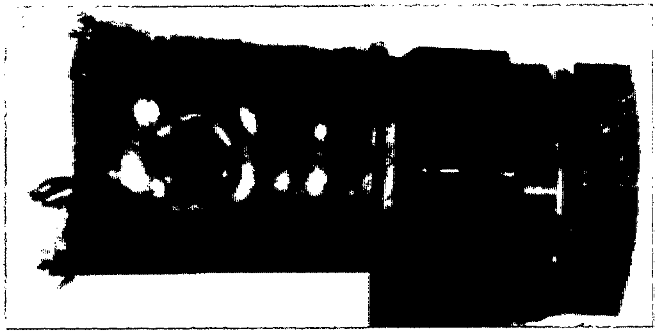


Figure 4-21. Perforation in Self-Sealing Hose Coupling That Did Not Seal (Ref. 30)

tem reliability and decrease combat vulnerability, redundancy can also increase the potential for fire if not carefully designed and implemented. By definition, redundant systems can double the area presented for hits, provide additional sources of fuel leakage, and greatly increase system complexity. Redundant systems must have control valves to isolate damaged components in order to control fuel leakage so that the operational circuit can continue to function. These systems require sensors and fast-acting valves, as well as a preconceived battle damage control strategy.

4-3.4 FUEL TYPES

The propensity of gasoline to ignite readily over the temperature ranges normally encountered in combat, from −40°C (−40°F) to 49°C (120°F), was a major factor in the decision in 1959 to convert all US combat vehicles to diesel fuel. Similarly, to lessen the hazard that gasoline-type fuel presented, the US Navy converted from JP-4 to JP-5 for all carrier-based aircraft after disastrous fires in the USS *Lexington* in 1965 and the USS *Forrestal* in 1967.

The decrease in vulnerability of diesel-fueled US combat vehicles is due solely to the fact that kerosene-type fuels must be at a higher temperature to vaporize sufficiently to have a combustible air-fuel-vapor mixture above the surface of the fuel. Heated DF-2 provides just as ignitable an air-fuel-vapor mixture as cold gasoline. Also DF-2 sprays are almost as ignitable as gasoline sprays given a ballistic impact through a fuel tank. Burning DF-2 produces almost the same quantity of heat, 42,537 kJ/g (18,300 BTU/lb), as gasoline, 44,164 kJ/g (19,000 BTU/lb). Therefore, once a fire starts and burns long enough to heat the DF-2, a DF-2 fire is as hazardous as a gasoline fire.

When more volatile liquids are mixed with less volatile liquids, the flash point of the resulting mixture is basically that of the more volatile liquid, as described in subpar. 3-2.5.7.1. Therefore, use of a mixture of DF-2 and JP-4 for a winter fuel would be a poor practice. Instead, a fuel with the volatility of JP-8 over the range of winter temperatures should be supplied for winter use rather than field mixtures. Either DF-1 or DF-A could be supplied in winter rather than DF-2. Where JP-8 is normally used in summer, it will also be usable in winter. An alternate solution for winter operations would be to include a fuel heater in the winterization kit for the vehicle concerned.

4-3.5 LESSONS LEARNED

Many lessons have been learned on the subject of making the fuel system of combat vehicles less vulnerable to fire. These lessons concern (1) design of the vehicular bilge, (2) selection of engine types, (3) design and location of fuel cells, (4) design and location of fuel lines, and peripherally, (5) design and location of space heaters and (6) design and location of smoke generators.

4-3.5.1 Design of Vehicular Bilge

In a series of tests to establish the propensity of a vehicular bilge to sustain a DF-2 fire, the following conclusions were established:

1. A fire ignited with a propane torch would not be sustained in a covered bilge even with DF-2 near its flash point if there were floor plates covering the bilge, even though there were finger holes in these floor plates as well as leakage paths around the edges (Ref. 22).
2. A rag protruding above the surface of the DF-2 could provide sufficient wicking to support a sustained fire, but the DF-2-wetted wall of the test fixture would not. Also reticulated foam or aluminum mesh (Explosafe®) could not provide sufficient wickage to sustain combustion (Ref. 22).
3. Hot DF-2 sprayed on the steel walls of a test fixture would not burn unless there was a strong fire within the fixture that heated the fixture sufficiently to vaporize the fuel. This sprayed fuel would bead and then flow down the wall into the bilge where it would pool but not burn. Once the fixture was heated sufficiently for the DF-2 to vaporize, the DF-2 would burn.

The lessons learned are

1. The use of high-flash-point fuel can make fuel fires more difficult to ignite and easier to extinguish in the early stages than the use of low-flash-point fuel.
2. Rags and other wicking materials must be kept out of the bilge and out of open crew compartments.
3. The bilge is a relatively safe location for collection of leaked fuel when air convection is minimized. (Retention of leaked fuel in the bilge, however, is not recommended. This collected fuel should be drained overboard at the first opportunity.)
4. A fire within a combat vehicle should be extinguished long before the vehicle heats sufficiently to vaporize the fuel.
5. The fuel should be kept as cool as practical because cool fuel provides less vapor to ignite. Heat must be added to fuel before it can burn.

4-3.5.2 Selection of Engine Types

Engines are not selected for fire safety. Fire safety, however, should be considered in engine selection, design, and installation. The main features that should be considered are that the fuel should not be returned to the fuel cell when heated, the engine should not present hot spots for fuel ignition, and the fuel lines should have minimum exposure to ballistic damage.

Preferably, if the fuel is used as a coolant, the heated fuel should be consumed, not returned to the fuel cell. A diesel engine that uses a jerk-pump injection system heats the stored fuel much less than a diesel engine that uses either a unit injector or a common rail injection system. For fire survivability, diesel engines that use a jerk-pump injection system are preferred to ones using either a unit injection or a common rail injection system. If a diesel engine does use an injection system that returns heated fuel, that fuel should be cooled before it is returned to the fuel cell.

Another lesson is that hot spots should be either eliminated or shielded, or fuel and other combustible fluids should be routed so they cannot contact the hot spots given any combination of component malfunction, accidental or ballistic damage, or mechanic's error during maintenance operations.

4-3.5.3 Design and Location of Fuel Cells

One of the first lessons learned by the British in 1916 was that a gasoline fuel cell made of light gage steel should not be emplaced over the engine within the combination engine and crew compartment, as was done in the Mark I tank. In the next model in which a change could be introduced, the Mark IV, the fuel cell was relocated from inside the vehicle to the exterior rear; see Fig. 4-22. The rear-mounted fuel cell was made of the same armor plate as the tank itself, 12.7-mm (0.5-in.) steel plate, and the feed system was changed from gravity to pump. Even though the tank designers had learned this lesson, the men in the field did not, as is illustrated by the following story.

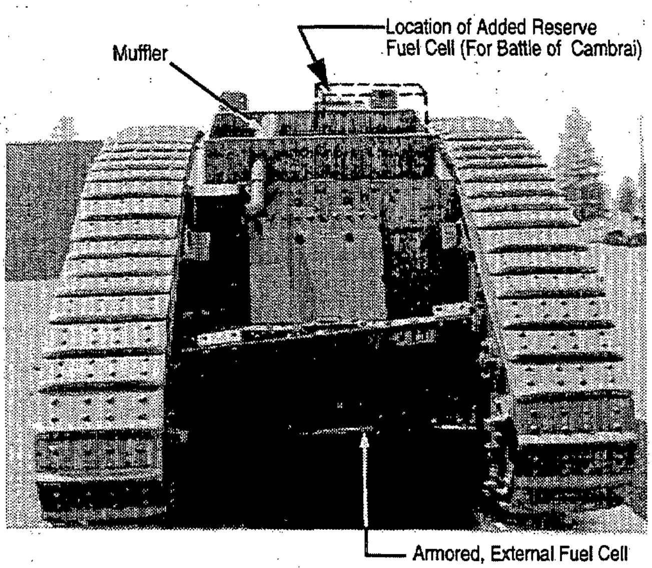


Figure 4-22. External, Rear-Mounted, Armored Fuel Cell of the Mark IV Tank

Tanks were first used in combat toward the end of the Battle of the Somme in September 1916. Forty-nine Mark IV tanks were assigned to attack German lines between the Combes ravine and Martinpuich. The Mark I tanks had a single gasoline cell high within the driver's compartment to allow the use of gravity feed, and this internal fuel cell was found to be excessively vulnerable. (The Mark II and III tanks were interim models with somewhat heavier armor.) The Mark IV tank incorporated all the changes found necessary in the Mark I. Among these changes were that the petrol* fuel cell, now with a 227-L (60-gal) capacity, was moved to the rear of the tank and made of 12.7-mm (0.5-in.) armor plate, and the fuel feed was by vacuum. The exhaust was moved to the top of the tank and a silencer (muffler) installed. The armored, external fuel cell on the rear provided a true survivability enhancement, but sometime before the Battle of Cambrai, someone decided that 227 L (60 gal) was not sufficient. A field modification was made to install a reserve cell on the roof of the vehicle, adjacent to the muffler, over the rear personnel exit. The armored, external fuel cell can be seen on Fig. 4-22, as can the muffler and rear exit. The added reserve fuel cell was in the rectangular box enclosing the muffler, and it protruded upward out of the rectangular box approximately the height of the box. Thus the added fuel cell was an easily hit target.

During the Battle of Cambrai, one of the Mark IV tanks entered the village of Havrincourt. A bullet hit the reserve petrol cell on the roof, the petrol ignited, and the flaming petrol streamed down inside the tank. The crew tried to extinguish the fire, but the fumes eventually forced them to evacuate and take cover in a shell hole. The Germans tried to rush the tank, but the tank commander climbed back inside and held the Germans off by firing through the doorway. He killed eight Germans with his revolver. He then managed to bring the fire under control and called the crew back (Ref. 31).

This story illustrates the value of armored, rear-mounted, external fuel cells. It also illustrates how an excellent survivability enhancement device can be negated by the poorly conceived addition of another device. The reserve fuel cell was not armored and was located where it could easily be hit, and fuel leaking from the cell would ignite because the adjacent muffler was a strong ignition source. The resulting fire could render the vehicle uninhabitable and block the primary exit.

After the shooting stopped in 1918 even the tank designer forgot this fuel location lesson because the tanks again had light gage steel fuel cells located within the vehicles when

*The English refer to gasoline as "petrol".

the next major war began. Generally, all US and British armored vehicles continued to use internal fuel cells until the development of the M113A3 armored personnel carrier.

The M113 APC was initially gasoline powered, but to reduce the potential for fire and to reduce the logistic requirements of stocking two types of fuel, the M113A1 was diesel powered. The diesel engine selection, however, was the Detroit Diesel Allison 6V53, which has a unit injector system that returns heated fuel to the fuel cell. This engine selection partially negated the fire safety advantage of using diesel power. The fuel cell was located in the upper left rear wall of the troop compartment immediately adjacent to the small door in the ramp. On the night of 3-4 November 1969, Troop I of the 3rd Squadron, 11th Armored Cavalry Regiment, was in a night defensive position. The North Vietnamese attacked shortly after midnight (DANs* 381, 383, and 385) and by coincidence hit the right sides of three M113A1 APCs with RPGs at almost the same location and angle of obliquity. In at least two vehicles, a shaped-charge jet traversed the troop compartment and entered the fuel cell on the left wall of the vehicle. The results of these two attacks were described by the BDARP investigator: "These are the worst damaged vehicles we have looked at. The fire was so hot, the hulls melted and dripped. It was also the first time that we have seen an APC that caught fire because of a hit in the fuel [cell]. Is there any evidence of a warhead for the RPG other than the HEAT type? Possibly a delay fuze or something that would explode after penetration was made.". The third vehicle had a small fire, which apparently initiated explosives stowed within; the vehicle was completely destroyed by the explosion.

This same circumstance of a shaped-charge jet traversing an open compartment to enter a fuel cell was repeated in a series of tests performed in 1986 (Ref. 22). In Test 26 of that series, shown in Fig. 4-23, the jet traverses the compartment; almost immediately a spurt of fuel, burning on the periphery, comes back across the compartment in Fig. 4-23(D). This is undoubtedly the phenomenon that occurred in two of those three APCs.

At least three vehicle modifications using passive fire prevention or suppression techniques have been effective for this event. The first technique is to constrain or reinforce the fuel cell so that it will not rupture with a hole larger than that punctured by the shaped-charge jet and to provide an extinguishant and/or inerting agent for the jet to release, which prevents ignition or suppresses combustion (Test 27 of Ref. 22). The second technique is to replace the existing fuel cell with a double-walled fuel cell and locate the extinguishant or inerting agent between the two walls, as is described in Ref. 24. (The double-walled fuel cell is described in subpar. 4-8.1.3.) The third technique is to relocate the fuel cell so that it is not within a vehicle side wall but is exterior to the vehicle and to provide a barrier to preclude the fuel spray and an extinguishant to preclude a fireball from an initial spray (described in Ref. 23 and subpar. 4-8.3.1).

*Refers to document acquisition numbers in the SURVIAC files; see subpar. 4-1.2.

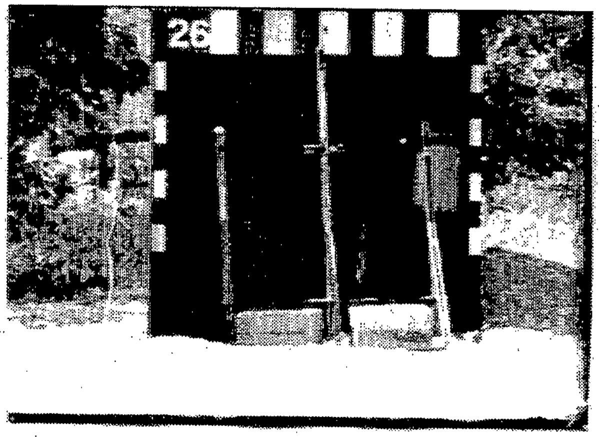
4-3.5.4 Design and Location of Fuel Lines

During a visit by this writer to Fort Hood, TX, a maintenance sergeant explained how an engine fire had occurred in an M1 MBT when an elbow connecting the fuel line to the fuel regulator was rotated 90 deg (Ref. 16). Due to the rotating of the elbow, the fuel line passed the combustor can at a distance of approximately 51 mm (2 in.). (The fuel line is a rubber hose covered with a woven wire sheath.) The heat from the combustor can was so great that it baked the rubber, boiled off the volatile constituents, and left a brick-like residue. This brick-like residue cracked from engine vibrations and provided passages through which the fuel sprayed on the combustor can and ignited. The sergeant stated that this series of events had occurred on more than one M1 MBT to his knowledge. This improper elbow installation is not precluded by fuel line length or component design. When such a potential hazard exists, either a fuel line that can withstand the elevated temperature should be used or the fuel line, the elbow, and/or the fuel regulator should be designed to preclude incorrect assembly.

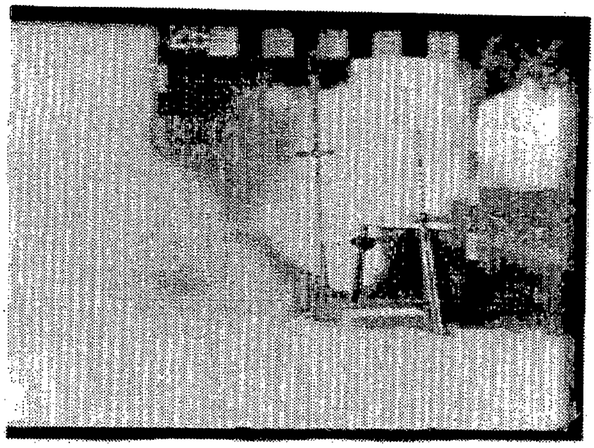
In two instances in SEA (DANs 312 and 388) M113A1 APCs were hit by shaped-charge jets, and hydraulic fluid fuel lines, located within a covered bilge, were severed. In neither case, however, was fire reported. This preclusion of a sustained fire within a covered bilge was also demonstrated in tests (Ref. 22). The lesson to be learned is that a covered bilge is a comparatively safe location for fuel lines.

4-3.5.5 Selection, Design, and Location of Space Heaters

In several incidents reported by the US Army Safety Center, fires have occurred where a fuel line to a space heater had leaked, where space heaters had not been purged after a previous use, or where objects had been placed on or near the space heater or its ducts. In most cases, the soldiers using the vehicle were not taking proper care of the equipment; however, these troops are expected to use these vehicles for extended periods, under the most stressful of conditions, and when they are probably extremely exhausted. Therefore, the equipment must be designed to be user-friendly, i.e., to require a minimum of maintenance or adjustment, to be fail safe, and to prevent the placement thereon of what could be hazardous items. There is some evidence (Ref. 32) that some of these heater fires may be due to an error in qualifying heaters for use from a second source even though the operator's instructions apply only to heaters from the first source. Whatever heaters are used must be simple and safe. Heaters are essential because the temperature inside armored vehicles usually is colder than

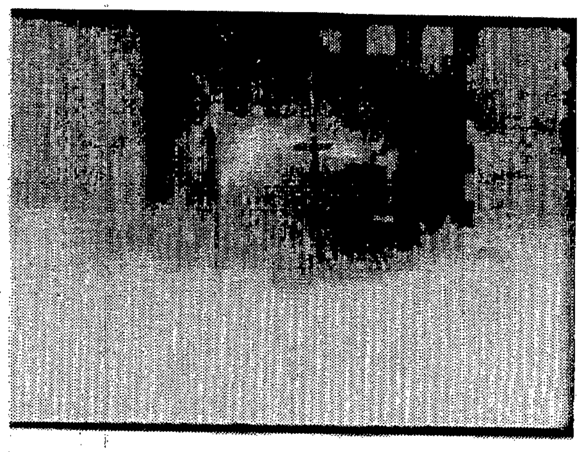


(A) $t = 0$

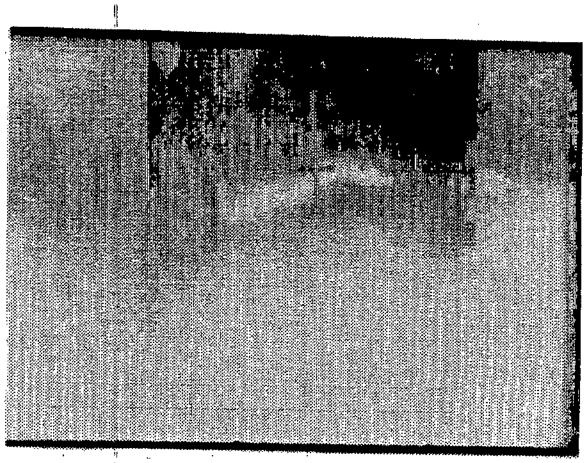


(B) $t = 2$ ms

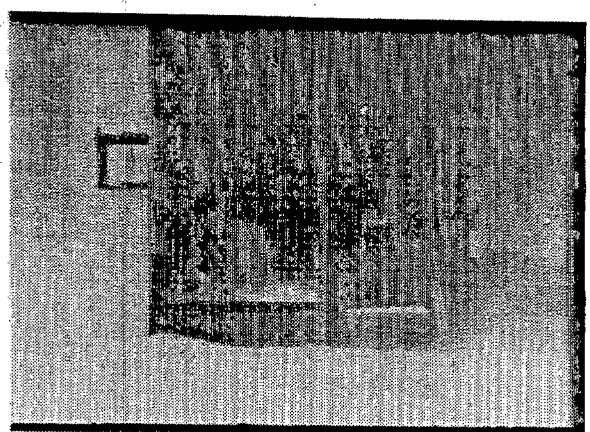
(C) $t = 7$ ms



(D) $t = 20$ ms



(E) $t = 35$ ms



(F) $t = 100$ ms

Figure 4-23. Progression of Combustion in Test No. 26 (Ref. 22)

the temperature outside in the winter. The lesson learned is to design the heater to preclude fires or explosions as well as to heat the vehicle.

4-3.5.6 Smoke Generators

Modern armored vehicles need to be capable of laying both an immediate small-scale smoke screen and a heavier long-term obscuration. For the first purpose, a cluster of smoke grenade launchers are mounted on the turret of most combat vehicles. For the second purpose, a smoke screen can be laid by spraying diesel fuel in the muffler or exhaust pipe of the vehicle. This is the system used for both the M60 and M1 series of MBTs and for the BFVs.

In the fire incidents database collected by the USASC, there are at least two incidents of the fuel line to this smoke generator leaking and permitting diesel fuel to collect in the muffler or exhaust pipe area that later ignited and resulted in a fire where there was no fixed fire extinguisher or fire detector. The designer must assure that fluid systems do not permit collection of combustible fluids where combustion can occur that will damage the vehicle.

4-4 HYDRAULIC AND ANCILLARY POWER SYSTEMS

Ancillary power systems are used to rotate turrets; to lay weapons; to move ramps, dozer blades, and cranes; to lay and retrieve bridges; to operate munition handling equipment; to apply brakes; and to perform other tasks.

Ancillary power systems require power elements and control (e.g., sensing and signaling) elements. Both types of elements use energy from electricity, pressurized or flowing liquids (hydraulic) or gases (pneumatic), or a combination of these sources. Most electrical power systems are wholly electric for both power and control elements, but most hydraulic power systems use electric control elements. Pneumatic systems are used least (Refs. 33-35). The fuel regulation and inlet systems for the X211 nuclear-conventional turbojet engine (Ref. 36) used pneumatic power and control elements. A combination of hydraulic power and pneumatic controls was used in both the bellmouth bypass system for the air intake of the F4 *Phantom* aircraft and the inlet spike control of the GAM 77-A Hound Dog missile. All of these systems convert to mechanical motion eventually.

All fluid power systems are hybrid because they all use mechanical devices. Most sensors have a mechanical output, which usually is transduced to an electrical signal. Most output from these systems is converted into mechanical motion, usually linear or rotary.

Electrical systems are subject to electromagnetic interference (EMI) and can become inoperable by exposure to strong electrical inputs, such as a lightning strike or shorting of an electrical power line. Liquid systems can be affected by excessive heat or cold and by contamination of the liquid. Pneumatic systems can be affected by condensation and freezing of moisture in the gas or by oil in the gas. The mechanical elements of all three types of systems can be affected by dirt, and all three types of systems and their mechanical elements can become inoperable by ballistic damage. All three types of systems must have power sources.

The basic choice for power in combat vehicles is either electric or fluid power. A shorted electric power line is a strong ignition source that can ignite hydrocarbon fluids and other combustible materials, and electric shorts have ignited the propellant of cartridges, cased and uncased. Leaked hydraulic fluid can flow or spray over large areas and, when ignited, burn vigorously. Generally, the fire hazard potential is not the dominant determinant for the choice of an ancillary power system. This paragraph contains information on fluid power systems. Electric power systems are discussed in par. 4-5.

4-4.1 POWER MEDIA CHOICE

Fluid systems can be either liquid or pneumatic. The liquid systems usually use a hydraulic fluid, which can be petroleum based, water based, or synthetic. Each liquid has its own peculiarities, which require additional system components and design features. Since hydraulic systems have been used extensively, designers and maintenance personnel tend to favor them. Pneumatic systems often use air for the fluid; steam or the products of combustion of a material, such as solid propellant, have also been used.

4-4.1.1 Liquid Systems

Liquid fluids include the petroleum-based MIL-H-5606 (Ref. 37) and MIL-H-6083 (Ref. 38) described in subpar. 3-3.3, the fire-resistant MIL-H-83282 (Ref. 39) and MIL-H-46170 (Ref. 40) described in subpar. 3-3.1, and the nonflammable MIL-H-53119 (Ref. 41) described in subpar. 3-3.2. Water-based hydraulic fluid MIL-H-22072 (Ref. 42) is used in Navy aircraft catapults. The petroleum-based MIL-H-5606 and MIL-H-6083 burn readily in spray or mist form and will burn sustained from a pool. The fire-retardant fluids MIL-H-83282 and MIL-H-46170 will burn readily in spray or mist form but will self-extinguish in a pool. The nonflammable MIL-H-53119 will not burn as a mist or spray or from a pool, but it is toxic and harmful to personnel on contact and has not yet received Environmental Protection Agency (EPA) approval as being benign to the ozone layer of the earth. Water-based MIL-H-22072 is approximately 50% ethylene glycol. Thus once the water is removed, the ethylene glycol will burn. Also the ethylene glycol is toxic if swallowed and otherwise harmful to personnel upon skin contact. Solutions of potassium acetate or calcium chloride could be used to satisfy low-temperature requirements, would be nonflammable, could be benign to humans, can be made benign to metals and elastomers, and could have additives for lubricity, but these solutions have not been tested as hydraulic fluids.

Most hydraulic fluids have additives to provide the needed lubricity, oxidation and corrosion resistance, and sometimes the needed viscosity. Some have additives to raise the boiling point or to lower the freeze point. Very few liquids are usable neat, i.e., unadulterated. These liquids have different operational temperature ranges based primarily upon their freezing and boiling points and how temperature changes alter them chemically. The power source for these liquids is usually a pump. The systems often use accumulators—reservoirs that use a pressurized gas to maintain a high pressure on the liquid—and sumps—reservoirs to collect the liquid at low pressure to feed to the pump. There are also filters, valves, piping, actuators, gears, vane or nutating disc motors, sensors, and other devices. Elastomeric items, such as seals or diaphragms, must be compatible with the liquid used and able to withstand the environment in which the system operates.

4-4.1.2 Pneumatic Systems

Pneumatic systems can be made for air, steam, products of combustion, or other gases. Air systems can operate hot or, with appropriate demoisturizing, cold and in a radioactive environment. Steam systems operate hot. Products of combustion from these systems start hot and then cool off to ambient temperature; these systems have to be designed accordingly. Power sources for pneumatic systems include ram air for aircraft, pumps, combustion chambers such as solid propellant cartridges or turbine engine combustion cans, or any other device or phenomenon that can produce quantities of gases at above ambient pressure. The components of pneumatic systems include plenums, valves, motors, actuators, filters, sensors, piping, orifices, nozzles, bellows, and other devices. Again, seals and diaphragms, which may be elastomeric, must be compatible with the gases and operating environment.

Pneumatic systems can be temperature compensated and are inherently less sensitive to environmental changes, particularly air systems, than most other control or power systems. Air, steam, and products of combustion are not combustible. Steam and hot products of combustion are hazardous. Air can be used in temperature ranges that are not hazardous to personnel. Personnel unfamiliar with pneumatic systems may think that a pneumatic system is less stable or less accurate than a hydraulic system, but this assumption is not correct. With proper design, a pneumatic system can be just as stable and accurate as a hydraulic system, and it can have a faster response (Refs. 34 and 35). For example, flowing air systems are not sensitive to dust contaminants in the air. As a contaminant, oil might be different, but even oil would tend to pass through the system, particularly through pressure dividers, and not affect performance. Air motors are well-developed and air-powered actuators are in use in many places. Filament-wound pneumatic bottles have been demonstrated not to project fragments when punctured (Ref. 43).* The Russians used an air-bottle-powered system to start T55 MBTs. The bottle could be pumped up by hand so that the noise of an auxiliary engine would not disclose the position of the MBT, and the air system could better withstand cold than could electric batteries.

4-4.1.3 System Specifications

When a vehicular fluid power system is selected and installed in a vehicle, it is imperative that the fluid for that system be specified in considerable detail. If a nonflammable fluid is desired, it must be specified, and the military specification must contain firm test requirements to assure that the fluid is truly nonflammable. Therefore, the vehicle designer must specify the fluid that should be used in a combat vehicle to obtain the necessary fire survivability.

Government purchasing agents are not allowed discretion in selecting the materials to be used in equipment. The agents must justify purchasing any material that is not on the published qualified products list (QPL) of the military specification, or equivalent, for the material designated for use in a specific vehicle. Therefore, if a designer determines that a specific fluid must be used to assure fire survivability of a given vehicle, he must specify that fluid or prepare a specification for it. The designer should also determine that there are qualified suppliers of the material or notify the equipment program manager that special action must be taken to assure the needed material is available.

4-4.2 COMPONENT LOCATION, MATERIAL SELECTION, AND PROTECTION

The location of hydraulic components and the potential for damage and subsequent release of hydraulic fluid are of prime concern. Extreme care must be taken in designing the system and locating the components so that the risk of fluid release into an occupied compartment or onto a hot spot in the engine compartment is minimized. A brief discussion of the general types of hydraulic systems used will aid understanding of the associated fire risks.

Hydraulic systems can be described by a few general categories that should be considered when designing the system for fire survivability. First, there are closed-loop and open-loop systems. Hydrostatic transmissions are typically closed-loop systems because the inlets and outlets of the pump and motor are connected directly to each other and the reservoir serves only to collect internal component leakage, condition the fluid (filter, cool, etc.), and provide

*A fiberglass-reinforced spherical bottle, approximately 457 mm (18 in.) in diameter, was pressurized to 9.38 MPa (1360 psi) with gaseous nitrogen and perforated by a 7.62-mm (0.30-cal) armor-piercing (AP) bullet traveling 792 m/s (2600 ft/s). There was no explosion or production of secondary missiles. The bullet perforated both sides of the bottle.

replenishment fluid. Hydrostatic transmissions usually have the capability to reverse direction of the fluid flow so that the low-pressure line in one flow direction becomes the high-pressure line in the reverse flow direction.

Open-loop hydraulic systems are the most common type used for actuation of hydraulic cylinders, motors, and other actuators. In open-loop systems the low-pressure return flow from the actuators is usually ported back to the reservoir. The pump provides flow in only one direction, although the direction of flow to an actuator may be reversed by means of a directional control valve. The actuator may contain a spring or springs to provide a fail-safe feature.

There are two main types of open-loop hydraulic systems: open center and closed center. The open center designation refers to function of the directional control when in the neutral position. When actuation is not required, full pump flow is returned to the reservoir under low pressure through the "open center" of the directional control valves. These systems usually have a fixed displacement pump so that when only a portion of the flow is required for actuation, the remaining flow must pass through a relief valve to prevent overpressurization.

The second type of open-loop hydraulic system has a closed center, i.e., when actuation is not required, the center of the directional control valve is closed and blocks pump flow. The pump in this case is usually a variable displacement pump that will automatically adjust itself to produce zero flow when the flow path is blocked. There are many different variations—e.g., pressure compensated, pressure and flow compensated, and power limiting—of this type of system. The most common function that is usually present in any of these variations is pressure compensation. Under pressure compensation, displacement of the pump is regulated to provide a constant pressure regardless of what fraction of the full flow capacity of the pump is required. In a purely pressure-compensated system, the high-pressure side of the system is always at this pressure-compensated level, except when flow demand exceeds the flow capacity of the pump.

Reducing the physical size of components of a hydraulic system reduces the probability of the system being hit by a threat. Secondary benefits from this system shrinkage method of vulnerability reduction include (1) reduction of the amount of vehicle space required to contain the hydraulic system, (2) weight reduction, and (3) ease of installation and maintenance. Specific techniques include relocation of lines, manifolding, and fluid volume reduction. Since the system with the small components has to work against the same loads, the hydraulic pressure would have to be increased. This increased pressure would produce a greater spray given a line puncture, which could produce a greater probability of ignition.

Shielding can be provided to further reduce direct contact vulnerability. Shielding can be classified as parasitic or natural. Parasitic shielding is protective shielding that has no load-bearing or other subsystem function. Conversely, natural shielding is protective shielding that is primarily structural or load bearing.

Parasitic shielding offers no secondary benefits and has disadvantages such as an increase in system weight and in time and effort during inspection or maintenance. Natural shielding is the preferred method to shield hydraulic components. To take advantage of natural shielding, directly vulnerable hydraulic components are located away from the periphery of the vehicle in more protected areas within the inner structure of the vehicle. Such a technique eliminates most of the disadvantages associated with parasitic shielding. Burying hydraulic components within the vehicle structure, however, has a disadvantage in accessibility for maintenance and inspection unless adequate provision is made for access.

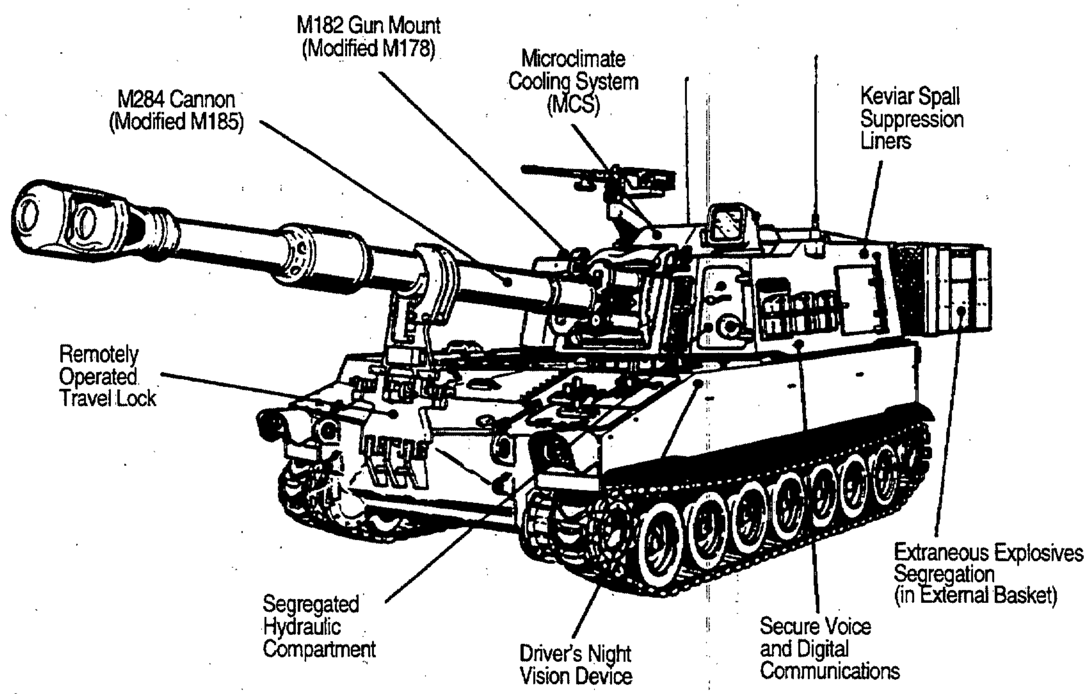
The hydraulic system for the M109A6 SPH was made less vulnerable by moving the hydraulic accumulator to a separate compartment, which is illustrated in Fig. 4-24, in the left front of the turret. This change shortened some hydraulic lines and enclosed this accumulator with steel. The hydropneumatic recuperator for the cannon was also placed within this compartment; therefore, the largest hydraulic fluid and recoil fluid containers were compartmentalized. Access to this compartment is provided only from the exterior of the vehicle.

4-4.2.1 Pump

When a hydraulic pump converts mechanical power into fluid power, it must be located close to a mechanical power source. Generally, hydraulic pumps are driven by the engine or transmission of a vehicle. Sometimes for low power requirements they are driven by an electric motor using the electrical power of the vehicle. This method of driving the pump by the engine or transmission uses either an internal lubricated coupling or an external unlubricated coupling or belt.

A common source of slow leaks in most hydraulic systems is the rotary shaft seal of the hydraulic pump. This seal wears due to abrasive dust, varying temperatures, and friction from high speeds. In addition, the shaft may not rotate exactly concentrically with the seal. Any one, or any combination, of these factors often contributes to a slow leak of the seal. For an internally driven pump, this leakage is contained in the engine or transmission. For an externally driven pump, this leak first creates a wetting around the pump shaft and eventually leaves a puddle. This leak must be handled in the same manner as similar engine oil, transmission fluid, fuel, and lubricant leaks.

When the hydraulic pump is located in the engine compartment, it is subjected to the ambient conditions of the compartment. Under normal operation the pump should not be subjected to temperatures exceeding the temperature lim-



Courtesy of BMY Combat Systems, a Division of Harsco Corporation.

Figure 4-24. SPH M109A6 Paladin Modifications

its of its elastomers. Embrittlement of elastomer material due to excessive heat can result in a slow leak and subsequent fire hazard.

Unless the pump receives direct physical damage, it is unlikely to be a direct source of a gross hydraulic fluid leak. If, however, a condition exists in which the normal pressure control valves become disabled and allow the pump to overpressurize, the drive mechanism may fail, an internal failure of the pump may occur, a hydraulic line may rupture, and/or a high-pressure cavity of the pump itself may rupture. In the latter two situations the pump will continue to pump fluid until the reservoir is drained. One level of redundancy should be available to avoid such an occurrence, or another weak link must be designed in the system to prevent an external rupture. This weak link may be in the pump drive, e.g., a soft keyway or shear pin, or it may be internal to the pump or valving, e.g., intentionally thin or weak sections that separate outlet from inlet.

4-4.2.2 Reservoir

The hydraulic fluid reservoir usually contains the largest concentration of hydraulic fluid in the vehicle. The same care must be taken to protect it as is used to protect the fuel cells. The hydraulic fluid reservoir should be located in close proximity to the hydraulic pump to minimize the pressure drop in the suction line to the pump, especially in cold weather. The most probable location for the reservoir is in the engine compartment or close to it. Location in personnel or ammunition compartments should be strictly avoided.

To reduce the weight of vehicles, hydraulic reservoirs were made of lightweight aluminum approximately 6.35 mm (0.25 in.) thick. In one series of tests shaped-charge jets passed through such reservoirs (Ref. 25). These lightweight reservoirs disintegrated, and the hydraulic fluid became an extremely hazardous fireball. This result occurred in five of six tests. In the sixth test, from the description of the damage, one would suspect that the jet entered the ullage, i.e., the air space above the hydraulic fluid. In four more tests, a 6.35-mm (0.25-in.) thick mild steel jacket was emplaced over the aluminum reservoir. In all four tests the aluminum reservoir disintegrated, but the steel jacket maintained sufficient integrity to reduce the resulting fireball greatly. The material of the reservoir was changed to 6.35-mm (0.25-in.) thick mild steel. In a subsequent series of seven tests, the steel reservoirs were perforated by shaped-charge jets; fires occurred but were again much reduced in size and violence. In another series of tests the addition of powder packs containing powdered potassium bicarbonate reduced the duration of the fireballs below 250 ms (Ref. 44). Consequently, steel reservoirs should be used in combat vehicles, and consideration should be given to incorporating a threat-released fire extinguishant, unless a nonflammable hydraulic fluid is used.

Also associated with the reservoir are other components that condition the fluid. These include the filtration system and the cooling system. Very basic, low-performance hydraulic systems may rely on the reservoir for cooling by convection and radiation and as a place for contaminants to settle out. In systems that rely on the reservoir for cooling, the reservoir must be placed where it can receive sufficient air circulation. Air cooling requires a strong flow of air over a hydraulic fluid container. This provides a significant amount of atmospheric oxygen in a region in which a ballistic perforation could cause a spray or mist of combustible fluids and could provide a strong ignition source. Thus there is an increase in vehicle vulnerability, which could require armor protection for alleviation.

A similar problem exists with reservoirs that use air coolers. The reservoir itself may be smaller in size than convection-cooled systems and be placed in a more protected location; however, the cooler must be located in a high-velocity airstream and may need armor protection.

Another option for cooling the hydraulic fluid is to use a liquid heat exchanger that uses the engine cooling fluid as the cooling medium. This would not apply, of course, to vehicles with air-cooled engines, unless a separate liquid system is provided for the hydraulic system. This option allows both the reservoir and the hydraulic fluid cooler to be located in protected areas, and only the radiator for the nonflammable coolants requires airflow.

The reservoir fill cap should be located where it can be easily accessed and where spills can be easily cleaned up. The cap should have a level indicator on it, or there should be an easily visible level indicator on the reservoir. If the fill cap is located externally to the vehicle, it should be well-protected and as rugged as fuel fill caps. Providing ullage is as important with hydraulic fluid reservoirs as it is with fuel cells. Fill caps and breather caps should be engineered to withstand the pressure surges of the fluid against them when a penetrator passes through the reservoir.

All hydraulic systems require some type of breather system. As temperatures change, fluid loss occurs, and as actuators are stroked, the volume of fluid in the reservoir changes. The most common type of breather has a filter in the fill cap to allow free exchange of air. However, leakage out of the fill cap through this filter can result due to splashing of the hydraulic fluid.

Another type of breather cap is similar to a radiator cap. It maintains a 34- to 69-kPa (5- to 10-psi) pressure in the reservoir, and it allows air to escape when the upper pressure limit is exceeded. It allows air to enter through a filter with no restriction. (Some provision must be made to exclude dust, such as was encountered in SWA.) This type of breather is less susceptible to leakage from splashing because there is usually a positive pressure in the reservoir and no free leak path. To use this type of breather, the reservoir must be capable of withstanding the small amount of pressure involved. This type of system can improve the performance of the hydraulic system by providing a pressurized supply of fluid to the pump.

Provisions should also be made for the crew to be able to drain the reservoir to clean out contaminants or to replace the fluid. This drain should be located so that spills that are difficult to clean up can be avoided. If an open drain overboard is not possible, a length of line should be run from the bottom of the reservoir to a place where it can easily be drained externally. This drain valve or plug must be protected to minimize the possibility of the hydraulic system being inadvertently drained.

4-4.2.3 Accumulators

Hydraulic accumulators are used primarily for two purposes, namely, as a fluid power storage device and as a pressure attenuator to absorb pressure spikes. They exist in various configurations for storing the energy. The most common method of operation is to compress an inert gas, usually nitrogen. The pressurized gas and the accumulated fluid are separated by either a flexible elastomeric bladder that holds the gas or a piston (much like a hydraulic cylinder, but without a rod). In either case the gas is usually precharged to a preset pressure, which must be exceeded before the accumulator will begin to accumulate hydraulic fluid.

A rupture of any of the plumbing that contains an accumulated volume of hydraulic fluid can be very dramatic. If not properly contained, the resulting very short duration, but extremely high rate of flow of fluid being released can result in considerable damage and personal injury. The rupture of an accumulator can greatly complicate an already hazardous fire situation.

The risks associated with accumulators can be minimized by using certain precautions in the layout and design of the system. The accumulators should be located remotely from any occupied compartment, and there should be a valve to shut off the discharge of fluid from the accumulator if a line or fitting bursts. This valve should be located as close as possible to the accumulator. One type of valve that can be used is a velocity fuse; it is sized so that if the flow through it exceeds a certain level, it will block the flow. Another possible valve is a pilot-operated check valve that would block the flow of fluid out of the accumulator unless there is a sufficient pilot pressure signal applied to it to indicate that the system is intact.

An accumulator unloading valve should be used as a general safety precaution, as well as a fire prevention measure. This valve gradually releases the fluid from the accumulator thereby relieving the pressure when the vehicle is shut off. Thus unintentional actuation of a system function is avoided when the system is off. Also, when service or repairs are made on the system and fittings are loosened, the risk of fluid squirting all over the vehicle due to unsuspected trapped pressure is reduced with this type of valve. Thus the chances of spraying hydraulic fluid onto a hot surface or creating a fluid spill that cannot be easily cleaned up are reduced. This pressure-drain system should have a selector valve switch that permits pressure retention in a combat situation when the hydraulic system is needed while the main vehicle power is off.

A precaution that should always be taken with accumulators is to mount them and their connecting lines so that no external forces can cause any of the connecting line fittings to fatigue and fail. Preferably the accumulator should be rubber mounted, and the line joining it should have at least a short section of flexible hose.

4-4.3 CIRCUIT LAYOUT AND LOCATION

The location, routing, and retention of lines, valves, fittings, and other hydraulic system components can contribute considerably to the fire survivability of a vehicle. Vehicular vulnerability can be reduced and hazardous situations avoided by selection of the proper system design and appropriate components.

Isolation of hydraulic subsystem damage is an extremely important survivability technique that should be designed into hydraulic systems. The goal of this technique is to prevent a single damaged subsystem from affecting the operation of an undamaged subsystem if a redundant system is used. The benefits of using dual controls are voided, however, if the controls are not isolated from each other, e.g., if a main line is severed, all hydraulic subsystems become nonfunctional. If this condition occurs and the pumps continue to operate, a potentially serious flammability hazard could develop.

4-4.3.1 High-Pressure Side

Hydraulic fluid lines are usually highly pressurized and are located throughout the vehicle. Therefore, the hydraulic power system of a vehicle can be more hazardous than a properly designed fuel system. It is highly recommended, therefore, that high-pressure hydraulic lines not be located in occupied compartments of a vehicle. The entire fluid volume of the hydraulic system can be pumped into the compartment in a matter of seconds if proper precautions are not taken. A pinhole leak or a crack in a high-pressure line can present several hazards. It can cause a spray of fluid that can leave an ignitable mist or fog in the compartment, as well as create a serious breathing problem for the occupants. Also high-velocity jets of high-pressure fluid can result in physical injury, such as cutting the skin and even injecting the fluid into the blood stream. If such an injection were to enter a vein so that a mass were to enter the heart, death could result. More probable, though, would be a spreading of the hydraulic fluid through the tissue, which would result in severe tissue damage.

The location of high-pressure hydraulic lines and components in occupied compartments can usually be avoided by using remotely actuated control valves. Remote operation can be mechanical by using linkages and/or cables. Pilot pressure for an actuator is controlled by a smaller directional control valve manipulated or pedaled by the operator. Control valves can also be actuated by using a pilot pressure, usually less than 1.4 MPa (200 psi). The use of pilot control valves replaces the larger high-pressure lines with smaller low-pressure lines and requires additional pilot control valves. Other considerations that impact the selection of the type of control valve actuation to be used are function, reliability, and fluid type.

If it is not possible to eliminate the high-pressure hydraulics, including the hydraulic recoil components of main guns, from the occupant compartment, precautions such as using nonflammable fluid or spall liners should be taken to minimize the hazard of impact by spall and to prevent the spray of fluid within the compartment. These same precautions should apply to the engine compartment or other areas that may contain ignition sources. Provisions should be made in the circuit to shut off the flow automatically from each side of the break if a line ruptures.

All actuators should have crossover load-holding or load-controlling valves located at the actuator. An actuator that is supporting a load can act as a pump and discharge its fluid contents if a line ruptures. A crossover load-holding valve consists of two pilot-operated check valves, each of which allows free flow into each side of the actuator. The pilot pressure for each check valve is sensed from the opposite side of the actuator. Thus the only time fluid can discharge from the actuator is when the opposite side is pressurized. A crossover load-controlling valve is very similar except that a pilot-operated relief valve is used for applications that require accurate control of high loads.

All directional control valves whose discharge lines pass through an occupied compartment or other critical areas should have provisions to shut off the flow if a discharge line ruptures in order to contain the supply side of the rupture. These provisions could include pilot-operated check valves or pilot-operated relief valves that shut off the flow at the directional control valve or even closer to the pump.

4-4.3.2 Low-Pressure Side

The low-pressure hydraulics include all of the return lines from all of the control valves and also the suction line from the reservoir to the pump. Although these lines are not exposed to high pressures, they must be treated with somewhat the same precautions as the high-pressure side of the system. Although there will be no high-pressure leaks, poor line and fitting connections can still leak and leave puddles of fluid, and ruptured lines can allow the release of large quantities of fluid.

The rupture of a low-pressure return line can result in the discharge of all fluid being returned through that line. In addition, the reservoir side of a ruptured return line can allow the fluid from the reservoir to be siphoned out since the return line usually empties into the reservoir below the fluid level to avoid aeration. Each return line to the reservoir should have a check valve to allow free fluid flow only into the reservoir.

To contain the system fluid on the control valve side of a ruptured return line requires special consideration. If the return line from a directional control valve to the reservoir is in a vulnerable location, the potential for that return line to rupture must be addressed. Since the return line pressure is usually equivalent to atmospheric pressure, it cannot be used as a pilot pressure to signal the control of the high-pressure side. One technique is to install a pressure-regulating valve in the return line at the reservoir after any coolers or filters. The back pressure of the return line could then be regulated at a low level, i.e., below the pressure limits of the cooler and filter, but high enough to provide a reasonable pilot pressure signal. A pilot-operated check valve or a pilot-operated load-controlling valve could be placed in the high-pressure side just following the main system relief valve. This valve should be sized so that as long as sufficient back pressure exists in the return line, unrestricted high-pressure fluid will flow to the system. If back pressure is lost (due possibly to the rupture of a return line), the valve will close. For a closed center system the pump flow would be returned directly back to the reservoir through the main system relief valve, and for an open center system the pump would destroke. For start-up conditions provisions must be made to allow some flow to the return line so that back pressure can build up; the internal leakage past the pilot-operated load control valve may be sufficient.

4-4.4 MATERIAL CHOICES

The materials used in hydraulic systems can have an impact on the fire survivability of a vehicle. Material choices must be made for the following areas of consideration: the hydraulic piping, hydraulic fittings, and elastomers contained in other hydraulic components.

4-4.4.1 Hydraulic Piping

Hydraulic piping systems usually are constructed from three types of fluid conductors: flexible hose, tubing, and pipe. A flexible hose is used to accommodate relative movement between components. Most of the stationary piping, however, is either tubing or pipe. The advantages of tubing include better appearance, greater flexibility, better reusability, fewer fittings, less leakage, and simpler battle damage repair. The principal advantage of pipe is relatively low component cost.

The use of flexible hose should be minimized. Flexible hose is susceptible to damage by heat from engine hot spots and from an existing fire; it may begin to leak and thus provide additional flammable liquid to the fire. The hose is also susceptible to wear from abrasion, and its fittings are susceptible to fatigue from vibration to the point of rupture. Flexible hose should, however, be used where significant relative external loads that cause deflections are applied to the hydraulic lines. Thus overstressing and fatiguing of steel fittings and tubing can be minimized.

An appreciation of the amount of damage these hydraulic lines could sustain can be gained by examining some CRES 321 and Aluminum 6061 tubing, shown on Fig. 4-25. The CRES 321 tubes had been filled with Oronite 8515, a silicate ester hydraulic fluid with a flash point of 202°C (395°F), and pressurized to 27.6 MPa (4000 psi) before being hit by fragments from a 23-mm HEIT projectile. The Aluminum 6061 tubing was empty when hit by fragments from the same projectile. These tubes had been located behind an aluminum box into which the 23-mm projectile had been fired. Fragments from the projectile penetrated the box, made of 2.29-mm (0.090-in.) thick 2024-T3 aluminum sheet, before striking the tubing. The extreme damage to the larger aluminum tube and to the two CRES tubes was due to impact by both the heaviest—some over 6.5 g (100 gr) moving approximately 610 m/s (2000 ft/s)—fragments and the blast from the 23-mm projectile. Note that the 25.4-mm (1-in.) outside diameter (OD) CRES 321 tube was severely distorted and bent, as well as perforated, the 12.7-mm (0.5-in.) OD Aluminum 6061 tube was severed and a section blown away, and the 12.7-mm (0.5-in.) OD CRES 321 tube had a short section cut out, as well as being nicked. These tubes were located approximately 51 mm (2 in.) behind the rear surface of the box, and the box immediately in front of the 12.7-mm OD aluminum tube had a 51- × 76-mm (2- × 3-in.) hole cut out by the fragment impacts and blast. A series of titanium 3% by weight aluminum 2.5% by weight vanadium (Ti-3Al-2.5V) tubes had been mounted on the right side of the box. These tubes were filled with silicate ester hydraulic fluid and also were pressurized to 27.6 MPa (4000 psi). They were subjected to impacts of "side spray" fragments—0.9 g (14 gr) moving approximately 1220 m/s (4000 ft/s)—but no blast. These Ti-3Al-2.5V tubes were merely perforated by the fragments that impacted. In an earlier test several lengths of dry Ti-3Al-2.5V tubing located behind the box sustained multiple heavy fragment impacts, blast, and damage similar to that sustained by the CRES 321 tubes. The silicate ester hydraulic fluid sprayed into the test chamber, ignited, and burned explosively.

Stainless steel lines should be used where possible. Any long section should be supported by insulated clamps to stiffen the section in order to prevent excessive vibration and possibly fatigue and failure. The insulating material should be flexible and nonflammable, but not rubber.

4-4.4.2 Pipe Fittings

Pipe and tubing fittings can be either threaded or permanent. Permanent methods include various forms of brazing, welding, swaging, and adhesive bonding, and these assembly methods can be applied where low initial cost, reliability, and weight are important factors. Permanent installation, however, makes battle damage repair more difficult.

Threaded pipe-fitting techniques include tapered pipe threads, flanges with O-ring seals, Society of Automotive Engineers (SAE) O-ring ports, O-ring face seals, and straight thread ports with metal seals, which include flared fittings.

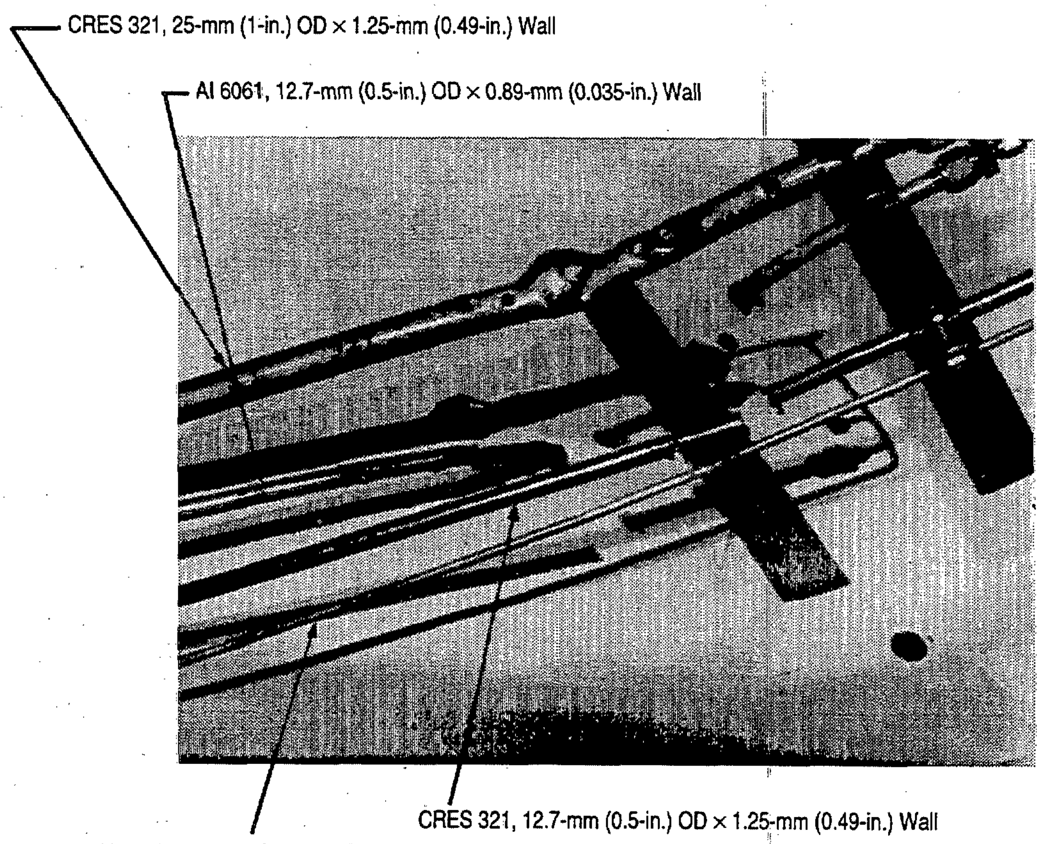


Figure 4-25. Damage to Stainless Steel and Aluminum Tubing

There are several concerns in selecting fitting types with regard to fire survivability. Typically, fittings that contain an elastomer seal are less likely to weep and leak over an extended period of time. If subjected to high temperatures, however, the elastomer compound can break down and the seal can fail. On the other hand, fittings that rely on metal-to-metal sealing are less susceptible to failure under high temperatures, but they have a tendency to develop weeps and leaks under normal operation, particularly when they are subjected to high vibration levels. Because of their historical tendency to leak, tapered pipe fittings should be avoided, especially on the high-pressure side.

What type of fittings to use depends upon which is more critical, elimination of any continuous leaks or weeps that may provide fuel for an ignition source or minimization of the chance for subsequent leaks given the presence of high temperatures and an existing fire.

4-4.4.3 Elastomeric Seals

One challenge of designing hydraulic fluid systems is ensuring the compatibility of the fluids with the elastomeric seals and metals. The petroleum-based hydraulic fluids usually cause most elastomeric materials to swell; most seal designs assume that the elastomeric material swells approximately 5%. The elastomeric material is selected to minimize dissolution in the fluid. Hence butyl and natural rubbers are excluded. Chlorotrifluoroethylene (CTFE) swells, softens, and dissolves rubber, both natural and synthetic, and requires the use of vinylidene fluoride-hexafluoropropylene copolymer Grade G, low temperature (GLT) for elastomeric seals. CTFE also attacks pure aluminum. As for water-based fluids, water hydrolizes the outer surface of nitrile and natural rubbers, i.e., water leaches the plasticizer and causes surface hardening and crazing. If salts are used to suppress the freeze point of the water, the alkaline salts, such as potassium acetate ($KC_2H_3O_2$)*, could attack pure aluminum, but could passivate steel, whereas the acidic salts, such as calcium chloride ($CaCl_2$)*, could corrode both steel and aluminum. Neoprene is not recommended for use with either petroleum- or water-based fluids because it swells in the presence of the petroleum component. Simi-

*When either potassium acetate or calcium chloride is used in aircraft or ground vehicles, the formulation used should include corrosion inhibitors.

larly, both natural rubber and butyl swell. The capabilities of elastomeric materials with various types of hydraulic fluids are shown in Table 4-3.

4-4.5 LESSONS LEARNED

4-4.5.1 Locating Hydraulic Lines Near Hot Spots

The USASC records document several incidents of M1 MBT engine compartment fires that occurred when a hydraulic line fitting failed due to fatigue and provided a spray of hydraulic fluid onto the hot combustor can. The spray ignited on contact with the hot can, the fire burned through the hydraulic lines and increased the leakage, and a major engine compartment fire ensued. The Halon fire extinguisher extinguished the fire, but as soon as the Halon concentration dropped to the point at which it no longer inhibited combustion, the fire reignited since there was still hydraulic fluid in contact with the hot combustor can. This process was repeated for a second fire extinguisher action (manual this time); then the crew used portable fire extinguishers on the fire and/or summoned other help.

Solutions to this challenge include (1) not locating hydraulic lines where they can spray fluid onto hot spots, (2) using nonflammable hydraulic fluid, (3) eliminating or covering the hot spots, (4) using electric power instead of hydraulic power, (5) designing better lines and fittings or their installation, and/or (6) using a more effective fire-extinguishing system, i.e., one that cools the heated metal items below the ignition temperature of the combustible fluids.

4-4.5.2 Hydraulic Fluid Line Cut With a Torch

In one incident in the USASC database, a mechanic severed a pressurized hydraulic fluid line with a cutting torch while working on an M110 SPH. The hydraulic fluid sprayed out and ignited. This error might not have happened if the lines containing flammable fluids were color coded red.

4-4.5.3 Hydraulic Fluid Line Protection

The test program involving simulated behind-armor debris impacting pressurized fire-resistant hydraulic (FRH) fluid tubing (Ref. 46) (described in subpar. 3-3.4.1) provides design information and potential survivability enhancement techniques. Finnerty et al found that FRH fluid per MIL-H-46170 would emerge from a 304 stainless steel tube in the form of a mist, ignite when exposed to an ignition source at a temperature below the FRH fluid flash point, and burn to completion. They also established that tubing perforation could be predicted using a simple extrapolation of THOR equations (Ref. 47) by assuming that the CRES 304 would react as does mild steel. They found that the tubing was less likely to be perforated when the fragment size approached the tubing diameter. They also found that perforation of the tubing was not a function of the internal pressure.

The two survivability enhancement techniques that they tested, but did not optimize, were (1) using steel shielding over the hydraulic tubing and (2) enclosing the hydraulic fluid tube in a layer tube and packing the annular space with a powdered fire extinguishant. The shielding was to prevent rupture of the hydraulic fluid lines. The fire extinguishant jacket was to preclude sustained combustion. Both techniques were effective.

4-5 ELECTRICAL SYSTEMS

The design of wiring for military vehicles should be addressed from the inception of the vehicle design itself. The appropriate military standards should be consulted during all design phases. Easy accessibility to all electrical system components for ease of field service and repair must be addressed. Methods to prevent the electrical system from becoming the ignition source for fires can be integrated into the system design. Abrasion and breakage of wiring have always been a problem. Corrosion of electrical contacts and wire surfaces produces resistance heating, which can be an ignition source. These problems should be addressed during the design phase to circumvent future problems and help prevent fires.

TABLE 4-3. ELASTOMERIC MATERIALS COMPATIBILITY (Ref. 45)

HYDRAULIC FLUID	NATURAL RUBBER	NEOPRENE	NITRILE	BUTYL	FLUOROCARBON
Petroleum-based*	P	F	Ex	P	Ex
CTFE**	P	P	P	P	G
Water-based†	F	F	G	F	Ex

Ex = excellent, G = good, F = fair, P = poor

*Based upon oil resistance data in Table A3-10, Ref. 45.
**Based upon Parker Report DD3562, Ref. 45.
†Based upon water/steam resistance data in Table A3-10, Ref. 45.

Future electrical and electronic subsystem requirements and functions of combat and tactical vehicles are to be defined in accordance with the Standard Army Vetronics Architecture (SAVA) (Ref. 48). SAVA provides more efficient integration of the vehicle electrical systems and real-time integration with the electronic battlefield.

The four functional SAVA subsystems are (1) data control and distribution, (2) power generation and management, (3) computer resources, and (4) crew controls and displays. SAVA is to be implemented as a family of basic modular hardware and software elements, i.e., building blocks, that can be assembled in a variety of configurations tailored to the requirements of a specific vehicle. SAVA permits the designer to select a higher voltage level (270 V dc) in addition to the nominal 24 V dc under the power generation and management subsystem with accompanying safeguards. The capability is achieved through conversion or dual generation.

Vehicular subsystems, such as fire detection and extinguishing, should consider the interface requirements of SAVA. SAVA has the ability to recognize and service a vehicular fire emergency, but the agency responsible for procuring a specific vehicle must approve the SAVA design implementation because of the stringent time and reliability requirements for firing the extinguisher using a bus system. Finally, SAVA requirements should be considered in making choices regarding the voltage of the system, circuit design, and interconnecting wiring, including material. (Ref. 49)

An alternative to the hydraulic power system for gun and turret is an electric power system. The French use an electric power system for turret and gun in their latest MBT, the Leclerc, and the Israelis have selected an electric power system for their Merkava III.

The US Army Armament Research, Development, and Engineering Center has explored the feasibility of using electric power for the turret and main gun of the M1A1 MBT with the following results (Ref. 50). The electric power system could achieve a 20 to 30% decrease in power system weight and volume over the current hydraulic power system. The electric system has higher efficiencies for dynamic loads, but the hydraulic system performs better for static loads. A comparative evaluation of electric versus hydraulic power systems indicates that an electric system should be easier to maintain. An electric system might be subject to EMI, whereas a hydraulic system would not, except for the electric controls of the hydraulic system.

There are advantages and disadvantages stated in Ref. 50 for each system, such as quiet operation for an electric system, especially in a static situation, but batteries must be recharged. In Cassino in March 1944 some New Zealanders detected a German tank that had been built into the cellar of a building by hearing the tank motor running. The tank crew had been directing artillery fire onto the New Zealanders from within the New Zealand position for five days, but the Germans had to recharge the batteries in the tank to continue operating their radios (Ref. 51).

Electric power is a feasible alternative to the hydraulic power system currently used in US combat vehicles; the details have to be worked out.

4-5.1 VOLTAGE CHOICE

Presently, US military vehicles use a 24-V dc system. There are pros and cons to going to a higher or lower voltage circuit for power. A higher voltage circuit is more efficient, can lower contact resistance, and decreases current requirements. Shock hazard and arcing, which may cause fires, however, become a much greater risk. A lower voltage circuit increases current flow, and wire sizes would have to be adjusted for this increase in current. With a lower voltage, contact resistance or any corrosion on the wiring can cause excessive heating and result in insulation melting, arcing, or fire. The 24-V dc system is a compromise established as a standard for military vehicles. Some combat vehicles, however, also have higher voltages for special equipment. As of May 1993, combat ground and air vehicles being designed may use 270-V dc for some of their systems. For example, some of the newer combat vehicles might use 270-V dc electric power for turret drive and/or power loader for the main gun.

Storage batteries located on modern combat vehicles must provide both the power required to start the engine and the considerable power required by the many systems of the vehicle during extended periods of use when the engine is not operating. In some vehicles the storage batteries provide power during load peaks while the engine is operating. These requirements, combined with the vehicle requirement for operation in a wide variety of severe environments, pose a significant challenge to combat vehicle designers. Two types of storage batteries are commonly used to provide the necessary power, namely, lead-acid and nickel-cadmium. Lead-acid batteries are the primary reservoir of stored power because they are best able to provide the large amounts of power over extended periods at environmental extremes. For a variety of reasons, modern combat vehicles use several lead-acid batteries wired together in series and parallel to provide the necessary power at the 24-V dc system voltage. Several disadvantages of such batteries, in addition to the large volume they occupy, relate to their potential for being an ignition source for fire. Lead-acid batteries must be kept charged at all times to preclude early failure. Thus a spark hazard can exist if the batteries are overcharged. Overcharging the batteries can also result in the generation of combustible gases. During servicing or replacement, connections can generate sparks if a load is present, or inadvertent shorts can occur. Battery connector corrosion can cause excessive heating and become an ignition source. Finally, the corrosive nature of the electrolyte combined with the need for battery servicing can lead to accidental spills of acid on adjacent components.

Nickel-cadmium batteries use an alkaline-based electrolyte. Such batteries are used in a wide variety of special purpose situations. They can be charged or discharged at high rates without formation of the corrosive fumes that are characteristic of a lead-acid cell. If a nickel-cadmium battery is sufficiently discharged, however, a reversal of chemical action can occur and be accompanied by a release of hydrogen and oxygen, a highly flammable or explosive mixture.

For some very high-voltage applications, lithium batteries are being considered for use (Ref. 52). For low-voltage (24-V dc), but high-amperage, use, lithium sulfur dioxide or lithium thionyl chloride batteries are under consideration, as are other batteries (Ref. 53).

4-5.2 MATERIAL CHOICES

Consideration must be given to the materials used to wire military vehicles. Each wire that delivers electricity to the various electrical accessories must be capable of carrying the amount of electricity required by all of the accessories serviced by that wire. Momentary peak current and sustained current must be considered for each circuit. Wire that is of too small a size for a circuit can be a potential fire hazard due to overheating. Copper should be used as the primary wiring because of its conductivity, durability, and resistance to corrosion. The choice between using solid or stranded copper wire must be made while considering both corrosion and fatigue resistance. Solid wire is more resistant to corrosion; stranded wire is more resistant to fatigue caused by vibrations and flexing. Aluminum wire should be avoided due to its rigidity and the fact that its electric current densities are 75% of those permitted in copper. The maximum current capacity for stranded copper wire is a function of many things, such as insulation, temperature, ventilation, wire length, and bundling, as discussed in AMCP 706-360 (Ref. 54). Coaxial and special purpose cabling must not only meet the operational and current capabilities of the circuit but also should be flexible enough to withstand the constant vibration. Broken wires and cables can lead to arcing, which can ignite combustibles.

Insulation used on wire and cables should (1) be impervious to all of the fluids typically used in military vehicles, (2) remain flexible at low temperatures and throughout its life cycle, (3) be flame resistant, (4) not produce toxic products when exposed to fire, and (5) possess high abrasion resistance. Some types of insulating materials contain added chemicals that inhibit combustion and may reduce or nearly eliminate smoke. Smoke and noxious fumes from burning or smoldering insulation and adjacent materials can induce personnel to evacuate combat vehicles prematurely. Wire and cable insulation used in modern combat vehicles includes neoprene, nylon, and Teflon™. Insulation properties must be considered from a safety, as well as from an operational, point of view. For further information on the properties of insulators, see subpars. 3-6.1 and 3-6.6.1.

Connectors must withstand the rigors of military operation and meet the operational requirements of voltage, current, mechanical strength, vibration resistance, water and corrosion resistance, and serviceability. To facilitate field maintenance in a combat environment, separable, quick-disconnect, keyed connectors that provide strain relief to the wires should be used to allow quick electrical component replacement. Connections meant to be permanently installed should be made with a high-pressure joint or solid metal joint that is both mechanically and electrically stable. Printed circuit vehicle wiring should not be considered because it is not readily field repairable nor can it withstand heavy vibration.

4-5.3 CIRCUIT DESIGN

Electrical circuits within a military vehicle must be properly designed to meet operational capabilities safely. The correct wire material, size, and insulation must be selected for each circuit. Fuses, circuit breakers, or ground fault interrupters (GFI)* must be used to protect the various circuits. These fuses, circuit breakers, or GFIs must be rated at a current value above the normal operating current of the line they are protecting, but not so high that damage or fire can occur because of an underprotected circuit. All three devices must be fast acting and sealed to prevent ignition due to an exposed arc in a combustible atmosphere. The circuit breakers should reset automatically when the excessive load is removed from the circuit. The use of fuses that must be replaced when they fail should be avoided if possible because stocks of fuses would have to be carried and personnel trained in the proper replacement procedures. Visible arcing can recur if the reason the device malfunctioned was not fixed prior to fuse replacement or circuit breaker or ground fault interrupter reset.

Diode protection devices are available to ensure that batteries are installed with the correct polarity of voltage for their respective circuits. Wiring cables for battery compartments should be designed so that it is impossible to install the batteries incorrectly. Wire numbering and circuit tagging should be done to facilitate maintenance. Judicious use of connectors in the wiring scheme is imperative. Electrical systems that provide survivability should be redundant, and circuit breakers should protect the redundancy. An "H" pattern with circuit breakers at the ends of the cable and one in the center tie cable provides a much greater redundancy than two separate circuits. Redundant cabling should be kept separate from primary cabling. The redundancy should

*A fuse is a piece of metal that will melt when heated by excessive current. A circuit breaker is a bimetallic element, which, when heated, springs to another position and opens an electric circuit. A ground fault interrupter is a circuit breaker, the element of which is heated by a current flow to ground.

be automatic so that no mechanical switching is required when a primary line is lost. Redundancy of critical circuits should be evaluated during the circuit design. The type of power plant to be used must be considered when discussing redundancy of wiring and "limp home" capabilities. Diesel and turbine engines generally keep running after loss of battery systems; gasoline engines, however, require some battery support. All three types of engines need battery support to restart after a stop. The ability to switch a battle-damaged electrical circuit easily to an undamaged vehicle system would be an asset. Designs for redundant circuitry should be kept simple yet provide the necessary power to a critical circuit should one line be damaged. Wiring should be routed so that it is protected from damage caused by normal vehicular operations and normal loading and unloading of equipment, as well as from battle damage. If possible, electrical cables should be routed away from hazardous fuels and combustible fluids and sharp implements that can cause insulation damage. A conduit can provide protection, but maintenance of a wire within a conduit can be difficult. Cable troughs with easy-opening covers may be a better solution. The wiring should be retained in place by cable ties or clamps to eliminate wire breakage or insulation damage due to vibration. The wiring should not be stressed by the retention device, and adequate slack for expansion and contraction must be provided. Cabling that requires constant flexing should be able to withstand this abuse.

4-5.4 LESSONS LEARNED

Most of the lessons learned are from the USASC data packet. There were 77 incidents from a total of 237 in which the fires were ignited by the electrical system of the vehicles.

4-5.4.1 Flammability of Electrical Wire Insulation

In at least 18 of the USASC fire incidents, the only combustible that burned was the wire insulation.

Three incidents in the SEA BDARP database illustrate the flammability of electrical wire insulation. In two incidents (DANs 463 and 670) AR/AAV M551s were hit in the turret by RPGs, and in the other incident (DAN 671) an APC M113A1 was hit by an RPG; the electrical wiring harness was damaged and the insulation was ignited. In two of these three incidents the vehicle sustained major damage due to the insulation fires; in the third incident (DAN 670) the damage was minor because the vehicle commander extinguished the fire with a handheld extinguisher. In another incident in SEA (DAN 632) the jet from an RPG passed into the battery box of an AR/AAV M551 and again caused the electrical wiring insulation to burn. Had the wire insulation been nonflammable* or at least self-extinguishing**, the vehicles could have been repaired much more quickly.

4-5.4.2 Electrical Fusing Improperly Sized, Selected, or Located

In approximately 77 of the 237 incidents of fires in the USASC data packet, the fires were ignited by electrical short circuits. In the vast majority of these incidents, the short circuit had to dwell a significant time before the combustion was well-seated. This fact indicates that whatever current-interrupting device was used was either not located to react to the short circuit, was not properly sized, or did not have an adequate response. Better circuit design or selection of a more responsive device could prevent such vehicular damage.

In three of these USASC database incidents, jumper cables connected to other vehicles were overloaded and resulted in ignition of the jumper cable wire insulation. When a vehicle needs a jump-start, personnel in any nearby vehicle will attempt to provide that jump-start, and the vehicle will often draw much more current than usual. One way to protect the jumper cables would be to build in a circuit breaker.

In two other USASC database incidents, radio antennae contacted external power cables. Antennae could also be provided with excess current interruption capability, i.e., an in-line fuse located, preferably, within the vehicle. A fuse will not cause undesirable radio "noise".

4-5.4.3 Electric Short Melts Through Combustible Fluid or Gun Propellant Container

In twelve of the incidents of electrical shorts in the USASC database, the electrical discharge caused a melt-through in a fuel cell wall or a fluid line and ignited the combustible fluid; in five other incidents the electrical discharge resulted in a melt-through in a main gun cartridge case and ignited the gun propellant. These cases occurred in M1, M48A3, and M60 MBTs and in M88 TRVs. In an incident that occurred in Amberg, Germany, in 1966, the electric power shorted in an M109 turret ring and ignited propellant. The crew chief could not extinguish the resulting fire with a portable carbon dioxide fire extinguisher. The fire continued until some of the high-explosive-filled munitions

*At the present time the only truly nonflammable electric wire insulation is a combination of ceramic beads strung on the wire and a metallic sheath. This type of insulation is not flexible; it would be installed in the same manner as stainless steel hydraulic tubing.

**Sulfinated chloropolycarbonate and sulfinated polyvinyl chloride wire insulations are self-extinguishing under most conditions.

stowed aboard started to explode and blew the turret from the vehicle. The local fire department managed to extinguish the fire by using a water cannon from behind cover. The vehicle was a total loss (Ref. 55). Vehicular design should assure that electric power cables are isolated from fuel-containing components and stowed ammunition.

4-5.4.4 Electric Spark Ignition of Flammable Fluids

In another nine incidents in the USASC data packet involving M60 MBTs and M113 series vehicles*, flammable fluids were sprayed on electric generators whose sparks, which are normally emitted when a rotor spins past brushes, ignited the combustible sprays. These fires could have been prevented by installation of a cover over, or explosion-proofing, the generator or by routing the plumbing containing combustible fluids so that any drip or spray could not contact the electric motor or generator.

4-5.4.5 Wiring Routing and Fastening

In a fire incident in the USASC database, the power cable near the bottom of the turret basket of a BFV was not fully clamped down after a maintenance operation. This cable protruded so that the turret basket abraded the insulation, then shorted the cable, and a fire of the wire insulation resulted. Use of nonflammable insulation would have reduced the resulting repair effort, but a better solution is to install the cable where contact with other items is not probable and to use a conduit or metal cover (which would also provide protection from spall) to protect the cable so that even a sloppy maintenance operation could not cause a component to contact the wire or cable.

4-6 AMMUNITION

A description of the effect of antitank fire on tanks in North Africa (1941-1942) follows:

"A direct hit in the fuel [cell] was crippling, but more dangerous was the shot that, penetrating the main armor, set fire to the cartridges of the gun ammunition. In a few seconds, the tank became a furnace." (Ref. 56).

This effect has not changed with time. In one of the incidents in the SEA BDARP database (DAN 157), an RPG-2 jet hit the case of a stowed 90-mm cartridge in an M48A3 MBT. There was a flash fire followed in approximately one minute by an explosion. The driver was killed, and the tank commander and loader, who were standing partially out of their hatches, were blown out of the vehicle. The vehicle was damaged so severely that it was not worth repairing. In a second incident involving an AR/AAV M551 (DAN 310), the charge of a single 152-mm cartridge was ignited by the jet of an RPG-2. The resulting flash fire severely burned all four crewmen. The vehicle suffered major damage (200 man-hours of repair time), but it was repairable. Fortunately, the rest of the ammunition did not ignite. In another such incident, again involving an M551 hit by an RPG-2 (DAN 1550), the crew was not as fortunate. All four crewmen were killed and the vehicle was destroyed. The jet apparently hit rounds in the right front ammunition rack. Witnesses said that a huge fireball engulfed the vehicle and was followed in 3 to 5 s by an internal explosion, which was in turn followed in another 3 to 5 s by a second internal explosion. The jet might have hit more than one cartridge case, all of which are combustible.

Even vehicles that use main gun calibers smaller than the 105 mm are not immune to the explosion of cased propellant, as was shown in Southwest Asia in 1991. An M2A2* infantry fighting vehicle (IFV), which mounts a 25-mm main gun, was outmatched by an Iraqi T-72 mounting a 125-mm main gun (Ref. 57). The 125-mm projectile penetrated the IFV M2A2 frontal armor and initiated the propellant charge(s) of one or more 25-mm cartridges. Some of these cartridges deflagrated and ignited a fire that quickly destroyed the vehicle. The driver was hit by large fragments, and the gunner, in an open hatch, was "lifted off" the vehicle. (Two other crew members, the vehicle commander and another soldier, evacuated the vehicle; the TOW missiles were apparently not involved until after the personnel evacuated the vehicle.) As a result of the fire and explosions, the largest piece remaining of the vehicle "could probably fit into your briefcase." (Ref. 58).

Solid rocket motor propellants, and to a lesser degree, solid gun propellants, and high explosives contain most of the oxidizer, as well as the fuel, needed for combustion. For this reason, propellant or explosive fires are more likely to occur given a ballistic hit than are liquid fuel fires. Solid rocket propellants are usually closer to a stoichiometric oxidizer-to-fuel mixture ratio than are high explosives; therefore, they are more susceptible to reacting violently given a ballistic impact. Methods for enhancing crew and vehicle survivability after solid propellant or high-explosive initiation due to ballistic impact usually are containment and/or redirection of the explosive effects away from critical areas.

The subsequent subparagraphs identify various munitions types, the types of storage provisions and locations in use, and the potential types of fire damage. New propellant developments that reduce the possibility of a catastrophic fire are discussed.

4-6.1 AMMUNITION TYPES

The ammunition stowed in combat vehicles is either for onboard use or is being transported. Its stowage must be planned to minimize the hazard it presents, as well as to

*Usually the M577 command vehicles, which have an electric generator with associated engine and gravity-feed engine fuel supply mounted above and forward of the troop compartment

*This IFV M2A2 was assigned to the armored cavalry unit because CFVs M3A2 were not available.

assure its availability for use. The ammunition for onboard use is either for the main weapon or for a secondary weapon or ancillary device. The ammunition for the main weapon usually presents the more severe hazard; both the type of propulsion and warhead must be considered. Secondary weapons are usually small arms, but they may also be small mortars, semiautomatic grenade launchers, or light antitank weapons (LAWs). Ancillary devices include smoke grenade launchers. The individual crewmen's weapons are also included. The ammunition being transported must be considered primarily for the types of hazards presented. These hazards are due to the contents, explosive or chemical, of the transported ammunition.

4-6.1.1 Ammunition for Onboard Use

Ammunition for onboard use must be readily available. Primarily the main weapon must be serviced. This main weapon can be a high-velocity gun, as for the M1 MBT; a lower velocity howitzer, as for the M109 SPH (155 mm) and the M110 SPH (203 mm or 8 in.); a combination gun and missile launcher, as for the M551 AR/AAV (152 mm); or a missile launcher. There can be two primary weapons, e.g., the Bradley fighting vehicles that have both a TOW launcher for antitank use and a 25-mm automatic cannon.

Vehicles are designed to carry a given quantity of ammunition based upon specific needs; however, the ammunition needs frequently change. Although the ammunition mix to be stowed at any particular future time cannot be predicted, ammunition stowage capability to handle any mix within current ammunition availability should be provided in the design.

4-6.1.2 Transported Ammunition

Some vehicles are intended to transport bulk ammunition, and on some occasions any vehicle may be required to transport such ammunition. The ammunition can be for onboard use in any of the combat vehicles, for use by infantrymen or artillery, and items such as ammunition for aircraft or bulk explosives. Transported ammunition need not be available for use within the transporting vehicle or readily available when the troops dismount. Therefore, reduction of the hazard presented to the vehicle and its crew should be the primary stowage design goal. In fact, these items could be carried in a trailer, the loss of which would not have anywhere near the import of the loss of the vehicle.

4-6.1.3 Relative Ammunition Hazard Assessment

To assess the relative hazards presented by different types of ammunition, the means of propulsion and the types of warheads must be considered. The means of propulsion are rocket motor, gun propellant, or none, e.g., bulk explosives or hand-thrown grenades. Warheads are high explosive (HE) filled, pyrophoric chemical filled, reactable chemical filled, toxic or irritant chemical filled, inert, or radioactive. The sensitivity of these munitions to ignition or initiation must be considered, as well as the effects the ammunition could have upon the personnel and the vehicle if the energetic materials were ignited or initiated. With regard to sensitivity to initiation or ignition, the threat impacting the cartridge or device is of greatest importance. The capability of a shaped-charge jet to ignite or initiate energetic materials can be equaled only by a strong electrical discharge. The detonation of a high-explosive shell is a close third in its capability to initiate explosives. Kinetic energy penetrators, however, have a lesser ignition capability.

The initiation and ignition agents to be considered are (1) a shaped-charge jet, (2) the arc from an electrical short, (3) the detonation of a small high-explosive projectile (20 mm, 23 mm, 25 mm, 30 mm, or other calibers that would not severely distort the vehicle structure), (4) the impact of a KE penetrator or a fragment from a high-explosive shell, (5) spall from vehicular components that results from a ballistic penetration, (6) the impact of the slug from a shaped charge, (7) fragments from a bursting cartridge case, and (8) heat or flame from burning items within the vehicle. In general, a shaped-charge jet, small HE projectile, or KE penetrator must perforate the case or body surrounding the energetic material for it to be affected. Usually the more energy imparted to the energetic material, the more violent the reaction. In addition, the reaction can well increase in violence as it proceeds, i.e., a combustion can increase to a deflagration, and/or a deflagration can increase to a detonation.

When K. S. Jones (Ref. 59) conducted tests in which TNT- or Composition-B-filled aerial bombs were hit by bullets, fragments, or even small, superquick fuzed, high-explosive projectiles, only one detonated immediately in 641 tests in which the casings were perforated, although in two tests the high explosive detonated after it burned for 25 or 50 min. In 422 of these tests there were no chemical reactions, in 13 tests fires ignited but self-extinguished, and in 203 tests part of the HE deflagrated (Two to 90% of the HE burned.). In an additional 245 tests the impacting object failed to perforate the bomb casing—214 were ricochets and 31 were stuck in the casing—and no chemical reaction occurred.

On the other hand, Beale, Roe, and Bailey (Ref. 60) reported that in all 39 tests in which aircraft missile rocket motors were hit by a bullet or small HE projectile, a fire resulted, and in 3 tests with delay-fuzed projectiles, the propellant detonated.

Reeves and Anderson (Ref. 61) had results similar to those of Jones and Beale et al. In 85 tests in which fragments or projectiles impacted rocket motors, there were 12 in which the case was not perforated (no chemical reactions), 18 in which the case was perforated but did not chemically react, 43 in which the propellant ignited and burned without exploding, 11 in which the propellant deflagrated at least partially, and 1 in which the propellant detonated (with a Russian rocket motor). In 41 tests in which fragments or projectiles penetrated into warheads, there were no chemical reactions in 21 tests, but there was burning in 8 tests, deflagration in 6 tests, and detonation in 6 tests (All six occurred when a delay-fuzed projectile detonated within the warhead.).

These three programs demonstrated that a ballistic penetration into a warhead or a rocket motor does not inevitably cause an explosion. The faster the penetrator is moving, the greater the probability of a violent reaction. That spall presents a lesser hazard than the residual pieces of the impacting projectile is assumable.

An estimate of the sensitivity and probable reaction to impact by the threats is provided in Table 4-4. The probable mitigation by component construction is included, i.e., a projectile body is probably made of steel and is thicker than a rocket motor casing and would therefore resist spall impact better. The rocket motor is not, however, assumed to incorporate the new, insensitive designs. Pyrophoric fillers are assumed to burn whenever the shell casing is ruptured, and fires are assumed to burn long enough to ignite or initiate the explosives.

Fires in combat vehicles do not necessarily cause an immediate explosion of onboard ammunition; US Army policy assumes that after being engulfed in flame for five minutes, high-explosive-filled projectiles are liable to detonate (Ref. 55).

In four incidents in SEA a shaped-charge jet initiated a fire in fuel or some combustible other than gun propellant, and the fires burned for 10 to 15 min (in an M48A3 MBT—DAN 1839) or for 45 to 60 min (in three M113A1 APCs containing cases of Claymores, small arms ammunition, or bulk C4 explosive—DANs 381, 383, and 385) before the explosives aboard exploded. This was not the case when a shaped-charge jet hit the main gun cartridges (as in one M48A3 MBT, DAN 157, and in two M551 AR/AAV, DANs 310 and 1550). In all three of these incidents, an explosion occurred almost immediately. In two incidents fires were ignited within the turrets of M551 AR/AAVs. In one (DAN 463), the fire burned for a considerable time without igniting the combustible cartridge cases of stowed ammunition; the crew had evacuated the vehicle in fear that the onboard ammunition would explode. In the other case (DAN 670), the vehicle commander extinguished the fire with a portable fire extinguisher.

In the incident in SWA described in par. 4-6, although the gunner was "lifted off" the vehicle, at least two other crew members had time to evacuate the vehicle before it was destroyed, probably by explosion of onboard ammunition cooked off by internal fuel and propellant fire (Refs. 57 and 58).

4-6.2 STOWAGE LOCATION AND DESIGN

The most dangerous item stowed within a combat vehicle is the ammunition for the main weapon. Therefore, the stowage of this ammunition receives the highest priority in design consideration. At the same time, the ammunition must be readily available for loading into the weapon.

Design of these ammunition magazines requires consideration of the threats, tactical usage of the vehicle, and

TABLE 4-4. ESTIMATES OF SENSITIVITY OF EXPLOSIVE-FILLED OBJECTS AND PROBABLE REACTION TO POTENTIAL THREATS

EXPLOSIVE-FILLED COMPONENT	SHAPED-CHARGE JET		ELECTRIC ARC*		HE DETONATION		KE IMPACT		SPALL IMPACT		SLUG IMPACT†		HEAT OR FLAMMABILITY	
	Sens.**	Prob. Reac.***	Sens.	Prob. Reac.	Sens.	Prob. Reac.	Sens.	Prob. Reac.	Sens.	Prob. Reac.	Sens.	Prob. Reac.	Sens.	Prob. Reac.
Rocket motor	H	LO-HO	H	LO	H	LO-HO	H	LO-C	L	NR-LO	M	LO-C	H	C
Cased gun propellant	H	LO	H	C-LO	H	LO-C	M	C-LO	L††	C-NR	L	LO-C	H	C-LO
Caseless gun propellant	H	LO	H	C	H	C	M	LO-NR	L	C-NR	H	C	H	C
Bagged gun propellant	H	LO-C	H	C	H	C	M	C-NR	L	C-NR	H	C	H	C
High-explosive fillers	H	HO-C	H	C-HO	M	C-HO	M	HO-NR	L	C-NR	L	C	H	C-HO
Pyrophoric fillers	H	C	H	C	H	C	H	C	L	C	L	C	H	C
Other energetic fillers	H	C	H	C	H	C	M	C-NR	N	C-NR	L	C	H	C
Bulk explosives	H	HO	H	C-HO	H	HO-NR	M	NR-HO	L	NR-HO	M	NR-C	H	C-HO

*Melt-through of case is assumed.
**Sensitivity (Sens.): H = high, M = medium, L = low, N = nil
***Probable Reaction (Prob. Reac.): HO = high order (or detonation), LO = low order (or deflagration), C = combustion, NR = no reaction
†The slug usually deviates from the jet trajectory after passing through the armor.
††Assumes a steel-cased cartridge; a brass-cased cartridge would be M.

ammunition response to ballistic effects. Two trends are obvious from any analysis of threat weapons, i.e., increasing penetration capability and increasing accuracy. Over time, the penetration capability of weapon systems will be improved to overcome improved vehicular armor. What the vehicle designer must recognize is that in the fielded life of any vehicle, there will come a time when widely available threat munitions will be able to defeat the vehicle armor. Consequently, the design cannot rely solely upon the vehicle armor for protection of internally stowed munitions. The other long-term trend is improved weapon accuracy. This trend is the result of higher projectile velocities and improved projectile design with consequent flatter trajectories, improved targeting, and improved terminal guidance. The logical product of this trend is greater hit probability on a target vehicle.

4-6.2.1 Stowage Locations

Data obtained from a different conflict and with different weapons (Ref. 62) verify that the impact scenarios shown on Figs. 4-3 and 4-4 are also applicable to impacts on MBTs in the defense that were experienced from higher velocity, direct-fire weapons and from wire-guided, rocket-propelled missiles, shown on Fig. 4-26. These tanks were generally in fixed defensive positions; most of them were probably in hull defilade, i.e., the lower portion of the hull was protected by earth from direct antitank fire. Therefore, these tanks received most of the hits above the deck. In addition, the tanks were generally stationary. Tanks in the attack had hits distributed all over, as shown on Fig. 4-27. Figs. 4-26 and 4-27 indicate that even with weapons that have more in-flight stability, flatter trajectories, and improved fire control systems, the impact still is probably going to be anywhere on the exposed portion of the target. Thus, improved accuracy

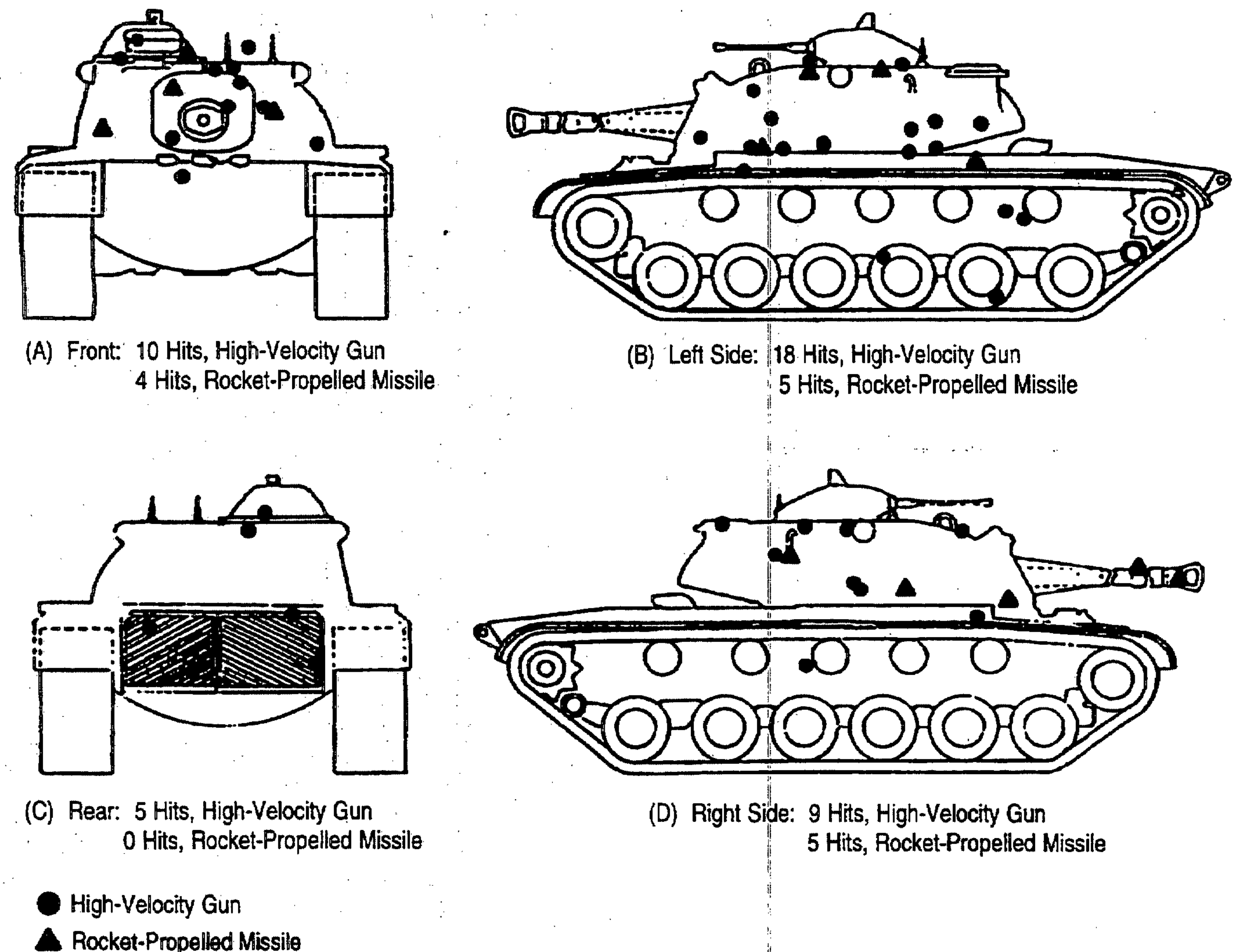


Figure 4-26. Hit Pattern, MBT in Defense, Direct-Fire, High-Velocity Gun and Rocket-Propelled Missile (Ref. 62)

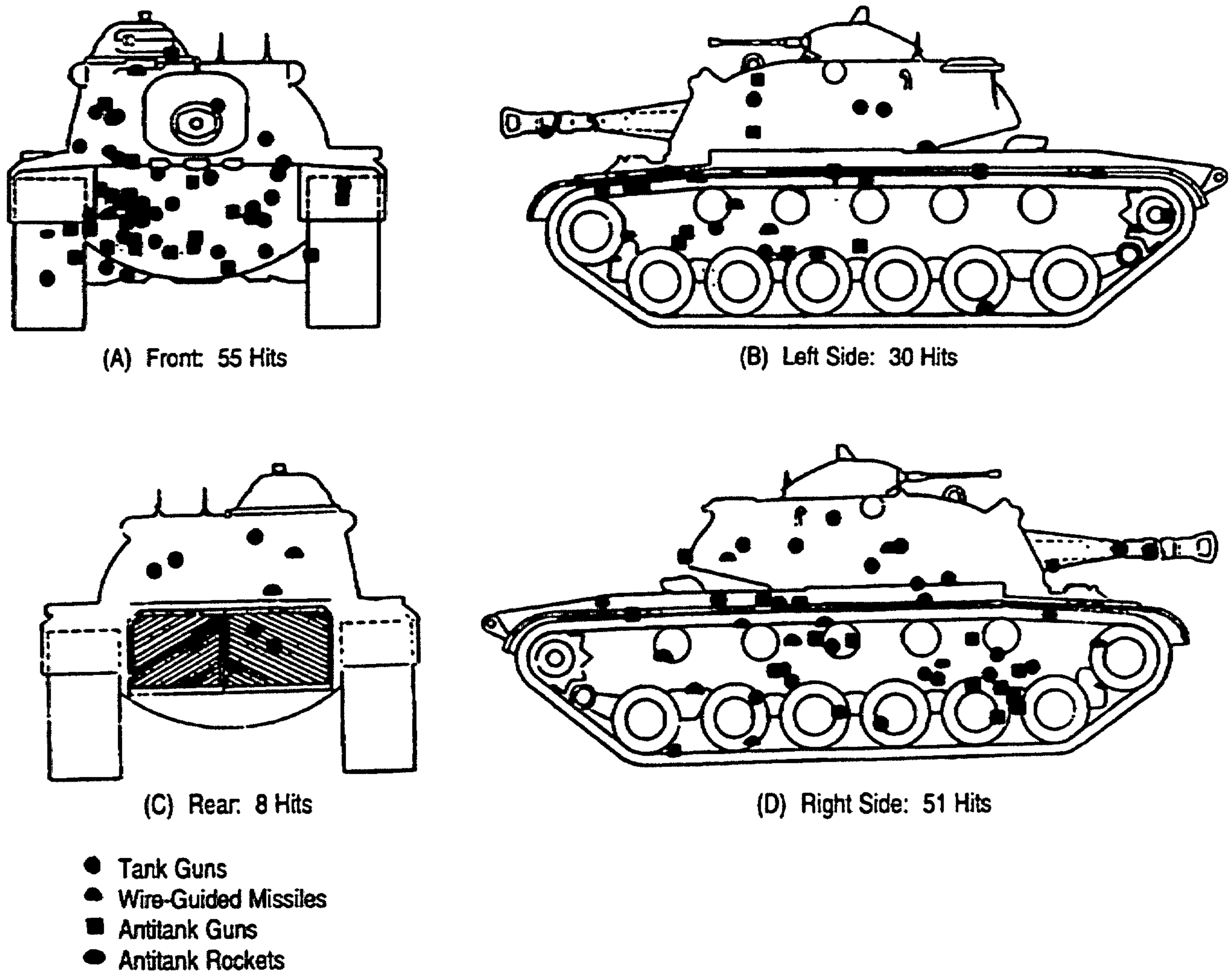


Figure 4-27. Hit Pattern, From Tanks, Antitank Guns, and Wire-Guided, Rocket-Propelled Missiles Upon MBTs Usually in the Attack (Ref. 62)

usually means the weapon will be fired at a greater distance and the impact pattern will probably remain the same. Also onboard terminal guidance means that the missile will be directed toward a set source of emissions (heat or infrared or rebounding radio or laser radiation) and may not have the net effect of having the missile impact upon a selected weak point. On the other hand, television-guided missiles have the potential to be guided to a selected point.

Direct-fire threats will probably hit the vehicle on the front or either side. The top of the vehicle will be the target of indirect or aerial threats and of some guided threats. The bottom of the vehicle, particularly the front one-third, will be subjected to mine threats, e.g., blast, explosively formed projectiles, and shaped charges. The least likely part of the vehicle to be hit will be its rear. The other major factor affecting threat weapon hits upon a vehicle is defilade. Defilade is sufficiently important that it is sought or created for vehicles, both attacking and defending. Its effect is to skew hit distribution toward higher locations on the vehicle. Some stowage conclusions can be drawn from consideration of threat accuracy and penetration, namely, that items located low and to the rear of the vehicle are somewhat less likely to be hit.

Guidance given in World War II was to locate the main gun ammunition below the turret ring. Other guidance was to protect the cartridges from the impact of spall and from the fragments and flash of exploding adjacent cartridge cases (Ref. 63).

External stowage of some munitions is also worthy of consideration. The obvious disadvantages of exterior ammunition stowage are the unavailability of the ammunition during an engagement and the need for adequate hull strength to preclude vehicle damage if the ammunition is hit and explodes. External stowage does provide more ammunition-carrying capacity, and creative design can make the ammunition part of the vehicle protection.

Stowage of ammunition within mobility fuel cells, as was done in the Russian T62 MBT, as shown on Fig. 4-28, may not be a good practice. The probable concept was to have the diesel fuel quench the combustion of the solid gun propellant, but indications are that instead the solid gun propellant exploded and atomized the diesel fuel, which then burned violently. Some data from Near Eastern conflicts indicate that T62 MBTs have had a very high incidence of destruction from fire and explosion (Ref. 62), whereas most US-designed MBTs were lost to either fire or explosion, not to both, unless the fire went unchecked so that the explosives later cooked off.

Armored personnel carriers or cargo carriers often must transport munitions or other energetic materials, and either strong, vented magazines or munition trailers should be used. Such trailers should protect the ammunition from small arms fire and shell fragments.

4-6.2.2 Ammunition Stowage Designs

4-6.2.2.1 Early Designs

In World War II the M4 Sherman medium tank had gained an unenviable reputation for burning when hit by antitank fire. In fact, it was called the "Ronson lighter", because it could be guaranteed to light the first time (Ref. 64). Also apparently 95% of irreparable tanks were due to ignition of the main gun cartridge propellant (Ref. 63).* To reduce this probability of igniting, additional outside armor was scabbed onto the tank at the ammunition stowage locations. This solution was temporary until a better modification could be incorporated in the tank design. The "better modification" was to remove the ammunition from the sponsons, place the stowage racks low in the vehicle, and incorporate water jackets into the stowage racks (Refs. 64 and 65). For the 75-mm gun on the M4A3 medium tank, 10 storage boxes were emplaced in the hull floor containing 10 75-mm rounds each and required a total of 37.1 gal of water. The four 75-mm rounds in the ready rack on the turret floor were protected with one gallon of water. For the 76-mm gun on the M4A1, A2, and A3, a rack for 30 rounds was on one side of the driveshaft, and a rack for 35 on the other side on the hull floor. A total of 34.5 gal of water was used. A ready rack on the turret floor held six rounds and used 2.1 gal of water. This water contained some ethylene glycol to reduce its freeze point and a proprietary compound, Ammudamp®*, to inhibit corrosion (Ref. 66). These water racks delayed the ignition of the propellant charges and also reduced the intensity of the fires. The ignition delay, however, was probably not long enough to allow the crew to escape from the vehicle, and the intensity of the fire, even though reduced, was still sufficient to cause serious damage to the vehicle and injury to its crew (Ref. 63).

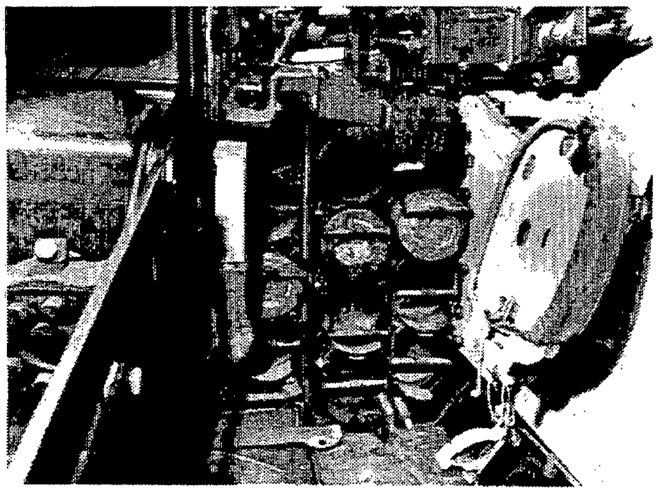


Figure 4-28. Ammunition Stowed in Recesses in Fuel Cell of T-62 MBT

In the 1940s a series of tests showed that armor-piercing cartridges could be protected by covering each cartridge with a 6.35-mm (0.25-in.) thick mild steel cover. Basically, the cartridges were being protected from spall and fratricide, i.e., sympathetic detonation, by use of individual cartridge armor. This method effectively reduced the incidence of fire due to spall impact, but the armor racks tended to break up and form dangerous flying fragments when cartridges were impacted by residual penetrators (Ref. 63).

Another series of tests conducted during World War II demonstrated that ammunition boxes that were strong enough to withstand the explosion of the cartridges within them and that were vented overboard would effectively protect the vehicle from fire. These boxes were made of 6.35-mm (0.25-in.) thick steel and could withstand the explosion of the propellant of 16 75-mm armor-piercing M72 cartridges (Ref. 63).

4-6.2.2.2 Ammunition Magazines for the M1 and M1A1 MBTs

Conflicts in Southeast Asia, Palestine, India, and Afghanistan demonstrated that high-explosive shells stowed in armored vehicles are extremely hazardous, especially given a shaped-charge impact. Magazines could be designed to contain the detonation of one warhead, but not 40 warheads. A program was initiated at the US Army Ballistics Research Laboratory to establish the causative phenomenology for

*When the explosion occurred is not available. Most of these explosions probably occurred after the ammunition cooked off, as opposed to being directly initiated by the threats.

*Use of the registered name does not constitute Government approval of the product.

fratricide of warheads and to devise preventive techniques for use in the M1 MBT, which uses 105-mm ammunition (Ref. 67). This study established that it is necessary to perforate the case of a warhead to get a quick, violent reaction and that the scaled impulse density is the most pertinent parameter for fratricide. For the impact of single fragments, the most pertinent parameter is the areal or specific impulse to target casing thickness ratio.

A protective technique devised was to place a low shock impedance material between warheads to reduce the rate of deformation of a warhead impacted by fragments. A polyvinyl chloride bar, 5 × 5 × 40 cm, was found to be sufficient to prevent fratricide of 105-mm HEAT M456 projectiles. This technique was incorporated into the two magazines of the M1 MBT shown on Fig. 4-29(A). The ready rack, which is a basket located on the floor below the breech of the weapon, is protected by location only. There are no restrictions on the type of cartridge that can be placed in the three-round ready rack.

Further work performed at BRL provided nonhazardous ammunition magazines for the M1A1 MBT, which uses 120-mm ammunition, and is applicable to other armored vehicles (Ref. 68). Ammunition compartments obtain vulnerability reduction through improved engineering in the stowage of ammunition. The basic principles used follow:

1. Remove the ammunition from the crew compartment by using a separate ammunition compartment.
2. Prevent fratricide of the ammunition by reducing or eliminating sympathetic reactions of warheads and propellant charges.
3. Provide vents to preclude pressure buildup and to vent noxious gases to the outside of the vehicle.
4. Provide armor to reduce the severity of the impact upon the explosives and thereby reduce the violence of their reactions.
5. Protect the ammunition from spall and thereby reduce the number of reacting items.

The vehicle structure must be strong enough to withstand internal as well as external explosions. In many current vehicles the armor forms an exoskeleton with primary consideration given to being strong enough to carry vehicular loads and secondary consideration given to withstanding external blast loads, but little consideration is given to internal blast loads. In attempting to reduce vehicular weight and production labor, manufacturers often use "ballistic welds", i.e., partial or shallow welds, which can carry vehicular loads and prevent direct bullet penetration, but which fail to carry blast loads, particularly internal blast loads. Vehicles must be designed to carry gross overloads (particularly of internal blast loads), which may be alleviated by venting.

The blast loads from stowed ammunition must be available to the designer to analyze stress properly on an ammunition magazine. In addition, the designer must know the probable warhead and propellant load reactions to ballistic impact. For example, if a HEAT warhead is hit by a shaped-charge jet at Point A and the jet trajectory is as indicated on Fig. 4-30, the HEAT warhead itself would launch a jet that could achieve close to design penetration in the magazine wall. (This information indicates that the designer would be well advised to have these cartridges pointing overboard in the magazine.) If the warhead is hit at another location (where peripheral initiation* is not achieved), such as Locations B through F on Fig. 4-30, however, the penetration drops dramatically. Such information is needed to design onboard magazines. Penetration is not as important to magazine design as are the loadings due to explosion of the warheads. These explosions must be minimized, primarily by preventing fratricide.

The three devices used to preclude fratricide of warheads are buffers, deflectors, and spoilers, Fig. 4-31. The buffer is a solid shield located between the donor, the warhead initiated by the ballistic impact, and the acceptor, an adjacent warhead. This buffer captures or deflects fragments and blast. The buffer itself may impact the acceptor, but this type of impact, which is slower and more massive, is not the type of impact that results in acceptor warhead detonation. A deflector is a shield that is at an angle to the more dangerous fragments and deflects these fragments and their accompanying blast rather than stopping them. The spoiler, on the other hand, affects only those fragments and blast that would actually impact the acceptor. The spoiler employs a combination of geometry and material to trap or deflect the fragments. Of the three devices, the spoiler is the most effective, particularly on a weight basis. All three devices provide good protection, even with sensitive explosive fillers in the acceptor warheads. Some of the more recently developed insensitive explosives could withstand fragment impacts and blast loading with much lighter devices or even with no devices.

Spoilers are used in the M1A1 MBT bustle and hull magazines, which are shown on Fig. 4-29(B). This antifratricide device and the vents and sliding doors have been proven in tests to protect occupants of the vehicle from the detonation of a HEAT warhead. This 120-mm HEAT warhead contains approximately twice the quantity of high explosive as the 105-mm HEAT warhead of the M1 MBT. The M1A1 has, in addition to the magazines shown on Fig. 4-29(B), a ready rack for two additional rounds located on the floor of the turret basket below the breech of the weapon. Guidance from the M1 Project Office is that no HEAT cartridges are to be placed in that rack—only KE ammunition should be placed therein.

*Shaped-charge warheads can be initiated around the outer edge rather than in the center of the end of the charge. This technique is called peripheral initiation and is usually achieved by use of wave shapers, i.e., inert inserts, in the explosive. It allows designers to use shorter charges than those required for base initiation.

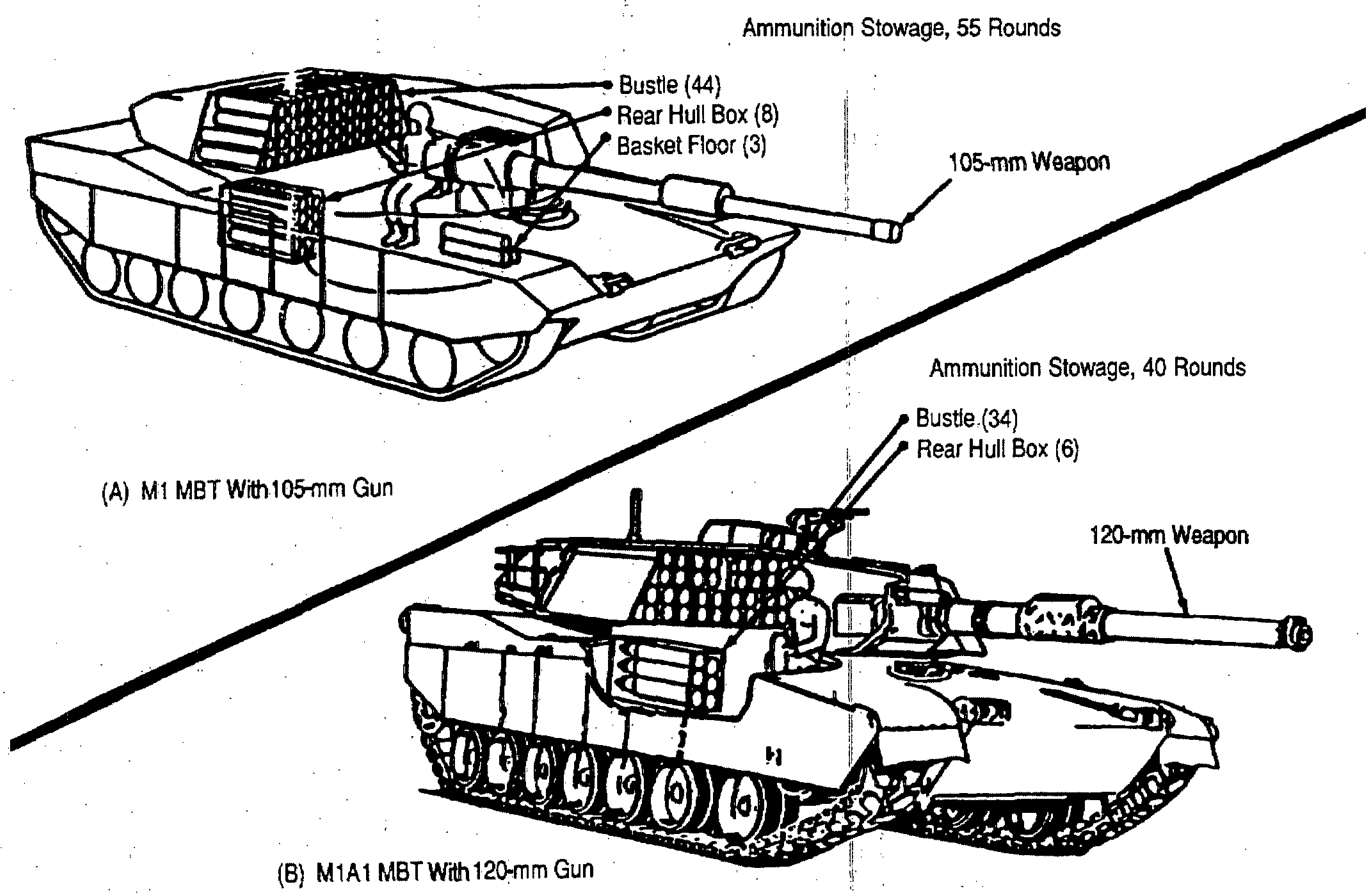


Figure 4-29. Ammunition Stowage in M1 and M1A1 MBTs

4-6.2.2.3 Advanced Survivability Test Bed Ammunition Stowage

A thorough reevaluation of one vehicular design to increase survivability was made with the ASTB vehicle. This vehicle was designed by a special task force (Ref. 69). The design of the ammunition stowage system was dominant since the ammunition was the most hazardous material stowed aboard the vehicle. The ASTB was a crew-protective version of the BFV. The ASTB was to meet all the BFV performance requirements except those for air transportability and swimming. Four ASTBs, 2 infantry and 2 cavalry versions, were built by August 1987 and were submitted for both operational and live-fire tests. The ASTB gross vehicle weight was limited to 26,760 kg (59,000 lbs). The ASTB was to stow seven TOW missiles; the infantry version could have five TOWs and two Dragons. The cavalry version was to stow 1500 rounds of 25-mm ammunition (The infantry version carried a total of 891 rounds, 300 ready and 591 stowed.), and both versions were to have a minimal degradation of operational effectiveness and were to provide armor protection against a 30-mm KE* round (Ref. 71).

The ASTB TOW missile stowage system, Fig. 4-32(A), accommodated seven TOWs: two in the launcher, three in external stowage, and two (either TOWs or Dragons) under the crew compartment deck. Access to the externally stowed missiles was through an outwardly opening door at the top of the compartment. To reload the TOW launcher, the loader would stand in the cargo hatch, reach over the 25-mm stowage compartment, remove the top TOW assembly, and

*The threat presented by the Russian 30-mm 2A42 gun (Ref. 70), mounted on the BMP-2 and BMD-M-1981, fires either API or Frag-HE with a muzzle velocity of 1000 m/s at a cyclic rate of either 200 to 300 rd/min or 500 rd/min selectable. The effective range is 1000 m, and the maximum penetration is 55 mm (of RHA) at 500 m. It is believed that the same gun is used on the Zenitnym Samokhodnaia Ustanovka—antiaircraft self-propelled mount—ZSU-30-2—30-mm dual gun, which uses high-explosive tracer (HE-T), HEIT, and APIT, and probably APHEI cartridges (Ref. 17). Thus any of these projectiles could be encountered.

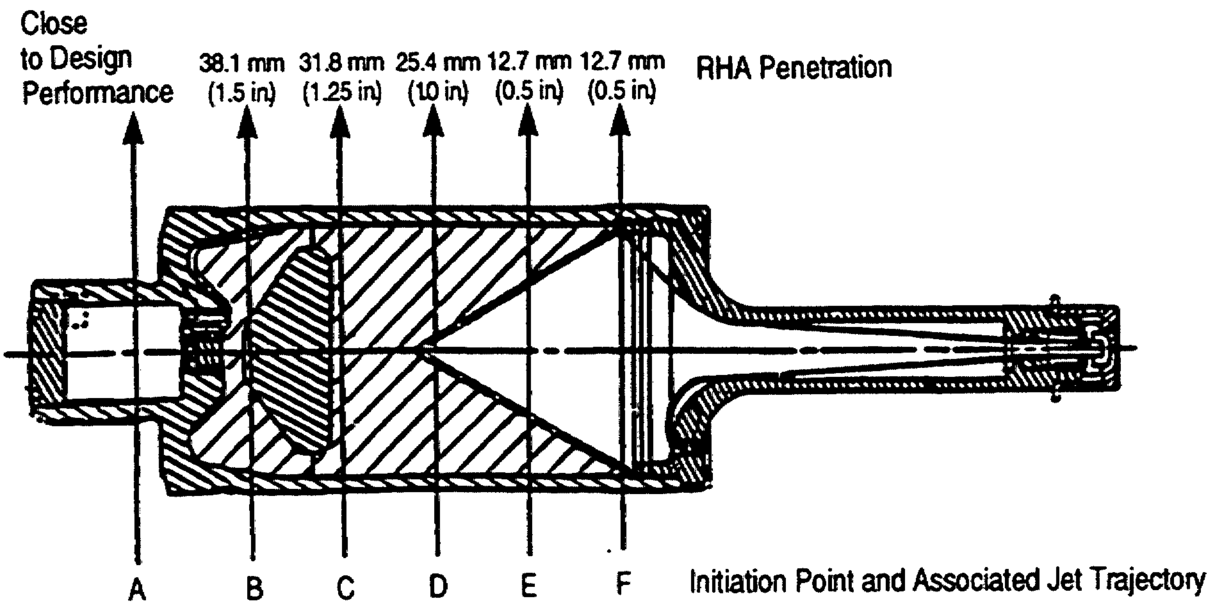


Figure 4-30. Rolled Homogeneous Armor (RHA) Penetration of a Side-Initiated M830 HEAT Warhead (Ref. 68)

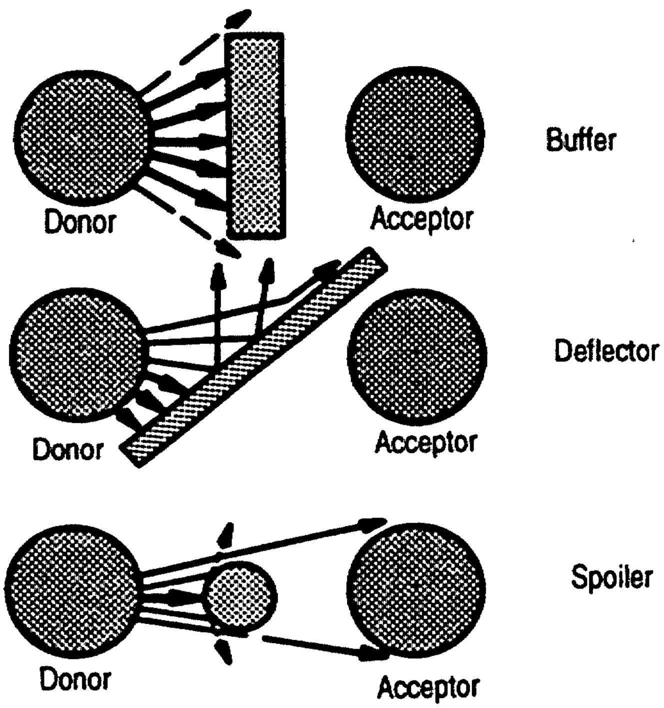
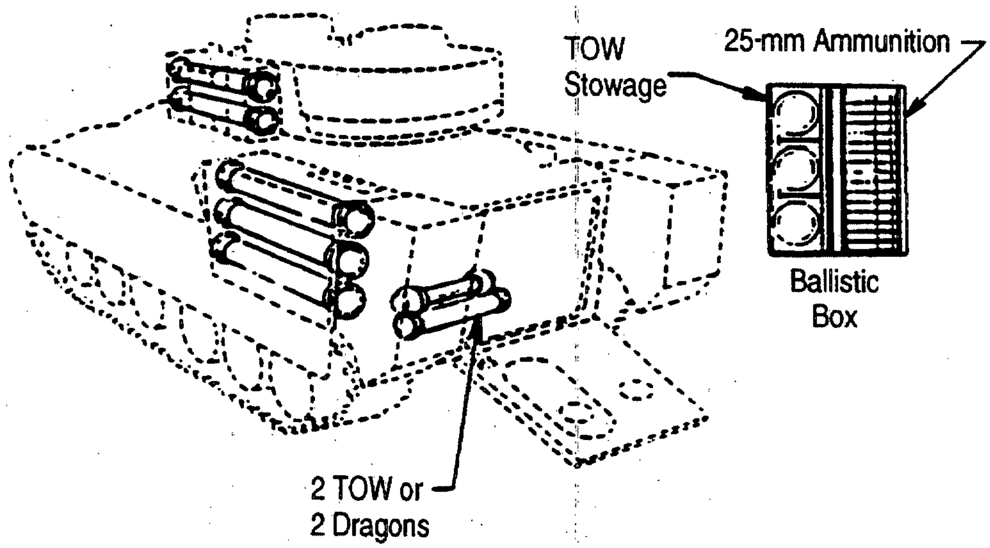


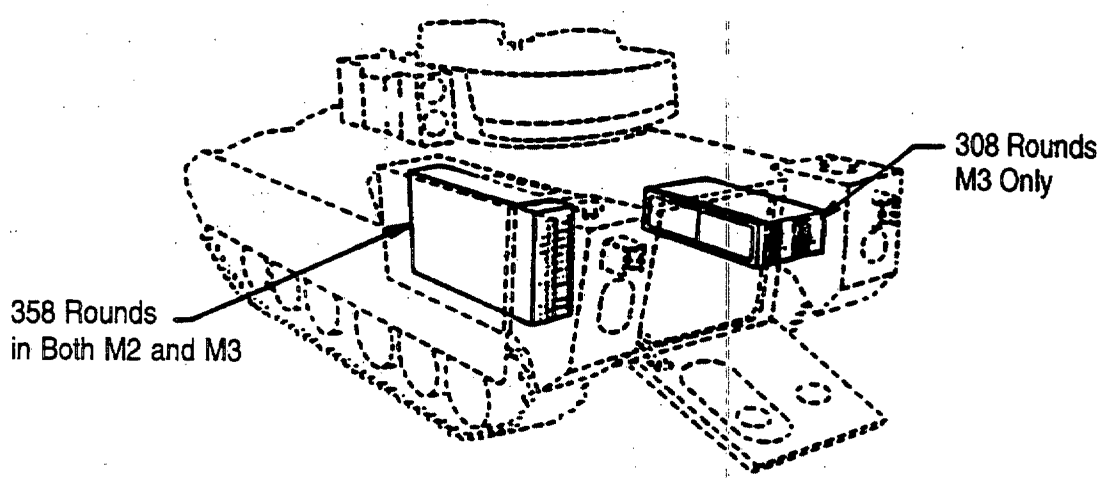
Figure 4-31. Types of Antifratricide Devices (Ref. 68)

insert the TOW assembly into the launcher, which could be swung rearward for easier access. The next TOW in the exterior stowage compartment would be cranked up to the upper position ready to be loaded next (Ref. 72). The TOWs stowed within the vehicle were located below the decking within the bilge. The only protection afforded these two missile assemblies, other than the vehicle skin, was their location. The TOW launcher was spaced far enough from the side of the turret that if the TOWs within the launcher were initiated by a shaped-charge hit, the vehicle would not suffer catastrophic damage. The stowed missiles in the external compartment were staggered so that the warheads alternated facing forward or aft to reduce the potential for fratricide, and an antifratricide material package was emplaced between adjacent missiles. An energy-damping "crush" package was placed between the missile compartment and the 25-mm ammunition compartment. Within the 25-mm ammunition compartment fratricide was precluded by antifratricide design techniques, such as rounds being located in trays with an antifratricide device between adjacent rounds, which were all pointed in a single direction (as opposed to being tip to toe).

The 25-mm ammunition stowage provided 300 rounds in a ready rack immediately below the weapon, 358 rounds in a left compartment, and sometimes more as shown on Fig. 4-32(B). The unique design feature was that the left com-



(A) TOW and Dragon Stowage



(B) 25-mm Cartridge Stowage

Figure 4-32. Ammunition Stowage for the ASTB (Ref. 71)

partment acted as a buffer between the external TOW stowage compartment and the crew compartment. Thus the less hazardous 25-mm cartridges were used to protect the crew and vehicle from the more hazardous TOW missiles. This function was successfully demonstrated in tests.

4-6.2.2.4 Armored Mobile Flamethrowers

Flame is an excellent weapon. It is highly effective for killing or disabling personnel even in areas protected from direct and indirect fire of KE or HE weapons. Flame also has a profound psychological effect on enemy troops. In World War II the US and Britain mounted flamethrowers in M3 and M4 medium tanks (Ref. 66). The US had two types of flamethrowers: one had the nozzle fitted into the location of the bow machine gun, and the other had the nozzle fitted into the 75-mm main gun. The US and British flamethrowers usually consisted of a fuel storage bottle, a high-pressure gas bottle, a pressure regulator, a nozzle with igniter, and associated plumbing. Prior to use, the fuel storage bottle was pressurized to a preset pressure. To use, the nozzle was directed toward the target, and a valve in the nozzle assembly was opened. The igniter, located at the outlet of the nozzle, could be started either before the valve was opened so that the fuel stream was initially burning or after a desired quantity of fuel had reached the target. Experience has shown that a burning jet of gelled gasoline has a slightly longer range than a jet that is not burning. On the other hand, more gelled gasoline can be placed on a target if some is not burned enroute.

The British used a trailer towed by their Churchill VII medium tank to provide fuel for their Crocodile flamethrower (Ref. 66). The Germans had a flamethrower that could be used in an armored vehicle or a trailer and used a gasoline, engine-driven centrifugal pump to pressurize the fuel. The Germans also had tank flamethrowers with either externally or internally mounted fuel cells, at least one of which pressurized the fuel with nitrogen (Ref. 73). This fluid pumping system would present a much smaller vulnerable area than the pressurized bottle systems used by the US Army. Also, concealing the fuel cells and disguising the projector reduces the probability the enemy will realize that the vehicle is a flamethrower.

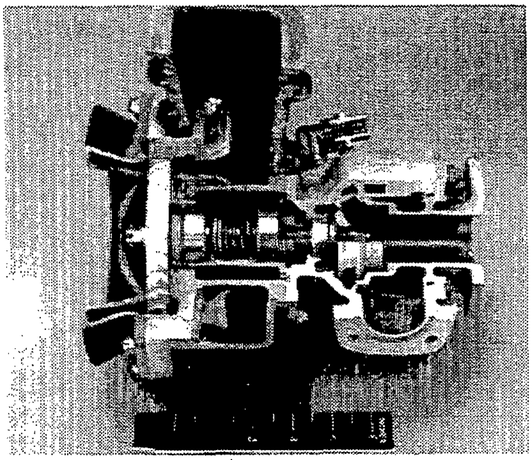
During World War II, the Russians equipped some T-34 tanks with flamethrowers. This Ognemetnyy tank (OT)-34 (flamethrower tank) was fitted with an Avtomaticheskiy Tankovyy Ognemet (ATO)-42 (automatic tank flamethrower) with the nozzle replacing the bow machine gun. The 200-L fuel cell in the fighting compartment used some of the space normally allocated for the main gun ammunition. Some OT-34s had additional flamethrower fuel cells mounted externally (Ref. 74).

The fuel used in these mechanized flamethrowers was a munition. The usual fuel was gasoline that had been modified either by the addition of lubricating oil or diesel fuel or a gelling agent like napalm to maintain a liquid jet. These flamethrowers were usually used against field fortifications whose main defense was small arms fire, against which the vehicle armor was adequate protection. With the advent of the Panzerfaust, however, these mechanized flamethrowers became more vulnerable.

The Russians have a flamethrower version of the T-55 MBT (Ref. 75) designated the TO-55. The flamethrower, ATO-200, fires a burst of 35 L to a maximum range of 200 m. A total of 460 L of fuel is carried (Ref. 17). The Russian flamethrower consists of one or more fuel storage cells connected to a cylinder-piston assembly, which in turn is connected to a nozzle with igniter, using appropriate plumbing. Prior to use, the fuel is ported into one side of the cylinder, and a small quantity of fuel is injected into the cylinder on the other side of the piston. To use, the small quantity of fuel is ignited and forces the piston to eject the large quantity of fuel through the nozzle. This fuel is ignited as it leaves the nozzle (Ref. 74). The flamethrower is also reported to be used in the T62 MBT.

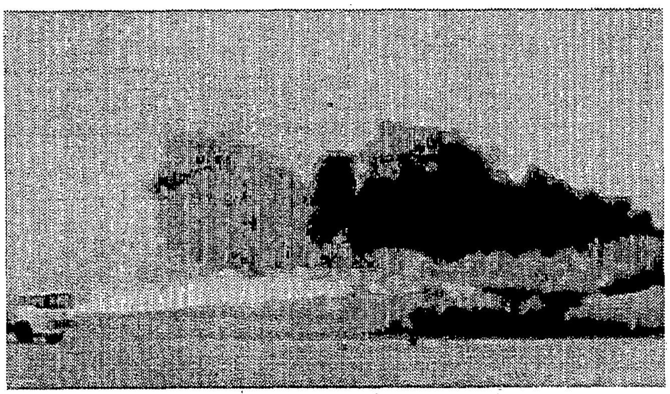
In Korea flamethrowers were mounted in M26 tanks. In Vietnam flamethrowers were mounted in APCs by the US Army and on M48 MBTs by the Marines. The four 190-L (50-gal) pressurized fuel storage bottles, used for the US Main Armament Mechanized Flamethrower M10-8 (Ref. 76), are the singly most vulnerable item, especially to a shaped-charge threat. A shaped-charge jet could not only puncture the bottle but would also provide a means to spray the fuel and ignite it. In the self-propelled flamethrower M132, a version of the M113 APC, these large vulnerable components were stowed within the vehicle and almost filled the cargo space. In addition, the single 19-L (5-gal) igniter gasoline can, located immediately in front of the flamethrower operator, added to the hazard. An RPG attack on such a vehicle would probably have resulted in catastrophic fires. These vehicular flamethrowers used fuel bottles that were pressurized to 1.40 to 2.1 MPa (200 to 300 psi) to force the gelled gasoline through the flamethrower nozzle.

In the mid-1960s the Limited Warfare Laboratory funded a program to demonstrate that the turbine-driven fuel pump, illustrated by Fig. 4-33, for the Ramjet RJ43 engine of the Bomarc Missile (Ref. 77) could successfully power a mechanized flamethrower. This demonstration was accomplished successfully, as shown on Fig. 4-34. The centrifugal pump did not shear the napalm-thickened gasoline to an ungelled state. Such a system could be powered by a low-temperature gas generator in order to provide a detachable mechanized flamethrower to be mounted on a standard vehicle for special use. The fuel cell and gas-generator-turbopump systems could be mounted on a trailer, and the nozzle-ignition-control system could be attached to the vehicle. This setup would provide a much less hazardous mechanized flamethrower for special use than one using pressurized bottles.



Courtesy of The Marquardt Company.

Figure 4-33. Turbine-Driven Fuel Pump for the Ramjet RJ43 Engine



Courtesy of The Marquardt Company.

Figure 4-34. Truck-Mounted Flamethrower Powered by the Turbine-Driven Fuel Pump

The use of a pump system rather than pressurized bottles is recommended for inclusion in the design of flamethrower vehicles. Mounting the fuel cells on a trailer rather than on the combat vehicle is also recommended.

4-6.3 NEW DEVELOPMENTS

New developments are mainly in the field of insensitive munitions (IM). These munitions will not explode given accidental or combat loadings or at least will withstand these loadings for longer periods before exploding. This subparagraph presents the background and requirements for insensitive munitions and then covers some specific types of munitions that meet or approach these requirements.

These new developments are promising but are not yet developed sufficiently to be used in combat vehicles. The designer must be alert to the stage of development of these items so that developed IMs can be used when available.

4-6.3.1 Insensitive Munitions: Background and Requirements

One of the reactions of the US Navy to the disastrous fire on the *USS Forrestal* in 1967 was to conduct a program to develop munitions that would not contribute to the effects of an accidental fire. That effort was the first to attempt to render ordnance relatively insensitive to pool fires but has since progressed to many other phenomena. MIL-STD-2105 (Ref. 78) provides test criteria for a fast cook-off, such as from a hydrocarbon fuel pool fire, multiple impacts of 12.7-mm bullets, an impact by a 16.2-g (250-grain) fragment at 2530 m/s (8300 f/s), the sympathetic reaction to the detonation of a similar warhead, an impact by a shaped-charge jet, and impact by spall from a 25.4-mm (1-in.) thick RHA plate hit by a shaped-charge jet, as well as for environmental and shipping extremes. The munition is to have no reaction more violent than combustion of the explosive filler(s) from any of these loadings. These IM requirements have also been adopted by the Army and Air Force.

4-6.3.2 Liquid Gun Propellants

Liquid gun propellants (LGPs) were first explored because of their potential weight, volume, and cost savings for artillery. For large caliber guns LGPs offer the potential to reduce the vulnerability that results from the extreme sensitivity of solid propellant to ballistic impacts. In general, LGP ammunition is separate loading; therefore, the propellant can be stored compactly in one, two, or more locations rather than be attached to each projectile. These fewer compact locations can be better protected than the much larger magazines needed by solid propellant cartridges. Also the particular LGP currently being developed by the Army, LGP 1846, is much less sensitive to ballistic impact than a typical solid gun propellant M30 if the LGP 1846 is properly contained (Ref. 79), i.e., within a container that has at least one dimension smaller than the critical dimension necessary to propagate a detonation wave. LGP has no voids and is more dense as packed than solid propellant (which contains passages in each grain plus voids between grains); hence it can be stowed in a smaller volume. LGP requires the use of pumps, lines, valves, and a storage bottle, which solid propellant does not need, but the solid propellant is in a case or bags, which are stowed in a magazine with diverters, shields, and other antifratricide devices.

LGP 1846 is unaffected by the compression of vapors, does not react violently when stored in a container that has at least one dimension smaller than an established critical dimension, and is resistant to reactions given hydraulic ram (Ref. 79). It has demonstrated a desirable lack of response to shaped-charge jet impact tests and the spall test of MIL-STD-2105A (Ref. 80).

4-6.3.3 Insensitive High Explosives

The sensitivity of plastic-bonded explosives (PBXs) has proved to be less than that of trinitrotoluene (TNT) based explosives. This difference is attributable to the use of polymeric binders that result in nearly voidless, pliant, rubbery materials with fewer discontinuities than granular solid propellant, and hence low-energy breakup characteristics and reduced tendency to form hot spots. An additional feature of some composite PBXs is the separation and sealing of fuel and oxidizers, which possibly simultaneously increase the chemical energy output and decrease the sensitivity to impact loadings. Some insensitive explosives are warhead design sensitive, i.e., the explosive passes the test criteria in one warhead but not in another. These high explosives have been classified by application. In each classification at least one explosive shows promise, and these explosives are shown in Table 4-5. One major problem has been to establish warhead-loading techniques usable in mass production. The development status of these explosives is published annually in a document similar to "The Insensitive Munitions Advanced Development FY91 Development Plan" by the Naval Sea Systems Command (Ref. 81).

A BRL program to protect armored vehicles developed a protective technique to reduce the incidence of violent reaction given a ballistic impact on a high-explosive munition by preventing the rapid extrusion of the explosive through the cracks generated in the warhead casing of the acceptor. To prevent this rapid extrusion of the acceptor explosive, a thin, pliable layer of a polymeric material was placed on the inside surface of the acceptor warhead. Tests were conducted with 105-mm M1 casings lined with 3 mm of cellulose acetate butyrate. This lining increased the 50% threshold input velocity of fragments for reaction from 1470 m/s (4823 ft/s) to over 1740 m/s (5700 ft/s). Mild burning reactions were obtained at higher velocities, and even at impact velocities near 1980 m/s (6500 ft/s), the warhead reaction was not sufficiently violent to split open the casings (Ref. 68).

4-6.3.4 Insensitive Propellants and/or Propulsion Systems

The US Navy has done considerable work to make rocket motors less sensitive to pool fires; the US Army has worked on low-vulnerability ammunition (LOVA) propellants for gun propulsion.

The Navy has successfully reduced the violence of the response by rocket motors to pool fires (fast cook-off) by building in means for actively reducing case confinement under fast cook-off temperature conditions. This technique can also apply to the slow cook-off scenario. Some work has also been successful to counter bullet impact. All of these efforts, however, are design sensitive. In short, every rocket motor is different and will probably need a different technique by which to become insensitive. Pursuing a technique to separate the oxidizer and the fuel seems worthwhile. Also some new rocket motor case concepts, i.e., strip laminate, composites, and hybrids, are encouraging.

More success has been obtained in compounding LOVA gun propellants. IM vulnerability testing of LOVA propellants for the Navy 76-mm and 127-mm/54 (5-in./54)* guns was completed in FY87, but efforts to develop insensitive primers were stopped in FY88 by a major budget cut.

4-6.4 LESSONS LEARNED

The hazard presented by ammunition was recognized as early as 1942. Reports from US sources indicated that 90 to 95% of all nonrepairable tanks were burned out and that practically all of these were from ammunition fires.** The standard practice for US combat vehicles was to store ammunition without the protection of armored containers (Ref. 63). The magazines of the M1 MBT, described in subpar. 4-6.2.2.2, were the first well-designed ammunition storage concept to be incorporated into a US combat vehicle. Also the concepts for the ASTB, described in subpar. 4-6.2.2.3, are novel and worth considering.

The lessons learned were drawn from experience in Southeast Asia; as well as development programs in the United States and elsewhere.

*The US Navy designation for guns is the gun caliber. In this case 5 in., i.e., the distance between rifling lands, followed by the barrel length in calibers, in this case 54 calibers or 270 in.

**This attribution must be considered cautiously. A sustained fuel fire would cook off the ammunition. Examination of the tank remnants often would not disclose which combustible was ignited first, the mobility fuel or the gun propellant, and the personnel examining the vehicle probably would merely look to see whether the vehicle was repairable.

TABLE 4-5. INSENSITIVE HIGH EXPLOSIVES (Ref. 78)

CLASSIFICATION	EXPLOSIVE
General-purpose explosive for fragmentation and blast	PBXN-109
Metal accelerating explosive (shaped charge, antiaircraft)	PBXN-109 Type II, PBXN-106, PBX(AF)-108, PBXN-110, PBXC-121, PBXW-114, PBXC-126
Underwater explosives	PBXN-103, PBXN-105, PBXN-115
Booster explosive	PBXN-5, PBXN-6, PBXN-7
Initiation train and primary explosives	PBXN-301, DXW-1

4-6.4.1 Stowage of Main Weapon Ammunition

The lesson learned from several incidents in Southeast Asia is that ammunition is too hazardous to be stowed unprotected in the crew compartment, as was done in the M48 MBT and the M551 AR/AAV.

Propellants, particularly those in caseless or combustible-cased cartridges, can be much more prone to fratricide than warheads. Solid propellants under pressure burn more rapidly, and the burn rate increases almost exponentially with increased pressure. In addition, the solid propellant used in rocket motors is now primarily a high explosive. The old solid gun propellant would burn when impacted by a shaped-charge jet. If it were in a cartridge case, it would rapidly pressurize the case and thus increase the burn rate. This increased pressure in a magazine has a synergistic effect on the warheads and it increases the probability of their detonating even with the use of antifratricide devices. This situation can be remedied by venting the combustion products: A properly designed vent can prevent such magazine overpressure. Current designs provide that one or more faces of the magazine will be blown open to relieve overpressure. Care should be exercised to direct such venting overboard so it does not inhibit other vehicular functions. In particular, the magazine vent should not dump the combustion products into the engine air intake, because there would be an adverse effect upon vehicular mobility.

Propellant combustion can be controlled by compartmentalization and/or other means. No longer should entire crews and their vehicles be lost, as happened in SEA with both the MBT M48A3 (DAN 157) and the AR/AAV M551 (DAN 1550) when the propellant deflagrated. Now that warhead antifratricide techniques are under development at the US Army Research Laboratory (formerly the US Army Ballistic Research Laboratory), Aberdeen Proving Ground, MD (Refs. 67 and 68), the warheads should no longer present such a potentially catastrophic hazard.

Starting in World War II, the British placed water jackets around the main gun ammunition in their MBTs, but this practice has been abandoned with the latest Challenger MBT. At present, Fire and Safety International (FSI) is developing a system that would inject water into threatened combustible-cased main gun cartridges (Ref. 82). This water injection technique is intended for use with the 120-mm combustible-cased ammunition.

The protective designs for both the M1 MBT and the M1A1 MBT, described in subpar. 4-6.2.2.2, were based upon the assumption that the detonation of a single HEAT warhead has to be contained. Note on Fig. 4-29(A) that the stowage configuration of the 55 rounds of 105-mm ammunition is 44 rounds in the bustle magazine, 8 rounds in the rear hull box, and 3 rounds in the ready rack, and there is no restriction on which type of ammunition can be in any of the three locations. The 105-mm HEAT-MP M456 cartridge warhead contains 0.971 kg (2.14 lb) of Composition B explosive, which has a TNT equivalence* of 1.101, and a propellant charge of 5.22 kg (11.5 lb) of M30 propellant, which has a TNT equivalence of 0.895, within a steel case. The 105-mm APFSDS-T M833 cartridge has an inert warhead and a propellant charge of 5.81 kg (12.8 lb) of M30 propellant. The ammunition load for the M1 MBT main gun is strictly antitank, and the ratio of HEAT to KE is not specified.

The bustle and rear hull magazines are designed so that if one HEAT warhead were to detonate within either magazine, the crew of the tank would not be affected. This protection is accomplished by precluding fratricide between warheads, by providing a blowout panel for each magazine, and by placing sliding doors between the magazine and the crew compartment. The bustle has two internal dividers providing, in essence, three separate compartments; therefore, there are three separate blow-away panels on the top of the turret, one for each "compartment". The blow-away panel for the rear hull magazine is on the bulkhead separating the engine and crew compartments. In case of a greater-than-design pressure or impulse, the bottom side of each magazine is purposely weaker than the sides that must remain. Rupture of the magazines would vent explosion products downward from the turret or into the engine compartment.

The propellant charges were not considered for the explosive loading, but other programs have indicated that a shaped-charge jet passing through the case and propellant will cause a violent reaction, as shown on Fig. 2-18. The steel cartridge case will rupture and provide many large fragments, which can impact on surrounding cases. The heat generated by the combustion of the propellant can, after a period of minutes, cook off the propellant in intact cartridge cases and, after approximately 20 min, cook off the explosive of the HEAT warheads.

*The method used to compare explosion effects is to establish the quantity of TNT that would have the same explosion effect. The equivalence between a given explosive and TNT can be estimated by using the ratio of the heat of explosion of the explosive to the heat of explosion of TNT, e.g., the equivalence of Composition B, using data from Table 3-12, is 5.02 MJ/kg divided by 4.56 MJ/kg, which equals 1.101. The TNT equivalence can be computed using either calculated or experimental values of the heats of explosion, but these values usually vary. For example, for TNT when the water produced is still gaseous, Ref. 83 gives a calculated value of 5.40 MJ/kg, but an experimental value of 4.27 MJ/kg. For Composition B-3 under similar circumstances, the values are 5.86 and 4.69 MJ/kg. The TNT equivalence of Composition B-3 found by using computed values of the heats of explosion is 1.085, whereas by using experimental values it is 1.098. This is a variation of ±0.6% from the mean. If a combination of calculated and experimental values were used, this equivalence could vary as much as from 0.869 to 1.372, or a variation of ±22.4% from the mean. When computing the TNT equivalence for a given material, use either computed values of the heats of the explosion for both materials or the experimental values for both, but do not use a combination of these values.

The gun used on the M1A1 MBT is the 120-mm Rheinmetall smooth bore. As in the M1 MBT, the ammunition carried is entirely armor-piercing—both the APFSDS-T and the HEAT-MP rounds. The cartridge cases of the 120-mm rounds, however, are combustible, except for a stub base made of steel, and the propellants for the two types of cartridges are different. In general, the propellants for the 120-mm cartridges are more energetic—TNT equivalence for JA-2 is 1.029 and for DIGL-RP is 0.941 compared to M30, which is 0.895—and there is more propellant per cartridge, 8.128 kg (17.92 lb) of JA-2 per KE round or 5.40 kg (11.9 lb) of DIGL-RP per HEAT round. Further, the propellant in a combustible case is ignited more readily by an external ignition source than that in a steel case. The high-explosive charge in the 120-mm HEAT warhead—1.91 kg (4.2 lb) for Composition A, Type 3—is greater in size and specific energy—TNT equivalence of 1.110—than that of the 105-mm HEAT warhead. Thus an M1A1 magazine is designed to withstand the detonation of 2.12 kg of TNT compared to 1.07 kg of TNT for an M1 magazine. The equivalent TNT mass for a 120-mm KE cartridge propellant is approximately 8.4 kg, and for the HEAT cartridge propellant it is approximately 5.1 kg. Both of these exceed the 2.12 kg of TNT equivalent for which the magazines were designed. Also the lateral area presented by the 120-mm cartridge propellant charge is significantly greater than that presented by the HEAT warhead—approximately 0.160 m^2 for the propellant charge compared to approximately 0.023 m^2 for the HEAT warhead*—and offers a larger target area.

For an M1A1 where a bustle magazine can be hit so as to ignite the propellant charges, which can generate sufficient heat energy to cook off the HEAT warheads in approximately 20 min, the crewmen are taught to rotate the turret before they evacuate so that the bustle protrudes over one side of the MBT. This procedure is followed so that the products of combustion are not vented onto the hull or into the engine air intake. Thus when the HEAT warheads detonate, the explosion would demolish no more than the turret; the vehicle body could be salvaged and the tank rebuilt.

There are spaces for forty-two 120-mm cartridges in the M1A1 MBT. Fig. 4-29(B) shows the location of the bustle magazine, which has a divider separating it into two compartments. Each compartment holds 17 cartridges, and each compartment has a blow-away panel on its upper surface. Fig. 4-29(B) also shows the location of the rear hull box magazine that contains six 120-mm cartridges. The blow-out panel for this magazine is in the bulkhead separating the crew compartment from the engine compartment. These magazines, i.e., the bustle and the rear hull box, can contain either KE or HEAT cartridges without restrictions on the mix or the relative locations of the two types of cartridges. Not shown on Fig. 4-29(B) is the two-round ready rack located on the basket floor. Crewmen are instructed to use this ready rack for KE cartridges only; HEAT cartridges should not be placed in this ready rack (Ref. 85). The ready rack is protected only by location.

The high-explosive and propellant masses and power indicate that the design of these magazines should consider the effect of propellant charge initiation, as well as explosive warhead initiation. The blow-away panels could vent a propellant explosion, but this fact has not been established in tests.

Some other ammunition magazine design features have been explored but not yet incorporated into the design of any MBT.

E. H. Walker (Ref. 86) suggested that the rear surface of the bustle be hinged so that an explosion of even a portion of the contents of a magazine would eject the remaining contents of the magazine out of the vehicle. This concept was tested and performed excellently.

Dr. A. E. Finnerty (Ref. 87) demonstrated that injecting a fire extinguishant into a magazine could reduce the reaction of the propellant. He also tested the effect of having a shaped-charge jet perforate a container of fire extinguishant before entering a 105-mm cartridge case containing M30 propellant (Ref. 88). In both of these programs the fire extinguishant reduced the violence of the reaction, i.e., aqueous extinguishants reduced the violence more than did powdered extinguishants, but neither technique eliminated the reaction.

J. F. Mescall and D. P. Macione (Ref. 89), in a program for the Program Manager, Cannon and Weapons System, demonstrated that by encircling the propellant charge of each round with a cylinder of intumescent material, flames from a similarly protected, but ignited, propellant charge would not induce ignition of neighboring charges. The test results indicated that intumescent cylinders could be used as antifratricide devices within magazines of the M109 SPH to reduce ignition by combustion from an adjacent propellant charge analogously to the antifratricide devices used in the M1 MBT for explosive warheads.

The tests were performed on bagged M3, M30, and M31 propellant stowed in sleeves. These propellant bags were placed in three parallel sleeves laid in close contact on a flat surface. One of the outer sleeves was unprotected, whereas the other was protected, and the propellant in the inner sleeve was ignited by a long fuse. In the early tests the sleeves were made of aluminum, steel, or fiberglass-epoxy, and the ends were sealed with rubber stoppers. Two types of materials were used to protect the propellant, an intumescent material manufactured by 3M known as INTERAM™ and a foamed material manufactured by Ethyl Corporation known as EYPEL-A™, which were strapped onto the outside surface of the "protected" sleeve. Each test was conducted with one or the other material, not with both materials in the same test. In every test the propellant within the unprotected sleeve ignited. The INTERAM™ successfully protected the propellant every time it was tested and

*Based upon measurements made on an illustration in Ref. 84

sustained so little damage that it was deemed capable of reuse. The EYPEL-A™ failed to protect the propellant in its first two tests, but after the addition of an overwrap of fiberglass fabric, it successfully protected the propellant in subsequent tests. Of the two, INTERAM™ appears to be the more satisfactory because it has the sturdiness to withstand the vibrations and impacts to which it would be subjected within a combat vehicle. (Ref. 89)

4-6.4.2 High-Explosive Stowage

High-explosive stowage is more difficult to design than low-explosive stowage since a detonation imparts a blast wave of energy rather than an extremely rapid impulse of quasi-static pressure, as does a deflagration. The blast wave shock passes through the wall of a container, whereas quasi-static pressure builds up within a container. If a pressure relief device is built into the container, the quasi-static pressure can be relieved, as is done by the blow-off panels of the separate magazines of the M1 series MBTs. The shock wave from a detonation, however, cannot be relieved by such a pressure relief device. Thus the container must be strong enough to withstand the shock wave. Such a container has been demonstrated (Ref. 90), but it is heavy. A buffering system has also been demonstrated (Ref. 91), but the vehicle must be able to withstand the momentum imparted; See subpar. 4-8.1.2. The lesson learned is that the vehicle must be designed to withstand detonation of onboard high explosives and that this design must be started with the first vehicle concept.

Gun-carrying vehicles, such as MBTs, BFVs, and SPHs, usually carry high-explosive projectiles; APCs also carry high explosives in the form of mines and explosive charges for use by the troops. Many M113A1 APCs were destroyed in SEA when the onboard explosives were cooked off by diesel fuel fires or other fires after the vehicle was hit while transporting explosives. These explosives could be stowed in a trailer, or special, vented compartments could be provided.

4-6.4.3 Chemical Ammunition Stowage

In Southeast Asia the Viet Cong (VC) often dug extensive tunnel systems (Ref. 92). These tunnels went down to three stories in depth and often contained booby traps for unwary visitors. Chemical agents, such as smoke, were often used by US troops to incapacitate or drive out the VC. Sometimes tear gas was used for the humanitarian reason that noncombatants were often forced into the tunnels by the VC. Therefore, there were tear gas grenades in the combat area.

For unknown reasons several of these chloracetophenone solution (CS) grenades were in the turret of an M48A3 MBT when an RPG struck (DAN 153). The shaped-charge jet perforated two CS grenades. The crew abandoned the M48A3 so quickly that one crew member was injured during dismounting. A second crew member was killed and a third crew member wounded by small arms fire. This action not only incapacitated the crew but also left an otherwise usable M48A3 sitting without a crew. The lesson learned here is not to carry unnecessary chemical ammunition within an armored vehicle. If such ammunition has to be carried, it should be stowed in external boxes so, if hit, it cannot affect the crew, or an overboard-ventable compartment should be provided for smoke or incendiary items.

Designers should provide a protected box on the exterior of the vehicle for such items, or these items could be shipped in special boxes to be attached to the exterior of the vehicle. There may be a bonus for such external stowage of some chemical devices. When an RPG-2 hit an AR/AAV M551 on the side of a sponson, the jet entered a smoke grenade launcher but did not exit (DAN 1696). Could that smoke grenade have functioned like a reactive armor packet?

4-7 MATERIALS SELECTION

Selection of firesafe material products for the interior of combat vehicles must have a high priority. A small fire inside an enclosed environment can quickly and easily spread by means of flammable materials and create unsafe conditions and possibly necessitate evacuation from the vehicle. Materials that smolder rather than burn can also produce an untenable environment in a slower, insidious manner. Smoldering is often harder to detect and more difficult to extinguish than flaming combustion. Currently used extinguishants, Halon 1301 and carbon dioxide, are not effective against smoldering fires. Under certain conditions smoldering fires may progress to flaming fires. Materials are desired that do not ignite or burn given a flash hydrocarbon fuel fire or similar gun propellant fire or given continued contact with particles from the shaped-charge jet.

Actual fires may grow very rapidly by feeding on the heat produced and may quickly become out of control. Furthermore, toxic smoke from such fires may be highly dependent on the combustion conditions and the surrounding atmosphere. Simulation of these conditions for smaller scale flammability and toxicity test procedures is difficult; therefore, data from these tests must be analyzed and carefully interpreted before product selection. Perhaps newer test methods should be developed, e.g., one for fire resistance to a short, intense flash fire or prolonged contact with heated copper.

In the paragraphs that follow, flammability properties and pyrolysis and combustion product evolution from materials that are typically used in the interiors of combat vehicles are discussed. It should be emphasized that fire tests on the constituent materials of components may produce a different result from the same test on a finished product composed of multiple materials, e.g., a seat cushion made of a fabric exterior and a foam interior.

The ultimate selection process for materials in a critical environment such as a combat vehicle should involve an assessment of the potential hazards of the materials in likely fire scenarios. This assessment need not be delayed until computerized hazard and risk analysis procedures have been developed. Such procedures can be developed by using the data and test methods presently available.

4-7.1 FLAMMABILITY

There are several different flammability properties that must be considered in the selection of materials for combat vehicles:

1. Ease of ignition
2. Rate of flame spread
3. Rate of heat release
4. Rate of smoke evolution (including toxic gases).

All of these properties are important and must be subjected to a hazard analysis in order to define the most important factors for any given fire scenario. For example, ease of ignition is an obvious property to consider for any material likely to be the "first object to ignite". Resistance to ignition in a laboratory test, however, does not necessarily mean that the material will not ignite readily in a larger scale scenario with an external heat flux from other burning materials or from prolonged contact with heated particles from impacting warheads. Rate of smoke evolution is also an extremely important criterion for fire in an enclosure; however, the rate of evolution and the composition of the smoke are highly dependent on the other flammability properties and on the particular fire environment being considered.

Rate of heat release is a significant property in determining fire spread. This value is important in computer fire modeling calculations and may determine in large part how hazardous a material would be in an actual fire. Rate of heat release is dependent on the applied heat flux; therefore, interpretation of the data as related to anticipated fire scenarios is essential.

There are many laboratory test methods for evaluating flammability properties of materials. Some of the more common standard procedures for flammability and smoke, including those used by the military, are listed in Table 4-6. Included in the table is a brief description of the types of materials tested and the flammability property measured.

The test methods listed in Table 4-6 under Federal Test Method 191A (Ref. 93) illustrate the complexity of testing a material (in this case, cloth) for "flame resistance", which includes ease of ignition and flame spread. The tests cover ignitability; horizontal, vertical, and 45-deg angle burning; a test for field use; and a higher heat flux flammability test. The procedure for horizontal burning is the least rigorous of these tests; the method that uses the larger burner, i.e., the "high heat flux" test, is probably the most rigorous. The application of the fabric and consideration of the relative importance of flame resistance in that application must be considered in the selection of standard flammability test protocols. None of these fabric flammability test methods would be suitable alone for evaluating the unique properties of fabric and foam combinations, such as in upholstered seats.

Caution must be used to assess the "ignitability" of materials. This property is very dependent on the test method. For example, a material that would not ignite under certain flame exposure may ignite readily under a higher heat flux. Fire-retardant treatment causes materials to self-extinguish in certain tests; however, in other tests these materials may burn readily. The term "flameproof" (presently in Methods 5900, 5906, and 5908) must not be used. "This term was originally used to describe the treatment of textile fibers or other organic products to make them resistant to ignition. However, the term has been misunderstood to mean an absolute or unconditional property, and therefore, the use of the term, flameproof, is inappropriate and misleading." (Ref. 94)

The method currently used to assess the rate of heat release of materials on a laboratory scale was developed at Ohio State University, ASTM E 906 (Ref. 95), and is currently a requirement for materials used in commercial aircraft. This test method is valuable for assessing key flammability parameters, i.e., the quantity and rate at which heat is released from a burning material. Selection of the heat flux for irradiating the specimen must conform with an analysis of the potential fire environment for the material.

Determination of the quantity of "smoke" produced from any given material is listed here under "flammability" because it is an important fire parameter related to the other flammability characteristics of a material. Test Method E 906 for rate of heat release can also measure the rate of smoke release. Test Method E 662 (Ref. 96) is designed to measure the total smoke evolved from a material under a constant heat flux condition. Criteria used to evaluate smoke optical density should be based on consideration of the possible quantity of material and the size of the compartment in which the smoke will be collected. Arbitrary standards for smoke should not be used because smoke evolution is so dependent on the other flammability properties.

There are other tests for the flammability properties of materials than those listed in Table 4-6. Furthermore, larger scale flammability tests are available or could be developed that subject materials to the more rigorous fire conditions which may exist in a real-life situation. Different results are likely when full-size products are used in larger scale flammability simulations. Ideally, all materials should be tested for fire performance properties either in a full-scale mock-up or under conditions conducive to a hazard assessment of the fire scenario under consideration. This testing is not always practical, however, and small-scale tests are used. Caution must be exercised against possible misinterpretation of the results of standard laboratory-scale flammability tests.

The relative flame response properties of materials typically used in combat vehicle interiors are presented in Table

TABLE 4-6. STANDARD LABORATORY-SCALE FLAMMABILITY TEST PROCEDURES

STANDARD	COMMON TITLE OR DESCRIPTION	MATERIALS TESTED	FLAMMABILITY PROPERTY
ASTM D 635/UL 94	Flammability of rigid plastics	Rigid plastics, usually for electrical housing	Ignitability, burn time
ASTM D 2863	Oxygen index test	Rigid plastics, also used for fabrics, thin films	Oxygen concentration required to sustain combustion
SAE J369/FMVS302	Motor vehicles interior materials	Foams for seat cushions	Burn rate (horizontal)
ASTM E 162	Vertical radiant panel test	Rigid plastics, fabrics	Flame spread (vertical)
ASTM E 136/ASTM D 1929	Setchkin ignition apparatus	Almost any material	Ignition temperature
Federal Test Method 191A:	Methods for testing flammability properties of flame-retardant fabrics:		
Method 5900	Flame resistance of cloth, horizontal	Fabric	Outward flame spread
Method 5904	Flame resistance of cloth, vertical, for field use	Fabric	Flame time, char length
Method 5905.1	Flame resistance of cloth, high heat flux flame contact	Fabric	Reaction to flame (burn, melt, etc.)
Method 5906	Burning rate of cloth, horizontal	Fabric	Burn rate
Method 5907	Flammability test for sleeping bag cloths, tablet method	Fabric	Burn time, char length
Method 5908	Burning rate of cloth, 45-deg angle	Fabric	Burn rate
ASTM E 662	Smoke density chamber	All materials	Smoke evolution
ASTM E 906	Ohio State University rate of heat release	Most materials	Heat and smoke evolution

4-7. Included are seat materials, materials for electrical wire coverings and instrument housings, and fabrics for clothing, sleeping bags, tents, equipment covers, tarpaulins, etc.

Materials that melt, as illustrated in Table 4-7, present a particular problem in evaluation of flammability test results. This is due to the fact that melting removes heat from the flame and may enable a specimen to "pass" a small-scale controlled test procedure; however, melting in a larger scale fire may spread the flames and add to the intensity of the fire by creating a pool of liquid fuel. Thus the physical properties of the material must be considered in any selection process based on flammability considerations.

Materials that form a char often burn more slowly than those that do not because the char protects its substrate from the heat and flame. However, such materials, e.g., cellulosic materials such as cotton or burlap, may propagate a smoldering fire by forming a self-propagating char. The application of such materials determines whether or not char formation is an acceptable characteristic.

Selection of naturally flame-resistant materials, e.g., Nomex® and Kevlar®, which are resistant to ignition because of their thermally stable polymer structure, should be made wherever possible and with due consideration for the performance of these materials under large-scale test procedures and in smoke toxicity evaluations. Also materials containing fire or flame retardants (either "added" to the polymer matrix or "reacted" into the polymer chain) must be evaluated carefully, preferably under simulated or actual full-scale test conditions. Fire-retarded materials are generally more difficult to ignite than comparable nonfire-retarded materials. Once ignited, however, fire-retarded materials will burn and may produce more noxious and toxic products than the nonretarded base material. Fire retardants may be appropriate and beneficial from a fire safety point of view in many situations. These should be reviewed on a case-by-case basis.

Foam materials, e.g., seat cushions, may burn rapidly and should be protected by a fire-blocking layer or covered by a highly fire-resistant fabric. (See subpar. 3-6.3.) Evaluation of the fabric and foam composites should be conducted under procedures such as ASTM E 906 or full-scale simulations.

Clothing and miscellaneous debris pose a fire hazard that is difficult to predict and/or to regulate because the quantity and types of materials are so variable. General flammability considerations and knowledge of fire property data by designers and users of combat vehicles are valuable in developing an awareness of the potential hazards of these materials.

4-7.2 PYROLYSIS AND COMBUSTION PRODUCTS

When a natural or synthetic polymeric material undergoes pyrolysis (nonoxidative thermal decomposition) or

TABLE 4-7. FLAMMABILITY PROPERTIES OF MATERIALS TYPICALLY USED IN COMBAT VEHICLES

MATERIAL	REACTION TO HEAT*	REACTION TO FLAME**	USE OF MATERIAL
Vinyl (PVC) fabric	Char	Self-extinguish	Seat covering
Polyurethane foam (flexible)	Melt	Burn***	Seat cushioning
Wool batting	Char	Burn slowly	Seat cushioning
PVC (polyvinyl chloride)	Char	Self-extinguish	Electrical wire insulation
Nylon	Melt	Burn	Electrical wire insulation
Teflon® (polytetrafluoroethylene (PTFE))	Melt	Self-extinguish	Communications cable insulation
ABS (acrylonitrile butadiene styrene)	Melt	Burn***	Electrical/electronic housing
High-impact polystyrene (HIPS)	Melt	Burn***	Electrical/electronic housing
Fabrics:			Fabrics for clothing, sleeping bags, tents, and equipment
Nylon	Melt	Burn	
Cotton	Char	Burn***	
Wool	Char	Burn	
Nomex®	Melt	Self-extinguish	
Kevlar®	Melt	Burn***	
Polyester	Melt	Burn***	
Burlap	Char		
Fiberglass (polyester or epoxy resin on glass fiber)	Melt	Does not readily burn	

*A high-temperature environment or contact with a hot object is assumed.
**For purposes of comparison, the expected reaction to flame in a typical laboratory flammability test with commonly available materials is shown.
***Any material with added fire retardant, e.g., polyurethane foam, will "self-extinguish" under some test procedures.

combustion (including oxidative pyrolysis, or smoldering, as well as flaming), the resulting smoke probably contains toxic or corrosive products. The common synthetic and natural materials that may typically be found in the interior of a combat vehicle are listed in Table 4-8. All carbon-containing materials (even simple fuels) produce carbon dioxide, an asphyxiant, and have the potential to evolve lethal carbon monoxide and partially oxidized hydrocarbons, such as aldehydes, many of which are toxic. Also nitrogen-containing materials might produce toxic gases, which include nitrogen oxides, hydrogen cyanide, and organic nitriles, amines and isocyanates. Materials that contain halogens, i.e., fluorine, chlorine, bromine, or iodine, may produce corrosive and toxic gases, such as phosgene ($COCl_2$) or the halogen acids, e.g., HCl. The possible smoke products must be considered in the selection of materials for the interior of a combat vehicle; preferably, materials that generate noxious products will not be used.

The term "smoke" is used here as defined in ASTM E 176, *Standard Terminology Relating to Fire Standards* (Ref. 94), as "the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion.". The composition of the smoke from individual materials is highly dependent on the combustion conditions, which include the applied heat flux, the availability of air to the combustion site, and flaming versus nonflaming combustion. Thus any laboratory test protocol for evaluating the composition of the smoke, e.g., by analytical procedures or smoke toxicity experimentation, must be evaluated in terms of the test conditions relevant to the actual fires possible. The smoke products, however, cannot be predicted from a given set of combustion conditions without extensive empirical data. All smoke may be toxic and many smokes are corrosive. Therefore, any smoke in an enclosure is a potentially serious problem. The toxicological significance of the gases listed in Table 4-8 is discussed in par. 5-6.

Smoke also contains aerosols (liquids in suspension) and soot (carbonaceous solids) in addition to the gaseous products previously described. Generally, pyrolysis—in this case, either nonoxidative or oxidative pyrolysis, including "smoldering" and "nonflaming combustion"—produces aerosols. Only flaming combustion produces soot. The aerosols are often white or yellow in color and comprise polymer fragments, such as aldehydes from cellulosic materials or isocyanates from polyurethane. Soot, on the other hand, is composed almost exclusively of multiring aromatic molecules, essentially graphite or carbon, and is always a secondary combustion product, i.e., it does not arise directly

TABLE 4-8. TOXIC PRODUCTS THAT MAY BE PRODUCED FROM SELECTED MATERIALS UNDERGOING PYROLYSIS OR COMBUSTION

MATERIAL (CONSTITUENT ELEMENTS)	POSSIBLE HAZARDOUS COMBUSTION PRODUCTS
PVC (C_2H_3Cl)	HCl, CO, CO_2, $COCl_2$
Polyurethane foam ($C_{6.3}H_{7.1}NO_{2.1}$)	HCN, NO_x, CO, CO_2, NCO
Wool (N, C, H, O, S)	HCN, CO, CO_2, NO_x
Nylon ($C_6H_{11}NO$)	NO_x, HCN, CO, CO_2
Fluorocarbons, e.g., Teflon®) (F,C)	HF, perfluorocarbon compounds, CO, CO_2
Nomex®, Kevlar® ($C_{14}H_{10}O_2N_2$)	NO_x, HCN, CO, CO_2
Polyester ($C_{5.77}H_{6.25}O_{1.63}$)	NO_x, CO, CO_2
Burlap (C, H, O)	CO, CO_2
Fiberglass (Resin Coating: C, H, Si, N, O)	CO, CO_2, NO_x, HCN, NCO
ABS (C, H, N)	HCN, CO, CO_2, NO_x
HIPS (C_8H_8)	CO, CO_2

Note: Fire extinguishants can add to the number of hazardous products possible.

from the polymer structure. Some aerosols are also produced during incomplete flaming combustion. Thus the composition of "smoke" from any given material under a given set of fire conditions is difficult to predict and comprises a mixture of many products.

Other items that can be included with "smoke" are particles of the fillers added to new composites. Items such as carbon or boron filaments can become airborne when the composite burns or is pyrolyzed and can alter chemically and change shape to become small airborne particles, which can cause damage to unprotected eyes, skin, or lungs (Ref. 97). Again, composite materials must be tested to determine whether there are potentially hazardous combustion products or by-products, and if there are, those composites should not be used in combat vehicles.

Fire extinguishants, e.g., Halons, may produce toxic or corrosive products, e.g., halogen acids or phosgene, upon reaction with a fire (Ref. 98). Presently, the use of many of the common extinguishing agents that have been recommended for enclosures is being reassessed; toxic and corrosive effects are coming under more careful scrutiny.

Because the pyrolysis and combustion products generated are functions of the type of combustion, the interior materials present, and the extinguishant used, a recommended list of interior materials cannot be given. Instead the designer should have potential interior materials tested to establish the pyrolysis and combustion products from the various types of combustion, mixes of other materials present, extinguishants to be used, and climatic conditions. Then he should preferably exclude any materials or material combinations that produce noxious products. Any remaining noxious products can be removed by the extinguishing techniques incorporated in the vehicle design and/or by appropriate vehicular ventilation.

4-7.3 LESSONS LEARNED

4-7.3.1 Ballistic Fabric Selection

Three unbonded ballistic fabrics were used as spall curtains in several tests described in Refs. 22 and 23. These fabrics were Kevlar® 29, ballistic nylon, and highly oriented polyethylene, Spectra® 900. These spall curtains were intended not only to trap spall but also to confine fires to a small compartment. In general, the Kevlar® was highly satisfactory. Ballistic nylon melted when the fire had enough duration and intensity to heat the nylon above its melting point. The highly oriented polyethylene ignited and burned. In an additional effort to make the polyethylene fire-retardant, some polyethylene material was treated with an enzyme solution that had made certain other fabrics more fire-resistant. This enzyme solution made the polyethylene a little more difficult to ignite, but once ignited, it burned as rapidly as it had in an untreated condition.*

The lesson learned is to select fabrics that will not burn for spall curtains in combat vehicles. Kevlar® is highly satisfactory, fiberglass or Nomex® should be satisfactory, nylon will melt, and polyethylene is not recommended. These recommendations are for unbonded fabrics only; bonded fabrics should be tested for fire resistance.

4-7.3.2 Hazard Potential From Use of Composites

The crash of a Royal Air Force (RAF) Harrier on the island of Moess in Denmark, 17 October 1990, brought attention to the production of noxious particles through combustion of a carbon-filament-reinforced composite. Investigators were forced to wear protective clothing, including dust helmets, to avoid particle ingestion (Ref. 97).

*Test conducted by W. A. Mallow and P. H. Zabel at Southwest Research Institute, 1987.

This example illustrates that reinforcements used in composites can become small, hazardous airborne particles upon combustion of the composites. The lesson learned is to determine what can be produced by the combustion of composites and to avoid the use in combat vehicles of composites that produce noxious particles.

4-7.3.3 Fire-Resistant Polymers and Polymeric Composites

There is a pressing need to improve substantially the fire resistance of polymers and polymeric composite structures. For thermoplastic polymers there are really two applications. The first is in the internal cabin fitting and fixtures. This application may not be a primary concern in combat vehicles, but it is likely to become more important as the applications of polymers increase. The second application relates to the control of electrical fires and the critical role polymeric materials play in insulating the electrical cables.

The general approach to making polymers fire-resistant has been to formulate the polymers with additives that inhibit oxidation of the polymer. The addition of red phosphorus to polyethylene reduces flammability and increases charring. The detailed mechanism is not known, but it is plausible that phosphorus oxidizes to the large number of phosphorous oxides, which have high heat capacity and high latent heat of fusion.

The use of phosphorus-containing flame retardants is one of the best known methods for improving the resistance of a large class of polymers to combustion. This technology is mature, and an extensive body of literature is available, as exemplified by a number of recent contributions (Refs. 99 and 100).

Also, the use of polymeric composite structures provides significant weight benefits and future combat vehicles will contain more structural composites. Fortunately, there is reliable evidence which suggests that the fire dynamics may be quite manageable from the materials point of view (Ref. 101).

Parker et al (Ref. 102), have reported a new class of resins, which incorporate the phosphorous-nitride trimer to yield polymers that will not burn even in pure oxygen.

A number of bismaleimide polymers, which incorporate the phosphonitrilic trimer, generate fire-resistant polymers that have good thermooxidative stability in air at temperatures up to 816°C (1500°F). Chemical linkages, which are susceptible to thermal degradation by the methylene units in methylene dianaline, have been replaced by phosphonates and cyclotriphosphazenes. This replacement has resulted in the development of virtually completely fire-resistant polymers with limiting oxygen indices of 100 and residue weights in excess of 80% in air at 871°C (1600°F). Table 4-9, derived from data in Ref. 102, compares the thermooxidative stability of incydophosphazenes with state-of-the-art bisimides and aromatic matrix resin polymers.

TABLE 4-9. CHAR YIELD FOR SELECTED POLYMERS (Ref. 102)

POLYMER	CHAR YIELD, % AT 800°C IN AN N_2 ENVIRONMENT
Phenolics	45
Phosphorylated epoxy 1	38
Polyphenylsulfone	48
Bismaleimide	50
Phosphorylated epoxy 2	56
Cyclophosphazene polymer	82

4-8 SYSTEM INTEGRATION

To obtain a system that prevents the occurrence or continuation of fires, a designer must consider the threat effects and the combat vehicle response to those effects for all of the systems, subsystems, and components involved. The designer must also consider combustion and explosion and the phenomena that affect ignition of a fire or initiation of an explosion. Combat vehicles must carry fuel for their internal combustion engines and ammunition for their weapons, and they must go where the enemy will do its best to destroy those vehicles. To depend upon armor to defeat all hits or countermeasures to avoid being hit in all instances is poor practice. As was stated by the ASTB Task Force,

"Combat vehicle survivability discussions frequently center on this survivability rule:

- Don't be detected; but if you are,
- Don't be acquired; but if you are,
- Don't be hit; but if you are,
- Don't be penetrated; but if you are,
- Don't be killed." (Ref. 69).

Since combat vehicles contain flammable mobility fuel and highly flammable solid propellants and high explosives, a "simple fix" will not be adequate to prevent fires. Advantage should be taken of any fire prevention potential presented by the materials present.

4-8.1 COMPARTMENTALIZATION

Most combat vehicles are compartmentalized, at least into an engine compartment and a fighting or crew compartment. The crew of a combat vehicle is protected best by placing the most hazardous materials—ammunition and mobility fuel—in separate compartments. The crewmen do not have to handle the mobility fuel when operating the combat vehicle, so compartmentalizing the mobility fuel is a design challenge in engine and fuel cell placement. Ammunition stowage is different.

4-8.1.1 Ammunition Magazines

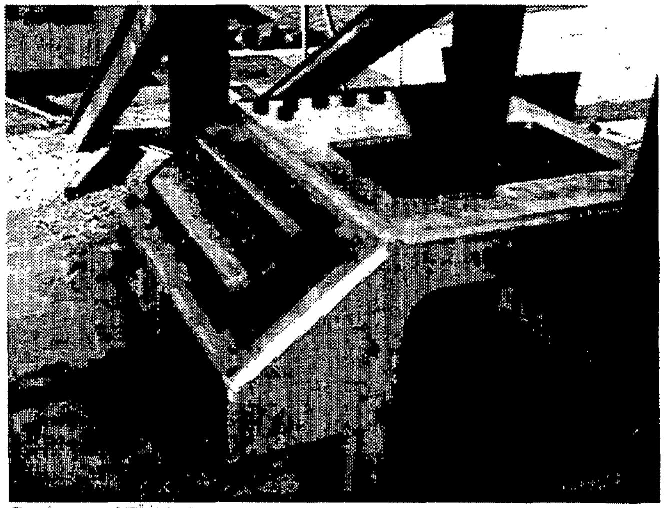
An excellent use of compartmentalization is the separation of ammunition magazines from the occupied compartment of the M1 and M1A1 MBTs and the ASTB as described in subpars. 4-6.2.2.2 and 4-6.2.2.3, respectively. On these vehicles there are exterior blow-away panels that permit venting of the products of explosion to the outside. Thus an explosion in any magazine will probably result in the loss of the remaining cartridges in the affected magazine only. Of all rounds carried, however, only the few in the ready rack present a danger to crewmen. Surrounding these ready rounds with a water jacket could reduce the explosion effects but not eliminate them.

Unless there is an automatic loader, ammunition must be handled by personnel. The rounds for tank guns must be readily available to the loader, who must physically insert the cartridges into the breech. The main gun cartridge magazines therefore must have a sealable access strong enough to withstand the explosion of the stowed ammunition propellant. These magazines should be vented to the outside to reduce quasi-static pressure resulting from explosion of the contents. These vents and the other components of the vehicle should be located to preclude undesirable interactions, such as those described by Watson and Gibbons in Ref. 68, as well as the dumping of propellant products of combustion into the engine air intake. Descriptions of potential improved designs are given in subpar. 4-6.4.1.

4-8.1.2 External Ammunition Stowage

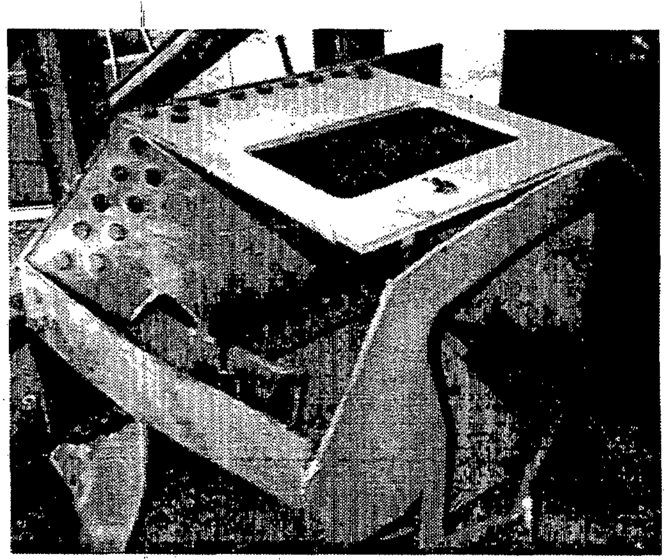
Early in the ASTB program, plans were made to stow some of the TOW missiles externally. These TOWs were mounted on the upper rear side surface of the crew compartment. A ballistic shield was placed over the missile assemblies to provide protection from 7.62-mm or smaller small arms fire and from artillery shell fragments. A layer of cushioning material was emplaced between the missiles and the hull to prevent damage to the hull if the missile motors and/or warheads were initiated by a shaped-charge jet or other ballistic penetrator that could defeat the shield. Tests and analyses showed that a cushioning layer consisting of approximately 25 mm (1 in.) of an elastomeric material, 102 mm (4 in.) of aluminum honeycomb, and 38 mm (1.5 in.) of steel was needed to prevent rupture of the hull. But even with this buffering material in place, in a test the hull was still distorted to a parallelogrammatic shape so that the rear ramp door became jammed. A scale model test was performed in which a single missile motor and warhead were detonated under a ballistic shield but without the buffering layers. Fig. 4-35 shows the pretest configuration and Fig. 4-36 the posttest condition.

A different solution was demonstrated in which the impulsive loading from the exploding energetic materials is diverted so that the structure on which the missile assembly holder is mounted will not be subjected to loading (Ref. 90). This solution is to install each missile assembly within a cylindrical shield that is strong enough to contain the blast impulse and quasi-static overpressure radially but also to



Courtesy of FMC Corporation.

Figure 4-35. Ballistic Shield on Scale Model Crew Compartment (Ref. 91)



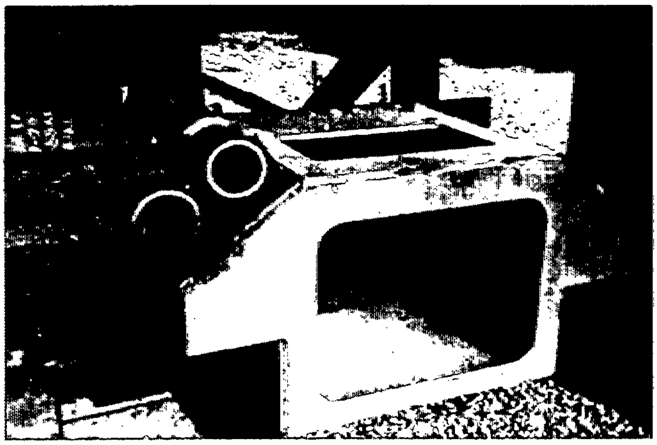
Courtesy of FMC Corporation.

Figure 4-36. Posttest Condition of Scale Model Crew Compartment (Ref. 91)

permit both ends to blow out and vent the quasi-static overpressure. This concept was tested in a subscale model and has been demonstrated to be feasible in six scale model tests, but it has not been optimized for size and weight. By using a scaled missile simulant of the same design and size as the one that destroyed the model structure, the missile container shown on Fig. 4-37, i.e., the lower one, was bulged, but the structure of the model was unaffected (Ref. 91).

4-8.1.3 Jacketed or Double-Walled Fuel Cells

In a sense, a hollow wall or jacket is a compartment, which can contain a liquid, added to another compartment. The use of a double-walled fuel cell with extinguishant



Courtesy of FMC Corporation

Figure 4-37. Posttest Condition Showing Bulged Missile Container (Ref. 91)

within the jacket provides multiple benefits. Not only may this double wall provide a threat-released fire extinguishant in the exact region in which ignition would occur, but also the presence of the fire extinguishant on the outside surface of the fuel cell wall greatly reduces hydraulic ram damage to the wall and thereby reduces the amount of fuel thrown into the compartment housing the fuel cell. Fig. 4-38 allows comparison of the lower fuel cell to the upper fuel cell, and Fig. 4-39, the upper fuel cell to the lower cell. In all four tests the shaped charges were M28A2 HEAT warheads from the 3.5-in. rocket, the diesel fuel was from the same batch for all four tests, and the fuel cells were all the same size (Ref. 24). The fuel cells in Fig. 4-38 were made of 16-gage stainless steel, and of 12-gage stainless steel in Fig. 4-39. The lower fuel cell in Fig. 4-38 and the upper fuel cell in Fig. 4-39 were welded with single walls. The upper cell in

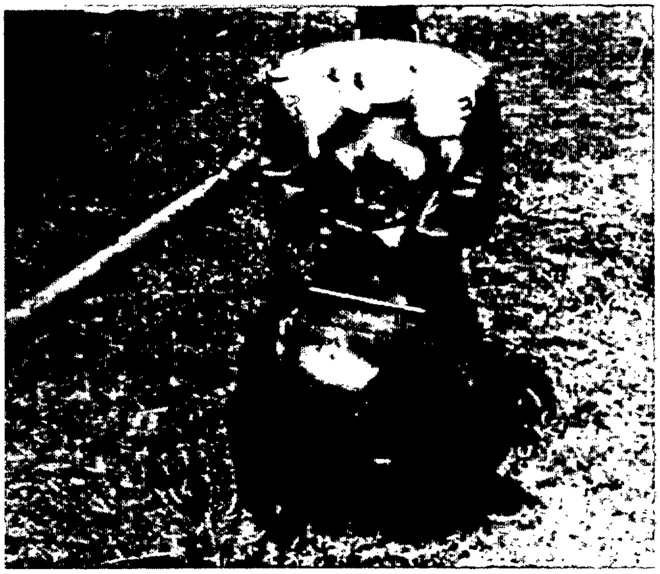


Figure 4-38. Fuel Cells From Tests No. 2 and 3 (Ref. 24)

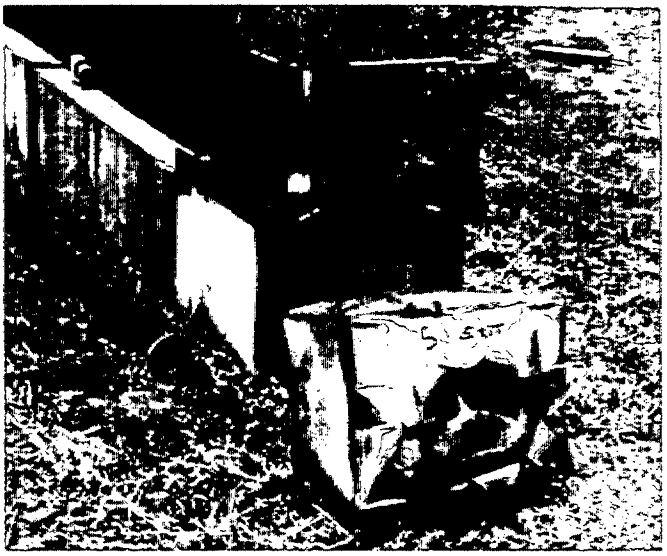


Figure 4-39. Fuel Cells From Tests No. 4 and 5 (Ref. 24)

Fig. 4-38 and the lower cell in Fig. 4-39 were jacketed on two sides with 18-gage stainless steel with water as an extinguishant placed between the jacket and the fuel cell. From these and other tests described in Ref. 27, the following can be established:

1. The fire extinguishant was effectively dispersed by the threat and extinguished combustion of the fuel. The tests showed that water and the dry chemical fire extinguishants were highly effective in extinguishing the fires.
2. The jacket and extinguishant greatly reduced damage to the fuel cell due to hydraulic ram. Both the liquid (water, water-based extinguishants, or bromochloromethane) and solid (pulverized potassium bicarbonate or granulated monoammonium phosphate) extinguishants in the jackets acted to reduce the hydraulic ram damage to the fuel cell walls.
3. The hole caused by the jet enhanced by fuel hydraulic ram can be much larger for thinner skin materials than for thicker. The weaker the cell wall, the larger the hole that can be expected; however, the cell wall thickness or strength can be increased to a point at which hydraulic ram no longer has an effect.

The double-walled fuel cell concept is very promising, but there are currently no established design parameters for which an optimal design can be made.

4-8.1.4 Storage Compartments and Bilge

Most combat vehicles have many small cubbyholes for storage of incidentals. Thus without too much effort, the compartments and the items themselves can be converted into traps for fuel spray, spall, flash, and fragments of penetrators. These small compartments can also trap whatever fuel combustion may occur.

The key design features of these small compartments are simple. The compartment should be at least 152 mm (6 in.) deep to permit fuel droplets in the wake of the jet to move out of the path of the jet or to permit spall to spread out. The compartment cover should be made of a material that does not emit a flash when impacted by a jet or KE penetrator and should be strong enough to stop spall. These compartments are made to store items such as those given on Fig. 3-4. Most of the items shown on Fig. 3-4 are not readily flammable; therefore, they can be used to trap spall and flash and, if between a fuel cell and an occupied compartment, fuel spray. Storage compartment walls and doors can also serve as spall curtains.

Liquid DF-2 was difficult to ignite when it had been sprayed onto the walls or into the bilge of a test fixture simulating the crew or engine compartment of an armored vehicle (Ref. 22). In fact, DF-2 in the bilge did not ignite even with a conflagration within the fixture as long as the deck plates were in place. The DF-2 vaporized and burned within the fixture after the fixture had been heated above the vaporization point of the fuel, but combustion did not occur below the decking. The bilge was the space between the hull and decking, and this bilge was not airtight. There were finger holes to facilitate decking removal, and the interstices between fixture walls and deck plates permitted the ready flow of liquid DF-2 from the interior of the test fixture to the bilge. These tests indicate that the bilge, if covered, is a relatively safe collection location for combustible liquids, such as diesel fuel or hydraulic fluid. Tests should be performed using JP-8 or Jet-A1 to establish whether or not the lower flash point fuel should affect the design.

4-8.1.5 Spall Curtains

Spall curtains are intended to capture small projectile fragments and spall particles, which would injure personnel or damage hardware. These curtains can also trap larger projectile fragments after they have slowed down. Material chosen for spall curtains should be "nonsparking" and nonflammable. The location of spall curtains, i.e., their distance from the compartment walls, should be selected to capture spall most effectively. This distance, estimated at a minimum of 152 mm (6 in.) from a penetrated wall, should also provide space to store some of the impedimenta carried in the combat vehicle. By rigidizing the spall curtains, a useful storage compartment results, but there is reduced ballistic performance of the curtains and a lesser dampening of noise. If the storage compartment is inside the vehicle hull with an energetic material container, such as a fuel cell, directly on the outside of the hull, the compartment contents should be materials that are relatively inert, can act as fire extinguishants, or at least can collect droplets or particles of the energetic material and the spall or flash from the hull. Thus the spall curtains serve multiple purposes, which include separating the flammable mixture from the ignition source generated by penetration impacts and providing a separate compartment for innocuous combustion.

The designer should assure that the original capabilities of the vehicle are maintained when spall curtains are installed. For example, the ambulance version of the M113 APC originally was capable of having four litters installed, but after spall liners were incorporated, the litters could not be installed without removal of the spall liners (Ref. 103). Provisions should have been made so that litters could be installed without removing the spall liners, which protect the wounded during evacuation.

4-8.2 SYNERGISM OF FIRE PROTECTIVE COMPONENTS

The design of the fire protective components of a combat vehicle must be such that each component aids in preventing fires so that the sum of the contributions of two or more components preclude the fire, even though any one component alone may not. A good example is two of the components described in the immediately preceding paragraph. The double-walled fuel cell could prevent an immediate fire from a hit by a shaped-charge jet, but unless there is a safe collection location for the sprayed fuel, another fire could start and ignite the fuel. If fuel can flow into a covered bilge, however, a sustained fire could not exist because the majority of the fuel would have collected in the bilge. Some other synergisms are described in the paragraphs that follow.

4-8.2.1 Less Hazardous Ammunition

To prevent a fire, the designer should assure that there is insufficient fuel or oxidizer, that the oxidizer and fuel do not mix in flammable ratios, that an ignition source is not strong enough for ignition to occur, or that the ignition source and flammable mixture do not meet for sufficient time for a fire to kindle. If ignition cannot be prevented, the designer should assure through starvation of fuel or oxidizer that the fire will not be sustained. If the fire becomes sustained, it should occur in an innocuous location and not catastrophically affect the vehicle or its occupants. The latter solution is highly appropriate for solid gun propellants, rocket propellants, or high explosives. The fuel or the oxidizer cannot be excluded because both are already present in an intimate mixture that is imminently combustible. If a ballistic penetration occurs, particularly by a shaped-charge jet, the ignition source is present in sufficient strength and duration for ignition. The explosive cannot be made inert with an extinguishant. Therefore, the best solution is to isolate the explosive-containing objects.

The ASTB design solution for main weapons ammunition storage in the ballistic boxes described in subpar. 4-6.2.2.3 is an excellent solution. The TOW missiles presented a far greater hazard than the 25-mm cartridges, so the 25-mm cartridges were used as buffering material between the TOWs and the crew compartment. See Fig. 4-32. Any TOW missile motor or warhead reaction could be a low-velocity, high-mass push against the 25-mm cartridge box; such a loading has a low probability of initiating reactions by the 25-mm cartridges. The compartment for the 25-mm cartridges was made strong enough so that if some cartridges exploded, personnel in the crew compartment would not be affected. An explosion in the TOW compartment would destroy all the TOW missiles therein and would probably damage many of the 25-mm cartridges in their compartment but would not seriously affect personnel within the vehicle. Further the TOW explosive-filled components and the 25-mm cartridges would probably behave somewhat like reactive armor to inhibit the jet and thereby protect other components and personnel that are farther away but in the path of the jet. Thus less hazardous ammunition was used to protect personnel from more hazardous ammunition. This concept was verified in live-fire testing.

4-8.2.2 Water Storage

The efficiency with which water prevents ignition was demonstrated in one of the external fuel cell tests described in Ref. 23. Test 10 in that program demonstrated that although the M28A2 jet passed through an external fuel cell made of 25.4 mm (1 in.) of aluminum 5083 and an internal compartment containing a 5-gal can of water, there was no visible flash from fuel or Al 5083, but a strong flash from the aluminum 6061 mounted on the far wall of the test was visible. The water-filled can, shown on Fig. 4-40, was destroyed but would have protected occupants. Every combat vehicle carries drinking water for the crew, and many have additional coolant water for either the engine or the engine oil or for some other item. The crew's water container is often placed on the outside of the vehicle because

Figure 4-40. Five-Gallon Water-Filled Can After Test No. 10 (Ref. 23)

the water is not essential to the immediate combat capabilities of the vehicle or crew. Water is a convenience, not a necessity, for a short-term fight. When an external fuel cell is traversed by a shaped-charge jet, a water container located on the inside of the penetrated armor can provide a quenching agent. (As a bonus, in the summer the drinking water would stay cooler within the vehicle than it would outside in the sun. Also, in winter the water would be less likely to freeze.) In the ASTB a 51-mm (2-in.) thick layer of gelled water was so emplaced for each external fuel cell (Refs. 23 and 71). Those layers of water were unnecessarily added weight because there was a water container present on the vehicle elsewhere that could have been divided and placed in those two locations. This water container was on the outside of the vehicle, so it did not contribute to the solution of a specific fire survivability problem. Due to consumption by the crew, drinking water should not be a primary fire-protective component, but its placement should be considered during design. See subpar. 4-8.4.4 for incidents in Southeast Asia that demonstrated the effectiveness of water in protecting against shaped-charge attacks.

Some combat vehicles also carry coolant water. When considering coolant water, the designer should assure that if a freeze point suppressant is required, it will be nonflammable; otherwise, it will burn in a fireball if hit by a shaped-charge jet. Care must also be taken so that the crew will not be sprayed with heated coolant if the cooling system is penetrated.

4-8.2.3 Space Heaters and Exhaust Systems

Combat vehicles must operate in winter, even in arctic regions; therefore, space heaters are provided. Because it is not desirable to have the engine run continuously when the vehicle is not moving, space heaters often burn fuel to prevent frostbite of crewmen, to assure proper functioning of vehicle hardware, and to prevent freezing of liquids within the vehicle. These space heaters should not add significantly to the maintenance or operational workload, and they especially should not present a hazard. There have been many instances of space heaters in combat vehicles exploding or catching fire because they were turned on when the fuel from a previous use had not been fully purged. See subpar. 4-3.5.5. A space heater requiring that degree of operator maintenance should not be used in a combat vehicle. "User-friendly" equipment, as computer buffs would say, is needed.

If fuel-burning heaters are used in combat vehicles, the burner should not be located where fuel from a perforated or ruptured fuel cell could spray or pour on it. This event would provide a source of certain ignition for spilled fuel, particularly if a shaped-charge jet or KE penetrator could perforate the heater and puncture a nearby fuel cell. In addition, stowed ammunition, particularly in combustible containers, should not be located close enough for the heater to ignite the container and cause the stowed ammunition to explode.

Even in World War I, mufflers ignited spilled fuel (Ref. 31). The muffler of the Mark IV English tank was placed on the roof, as shown in Fig. 4-22, to prevent adding to the heat within the vehicle; emplacing an unarmored fuel cell beside that muffler was not a well thought out field modification. See subpar. 4-3.5.3. Currently, exhaust systems are buried within vehicles to avoid broadcasting an infrared signature that could identify the vehicle. Exhaust systems and fuel cells, however, should not be located so that a ballistic perforation would provide a path for fuel to the exhaust system. (The results of providing such a path are described in Ref. 22.) The exhaust system is too certain an ignition source.

4-8.3 EXAMPLES OF SYSTEM INTEGRATION

Some examples of system integration, such as (1) locating the magazine containing less volatile ammunition between more highly volatile ammunition and the crew compartment (subpar. 4-8.2.1), (2) the use of storage compartments and their contents as additional shielding (subpar. 4-8.1.4), and (3) the use of water storage to protect the crew compartment (subpar. 4-8.2.2), have been presented. In all of these examples, items installed within a combat vehicle are made to serve an additional function.

Mobility fuel is a necessary evil in combat vehicles. The next three examples provide good and bad techniques of fuel storage to assist vehicle designers.

4-8.3.1 Advanced Survivability Test Bed (ASTB) Fuel Barrier

When a material is placed in a separate compartment to avoid hazardous effects, the designer must assure that ballistic damage does not allow entry of the hazardous material or its effects into the protected compartment.

Early designs of external fuel cells mounted on the rear of the ASTB vehicle allowed a significant amount of fuel to enter the troop compartment when a shaped-charge jet passed through the external fuel cell into the troop compartment (referred to as "forward trajectory") (Ref. 23). Similarly, when the shaped-charge jet passed through the vehicle hull, the troop compartment, the vehicle hull on the other side, and then into the external fuel cell (referred to as "reverse trajectory"), shown in Fig. 4-23, the jet pressurized the fuel via hydraulic ram and fuel spewed back into the troop compartment through the hole made by the jet. In both cases the flash and/or splash back of the hull ignited the fuel spray and conflagrations occurred.

The means used to preclude these "fuel injections" into the troop compartment was placement of a box containing flint river gravel between the vehicle hull and the external fuel cell. This setup was a larger version of a bullet baffle egress from a 25-m rifle range (Ref. 104). This box was the size of the area of contact of the fuel cell and the vehicle hull. These are the design criteria followed:

1. The individual stones were to be larger than the hole the jet would make in the walls of the box. The stones were to be rounded to facilitate repacking by gravity after the jet fragmented or pulverized the stones in its trajectory. The stones were to be hard enough not to pulverize quickly from the jolting received during the cross-country traveling of the vehicle and not to be subject to interpiece welding from the ballistic impact.

2. The sides of the box were not to distort from the ballistic impact so that fewer than two pieces of gravel could be abreast between the surfaces of the fuel cell and the vehicle hull. Such gravel piece packing would be deemed sufficient to interrupt a fuel jet and allow gravity to force the fuel to flow downward.

3. The bottom and lower portions of the outer sides were to have drain holes so that the fuel flowing out of the fuel cell would drain onto the ground.

Tests established that 37-mm (1.5-in.) gravel (maximum diameter) was appropriate. A box constructed of 6.25-mm (0.25-in.) thick steel sides, top, and bottom and with 3.125-mm (0.125-in.) thick faces against the fuel cell and hull was adequate to withstand the ballistic impact of the 88.9-mm (3.5-in.) warhead jet, and there should be a layer of gravel 76 mm (3 in.) thick. Further, these tests showed that a box which provided a gravel space 41.4 mm (1.63 in.) thick would deform under ballistic impact to the point at which the gravel could not settle freely and properly to fill the passage the jet made. Also porous lava rock would pulverize too readily and would not gravity pack as would the rounded river gravel given the same ballistic impact. An empty box proved to be inadequate because the fuel, given a fair head, could traverse the gap and pass through the hole made by the jet. Further design optimization was not pursued.

This design, which was used in the ASTB (Ref. 71), was tested successfully for both forward and reverse trajectories (Ref. 23). For the reverse trajectory, a baseline test with no fuel barrier produced a conflagration, whereas the protected version produced a short-lived fireball. In some earlier work by Dunn (Ref. 105), the shaped-charge slug plugged the hole in the vehicle hull, as shown on Fig. 4-41, but plugging by the slug cannot be depended upon since it occurred only three times in 30 tests (Refs. 23, 24, and 105).

A supplementary ASTB system design feature was placement of a compartment covered with a ballistic fabric immediately inboard of the hull wall to which the gravel box and fuel cell were attached. The compartment contained a 51-mm (2-in.) layer of gelled water. Examination of the ASTB vehicles after several months revealed that a fungicide and/or bactericide should have been used in the gelled water. The ballistic fabric traps both spall and spray. The

Courtesy of FMC Corporation.

Figure 4-41. Slug Plugging Hole in Troop Compartment Wall of the APC M113A3 (Ref. 105)

small punctures in its container, but a shaped-charge jet passing through fuel and gelled water disperses the water through the same region in which the fuel is dispersed.

4-8.3.2 LVTP-5A1 Fuel System Reticulated Foam

When a device is described as providing a given benefit, the designer must establish the conditions and circumstances under which that benefit was obtained and then evaluate whether the device will provide the same benefit given the conditions and circumstances prevailing with the new application.

Explosive tests were performed on the LVTP-5A1 in the late 1960s to establish crew survivability given detonation of a beach or land mine under a track (Ref. 18). The beach mine was simulated by two white phosphorus grenades above a box that contained 4.54 kg (10 lb) of Composition C-4, 1.134 kg (40 oz) of which were packed into two Mark 3 shaped charges. These Mark 3 charges are Explosive Ordnance Disposal (EOD) devices consisting of a can with a shaped-charge liner in one end into which a plastic explosive, like C3 or C4, can be hand packed. These simulated mines were placed underneath the hull of the LVTP-5A1. The space between the 9.53-mm (0.375-in.) BHN 300 steel hull and the 4.8-mm (0.188-in.) BHN 120 corregated steel decking contained 12 bladder fuel cells with a total capacity of 1726 L (456 gal) of gasoline. These bladders were constructed of relatively lightweight rubberized fabric 0.81 mm (0.032 in.) thick with a heavier layer of polyurethane approximately 3.2 mm (0.125 in.) thick on the exterior to provide abrasion resistance. These bladders were not self-sealing or even tear resistant (Ref. 106). In some tests these bladders were filled with Scott Type I, 0.4 pore per mm (10 pore per in.) reticulated foam. The fuel cell bladders were held 38 mm (1.5 in.) above the hull by trays made of 3.18-mm (0.188-in.) thick corrugated steel, which had 19- × 76-mm (0.75- × 3.0-in.) slots to pass sand so that the bladders would not abrade.

Each fuel cell had a capacity of 144 L (38 gal). The fuel cells in these tests were usually filled with gasoline to 25 or 62.5% capacity and in some tests to 0.6, 37.5, or 75% of capacity. The fuel cells were approximately 965 × 762 × 193 mm (38 × 30 × 7.6 in.). The reticulated foam was fully packed in each cell. The less than full level of gasoline in these cells translated to the unwetted foam thicknesses in the ullage of the test cells from 48 to 193 mm (1.9 to 7.6 in.).

When the simulated mine exploded under the vehicle, the shaped-charge jets passed vertically in turn through the hull, the penetration detector, a fuel cell, and a floor plate. In addition, the blast from the remainder of the simulated mine heaved everything upward, including numerous pieces of spall from the hull. Gasoline from the ruptured cell was sprayed into the vehicle and burst into flame. On some occasions the atmosphere within the vehicle was too fuel rich for ignition (Ref. 107).

Several fire suppression techniques were tried. Some of these restricted the quantity of gasoline thrown into the crew compartment. These tests used a fire suppression system that consisted of numerous Freon®* (Halon 1301) extinguishers, that were activated by optical sensors. The sensor system signaled the extinguisher system within 3.5 to 4.0 ms after fire initiation. The Halon was discharged into the troop compartment about 20 ms after hull penetration with a discharge duration of 20 to 120 ms (Ref. 18). In all tests a penetration detector (break-wire type) provided additional data. This penetration detector system was tested as a potential replacement for the optical sensor system. Not enough tests were conducted to explore each parameter separately, but in general, when no Halon was used, there was usually a conflagration. When Halon was used, there was normally a 457-mm (18-in.) diameter fireball approximately 1.22 m (4 ft) above the deck. When there was no reticulated foam in the fuel cell, the fireball expanded to the deck, but when there was reticulated foam in the fuel cell, the fireball did not spread. If there was not reticulated foam in the cell where the shaped charge perforated the fuel cell, the exit hole was approximately 305 mm (12 in.) in diameter. If there was reticulated foam in the fuel cell, the exit hole was approximately 51 to 76 mm (2 to 3 in.) in diameter (Ref. 107). When the fuel cell was 62.5% full (a fuel depth of approximately 121 mm or 4.75 in.) and there was reticulated foam in the cell, a great amount of spall was captured within the fuel cell (Ref. 18).

The reticulated foam was credited with reducing the size of the fireball, reducing the effect of blast upon the bladder,

*These tests were performed before the generic term Halon had been adopted. The material used was Freon® FE 1301, which was renamed Halon 1301.

and capturing fragments from the charge assembly and spall from the hull. However, these charges were pointing upward; thus there was an unwetted thickness of reticulated foam above the fuel level. Since the shaped-charge jet would core out reticulated foam, the foam surrounding the hole undoubtedly captured the fuel droplets that would travel in the wake of the jet and move radially outward from that wake. In addition, the hole in the bladder was significantly smaller when the foam was present. Undoubtedly the fuel was effective in stopping most of the spall, and the foam impeded the liquid fuel, which otherwise would have splashed against the bladder and increased the size of the hole.

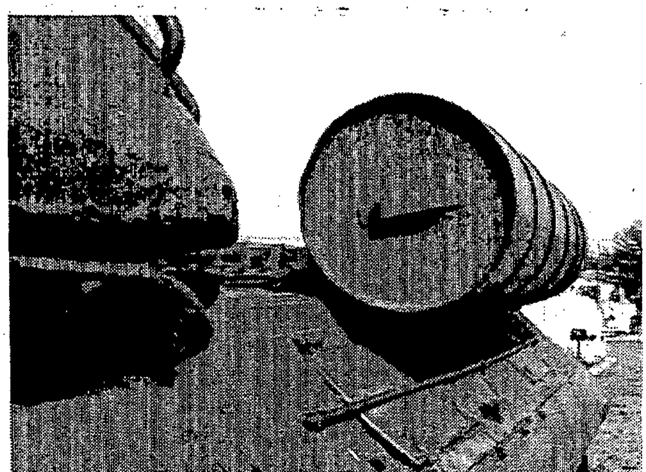
At a much later date, the use of reticulated foam was suggested to reduce the size of the fireball generated when a shaped-charge jet perforated a fuel cell because the foam had worked so well before. However, this time the jet was traveling horizontally, not vertically, so that there was no unwetted foam and no rubberized fabric with a urethane coating backed up with mild steel to capture some of the fuel spray. Therefore, no decrease in fireball size due to the reticulated foam was noted. In fact, there appeared to be numerous sparklers present in the fireball that were absent in the tests without reticulated foam; thus these sparklers were assumed to be minute burning particles of the reticulated polyurethane foam (Ref. 24).

4-8.3.3 Jettisonable Fuel Cells

Practically all Russian tanks have provision for attachment of jettisonable fuel cells on the rear. These fuel cells are thin steel drums, which, on the most recent vehicles, are cantilevered off the rear. These drums are intended to provide fuel to enable the tank to reach the battle area where the drums are then jettisoned. The jettison is done when the tank is stationary because a crewman has to disconnect the fuel line and unbolt the drum-holding straps. Since these drums are cantilevered off the rear of the vehicle, the possibility that a ballistically generated fuel fire will affect the vehicle is remote unless the threat throws the fuel onto the vehicle. The situation was different with the T34 tank and the JS-3 tank because the drums were mounted on the rear fenders, as seen in Figs. 4-42 and 4-43(A), and spilled fuel could enter the engine compartment. As illustrated on Fig. 4-43(B), fuel flowing out of perforations would not travel downward into the engine compartment, but a rupture of these drums could result in fuel being thrown onto the rear deck. The latest MBTs are built so that these jettisonable fuel drums are cantilevered off the rear; therefore they can be perforated and the fuel ignited without endangering the vehicle or crew. An explosion from below and to the rear of the vehicle, however, could throw diesel fuel up on the vehicle. If the hatches were open, this fuel could incapacitate exposed personnel, and if sufficient fuel entered the hatches, it could damage the vehicle.

Figure 4-42. Russian T34/85 Tank Showing Jettisonable Fuel Cell

(A) Overall View



(B) Close-Up of External Fuel Drums

Figure 4-43. Russian Joseph Stalin III (JS-3) Heavy Tank

One test described in Ref. 23 illustrates the advantage of using a jettisonable fuel cell. The external fuel cell was held by a steel platform held by two bolts that had been weakened by previous tests. In Test 3 the bolts failed and the fuel cell dropped. (See Fig. 4-44.) Thus fuel stopped flowing through the jet perforation in the simulated vehicular hull. With this cessation of fuel the fire within the simulated vehicle burned out. It also illustrated that if the external fuel cell were removed after it was hit by a projectile that would overwhelm the vehicular armor, no more fuel would flow into the vehicle to burn. This same result was obtained in five more tests with frangible or jettisonable fuel cells (Refs. 26 and 27).

Use of jettisonable fuel cells could provide a means to have a combat vehicle travel to a combat area without using the internally stowed fuel and without requiring a refueling operation before it could be committed to action. Also the jettisonable fuel cell would not make the combat vehicle more vulnerable while traveling. Jettisonable fuel cells could be considered for use on US vehicles.

4-8.4 LESSONS LEARNED

Several lessons have been learned in combat and in development or qualification tests.

4-8.4.1 Lessons Learned From Tests of External Fuel Cells

In a recent program to explore the vulnerability of external fender-mounted fuel cells to incendiaries, response to an incendiary grenade was tested. The incendiary grenade products melted through the upper fuel cell surface, passed through a 51-mm (2-in.) layer of diesel fuel, and made a small hole in the lower fuel cell surface, but sustained combustion of the diesel fuel within or leaked from the fuel cell did not occur (Ref. 108). This test showed that diesel fuel in a fender fuel cell will not necessarily burn, even though it is ignited by a material hot enough to melt through a thin steel sheet.

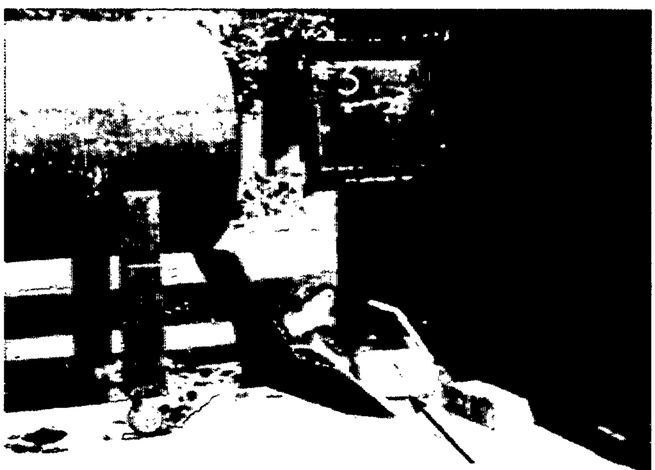


Figure 4-44. Test No. 3 Showing Jettisoned Fuel Cell (Ref. 23)

In another test program an externally mounted frangible fuel cell had a shaped charge fired through the fuel cell. There was a fireball within the fixture. The external fire was spectacular, but the burning within the fixture was not sustained. In other tests the external fire was a little less spectacular when the frangible fuel cell was covered with packets of dry powder fire extinguishant, i.e., Purple K®. Another test demonstrated that if three frangible fuel cells were separated by metal dividers, only the fuel cell hit by the shaped charge would be lost, as shown in Fig. 4-45. Use of frangible fuel cells is promising, but another device must be used to eliminate the internal fireball if the compartment is occupied (Ref. 26).

The potential use of such fuel cells requires further evaluation.

4-8.4.2 Use of Intumescent Coatings

The main bustle magazine for the M1A1 MBT is divided into two separate compartments, each of which contains 17 combustible case cartridges. Each KE cartridge has an 8.1-kg (17.9-lb) JA-2 (Ref. 109) propellant charge, and each HEAT cartridge has a 5.4-kg (12-lb) DIGL-RP propellant charge (Ref. 84). Both are in combustible cases with metal bases. The magazine is designed to withstand the detonation of one warhead—the high-explosive charge in the HEAT warhead is much smaller than the cartridge propellant charge—and the explosion of all 17 propellant charges with only the loss of two blow-away doors, one on the top of the magazine and the other on the bottom. Access to this magazine is provided by two sliding doors—a "ready" door at the loader's station and a "storage" door at the commander's station—which are opened or closed by hydraulic power operated by the loader's knee switch (Ref. 110). These

Figure 4-45. Posttest Condition of Frangible, External Fuel Cells (Ref. 26)

doors are made of 1020 mild steel 28.6 mm (1.125 in.) thick and measure 762 × 762 mm (30 × 30 in.) (Ref. 111).

In some tests these doors appeared to leak combustion products due to heat distortion. Blackbody temperature in a propellant fire is a function of the propellant type, and for this propellant it is approximately 3092°C (5598°F). The duration of the fire was from 8 to 30 s. The temperature and duration of the fire could result in a thermal gradient through the door thickness, which in turn could cause the door to warp temporarily and thus allow the leakage noted (Ref. 111).

This thermal gradient could be reduced by coating the inside surface of the door with an intumescent material, and several candidate intumescent materials were recommended (Ref. 112). In tests after the intumescent coating was installed, the leakage did not recur. This intumescent coating also kept the temperature of the doors low. This intumescent coating was incorporated into the M1 series MBT design.

4-8.4.3 Lessons Learned From North Africa, 1942

There were two lessons—well-illustrated in Phillips' *Alamein* (Ref. 56)—which have been taught and retaught. These lessons are (1) combat vehicles should be as maintenance free as possible and (2) vehicle armor is too protective, too safe, for the crewmen to abandon their vehicle too quickly.

Writing of operations in North Africa, Phillips stated:

"Tanks could carry only a limited amount of fuel and ammunition and these had to be renewed in a long action. For this purpose regiments had a special echelon of unarmored lorries ('soft skins'). When ammunition was needed, they might often be required to drive right up into the heart of a battle and unload, round by round, by hand. For fuel replenishment, however, the tank had to withdraw. Except in the most critical situations, it also had to withdraw every night for mechanical maintenance tasks, for general replenishment, for food, and for such rest as was possible.

"Withdrawal was usually into a 'leaguer,' which in the open desert, meant 'close leaguer,' with all the tanks, soft skins, field and anti-tank artillery and infantry in a solid phalanx, defensively disposed. Withdrawal, which might involve an hour or more of cautious and difficult driving, could not take place until well after dark. Maintenance by the crews and repairs by the [Royal Electrical and Mechanical Engineers] REME detachments would go on far into the night. The crews were often too dog-tired at the end of it to bother about cooking a meal and would eat nothing but a little hardtack before bedding down where they were.

"Each man then had to stand an hour's guard, so that about three hours was the maximum of sleep before the crew had to be up again, and after tea and a biscuit, drive back to their battle or patrol position."

This quotation illustrates why combat vehicles should be designed to be as maintenance free as possible. Crewmen have a difficult enough job just to keep operating as is. They do not need items that require constant attention. A fire prevention device that does not require daily maintenance and that does not require a crewman's conscious action to be activated is preferable to one that needs testing and has manual initiation.

For the second lesson Phillips provides two passages, which are highly illustrative:

1. "In terms of human casualties, however, the tank crews were far more fortunate than the infantry and the gunners who accompanied the infantry. The man with the rifle, the artillery [forward observation officer] FOO and the anti-tank gunner had no shield against the flying shell-splinters and the bullets. But tank wounds could be shocking."

2. "To the surprise of the garrison, a number of German panzers which had halted in dead ground after their attempted move in the night suddenly broke cover at ranges of from 600 to 800 yards. They thus offered highly tempting rear and flank targets at killing ranges to the riflemen's gun detachment* as they peered out in the biting wind.

"In such circumstances, it was perhaps not in accord either with doctrine or with their mission for the garrison to disclose their positions and engage. But they did not feel in a calculating spirit that day and could not resist the temptation to attack. The dawn was shattered as eight or nine guns barked with the 6-pdr's sharp, high velocity crack. The results were spectacular. Eight tanks and self-propelled guns were destroyed to the north (all being found derelict on the battlefield subsequently) and a further eight were claimed from Teege's battle group to the southwest of which three were still derelict on the ground a month later. Upon the unfortunate crews who attempted to escape the machine guns poured their streams of bullets."

These passages illustrate not only that the tank armor protects the crew from artillery shell fragments and bullets, but also that in the confusion of battle, combat vehicles can be hit from the side or rear and that where there are antitank weapons, there will also be machine guns. Colonel Teege, of the Stifflemayer Battle Group of the Deutsch Afrika Korps, would not have taken his panzers in front of the English position "Snipe" if he had known it was there. The best survivability enhancement feature that can be given a combat vehicle is the capability to continue to move until the vehicle reaches a location where the crew can safely dismount or to preclude fire within the vehicle so that the crewmen can stay within their vehicles to defend against attackers. Since most vehicles in World War II stopped when the ammunition exploded or the fuel ignited, prevention of these events can do a great deal toward providing this movement-to-cover capability or the capability to fight from within an immobilized vehicle.

*These were six-pounder antitank (AT) guns (The US used this same gun, the 57-mm AT gun.) manned by men from the 60th Rifles of the Rifle Brigade.

4-8.4.4 Protection Afforded by Water and Other Materials in SEA

There were several incidents that occurred in SEA which may provide lessons for fire protection.

In one incident an RPG hit an M551 in the rear. The jet passed through a Marmite can containing food and into a 19-L (5-gal) water can. The jet stopped in the water (DAN 333). In three incidents in which RPGs hit APCs M113A1 and the jets entered radiators, the jets stopped in the radiators or were otherwise ineffective (DAN 360, 331, and 1874). These incidents indicate that locating items containing water within a vehicle may increase fire survivability.

In one incident an RPG hit an AR/AAV M551 smoke grenade launcher and the jet stopped in the grenade (DAN 1696). In another incident (DAN 336) a shaped-charge jet entered through the side of an APC M113A1, hit a fire extinguisher bottle, and stopped. These incidents indicate that there are a number of items that, when mounted on the exterior surface or the inside of the wall opposite that surface, can prevent fire by stopping the jet.

4-8.4.5 Engine Compartment Design

For several reasons and regardless of engine type, there should be no gravity flow path for liquid fuels from the vehicle deck to the engine, the air intake, or the radiator. Elimination of such flow paths precludes contamination of these components by accidental combustible fluid spills and would render Molotov cocktails ineffective.

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CHAPTER 5
CREW SURVIVAL CRITERIA

Threat effects as they affect crew survival are described. The need for crew performance criteria is stated. Crew survival criteria are given for thermal, ear, lung, and eye injuries. Criteria concerning asphyxiant and toxic gases and particulate solids are given. Finally, the effects of these threats on human performance are described. The Surgeon General has not reviewed this chapter; therefore, the recommendations given should not be considered official Department of the Army policy.

5-0 LIST OF SYMBOLS

A = cross-sectional area perpendicular to the heat flow, m^2
A_p = pupil area, mm^2
A_1 = total area of body contacted by flames, m^2
a_o = velocity of sound in air, m/s
d_i = distance between the point of entry of the jet and plane of transducer P_i, m
d'_i = distance between jet and axis of transducer P_i, m
h = film coefficient of heat transfer, $W/(m^2 \cdot K)$
h_1 = film coefficient of heat transfer between flames and body, $W/(m^2 \cdot K)$
i_s = specific impulse, Pa·s
$\bar{i}_s$ = scaled specific impulse, $Pa^{1/2} \cdot s \cdot kg^{-1/3}$
K = thermal conductivity, $W/(m \cdot K)$
ℓ/d = penetrator length-to-diameter ratio, dimensionless
m = mass of body, kg
m_a = mass of test animal, kg
m_m = mass of an average man = 70 kg
P_{OS} = reference pressure, usually 20 μPa (2.9×10^{-9} lb/in.^{2})
P_s = peak incident overpressure, Pa
P_{sl} = mean atmospheric pressure at sea level, Pa
$\bar{P}_s$ = scaled incident peak overpressure, Pa
$\bar{P}_{SwRI}$ = scaled incident peak overpressure (using Southwest Research Institute (SwRI) practice), dimensionless
P_0 = ambient atmospheric pressure, Pa
P_{50} = peak pressure at which 50% of the exposed population will die, Pa
$P(I|H)$ = probability of incapacitation given heat exposure, dimensionless
p = sound pressure being measured, Pa (lb/in.^{2})
q = rate of heat transfer, W
SPL = sound pressure level, dB
T_b = body temperature, °C
T_m = measured air temperature, °C
T_1 = heat source temperature, K
T_2 = heat sink temperature, K
t = time, s
t_a = time of arrival, s
$(t_a)_{P_i}$ = time of arrival of shock wave at pressure transducer P_i, s
$\int t_i$ = temperature-time integral, °C·s
$\bar{t}$ = scaled positive duration, ms
$\bar{t}_{SwRI}$ = scaled time (using SwRI practice), $Pa^{1/2} \cdot s \cdot kg^{-1/3}$
t_+ = positive duration of pressure (measured at test site), ms
V = shock wave velocity normal to jet trajectory, m/s
V_j = jet tip velocity, m/s
v_f = fragment velocity, m/s
x = thickness of material through which heat is transferred, m
α = angle between jet trajectory and shock wave, deg or rad
$(\Delta t_a)_{P_i P_j}$ = difference in time of arrival of shock wave at two transducers P_i and P_j, s
ϵ = emissivity or absorptivity of the body, dimensionless
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/$(m^2 \cdot K^4)$

5-1 INTRODUCTION

5-1.1 PURPOSE

This chapter provides a statement of the crew survival criteria and describes the origin of these criteria and the bases for them.

In general, the survival criteria are the limits of the conditions to which men can be subjected and still continue to perform their functions as crewmen of combat vehicles. These criteria are established by the Surgeon General, United States Army, and are usually based upon test data (Ref. 1).

5-1.2 THREATS

The primary combat threats to crew and/or vehicle survivability are those that penetrate through the armor into the vehicle. These threats are ballistic penetrators that can ignite or initiate explosives or ignite mobility fuel or other combustibles, as well as kill or injure personnel and destroy or damage equipment within the vehicles. These ballistic penetrators also can project spall. The two types of ballistic penetrators are the kinetic energy (KE) projectile and the chemical energy (CE) high-explosive antitank (HEAT) projectile. Some KE penetrators contain a small high-explosive charge in the base, which fragments the rear of the projectile and projects fragments in a radial pattern. Currently, the shorter hard steel or tungsten carbide subcaliber penetrators with a length-to-diameter (ℓ/d) ratio of approximately 5:1 are being replaced with finned, long-rod penetrators made of tungsten or depleted uranium (DU), which have an ℓ/d ratio nearer 20:1. These long-rod penetrators are referred to as armor-piercing, fin stabilized, discarding sabot (APFSDS) projectiles (Ref. 2).

The United States (U.S.) and Russia have cluster warheads that provide many small bomblets, some of which are HEAT warheads that can strike combat vehicles from above. One used in Operation Desert Storm in 1991 was the Mark (MK) 20 antitank cluster bomb (Rockeye).

Another type of threat that has been used is the spall-generating, high-explosive plastic (HEP) projectile, called high-explosive squash head (HESH) by the British. Upon impact on a hard target, these projectiles deform plastically or squash prior to detonation and provide an intimate contact with the armor over an area larger than the projectile caliber. These high-explosive (HE) projectiles are intended to generate spall from monobloc armor. Ordinary high-explosive projectiles can also generate spall but less effectively. HE, HEP, and HEAT projectiles can remove items mounted on the exterior of the vehicle. The blast alone from these projectiles can damage or destroy lightly armored combat vehicles. Also the blast and fragments from these warheads can damage or sever the tracks of heavily armored vehicles.

In World War I the Germans found that the explosion from four stick grenades clustered together could break the track of a Mark I tank (Ref. 3). This discovery led to the use of land mines, some of which are designed and fuzed to launch a missile (flyer plate or jet) upward to penetrate the bottom of a tank (Refs. 2 and 4). Another type of "land mine" is the rocket-propelled HEAT missile with a trigger set so that the tank itself will fire the missile into the side of the vehicle. Thus land mines are not only a threat to the tracks of the tank but also to the bottom and sides of the tank.

Another means used by the Germans in World War I to attack the British tanks was to spurt burning liquid from their man-portable flamethrowers onto the tanks (Ref. 5). However, these flamethrowers were not effective because it is difficult for a man to leave cover and pursue a tank with a 36-kg (79-lb) item strapped to his back. In addition, the burning gasoline would not have been very effective even on those early tanks, but it gave the Germans' morale a boost just to think that they had such an impressive weapon to use.

In the Russo-Finnish War of 1940 the Finns were highly successful in using hand-thrown gasoline bombs, "Molotov cocktails", against combat vehicles. These Molotov cocktails were effective because they were thrown on the grille over the engine and would ignite oil and wiring in the engine compartment.

Threats that are no longer effective against main battle tanks (MBTs) can be highly effective against more lightly armored vehicles and may well be encountered. Further, weapons that are no longer effective against the main armor of the MBT can be highly effective against the more lightly armored portions of the MBTs.

5-1.2.1 Threat Effects in General

The threats previously described provide kill mechanisms that can affect combat crewmen differently. These kill, injury, or damage mechanisms follow:

1. Large, fast-moving particles of metal that can kill, injure, or damage by simple mechanical impact, e.g., residual KE penetrators, shaped-charge jets or slugs, plugs or central spall from the armor, or fragments from an armor-piercing, high-explosive incendiary (APHEI)-type projectile (Ref. 6)
2. Small pieces of metal, ceramic, or glass, such as spall or splash, projected peripherally, forward along the trajectory of the projectile, or rearward toward the weapon during ballistic penetration
3. Shock waves that result from the passage of a shaped-charge jet or high-velocity penetrator
4. Blast waves and overpressure from explosions
5. Heat from explosions, combustion, and/or other chemical reactions including those from fireballs that result from perforation of cells containing combustible liquid
6. Toxic, asphyxiant, or irritant gases, vapors, liquids, mists, or solid particulates liberated by ballistic impacts or explosions or by the combustion that can occur afterward
7. The flash or light generated by or resulting from the other effects.

The entire antitank projectile does not usually penetrate through the armor; Only the jet, core, or penetrator does so. Once the armor is perforated, however, not much can be done to protect against the large metallic penetrators except to inhibit ricochet. The smaller penetrators, spall, etc., can be trapped; therefore, a vehicle can be designed to protect personnel from spall or to trap ricocheting particles. Shock waves and flash can be mitigated, explosions can be limited or made less probable, and the presence of toxic, asphyxiant, or irritant gases, mists, or solid particles reduced. Toxic chemical, biological, or radiological threats are not considered in this handbook, except as incident to fires.

The most hazardous secondary effects are those resulting from explosions and fires. There is little reason to quantify explosions in this chapter. Explosions are best eliminated by the means described in Chapters 4 and 7. The most serious fires, i.e., propellant, mobility fuel, and hydraulic or recoil fluid fires, should be precluded by passive fire prevention designs. Thus only the smaller or slow-growth fires would remain to be extinguished. Quantifying or describing heat from these fires, combustion products, shock waves, and the light from flash is useful because it provides designers with quantities to reduce.

5-1.2.2 Shock Pressure and/or Impulse

The most severe shock waves are generated by the fastest moving items, e.g., the tip of the shaped-charge jet. This shock wave is initially an aerodynamic shock formed at the tip of the jet. The initial shock bounces off the internal surfaces, reinforces or mitigates other shock waves within the vehicle and results in a cacophony of shocks on occupants. Jet velocity is a function of shaped-charge design and materials, i.e., primarily from the cone angle of the liner, the cone material, and the detonation velocity of the explosive used. More information on shaped-charge warhead design and functioning can be obtained from Refs. 7, 8, and 9.

The shock pressure and/or impulse due to the jet from an M28A2 HEAT warhead (used on a 3.5-in. bazooka rocket) apparently is not a function of material properties of the inside surface of the target; however, the emitted flash and spall and the reflected shock waves certainly are (Ref. 10).

The initial shock wave from the jet passage, which is discussed in subpar. 5-3.4.1, has neither the greatest peak pressure nor the greatest impulse. The greatest peak pressure and greatest impulse usually occur when shock waves reflect from various surfaces and combine. This action suggests that vehicle designers might obtain benefits from using materials or surface finishes that have sound-deadening features.

5-1.2.3 Light

The light generated by ballistic penetrations has not been quantified in tests. A shaped-charge jet passing through an aluminum-walled chamber would emit enough light to saturate motion picture film for three to five frames at a rate of 1000 frames per second and do the same to real-time video tapes. Figs. 2-14 and 2-15 provide qualitative evidence that such flashes and fireballs can be reduced by selection of the proper interior material for the vehicle. The shorter duration and less intense flash would probably present a lesser ignition source, as well as have less effect on eyesight. (Materials that tend to diffuse or absorb light would reduce the effect of these strong flashes on the eyes of crew members.)

5-1.2.4 Vapors, Mists, and Solid Particulates

Many mists, vapors, and solid particulates are broadcast within combat vehicles from ballistic impacts, from fires, and from the extinguishment of fires. These mists, vapors, and particulates are described in Chapters 3 and 7, and their effects upon crewmen, in par. 5-6. Although phosgene ($COCl_2$) is a potential product of combustion or reaction of the various materials carried in combat vehicles, little evidence of the presence of phosgene has ever been identified in instrumented tests (Ref. 11).

5-1.3 CREW PERFORMANCE

Current crew survival criteria assume that fatalities from secondary effects are preventable, but these secondary effects can cause nonfatal injuries that may degrade the crew's performance if crew members do not evacuate the vehicle. These current survival criteria were developed for combat vehicles which use fire extinguishants that should not be breathed for long periods of time, i.e., carbon dioxide or Halon 1301. The formation of products of incomplete combustion, such as carbon monoxide or smoke, could be hazardous. If an extinguishant were used that would not provide noxious products and would flush toxic and irritant gases out of the air, the crew could remain within the vehicle and continue to fight. Such a system has been demonstrated for commercial aircraft (Ref. 12). The purpose of this handbook is to show how to design vehicles to absorb hits without losing their viability as effective military assets due to fire. As viable military assets also, the crew members must retain their major assigned functional capabilities.

There is little that can be done to protect crew members from primary penetrators that have breeched the vehicle armor. Crew members, however, can be protected from the secondary effects, i.e., the spall, flash, fireball, explosions, and, particularly, fire.

Crew-member-worn clothing is not discussed in this handbook as a device that can be used by vehicle designers to achieve a vehicle survivability goal. Clothing and personal equipment are designed or specified by Government agencies other than those responsible for the design of combat vehicles. Clothing and personal equipment, however, are extremely important to the severity of injury to a person subjected to fire, and spare clothing carried in vehicles can affect the survivability of the vehicle and its crew. Therefore, the potential benefits and hazards of clothing and equipment are included here.

Soldiers must "be able to see, hear, think, and communicate with others—in an active stress situation" (Ref. 13). The senses that infantrymen and other soldiers in combat must be able to use to the best of their ability are sight, hearing, smell, and touch. A soldier must be able to see to aim a weapon or to detect most targets; he must be able to hear oral communications and enemy activity; he must be able to smell to detect some fires or some toxic gases, fuel leakage, and/or many other phenomena present on the battlefield; and he must be able to operate the equipment and weapons and often receive tactile feedback from them. The threats to sight are small flying objects, flash, and very small objects in great quantity, such as smoke, dust, or mist, that can irritate the eyes, cause tearing, and thereby obscure vision. The threats to hearing, once explosions have been precluded, are shock and aftershock—shocks reflected from the surrounding walls—waves. In addition to affecting a person's hearing, extremes of shock to the body and aftershock waves can affect a person's sense of balance. The threat to smell is saturation of the nasal receptors and taste buds that can occur from prolonged exposure to fumes, especially those from mobility fuel and some fire extinguishant by-products. Another threat effect similar to those attacking the sense of smell is irritation to nasal passages and breathing passages, which would cause troops to sneeze or cough. Extremes of either sneezing or coughing render personnel incapable of performing their tasks.

5-2 THERMAL INJURY

5-2.1 BACKGROUND

The modern study of lethal factors associated with exposure to fire in wartime was begun in this country in 1944 by Dr. Alan R. Moritz and his colleagues at Harvard University. First, they studied the effects of heat on the air passages and lungs of dogs (Ref. 14). Then they studied thermal damage resulting from excessive heat applied to the skin (Refs. 15 through 22). These later studies primarily involved pigs, but some human volunteers participated also.

Shortly thereafter, the US Army studied the kill mechanisms associated with flame weapons. Initially, the scope of these investigations was limited to determining what the lethal factors were and ranking their relative importance in conditions of poor, moderate, and good ventilation (Ref. 23). Commentary on the cause of some fire-related deaths during World War II was confusing; some soldiers apparently killed by fire in bunkers and other enclosed spaces were noted to have no evident burns. In the absence of wounds of any kind, a lowered partial pressure of oxygen or the breathing of toxic gases generated by the fire quickly became suspect. Later work, however, showed that pooled gasoline-fueled fires in poorly ventilated spaces will self-extinguish while the oxygen content of the ambient air remains above 14% (which will support life), and measured concentrations of common toxic gases are frequently not sufficient to cause the deaths that were observed. Of course, vigorous agitation of the fuel-air mixture (as effected by a flamethrower spurt) can cause consumption of virtually all available oxygen and produce lethal concentrations of carbon monoxide, carbon dioxide, and other noxious gases. This work, however, suggested that heat alone could be a lethal factor, whether or not skin burns were evident (Refs. 18, 20, and 21). Most of this work involved goats. Obvious burns then must be regarded as indicators of excessive heat but not necessarily as accurate predictors of the total amount of heat damage that has been done or the performance degradation that may result.

Studies have been performed to assess how effectively fire-extinguishing systems protect occupants of combat vehicles from a fireball that results when a shaped-charge jet passes through a hydrocarbon fuel cell and then enters an occupied compartment. These studies usually involved the placement of animals, usually pigs, within the vehicle. The first such study was in 1967 for an automatic fire-extinguishing system planned for the Landing Vehicle, Tracked, Personnel (LVTP)-5A1 (Ref. 24). In the late 1960s and early 1970s, studies were performed to evaluate the adequacy of the fire detection-extinguishing systems for the armored personnel carriers (APCs), M113 and M113A1. These studies used pigs and sometimes rabbits (Refs. 25 through 27). In the 1970s some studies were performed to evaluate the protection provided by helicopter crewman clothing in a fuel fire (Ref. 28); these studies also used pigs. These animal studies are reviewed in subpar. 5-2.2.3. Recently there have been studies on smoke inhalation that used sheep (Refs. 29 through 31).

Thus much of the experimental work on burns in the past 50 years has not directly addressed the problem of predicting the degree of incapacitation in humans due to heat injury. The reactions of animal models (rabbit, dog, goat, sheep, and pig) to heat stress were certainly useful in these studies. The pig, in particular, has been extensively studied (Refs. 15 through 22, 24 through 27), and in many respects is an excellent model for human skin burns. The fact that pigs do not sweat, however, limits their usefulness in tests requiring prolonged high heat loads because the sweat mechanism in humans is important. In fact, none of these animal models sweat the way humans do. There is no generally accepted model of the degree of incapacitation caused by heat, especially when conduction, convection, and radiation can each furnish significant heat flux and when the common complicating conditions found on the battlefield are superimposed on the heat injury. Data from the Southeast Asia (SEA) conflict are reviewed in subpar. 5-2.2.4. General health, the presence of certain drugs (such as atropine) that can alter heat tolerance, fractures, dehydration, hemorrhage, crush and penetration injuries, and blast overpressure can all be expected to change the predicted degree of incapacity from heat exposure, but the relationship among these is not described in the available literature. When the confounding variations of individual responses to heat (Ref. 32) are added to the poorly understood interactions of heat with other stress factors, it becomes apparent that extrapolation of existing data is problematic. Therefore, predictions of future levels of disability, either on the battlefield or during recovery, should be expected to contain significant error on this basis alone.

There is a problem defining thermal injury. The commonly used benchmark has been a second-degree skin burn. The second-degree burn is associated with a wide range of disability and recovery times because it includes all depths of skin burns from shallow to deep. Degrees of a burn are no longer considered in burn clinics, such as the US Army Brooke Burn Center, which now classifies burns by whether or not the burn damage extends through the skin (Ref. 33). First-degree burns, e.g., mild sunburn, are not considered because they should not require hospitalization. Excessive heat intake can be fatal even without visible skin burns, as has been shown by animal tests. On the other hand, when personnel at the US Army Aeromedical Research Laboratory developed a computer model to predict the severity of burns behind clothing, they used a 16-point clinical burn grading system, a 10-point micrograde system, and a mean burn depth determination to resolve better the relative efficacy of fabrics to provide protection (Refs. 34 and 35).

5-2.1.1 Problem Magnitude

The degree (depth), location, and incapacitating potential of thermal burns—based on commonly measured parameters—that may be suffered by crew members in armored vehicle fires are highly variable and not precisely predictable. Ignition of solid gun propellant produces gas temperatures of approximately 2527°C (4580°F) for M30 propellant or 2256°C (4093°F) for M26 propellant (Ref. 36); the resulting short-duration, high-intensity radiation can cause flash burns that may vary in character from those produced by nuclear weapons to those produced by a carbon arc. Tests with aerial bombs and flamethrowers suggest that temperatures in fires that follow rupture of fuel cells or injection of burning liquids into the crew compartment can exceed 1000°C (1832°F) (Ref. 37). The Army currently uses the time integral of temperature difference, i.e., measured air temperature minus skin temperature, to predict risk of thermal injury in vehicle fires (Refs. 1 and 37). If the integral over 10 s exceeds 1316°C·s (2400°F·s) for unprotected skin, the occurrence of second-degree burns or worse is likely. However, the presence and type of protective clothing or heat shields, amount of ventilation, duration of heat exposure, temperatures and types of hot materials, and initial conditions determine the final injuries and the degree of incapacitation. Each of these factors is discussed in this paragraph. Problems associated with the heat content of gases generated during armored vehicle fires are discussed in this paragraph, but the discussion of problems associated with their toxicity is reserved for par. 5-6.

5-2.1.2 Medical Considerations

The heat effects or thermal injury to personnel that concern the survivability engineer are divided into five categories:

1. *Skin Burn*. The degree of a burn can range from sunburn to charring of muscle or bone.
2. *Body Overtemperature (Hyperthermia)*. Hyperthermia is a form of heatstroke in which the overall body temperature rises. (For adults a core temperature over 43°C (110°F) is usually fatal.)
3. *Localized Overtemperature of Body Parts*. This heat effect results in heat exhaustion or in hyperkalemia (excessive potassium in the blood), which causes central circulatory failure (The heart stops pumping effectively.) that often results in shock.
4. *Upper Respiratory Tract Damage*. When overheated, the tissue swells (edema), the throat (pharynx), vocal cords (larynx), and/or windpipe (trachea) close, and the lungs do not receive air.
5. *Lung Damage*. Lung damage is caused by smoke inhalation, which may later develop into pneumonia, and by toxic or asphyxiant gases and noxious liquids and particulates that can be introduced.

5-2.1.2.1 Skin Burns

5-2.1.2.1.1 Heat Transfer

Heat energy transfers into the skin by conduction, convection, and/or radiation. When hot solid objects or droplets of hot liquids contact the skin, heat is transferred by conduction through a film. The film heat transfer coefficient is a function of the intimacy of contact between the hot object and the skin. Where there is intimate contact, the film resistance approaches zero; where there is a gap, the film resistance approaches that of conduction through the thickness of air or fluid within the gap. The film coefficient for transferring heat from a stationary hot liquid droplet to skin is roughly equivalent to the lesser values for water or oil given in Table 5-1. The form of the equation for conductive heat transfer from a heat source to a heat sink is

$$q = KA\,(T_1 - T_2)\,/x,\ \mathrm{W} \qquad (5\text{-}1)$$

where

q = rate of heat transfer, W
K = thermal conductivity, W/(m·K)
A = cross-sectional area perpendicular to the heat flow, m^2
T_1 = heat source temperature, K
T_2 = heat sink temperature, K
x = thickness of material through which heat is transferred, m.

This equation applies when the heat source and heat sink stay at constant temperatures. This equation does not apply to a small fragment or droplet that has a finite quantity of heat available for transfer; as the heat is transferred, T_1 quickly approaches T_2 (Ref. 38).

TABLE 5-1. APPROXIMATE RANGE OF VALUES OF THE COEFFICIENT OF HEAT TRANSFER BETWEEN A SOLID SURFACE AND A FLUID (Ref. 38)

	$\frac{\mathrm{W}}{\mathrm{m^2{\cdot}K}}$	$\left(\frac{\mathrm{Btu}}{\mathrm{h{\cdot}ft^2{\cdot}{}^\circ F}}\right)$
Air, Heating or Cooling	1.14-57	(0.2-10)
Oils, Heating or Cooling	57-1700	(10-300)
Water, Heating	284-17,000	(50-3000)
Steam, Film-Type Condensation	5700-17,000	(1000-3000)
Steam, Dropwise Condensation	28,000-114,000	(5000-20,000)

The primary means of heat transfer to the skin from moving fluids is convection. Convection is related to the movement of fluids, both gaseous and liquid. Fluids that are stagnant, i.e., are not flowing laterally or through a passage, expand or contract as they gain or lose heat and thereby become less or more dense and move vertically because of changes in buoyancy. This transfer process is called natural convection. If the fluid is forced through a passage or is otherwise imparted motion, the heat transfer process is called forced convection. In both cases heat is transferred to a solid object through a stagnant film, which is in intimate contact with the object. This film has zero velocity immediately adjacent to the surface of the solid object. The faster the fluid flows, the thinner the thickness of this stagnant film. Rather than compute the thickness of the film to compute heat transfer, empirical relationships are used to establish a film coefficient of heat transfer for each fluid. This film coefficient contains both the thermal conductivity of the fluid and the thickness of the film; therefore, Eq. 5-1 becomes

$$q = hA(T_1 - T_2), \text{W} \tag{5-2}$$

where

h = film coefficient of heat transfer, W/(m^2·K).

Because the fluid is moving, T_1 can be considered constant. Relative values of the film coefficients for heat transfer are given in Table 5-1. The lesser value is for slower moving fluids, the greater value, for fast-moving, turbulent fluid flows. Convective heat transfer applies to the exposed surface only. If clothing is the outer surface, the heat transfer from the fluid to the clothing is by convection, but the heat transfer from the clothing to the body is by conduction.

The third means of heat transfer is radiation. All bodies radiate heat as a function of their temperature and the emissivity of their external surface. These same bodies receive radiated heat as a function of their temperature and the absorptivity of their external surface. The form of the radiant heat transfer equation (Ref. 38) between a body and a blackbody is

$$q = A\epsilon\sigma(T_1^4 - T_2^4) \tag{5-3}$$

where

ϵ = emissivity or absorptivity of the body, dimensionless

σ = Stefan-Boltzmann constant = 5.67×10^{-8} W/(m^2·K^4).

Heat transfer to a body engulfed in flame is through a combination of radiation and convection. The equation (Ref. 38) is

$$q = A_1\epsilon\sigma(T_1^4 - T_2^4) + h_1A_1(T_1 - T_2) \tag{5-4}$$

where

h_1 = film coefficient of heat transfer between flames and body, W/(m^2·K)

A_1 = area of body contacted by flames, m^2.

5-2.1.2.1.2 Degree and Extent of a Burn

The degree of a burn is defined in older literature (Ref. 39) as

1. *First Degree*. Redness of skin (erythema) without blistering
2. *Second Degree*. Redness of skin with blistering
3. *Third Degree*. Destruction of full thickness of skin and often of deeper tissue.

A fourth degree is referred to in some references. This fourth degree would be a very severe burn in which charring occurs well into the muscle or to the bone. The current clinical division of burns is either as partially or wholly through the skin (Ref. 33). "Partial" is the old second degree; "wholly" is the old third degree. The extent of a burn can be estimated by using Table 5-2.

Data presented by Dressler et al (Ref. 40) suggest that mortality from skin burns has decreased markedly as better treatments have been developed. The fatality rate when third-degree burns cover more than 75% of the body surface is nearly 100% (Ref. 41). In the period 1956 through 1964, second- and third-degree burns over 26% of the skin area of the entire body had a 50% probability of fatality. In the period 1965 through 1968, burns over 38% of the total body skin area had the same probability of causing fatalities, whereas in the period 1980 through 1981 this result was caused by burns covering 65% of the skin area. (Ref. 40) In these cases, infection of the burns was not always deemed

TABLE 5-2. PERCENT OF BODY SURFACE AREA FOR ADULTS (Ref. 40)

	EACH, %	TOTAL, %
Head	7.0	7
Neck	2.0	2
Half Trunk, Anterior or Posterior	13.0	26
Buttock, Right or Left	2.5	5
Genitalia	1.0	1
Upper Arm, Right or Left	4.0	8
Lower Arm, Right or Left	3.0	6
Hand, Right or Left	2.5	5
Thigh, Right or Left	9.5	19
Leg, Right or Left	7.0	14
Foot, Right or Left	3.5	7
		100

the primary cause of death. Shock or respiratory complications were often the primary cause of death, but the burns were at least contributory factors.

5-2.1.2.1.3 Results of Skin Burn Tests

Some results of skin burn tests are shown on Fig. 5-1. The threshold first-degree and second-degree exposures, shown as lines, were obtained using flowing water on limited areas of pigs. Similar tests were conducted with human volunteers, indicated by symbols on Fig. 5-1, using flowing water or oil (Ref. 16). These burn thresholds were later duplicated using radiant heat instead of flowing liquids (Ref. 18). In short, the method used to transfer the heat to the skin is not important. Only the temperature of the skin and the length of exposure are important in determining the resultant skin burn.

Similar exposure time data are available for radiant energy. For example, Fig. 5-2 shows the radiant energy versus time needed to obtain moderate first-, second-, and third-degree burns (Ref. 42).

5-2.1.2.2 Hyperthermia

5-2.1.2.2.1 Body Temperature Regulation

Heat is added to the body from the basic metabolic processes (breathing, blood circulation, alimentary tract, food movement, etc.), food intake, and muscular activity. Heat is lost from the body by radiation, convection, and conduction from the skin; vaporization of sweat; respiration; and by urination and defecation (Ref. 41). In an environment of 21°C (70°F) approximately 97% of the heat is lost from the skin. Heat is brought to the skin from the body core primarily by the blood.

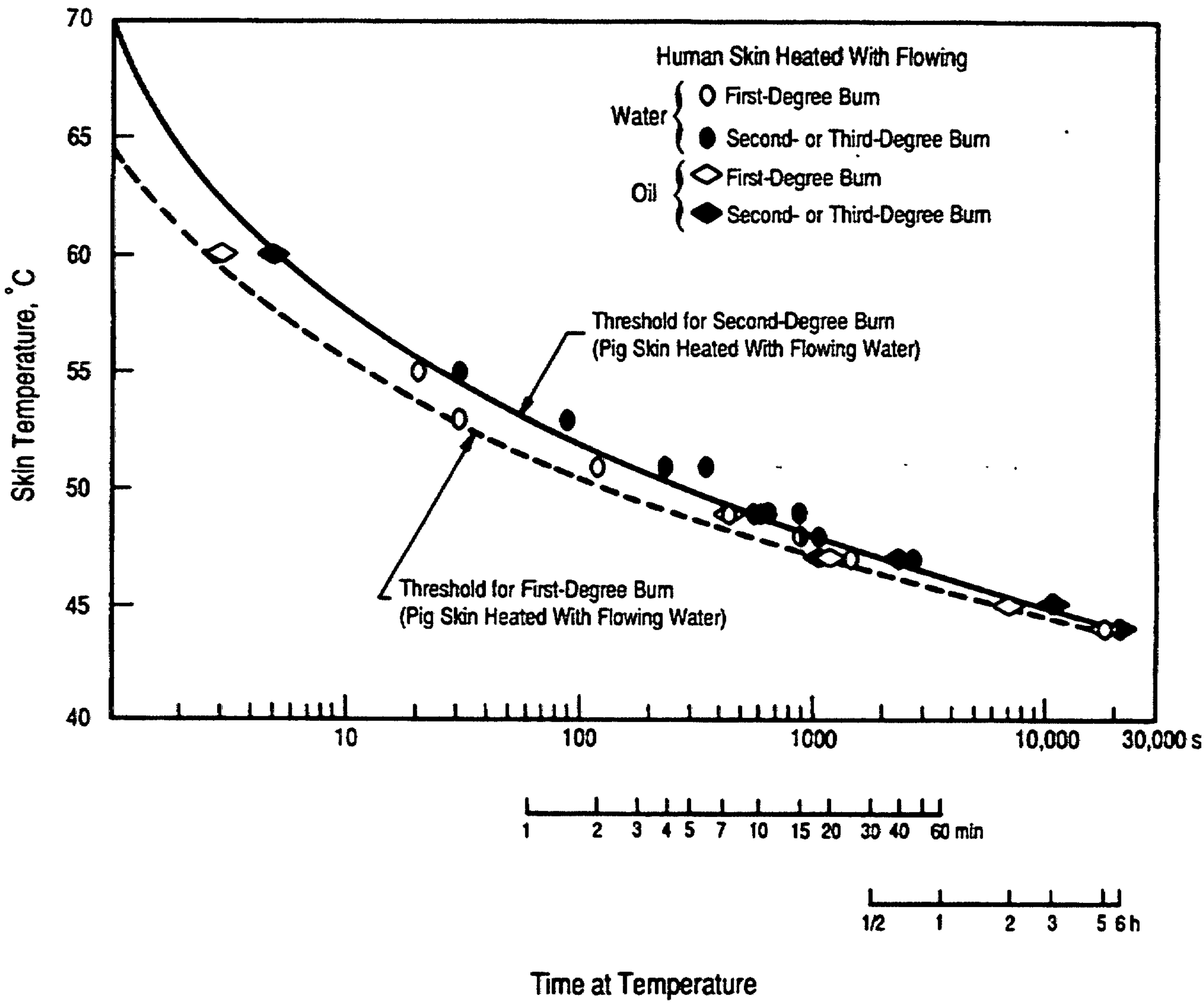

Figure 5-1. Skin Response From Temperature Exposure (Ref. 16)

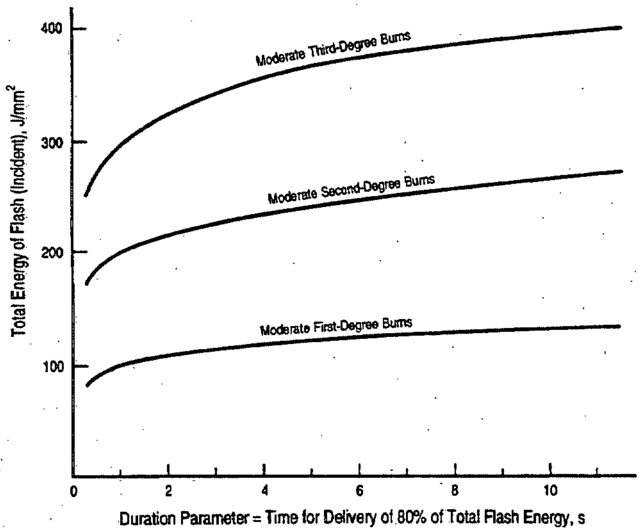

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Figure 5-2. Radiant Energy Required to Cause Flash Burns (Ref. 42)

The human body regulates its temperature within a very narrow band, i.e., usually within 0.5 to 0.7°C (0.9 to 1.3°F); the core temperature is approximately 37.5°C (99.5°F). Heat that is transferred to the body from external sources is retained until it is transferred from the body by the normal body processes. The primary means used by the body to lose excessive heat is sweating. The heat loss from sweating is due to evaporation of the water in the sweat. Vaporization of one gram of water requires approximately 2512 J (2.379 Btu) of heat, which would normally come from the skin. Sweating is not effective when the sweat glands are damaged, the person is dehydrated, the humidity is high, the person is immersed in moisture-saturated air or a liquid, or the person is wearing clothing impermeable to moisture, such as certain chemical warfare protective clothing or even rain gear or arctic outer clothing.

5-2.1.2.2.2 Reaction to Excessive Heat

The reaction of the human body to excessive heat is either to elevate the body temperature (hyperthermia) or to suffer local injury. Elevating the body temperature results in drowsiness and loss of mental control with death a possible result; for adults a core temperature of 43°C (110°F) is usually fatal. Hyperthermia is basically heatstroke and is characterized by loss of consciousness and failure of the heat-regulating mechanism (Ref. 39). Local injury can be skin burns, local swelling (edema), or heat damage to the muscle tissue beneath the skin that results in rapid liberation of potassium, which can result in hyperpotassemia.

Raising body temperature 1 deg C (1.8 deg F) requires adding about 251 kJ (238 Btu) of heat per 70 kg (154 lb) of body weight. Pigs exposed for varying lengths of time in air temperatures ranging from 70 to 550°C (158 to 1022°F) have been studied (Ref. 22). Pigs exposed for 15 min to an air temperature of 80°C (176°F) and for 30 s to an air temperature of 500°C (932°F) while breathing cool air (20°C (68°F)) suffered acute hyperthermia and death. In each case there was circulatory failure. During the longer exposures, peripheral vascular control was lost; this loss resulted in lethal drops in blood pressure. During the short exposures there appears to have been failure of the heart to continue effective pumping action. Each of these exposure models is considered in greater detail in the paragraphs that follow.

During prolonged exposures the effects of body cooling should be considered. The same 251 kJ (238 Btu) of heat that can raise body temperature by 1 deg C (1.8 deg F) in a 70-kg (154-lb) person can be removed by evaporation of 100 mL (3.38 fl oz) of sweat. Under favorable temperature and humidity conditions, a 70-kg (154-lb) person can maintain a stable body temperature while producing and absorbing a total of 1.26 to 2.09 MJ/h (1191 to 1985 Btu/h) during strenuous exercise. Thus existing animal data must be carefully interpreted when predicting the work capacity of people under high heat loads. The normal oral body temperature is 37°C (98.6°F). Although a core temperature of 39.5°C (103.1°F) means collapse is likely, a core temperature of 43°C (110°F) is lethal. Effective cooling through normal mechanisms is highly dependent on the relative humidity and velocity of the ambient air over exposed body parts. Avoidance of incapacitating heat loads during normal operation of a vehicle may, by providing reserve heat storage capacity in each person, lengthen the period of useful function under emergency high-heat conditions. By prolonging the period before cell injury or serious performance degradation becomes inevitable, the likelihood of survival and successful escape or fire suppression increases.

5-2.1.2.2.3 Localized Overtemperature of Body Parts

Exposure to severe heat can also cause heat exhaustion, which is due to inadequacy or collapse of the peripheral circulation with associated salt depletion and dehydration. Mental confusion and muscular incoordination may also occur (Ref. 39).

Hyperpotassemia, which can result from localized overheating, is caused by the release of potassium by damaged muscle tissue (Ref. 39). When it reaches the heart, this potassium can cause shallow, rapid, and irregular heartbeats (ventricular tachycardia) and fluttering of the heart muscles (ventricular fibrillation), which result in failure of the heart to pump blood and possible death (Ref. 41).

Heating of the skin can result in expansion of the underlying blood vessels (cutaneous vasodilation). This can result in shock.

The cell damage and death that result from thermal injury are in turn associated with increased permeability of cell membranes and capillaries. The potential for incapacitation due to a burn injury is highly dependent on its location, depth, and area. For example, the tissue swelling that accompanies burns may be relatively inconsequential if it occurs on a small portion of the back, but the same amount of swelling may be lethal if it occurs in the airways. Depending on the temperature of the heat source, radiant energy may penetrate well below the skin surface before being converted to heat (Ref. 43). Experimental work with a carbon arc source applied to rats at energy densities between 0.33 and 0.67 J/mm^2 (8 and 16 cal/cm^2) showed that most of the damage was done after 0.5 to 1.0 s of exposure. The author of Ref. 43 observed that contact burns with the same appearance as flash burns are not associated with the same deep tissue damage. Thus brief exposure to high-temperature (radiant energy) sources may result in flash burns that leave little or no evidence of skin injury but cause both acute and delayed destruction of muscle cells. Death may result due to the release of potassium from the heat-damaged red blood cells (Ref. 40). The excess potassium causes changes in heart rhythm that reduce the pumping efficiency of the heart, and it causes death due to shock (inadequate blood circulation to vital organs). Incapacitation from thermal burns may be immediate or delayed.

Shock may also ensue if the peripheral circulation is damaged by heat that is more slowly applied. It may result primarily from the shift of fluid out of the bloodstream into the surrounding tissues because of capillary leaks. Following more prolonged heat exposure, shock can also be caused by imperceptible water losses, e.g., perspiration and moisture in the breath. Crew members may lose more than 2 L/h (2.1 qt/h) of fluid through perspiration. To a person who had a mild fluid deficit before entering the vehicle, the loss of an additional 2 L of fluid could be incapacitating or even fatal. The Combat Lifesaver program was started to reduce the incidence of shock in US casualties. Special training teaches participants how to reduce shock, and supplies of water and intravenous injection devices and fluids are provided (Refs. 44 and 45). If fire-fighting and escape procedures occupy more than a few minutes, crew members who were not fully hydrated initially can be expected to suffer rapid and severe performance decrements.

5-2.1.2.2.4 Upper Respiratory Tract Damage

The tissue lining the throat (pharynx) and the vocal cords (larynx) is particularly sensitive to heat. These tissues swell readily when exposed to heat, e.g., when a person breathes heated air. The swelling can be great enough to close the air passage (upper respiratory tract obstructive asphyxia); then air cannot reach the lungs (Ref. 14). For this reason when studies were made of the effects of heated fluids or smoke on the lungs, either an insulated tube was emplaced in an animal so the researchers could preclude heating of the throat or the vocal cords (Ref. 14) or the smoke was cooled to ambient temperature before it was inhaled (Ref. 31).

All inhaled fluid that includes a mist or spray of hot liquid droplets contains much more heat than gas molecules do. Therefore, the spray transfers a greater amount of heat to the air passage tissue, so it greatly shortens the time required for the passage to close. This reaction is also true for live steam (Ref. 14). Inhalation of hot, dry gases causes heat injury mainly to the mouth and windpipe (trachea); however, inhalation of steam, small solid particles, or other components with relatively high specific heats compared to the specific heat of air causes tissue damage that extends into the lungs. Except when accompanying lung damage is extensive, the physiological response to upper airway burns may be delayed for several minutes to several hours. The delay is due in part to the fact that though swelling begins almost immediately after a burn, it does not reach a maximum until the second postburn day. Thus crew members may have time to execute escape maneuvers even after they have sustained potentially lethal burns. After upper airway or lung burns, obstruction of respiration may develop acutely and in conjunction with delayed swelling of lung tissue (pulmonary edema).

5-2.1.2.2.5 Lung Damage

5-2.1.2.2.5.1 Smoke Inhalation

The most serious problem for people caught in fires is smoke inhalation. One of the most hazardous materials that can be breathed is carbon monoxide (CO), which results from incomplete combustion of many materials. Another hazardous condition is the reduced oxygen level caused by the combustion. Table 5-3 provides a relationship between CO concentration and human response. Inhalation of smoke and other materials present during combustion of most combustible items can have similar noxious or toxic effects.

5-2.1.2.2.5.2 Heated Air

Inhalation of hot air that actually reaches the lungs would probably have little effect upon the lungs. This conclusion was demonstrated in several tests with dogs, seven of which inhaled clean hot air at 159 to 291°C (318 to 556°F). At most these temperatures caused moderate injury to only the upper windpipe (trachea). One dog inhaled 106 breaths of 350°C (662°F) air and survived. In these tests the throat and vocal cords were protected by an insulated tube (Ref. 14); otherwise, the dogs would probably have been choked by a throat swollen shut. Hot air alone would not contain enough heat to damage the lungs, but live steam would.

TABLE 5-3. RELATION BETWEEN CARBON MONOXIDE CONCENTRATION AND HUMAN RESPONSE (Ref. 46)

CO CONCENTRATION, ppm	SYMPTOMS OR REMARKS
25	TLV for conditions of heavy labor, high temperatures, and decreased air pressure
50	TLV and MAK value
100	No poisoning symptoms, even for long periods of time
200	Headache after 2 to 3 h
300	Distinct poisoning after 2 to 3 h
400	Distinct poisoning after 1 to 2 h
500	Hallucinations felt in 30 to 120 min
1000	Difficulty of ambulation; death after 2 h of inhalation
1500	Death after 1 h of inhalation
3000	Fatal in 30 min
8000 +	Immediate death by suffocation

TLV = tentative limit value in a working area (US)
MAK = maximum allowable concentration in a working area (Germany)

5-2.1.3 Protective Equipment and Protection Factors

5-2.1.3.1 Vehicular Requirements

Burns over large areas of skin result in the rapid depletion of circulating blood volume with accompanying hemoconcentration. Rapid infusion of replacement fluids can delay the incapacity that will inevitably accompany the slow healing process characteristic of burns. However, the immediate return-to-duty rate for crew members with burns of hands, face, feet, or the genital area is low. Many of these patients are at risk for kidney (renal) failure and will require long-term, intensive care.

The complications crewmen suffer and the length of their hospital stay can be reduced through appropriate early medical intervention. In the early management of burns there are three priorities: (1) maintenance of an airway, (2) control of blood loss, and (3) fluid replacement (Ref. 47). Depending on the current doctrine in far-forward medical care, certain instruments and supplies to accomplish these tasks may be carried in the vehicles. Combat medics carry the special equipment needed, but the number of these medics is limited. A special kit, which weighs approximately 4.1 kg (9 lb) and has a volume of 0.125 m^3 (0.44 ft^3), has been developed and contains most of the supplies needed (Ref. 45). These supplies are used for all types of casualties not only fire injuries because fluid replacement is a first principle of combat casualty care (Ref. 48) and the best preventative of heat exhaustion. Combat vehicles should carry a supply of drinking water. Because of the high percentage of wounded arriving at field hospitals during the Vietnam conflict in a state of shock from which approximately 15 to 20% died, the US Army introduced the Combat Lifesaver Program in 1982 (Ref. 47). The Army has approximately one trained Medical Corps person for every 40 frontline soldiers. This ratio, however, is not sufficient to provide first aid to the wounded, who often need treatment sooner than the Medical Corps personnel are able to provide it. All soldiers receive training in first aid, but the only equipment provided to individual combat arms soldiers is a first aid packet suitable for bullet wounds. As long as individual soldiers had to carry all their equipment, it was not practical to issue infantry or cavalrymen with the items needed to treat shock. With the high level of mechanization today, however, such items can be stowed aboard vehicles. The equipment furnished by the US Army Academy of Health Sciences includes the items needed to administer intravenous solutions and other more advanced first aid treatments. The intent is that one crewman on each vehicle be trained in the use of the medical supplies. This program operated outstandingly well in Panama in 1989; there was only one incident of shock in 250 cases of wounded evacuated to the rear from clearing stations. Records are not available to evaluate results from Desert Storm, but a total of 36,000 kits were sent to Southwest Asia (SWA), which included an instructor's manual (Ref. 49), two student's manuals (Refs. 44 and 45), and the equipment and supplies necessary for this expanded first aid treatment.

Another aspect of thermal burns that may delay recovery or cause death is the possibility of contamination of open burn wounds by common disease-producing (pathogenic) bacteria or chemical warfare agents. Incapacitation due to these exposures may be abrupt or delayed by several days, depending on the general health of the crew member and the type and concentration of the contamination. Consideration of these factors is governed by current medical and chemical defense doctrine and the threat assessment. Nearly all modern armored vehicles contain toxic gas filtration systems that function in both offensive and defensive chemical warfare operations. At least one recent war (the Iran-Iraq war, 1980 to 1988) reportedly produced large numbers of chemical agent casualties. The most likely materials to be encountered are persistent agents such as thickened mustard (HD) or soman (GD), and nonpersistent agents, such as sarin (GB) or hydrogen cyanide (AC). All of these chemical agents, except perhaps hydrogen cyanide, are absorbed at accelerated rates through burned or otherwise damaged skin.

5-2.1.3.2 Protective Clothing

Although a detailed discussion of protective clothing is not within the scope of this handbook, it is appropriate for designers and crew members to remember the substantial reduction in burn severity that can result from the proper use of protective clothing. Survivors of fires routinely report the importance of protecting exposed skin areas, often with relatively light materials. The very brief duration of exposure to high temperatures that characterizes some munitions fires emphasizes this point. Thus it is important that the vehicle designer, who is not expert on the types of protective clothing available, should nevertheless have an understanding of the physiological heat loads the clothing imposes, as well as other factors that may affect performance of the wearer. If design options can alter the expected spectrum of injury, the type of protective clothing available may influence the final vehicle configuration choice. It is impractical to protect people against sustained high temperatures in the crew compartment, but it appears feasible to offer some protection with two light layers of clothing (Ref. 50), which should include gloves, caps, and goggles. A computer model is available to predict the burns to bare skin (Ref. 34). There is a potential to expand this to include protection from heat provided by a fabric (Ref. 51). In the absence of more sophisticated guidance, each vehicle should have sufficient ventilation and/or cooling to allow the crew members to wear this minimum protective ensemble comfortably.

Table 5-4 provides the reaction of fabrics to heat. All fabric in modern battlefield garments can be expected to react eventually in a vehicle fire, but until the fabric is consumed two light layers of fire-resistant fabric offer a skin protection factor of about 2.5. This means that the time integral of temperature difference previously described may rise to approximately 3290 (2.5×1316)°C·s before second-degree burns are likely. If radiant energy is an important factor, as it is in armor-penetrating events, evaluators must consider the use of heat flux calorimetry to measure total heat transfer.

Heat flux was not measured in early vehicle fire tests, but recent tests of the M1 MBT included it. Calorimeters were placed at face, waist, and calf levels. For these and similar tests the criterion for significant thermal injury has been 0.15 to 0.17 J/mm^2 applied to unprotected skin within 10 s. Two layers of light clothing would provide protection equivalent to about 0.23 J/mm^2. Thus the thermal criterion for injury of a protected person would be 0.38 J/mm^2, i.e., 0.15 + 0.23, within 10 s. These values represent only rough guidance; however, they do illustrate the substantial protection that relatively simple clothing can provide. Thus insuring sufficient cooling in the crew and passenger compartments to allow use of at least the minimal protective clothing described should be a minimum design goal. In addition to reducing the debilitating effects of heat stress, this capability would also prevent the accumulation of perspiration on clothing. Damp clothing tends to defeat the protective characteristics of the chemical warfare protective ensemble, and it subjects the wearer to steam burns if the outer garment flames or heats above 100°C (212°F) or if there is contact with hot surfaces.

5-2.1.4 Full-Scale Tests

Instrumentation requirements and injury criteria to be used in a medical evaluation of nonfragment injury effects in live-fire tests of armored vehicles have been prepared by personnel at the Walter Reed Army Institute of Research (Ref. 1). This document (Ref. 1) was reviewed by the Armed Forces Epidemiological Board of the Department of Defense (DoD) which has made the following statement:

TABLE 5-4. REACTION OF FABRICS TO HEAT (Refs. 52 through 55)

FABRIC	MELTS °C (°F)	DECOMPOSES °C (°F)	IGNITES °C (°F)	BURNS °C (°F)	CHARS °C (°F)	LOI*	OTHER °C (°F)
Cotton	—	305-320 (580-610)	255-400 (490-750)	850 (1560)		16.0-19.0	
Wool	—	230 (950)	570-600 (1060-1100)	940 (1720)		23.8-28.0	
Acrylic	—	285-310 (540-590)	460-560 (860-1040)	850 (1520)		17.3	
Nylon	215-255 (420-490)	315-420 (600-790)	450-570 (840-1060)	875 (1600)		20.1-26.0	
Kevlar®						29.0	
Nomex®		371+ (700+)				26.7-30.0	
Polybenzimidazole (PBI)		425 (797)			540 (1004)	41.0-58.0	425** (797)

*LOI = limiting oxygen index, i.e., the percent oxygen in a nitrogen-oxygen mixture that just sustains combustion
**Temperature at which tensile and compressive strengths both approach zero

"The technical document outlining the criteria for estimating nonfragmentary injuries behind defeated armor represents an appropriate and systematic approach on this topic. The Board further recommends the use of animal subjects in any continuing studies. Failure to do so would ultimately risk the possibility of subjecting human occupants of armored vehicles to serious injury or death." (Ref. 56)

Full-scale vehicle tests have been limited in scope to considerations of air temperature, heat flux, and damage to animal models or manikins (Refs. 24 through 27). At the time of those tests, criteria used to assess the severity of thermal burns were general in nature and provided little guidance regarding the incapacitating effects of the different types of burns that can be expected. An approach that would yield more useful results would describe the crew and passengers of the vehicle realistically with regard to clothing, state of health, heat tolerance, and ability to act to limit burn injury after a fire has started. Minimization of injury will be dependent on all of these factors plus training in the proper emergency procedures. Appropriate use of animal models would require extension of experimental work to combined injury models including hot liquids, flame, radiant heat, hot solid surfaces and particles, and the related trauma, i.e., fractures, bruises, penetrating wounds, crush injuries, and blast damage, observed in manikins. No controlled human trials are reported with this type of data, and it is unlikely that any will be conducted. Review of combat records, some of which are in the Battle Damage Assessment and Repair Program (BDARP) database described in subpar. 4-1.2, can provide guidance on the general classes of injury that should be represented, but further part- and full-scale tests will be needed to collect the quantitative data necessary to draw conclusions on vehicle design. It will be especially important to characterize completely the physical environment in the vehicle through improved heat-sensing instrumentation. In this respect, use of animal models should be reduced by use of more and better instruments. Existing data and mathematical models can provide most of the information needed to locate a burn physically and to describe it grossly (Refs. 51 and 57), but more precise measurements of the vehicle environment combined with simulation trials are required to allow realistic extrapolation of the animal data to quantify human incapacitation.

5-2.2 THERMAL INJURY ASSESSMENT

Accurate prediction of crew survivability from fires within armored combat vehicles (ACVs) is difficult because of complex interactions between the thermal environment, biologic response, and clothing protection. This subparagraph addresses the technique used in tests to predict a crewman's receiving second-degree (or worse) burns (Ref. 1) and provides the available combat data and descriptions of the combat vehicle tests conducted to date.

After penetration of an ACV, the first 10 s are critical to the risk of thermal injury. A significant temperature elevation beyond this time would compel the crew to evacuate the vehicle unless they could control the fire. Slowly developing thermal events could be identified by the crew, which could then jettison the burning material, control the fire with handheld fire extinguishers, or evacuate.

5-2.2.1 Data-Gathering Techniques Used in Live-Fire Tests

The best measurable, environmental correlate of burn potential is heat flux calorimetry. In early live-fire tests (LFTs) this parameter was not measured. In the M1 LFT, however, heat flux measurements were taken that allowed the summation of radiant, conductive, and convective, thermal loads. The source and duration of the thermal exposure were found to be quite important. In the Bradley fighting vehicle (BFV) LFTs most of the heat recorded during armor-penetrating events came from convection of heated gases and irradiation by long-duration, infrared energy (Ref. 1).

During the M1 and M1A1 tests, exposed calorimeters were placed at the face and waist region of each manikin, and additional calorimeters were located beneath clothing in the chest and calf regions. To assess injury, the criterion of $0.16\ \mathrm{J/mm^2}$ ($3.9\ \mathrm{cal/cm^2}$) applied over 10 s was used. This procedure was judged reasonable by a group of burn experts (Ref. 1).

Witness boards developed by the US Army Environment Hygiene Agency (AEHA) were placed at the head, waist, and calf locations for each crew position. Although they are calibrated to indicate the presence of heat flux below the level capable of causing second-degree burns, they were used in this test to assure that burn data were obtained even when electronic instrumentation was lost.

The instrumentation recommended by the Surgeon General is described in Ref. 1.

5-2.2.2 Second-Degree Burn Criterion

The Army's second-degree burn criterion uses free air temperature and is correlated loosely with heat flux criteria (Ref. 1). As in the BFV Phase II LFTs, continuous free air temperature measurements were made at calf, waist, and eye levels for all crew positions. Free air temperatures and exposure times were related to second-degree burn predictions for exposed bare skin by using the time integral $\int t_i$ of measured air temperature T_m less body temperature T_b (37°C (98.6°F)) according to the following equation:

$$\int t_i = \int_0^t (T_m - T_b)\,dt,\ ^\circ\mathrm{C{\cdot}s} \qquad (5\text{-}5)$$

where

t = time over which temperature is measured, s.

Second-degree burns to bare skin were predicted if the integral of temperature over 10 s exceeded 1316°C·s (2400°F·s). Since convective and conductive heat transfer are nearly linearly correlated with free air temperature, the temperature-time integral should also be linearly related to the measured heat flux.

Unless it catches fire or melts, any type of clothing offers some protection in a brief thermal exposure. In a significant thermal environment, however, no presently used battlefield garment will resist ignition for longer than 10 s. As noted in the BFV Phase II LFT report, either battle dress uniform (BDU) or Nomex®, plus either an air space or an undershirt, affords 0.22 J/mm^2 of protection—an arrangement that protects the skin by a factor of 2.5. This protection factor can also be used for helmet, goggles, boots, ballistic vest, etc, even though these materials are expected to protect crewmen more than clothing does. To predict the second-degree burn protection provided by clothing, 0.22 J/mm^2 should be added to 0.15 J/mm^2, and the time-temperature integral before the garment ignites should be multiplied by the protection factor. If the measured heat transfer exceeds 0.37 J/mm^2 or if the value of the corrected integral exceeds 3300°C·s (6000°F·s), second-degree burns are likely (Ref. 1).

A thermal equivalency chart that compares the time-temperature integral and the heat transfer required to obtain a second-degree burn on skin is presented in Table 5-5. Other units of heat transfer measurement were reported in the data and were converted as indicated in this table.

5-2.2.3 Vehicle Tests Involving Animals

Three sets of vehicle tests involving animal models were conducted in the late 1960s to middle 1970s. There were also tests of aircrew uniform materials during this period.

5-2.2.3.1 Tests of the LVTP 5A1

The first set of two tests was conducted to establish the efficiency of the Freon®* fire-extinguishing system with an optical fire-sensing system plus other miscellaneous devices to protect occupants of an LVTP 5A1** from fire ignited by the explosion of a beach mine (Refs. 24 and 58). The LVTP 5A1 was a steel-hulled, gasoline-fueled amphibious vehicle. Six anesthetized weanling Chester white pigs, plus several window display manikins dressed in Marine Corps fatigues or Nomex® uniforms, were emplaced for each test. In both tests each of the eight fuel cells located beneath the troop compartment contained 94.6 L (25 gal) of 80-octane gasoline, i.e., 83% full. These fuel cells were fully packed with Type I (orange) reticulated polyurethane foam. The bladders were made of conventional aircraft bladder material with a urethane coating to provide abrasion resistance (Ref. 59). The troop compartment fire-extinguishing system used four CO_2 cylinders each containing 4.5 kg (10 lb) of Freon® FE 1301 per MIL-M-12218B (Ref. 60). This system had six optical detectors, which provided the signal for the controller to initiate the extinguisher squibs. A wire-grid penetration sensor system was also installed to test an alternate system; it supplied a signal to a recorder to establish comparative times. All hatches were closed in both tests.

The explosive charge used for the first test on 28 February 1967 included two MK 3 shaped-charge cans, each of which contained 0.57 kg (20 oz) of Composition C4 explosive. The MK 3 demolition charge container is a 76-mm (3-in.) diameter can 102 mm (4 in.) long with an 80-deg

*This extinguishant, bromotrifluoromethane, was a Du Pont product, Freon® FE 1301; this was before the generic name Halon 1301 was adopted.

**US Marine Corps LVTP 5A1s were never modified to include this fire-extinguishing system.

TABLE 5-5. THERMAL EQUIVALENCY TABLE FOR SECOND-DEGREE BURN OF SKIN (Ref. 1)

	EXPOSED SKIN	UNDER CLOTHING
TIME-TEMPERATURE INTEGRAL:	1300°C·s	3300°C·s
	2400°F·s	6000°F·s
HEAT TRANSFER:	0.035 cal/mm^2	0.088 cal/mm^2
	0.15 J/mm^2	0.37 J/mm^2
	12.9 Btu/ft^2	32.5 Btu/ft^2
	1.46×10^5 W·s/m^2	3.68×10^5 W·s/m^2

included angle copper liner in one end and a filler of hand-packed Composition C4. The two shaped charges were placed under the LVTP 5A1 below the second port fuel cell; one MK 3 was at a 63.5-mm (2.5-in.) standoff, and the other at an 88.9-mm (3.5-in.) standoff. These two improvised shaped charges were initiated simultaneously. The optical detectors began sensing light above the deck in 3 ms. The extinguishant valve squibs were initiated at 18 ms, and the fire was out in 64.5 ms.

All six pigs survived. Pigs 1 and 2 were singed and soaked with gasoline but had no skin burns. Pig 1 had a small spall injury. Pigs 3 and 4 also had small spall injuries and some tiny burns from hot metal bits. Pigs 5 and 6 had no apparent injuries. All of the pigs were sacrificed, half immediately and the other half 24 h later. None of these pigs had injuries to the respiratory tract or lungs that could be attributed to the test. Examination of the manikins indicated that personnel would not have sustained skin burns. Several manikins showed evidence of a fireball. Three manikins were sprayed with gasoline, and four had spall hits.

The disc-shaped explosive charge used for the second test on 2 March 1967 was 4.5 kg (10 lb) of Composition C4 in a wooden box with two white phosphorus grenades secured to the top of the box. There was no discernible fire seen in the high-speed motion pictures taken within the LVTP 5A1, nor was there any signal from the optical detectors. The amplifiers used with the optical detectors apparently actuated due to shock from the explosion and activated the extinguisher squibs 6 ms after the charge detonation. The reason for no fire within the vehicle could not be established. The strong ignition source that the shaped-charge jets provided in the earlier test was absent, and the released Freon® FE 1301 could have caused the inside of the vehicle to become temporarily inert. The fuel cell and the deck plate immediately above the charge were thrown rearward in the vehicle. Pig 2 was dead, apparently the victim of impact by the fuel cell and/or deck plate. Neither the pigs nor the manikins showed any evidence of fire.

Conclusions derived from this program included (1) that the fire suppression system tested is capable of extinguishing fire in time to protect occupants of the vehicle from skin burns without producing lung injury under the conditions tested (Ref. 24) and (2) that the optical sensing system used was not adequate even as modified during the program due to lack of reliability. The evaluation personnel also established that the wire-grid penetration detection system was adequate; they recommended that the wire-grid penetration system be used (Ref. 58).

5-2.2.3.2 Tests of Diesel-Fueled APC, M113A1

Due to incidents in SEA, an automatic fire-extinguishing system (AFES) for the APC M113 series was needed. The design of the AFES for the APC M113 series was initially based upon that recommended for the LVTP 5A1 described in Ref. 58. A program was started in 1968 to provide such a system. As was described in subpar. 4-1.2, the APC M113 was used as an armored cavalry assault vehicle (ACAV) in SEA at that time; hence most of the testing was done with open hatches. After completion of the development program in which the fire-sensing system was redesigned (The LVTP 5A1 had the breakwire between the hull and the fuel cell, but the M113 had the breakwire between the fuel cell and the occupant compartment.) and the extinguishant system sized, three confirmatory tests were performed, which included animal models. For the first test eight pigs with an average mass of 17 kg (weight of 37.5 lb) were placed in the crew compartment or suspended over open hatches of an APC M113A1 (Ref. 25). In order to determine their physiological reactions, these pigs were not anesthetized. The fire-extinguishing system consisted of two 5.4-kg (12-lb) CO_2 bottles, each containing 2.3 kg (5 lb) of Halon 1301 pressurized to 5.2 MPa (750 psi) with dry nitrogen, and a grid-activated initiation system. The grid was mounted on a 0.76-mm (0.030-in.) thick sheet of aluminum that fully covered the side and forward end of the fuel cell exposed within the troop compartment. This aluminum sheet served as a shield to prevent a gross spray of fuel into the troop compartment upon fuel cell rupture. For the first two tests the fuel cell located in the rear left interior of the vehicle contained approximately 227 L (60 gal) of DF-2 heated to 57 ± 3°C (135 ± 5°F). A 3.5-in. HEAT M28A2 warhead was detonated statically so that the jet passed through the fuel cell into the troop compartment.

In the first test the pigs had been kept in the open in the sun with a surrounding air temperature of 35.6 to 37.2°C (96 to 99°F) and high humidity for approximately 3 h before being placed in the APC. The temperature within the APC was 33.9 to 35.6°C (93 to 96°F). These conditions were severe enough to affect the pigs' reactions but would probably not cause death. Upon detonation of the M28A2 warhead, a very large fire ensued within the vehicle. The AFES extinguished the internal fire in approximately 200 ms; the Aberdeen Proving Ground (APG) fire department extinguished the adjacent ground fire in approximately 1 min. Two pigs located inside the crew compartment died shortly after the fire apparently from extreme heat stress and lack of water; both had smoke inhalation damage to their upper respiratory tracts. The pig suspended over the commander's hatch was the only pig actively moving; all the other surviving pigs—four inside the vehicle and one suspended over the cargo hatch—were subdued*. These five subdued pigs had been exposed more directly to the events within the vehicle than had the one active pig. When the surviving pigs were released 7 to 10 min after the test, their activity appeared normal. They exhibited no visible loss of equilibrium nor any sign of eye irritation, and none had any visible

*"Subdued" has been equated to "shell shocked" by one of the veterinarians involved in these tests (Ref. 61).

skin burns. Later, when they were sacrificed, their lungs and upper respiratory tracts did not exhibit any life-threatening conditions (Ref. 25). The two pigs that died were the only ones with blackened larynxes; apparently they breathed something that was extremely injurious. This test indicated that those pigs subjected to thermal stress prior to the test and to severe thermal conditions during the test were at the survival-nonsurvival point. Only the pig subjected to the least stress during the test was apparently still fully active immediately after the test.

In the second test again a very large fire ignited within the vehicle; this fire was extinguished in approximately 150 ms. The pigs for this test had been subjected to much less preliminary thermal stress. One pig died shortly after the test; it had been located immediately beside the fuel cell and had been drenched with hot fuel. All the other pigs were moderately subdued after the test. The pig that died had third-degree burns on the ears and second-degree burns on its snout and exhibited burns and damage to its breathing tract. None of the others had any skin burns or discolored larynxes (Ref. 25). This test was much less severe than the earlier test primarily because the pigs were not subjected to severe thermal conditions before the test, and only the pig subjected to extreme conditions, including breathing something extremely injurious, such as hot fuel, died.

The next test differed from the two earlier in that the vehicle was being towed at 24 km/h (15 mph). In this test the ambient temperature was 0 to 3°C (32 to 37°F), and the DF-2 had been heated to 57 ± 3°C (135 ± 5°F) prior to firing the charge. Again a very large fire was ignited; it was extinguished in approximately 125 ms. All the pigs survived but appeared moderately subdued. None of the pigs were burned. Upon sacrifice, none exhibited any life-threatening breathing tract damage (Ref. 26). This test indicated that if a fire is quickly extinguished, it should be survivable by unprotected beings, but it also indicated that the beings probably would not be capable of performing their duties.

5-2.2.3.3 Test of Gasoline-Fueled M113 APCs

The AFES used was basically the same as the one for the diesel-fueled M113A1 (Ref. 25). In the four tests the 227 to 265 L (60 to 70 gal) of gasoline were heated to 35 ± 3°C (95 ± 5°F) before the test. The shaped charge used in each test was the M28A2 warhead.

In the first test six pigs had their feet lashed together and were laid on the deck within the vehicle. The upper hatches and ramp door were closed. The internal fire was extinguished in 212 ms. The APG firemen extinguished the external fire 3.5 min after the test. The hatches were opened 5 min after detonation. The pigs, whose average mass was 25 kg (weight of 55 lb), were removed 5 to 8 min later. They were all bluish, frothing at the mouth, and gasping for air (Ref. 27). The veterinarian who was handling these pigs later described them as being "shell shocked" (Ref. 61). Two of these pigs died shortly thereafter. The survivors were aroused 15 min after the test. They lacked muscular coordination but were able to stand. The two pigs that died had first-degree burns, but none of the others had any skin burns. All of the pigs exhibited some respiratory tract injury (Ref. 27). This test indicated that ventilation within the vehicle was inadequate for the situation.

In the second test six pigs were suspended in harnesses, and the upper hatches were closed. The commander's hatch and the cargo hatch blew open after the charge detonation. The internal fire was extinguished in 190 ms, and the external fire was extinguished and the ramp door opened in 2 to 3 min. When the pigs were removed after 4 to 6 min, they were all breathing normally, their color was normal, and they acted normally in the field pen. When they were sacrificed, there was some indication of breathing tract injury, but none that was life threatening (Ref. 27). This test indicated that because the hatches were blown open, the ventilation was much more adequate.

In the third test the upper hatches were open, and a total of 8 pigs were suspended within the vehicle or over open hatches. Upon detonation of the charge, the aluminum sheet on which the grid was mounted came loose and was thrown to the deck when 8 of 10 bolts securing it to the wall sheared. This situation permitted gasoline to spray into the troop compartment; the aluminum sheet had acted as a baffle and trapped much of the gasoline spray in the other tests. The extinguishant bottle mounted on that sheet discharged, but the flow of Halon was not effective, i.e., the Halon flowed out between the aluminum sheet and the deck. Also the personnel door in the ramp came open and permitted the Halon to exit the troop compartment. The initial fire was extinguished in 892 ms but reignited after 4 s. The fire was reextinguished and then reignited in 2 s. This fire was again extinguished but reignited in 1 s. Neither automatic nor manual systems were able to extinguish this fire; it had to be extinguished by APG firemen with portable extinguishers approximately 1 1/2 min after the charge detonation. Five of the pigs died, and the other three were moribund. Six had up to fourth-degree burns* over 90% of their bodies. The other two were also badly burned. All suffered extreme injury of the respiratory tract (Ref. 27). This test demonstrated that the Halon extinguishant had to be contained and circulate within the compartment to be effective.

The fourth test was a repeat of the third. This time, however, the bolts holding the aluminum sheet with the wire grid and extinguishing bottle did not shear. The AFES extinguished the fire in 100 ms. The six pigs, whose average mass was 15 kg (weight of 33 lb), were removed from the vehicle in approximately 6 min. The cable suspending two pigs was severed by the shaped-charge jet, so the pigs dropped onto the deck. These pigs were well-saturated with

*Fourth-degree burns are those in which the skin is charred and the burn extends into the muscle and sometimes the bone.

gasoline. One of these two pigs had breathed gasoline and was dead when removed. The other pig that had been dropped was prostrate, unconscious, had a first-degree burn, and had difficulty breathing when removed. The other six pigs had no skin burns, and three of them suffered some respiratory tract injury. None of the seven surviving pigs suffered injuries that would have proved fatal (Ref. 27). This test raises the question of whether being on the floor, being dumped into the gasoline spray, or breathing the gasoline spray is the most hazardous. The fast fire out time was not the deciding factor.

5-2.2.3.4 Tests of Aircrew Uniform Materials

Several series of tests were performed by the US Army Aeromedical Research Laboratory in the late 1960s and the 1970s. These tests were to determine the protection clothing provided the crewmen from a JP-4 fire in a crashed helicopter (Refs. 35, 62, and 63). The heat source used in these tests was a modified gun-type conversion oil burner burning JP-4. The device delivered 159 ± 6 kW/m^2 (14 ± 0.5 Btu/ft^2·s), which simulates the worst credible thermal environment in a helicopter crash fire (Ref. 62). This amount of heat would also simulate a fuel fire within a well-ventilated combat vehicle.

A shutter covering six holes in an insulated plate was used to control burn location and duration. Each hole provided a single skin burn specimen. These holes could be left empty to provide a baseline burn, could contain fabric specimens, or could contain a heat flux sensor (Ref. 35). Many fabric combinations were tested including Nomex®, polybenzimidazole (PBI), an experimental high-temperature polymer (HT4), and cotton.

In one series of tests (Ref. 62), the fabric samples were held against the pig's skin to preclude an air gap between fabric layers or fabric and skin. A thermocouple was emplaced between the skin and the fabric at the center of each skin burn specimen. The thermocouple sensed the surface temperature of the skin for three different exposure time intervals. Fig. 5-3 shows the skin temperature versus time for one of these tests. Note that the temperature trace for the single-layer Nomex® follows that for the unprotected specimen but lags it by 1.9 s. This lag is the time required for the approximately 1500°C (2732°F) JP-4 flame to remove, at least partially, the single layer of Nomex®. After removal of the single layer of Nomex® fabric, the skin heated at the same rate as did the unprotected skin (Ref. 62). These tests demonstrated that a single layer of even a highly fire-resistant fabric will not resist flames from a hydrocarbon fire for more than approximately 1.0 to 2.0 s. These tests also showed that two layers of material, particularly a fire-resistant layer over a standard cotton layer, would provide superior protection.

Later tests indicated that "loose-fitting" clothing, i.e., there is an air gap between the outer clothing and the inner

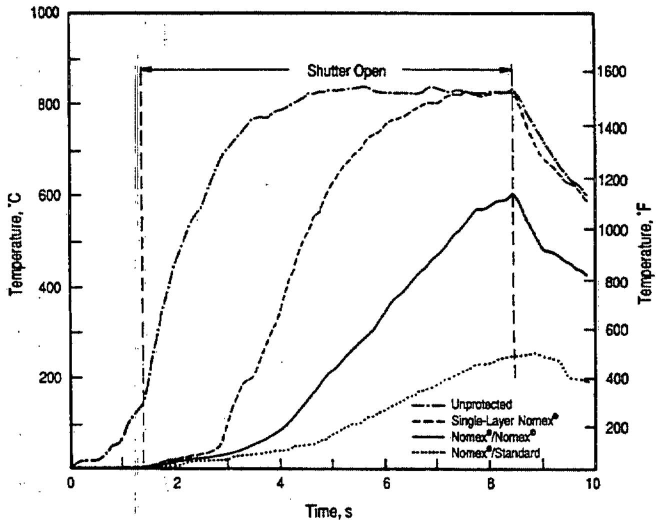

Figure 5-3. Temperature Traces for 7-s Exposure Tests (Ref. 62)

clothing or between the clothing and the skin, should provide much better protection from flame than "formfitting" clothing. A measure of the protection afforded by the most fire-resistant fabrics is shown on Fig. 5-4. For each fabric or fabric and cotton T-shirt combination listed, the gross burn grade for a 5-s exposure to JP-4 flame is shown (Ref. 35). The control specimen Groups 3 and 4 provide a measure of the protection afforded by the cotton T-shirt alone. Note that the multiple layers of loose-fitting clothing provide the best protection.

Because they are hotter, solid gun propellant fires would be even more hazardous, as indicated by an incident in Iraq

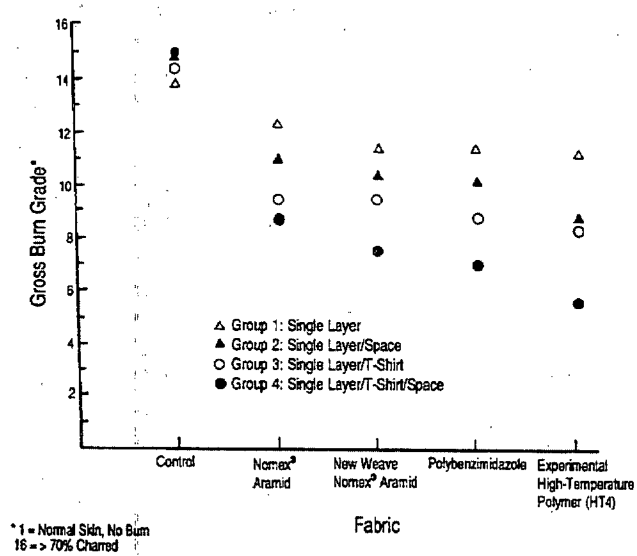

Figure 5-4. Mean Clinical (Gross) Grade for Each High-Temperature Fabric and/or Configuration (Ref. 35)

in which a T72 MBT hit an M2A2 BFV and initiated propellant, which in turn ignited the combat vehicle crewman (CVC) uniform of a trooper (Refs. 64 and 65). This uniform did protect the crewman from receiving fatal burns.

5-2.2.3.5 Overall Evaluation of These Animal Tests

These tests indicate that a short-duration hydrocarbon fire extinguished by Halon 1301 is not lethal as long as the animals are removed from the vehicles quickly. Thus, if the personnel evacuate a vehicle rapidly, the fire and extinguishant by-products may not be lethal or incapacitating. This evacuation would, however, expose the crewmen to small arms and artillery fire.

One test showed that if animals remain within a buttoned-up combat vehicle for five or six minutes, they will be incapable of effective action. This result indicates that even if crewmen are not burned within combat vehicles protected by a Halon 1301 AFES, they will probably succumb to "smoke inhalation" (1) if they do not evacuate or (2) if the products of combustion are not purged either by ventilation or by extinguishant spray flushing. Soldiers cannot effectively operate their equipment under the conditions that prevailed in these tests. This scenario illustrates the need for either a highly effective ventilation system or an extinguisher system that can flush noxious fumes out of the air. (A means to flush smoke and noxious gases out of the air is described in subpar. 7-2.3.1. Vehicle designs that preclude the burning of great quantities of fuel and/or hydraulic fluids within the occupied compartments are covered in Chapter 4.)

The fabric tests indicated that multilayers of loose-fitting clothing are best and that we do not have a truly fireproof fabric in use in the Army.

5-2.2.4 Combat Data from Southeast Asia

There is a very limited database available from Southeast Asia on fire casualties from combat vehicles hit by shaped-charge warheads. The data available in the BDARP database at the Survivability Information and Analysis Center (SURVIAC) are described in subpar. 4-1.2.

5-2.2.4.1 Casualties in ACAVs and Other APC M113 Vehicles

A review of the 47 reported incidents involving 43 armored cavalry assault vehicles (ACAVs), 2 mortar carriers (an M106 and an M125), 1 cargo carrier M548, and 1 M113A1 in which 78 casualties resulted indicated that 21 casualties were caused by fragments or small arms bullets impacting personnel exposed in open hatches or on top of the vehicles, 53 casualties were caused by impacts of jets or spall or by other behind-armor effects, and 4 casualties were dismounted troops near the vehicle (Ref. 66). These incidents are filed by document acquisition number (DAN).

Three of the behind-armor casualties suffered burns from diesel fuel fires, and one soldier was splattered with white phosphorous particles. Five casualties were caused by shock, blast, or flash. Diesel fuel that splattered the personnel and burned on their clothing caused two of the burn casualties; these two men were not evacuated beyond the clearing station (DAN 672). Another burn casualty was caused by a vehicle that was hit by a shaped charge on the right side, and the jet passed through the troop compartment before impacting the fuel tank on the left side (DAN 381). One burn casualty was in the 81-mm mortar carrier, M125, in which the RPG-2 shaped-charge jet passed through two white phosphorus (WP) projectiles. The gunner, who was sleeping in the vehicle, was burned badly by the white phosphorus (DAN 301).

Most of the flash or blast casualties were caused by the detonation of the shaped-charge warhead, not from any internal explosion; none of these casualties were caused by exploding stowed ammunition. None of the casualties were caused by inhaling combustion products, sprayed fuel, or the fire extinguishant, CO_2. None of these vehicles were buttoned-up; all had their hatches open when hit by the shaped-charge warhead.

5-2.2.4.2 Casualties in MBTs M48A3

The M48A3 MBT was diesel fueled and had a manually activated, fixed fire extinguisher system (FFES), which used CO_2, in the engine compartment. The crew compartment had two portable CO_2 fire extinguishers. Crewmen of the M48 were trained to evacuate their vehicle when it was hit and stopped. They were also trained to take their personal weapons and the coaxial machine gun, defend the vehicle from further attack, and assist in the evacuation of the vehicle. They were trained not to stay within the vehicle because it would probably be subject to additional hits (Ref. 67).

The BDARP database for SEA had a total of 19 incidents in which shaped-charge warheads hit MBTs M48A3, and 32 casualties resulted. The hatches were open in 17 of those incidents, the driver's hatch was closed in one (The vehicle was parked for the night.), and the other was unknown. When the hatches were open, the commander and loader were usually standing with their upper torsos exposed, and the driver usually had his head exposed. Nine (28%) of the casualties were thus exposed and were hit by fragments or bullets. Twenty (62.5%) of the casualties were caused by behind-armor effects. The other three casualties were due to evacuating the M48A3 after two tear gas grenades were punctured by a shaped-charge jet (described in subpar. 4-6.4.3). One soldier injured a leg after running off the vehicle; the other two were shot by small arms.

At least 13 of the behind-armor casualties were due to the jet, spall, or splash. In one incident (DAN 157) the jet hit a 90-mm cartridge case and ignited the propellant. One man was killed in the resulting explosion, and another was burned and hit by spall.

5-2.2.4.3 Casualties in AR/AAV M551

The armored reconnaissance/airborne assault vehicle (AR/AAV) M551 is a diesel-fueled aluminum armored vehicle. The ammunition cartridges used have combustible cases and are loaded with M26 propellant. The M551 is divided into three compartments to accommodate the driver, the rest of the crew, and the engine. A fire barrier is located between the crew and the engine compartment. No fire warning or sensing system is provided, but both the crew compartment and the engine compartment have a dedicated FFES. The FFES in the crew compartment has one 3.6-kg (8-lb) Halon 1301 bottle that is manually activated by pulling a handle located on the right side of the turret. The engine compartment has a 1.47-kg (3.25-lb) Halon bottle with one activation handle near the driver and a second handle on the exterior of the vehicle. There is one portable 1.25-kg (2.75-lb) Halon fire extinguisher in the driver's compartment. Fuel is carried in three cells. Two are located on the right sponson in both the crew and engine compartments, and the third is across the engine compartment adjacent to the fire wall that protects the crew compartment.

There were 16 incidents in the BDARP database in which M551s were hit by shaped-charge warheads. There were 22 casualties in these incidents. Six (27%) of these casualties were personnel exposed in hatches or on top of the vehicles, four of whom were hit by fragments from the warhead casings and two were injured by the blast or flash of the warhead detonation. The other 16 casualties (73%) were caused by behind-armor effects. Eight were caused by burns and/or blast effects from explosion of stowed cartridges hit by shaped-charge jets, and the other eight were caused by impacts of spall or splash from the jet or direct impact of the jet itself. The hatches were open in 14 incidents, closed in one incident, and were probably open in the other incident.

There were two hits in the engine compartment that resulted in hydrocarbon fuel fires. In one (DAN 1532) the FFES in the engine compartment was activated, and the fire was successfully extinguished by the FFES plus portable extinguishers. All four crewmen, however, evacuated the vehicle. In the other (DAN 1879) the fire had self-extinguished but the crew did not realize there had been a fire until later. They knew only that the engine had stopped running.

There were three other hits that resulted in fires. One hit was in the rear in the battery box. Electrical insulation burned and the fire self-extinguished (DAN 632). The other two were into the turrets. In both incidents the crew evacuated; the fires were of electrical wiring only. In one (DAN 670) the fire was extinguished by a crewman using the portable extinguisher, whereas in the other (DAN 463) the fire self-extinguished. In none of these incidents was the crew reported to have breathing tract injuries.

5-2.2.4.4 Evaluation of SEA Armored Vehicle Fire Casualties

The fire casualties from all three vehicle types were compared to the animal casualties in the tests described in subpar. 5-2.2.3 to see whether the test results could be validated. During evaluation of these results, it should be noted that the M551 had Halon 1301 and the M48A3 and M113A1 ACAV had CO_2 extinguishers, whereas all of the animal tests were with Halon 1301.

There were very few incidents in SEA in which crewmen were subjected to hydrocarbon fuel fires within vehicles. In all of those incidents the crewmen evacuated the vehicles very quickly, probably within seconds. In all of the animal tests the animals remained within the vehicles for at least 5 min. Thus the animals had much more time to breathe noxious combustion products and vapors than the humans. In almost all of the incidents in SEA, the vehicles were well-ventilated, i.e., the hatches were open and usually the men were breathing outside air. Most of the pigs were breathing air from within the vehicle. The men did not suffer excessive heat input in the vast majority of incidents, nor did they succumb to smoke inhalation or air passage edema. Some pigs did. If the vehicles had been buttoned up in SEA, however, there is good reason to believe the men could have suffered the same breathing passage injuries as the pigs. Therefore, although the combat incidents do not validate the test data, they do not contradict it. The animal tests illustrate the importance of ventilation.

There were no automatic fire-extinguishing systems in SEA. The incident reported in DAN 1839 with an M48A3 MBT was one in which the shaped-charge jet probably hit one or more cartridges in a ready rack and ignited the propellant. This scenario could cause the burns experienced by the crewmen. The jet probably also penetrated the fire wall between the crew and engine compartments and the right fuel cell and started a fuel fire in the engine compartment (Ref. 67). The combination of propellant fire in the crew compartment and fuel fire in the engine compartment probably caused the ammunition to bake off; the resulting explosion demolished the vehicle after the crew had evacuated. The commander undoubtedly had his upper torso out through his hatch, the driver undoubtedly had part of his shoulders out of his hatch, and the loader was probably sitting on the edge of his hatch with his legs in the turret and his hands on the hatch combing. This would explain the amount and location of first- and second-degree burns on each, i.e., 45% for the commander, 80% for the driver, and hands and legs only for the loader. Also the facts that they suffered only first- and second-degree burns and did not die were probably due to the protection afforded by their uniforms. (These uniforms were probably cotton fatigues, which afforded much more protection than bare skin.) Note that a propellant flash fire can produce second-degree burns.

In one ACAV incident the legs of two crewmen were sprayed with hot fuel that ignited (DAN 672), but their clothing protected them.* This incident illustrates the protection that clothing provides. These men were returned to duty from the clearing station; therefore, their burns could not have been serious.

The incidents in SEA have shown that if several propellant charges ignite, the crewmen within the vehicle are usually lost, whereas those in the hatches are usually blown out and may be fatally injured. If the propellant explosion is limited to a single charge, the crewmen are usually burned. Since no fire-extinguishing system, except one that floods water directly on the burning propellant grains, would be able to preclude the explosion, the only vehicle design that could protect the occupants would be one in which the propellant is compartmented away from the occupants as is done in the M1 MBT.

5-2.3 HUMAN INCAPACITATION

The criteria for human incapacitation due to thermal injury are taken from Ref. 1. These criteria have been approved by the Surgeon General of the Army and are intended to be used to evaluate injury effects in live-fire tests of armored vehicles. In general, these criteria are to establish the potential for second-degree burns. If that potential exists, the thermal injury criteria given in Edgewood Arsenal Publication EB-SP-76011-7 (Ref. 37) should be used. The second-degree burn criterion is given in subpar. 5-2.2.2.

If short-term diversionary effects, flash blindness, psychological effects, and the effects of oxygen depletion and toxic by-products are excluded, human incapacitation from thermal events can be predicted by three methods: thermal overload, local site disability, and systemic disability. These methods are described in the subparagraphs that follow.

5-2.3.1 Thermal Overload

Because heat input into a human body is difficult to quantify in a test, investigators have developed a means to estimate injury due to thermal overload by relating the thermal injury to the integral of the exposure of bare skin to heated air. Personnel at the former US Biomedical Laboratory, Edgewood Arsenal, established that approximately 99% incapacitation of approximately 99% of the population can be achieved in 2 min or less through the phenomenon known as "thermal overload". In this sense, thermal overload is the accumulation of thermal events (radiative, conductive, and convective) for exposed skin in a given environment expressed by the integral of the air temperature versus time in °C·s. The biological response to thermal overload is similar to the response to sunstroke and is characterized by the same progression of symptoms, i.e., dizziness, ataxia (loss of muscle coordination), disorientation, prostration, and ultimately death if the core temperature of the body is raised above its critical temperature. Thermal overload can be correlated with a given end point biological response. The predicted thermal overload value required to produce prostration in 50% of an exposed population within 2 min is approximately 16,000 to 18,000 °C·s when the exposure time is 30 s or less (Ref. 37).

The phenomenon of thermal overload has been reported in human subjects and was observed in tests involving pigs, which were conducted during evaluation of the M9-7 flamethrower and the M202 multishot flame weapon (Ref. 37).* In the first 30 s of exposure to flame from two M235 warheads fired from an M202 flame weapon at a two-second interval, heat energy was provided at a rate of approximately 9500°C·s, but no pigs collapsed. Four rounds from the M202 flame weapon provided approximately 16,000°C·s from which 54% of the pigs collapsed, and in another test the M9-7 flamethrower provided in excess of 20,000°C·s from which all the pigs collapsed (Ref. 37). There are limiting combinations of temperature and time that provide a critical constant value, expressed as °C·s, that is required to produce collapse in 50% of the exposed population. This appears to be at a level slightly in excess of 18,000°C·s for the asymptote that delineates the high-temperature case for which the exposure time is 30 s or less.

5-2.3.2 Local Site Disability

Incapacitation can be estimated from the disability or dysfunction of specific sites of the body that have been burned. The terms "disability" and "dysfunction" refer to the decrease in functional capacity of a given local site.

Nineteen nationally and internationally known surgeons who specialize in the treatment of burn casualties and 22 surgical residents at four major burn centers were interviewed to derive local site and systemic disability estimates for humans (Ref. 37). These estimates were based upon the premise that soldiers are fully motivated and will perform their duties as long as they are physically able. Human disability estimates for seven postburn time periods ranging from 30 s to 5 days were determined, and mission-related incapacitation levels were calculated. Disability estimates for only two time periods—30 s to 5 min and less than 5

---

*The two men were the right and left machine gunners. They were observing while their vehicle was backing up, so their heads were up through the open cargo hatch. The RPG jet passed through the left rear surface of the vehicle and exited through the fuel cell. As the jet exited, hot diesel fuel sprayed on the legs of the two men. The fuel and cloth ignited, but the trouser legs still protected the men from the heat and fire.

*The M9-7 flamethrower burned thickened gasoline, and the M202 flame weapon burned thickened triethylaluminum (TEA). The flame temperature of neat gasoline is approximately 743°C (1369°F) (Ref. 68), and the flame temperature of neat TEA is approximately 1204°C (2200°F) (Ref. 69). (The flame temperature of thickened fuel is less than that of the neat fuel.)

min to 30 min—were prepared. The less-than-30-s time period normally used in antipersonnel evaluation was omitted since it is believed that soldiers who receive burns would be made partially or completely ineffective by the concomitant diversionary effects for a short time period.* The exact length of this time period would depend upon several factors including the type of flame source, proximity to the affected area, and the military stress situation. The two time periods are equivalent to the assault and defense stress situations used to evaluate kinetic energy missiles, as described in Refs. 13 and 71.

Two interrelated methods used to predict the degree of incapacitation or the probability of incapacitation given heat exposure—$P(I|H)$—values ascribable to burns of the human body have been developed (Ref. 37). If it is known with some degree of certainty that a flame or incendiary system produces burns of specific body areas, the $P(I|H)$ can be calculated by an equation that allows calculation of the reduction of the individual's competence to continue his mission by a portion of the essential function of each burned site in a given situation and the number of sites burned.

The method used to estimate the incapacitation of a fully motivated soldier when a flame or incendiary system produces burns of specific body areas is described in Ref. 37.

5-2.3.3 Systemic Disability

Incapacitation can also be estimated from known systemic responses to burns that exceed the critical percentage of the body surface that must be burned to initiate these systemic responses.

If it is known or assumed that a flame or incendiary system will provide randomization of the burned areas of the body, a system to prorate these effects is provided as a relationship of percentage of body area burned versus $P(I|H)$, which for systemic effects is the incapacitation fraction described in Ref. 37.

5-2.3.4 Other Thermal Effects

5-2.3.4.1 White Phosphorus Burns

These thermal injury estimates are not valid for estimating disability or incapacitation produced by WP burns, which are more disabling than thermal burns in general (Ref. 37).

White or yellow phosphorus is pyrophoric. Its autoignition temperature in air is 30°C (86°F). On bare skin WP droplets usually cause third-degree burns. On clothed targets WP droplets tend to permeate through the cloth, char it, and then cause second- and third-degree burns on the skin underneath (Ref. 72).

Also phosphorus oxide fumes are very poisonous. The maximum allowable concentration for an 8-h exposure is 0.1 mg/m^3 (Ref. 72).

5-2.3.4.2 Oxygen Depletion and Toxic By-Products

There is evidence of effects from oxygen depletion and/or toxic by-products upon the animals in the test described in subpar. 5-2.2.3.3, which was the only test in which the hatches remained closed and the animals were not anesthetized. This test illustrates the importance of ventilation in preventing thermal injuries due to smoke inhalation. This subject is discussed more fully in par. 5-6.

5-2.3.4.3 Flash Blindness

There were at least two temporary casualties in SEA due to flash blindness. Both of these were caused by the detonation flash of shaped charges, as described in subpar. 5-5.2.4.

5-2.3.5 Ability of Dynamically Launched Flame and Incendiary Agents to Produce Burns

There are several methods by which flame or incendiary agents can be used against combat vehicles and their crews. One of these is by use of flamethrowers, the type that spurts a burning liquid jet and the type that projects a warhead which bursts and spews out a burning liquid. There are also land mines that contain a combustible liquid and a propelling charge plus an igniter near the open end, which can be observer initiated when an appropriate target enters the lethal area of the device. These flame or incendiary weapons (and Molotov cocktails) are effective only against exposed combat vehicle crewmen or against other crewmen if the flame or incendiary can enter an open hatch. The burning incendiary must contact exposed personnel or enter an open hatch or grill to affect crewmen or the vehicle (Ref. 69).

During the Korean conflict there were attempts to use aerial-delivered external aircraft fuel cells containing napalm against North Korean T-34/85* tanks. The tanks protected their crew when the hatches were closed, and they could be driven out of the napalm, which was burning on the ground. In one test napalm had to burn on a stationary T34/85 tank for over half an hour before crew members would have been seriously affected (Ref. 73).

Cannon can fire white-phosphorus-filled projectiles against combat vehicles, but again, unless the personnel are exposed or the white phosphorus particles enter through an

*This belief is counter to the experience of a young second lieutenant who was severely burned when his M4 tank was hit by a panzerfaust in 1944. He evacuated his tank, attempted to evade capture, was captured and marched to a prisoner of war stockade, but had not realized that he was burned until the interrogator sent him to an aid station without interrogating him because he was so badly burned (Ref. 70).

*The original T34 tank mounted a 76.2-mm gun. Since this 76.2-mm gun could defeat German Panther tanks only at close range, the Russians modified the T34 to take an 85-mm gun in late 1943. This newer version of the T34 was called the T34/85; the older version was called the T34/76.

open hatch, the personnel will probably not be affected. The white phosphorus can ignite exposed combustibles and is particularly effective when exposed light gage fuel cells have been punctured (Refs. 74 and 75).

All incendiary devices can ignite combustible items on the exterior of the vehicle, but the incendiaries seldom burn long enough on the vehicle to affect the personnel within. The key to the protection afforded by the combat vehicles is that the flame or incendiary cannot readily enter the crew compartment, and the fire does not last long enough to transfer heat through the vehicle hull. Also the incendiaries do not burn long enough to consume all available oxygen in and around the vehicle, and the vehicle can usually be driven away from the burning incendiary. Ignition of combustibles stowed on the exterior of the vehicle extend the burn time.

5-2.3.6 Psychological Effects

An insight into the psychological effects of thermal weapons was obtained by examining and analyzing interviews of burn casualties, reports of firebomb incidents, and interviews of military personnel concerning the effectiveness of the current use of flame weapons. All of these sources show trends and/or personal impressions, but none provide a quantitative evaluation technique (Ref. 37). Personnel will normally move away from fire.

5-2.3.7 Quality of Estimates

The data presented represent a considerable amount of detailed laboratory and field work in support of the disability and incapacitation estimates. Nevertheless, the link between either animal data or anecdotal reports of human exposures and actual field performance is tenuous or nonexistent. In the reports reviewed on this subject, no examples were found of formal attempts to extrapolate performance data quantitatively from animals to man. Indeed, there are very little performance data of any description presented. It appears that the investigators whose work was reviewed adopted a very crude measure, e.g., the number of pigs living after a test, to the task of predicting disability and incapacitation. References to bodies of expert opinion are noticeably lacking in descriptions of how the conclusions were derived. No mention is made of formal procedures to remove bias from the panel that polled results; consequently, the recommendations must be questioned on that basis as well as on the fundamental adequacy of the data considered.

The impossibility of doing controlled observations in humans suggests the need for behavioral observations in primate models, but no such observations are described. The investigators appear to have focused on quantification of certain heat injuries rather than on consideration of the totality of physiological and psychological stresses imposed on humans exposed to fire. The results therefore cannot be expected to predict actual combat experience accurately.

5-3 EAR DAMAGE

Current doctrine includes the use of the CVC helmet for all combat vehicle crew members. A panel of blast experts estimated that rupture of the crew's eardrums would be unlikely with the standard use of these helmets (Ref. 76). The panel further estimated that eardrum rupture should not be considered incapacitating.

Most ruptured eardrums can heal—the membrane knits back together—in two to four weeks if none of the membrane is torn out (Ref. 77). On the other hand, research laboratory personnel in informal discussions with field forces representatives have established that to be able to function in combat activities, soldiers must not only be able to move and operate weapons but must also be able to see, hear, think, and communicate with others (Ref. 71). Thus injury to the ears that affects hearing degrades the soldier's ability to accomplish his mission.

Therefore, it is advisable to review briefly the available information on hearing loss for blasts impinging on humans. Some crew members ignore instructions and fail to wear helmets with ear protection, and some passengers may not be equipped with CVC helmets.

5-3.1 THE EAR

The human ear, shown on Fig. 5-5, is divided into the external, middle, and inner ear.

Sound frequencies of 20 to 20,000 Hz are audible to humans, but the greatest sensitivity is in the range of 1000 to 3000 Hz. The ideal threshold of hearing is shown on Fig. 5-6(A). The audiometer test shows a higher threshold than the ideal due to test conditions and human response delays. The eardrum can respond to pressure levels as low as 2.0265×10^{-5} Pa (0.2 billionth atm), and the malleus head can move to its maximum displacement in approximately 25 ms (Ref. 78).

The moving parts of the ear are nearly critically damped; therefore, the eardrum stops moving almost as quickly as

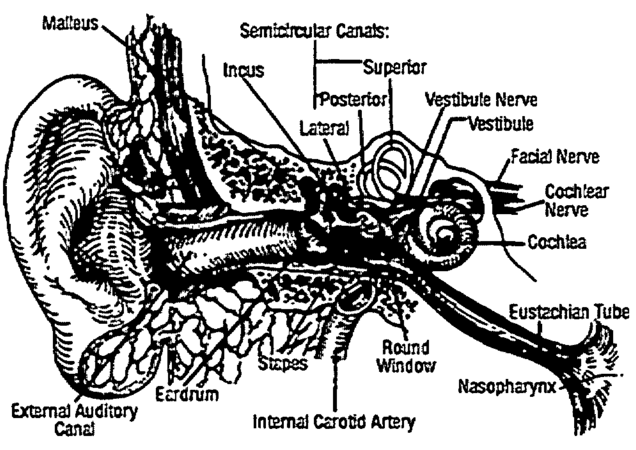

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Figure 5-5. The Human Ear (Ref. 41)

the sound wave stops. The middle ear also contains two small skeletal muscles that contract when exposed to loud sounds and thus prevent strong sound waves from excessively stimulating the auditory receptors (Ref. 41). Very strong sounds, however, can also rupture the eardrum.

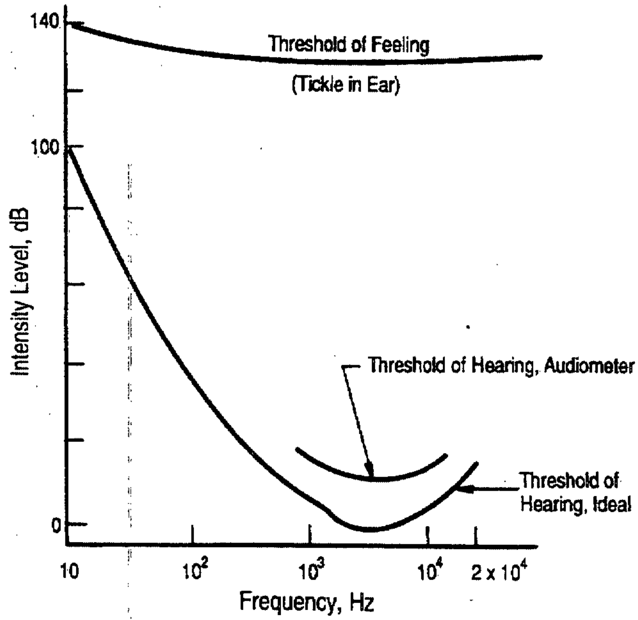
In addition to being conducted through these membranes and ossicles, sound can be conducted by vibrations of the secondary tympanic membrane and by transmission through the bones of the head. This latter mechanism is involved in transmission of extremely loud sounds.

The external ear amplifies the overpressure of the sound wave by approximately 20% and detects the location of the source of sound (Ref. 41). Rupture of the eardrum (or tympanic membrane), which separates the external ear from the middle ear, has captured most of the attention of clinicians, although it is not the most severe type of ear injury. The eardrum and ossicles of the middle ear transfer acoustical energy from the external ear to the inner ear where mechanical energy is finally converted into the electrical energy of the nerve impulse. The middle ear is an impedance-matching device as well as an amplification stage. The middle ear contains two dampers, i.e., the stapedes muscle and associated ligaments, which limit the vibration of the stapes when subjected to intense signals, and the tenser tympani muscle and its adjoining ligaments, which limit the vibration of the eardrum. The first damper is the more important. These dampers have a reflex time of approximately 0.005 to 0.01 s, which is longer than "fast" rising air blasts. The manner in which the malleus and incus are linked allows far more resistance to inward displacement than to outward displacement. If the eardrum ruptures, however, after inward displacement during the positive phase of loading of the blast wave, the malleus and incus are less likely to displace as far outward during the negative phase of loading of the blast wave as they would if the eardrum remained intact. The maximum overpressure and its rise time control the characteristics of the negative phase and are therefore of prime importance. In this case, eardrum rupture could be beneficial. The eardrum would rupture before the round window, which could result in the release of the perilymph fluid, or the oval window, which could result in the release of the same fluid. Either of these eventualities would be much more severe than the rupture of the eardrum. When the ear bleeds, the probable sources of the blood are the eardrum and/or the wall of the external auditory canal. Thus rupture of the eardrum becomes a good measure of serious ear damage.

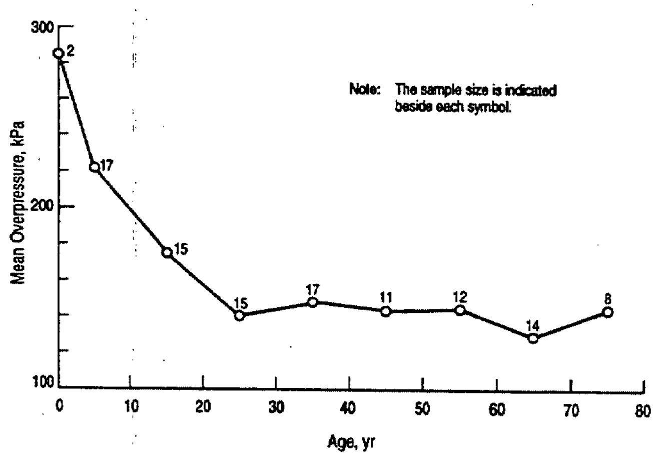
5-3.2 EAR INJURY LEVELS

5-3.2.1 Eardrum Rupture

The quasi-static eardrum rupture pressure of man was determined by Dr. T. Zalewski in Lemberg, Galicia, Austria-Hungary, circa 1906 (Ref. 79). Complete ears from fresh cadavers were removed and mounted in a fixture and then pressurized slowly to rupture. The ears were characterized by sex and age of individual, whether right or left, and condition, i.e., normal or evidence of infection or damage, which would have resulted in a weakening or strengthening. Zalewski found that the eardrums of men and women ruptured at essentially the same pressure and there was little difference between the rupture pressure of right and left eardrums. He also found that accidents, sicknesses, or infections can weaken the eardrums. The most significant difference in rupture characteristics is due to age, as is shown on Fig. 5-6(B): The mean rupture pressure of normal



(A) Audibility Curve for Man (Ref. 41)



(B) Eardrum Rupture Overpressure Versus Age (Ref.79)

Figure 5-6. Audibility Curve and Eardrum Rupture Pressure for Man

specimens for each decade is lumped at the mid-age, except for the two newborn infants. These data are from 59 male and 52 female subjects, all with normal eardrums. For normal eardrums 10.8% ruptured at an overpressure less than 101.4 kPa (1 atm), 65.8% at overpressures between 101.4 to 202.7 kPa (1 to 2 atm), and 23.4% at overpressures above 202.7 kPa (2 atm). The least rupture overpressure was 37.3 kPa, and the greatest, 304.1 kPa.

5-3.2.2 Temporary Threshold Shift

When a combat vehicle is hit by a ballistic projectile that is capable of igniting a fire, both the impact and the subsequent combustion are accompanied by sound. Airborne sound is a rapid variation in ambient atmospheric pressure. Noise is unwanted sound. Noise can cause temporary or permanent loss of hearing, can adversely affect the ability to communicate, can distract a person, and in extreme cases can adversely affect people's physiological processes (Ref. 80).

Steady state noise is a periodic or random variation in atmospheric pressure that has a duration in excess of one second. Impulse noise is a short burst of acoustic energy consisting of either a single impulse or a series of impulses. The amplitude of sound is expressed as a sound pressure level *SPL* and is measured in decibels (dB) (Ref. 80). *SPL* can be calculated from

$$SPL = 20\log(p/P_{OS}), \text{ dB} \qquad (5\text{-}6)$$

where

p = sound pressure being measured, Pa (lb/in.^{2})

P_{OS} = reference pressure, usually 20 μPa (2.9×10^{-9} lb/in.^{2}).

The sensitivity of human hearing is established with an audiometer, which establishes the threshold sound level in dB for selected frequencies for each ear. The degradation of hearing sensitivity can be attributed to some diseases, to aging, and/or to exposure to excessive noise. Exposure to noise can cause a lessening of baseline hearing sensitivity that is either temporary—the hearing sensitivity can recover in hours or days—or is permanent. A temporary change in the hearing threshold, temporary threshold shift (TTS), can be established by use of an audiometer. When a current test is compared to the audiometer test results in a soldier's medical file, the difference provides a measure of any change in hearing sensitivity. Thus TTS can be used as a limit for the maximum allowable noise (Ref. 80) and is a useful design tool.

A hearing loss that is not recoverable with time is a permanent threshold shift (PTS). The exact relationship between TTS and PTS has not been established. This relationship should be established before programs using TTS of human volunteers can be performed safely. The TTS of humans has been explored and represents the most injury a young adult human can suffer without permanent injury (Ref. 80).

In general, intermittent exposure to noise requires a higher noise level to produce TTS than would continuous exposure. With impulse noise, the higher the peak pressure, the greater the probability of TTS (Ref. 80). A trace of impulsive sound versus time is shown on Fig. 5-7. Ref. 81 provides two techniques for evaluation of sound pressure. The simpler of the two techniques is to consider the principal sound peak only, which is the "A" duration technique. The more complex technique is to consider all sound impulses with peak magnitudes within 20 dB of the principal sound peak level, which is the "B" duration technique. For an "A" duration evaluation, a point representing the principal positive peak pressure and the "A" duration time, which are taken from a trace similar to that shown on Fig. 5-7, is plotted on the graph in Fig. 5-8. If the point so plotted is to the left of or below "A" Duration Curve 1 on Fig. 5-8, the TTS has not been reached. For an explanation of the more complex "B" duration technique, see Ref. 81.

Curve 1 shown on Fig. 5-8 is the TTS for 75% of young adults exposed to side-on impulsive sound pressure that is repeated at a rate between 6 and 30 impulses per minute for a total of 100 impulses (Ref. 82). These are the assumptions that are normally used for hearing protection design, but they are not used for vulnerability reduction design. Coles et al in Ref. 82 provide advice by which the TTS can be modified to represent a more desirable set of assumptions. The trace of TTS shown as Curve 1 on Fig. 5-8 can be modified to represent the other assumptions that follow:

1. To have the TTS for 90% rather than 75% of the exposed population, Coles et al recommend lowering the curve by 10 dB, i.e., Curve 2 represents 90% rather than 75% of population coverage.

2. Because the crew of a combat vehicle would probably be subjected to one, two, or three hits rather than 100 over 10 to 17 min, the TTS curve should be raised 10 dB from Curve 2. Curve 3, which coincides with Curve 1, represents TTS for 90% of population coverage and the reduction in number of primary impulses received from 100 to fewer than 6.

3. If the TTS were to be for ears receiving reflected or normal stagnation pressure instead of side-on pressure, the curve would have to be lowered 5 dB. Therefore, Curve 4 represents the TTS for normal rather than side-on pressure. See Fig. 5-9 for head orientation. Fig. 5-8 presents the TTS of 90% of young adults, who are most likely to be combat vehicle crewmen and who thus could be subjected to six or fewer principal pressure pulses in a few minutes. Curve 3 should be used if their heads are oriented for side-on pressure, whereas Curve 4 is representative if their more vulnerable ear is oriented for normal pressure.

Although the method to obtain the "B" duration is not described in this handbook (Refer to Ref. 81 for that method.), the values of the "B" duration and the peak pres-

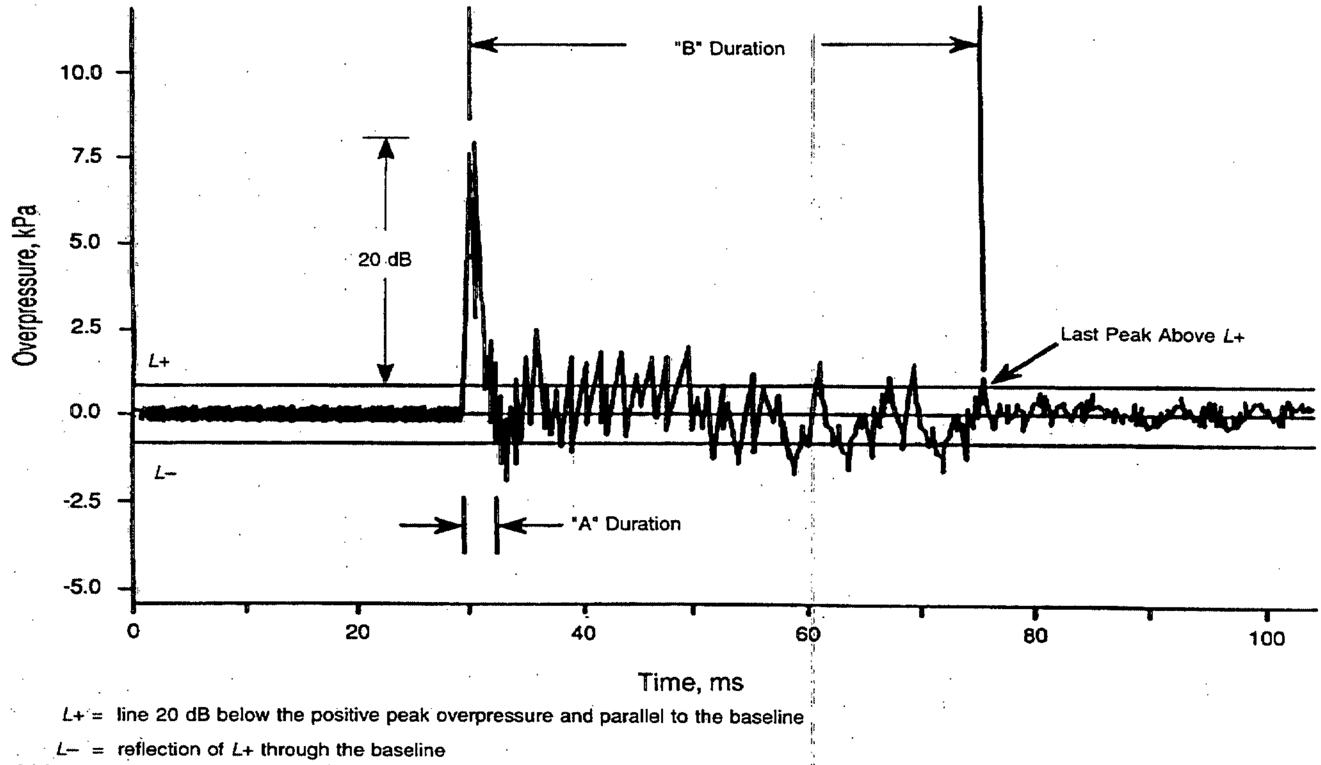


Figure 5-7. Representative Trace of Sound Pressures Showing Both "A" and "B" Durations (Ref. 81)

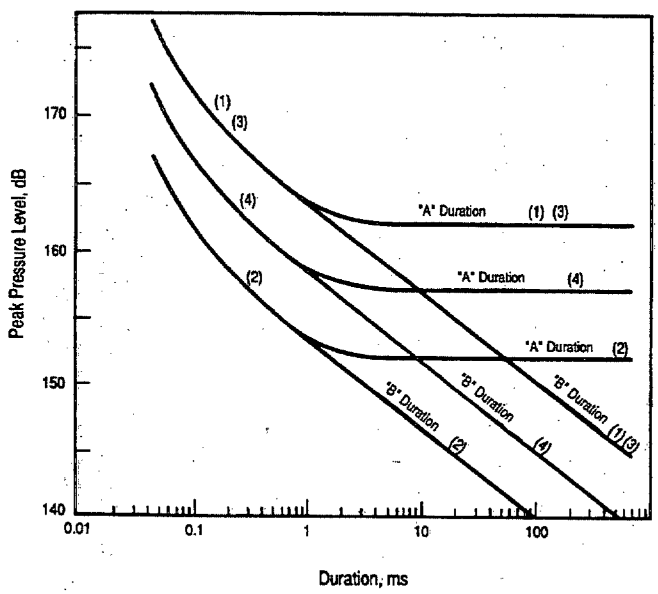


Figure 5-8. Temporary Threshold Shift Curves (Ref. 82)

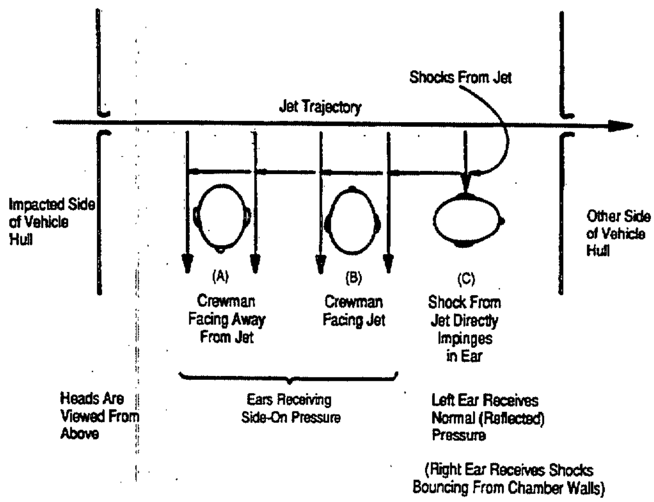


Figure 5-9. Shocks From Jet to Ear Aspects

sure are described. The TTS associated with the "B" duration is shown on Fig. 5-10. All of these curves are for the TTS of 75% of the population receiving a number of side-on pressure pulses daily. Line W is the peak pressure level under which no ear protection is needed even when the number of sound impulses is unlimited. Curve X is the TTS for an individual protected by either earplugs or earmuffs who is subjected to 2000 impulses daily or protected by both earplugs and earmuffs who is subjected to 40,000 impulses daily. Curve Y is the TTS for an individual protected by either earplugs or earmuffs who is subjected to 100 impulses daily or protected by both earplugs and earmuffs who is subjected to 2000 impulses daily. Curve Z is the TTS for an individual protected by either earplugs or earmuffs who is subjected to 5 impulses daily or protected by both earplugs and earmuffs who is subjected to 100 impulses daily. Effectively the CVC helmet is a pair of earmuffs.

5-3.3 EAR DAMAGE CRITERIA

The ear damage criteria recommended by the author of this handbook are criteria for TTS of unprotected crewmen for both side-on and reflected sound pulses and criteria for the threshold of eardrum rupture.

5-3.3.1 TTS Criteria

The criteria for TTS in terms of peak pressure versus time duration is shown on Fig. 5-8 for 90% of young adults exposed to less than six impulses as Curve 3 for side-on pressure and as Curve 4 for reflected pressure.

These criteria can be recomputed in terms of peak pressure versus specific impulse by assuming a triangular pressure wave and the given peak pressure and "A" duration shown on Fig. 5-8. The resulting plots of TTS are shown on Fig. 5-11 for both the side-on and reflected pressure loading modes.

5-3.3.2 Eardrum Rupture Criteria

The eardrum rupture criteria are from Ref. 79 and are independent of pressure loading mode. The threshold for eardrum rupture is 181 dB, i.e., 23.4 kPa (3.4 psig), which is peak pressure. The pressure peak for 50% probability of eardrum rupture is 195 dB, i.e., 110.3 kPa (16 psig). These eardrum rupture criteria are also shown on Fig. 5-11. The criteria given on Fig. 5-11 are more usable for engineers because the measuring and recording of peak pressures and the calculation and summing of impulse are well within the current state of the art of test instrumentation.

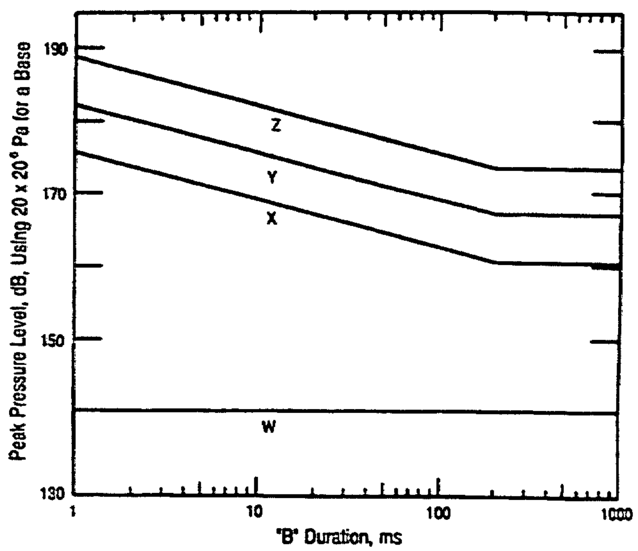


Figure 5-10. Peak Sound Pressure Levels and "B" Duration Limits for TTS (Ref. 81)

5-3.4 PRESSURE WAVES ASSOCIATED WITH SHAPED-CHARGE JET

Pressure waves associated with jets from four different shaped charges were measured with two different types of instrumentation in four programs. Ballistic Research Laboratory (BRL) precision 81-mm shaped charges were used in the first program (Ref. 83), in which side-on pressure was measured with pencil gages. Nonprecision 81-mm shaped charges with trumpet liners or nonprecision 105-mm shaped charges with conical liners with spit-back apexes were used in the second program (and later described in Ref. 84), in which side-on pressure was again measured. Nonprecision 81-mm shaped charges from the M28A2 HEAT warhead were used in the third program (Ref. 10), in which side-on pressure was again measured. The M28A2 HEAT warheads were also used in the fourth program (Ref. 85), but the instrumentation was changed so that reflected pressure was measured. In all cases the pressure transducers were installed to monitor the pressures generated by passage of the shaped-charge jet in the chamber. The results of these four programs show little difference among the shocks produced by the jets, especially since these jets had already penetrated relatively light armor, i.e., 25.4 mm (1 in.) of aluminum plus 6.25 mm (0.25 in.) of steel plate at most, and a fuel cell containing diesel fuel.

An evaluation was performed (Ref. 86) (1) to ascertain that the pressure recordings were meaningful and correct and (2) to determine the impulses to which personnel within the simulated troop compartment of a fighting vehicle would be subjected when a shaped-charge jet passed through the walls of the compartment. There was no significant difference when the jet passed through fuel prior to entering the test fixture or through the fuel cell within the fixture either before or after traversing the fixture; therefore, the shock is deemed due to jet passage only. A plan view of the test chamber for measuring shock effects of shaped-charge jets penetrating into the chamber is shown on Fig. 5-12.

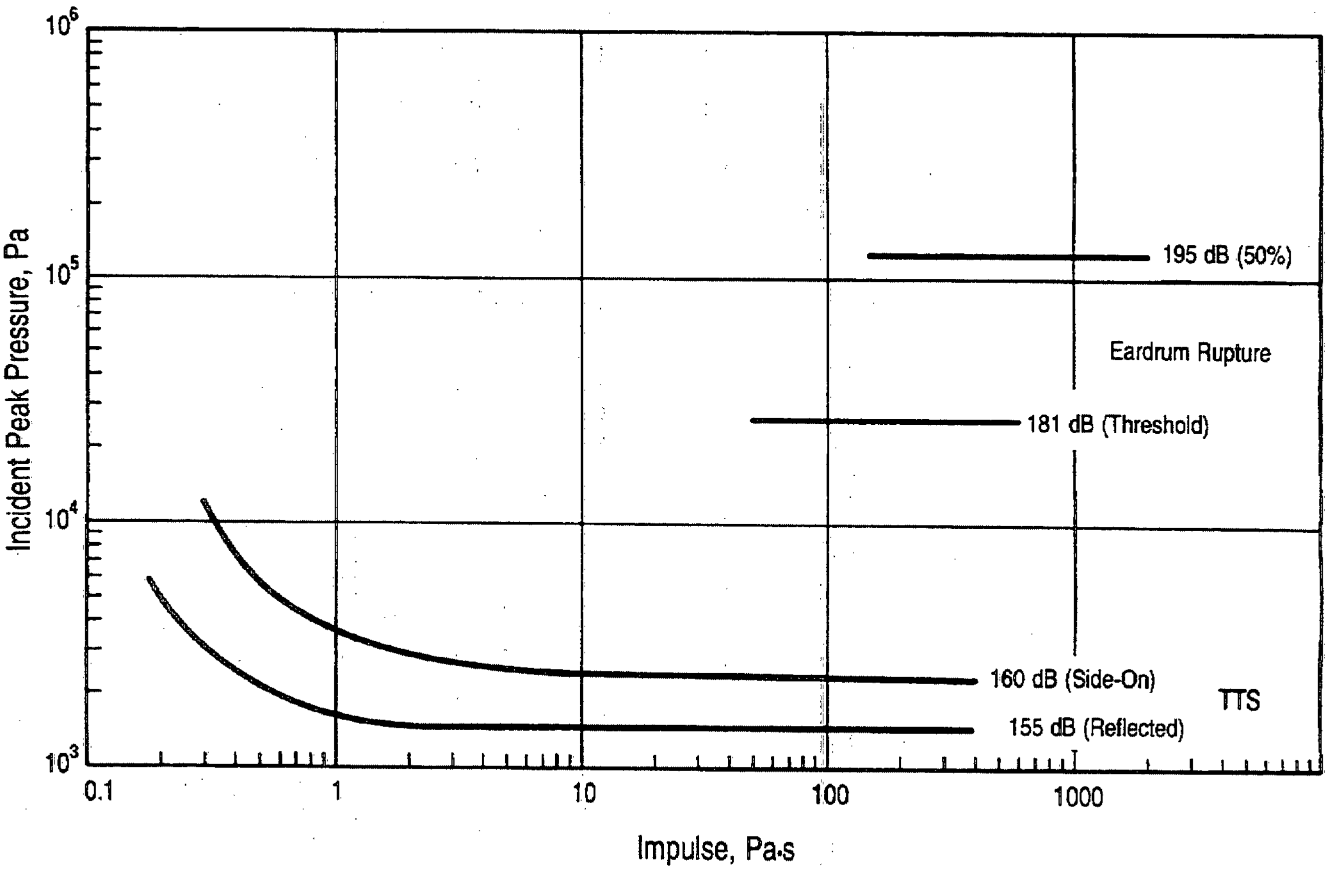


Figure 5-11. Ear Injury Criteria

5-3.4.1 Description of Events

When a shaped charge is fired, the jet from the charge moves along the axis of the charge at a velocity of 6100 to 7600 m/s (20,000 to 25,000 ft/s). As the high-speed jet travels through the air in the test chamber, it generates a shock wave. The jet tip moves forward at essentially a constant velocity while the shock front, detached from the tip of the jet, moves perpendicularly to the jet axis at the same velocity. Because this shock is continuously caused by the jet tip as it passes through air, the shock front propagates radially in the form of a cone. The general geometry of that shock (ignoring wall reflections) is as shown on Fig. 5-13 where V is the shock wave velocity normal to the jet trajectory. Only in the immediate vicinity of the jet tip is the shock strength great enough for higher shock propagation speed. A vector diagram for shock front propagation is shown on Fig. 5-14. The shock front forms a cone with an included angle α

$$\alpha = \tan^{-1}\left(\frac{a_o}{V_j}\right), \text{deg or rad} \qquad (5\text{-}7)$$

where

α = angle between jet trajectory and shock wave, deg or rad
a_o = velocity of sound in air, m/s
V_j = jet tip velocity, m/s.

Suppose the jet tip velocity V_j is 6100 m/s (20,000 ft/s) and at standard temperature and pressure a_o = 340.4 m/s (1117 ft/s); therefore, the angle between the jet trajectory and the shock wave cone is

$$\alpha = \tan^{-1}\left(\frac{340.4}{6100}\right) = 3.2 \text{ deg or } 0.056 \text{ rad.} \qquad (5\text{-}8)$$

The shock front propagates as a very small half-angle conical surface, which is not greatly different from a cylindrical wave front.

Estimated times of shock arrival based on an estimate of V_j and the given shock geometry can be determined. This estimate is done for a given transducer P_i by calculating the time for the jet to travel to the plane of the transducer and then using sound speed to calculate the time to propagate from the jet axis to the transducer $(t_a)_{P_i}$, i.e.,

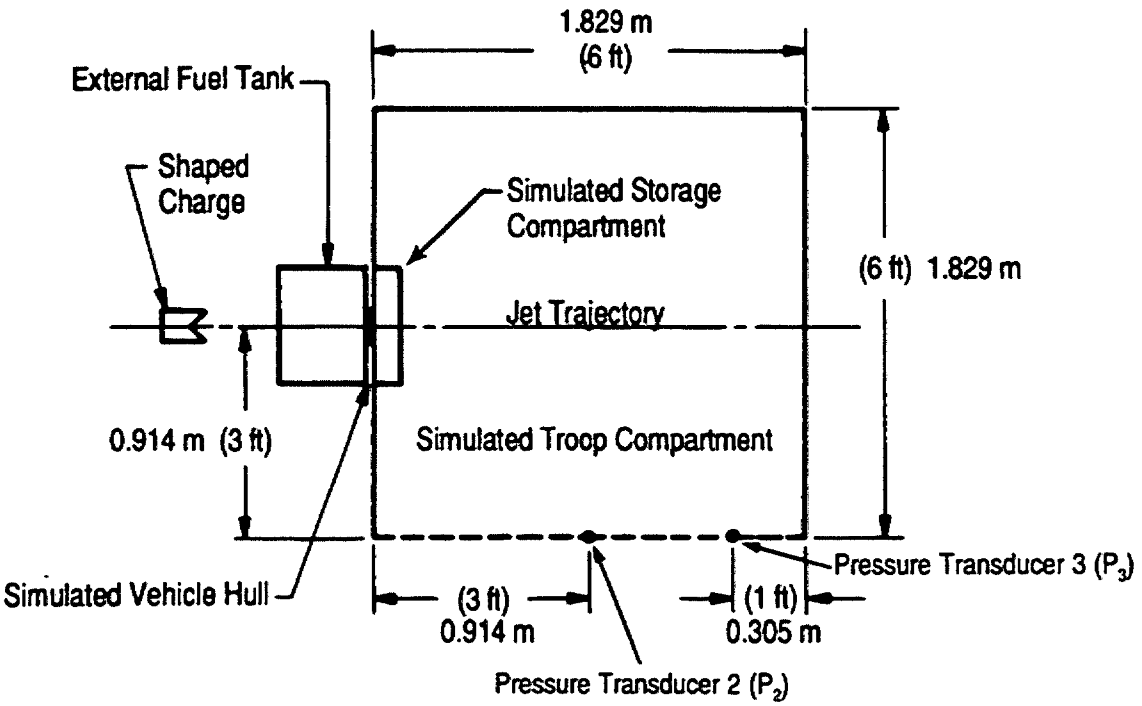


Figure 5-12. Test Installation (Ref. 86)

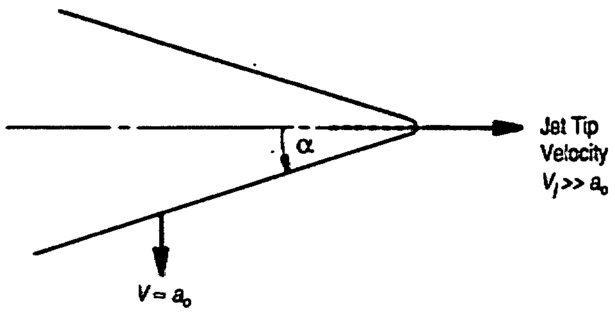


Figure 5-13. Shock Wave From Shaped-Charge Jet (Ref. 86)

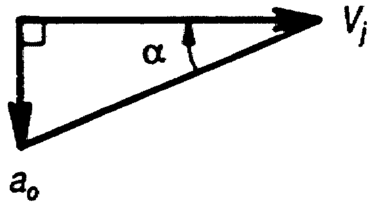


Figure 5-14. Vector Diagram of Velocities of Shaped-Charge Jet and Shock Wave (Ref. 86)

$$(t_a)_{P_i} = \frac{d_i}{V_j} + \frac{d'_i}{a_o}, \text{ s} \tag{5-9}$$

where

d_i = distance between the point of entry of the jet and plane of transducer P_i, m

d'_i = distance between jet and axis of transducer P_i, m

t_a = time of arrival, s.

Given V_j = 6100 m/s, a_o = 340.4 m/s, and $d_2 = d'_2$ = 0.914 m (from Fig. 5-12), the time for the shock wave to reach P_2 is

$$(t_a)_{P_2} = \frac{0.914}{6100} + \frac{0.914}{340.4} = 0.0028 \text{ s.} \tag{5-10}$$

Similarly, the time for the shock wave to reach P_3 given V_j = 6100 m/s, $d_{P_3} = 1.829 - 0.305 = 1.524$ m, and $d'_{P_3} = 0.914$ m (from Fig. 5-12) is

$$(t_a)_{P_3} = \frac{1.524}{6100} + \frac{0.914}{340.4} = 0.0029 \text{ s.}$$

The difference in time of arrival $(\Delta t_a)_{P_2,P_3}$ of the shock wave at the two transducers P_2 and P_3 is estimated to be

$$(\Delta t_a)_{P_2,P_3} = (t_a)_{P_3} - (t_a)_{P_2}, \text{ s} \quad (5\text{-}11)$$
$$= 0.0029 - 0.0028 = 0.0001 \text{ s or } 0.1 \text{ ms.}$$

For weak ballistic shocks, reflections off chamber surfaces can be traced as if they were sound waves, at least to estimate arrival times of reflected shocks at gage locations. Some incremental arrival times are given in Table 5-6.

5-3.4.2 Interpretation of Gage Records

An evaluation (Ref. 86) effort was undertaken to assure that the pressure recordings were correct and meaningful. The same test fixture was used in all four programs. With the help of the estimated times of arrival $(t_a)_{P_i}$ at specific pressure transducers, signals on the pressure gage records may be interpreted. Fig. 5-15 shows pressure gage records with notations to indicate probable signal sources.

Test No. 1, Fig. 5-15(A), presents a problem because there is a large-amplitude signal for P_3 prior to the signal on P_2, but the ballistic shock should arrive first at P_2. The first signal on P_3 is probably caused by the impact of a piece of spall from the back surface of the simulated hull material upon the gage housing. By using the distance from the entry point of the jet to the transducer and the measured time of arrival t_a, the fragment velocity v_f may be determined:

$$v_f = \frac{(d_i^2 + d'^2_i)^{\frac{1}{2}}}{t_a} \text{ m/s.} \quad (5\text{-}12)$$

TABLE 5-6. TIMES FOR REFLECTIONS OF SHOCK WAVES TO REACH PRESSURE TRANSDUCERS (Ref. 10)

Δt_a, ms	REFLECTED WAVE	
	From	To
2.7	Right End	P_2
0.9	Right End	P_3
5.4	Opposite Side	P_2
5.4	Opposite Side	P_3
2.7	Left End	P_2
4.5	Left End	P_3

Given $t_a = 0.9$ ms and $d_i = d'_i = 0.914$ m (from Fig. 5-12),

$$v_f = \frac{[(0.914)^2 + (0.914)^2]^{\frac{1}{2}}}{0.9 \times 10^{-3}}$$
$$= 1436 \text{ m/s (4714 ft/s).}$$

This is a reasonable velocity for a high-speed spall fragment, and there was a fragment impact dent in the pressure transducer casing.

Test No. 2, Fig. 5-15(B), shows signals ahead of initial and reflected ballistic shocks, which start at different times on different channels. The early signal for P_2 is probably electrical noise associated with the exploding bridgewire (EBW) firing circuit. This noise is not as visible on P_3 because of a lower sensitivity setting, but the signal ahead of the initial ballistic shock may again be a fragment strike.

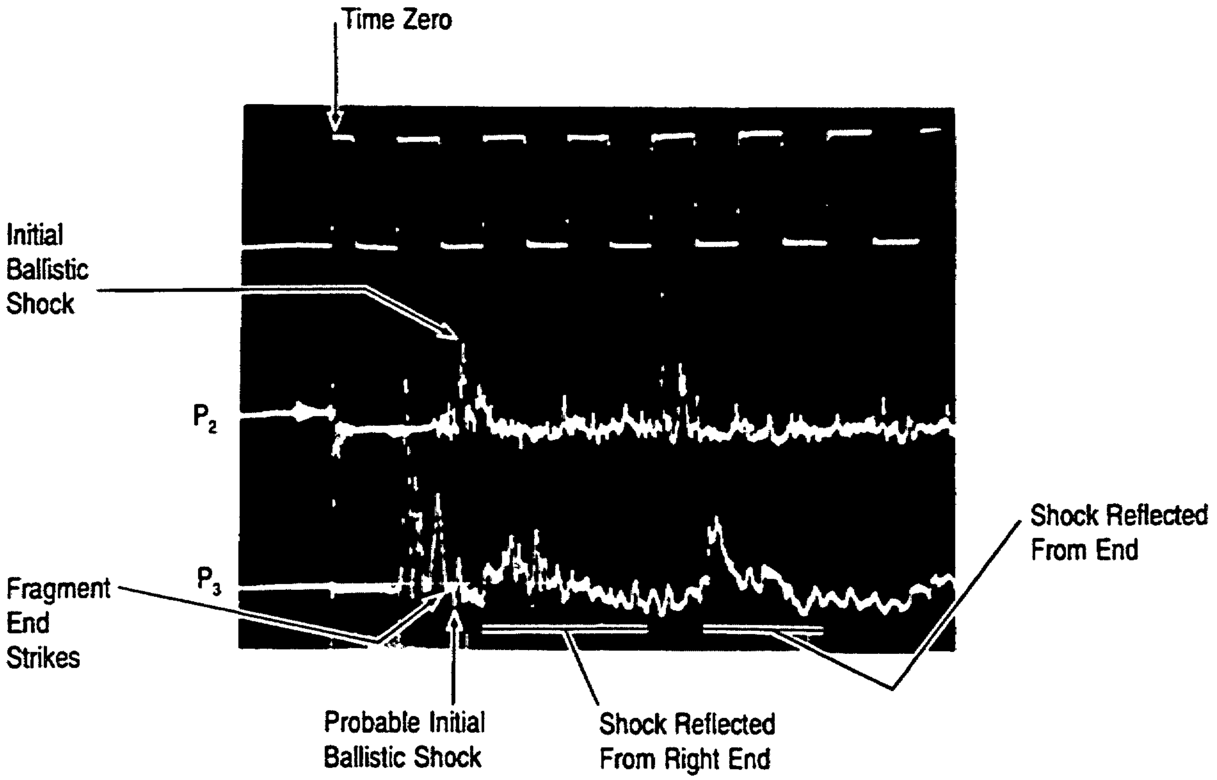
Test No. 3, Fig. 5-15(C) has clear initial ballistic shocks, but at least one reflected shock is hard to identify. Test No. 4, Fig. 5-15(D), shows shocks reflecting from the top of the fixture.

From this evaluation the conclusion is that the data generated in Refs. 10, 83, 84, and 85 were valid and meaningful. Reviewing pressure records and discarding the records that appear doubtful because of possible fragment strikes, instrument noise, or other unidentified problems provided the data used in Fig. 5-16 for side-on pressures and in Fig. 5-17 for normal pressures.

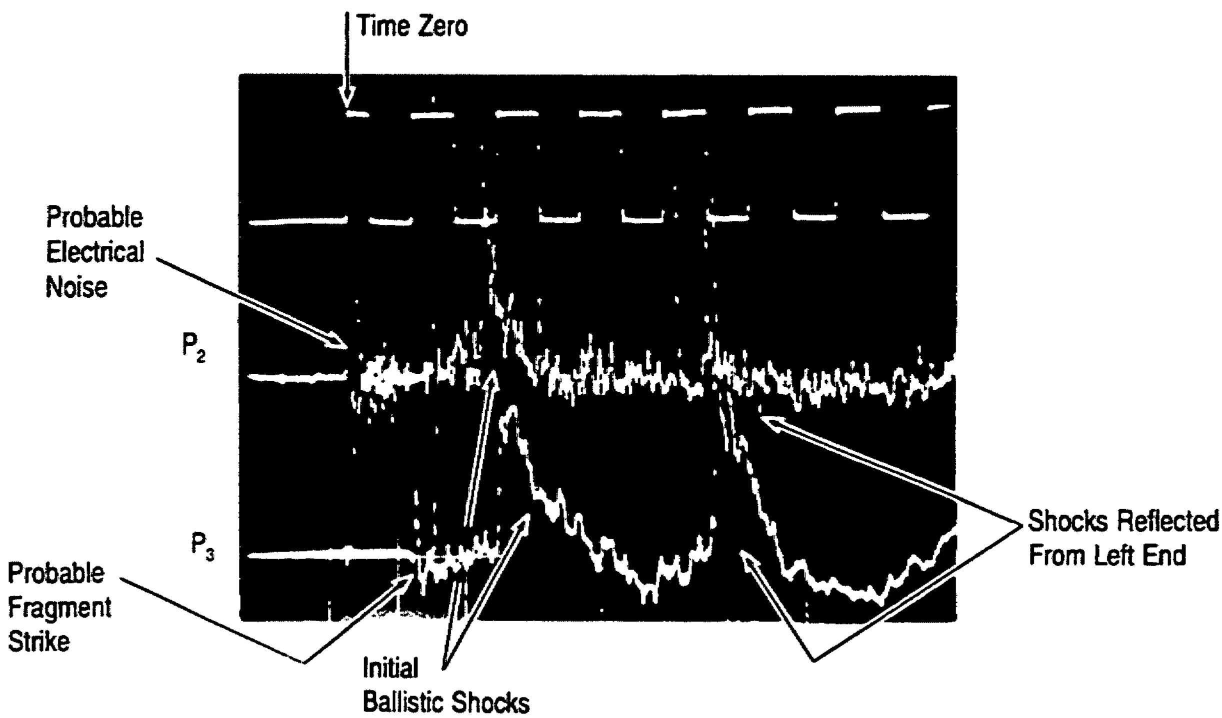
5-3.4.3 Assessment of Potential Injury to Humans in the Referenced Tests

Data are available to establish the overpressure or noise generated when a shaped-charge jet passes through the crew compartment of a combat vehicle. Effective sound-deadening design can reduce reverberations, but the initial shock wave from the jet will always be present when a shaped-charge jet perforates the armor. Examples of the shock overpressure versus time and impulse, which is the integral thereof, are shown on Figs. 5-7 and 5-15. Fig. 5-15 shows side-on pressure and impulse versus time from the jet of a BRL precision 81-mm shaped charge that perforated 6.25 mm (0.25 in.) of rolled homogeneous armor (RHA) steel and 25.4 mm (1.0 in.) of aluminum. Sometimes both the peak pressure and the impulse were greater for the reverberations than for the initial shock. Also a triangular approximation of the integral of the pressure would be very representative.

The data from the first three test programs referenced can be converted from side-on pressure to normal pressure. Similarly, the data from the fourth program can be converted to side-on pressure. Thus the potential for ear injury to crewmen within the simulated vehicle from the noise



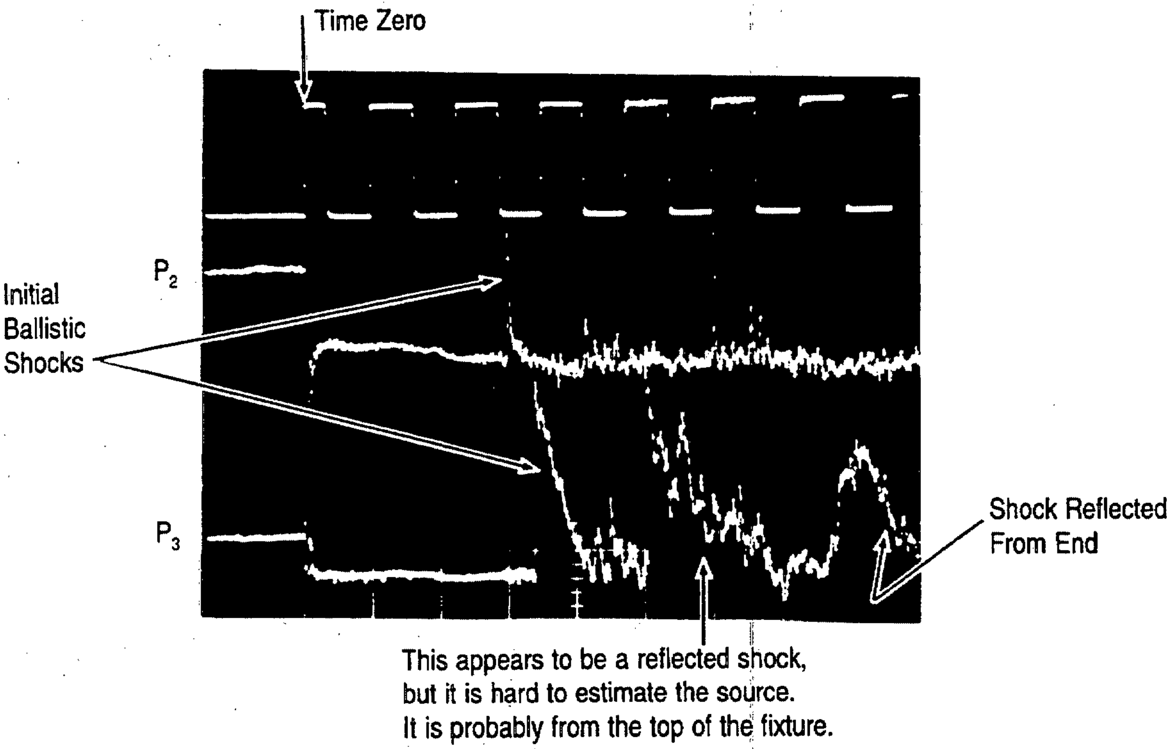
(A) Test No. 1



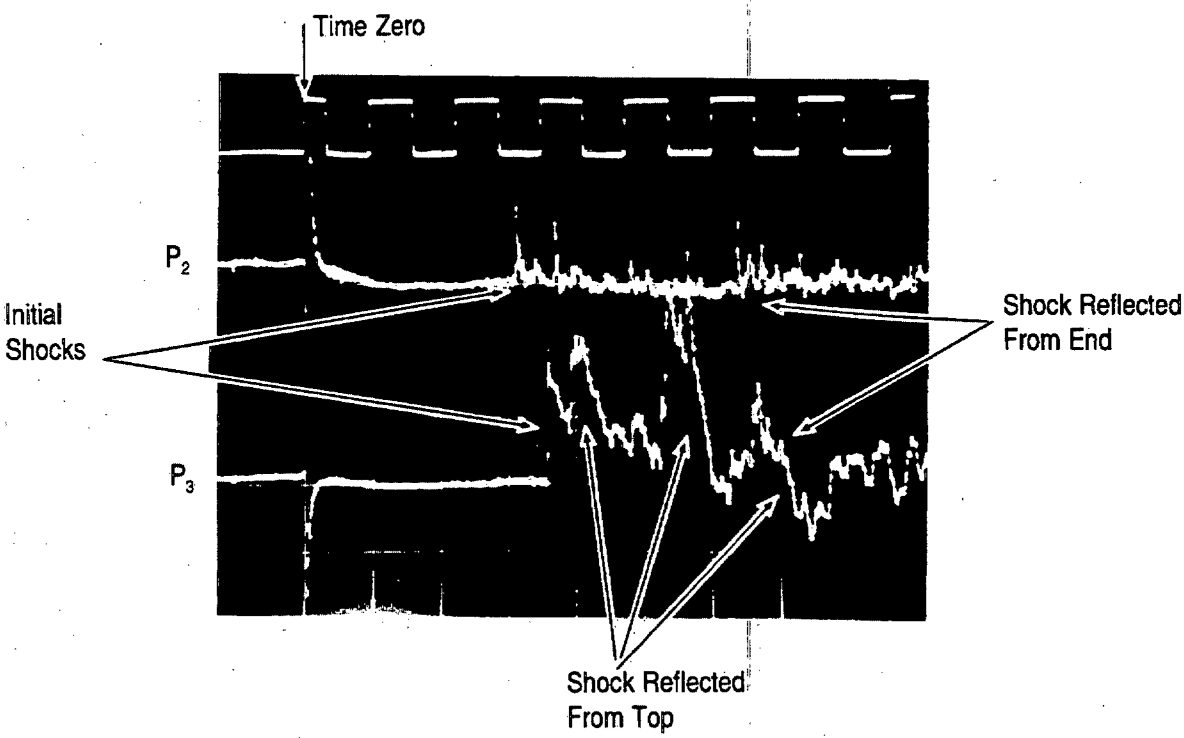
(B) Test No. 2

Figure 5-15. Pressure Versus Time, Tests 1, 2, 3, and 4 (Ref. 83)

(cont'd on next page)



(C) Test No. 3



(D) Test No. 4

Figure 5-15. (cont'd)

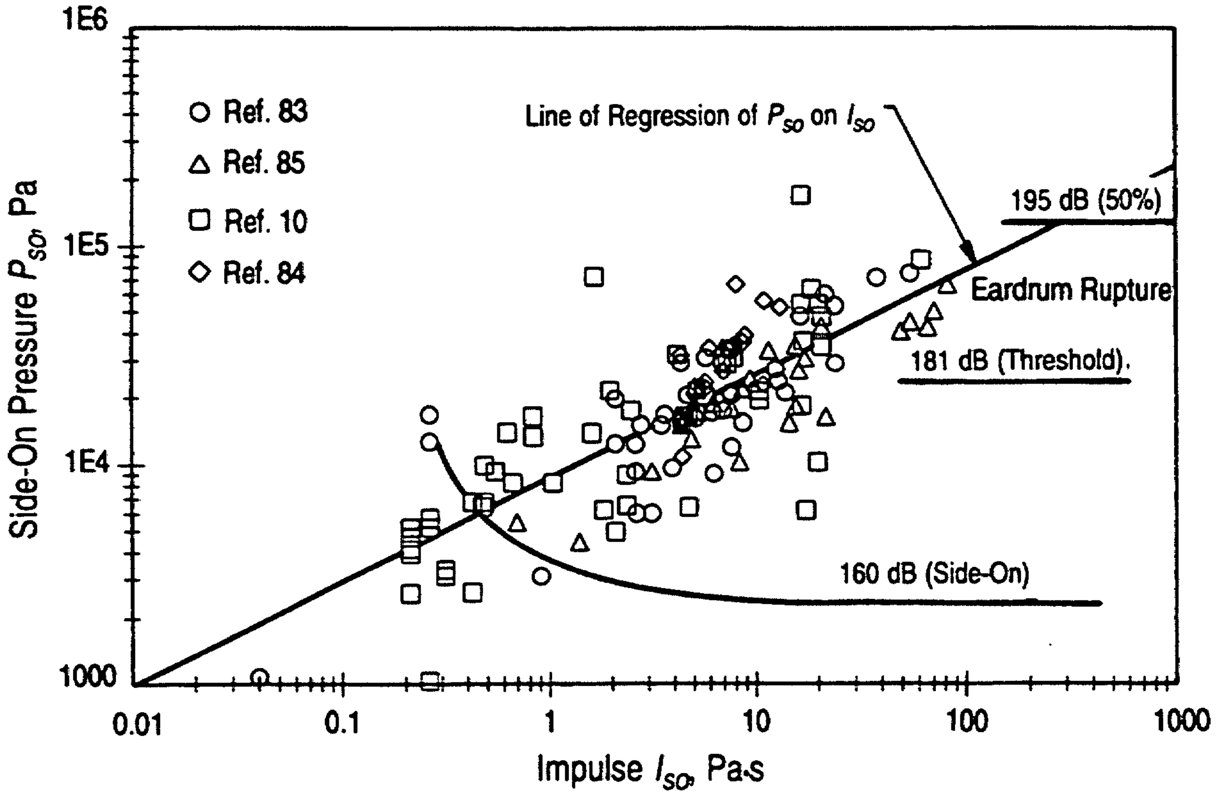


Figure 5-16. Side-On Pressure Versus Side-On Impulse for Ears

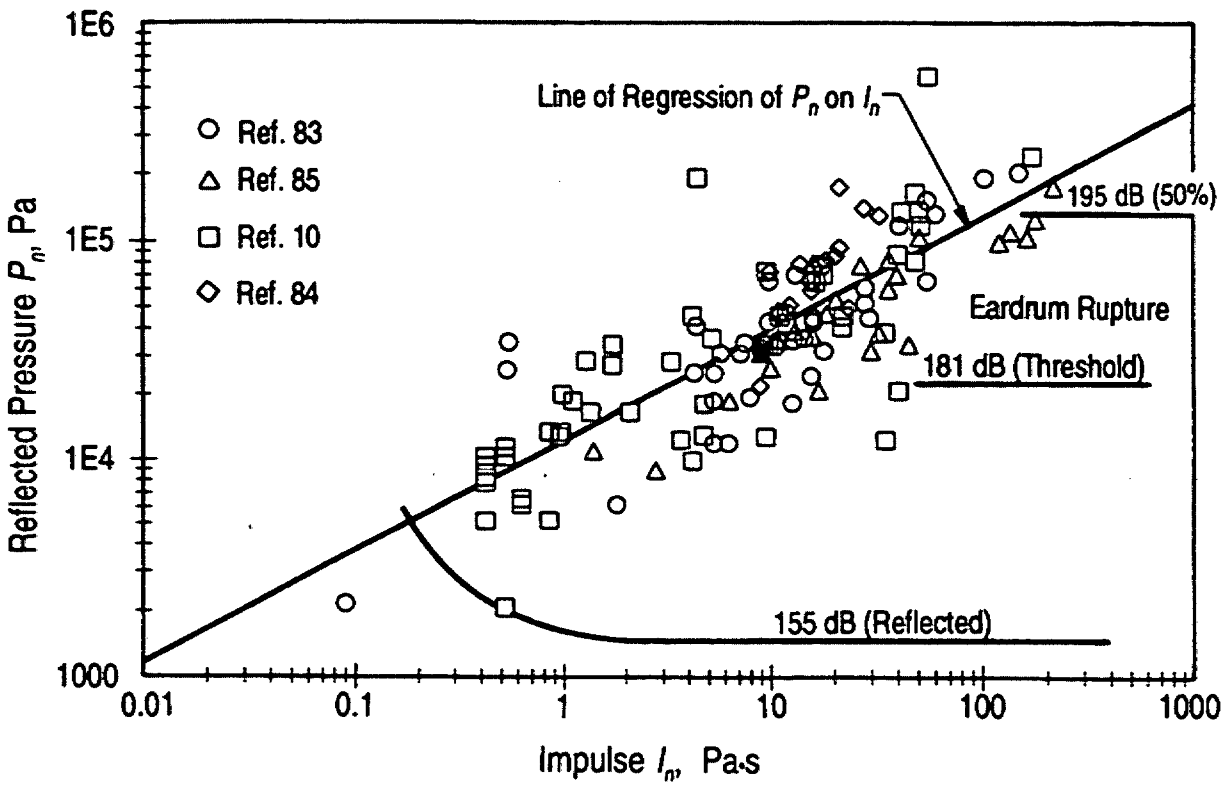


Figure 5-17. Reflected Pressures Versus Reflected Impulse for Ears

generated by passage of the jet alone can be evaluated. All of the side-on data from the first three tests plus the reflected pressure data converted to side-on data for the fourth program are plotted on Fig. 5-16. Also the side-on data from the first three programs converted to reflected pressure plus the reflected pressure data from the fourth program are plotted on Fig. 5-17. These two figures show that there is a high probability for ear injury from the passage of a shaped-charge jet approximately 0.61 m (2 ft) from the crewman's unprotected head. This ear injury, however, would more probably reduce the crewman's efficiency, not incapacitate him. The lines of regression of the pressure upon the impulse are shown on both Fig. 5-16 and Fig. 5-17 to provide an appreciation of data correlation.

There would, however, be an even higher probability of injury from reflected sound waves. In all cases the peak pressure and impulse due to the passage of the jet alone were much lower than the peak pressure and impulse due to later shocks reverberating from the walls of the simulated troop compartment. Thus, if the sound can be deadened rather than reflected from the interior surfaces of the vehicle, there will be a significantly lower probability of damage to unprotected ears.

Eardrums were ruptured in several incidents in SEA. This type of injury was reported for the left gunner of an ACAV from the nearby hit of a rocket-propelled grenade (RPG)-7 (DAN 101), the gunner of an M551 from the explosion of the propellant charge of a nearby 152-mm canister cartridge (DAN 310), and the vehicle commander of an ACAV from the detonation of an RPG-7 on the far side of his vehicle, even though the other three members of his crew did not suffer similar injury (DAN 336). In addition, the loader of an M551, who was on top of his hatch, suffered ear "injury" (not otherwise specified) from the nearby detonation of an RPG-7 (DAN 463). All of these incidents involved the explosion of warheads or propellant. There were no incidents in which "buttoned-up" vehicles were traversed by a jet and very few in which a shaped-charge jet passed near an unprotected crewman within a vehicle.

5-4 LUNG DAMAGE

Incapacitating primary blast injury is limited to the air-containing structures of the body, i.e., the lungs and gastrointestinal tract (Refs. 87, 88, and 89). Blast injury occurs as a result of an incident pressure wave directly loading the body. The resultant loading is distributed over the entire body surface in some manner and depends on the orientation of the body to the propagation of the incident wave. The exposure conditions that result in primary blast injury have been roughly determined; however, the precise injury mechanisms are not clearly understood.

A complex pressure wave similar to those shown on Figs. 5-7 and 5-15 occurs inside an armored vehicle penetrated by a HEAT jet. There is an initial fast-rising wave emanating from the point of penetration. Other shocks are superimposed, i.e., they emanate from the jet traversing the vehicle interior, the exit site penetration, and multiple internal reflections. After several milliseconds, a quasi-static pressure may occur due to heating of the air in the crew space of the vehicle and the accumulation of combustion products. This quasi-static pressure, however, depends upon how rapidly venting can occur through vents and breaks in the integrity of the vehicle. Potentially, additional internal blast events may occur from explosion of explosive-filled devices, vaporized fuel, and/or hydraulic fluid.

5-4.1 LUNG DAMAGE CRITERIA

Widely accepted injury criteria have been developed for simple (classical) blast waves, such as the dashed curve on Fig. 5-18. These blast waves have been defined in terms of peak pressure, impulse, and duration. The interaction of a human body with complex blast waves, however, has not yet been completely defined. Extensive data to support injury criteria for complex wave environments do not exist. As a result, blast injury assessments inside the reverberant space of a perforated armored vehicle must be related to the criteria developed for Friedlander blast waves. Although several methodologies have been suggested, none has proved satisfactory for all conditions. The technique presented in Ref. 1 for estimating nonauditory injury in live-fire tests is described.

Based on current understanding of the interaction between the body and blast waves, a set of injury assessment guidelines was developed for the BFV LFT (Ref. 1). First, the total positive duration is determined, and an "effective peak pressure" is graphically extrapolated (shown on Fig. 5-18) by drawing a "best fit" curve (Ref. 90). The "effective peak pressure" and the "best fit" curve are highly dependent on the person who establishes them. Thus conclusions based upon them must be used with caution. The total positive duration is likened to the duration term of a classical blast wave. The "effective peak pressure" ignores the random pressure spikes that do not contribute significantly to the overall impulse. Pressure pulses are not corrected for transducer orientation relative to the direction of travel of the blast wave. In an ACV gage position and orientation relative to the recorded shock waves cannot be determined accurately, but the pressure reflections are already accounted for in the pressure trace. The "effective peak pressure" and duration are then compared to the Lovelace pressure-duration injury criteria for a prone body in a free field blast wave environment (Ref. 91), as shown in Fig. 5-19. Because the "effective peak pressure" technique considers the total duration, quasi-static pressure is included in the injury predictions. A similar plot is presented for the case in which the person is near a surface subject to blast wave reflections, Fig. 5-20. Injury predictions with this technique have correlated well with injuries observed in studies for which anesthetized large animals were exposed to complex

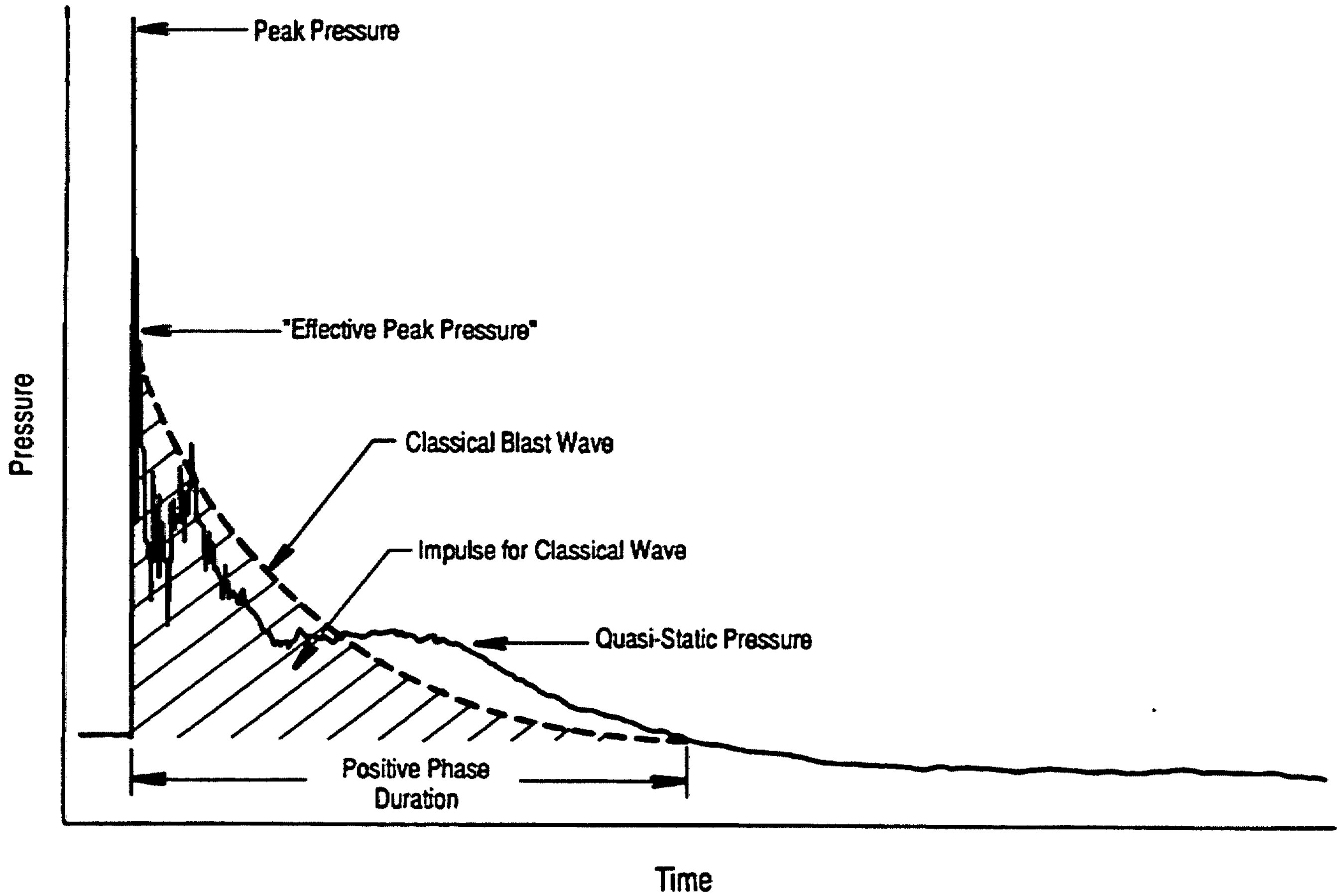


Figure 5-18. Example of Graphic Extrapolation of "Effective Peak Pressure" (Ref. 90)

blast waves from point source explosions in enclosures and from HEAT round penetrations of APCs.

In 1983 a panel of blast experts estimated incapacitation predictions based on classical blast wave environments (Refs. 1, 76, and 90). These guidelines were based on experimentally observed physical damage from classical blast waves and are shown on Fig. 5-21. Accordingly, affected soldiers can be expected to have a 1% incapacitation under conditions that result in threshold injury to the lung. Similarly, conditions that cause death in 1% of the exposed population, or lethal dose for 1% (LD_1), are equated to 50% incapacitation. An exposure lethal for 50%, or lethal dose for 50% (LD_{50}), is assumed to cause 99% incapacitation of the exposed population (Ref. 1). Intermediate degrees of incapacitation are estimated by assuming a lognormal probability distribution based on these three points as shown in Fig. 5-22 (Ref. 90). The injury predictions determined from application of the "effective peak pressure" technique were applied to this curve to determine the anticipated levels of incapacitation (Ref. 1).

5-4.2 EFFECT OF WEARING BALLISTIC VEST

Military personnel usually wear a cloth ballistic vest (CBV) primarily for protection against shell fragments. Vests containing ceramic and/or metal inserts can provide protection against small arms fire also. Normally, however, an armored vehicle provides protection against shell fragments and bullets. Thus only troops who dismount from armored vehicles, e.g., infantry or armored cavalry scouts, would normally need ballistic vests unless the combat vehicle in which they fight is prone to spall. The most common cause of blast within armored vehicles is explosion of stowed munitions.

Wearing of a Kevlar® ballistic vest has been shown to increase both mortality and morbidity for large animals in a strong blast environment (Ref. 92) and to increase intrathoracic pressures (ITPs) in humans at low overpressure levels (Ref. 93). This effect has also been demonstrated in complex wave experiments with animals. Estimates based on limited animal experiments with simple waveforms have

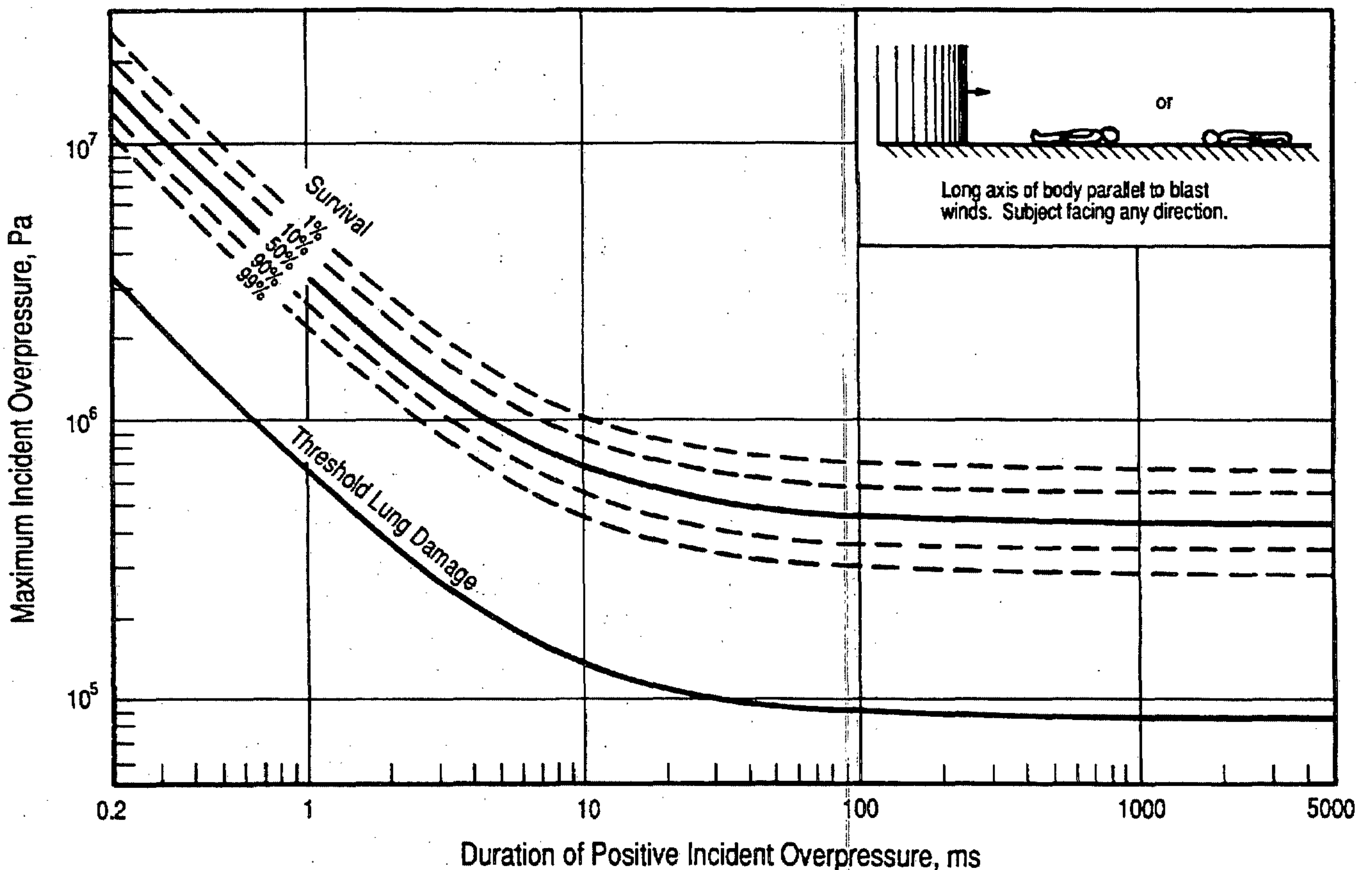


Figure 5-19. Lung Survival Curves With Free-Stream Pressures Propagating Parallel to the Long Axis of the Body (Ref. 91)

indicated that the use of a ballistic vest reduces the overpressure necessary to cause a certain level of mortality by about 25%. These extremely adverse effects were for the cloth ballistic vest, but the most severe tests were conducted with fatigues and cloth ballistic vests only (Ref. 92). In another program intrathoracic pressure changes due to air blast were monitored while five human volunteers wore different uniform combinations. A transducer was emplaced near the gastroesophageal junction of each of the volunteers. The uniform combinations were (1) fatigues, (2) fatigues under a field jacket, (3) fatigues under a cloth ballistic vest, (4) fatigues under a ceramic vest, and (5) fatigues under a cloth ballistic vest under a ceramic ballistic vest (Ref. 93). The mean maximum ITPs of these combinations were 7.4 kPa, 7.9 kPa, 8.7 kPa, 7.2 kPa, and 7.4 kPa, respectively. These test results, each the mean of five tests on different individuals, show basically the same results for combinations (1), (4), and (5), a slightly higher result for combination (2), but a significantly higher result for combination (3) (Ref. 93). The increase in the probability of injury caused by use of the cloth ballistic vest was shown in two other test programs and is shown on Fig. 5-23* (Ref. 92). The mechanism for this lung injury is not known, nor are the reasons that some clothing combinations enhance or attenuate the extent of injury. This subject is being investigated further. ACV crewmen, however, wear a Kevlar® ballistic undergarment rather than the bulky ballistic vest. The ballistic undergarment has not been evaluated for its effect on blast injury but is thought to be less hazardous than the ballistic vest because it is lighter, 1.7 kg versus 2.9 kg (3.75 lb versus 6.4 lb). To estimate the effects of protective clothing on blast injury for evaluation of the LFT program, the "effective peak pressure" was assumed, by representatives of the Surgeon General, to increase by 33% when the ballis-

*On Fig. 5-23 mortality rates for the 420-kPa group are plotted for animals with and without the cloth ballistic vest. Lethality lines are drawn using the common probability slope (5.593) determined for 13 species of animals (Refs. 92 and 94). In tests with sheep at peak overpressure loadings of 420 KPa, 5 of 6 sheep in cloth ballistic vests (CBV) died within 30 minutes of the blast, but in similar tests of sheep without the CBVs and with the same peak overpressure loadings, only 3 of 11 sheep died of the blast effects.

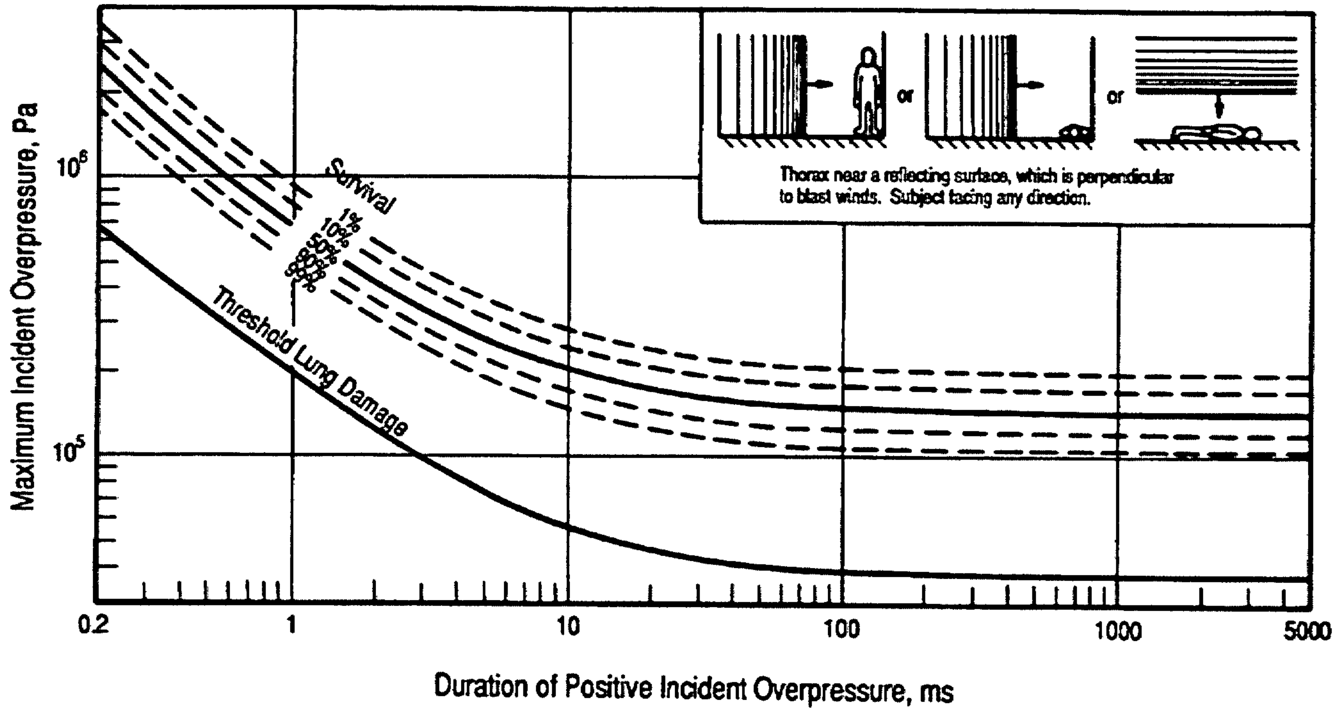


Figure 5-20. Lung Survival Curves With Body Near a Reflecting Surface (Ref. 91)

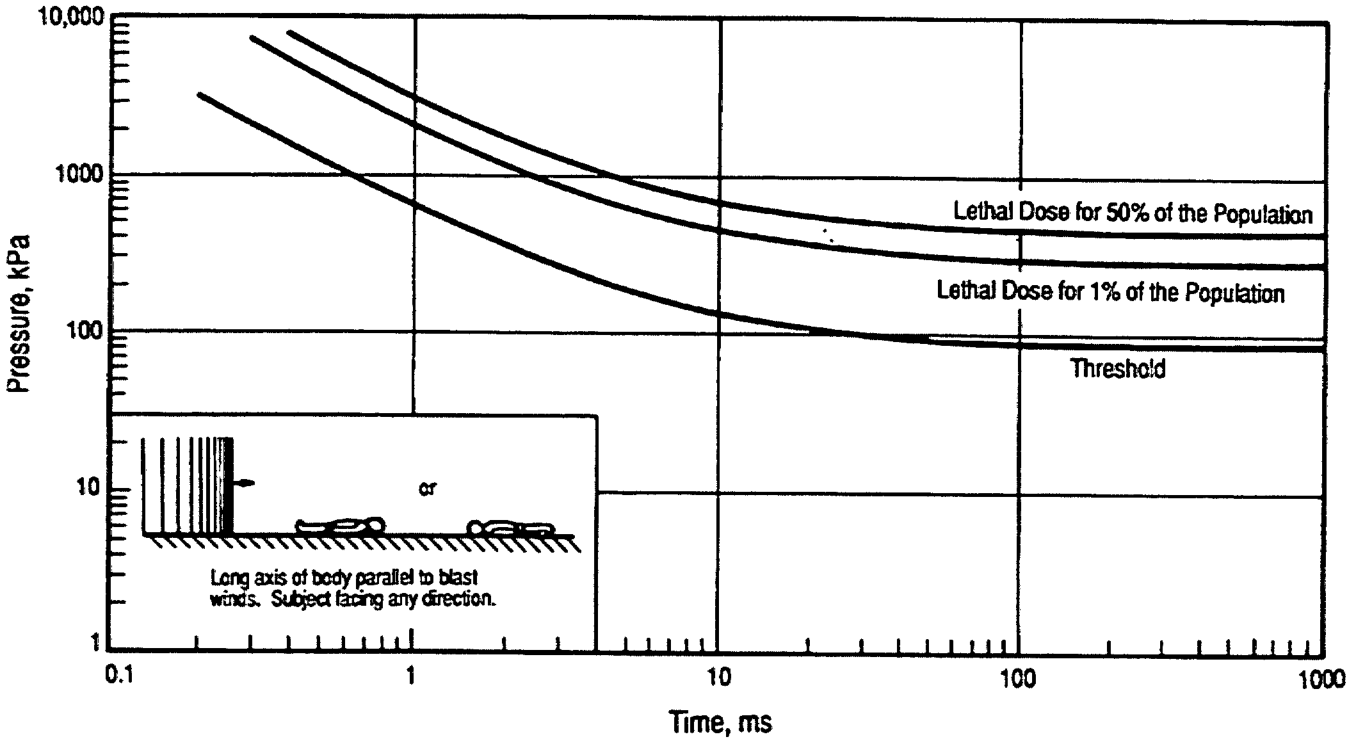


Figure 5-21. Bowen Pressure-Duration Injury Criteria (Refs. 1, 76, and 90)

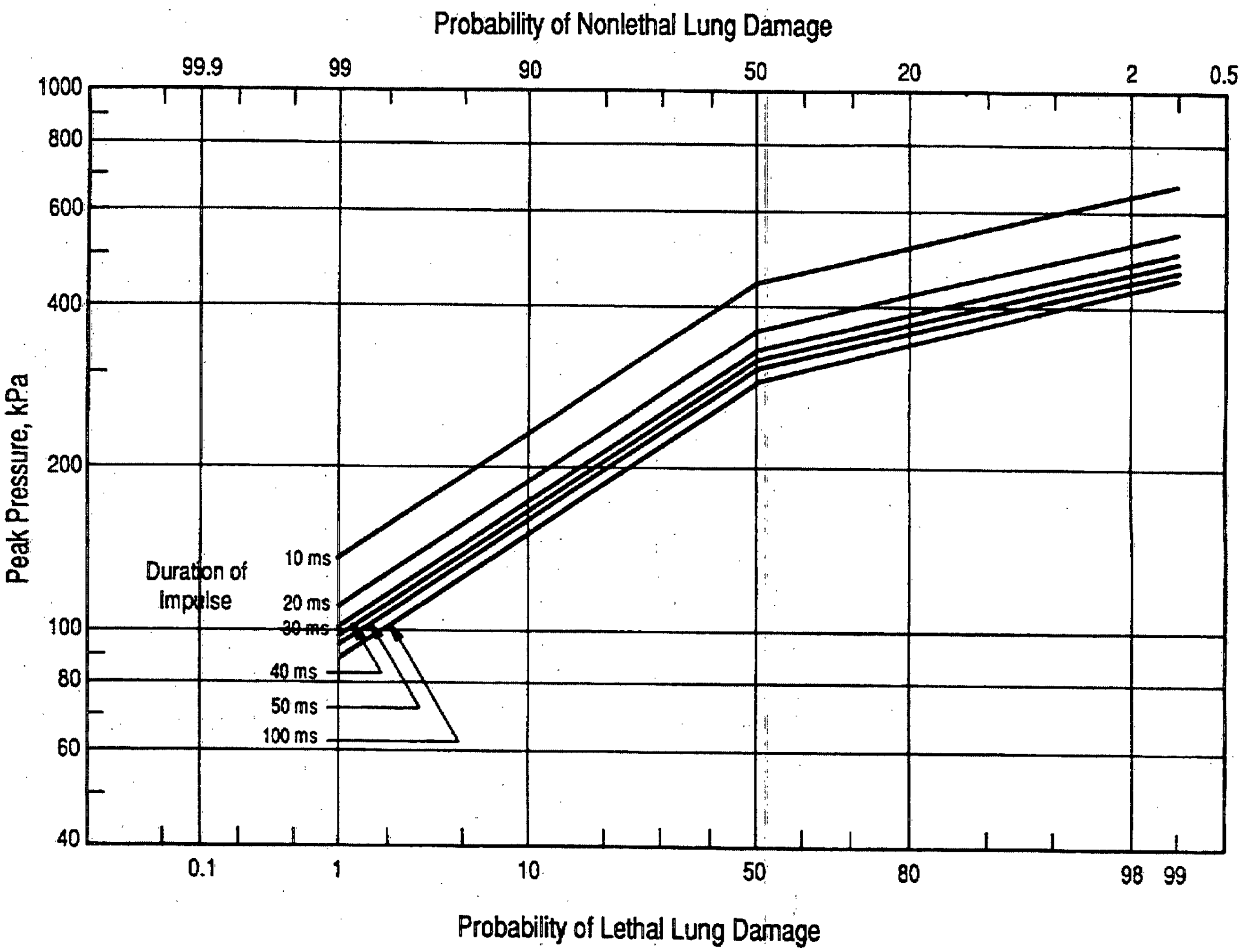


Figure 5-22. Probability Plot of Percent Incapacitation for Lung Injury (Refs. 1 and 90)

tic vest is worn and by 17% when the ballistic undergarment is worn (Ref. 1).

On the other hand, the ballistic vest worn by ACV crewmen can protect those crewmen from spall and other behind armor missiles, as was shown in SWA in 1991 where the vest is credited with saving the life of a BFV driver hit by a large piece of metal launched by the explosion of onboard ammunition (Ref. 65).

5-4.3 SCALING OF PRESSURE/IMPULSE LOADS

5-4.3.1 Scaling of Peak Pressure Versus Duration by Lovelace

Richmond et al (Ref. 94) and later White et al (Ref. 91) discuss the tendency of the lethality curves to approach isopressure lines for "long" duration blast waves. Therefore, the lethality curves shown in Figs. 5-19, 5-20, and 5-21 demonstrate dependence on only pressure and duration.

Data from impulsive loading tests on animals conducted at the Lovelace Foundation in Albuquerque, NM, were scaled for an average person of 70 kg mass at sea level (Refs. 88 and 91). The scaling techniques used are described in Ref. 95. The two scaled parameters used are scaled incident peak overpressure $\overline{P}_s$ expressed as

$$\overline{P}_s = P_s \frac{P_{sl}}{P_0}, \text{ Pa} \qquad (5\text{-}13)$$

where

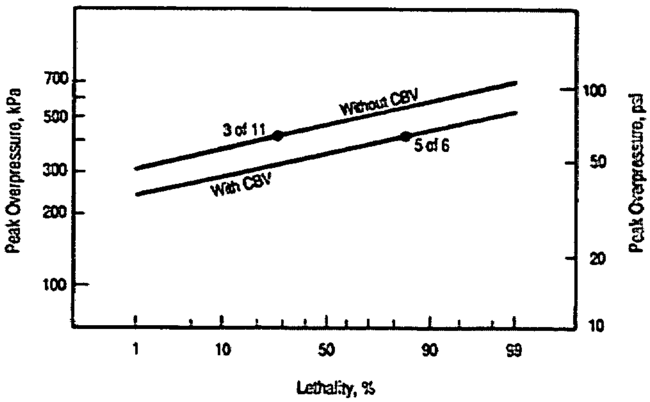
P_s = peak incident overpressure (measured at the test site), Pa

P_{sl} = mean atmospheric pressure at sea level = 101,353 Pa

P_0 = ambient atmospheric pressure, Pa

and scaled positive duration $\bar{t}$ expressed as

$$\bar{t} = t_+ \left(\frac{m_m}{m_a}\right)^{1/3} \left(\frac{P_0}{P_{sl}}\right)^{1/2}, \text{ ms} \qquad (5\text{-}14)$$



Yancy Y. Phillips, Thomas G. Mundie, J. T. Yelverton, and Donald R. Richmond, "Cloth Ballistic Vest Alters Response to Blast", *Journal of Trauma*, Vol. 28, No. 1 Supplement, pp. 149-152, © Williams & Wilkins, 1988.

Figure 5-23. Log Probit Plot for Lethality Following Blast Exposure (Ref. 92)

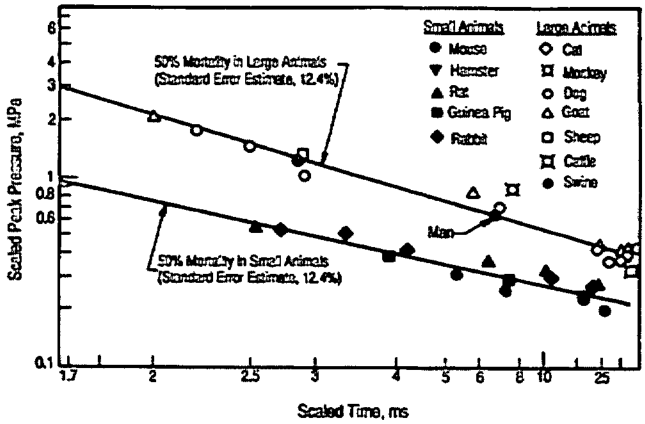


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Figure 5-24. Scaled Pressure-Duration and Partial-Impulse Analyses of Animal Tolerance (Ref. 95)

where

t_+ = positive duration of pressure (measured at test site), ms
m_m = mass of an average man = 70 kg
m_a = mass of test animal, kg.

These scaling factors are applied to data described in Ref. 91 and scaled for standard sea level pressure, i.e., 101,353 Pa (14.7 psi), and for the approximate mass of a human body, i.e., 70 kg (weight of 154 lb), to obtain the equations for a peak pressure of P_{50}, exposure to which results in the probability of death of 50% of the exposed population:

1. For large* animals (cat, monkey, dog, goat, sheep, cattle, swine, man) the curve in Fig. 5-24 is

$$\log(P_{50}/P_0) = 0.6146 + 1.4492t_+^{-1} \times (m_a/70)^{1/3}(101{,}353/P_0)^{1/2}, \text{ dimensionless} \quad (5\text{-}15)$$

2. For small* animals (mouse, hamster, rat, guinea pig, rabbit) the curve is

$$\log(P_{50}/P_0) = 0.3639 + 1.0595t_+^{-1} \times (m_a/70)^{1/3}(101{,}353/P_0)^{1/2}, \text{ dimensionless.} \quad (5\text{-}16)$$

Fifty percent mortality curves and data points for both "large" and "small" animals are plotted versus peak pressure on Fig. 5-24. The experimental data for all animals were obtained by exposing the animals near a reflecting surface to shock-tube- or high-explosive-charge-generated blast waves, and then the data were converted mathematically to the peak pressure that would be attained at sea level. The datum for man was obtained by analysis of an incident in World War II.

5-4.3.2 Scaling of Peak Pressure Versus Impulse by SwRI

An alternate presentation that relates morbidity to blast wave overpressure and impulse rather than to overpressure and duration was developed by Baker et al (Ref. 96). Because specific impulse is dependent on pressure as well as duration, pressure-impulse lethality or survivability curves appear to be more appropriate for use. Also values of peak pressure and impulse are routinely reported in blast wave measurements or predictions.

The following relationships or scaling laws were derived:

1. For the scaled incident peak overpressure (using SwRI practice) $\bar{P}_{SwRI}$, the effect of incident overpressure is dependent on the ambient atmospheric pressure and

$$\bar{P}_{SwRI} = \frac{P_s}{P_0}, \text{ dimensionless} \quad (5\text{-}17)$$

*The adjectives "large" and "small" for animals are unfortunate because the monkeys and rabbits, for example, are the same mean weight and cats are just slightly heavier. The "large" animals have lung densities (average of 194 kg/m^3) that are approximately one-half those of the "small" animals (average of 367 kg/m^3), and "large" animals have normalized lung volumes—lung volume divided by body mass—(average of 29.8 mL/kg) approximately three times those of the "small" animals (average of 9.08 mL/kg). (Ref. 95) where

P_s = peak incident overpressure, Pa
P_0 = ambient atmospheric pressure, Pa.

2. The effect of blast wave positive duration is dependent on ambient atmospheric pressure and the mass of the body. Scaled time (using SwRI practice) $\bar{t}_{SwRI}$ is

$$\bar{t}_{SwRI} = \frac{t_+ P_0^{1/2}}{m^{1/3}}, \text{ Pa}^{1/2} \cdot \text{s} \cdot \text{kg}^{-1/3} \quad (5\text{-}18)$$

where

m = mass of body, kg.

3. Specific impulse i_s can be approximated by

$$i_s = \left(\frac{1}{2}\right) P_s t, \text{ Pa·s.} \quad (5\text{-}19)$$

The use of Eq. 5-19 assumes a triangular wave shape. For "long" duration blast waves, which approach square wave shapes, this assumption is conservative from an injury standpoint because the assumption of a triangular wave shape underestimates the specific impulse required for a certain percent lethality. Eq. 5-19 is also a close approximation for "short" duration blast waves, which characteristically have a short rise time to peak overpressure and an exponential decay to ambient pressure. The total wave is nearly triangular. By application of the blast scaling developed at the Lovelace Foundation for peak overpressure and positive duration to the conservative estimate for specific impulse determined by Eq. 5-19, the scaled specific impulse $\bar{i}_s$ can be determined:

$$\bar{i}_s = \frac{1}{2} \bar{P}_{SwRI} \cdot \bar{t}_{SwRI}, \text{ Pa}^{1/2} \cdot \text{s} \cdot \text{kg}^{-1/3}. \quad (5\text{-}20)$$

Substituting Eqs. 5-17 and 5-18 into Eq. 5-20 and then using Eq. 5-19 provides $\bar{i}_s$ in terms of i_s, P_0, and m

$$\bar{i}_s = \frac{i_s}{P_0^{1/2} m^{1/3}}, \text{ Pa}^{1/2} \cdot \text{s} \cdot \text{kg}^{-1/3}. \quad (5\text{-}21)$$

As indicated by Eq. 5-21, the effect of scaled specific impulse $\bar{i}_s$ is inversely dependent on ambient atmospheric pressure and the mass of the human body.

As mentioned earlier, the air blast damage survivability curves constructed by researchers at the Lovelace Foundation (Refs. 88 and 91) are based on incident overpressure at sea level and duration. It was, therefore, necessary to modify the survival curves for free-stream applications for which the long axis of the body is perpendicular to the direction of propagation of the blast wave so that the axes are scaled incident overpressure and scaled specific impulse. To accomplish this modification, it was necessary to determine the pressure and duration combinations that produced each survivability curve, calculate the scaled incident overpressure and scaled specific impulse by using Eqs. 5-17 and 5-21, and reconstruct the survivability curves accordingly. These reconstructed curves are shown on Fig. 5-25. These curves represent percent survivability, and higher scaled pressure and scaled impulse combinations allow fewer survivors. Presenting the curves this way is advantageous because they apply to all altitudes with different atmospheric pressures and all masses (or sizes) of human bodies. Once the incident overpressure and specific impulse for an explosion are determined, they can be scaled by using Eqs. 5-17 and 5-21. The value for mass used in the scaling is determined by the demographic composition for crew members. Suitable averages for body mass are 55 kg (weight of 121 lb) for adult females and 70 kg (weight of 154 lb) for adult males. It should be noticed that the smaller bodies in this case are the more susceptible to injury.

5-4.4 LOADS FROM A SHAPED-CHARGE JET

Fig. 5-25 is used to evaluate the probability of lung damage. The data from the four test programs (Refs. 10, 83, 84, and 85) described in subpar. 5-3.4 were scaled by the technique described in subpar. 5-4.3.2 and are plotted on Fig. 5-26 for normal pressure. Scaled overpressure and scaled impulse values were calculated using Eqs. 5-17 and 5-21. These calculations were for a human with a mass of 74.8 kg (weight of 165 lb). All data fall entirely below or to the left of the impulse asymptote for the threshold of lung damage. Thus no lung injury is predicted for that shock from the jet of a warhead passing 610 to 914 mm (2 to 3 ft), i.e., the dis-

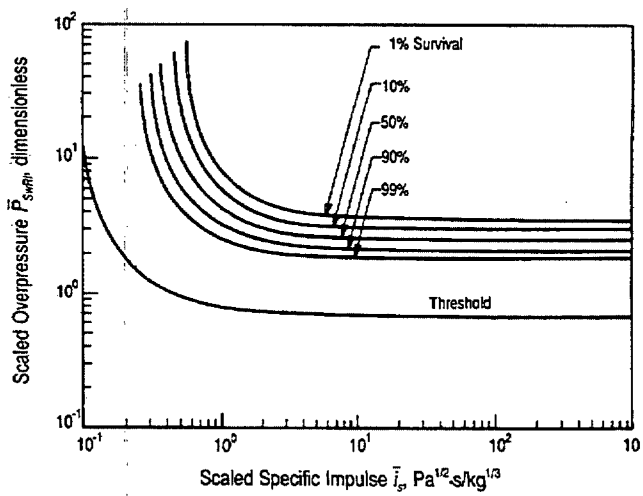

Figure 5-25. Survival Curves for Lung Damage to Man (Ref. 97)

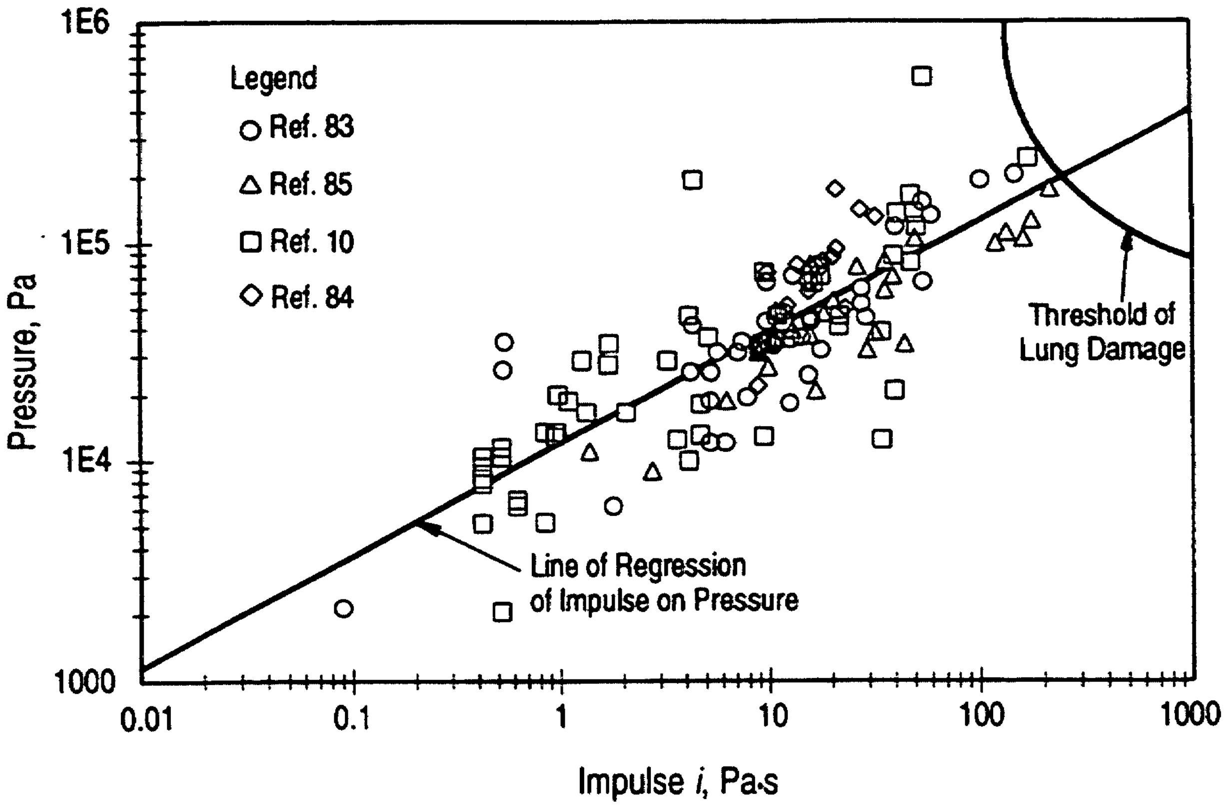

Figure 5-26. Lung Damage Potential From Test Data of Reflected Pressure Versus Reflected Impulses

tance of the pressure transducers from the jet, from an exposed crew member.

5-5 EYE DAMAGE

5-5.1 BACKGROUND

The potential for incapacitating eye damage in war has generated a large amount of research and writing. Because of the sensitivity of the eye, there is a higher rate of ocular injury than one might expect for the surface area exposed. The eyes account for about 0.3% of total body surface area, but eye injury is present in nearly 10% of nonfatal battle casualties (Ref. 98). Prior to World War II, bullets, shrapnel, shell fragments, spall, bayonets, chemical warfare agents (especially mustard), blunt objects, flame, and blast were the main causes of injury. Because of the wide use of armor-piercing ammunition in World War II and the threat of exposure to nuclear weapons after the war, there was increased emphasis on flash burns and flash blindness. During the Vietnam conflict the widespread use of mines and booby-traps resulted in a dramatic increase in eye injuries—about three times that for World War II (Ref. 99). The combination of greater risk and better methods of diagnosis and treatment has maintained a high level of interest in eye injury and eye care, but experimental work in battlefield trauma associated with ACVs has not kept pace. In many cases the same type of eye injury risk data is being generated in modern studies as was derived from combat records of the two world wars. A new threat to the eye is damage caused by lasers, which are being used in increasing numbers on the modern battlefield (Ref. 100).

Throughout all of this work, several themes have persisted. The primary one is that prevention is better than cure, and a corollary is that very little can be done on the battlefield to treat a seriously injured eye. The early treatment goal is to avoid further injury and transport the casualty to a medical facility as soon as possible. The opinion of W. T. Lister (Ref. 101) recorded in 1915 is still applicable to frontline medical care of eye injuries:

> "In reviewing the ophthalmic injuries in warfare, the outstanding features are their severity and the impossibility, in almost every case, of employing conservative surgery. If the eye is touched, it is spoilt."

Of course, modern ophthalmic surgery has much to offer even severely injured casualties, but it is still necessary to transport the patients to locations where the surgery can be performed. First aid for eye injuries is still limited to flushing with water and then protection of the eye from further damage by careful patching and the use of rigid shields. The complement to modern surgery in preservation of vision cannot be a dramatic improvement in frontline medical care; it must be prevention of the injury through better vehicle design and protective eyewear.

Crew members and passengers in armored fighting vehicles exposed to hostile fire have virtually the entire range of battlefield threats previously mentioned, which include flash that causes burns and blindness. Exploding munitions may produce gas clouds at temperatures of approximately 3000°C (5432°F) (Ref. 23), and penetration of armor plate may produce a ballistic impact flash with an effective temperature of approximately 3100 to 3700°C (5612 to 6692°F) (Ref. 102). Much of the work on modeling the physiological effects of such sources has been conducted with carbon-arc sources with temperatures of about 5500°C (9932°F) (Ref. 103). Consequently, a number of unanswered questions remain:

1. What is the full range of flash temperatures and durations seen in ACV fires including those produced by shaped charges, KE penetrators, conventional artillery, and mines?
2. How can the actual environment in the ACV be measured, thoroughly documented, and then reproduced under controlled conditions?
3. How can the effects of each factor on vision risk be evaluated separately, and how can the combined effects be realistically represented?
4. What are the cost and/or benefit factors for each proposed vehicle design change, and what are the principles of risk avoidance that suggest the type of design changes that will be most efficacious?

The answers to these questions cannot be found in the current literature for several reasons, the most important of which is that an experimental program to describe the incapacitating effects of eye injury would be complex, costly, and necessarily multidisciplinary. It would require study techniques and instrumentation not available as recently as 10 years ago. Reduction in performance by a human operator cannot be uniformly related to only one adverse medical condition or a set. Although evaluation of the medical condition(s) must play a role, the entire environment of the ACV must be considered. Because the vehicle environment is currently defined rather narrowly for only a few operational conditions, the broad study cannot be done until the missing data described by the previous questions are supplied. Some data are available in Ref. 1; these are presented in subpar. 5-5.2.4.

5-5.2 INJURY MECHANISMS

The eyeball, Fig. 5-27, is contained within the cavity of the orbit in the skull, which protects it from most damage. The eyeball is covered by the sclera or sclerotic coat, i.e., a dense, hard, transparent material, which protects the internal parts from most penetration injuries. The cornea is another hard, dense, transparent material that protects the iris and lens. The iris is a shutter that opens to admit more light or closes to admit less light. The lens focuses the light onto the retina, which contains rods, cones, and nerves that react to the light received to present a picture to the brain.

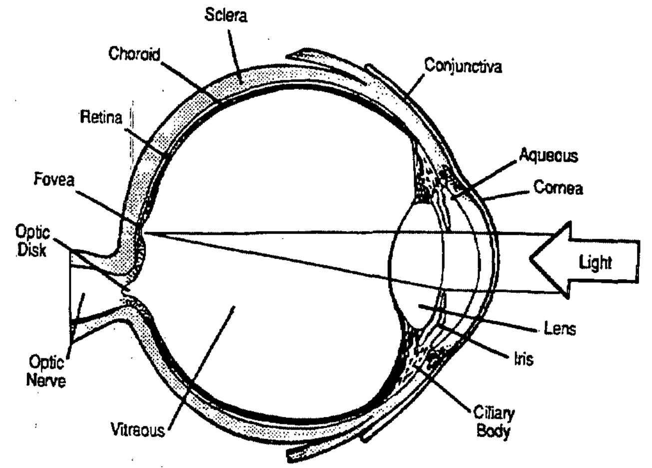

Figure 5-27. The Eyeball (Ref. 100)

5-5.2.1 Foreign Bodies

Injuries caused by foreign bodies are expected in ACV fires associated with exploding munitions or armor penetration. Manikins and pigs both showed evidence of penetration by small metal fragments (spall) when placed in test vehicles and subjected to explosive force created by shaped charges and a simulated beach mine (Ref. 24). Ballistic impact from armor-piercing projectiles may produce a similar effect. The interface between projectile and armor plate is hypothesized to be liquid (Ref. 102) and thus increases the likelihood of a shower of hot metal fragments entering the vehicle. The velocity of these fragments is of considerable interest. Although they noted the distribution of penetration and burn evidence from small metal fragments, neither the medical personnel (Ref. 24) nor the engineering personnel (Ref. 58) described either the size distribution or the terminal ballistics of these missiles. Both characteristics, however, are of great interest in assessing the likelihood of ocular injury. Particles less than 0.5 mm in size and less than 0.5 mg in mass are rarely found within the eye because they usually lack the kinetic energy required to penetrate the tough outer covering (sclera) of the eyeball (Ref. 99). Designs that favor the generation of many small, low-energy particles might be advantageous compared to those that produce a lesser number of high-mass, high-energy particles. Whatever the description, accurate characterization of the expected particle size and velocity distribution would aid in specifying practical protective eyewear. Much work is being done on predicting spall quantity, size, and velocity.

Another design consideration for material likely to become an intraocular foreign body is its reactivity within the eye. Even a material that is considered inert may cause degeneration of the retina and vitreous substance of the eye

(Ref. 24). If the foreign material is at all reactive, local liquefaction of the vitreous gel (vitreous humor) will lead to leaching of the material and rapid dissemination of active ions throughout the eye. Iron and copper are examples of common reactive materials that are also quite destructive and eventually lead to widespread liquefaction of the vitreous gel and to interference with membrane function in the eye (Ref. 99). In every case of foreign body penetration, the best course is early removal. In this regard, personnel should be aware of the ease with which fragments within the eye can be located by sonography, X ray, magnetic resonance imaging (MRI), or related techniques and removed with magnetic probes or other devices. There is a possibility that an ophthalmologist would recommend materials be used for an inside vehicle liner that are not reactive with eye liquids and are easily detected and removed from the eye. The best solution, however, is to use materials that will not spall or be pulverized. This solution poses a potential problem because liner materials that will not spall or be pulverized are apt to become a focusing medium that confines spall and pulverized armor into a smaller cone than otherwise generated. This action, much like a choke on a shotgun, focuses the debris and thus increases the potential for the debris to injure personnel. This effect has been observed in tests of both armored vehicles and aircraft canopies. While considering this guidance, design personnel should also obtain periodic updates on advances in ophthalmological science. The potential to protect, maintain, and restore sight is far greater now than it was 50 or even 20 yr ago, and as the underlying science continues to evolve, the design techniques used can be expected to change. This situation will also exist for other types of injuries including those caused by irritant chemicals, e.g., if dry chemical fire extinguishant is used in an active or passive fire extinguisher system and if it is thrown in the face of a crewman, it could irritate his eyes.

5-5.2.2 Hot and/or Burning Liquid Droplets

Prompt degradation of fighting or escape abilities would likely be caused by exposure to burning fuel droplets in the fireball that follows the penetration of an ACV fuel cell. Because its temperature may be 1000°C (1832°F) (Ref. 83), contact of the fireball with any tissue—including the eye—would result in an immediate burn with instantaneous pain. Loss of vision would be immediate. These fuel or hydraulic fluid droplets could have a bulk temperature of 71 to 177°C (160 to 351°F) as well as be surrounded by burning hydrocarbon vapor.

5-5.2.3 Irritant Chemicals

During World War I and more recent conflicts, the prominence of eye injuries involving chemical agents reflects the great sensitivity of the eye to irritant chemicals. An ACV fire could produce gases irritating to the eyes by the burning of clothing and equipment in the vehicle. The heat from fire could also vaporize chemical agents carried into the vehicle on the boots and clothing of its crew and passengers; mustard would be especially dangerous in this regard because it is persistent, stable, and still regarded as a likely chemical threat agent. Gas masks would furnish good protection for the eyes against this threat, but they would have to be put on before any exposure to the chemical agents. The need for such protection, however, might be overlooked because exposure to dangerous concentrations of mustard may not be noticed for two to six hours, by which time severe damage could be done (Ref. 104). The incapacitation that follows 6 to 12 h after exposure to mustard can be very severe initially, i.e., it can effectively blind the casualties (Ref. 105). Because the time required to cause injury decreases with successive exposures, even of a mild nature (Ref. 106), detection of low concentrations of such agents may be particularly important in an ACV due to the possibility of recirculating contaminated air and vaporizing any remaining agent should a fire occur.

5-5.2.4 Flash Effects

Eye damage caused by radiant energy has been studied extensively since World War II (Refs. 107 and 108) but usually with regard to nuclear explosions. The applicability of this work to the environment in ACV fires remains unclear. It is unlikely that the effective temperatures in ACV flashes reach the level of those of a carbon arc (about 5300°C or 9572°F), and the different effects that might be expected on the human eye are not defined. Investigators have assumed that animal eyes, e.g., rabbits and monkeys, are good models for human eyes, but the criteria for comparison are not well-developed (Ref. 108).

Nevertheless, the US Army currently believes a luminance level of 20 $mJ/mm^2 \cdot sr$ for 5 ms in the wavelength range of 400 to 1400 nm causes permanent retinal injury (scotoma). Injury to the cornea due to a welder's flash may be expected at a luminance of 0.1 $mJ/mm^2 \cdot sr$ at wavelengths of 200 to 320 nm. Similar to sunburn, though, this effect will be delayed for several hours. Crew members or passengers who are vulnerable to exposure to these light energy levels are assumed likely to be severely injured by related effects, such as blast or fragment penetration. Others may be affected by temporary flash blindness similar to that experienced by looking at a No. 2 Sylvania photoflash bulb. Luminance measurements in the BFV live-fire tests showed flash blindness could last up to 3 s in daytime and up to 6 s at night. Approximately two minutes* are required to recover fully to the dark adaptation levels that existed prior to the flash. In summary, the US Army currently believes

*This time estimate is related to an ACV crewman who has red lights and other vision aids within his vehicle. There is further discussion of dark adaptation in subpar. 5-7.1.3.

that survivors of ACVs attacked by antiarmor munitions will not have permanent eye injuries from flash (Ref. 1).

There was considerable experience during World War I with temporary blindness in patients who had been close to exploding artillery projectiles. In most cases this condition cleared within a week (Ref. 109). This type of injury also occurred in SEA, as has been noted in subpar. 4-1.2. In DAN 101 the left gunner of an ACAV suffered temporary blindness from the nearby burst of an RPG-7. In DAN 670 a crewman of an AR/AAV M551 suffered eye damage from the flash of a bursting RPG-2; he was reported to be unable to see and was evacuated by helicopter.

5-5.2.5 Concussions and Contusions

Concussions and contusions are frequently closely related; they originate from an explosion or the impact of or on a blunt object. Both can result in deformation of the eye, tearing of internal blood vessels, and/or detachment of the retina. Any of these conditions would result in decreased vision or even blindness, and the problem could be temporary or permanent. Because of the relatively small amount of space in an ACV, avoidance of concussion injuries is difficult when an explosive charge enters the vehicle.

5-5.3 SUMMARY

Eye injuries experienced during fires in ACVs have been well described in the literature. Projections of the incapacitation caused by these injuries can be expected to be in error to the extent that the actual environment in the vehicle is unknown. Because the human capacity to function requires the integration of many individual capabilities, it should be considered in the context of the whole ACV environment, not individual parts. In the case of eye injury, common battlefield experience suggests that damage to or loss of sight is one of the most traumatic events that can happen to a person. Whether temporary or permanent, such a condition can be expected to have a severe adverse impact on every person's ability to carry out instructions and perform a mission. Therefore, eye protection, or eye armor, must be provided.

5-6 ASPHYXIATION, TOXIC GASES, AND PARTICULATE SOLIDS

Smoke is commonly defined as a complex mixture of the airborne solid particulates, liquid drops, and gases that evolve when a material undergoes thermal decomposition (Ref. 110). Thermal decomposition of a material may occur as a result of anaerobic pyrolysis, oxidative pyrolysis (commonly referred to as "smoldering"), and/or flaming combustion. Although all of these processes could conceivably occur at some stage of a real fire, few fires start or progress without oxygen (Ref. 111). Exceptions are fires fueled by gun propellants and monopropellants that contain sufficient oxygen or other oxidizers to combust.

The thermal decomposition of any material results in the evolution of a wide variety of chemical species. Both natural and synthetic polymers contain carbon and, when combusted, evolve carbon monoxide and/or carbon dioxide. The relative quantities of gases generated by a material depend primarily on the amount of oxygen present during combustion and the combustion temperature. Gaume and Bartek (Ref. 112) cite the type of material burning, its combustibility, the temperature reached, supply of oxygen, air currents, and fire-retardant treatment. Bebrauskus et al (Ref. 113) cite literature that references over 400 compounds evolving from the decomposition of wood and 400 compounds from the decomposition of plastics. Material burned at one temperature might yield one set of gases and, when burned at a different temperature, yield another set of gases (Ref. 114). A harmless gas might become toxic when combined with another harmless gas (Refs. 115 and 116). In addition to gases prevalent in smoke, thermal decomposition products may include simple saturated and unsaturated hydrocarbons (e.g., methane, ethane, and ethylene), partially oxidized species (e.g., acetaldehyde and acrolein), and more complex aromatics (e.g., benzene and toluene). Materials also may contain nitrogen, sulfur, and halogens and, when thermally decomposed, may generate additional toxic gases including ammonia (NH_3), hydrogen cyanide (HCN), nitrogen oxides (NO_x), isocyanates, nitriles, sulfur dioxide (SO_2), halogen acids (HCl, HBr, and HF), and other halogenated species. (See also Refs. 117 and 118.)

The large number of diverse chemical species present in smoke affects many organs and/or systems in the body and causes myriad physiological and biochemical alterations. Many of these alterations are masked by the effects of hypoxia-producing and irritant gases, which are the most prevalent toxicants in smoke and generally are present in the highest concentrations. Some gases might have more than one physiological effect. Some toxins can have different effects that depend on dosage. For example, nitrogen dioxide (NO_2) is an irritant, but at high doses it can create mechanical barriers to oxygenation and become a mechanical asphyxiant (Ref. 112). Consequently, fire scientists often categorize the major fire effluents into two main classes: the hypoxia-producing gases (also referred to as narcotic or asphyxiant gases) and the irritants. Examples of common hypoxia-producing gases and a hypoxia-producing condition are carbon monoxide, HCN, and reduced oxygen. Examples of prevalent irritants are HCl, HF, acrolein, and solid particulates. A third catchall class has been designated for those chemicals with "other and unusual specific toxicities" (Ref. 119). Many components of smoke may fit into this category, but these compounds generally are present in low concentrations and are not analyzed. With few exceptions their effects are not monitored in laboratory experiments. Nevertheless, it is possible that some of these compounds contribute to the incapacitating and lethal effects of smoke inhalation, even though the effects of the hypoxia-producing toxicants and irritants predominate.

Few studies have been conducted with controlled combinations of gases and with observation of the resulting additive, synergistic, or antagonistic interactions (Ref. 120). One interesting model, however, is currently being pursued* (Ref. 113). The hypoxic environment and heat of a real fire might intensify the effects of the toxins, especially asphyxiants (Ref. 116). Belles (Ref. 121) showed that laboratory-scaled smoke toxicity tests do not predict toxicity in full-scale smoke toxicity tests. Different time courses for different toxins make it difficult to assess their combined effects. Also toxins have been shown to have both immediate and delayed effects (Ref. 120). Add to these chemical, physical, and/or physiological complexities another layer of animal and/or human performance complexities, and it is easy to see why scientific progress in predicting human performance during fires has been slow. Prevalent gases in smoke atmospheres generated by the combustion of natural and/or synthetic materials and the gas concentrations considered hazardous are shown in Table 5-7.

5-6.1 HYPOXIA-PRODUCING GASES AND CONDITIONS

For obvious reasons, there is little experimental data on the effects of various contaminants resulting from combustion on human performance. In addition, most of the literature on the effects of such contaminants on animals has used the lethal concentration at which 50% of the exposed subjects expire (LC_{50}) as the dependent variable. With a few notable exceptions (Ref. 126) most of these investigators have used nonprimate animal models.

Some researchers have reported behavioral measures such as the toxin concentration at which 50% of the animals became incapacitated (IC_{50}), i.e., the time of useful function, or the effective concentration (EC_{50}) at which animals produce a response 50% of the time. (The "time of useful function" was originated by Gaume and Bartek (Ref. 112) to index the length of time during which an animal could escape from a given concentration of contaminant.) In a comprehensive review of various approaches to combustion toxicology, Kaplan, Grand, and Hartzell (Ref. 127) described 22 different combustion toxicology methodologies. Of those, 16 involved measuring some end point short of lethality. The definitions of incapacitation and types of behavioral tasks, however, have varied greatly, and although such information might be relevant for predicting how long a soldier might have to escape from a vehicle, it is questionable whether such data could help predict how long a soldier and/or a crew could perform the cognitive, motor, and communication tasks necessary to move the vehicle to cover or to continue to fight in the vehicle.

The most prevalent asphyxiant gases and/or condition in smoke are carbon monoxide, carbon dioxide, HCN, and oxygen depletion. Each is discussed in the paragraphs that follow.

5-6.1.1 Carbon Monoxide

Carbon monoxide, the most ubiquitous product of combustion of both natural and synthetic materials, is formed when there is incomplete combustion of carbonaceous materials. This colorless and odorless gas combines with the hemoglobin of red blood cells to form carboxyhemoglobin (COHb) and interrupts the normal supply of oxygen to body tissues. The affinity of hemoglobin for carbon monoxide is more than 200 times greater than it is for oxygen. Even partial conversion of hemoglobin to COHb reduces the oxygen-transport capability of the blood and results in a decreased supply of oxygen to critical body organs, such as the brain and the heart. In addition, carbon monoxide impedes the dissociation of oxygen from oxyhemoglobin in the capillaries and thus further decreases the availability of oxygen to body tissues (Ref. 128).

The asphyxiants are some of the most deadly toxins. Belles (Ref. 121) found that in full-scale toxicity tests, carbon monoxide was the major toxicant. It is especially lethal in fires because of its insidious nature. Cagliostro and Islas (Ref. 129) reported that the general effects of carbon monoxide on humans reported in the literature include headache, lack of coordination, dizziness, weakness, blurred vision, nausea, vomiting, collapse, loss of consciousness, and death. The effects of carbon monoxide on the performance of lower animals, e.g., mice, are better known than for many other toxins (Ref. 129).

The toxic effects that result from exposure to carbon monoxide are due to hypoxia and depend primarily on the concentration of the gas, the duration of exposure, and the alveolar ventilation. Although other factors including the age and health of the individual may increase susceptibility to carbon monoxide intoxication, the symptoms produced by exposure to carbon monoxide are directly related to the amount of hemoglobin that is converted to COHb and thus is unavailable for oxygen transport. The symptoms and effects that have been reported in humans with various COHb saturations are shown in Table 5-8. These data indicate that at COHb levels below 30% the effects in most individuals would not be sufficiently severe to prevent escape from the fire environment, but at levels above 30% the effects could incapacitate some individuals. At COHb levels above 50% very severe symptoms occur. Some investigators consider that a blood COHb level of 50% or greater is evidence that carbon monoxide was the primary cause of death (Refs. 131 and 132), whereas others believe that death may be attributed to carbon monoxide when the COHb saturation is 60% or greater (Ref. 133).

*Babrauskas, Levin, and Gann have laid out an approach to use fire toxicity data systematically to apply available data to a new situation. These data are to be used in their N-gas Model to evaluate the toxicity hazard in a newly defined situation. This model is intended to reduce the need to conduct tests with animals in order to establish the concentration of combustion products needed to cause 50% of a number of animals to die. This model has been adapted to buildings but is not currently adapted to combat vehicles.

TABLE 5-7. HAZARDOUS CONCENTRATIONS OF MAJOR TOXICANTS GENERATED BY THERMAL DECOMPOSITION OF MATERIALS (Refs. 115 and 122 through 125)

TOXICANT	ACGIH TLV-STEL, ppm	IDLH, ppm	STLC, ppm	HAZARDOUS/LETHAL WITHIN A FEW MINUTES*, ppm or %
Carbon monoxide	400	1500	5000	8000
Hydrogen cyanide	—	50	350	280
Carbon dioxide	30,000*	50,000	—	12%
Oxygen depletion	—	—	—	<12%
Hydrogen chloride	—	100	>500	1000-2000
Hydrogen bromide	—	50	>500	—
Hydrogen fluoride	—	20	~ 400	50-100
Ammonia	35	500	>1000	2000
Acrolein	0.3	5	30-100	>10
Formaldehyde	2**	100	—	>50
Sulfur dioxide	—†	100	>500	600-800
Nitrogen dioxide	5	50	>200	250
Styrene	100	5000	—	—
Toluene-2, 2-Diisocyanate	0.02	10	~ 100	—

American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) (Ref. 108), short-term exposure limit (STEL) = The concentration to which workers can be exposed continuously for a short period of time (15 min) without suffering from irritation, chronic or irreversible tissue damage, or narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency

Immediately Dangerous to Life or Health (IDLH) = The maximum concentration from which one could escape within 30 min without any escape-imparing symptoms or any irreversible health effects. These IDLH levels were published (Ref. 124).

Short-Term (10 min) Lethal Concentrations (STLC), ie., from Terrill and others (1978) (Ref. 122)

*From Ref. 115 except for hydrogen chloride values from Ref. 125
**Proposed change value
†Proposed deletion of STEL value

5-6.1.2 Hydrogen Cyanide

Hydrogen cyanide (HCN) is one of the most rapidly acting toxicants. HCN causes histotoxic anoxia, in which enzyme inhibition prevents normal cellular metabolism (Ref. 127). According to Terrill et al (Ref. 122), HCN is a rapidly fatal asphyxiant that results from the combustion of wool, silk, paper, polyacrylonitrile, nylon, and polyurethane. Because HCN causes increased respiration, it could also cause increased intake of other airborne toxins. Inhalation of HCN vapors can cause severe toxic effects and death within minutes to a few hours, depending on the concentration in the atmosphere. The toxicity of HCN is due to the cyanide ion that is formed by hydrolysis of the chemical in blood. Unlike carbon monoxide, which remains primarily in the blood, cyanide ions are distributed throughout the body water and thus come in contact with the cells of tissues and organs. Cyanide reacts readily with the trivalent ion of the cytochrome oxidase enzyme to form a cytochrome-oxidase-cyanide complex and thereby inhibits cellular respiration. Since cytochrome oxidase is involved in the use of oxygen in practically all cells, its inhibition rapidly leads to loss of cellular functions (cytotoxic hypoxia) and then to cell death. In contrast with carbon monoxide, cyanide does not decrease the availability of oxygen; it prevents the use of oxygen by the cells. The heart and brain are particularly susceptible to inhibited cellular respiration. Although cardiac irregularities are often noted in HCN intoxication, the heart invariably outlasts respiration, and death is usually due to respiratory arrest of central nervous system origin.

The physiological responses of a human to various concentrations of HCN are shown in Table 5-9. According to these data, approximately 50 ppm may be tolerated by a human for 30 to 60 min without difficulty, 181 ppm may be fatal after 10 min, and 270 ppm or more is immediately fatal.

Because carbon monoxide interferes with the transport of oxygen by the blood and HCN interferes with the use of oxygen by cells, it might be expected that simultaneous

TABLE 5-8. HUMAN RESPONSE TO VARIOUS CONCENTRATIONS OF CARBOXYHEMOGLOBIN (Ref. 130)

BLOOD SATURATION, COHb, %	RESPONSE OF HEALTHY ADULT*
0.3-0.7	Normal range due to endogenous CO productions; no known detrimental effect
1-5	Selective increase in blood flow to certain vital organs to compensate for reduction in O_2-carrying capacity of the blood
5-9	Visual light threshold increased
16-20	Headache; visually evoked response abnormal
20-30	Throbbing headache, nausea, fine manual dexterity abnormal, judgment and calculation ability impaired
30-40	Severe headache, nausea and vomiting, and syncope
50-60	Coma and convulsions
67-70	Lethal if not treated

*Exposure to carbon monoxide concentrations in excess of 50,000 ppm can result in fatal cardiac arrhythmia before the carboxyhemoglobin saturation is significantly elevated.

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exposure to the two gases would result in additive effects. Experimental studies of the combined effects of HCN and carbon monoxide have yielded conflicting results, although most of these studies indicate additivity when carbon monoxide and HCN are both present in certain concentrations (Refs. 134 and 135). In a significant study by Higgins et al (Ref. 120), however, LC_{50} values for a 5-min exposure to HCN of rats (503 ppm) and mice (323 ppm) were not statistically different from those for both HCN and carbon monoxide. The concentration of carbon monoxide in the mixture was sufficient to produce a 25% blood COHb level. There was no evidence of additivity of effects even when animals were exposed to HCN after an exposure to carbon monoxide that produced blood levels of 25 or 50%. Despite the Higgins study, the majority of available evidence indicates that the effects of carbon monoxide and HCN are additive, except possibly at a low concentration of either toxicant.

TABLE 5-9. PHYSIOLOGICAL RESPONSE OF HUMANS TO VARIOUS CONCENTRATIONS OF HYDROGEN CYANIDE IN AIR (Ref. 123)

RESPONSE	CONCENTRATION mg/L	CONCENTRATION ppm
Immediately fatal	0.3	270
Fatal after 10 min	0.2	181
Fatal after 30 min	0.15	135
Fatal after 0.5 to 1 h or later, or life threatening	0.12-0.15	110-135
Tolerated for 0.5 to 1 h without immediate or latent effects	0.05-0.06	45-54
Slight symptoms after several hours	0.02-0.04	18-36

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5-6.1.3 Carbon Dioxide

Carbon dioxide is a colorless, odorless, noncombustible gas. Carbon dioxide is less lethal, but the presence of other toxicants intensifies its effect (Ref. 113). It stimulates the rate of breathing and thus can increase intake of other contaminants in the air (Ref. 124). When inhaled in elevated concentrations, carbon dioxide may produce mild narcotic effects, stimulation of the respiratory center, and asphyxiation, depending on the concentration present and the duration of exposure (Ref. 131). Although an increase in pulmonary ventilation may result from inhalation of 1% or less, the initial effect of carbon dioxide is noticed at concentrations of about 2% (20,000 ppm), at which breathing becomes deeper and the tidal volume increases. The depth of respiration increases with increasing concentrations of the gas and at 4% is markedly increased. At approximately 4.5 to 5% breathing becomes labored and distressing to some individuals. This information basically agrees with the symptoms given in Table 5-10.

There are conflicting reports regarding the concentrations of carbon dioxide that may present a serious hazard. One source (Ref. 131) has stated that concentrations of 8 to 10% have been inhaled by men for periods of up to one hour with no evident harmful effects. According to another source (Ref. 136), carbon dioxide is weakly narcotic at 3% and causes reduced hearing acuity and increased blood pressure and pulse, and at 7 to 10% it can produce unconsciousness within a few minutes. The American Council of Governmental Industrial Hygienists has recommended a threshold limit value for a short-term exposure limit of 15 min for 30,000 ppm (3%) of carbon dioxide (Ref. 123).

5-6.1.4 Oxygen Depletion

Oxygen is consumed from the atmosphere during combustion. A reduction of the oxygen concentration in the air

TABLE 5-10. HUMAN PHYSIOLOGICAL EFFECTS FROM VARIOUS LEVELS OF CARBON DIOXIDE (Ref. 46)

CONCENTRATION IN AIR, ppm	SYMPTOMS
250-350	Normal concentration in air
900-5000	Without effect
5000	TLV and MAK value
18,000	Ventilation increased by 50%
25,000	Ventilation increased by 100%
30,000	Weakly narcotic, decreasing hearing acuity, increased blood pressure and pulse
40,000	Ventilation increased by 300%, headache, weakness
50,000	Symptoms of poisoning after 30 min, headache, dizziness, sweating
80,000	Dizziness, stupor, unconsciousness
90,000	Distinct dyspnea, loss of blood pressure, congestion, fatal within 4 h
120,000	Immediate unconsciousness, death in minutes
200,000	Immediate unconsciousness, death by suffocation

TLV = threshold limit value in the working area (US)
MAK = maximum allowable concentration in the working area (Germany)

inhaled results in a decreased oxygen partial pressure in the blood stream and a decreased supply of oxygen to tissues. Although all cells of the body require oxygen for proper functioning, the brain and the heart are particularly susceptible to a reduced oxygen supply. Oxygen depletion, however, generally does not result in noticeable symptoms until the oxygen concentration is reduced to approximately 16% or less. The symptoms exhibited by humans as a result of inhalation of air with reduced oxygen content are shown in Table 5-11.

Whether due to asphyxiants or to the low-oxygen environment associated with fires, the effects of lack of oxygen are worth noting. Phillips (Ref. 114) reported a general psychological effect due to lack of oxygen: Individuals may think they are rational while exhibiting irrational behavior. Cagliostro and Islas (Ref. 129) reported that the general effects of low oxygen on humans include decreased night vision, stupefication, impaired coordination, malaise, loss of consciousness, and ultimately death.

TABLE 5-11. HUMAN PHYSIOLOGICAL EFFECTS OF REDUCED LEVELS OF OXYGEN (Ref. 46)

OXYGEN IN AIR, %	SYMPTOMS OR REMARKS
20	Normal
17	Respiration volume increases, muscular coordination diminishes, attention and clear thinking require more effort
12-15	Shortness of breath, headache, dizziness, quickened pulse, fatigue occurs quickly, muscular coordination for skilled movements lost
10-12	Nausea and vomiting, exertion impossible, paralysis of motion
6-8	Collapse and unconsciousness occur
6 or below	Death in 6 to 8 min

5-6.1.5 Synergistic Effects

Kaplan et al (Ref. 137) demonstrated a relationship between rodent performance and nonhuman primate performance during exposure to different concentrations of carbon monoxide, acrolein, and HCl. Such an approach could provide more accurate estimates of human performance, and a cost-effective research approach to predicting human performance capabilities during exposure. Animal models offer a solution, but care must be taken to avoid overgeneralization. For example, Kaplan et al (Ref. 127) noted that although the effects of carbon monoxide and HCN on humans and mice are believed to be relatively comparable, the effects of HCl may actually be far less severe for mice than for humans.

To evaluate the potential hazard of a smoke atmosphere, the possible interactive effects of all of the asphyxiant gases as well as the reduction of oxygen in that atmosphere must be considered. The effects of these gases and oxygen depletion should be considered additive and may under some conditions even be synergistic. Until there is evidence of synergism, however, assessment of the hazard should be based on summation of the asphyxiant effects contributed by the concentrations of each of these gases and the reduced oxygen concentration. For this summation the ACGIH additive formula (Ref. 123) for hazardous substances that act upon the same organ system may be modified to allow assessment of the hazard from acute exposure to mixtures.

5-6.2 THE IRRITANT GASES AND PARTICULATE SOLIDS

Smoke atmospheres contain a wide variety of irritant gases and particulate solids. Examples of irritant gases produced by combustion of many materials include hydrogen chloride (HCl), hydrogen fluoride (HF), and acrolein. In addition, burning materials may produce ammonia (HN_3), sulfur dioxide (SO_2), isocyanates, and various aldehydes and organic acids.

5-6.2.1 Irritant Gases

Irritant gases have been differentiated on the basis of their site of action as sensory irritants, pulmonary irritants, bronchoconstrictors, and respiratory irritants (Ref. 138). Sensory irritants, e.g., HCl, NH_3, SO_2, and acrolein, are highly soluble and primarily affect the upper respiratory tract. When inhaled, these gases stimulate the trigeminal nerve endings of the nose, evoke a burning sensation, and inhibit respiration. These gases also induce tearing, may cause a burning sensation in the skin, and most will produce laryngeal stimulation and coughing. Some sources indicate that the concentration is of far greater significance than the duration of exposure in estimating the hazards of exposure to sensory irritants (Ref. 139).

Pulmonary irritants like nitrogen dioxide are less soluble than sensory irritants, penetrate more deeply into the respiratory tract, and cause rapid, shallow breathing and a sensation of labored breathing (dyspnea) and breathlessness. Exposure to these gases also may result in development of pulmonary edema, which is accompanied by painful breathing, and may lead to death. These gases cause little or no irritation to the eye or nasal passages at concentrations sufficient for pulmonary irritation, and their odor can be disguised among all the other odors within a combat vehicle. Therefore, there can be little warning of their presence.

Bronchoconstrictors (HCl, NH_3, and toluene diisocyanate) are those gases that induce increased resistance to airflow within the conducting airways of the lung. Most of these chemicals also are sensory irritants and act on the bronchial mucosa to produce a painful sensation.

When inhaled, some gases can act as a sensory irritant, a pulmonary irritant, and a bronchoconstrictor (Ref. 138). Those irritants capable of all three actions are referred to by the general term "respiratory irritant". Examples are chlorine and very high concentrations of acid gases.

5-6.2.2 Particulate Solids

Phillips (Ref. 114) argued that although the effects of gases in smoke have received much attention, he noted that little has been done to determine the effects of particulate matter. Particles too large to be inhaled can lodge in the nose, mouth, and throat, and when swallowed, their aldehyde and acid coatings may cause nausea and vomiting. Acids absorbed in smoke particles might cause choking. Any of these disorders can disrupt human performance, especially when the tasks are highly cognitive or complex. Finally, any foreign matter inhaled in sufficient quantities irritates tissue and results in coughing and nasal discharge even though it might not formally be classified as a toxin.

All smoke atmospheres contain particulate solids that may irritate the eyes and respiratory tract. In addition, these particles may obscure vision and clog nasal passages. The size (aerodynamic diameter) of these particulates is a primary determinant of the extent of their penetration into the respiratory tract and their potential toxic effects. In general, particles with a diameter greater than 5 μm are removed in the nasopharyngeal region, and particles with a diameter of less than 1 μm may penetrate to the alveoli of the lungs. If irritating or corrosive chemicals are adsorbed onto particulates that reach the alveoli, these particles may severely damage the lungs. Consequently, any airborne, fire-related substance inhaled in large quantities irritates the respiratory system or the eyes and causes performance disruption. Materials used to control the fire, although not normally toxic, could significantly disrupt performance if present in large quantities. This disruption occurred in the test program described in Ref. 83. The technician was sweeping the dry chemical fire extinguishant out of the test fixture, he raised a cloud of Purple K*, which irritated his breathing passage, and he started coughing and had to leave the test fixture in order to breathe normally.

5-6.2.3 Toxic Effects

Most irritant gases exert their toxic effects locally on the skin, eyes, and respiratory tract, although some, such as HF and HBr, may be absorbed into the body and produce systemic effects. The irritant gases do not act on the same organ system or have the same mechanisms of action as the asphyxiant gases. Consequently, the effects of irritant gases and asphyxiant gases are not additive. Obviously, high concentrations of irritant gases markedly affect respiratory function and blood gases and impair an individual's tolerance to other toxicants including the asphyxiant gases. To evaluate the toxic hazard of an atmosphere containing a mixture of asphyxiant and irritant gases, the effects of the two classes of chemicals should be considered independently as recommended by the ACGIH for toxicants with dissimilar effects (Ref. 123). It is necessary in this evaluation, however, for the designer to take into account the fact that when present in sufficient concentrations, irritant gases produce physiological changes to the body, which may render the individual more susceptible to the incapacitating and lethal effects of asphyxiants or other classes of toxicants.

There could be indirect effects of fires on the lethality of any biological or chemical agents in the area. If persistent chemical nerve agents, such as thickened soman (GD), or

*A trade-named powdered fire extinguishant containing primarily potassium bicarbonate vesicants, such as mustard (HD), are being used in a conflict, they can be brought into a combat vehicle on the clothing and boots of crew members and passengers. Persistent agents have relatively low vapor pressures at temperatures under 40°C, but the higher temperatures expected in a fire would convert more of the agent to a gas and, therefore, it becomes a more dangerous inhalation threat. Even if decontamination procedures are followed, it may be a practical impossibility to remove all chemical agent contamination that a soldier might pick up from the ground, foliage, and the vehicle itself. The remaining amounts could be expected to be sublethal, but they might cause significant performance decrements in survivors of the fire.

Profound behavioral changes that result in a total loss of normal aggressiveness have been noted in baboons subjected to sublethal doses of GD (Ref. 140). Reports of controlled human exposures to GD are almost nonexistent, but one of the early senior investigators accidentally ingested a small amount and lived to describe his feeling afterward as one of profound sadness (Ref. 141). Notwithstanding the current attempts to eliminate chemical weapons, which date from the time of World War I, the Iran-Iraq conflict of the mid-1980s and the Persian Gulf conflict of 1991 demonstrate the ease with which nerve agents and mustard agents can be obtained and, as demonstrated by the Iran-Iraq conflict, used in modern warfare. Designers of military vehicles should be aware of this threat to performance as well as the lethal effects posed by these agents.

5-6.3 OTHER NOXIOUS PRODUCTS

Asphyxiants, irritant gases, and particulate solids are the most prevalent toxicants in smoke atmospheres. The effects of these gases undoubtedly dominate the toxicity of the smoke produced by most, if not all, materials. Limited analytical studies of smoke atmospheres using mass spectroscopy, however, have shown that many chemical species which are neither asphyxiants nor irritants are generated by the combustion of materials. These combustion products may be of a wide variety of chemical structures including saturated and unsaturated aliphatic hydrocarbons, ketones, aromatic hydrocarbons, etc (Ref. 117). Generally, these chemicals are produced in much lower concentrations than the prevalent asphyxiant and irritant gases. In a study of the thermal decomposition products of polyvinyl chloride (PVC) (Ref. 136), the quantities of the organics, i.e., saturated and unsaturated hydrocarbons and aromatics, from burning PVC were 36 mg/g or less each compared to 583, 729, and 442 mg/g of HCl, carbon dioxide, and carbon monoxide, respectively, Table 5-12. Although all of these organics depress the central nervous system, it is doubtful whether their combined effects would be significant relative to the effects of the major toxicants. For other materials the results of small-scale laboratory tests have shown that products of decomposition other than asphyxiant and common irritant gases could contribute significantly to the toxicity of the smoke produced. Two examples of these materials are polystyrene and Teflon®, which under certain conditions may generate styrene and an unidentified highly toxic chemical (possibly hexafluorobutylene), respectively (Ref. 110).

5-6.4 DESIGN CRITERIA FOR SMOKE INHALATION REDUCTION

Computer models of combustion and egress (Refs. 142 and 143) offer a useful tool to designers concerned about fire in vehicles. Any such models with human performance components, however, have to be generated from a relative paucity of data, and most of that is from animal models.

TABLE 5-12. VOLATILE COMBUSTION PRODUCTS OF POLYVINYL CHLORIDE SAMPLE (Ref. 136)

COMBUSTION PRODUCT	QUANTITY, mg/g*	COMBUSTION PRODUCT	QUANTITY, mg/g
Hydrogen chloride	583.0	Butane	0.28
Acetic acid	—	Isopentene	0.02
Carbon dioxide	729.0	1-Pentene	0.06
Carbon monoxide	442.0	Pentane	0.16
Methane	4.6	Cyclopentene	0.05
Ethylene	0.58	Cyclopentane	0.05
Ethane	2.2	1-Hexene	0.05
Propylene	0.47	Hexane	0.12
Propane	0.84	Methylcyclopentane	0.04
Vinyl chloride	0.60	Benzene	36.0
1-Butene	0.18	Toluene	1.3

*With this PVC sample no residue remained.

Because methodologies are still in a developmental state, animal models for performance effects in the presence of combustion-generated toxins appear to be the only reasonable approach. Mitchell et al (Ref. 144) and Rogers et al (Ref. 145) investigated the effects of combustion of natural fiber and synthetic polymeric furnishings on rat behavior. Mitchell et al found rats were able to perform various tasks three to five times longer during the combustion of wood and natural fibers than during the combustion of synthetic polymeric furnishings. In addition, they found that factors correlating with time-to-behavioral incapacitation differed for the two fire sources. For combustion of natural fiber furnishings, carbon monoxide, carbon dioxide, and total hydrocarbon concentration yielded the highest correlations, whereas for combustion of polymeric substances, temperature, hydrocarbons, carbon dioxide, and oxides of nitrogen yielded the greatest correlations. In related work with the same subjects, Rogers et al conducted blood analyses after exposure to natural fiber and synthetic polymeric combustion for different behavioral criteria and found physiological correlations to the behavioral and physical relationships described by Mitchell. More such research that links physical, physiological, and behavioral measures is needed.

There are not many design criteria concerning equipment that would reduce the possibility of personnel suffering smoke-inhalation-type injuries. Some localities prohibit the use of polystyrene foam for building insulation because it produces toxic gases when burned, but such prohibitions should be in local building codes. The Federal Aviation Authority prohibits use of some materials in commercial aircraft, but the prohibition generally is of readily combustible materials or of materials that lose strength.

The primary reason that the troops in Vietnam did not suffer smoke inhalation problems was the practice of operating with open combat vehicle hatches. The combat vehicles simply had more than adequate ventilation and/or the troops had their heads outside. Therefore, they could breathe fresh air, and smoke inhalation injuries were not considered a problem. Troops did, however, suffer a very high incidence of fragment or bullet impacts that would not have occurred if they had been within the vehicles. In other theaters or under other circumstances, combat vehicle crews will have to stay within the vehicles. When they do, ventilation will become a much greater problem.

The design objective for producers of combat vehicles should be to maintain the habitability of the vehicle in spite of ballistic and fire damage. This would mean preferably not to have a fire ignite. If a fire should ignite, it should not produce noxious fumes, or if noxious fumes are produced, the air within the vehicle should change quickly enough so that the occupants would not be forced to evacuate, or a fire extinguishant should be used that removes noxious products from the air. This concept also applies to particulates. The overall objective is to maintain vehicle habitability so that the occupants are not forced to evacuate.

Smoke generation should be precluded. Fire-extinguishing systems should be of the type that flush smoke particles and noxious gases out of the air. Fire extinguishants should be benign, i.e., have minimal toxic, noxious, or anesthetic properties. The soldiers should be trained to combat the fire first and consider evacuation of the vehicle only after they realize that the fire cannot be extinguished or that their safety is jeopardized by fire products. Power ventilation should be improved. Combustible materials should be eliminated from within occupied compartments, particularly those materials that burn rapidly. Materials used within and possibly adjacent to occupied compartments should be selected to preclude emission of noxious products when subjected to high temperatures.

5-7 EFFECTS ON HUMAN PERFORMANCE

In 1916 most of the crewmen in an English Mark IV tank fell asleep during an attack due to the heat and fumes from the engine (Ref. 3). This drowsiness is typical of the reactions of humans to moderate heat and fumes.

There is no question that a fire in a combat vehicle will have a significant effect on the performance of the crew and any passengers. Although the physiological effects of various stimulant components of combustion are often known for lower animals and to a lesser extent for humans, there is an unfortunate lack of information on their psychological and performance effects. The question thus becomes more complicated since most research has used escape response as the critical dependent measure, and that measure might or might not be appropriate for combat vehicle fires. For example, if the vehicle has a minor fire while engaged in heavy combat, evacuation from the vehicle might be more hazardous to the soldiers than continuing operation of the vehicle to effect evasion (as described in subpar. 4-8.4.3). Such vehicular evasion would require that the event and its consequences, such as the combustion components, not significantly affect the cognitive and/or motor functioning of the crew members.

5-7.1 KNOWN EFFECTS OF COMBUSTION-RELATED STIMULI

Specific effects of various combustion products are discussed in this subparagraph along with the likely implications for human performance. The effects of intense sound, intense light, and intense heat are not usually investigated in combustion-related research, but they are included here because of their obvious implications for combat vehicle fires. Although they are discussed separately, these effects would probably be combined in a real combat vehicle fire.

5-7.1.1 Effects of Contaminants

Gaume and Bartek (Ref. 112) place contaminants physiologically into one or more of the following categories:

asphyxiants, irritants, anesthetics and/or narcotics, systemic poisons, and particulate matter other than systemic poisons. These contaminants can have effects that disrupt performance in a number of ways. For example, irritants and systemic poisons can cause attention to shift from primary tasks, asphyxiants can distort reality and result in a physical inability to perform tasks, and anesthetics and/or narcotics can distort reality or numb sensation and perception.

Although many of the irritants are extremely unpleasant and painful, at least their presence is known. Often more dangerous is the insidious nature of some toxins, especially carbon monoxide and carbon dioxide, because the victim is unaware of their presence. According to Phillips (Ref. 114), some irritants, e.g., overheated chlorinated hydrocarbons such as carbon tetrachloride or trichloroethylene, can go undetected until it is too late. Many of the psychological or performance effects of various toxins are unknown, but a brief review of some of their more immediate physical effects is worthwhile.

As a group, irritants are likely to have profound immediate effects on ongoing performance because attention is almost certain to be diverted to more primary physiological needs. Known behavioral effects associated with various irritants include laryngeal and bronchial spasms, increasing hypoxia and asphyxia, blindness, rubbing of eyes, scratching, rubbing of skin, coughing, increased or decreased respiration, grand mal seizures (Ref. 146), and other abnormal behaviors that would interfere with normal operational or escape behavior long before a lethal exposure is reached. Some irritants occur more frequently, so they have received more attention (Ref. 122). Nitrogen dioxide and other oxides of nitrogen are strong pulmonary irritants. Ammonia causes primary damage to mucous membranes, skin, and eyes. If absorbed, ammonia produces some systemic effects. Hydrogen chloride gas is corrosive and can cause incapacitation long before death. On the moist eyeball, the resulting hydrochloric acid is an irritant, and pain and/or tearing are great. Terrill et al (Ref. 122) noted that HCl may be more toxic when coated on smoke particles. The halogen acid gases, e.g., HF and HBr, are sensory and respiratory irritants. Sulfur dioxide is a pungent intolerable irritant. Both isocyanates and acrolein are strong respiratory irritants. Kaplan et al (Ref. 127) report that the literature indicates that a decrease in respiration rates caused by some irritants can result in a longer period of useful function.

Hypnotic, narcotic, and anesthetic gases can cause irrational behavior, mood swings, or numbing of sensation and/or perception, which can interfere with escape or other tasks. Examples would include ketones, such as methyl ethyl ketone and isobutyl ketone, which do not affect the lungs, but when they reach the brain, they can cause confusion and unconsciousness (Ref. 114). Bromides have well-known sedative effects.

5-7.1.2 Effects of Sound or Blast Waves

According to Scharf and Buus (Ref. 147), the threshold for feeling sound waves is between the 120- and 130-dB sound pressure levels. Less-than-painful auditory stimuli, however, can cause both temporary and permanent loss of hearing that could impede the crew's performing subsequent tasks, especially communications. Jones and Broadbent (Ref. 148) discussed three types of hearing loss that follow exposure to loud stimuli; two of the three are relevant to this discussion.

The first relevant effect of exposure to loud noise, temporary threshold shift, is transient and recoverable. The magnitude of TTS depends on intensity and duration of the exposure. For example, data from Ward, Glorig, and Sklar (Ref. 149) indicate that 100 min of exposure to a 105-dB noise band results in a 40-dB TTS. Recovery depends on both the intensity and duration of exposure but usually is at least a number of hours for the kinds of loud stimuli to be expected in a combat environment. The hearing loss might be accompanied by subjective ringing in the ears (tinnitus) (Ref. 150), which also could disrupt subsequent performance.

The second relevant effect of exposure to loud noise is acoustic trauma, which results from short exposures to intense stimuli, such as those that might be experienced in a combat vehicle. Such noises might pass the pain threshold, could exceed the "elastic limits" of the auditory system, cause permanent damage, and disrupt subsequent performance of most tasks. Of course, crew members of combat vehicles should be wearing protective headgear that would attenuate the effects of loud stimuli to varying degrees (Ref. 151). The headgear of the crew members contains earphones needed for communication as well as protection. Passengers, primarily troops carried in APCs or IFVs, whose principal task is performed after dismounting from the vehicle might not wear headgear that protect hearing. In fact, such gear would inhibit the hearing of dismounted personnel and reduce their effectiveness. Headgear, amplitude-sensitive earplugs (Ref. 152), and other protective measures—while protecting hearing—can have subtle detrimental effects on human performance by reducing communication and the salience of alarms, warnings, and important auditory cues. Henry (Ref. 77) pointed out that of 292 men sustaining blast injuries to the ears during WWII, 70 suffered vertigo. Most of these 70 had stated that they had been unsteady on their feet for a few minutes or perhaps an hour or two. A few had been unconscious for a short time. Only three gave a history of a short, acute vestibular attack, i.e., damage to the inner ear. Sixty-four of the 70 had a perforated eardrum, and 14 of the 70 men complained of continuing occasional attacks of unsteadiness.

In summarizing the effects of noise on human performance, Kryter (Ref. 153) described the general disruptive effects of noise on mental and motor performance. In addition, he noted that individual differences have been reported in the literature with regard to the disruptive effects of noise. For example, there is evidence that persons with high anxiety exhibit more performance disruption due to noise.

5-7.1.3 Effects of Flash or Flying Particulates

For combat vehicles that are on fire, the two extremes of light intensity are relevant. For one extreme an intense flash might be present and have physiological, behavioral, and cognitive effects on the crew. The intensity of light incident on the cornea of the eye is not the same as the intensity at the retina. The amount of light arriving at the retina depends on a number of factors, which include the size of the pupil. The larger the pupil, the more light enters the eye. A unit of retinal illuminance, the troland (td), is based on the fact that the light passing into the eye is proportional to the area of the pupil. The troland is defined as the retinal stimulation provided by a source of 1 cd/m^2 viewed through a pupil of 1 mm^2. The troland value for the stimulus is given by td = 1 $(cd/m^2) \cdot A_p$ (mm^2), where A_p is the pupil area in mm^2. According to Hood and Finkelstein (Ref. 154), physical damage can occur to the eyes if they are subjected to a log luminance greater than 8 cd/m^2 or a retinal luminance greater than 8.5 trolands. Flashes below this intensity can cause temporary loss of visual acuity that would interfere with performance.

On the other extreme, smoke and fumes can obscure vision and create physiological impediments to good vision because of the toxic gases or particles in the smoke. Smoke, dust, and/or solid particulates can also cause eye irritation which results in tearing. Jin and Yamada (Ref. 155) showed that visibility, e.g., ability of subjects to read emergency exit signs, significantly decreased due to excessive tearing, itching, and burning when subjects were in a room filled with an irritant smoke more than when subjects were in a room filled with equally dense, nonirritant smoke. In addition, fire or explosive damage to the electrical system of a vehicle might interrupt normal light sources and disrupt human performance until light is restored or until adaptation to the dark occurs after 15 to 20 min.*

5-7.1.4 Effects of Heat and Burns

The variables affecting heat stress and the corresponding detrimental effects on performance are well-known for the general work population (Refs. 157 and 158). Kobrick and Sleeper (Ref. 159) have shown that performance can further degrade if soldiers are wearing their nuclear, biological, and chemical (NBC) protective clothing qualified per mission-oriented protection posture for threat level four (MOPP-IV). Of the critical thermal determinants (Ref. 160), which are dry-bulb temperature, water vapor pressure, mean radiant temperature, air velocity, operating temperature, clothing, metabolism, physical activity, and time, all are potentially relevant for assessing the effects of a fire in a combat vehicle. When the heat from a fire is added to what is likely to be already a hot, humid, and poorly ventilated environment, profound performance decrements or collapse are likely, especially when the probable combat-related mental and physical exhaustion of the crew is considered.

The most obvious effects of a burn other than pain are an increase in general arousal and decrease in motor control and tactile feedback. Both motor and cognitive performance will undoubtedly be affected. The amount of disruption is a function of the severity and location of the burn, the difficulty of the task, and the relationship of the task to the burned area.

Hughes and Cayaffa (Ref. 161) reviewed the literature on the effects of burns on the central nervous system. They found that even minor burns were known to be associated with delayed decrements in motor and cognitive performance. In addition, personality changes, e.g., hostility, aggression, hyperactivity, and emotionally unstable or assaultive behavior, often follow burns. Another notable delayed effect of burns is the occurrence of seizures, which are found to follow even minor burns, from 12 to 48 h following the mishap.

5-7.2 GENERAL EFFECTS OF HIGH AROUSAL ON HUMAN PERFORMANCE

The Yerkes-Dodson Law describes the classic "inverted U"-shaped relationship between level of arousal and performance. In general, as arousal from any source increases, performance proficiency initially increases and then decreases. Spence (Ref. 162) and Spence, Farber, and McFann (Ref. 163) have theoretically and empirically extended the relationship to include difficult tasks. Essentially, high levels of arousal have been shown to disrupt performance of difficult tasks more than of simple tasks. Consequently, the inevitably high levels of arousal that would accompany most of the specific effects of combustion-related stimuli would have marked detrimental effects on most human performance for all but simple, well-known tasks. Because of the highly cognitive and difficult nature of the tasks involved for many combat vehicles, marked deterioration must be predicted. In extremely arousing situations, tonic immobility, i.e., a catatonic-like, paralyzed state, has been observed (Ref. 164).

Jones and Broadbent (Ref. 148) discussed the general effects of loud noise on human performance. Portions of

*Adaptation to the dark is greatly affected by what the individual is doing. An ACV crewman, who has many vision aids built into the vehicle, can adapt more quickly than a person who is trying to get out of a dark building. A scout who is going on night patrol requires even more time—the time required for such adaptation to the dark was given to be 1 h for personnel in the US Army during World War II (Ref. 156).

their discussion can be extended beyond noise stimulation to other intense stimuli, e.g., light flashes, irritant gases, and burns, that have precipitous, often unpredictable onsets. They noted three immediate reflexive responses to such stimuli:

1. The startle response that is a protective reflex muscular response
2. The orienting reflex that is a "general alerting response (a 'what is it?' reaction)"
3. The defense reflex that describes more protective reactions to intense stimuli.

Any or all of these reflexes would almost certainly disrupt ongoing performance, and even a momentary disruption could seriously affect the crew's proficiency if it occurs during a lengthy or complex procedure.

Another effect of an unpredictable intense stimulus is the sense of reduced control and increased uncertainty. When subjects have been subjected experimentally to environments in which they have no control or lose control, performance of various subsequent tasks has been shown to degrade (Ref. 165). In addition, increased uncertainty can lead to bad decisions and performance, e.g., "We have been hit; can I trust the instruments now?". Keating (Ref. 166) argued that another effect of increased arousal is a narrowing of attention.

Jones and Broadbent (Ref. 148) described the following classes of tasks that are especially vulnerable to loud and unpredictable noises:

1. Those requiring steady motor performance such as tracking a target
2. Those occurring infrequently, such as engaging a surprise target, or those that are unimportant
3. Those demanding immediate actions required by almost all ACV crewmen
4. Those requiring comprehension of meaning, such as a gunner or loader responding to a fire command
5. Those requiring flexibility of response such as selecting the appropriate round, e.g., HE, HEAT, sabot, beehive, shot, or smoke.

Unfortunately, most of the these tasks are required of soldiers in a combat setting.

Another potentially counterproductive reaction to high arousal is the "panic response". Keating (Ref. 166) described the widespread belief that panic is an inevitable reaction to fire as a myth. He argues that true panic is defined by the presence of all of the following four criteria: perceives chances for escape are decreasing, models others who demonstrate extreme behavior, displays aggressive concern for own safety, and responds irrationally. After reviewing various reports of actual fires, he reported that by his definition panic is the exception rather than the rule.

Other important variables known to affect both the panic response and subsequent probability of survival are the social context and individual differences. Kelley (Ref. 167) showed that exposure to other individuals who do not react to smoke can greatly reduce the panic reaction. Phillips (Ref. 114) reported that it is a common military experience for individuals who are normally brave in the presence of fellow soldiers to freeze or run when suddenly isolated. Phillips noted that important individual differences in reaction to fire situations include physical fitness, emotional fitness, education and training, past fire experience, presence or absence of others, intelligence, physical reaction to contaminants from the combustion, and the individual's sense of responsibility. Keating (Ref. 166) reported that rational behavior is likely during fires; Glass (Ref. 168) reported that in a fire emergency about 1% of the population exhibits denial and withdraws from reality and either shows inappropriate activity or becomes motionless.

5-7.3 OVERVIEW OF DESIGN COUNTERMEASURES

This paragraph is intended to reinforce the importance of human factors considerations in system design to maximize performance in the event of fire. Because it is impossible to anticipate all the specific human performance questions that might emerge for various combat vehicles, the reader is referred to specific military (Ref. 169) and nonmilitary (Refs. 170 to 172) human factors and human performance references. Campbell and Cook (Ref. 173) reported that more noncombat fires (32.8%) in Army ground vehicles were started by soldiers than by any other source; thus vehicle designers should be aware of the specific soldier errors involved and attempt to design vehicles to minimize the effects of those errors.

5-7.3.1 Facilitating Cognitive and Motor Performance in a Crisis

When the combat vehicle is designed, a task analysis should be conducted to determine what decisions and/or actions are demanded of the crew in a fire situation. The resulting task demands should be addressed during the design process. Many assumptions should be avoided, e.g., assuming all sensory systems are functional, assuming rational decision making, and assuming full motor dexterity of crewmen even while something in the vehicle is burning. The designer should consider potential crisis environments, training implications, human expectancies, human anthropometry, and human performance variables when allocating functions and when specifying instrument and control configurations. When designing alarm systems, designers must ensure that soldiers are warned, but the designers also must be aware that the loud cues and bright lights typical of some warning systems can themselves disrupt human performance by increasing anxiety and making concentration difficult.

5-7.3.2 Facilitating Escape and Subsequent Survival

Combat vehicles should be designed to enable crewmen to continue to fight or, if necessary, to expedite human escape and subsequent survival. The designer should design the vehicle to negate the terminal effects of all potential threats or at least to eliminate the possibility of catastrophic results. Designers should assure that crewmen are not incapacitated by the direct threat effects, or by their indirect effects. The designer should select materials and systems that could reduce the probability of having a large fire, would enable the crewmen to extinguish a small fire, and would keep the vehicle habitable. The designer should consider crew variables (e.g., anthropometry, protective clothing, gear, probable psychological and physical condition, expectancies, etc.); variables affecting the design of the escape route (e.g., number of routes; visual, auditory, and tactile marking of routes; and, type, location, and size of passages); escape hatch variables (e.g., number, size, control characteristics, and markings); and subsequent survival variables (e.g., stowage contents, stowage location, first-aid considerations, communication considerations, and subsistence considerations).

5-7.3.3 Combat Experience From Southwest Asia

An incident in which an Iraqi T-72 MBT mounting a 125-mm gun hit a BFV M2A2 in the front with a main gun projectile that caused an explosion and a fire which wounded three crewmen allows the following conclusions. The initial combustible was probably propellant from a number of the 25-mm cartridges, probably the AP M791, because, had a TOW missile been hit and either a rocket motor or a warhead initiated, the BFV M2A2 would have been totally demolished rather than merely set afire. The vehicle burned for a period of time (Ref. 64) before it was destroyed by an internal explosion (Ref. 65). The driver was hit in the back by a large piece of metal, which was probably a piece of the ruptured steel case from an M791 cartridge. (This effect has been witnessed in tests of other cartridges (Ref. 174).) (The flame temperature of the propellant for the M791 cartridge is 2727°C (4941°F) (Ref. 175).) The driver was wearing a CVC uniform (Ref. 65), but this uniform was ignited by the initial fire (Ref. 64). The CVC uniform is made of Nomex®, but Nomex® can burn, as shown by Knox (Ref. 62) who reported that a single layer of Nomex® was consumed by a JP-4 torch—flame temperature of approximately 1500°C—in approximately 1.9 s.

This incident showed that the BFV crewmen had no difficulty evacuating the vehicle, that Nomex® can ignite and burn given a sufficient ignition source, and that the CVC uniform provides excellent protection. The incident also indicates that a better system for carrying the ammunition is advisable. Such a system could be like that devised for the Advanced Survivability Test Bed, subpar. 4-6.2.2.3, or at least the steel covers used in World War II, subpar. 4-6.2.2.1.

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CHAPTER 6
FIRE DETECTION SYSTEMS

Fire detection systems are described. Optical and thermal detectors are described, and their timing, false alarm susceptibility, sensitivity, durability, and suitability for use in combat vehicles are covered in detail. The optical detectors include infrared (IR), visible light, and ultraviolet (UV) types. The thermal detectors discussed are continuous thermal detectors, and they include thermistor, thermocouple, eutectic salt, and pneumatic types. Other systems, such as thermocouples, thermopiles, and penetration detectors, are described.

6-1 INTRODUCTION

A fire detection system establishes that a fire is present within a given compartment of a combat vehicle and provides a signal to the fire-extinguishing system (be it the crew or a fixed fire extinguisher) to extinguish that fire. To establish the presence of a fire, the detection system uses sensors to monitor parameters that are signatures of the fire and sends signals proportional to, or indicative of, the presence of the signature to a controller. This logic-following element may be remote, within the control module, or it may be local, within the sensing module. The logic element follows a preset logic pattern to establish whether there are signatures present that indicate a fire rather than other phenomena, and then it selects and signals the action to be taken to control the fire.

In this chapter, potential fire situations are described in order to provide insight into the signatures present for different types of fires and to establish the system timing needed to respond to each type of fire. Other background phenomena and conditions are described to provide information needed to prevent erroneous system reactions. Descriptions of the various types of detection systems are given that include details of the key components and provide information on their capabilities and limitations. Other information is provided on details needed to assure that these systems are suitable for use in combat vehicles.

6-1.1 BACKGROUND

The design of a combat vehicle is the product of the compromises necessary to assure accomplishment of its battlefield mission. Fire survivability can be enhanced by optimization of design, location of vehicular components, and materials selection, as described in other chapters. Current combat vehicles are divided into compartments; each compartment has different contents, characteristics, and operational requirements that affect fire survivability. The combustible contents of these compartments vary from explosives through readily ignitable materials subject to rapid combustion or less readily ignitable materials, which normally burn more slowly, to items that are difficult to ignite and tend to smolder for a long period of time until changing conditions enhance their rate of combustion. Within these compartments different degrees of combustion can be tolerated, but normally any extraneous fire is undesirable. When the fire prevention techniques described in previous chapters fail to suppress these extraneous fires, properly designed fire detection and extinguishing systems provide the final measure of fire survivability. The savings in personnel and equipment can be significant and can result in preserved battlefield capability. Combat loss data from Vietnam showed 2207 armored personnel carriers were battlefield losses in one year, 16% of which were destroyed by sustained fire. Subjective assessment indicated that half of these vehicles could have been saved if they had been equipped with a 100% effective fire suppression system (Ref. 1). Similarly, assessment of combat loss data from Vietnam indicated also that 13% of the M48A3 tanks subjected to direct-fire kills and 2% of the tanks subjected to mine kills could have been saved had they been equipped with a 100% effective fire suppression system (Ref. 2). An assessment of the M60 series tank against kinetic energy (KE) and shaped-charge weapons indicated that 4.8% would probably be destroyed by sustained fuel or hydraulic fluid fires if a 100% effective automatic fire suppression system is not used (Ref. 2).

Fire detection is a function of the signature of the fire, layout of the compartment, sensitivity of the sensors, and the logic followed by the detection device. The signatures of a fire are commonly thought of in terms of heat, light, smoke, and sound. A broader view, however, includes detectable pre-fire phenomena such as the imminent penetration of a fuel cell. A fire detector functions by responding to one or more signature elements of a fire. That information is provided through a controller to actuate the extinguishing system, which discharges an extinguishant. In its simplest form detection consists of a combat vehicle crew member who sees, feels, smells, or, in isolated cases, hears a fire. The crew member responds by determining the location and nature of the fire hazard and then taking action to extinguish the fire, perhaps with an onboard, portable fire extinguisher. The range of the crew's senses, however, does not extend to all compartments of a combat vehicle. The engine compartment, for example, is usually isolated from the crew. It is for these isolated compartments that remote detectors and fixed extinguishers were developed. The detectors sense one or more of the signature elements of a fire and convey that information to the crew, perhaps by an alarm. Extinguishant is then released into the compartment either automatically or by the crew. Experience and evaluation of the increased complexity of modern combat vehicles have demonstrated the importance of sensors providing timely, reliable information. Obviously, a remote sensor that signals a fire after considerable damage has already occurred is not very effective. Similarly, a remote sensor that reports a fire where there is none may cause prematurely emptied extinguishers. This situation unnecessarily exposes the crew and the vehicle to a greater risk of injury or damage due to a subsequent fire.

Selection of the technique and equipment to be used to detect combustion or combustion products should be driven by the type of fire and its signatures, the combustible, the characteristics of the extinguishant and extinguishing method used, the characteristics of other materials or phenomena present, the resistance to heat damage of the items to be protected from the fire or its products, and the configuration and contents of the volume in which the fire would occur. A fast-growth fire would require a fast-response detector system. Therefore, a sensor that requires a fairly large mass of material to rise in temperature would probably have too slow a response, but a detector system that uses incident electromagnetic radiation (emr) to heat a fairly small mass would probably have an adequate response. On the other hand, a detector system for a smoldering fire would have to sense the presence of smoke or the absence of emr due to the absorption of that emr by the products—probably carbon monoxide or smoke—of that smoldering combustion, and the response requirement would be much slower. A steel hull can tolerate a higher temperature for a longer time than an aluminum hull, electrical insulation and hydraulic fluid hoses can withstand flames for a few minutes, but a human cannot withstand the temperature of a hydrocarbon fuel spray fireball for more than a fraction of a second. Therefore, a steel-hulled vehicle can use a detector system that is slower, has a higher reaction temperature, and requires a greater change in temperature than an aluminum-hulled vehicle can without risking excessive damage. Also an engine compartment can resist a fireball and a short duration fire, but a human cannot. A fairly open compartment can depend upon a detector system that senses incident emr, but a cluttered compartment requires either a great number of incident emr sensors or a detector system that either senses ambient temperature or draws air samples representative of the entire compartment.

6-1.2 EXAMPLES OF FIRES TO BE ENCOUNTERED

The following are examples of fires that must be detected, the signatures of these fires, and other signatures that complicate detection. While considering these cases, the design engineer must keep in mind the events that are occurring, the reason the fire is being detected, and the capabilities of the fire-extinguishing equipment.

1. *Case 1.* A shaped-charge jet passes through both a hydrocarbon liquid in a container and an occupied compartment so that the hydrocarbon liquid is sprayed into the compartment. The jet appears as a very short duration rod of white light that is visible for 1 to 3 ms. Where the jet encounters solid layers of material, particularly metal, the material is splashed backward toward the source of the jet and spalled forward following the jet. Both the splash and the spall, which are hot particles, usually emit strong flashes of light. The flash from aluminum is much stronger and has a longer duration than that from steel. This splash and/or spall is normally the ignition source for a fuel spray fireball. This fuel spray when ignited emits an orange to yellow light. This incipient combustion normally spreads rapidly throughout the spray. Unless extinguished, this fireball heats and ignites other combustibles, and a catastrophic fire results. To prevent burn injury to the occupants, this fireball must be extinguished within 250 ms, a time to which the US Army Surgeon General agreed after considering both human reaction to heat and fire suppression equipment capabilities. The emr emitted by combustion of a hydrocarbon liquid has been characterized and is discussed in subpar. 6-1.4.

2. *Case 2.* The circumstances are the same as those for Case 1 except that the compartment is unoccupied by humans, e.g., an engine compartment, and the fire can burn longer because the items within the compartment are not as vulnerable as a human. For example, the fireball can be allowed to self-extinguish, but sustained combustion of other combustibles within the compartment is not permissible. An engine compartment differs from an occupied compartment in that there are usually exposed hot surfaces, which will ignite sprayed or spurted combustible liquids upon contact. Those hot surfaces, such as the combustor can in turbine-powered vehicles and the exhaust ducting in diesel-powered vehicles, also radiate heat, which can complicate fire detection. The rupture of the combustible fluid container can also be due to an accident, fatigue failure, or some other failure.

3. *Case 3.* A shaped-charge jet or a KE penetrator passes into a compartment and encounters an explosive-filled object. The results can be (a) a detonation of the explosive, (b) a deflagration of the explosive, (c) a less energetic combustion of the explosive, or (d) a mechanical rupture of the casing of the explosive with no subsequent chemical reaction or with chemical reaction of only part of the explosive charge. Result is a self-announcing and would probably be completed before a fire suppression system could react; hence it need not be detected. Results b and c should be detected and would cause emr to be broadcast. In some situations, the emr emitted by Results b and c have been characterized. Result d needs no response by an automatic fire suppression system because a partial chemical reaction self-extinguishes or ceases.

4. *Case 4.* A shaped-charge jet or a KE penetrator enters a compartment, and particles from either or their associated spall make contact with a slow-burning combustible. Combustion starts either immediately or later. The sig-

natures of this combustion may be emr, smoke, products of combustion, heat, and/or sound.

5. *Case 5.* Combustion initiates or becomes hazardous without a ballistic impact. An electric wire may short, or some nonballistic phenomenon may cause sparks or generate heat and then ignite some slow-burning combustible material. This can be caused by shorting of a wire bared by ballistic impact, accidental abrasion, fatigue failure, or some other failure. The signatures can be emr, smoke, sparking, products of combustion, heat, and/or unusual electric power loss or variations.

6-1.3 FIRE SIGNATURES

The signatures of a fire—means by which a fire can be discerned—follow:

1. *Type 1.* Electromagnetic radiation, which normally is lower ultraviolet, visible light, and/or infrared
2. *Type 2.* Smoke, combustible vapors, and products of combustion, which include water, carbon dioxide, and carbon monoxide
3. *Type 3.* Radiated heat, heated air, and heated products of combustion
4. *Type 4.* Sound.

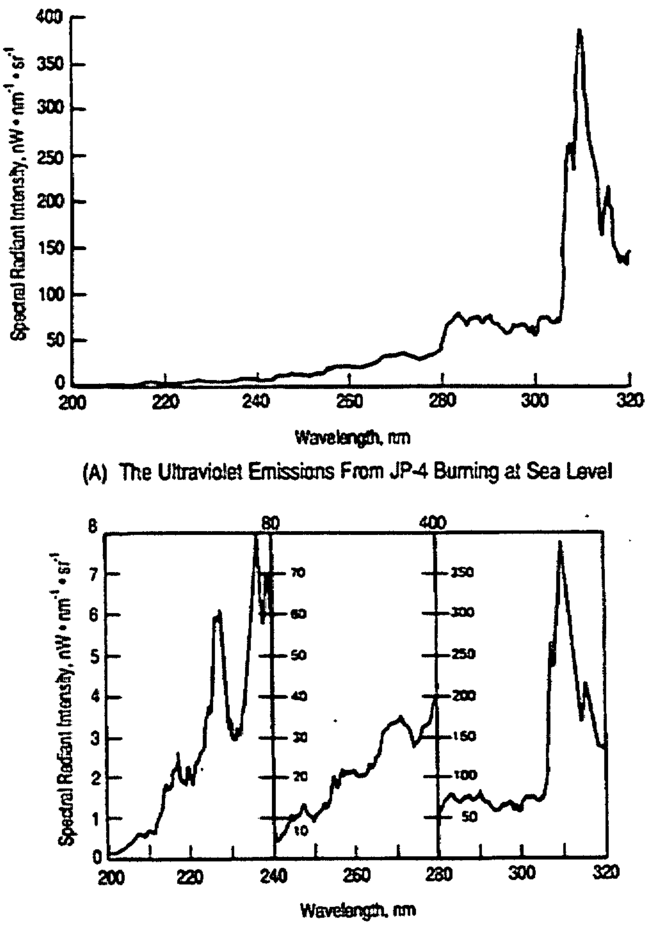
All of these signatures change with the intensity or rate of combustion. The intensity of Signatures 1, 3, and 4 increases with the availability of oxygen. It is common knowledge that an oxygen-rich fire burns hotter, whereas a fuel-rich fire is smokier. A common example often given is that a Bunsen burner, a propane torch, and a natural gas burner will produce yellow flame when the fuel valve is fully open; as the fuel supply is reduced, the flame will become blue—almost invisible—and the blue flame is hotter than the yellow flame.

When thermally excited, atoms and molecules emit or absorb emr when electrons within a molecule are excited from one quantum state or relax to a lower quantum state. Since the energy levels associated with an atom or molecule are uniquely defined, the energy spectrum associated with transition between these levels is unique, and the frequency of the radiation thus emitted is considered characteristic of that particular atom or molecule. As more heat energy is absorbed by the atom or molecule, however, electrons that are more firmly held will "jump" and cause emr of other frequencies to be emitted also. This additional energy also strains the bonds between atoms of the molecules, which may break. Since the emr frequency emitted by the constituent atoms can differ from that of the molecule, with added energy the spectrum emitted may change. Also molten particles of uncombusted material may be thrown off, and may radiate other frequencies or absorb some frequencies. This action in turn further alters the spectrum of frequencies that can impinge on the detector. Thus emr from a slowly combusting fire differ from those of a violently combusting fire. The incipient rapid-growth fire, such as that of a hydrocarbon fuel spray, would initially broadcast emr that are different from those of a sustained fire.

The radiation emitted by a hydrocarbon flame consists primarily of continuum radiation from minute soot, i.e., carbon, particles and infrared radiation from the hot gaseous products, which are mostly water vapor and carbon dioxide. An example of this radiation is shown on Fig. 6-1 for sustained combustion of JP-4 (Ref. 3). Other hydrocarbon fluids have similar emissions (Ref. 4), and their spectra have peak excitations at the same wavelengths but with slightly different magnitudes.

6-1.4 DEVELOPMENT OF AUTOMATIC FIRE DETECTION AND EXTINGUISHING SYSTEMS FOR COMBAT VEHICLES

Serious development of totally automatic fire detection and extinguishing systems began with the acceptance of Halon 1301 extinguishant for use in combat vehicle crew areas (Ref. 5). These systems are capable of automatically detecting and extinguishing a rapid-growth, hydrocarbon fuel spray fire within 250 ms of its initiation. Such automatic systems virtually eliminate hydrocarbon spray fireballs as a major casualty producer during combat, a level of

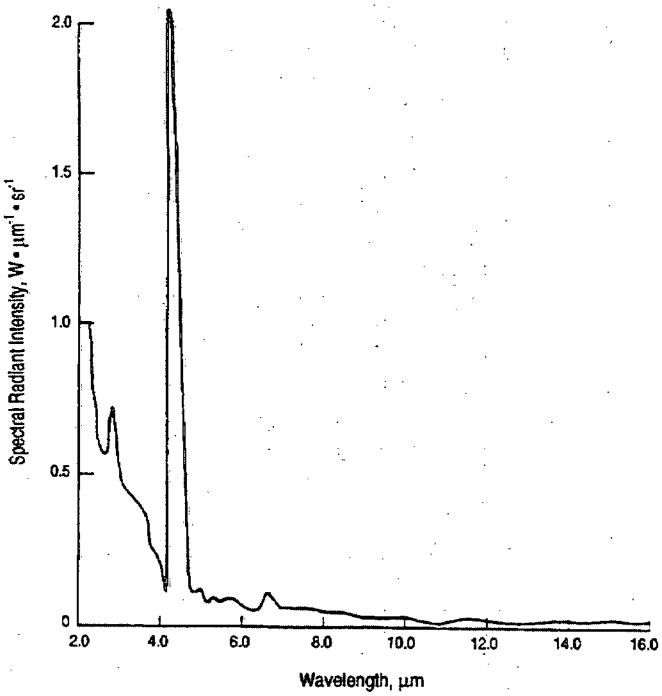


(A) The Ultraviolet Emissions From JP-4 Burning at Sea Level

(B) Spectral Radiant Intensity of JP-4 Burning at Sea Level (200-320 nm)

Figure 6-1. Electromagnetic Radiations From JP-4 Burning at Sea Level (Ref. 3)

(cont'd on next page)



(C) Far Infrared Emissions From JP-4 Burning at Sea Level

Figure 6-1. (cont'd)

effectiveness that cannot be approached by manual or semiautomatic systems (Ref. 6) but can be achieved by a passive system. Par. 4-8 and subpar. 7-3.2.3 describe such a passive system.

The phenomena upon which combustion detectors are based are (1) an increase in molecular activity when heat energy is absorbed, which is manifested as expansion of solid materials, (2) an increase in pressure by a confined fluid, (3) a change of resistance to electric current flow in a material, (4) a change in electric potential at the junction of two materials, (5) and/or emission of electrons from materials that normally retain them.

6-2 OPTICAL DETECTORS

Optical detectors have been widely applied in combat vehicles and are well-accepted throughout industry. The optical detector systems, e.g., MIL-S-62546 (Ref. 4), used in the fast response automatic fire detection and extinguishing systems sense emr from the fire that are directly incident on the sensor window or eye. These optical sensors are well-suited to situations in which speed of detection is critical. Optical sensors are selected or adjusted to sense specific spectral emissions that are characteristic of combustion but not normally present in ambient conditions. These emissions may be absorbed by smoke, dust, vapors present in the air, or deposits on the sensor eye and thus reduce the capability of the detector to identify their presence. Similarly, objects may mask the emanating source. These detector systems must be powered, and the detector output must remain connected to the control unit for the systems to be functional. The two primary types of optical detectors are the UV detector and the IR detector. There are also combination-type detectors that sense both UV and IR signals.

6-2.1 GENERAL CHARACTERISTICS

Optical detectors are selected for their sensitivity to specific wavelength bands and their responsiveness. Incident radiation optical sensors are of four basic types: photoemissive, photoconductive, photovoltaic, or photodiode. (Ref. 7)

The photoemissive type has a cathode-anode set encased within an evacuated, transparent container. When emr impinges upon the cathode (which is coated with a material containing excess electrons), it emits electrons that can flow in a circuit to the anode. The output of this device is a current proportional to the intensity of the incident emr. This device is bulky and requires a high voltage to function. At present, this type of sensor has been supplanted by solid-state devices.

The photoconductive-, or photoresistive-, type sensor has an emr-sensitive resistor between electrodes on a transparent plate and provides a change in resistance as a function of the intensity of incident emr. This type is relatively slow due to thermal inertia.

The photovoltaic-type sensor—or solar cell—uses a sandwich of unlike materials that develop a voltage across the junction when irradiated with emr. This is the only type that requires no external power, and although fast, it is not as fast as the photodiode type. This photovoltaic type can develop 0.4 to 0.5 mA in bright sunlight.

There are four major versions of the photodiode-type sensor: (1) with a PN junction, (2) with a PIN junction, (3) a phototransistor, and (4) a photodarlington. The simplest is the PN junction photodiode in which an N-type semiconductor, with a donor impurity that causes the matrix to have a negative charge, is abutted to a P-type semiconductor with an acceptor impurity that causes the matrix to have a positive charge (Ref. 8). When this PN junction is irradiated, a current can flow. This photodiode is faster than the photoemissive, the photoconductive, or the photovoltaic types. The PIN junction photodiode has an additional layer between the P-layer and the N-layer. This I-layer, or intrinsic layer, expands the range of sensitivity to emr of longer wavelengths. The PIN-junction photodiode is faster than the PN-junction photodiode. The phototransistor is basically a photodiode with one stage of amplification, and the photodarlington is one with two stages of amplification. The photodarlington is slower than the phototransistor, which is slower than the photodiode (Ref. 7).

These photoelectric devices can be made selectively sensitive to different wavelengths of emr by the choice of the base materials (the donor and/or acceptor material), by filtering the emr, and/or by design of the detector circuit.

Table 6-1 provides the relative requirements for detector system response and extinguisher timeliness; the cases of fires are matched to the required detector response and extinguisher timing. Detector response is characterized as ultra ultrafast (UUF) in microseconds, ultrafast (UF) in mil-

TABLE 6-1. FIRE CASES, SIGNATURES, AND REQUIRED DETECTOR RESPONSES

FIRE CASES (See Subpar. 6-1.2.)	SIGNATURES USED (See Subpar. 6-1.3.)	DETECTOR RESPONSE (In Compartment)	EXTINGUISHER TIMING
1	1,3	UF	UF
2	3,1	F,UF,S	F
3a	*	UUF**	UUF**
3b	1	UUF,UF	UF
3c	2,3,1	F,S,UF	F
4	2,3,1	(Occupied)—S,F,UF	F,S
		(Unoccupied)—F,UF,S	F,S
5	***,2,3,1	(Occupied)—S,F,UF	F,S
		(Unoccupied)—F,UF,S	F,S

*Imminent perforation of container
**Response or timing in microsecond range (beyond current state of the art)
***Signature used is change in resistance or voltage

liseconds, fast (F) in seconds, and slow (S), which is slower than the others but less than a minute. Extinguisher timing would be in the same time regime as the detector or slightly slower. The signatures used by the detectors are also indicated. The matchings are shown in Table 6-1 ordered from best to adequate; capability and expense are factored in.

In a manual fire-extinguishing system, detectors must transmit fire information (perhaps via an alarm) to the crew, which actuates the extinguishers. Operation of an automatic system adds additional requirements for electrical compatibility and false alarm rejection. MIL-S-62546 is for optical fire sensors, which are components of the automatic fire-extinguishing systems used in military ground combat and tactical vehicles. This specification details optical sensors that can detect rapidly growing hydrocarbon fireballs within 4 ms. This detector senses incident emr. The requirements of this specification are independent of the extinguisher and can apply to sensors using extinguishers such as the water-filled, explosion-pressurized, void-space extinguishers developed for the Air Force (Ref. 9). MIL-S-62546 includes both the technical requirements (Many of which are discussed in subsequent subparagraphs.) and the standardization features, which facilitate interchangeability.

6-2.1.1 Sensitivity

The sensitivity of a fire sensor describes its ability to react and its degree of susceptibility to the stimulation of a fire. That reaction ability and degree of susceptibility are results of the design, the technology, and the environment. A fire detector must be sufficiently sensitive to sense a fire during all of the operational circumstances the vehicle encounters. For example, a sensor would not be considered sensitive if it could not sense a fire through a certain density of smoke. Similarly, it would not be considered sensitive if its viewing window became opaque and thus precluded detection of a fire. Since the intensity of light from a point source varies inversely as the square of the distance from the source, the distance between the fire and the sensor adversely affects the sensitivity of the detector, particularly when the fire first starts. Finally, the sensor must be able to sense fire signatures that are not directly in front of the sensing element, i.e., at some angle to the sensor.

Sensitivity requirements are derived from the intended purpose of the fire detection and extinguishing system. Because it is desirable to minimize the types and numbers of sensors used, the detector selected should be able to detect more than one type of fire. As shown by Table 6-1, an optical detector that has a UF response and senses a Type 1 signature would be the detector of choice for a Case 1 fire, could be usable for a Case 2 fire or Case 4 or 5 fires in unoccupied compartments, and possibly could be usable for a Case 3c fire or Case 4 or 5 fires in occupied compartments. In order to calibrate a detector that is eminently suited to detect a Case 1 fire and is usable for a Case 2, 4, or 5 fire, the requirements of MIL-S-62546 are stated in terms of threshold bands. Above the upper end of a threshold band, an automatic fixed fire extinguisher would be actuated, within the threshold band an alarm would sound or light, and below the lower end the detection system would assume the signature was from an extraneous source and do nothing.

The width of the threshold band is determined by consideration of the consequences of a false alarm as well as the results of a fire in the specific compartment. If the consequences are not significant, the threshold band can be wide.

In a military environment (particularly in ground combat vehicles with automatic fire detection and extinguishing systems), consequences are usually significant. Hence the threshold band is made as narrow as the technology allows in order to minimize false alarms. The consequence of a slow-growth fire false alarm could be increased crew stress if the warning signal were a loud horn. In addition, false alarms could lead the crew to lose confidence in the system and to ignore a subsequent potentially hazardous fire. A fast-growth fire false alarm would release extinguishant when it was not required, and if released into the crew compartment, the crew could be forced to evacuate the vehicle or to cope with the extinguishant atmosphere to the detriment of mission performance. By wasting extinguishant, such false alarms unnecessarily expose the crew and vehicle to the damaging effects of a subsequent fire. Knowledge by an adversary that a combat vehicle used a system susceptible to false alarms could be exploited, as was planned in Ref. 10, and thereby would increase the vulnerability of the vehicle.

Sensitivity is determined by the fire signatures (emr in this case) and the intensities of the emr that a sensor can detect. Fire signature intensity is a function of the physical size of the fire, the fuel, and the distance of the fire from the sensor, i.e., a small fire close to the sensor and a large fire far from the sensor can register the same signature intensity.

It is not desirable to have an automatic fire-extinguishing system (AFES) actuate to extinguish a small fire that does not present a hazard to the vehicle or crew and could be readily extinguished by the crewmen. Efforts have been made, therefore, to distinguish between a small fire, for which an AFES should not actuate in the automatic mode, and a large fire that presents a hazard to crew and vehicle and thus would require automatic actuation of the AFES. The requirements for such a system are given in individual vehicle specifications and for the optical sensor in MIL-S-62546. The specification definitions of large and small fires are not quantifiable, and the techniques for differentiating between these fire sizes are not defined. In these specifications a small fire is identified as the flame from DF-2 in a 130-mm (5.1-in.) diameter pan at a distance of 1200 mm (47.2 in.) from the sensor or detector. A large fire is the same flame at a distance of 380 mm (15 in.) from the sensor. The goal to differentiate between a fire that does not represent a present threat and a fire that must be extinguished quickly is a good one, but either the current technology needs further development or the vehicles must be designed to preclude catastrophic fires so that such a device is not necessary. (See pars. 4-3, 4-4, 4-6, and 4-8 and subpar. 7-3.2 for descriptions of such design features.)

6-2.1.2 Response Time

One major advantage of optical fire detectors is their ability to detect, i.e., sense signatures and then follow a logic sequence to discriminate between fire and extraneous phenomena significantly faster than alternative detectors. This ability is critical to their application in automatic fire detection and extinguishing systems for crew-occupied compartments of modern combat vehicles that are subject to a combustible liquid spray fireball.

Quick detection is required in order to respond effectively to the rapid-growth fire described in Chapter 2. The rapid-growth fires of particular concern are those induced by threat munitions that breach protected compartment armor and encounter the hydrocarbon fluids contained in the vehicle. These fires pose such catastrophic risks of crew and weapon system losses that they must be detected and extinguished in a fraction of a second. The fire-out time limit for Army ground combat vehicle crew compartments has long been mandated to be no more than 250 ms (Refs. 11 and 12) based upon protecting the crew from second-degree burns and the effects of severe overpressure (Ref. 6). This fire-out time limit has been questioned as not being adequate to prevent second- or even third-degree burns (Ref. 13). A better criterion is the time-temperature integral described in subpars. 5-2.2.2 and 5-2.3. If the designer considers the time required for the extinguisher to open, for the halon extinguishant to flood the compartment, and for complete extinguishment of the fire, the time available for the sensors to function is very short. MIL-S-62546 requires detection and appropriate signaling in 3 ms. (4 ms is allowed for discriminating* detectors; see subpar. 6-2.1.4.)

Optical sensors have also been tested in a variety of other military roles with responses of less than one second. Prototype photoemission-type ultraviolet detectors for fuel leak fires in aircraft turbojets responded in 200 to 1000 ms (Ref. 14). These detectors were designed to monitor a large aircraft engine nacelle for combustion of leaked fuel, i.e., JP-4. The sensor, a type of Geiger-Mueller counter tube, responded to radiation wavelengths from 190 to 290 nm (1900 to 2900 angstroms), which are in the ultraviolet range. This detector was well-adapted to detect propane flame but had difficulty with JP-4 flame (Ref. 15). The longer count time for the latter was probably due to lower intensity in the shorter wave lengths, i.e., UV, the detector senses. Review of the spectra of JP-4, JP-8, JP-5, DF-2, and MIL-H-5606 hydraulic fluid flames (Refs. 3 and 4) implies that this particular detector would be insensitive to the DF-2 and MIL-H-5606 flames and only marginally sensitive to the JP-4 flame. Infrared sensors for hydrocarbon fires resulting from ballistic impacts on helicopters responded in less than 50 ms (Ref. 16).

Response time requirements for slower growth and small fires are significantly longer. Both MIL-F-23447 (Ref. 17) (for use in US Navy aircraft) and MIL-S-62546 (for use in US Army military vehicles) have established a time requirement of 5 s for detection of a small fire.

*A "discriminating" detector ignores the signature of a shaped-charge jet but reacts to a hydrocarbon spray fireball.

6-2.1.3 False Alarm Rejection

Full exploitation of the optical detector technology that afforded the rapid response was significantly delayed by its tendency to give false alarms (Ref. 18). Unfortunately, the false alarm problem was not confined to the issues of fire intensity and thresholds. Instead the problem encompassed numerous nonfire sources of similar signatures. Some false alarm sources were discovered during vehicle testing. During the durability phase of a military potential test of optical detectors on an M113 in the late 1960s, a crew member entered the crew compartment wearing a maroon shirt and caused the extinguishing system to discharge. It was subsequently determined that the cause was sunlight reflecting off the shirt. This false alarm led to additional testing of that detector, which showed it susceptible to sunlight reflecting off red objects, to white light reflecting off the red Halon 1301 extinguisher cylinders, and to a standard Army two-cell flashlight with a red filter (Ref. 11).

MIL-S-62546 contains an extensive list of phenomena that have been found to cause false alarms in the past or sources of radiation that will be encountered routinely. These false alarm stimuli are given in Table 6-2. In addition to not responding to the radiation signatures, the detector is not to give a false alarm when the electric power of the vehicle and detection system is turned on or if the battery power decays due to prolonged operation. Nor is the detector system to give a false alarm when subjected to these environmental exposures:

1. Temperature of 125°C (257°F) or −51°C (−60°F) or rapid temperature changes between these extremes
2. Shock or vibration to which the vehicle may be exposed
3. Immersion in water, mobility fuel, or salt fog or exposure to fungus, humidity, or sand and dust.

The consequences of false alarms are important in peacetime and potentially fatal in combat. Depending on system design, in peacetime a false alarm could sound an alarm or discharge extinguishant into crew-occupied space. Such actions interrupt the mission, reduce confidence in the system, and increase vehicle maintenance requirements. The current training procedure is for the crew to evacuate the vehicle as soon as practicable after the AFES discharges. In combat a discharge would immediately reduce crew performance while they coped with the halon-extinguishant-rich atmosphere. Equally important is that the extinguishant would not be available for a real fire. This fact would have a

TABLE 6-2. FALSE ALARM STIMULI (Ref. 4)

ITEM	RADIATION SOURCE DESCRIPTION	DETECTOR SYSTEM IMMUNITY DISTANCE, mm (in.)	
		SMALL FIRE	LARGE FIRE
1	Vehicle headlight (low beam) conforming to MS 53023-1	300 (11.8)	100 (3.9)
2	Sunlight—direct, indirect, or reflected	*	*
3	Incandescent frosted glass light, 100 W	150 (5.9)	25 (1)
4	Incandescent clear glass light, rough service, 100 W	225 (9)	50 (2)
5	Fluorescent light with white enamel reflector, standard office or shop, 40 W or 2 of 20 W each	150 (5.9)	*
6	Electric arc, 12-mm (15/32-in.) gap at 4000 V ac, 60 Hz	25 (1)	25 (1)
7	Vehicle IR light conforming to MS 53024-1, low beam	600 (23.6)	300 (11.8)
8	Ambient light extremes (vehicle darkness to bright light with snow, water, rain, desert glare, or fog)	*	*
9	Sunlight or artificial light reflected from brightly colored clothing, including red and safety orange at 1500 mm (59.1 in.) and to near zero	*	*
10	Electric flash (180 J minimum output)	450 (17.7)	225 (9)

*Immune at any distance

(cont'd on next page)

TABLE 6-2. (cont'd)

ITEM	RADIATION SOURCE DESCRIPTION	DETECTOR SYSTEM IMMUNITY DISTANCE, mm (in.)	
		SMALL FIRE	LARGE FIRE
11	Movie light, 625-W quartz DWY lamp (Sylvania SG-55 or equivalent)	1200 (47.2)	600 (23.6)
12	Red or blue-green dome light conforming to MS 51073-1	*	*
13	Flashlight (MX 991/U or other)	*	*
14	Chopped light—individual sources, such as Items 1, 2, 9, and 13	**	**
15	Chopped light—combination of sources, such as Items 1, 2, 3 ,4, 5, 7, and 8	**	**
16	Radiation heater, 1500 W	900 (35.4)	450 (17.7)
17	Radiation heater, 1000 W with fan	600 (23.6)	300 (11.8)
18	Arc welding—4-mm (5/32-in.) rod, 300A	1500 (59.1)	300 (11.8)
19	Acetylene welding—00 tip, 16- × 150-mm (5/8- × 6-in.) flame	1500 (59.1)	300 (11.8)
20	Muzzle flash from M16 rifle	250 (9.8)	50 (2)
21	Muzzle flash from 105-mm gun	†	†
22	Lit cigar or cigarette	100 (3.9)	25 (1)
23	Match or wood stick, including flare-up	300 (11.8)	100 (3.9)
24	Match or paper, including flare-up	200 (7.9)	100 (3.9)

*Immune at any distance
**Same as not chopped
†Distance to be measured and recorded

measurable impact on the survivability of the crew and vehicle.

Optical detector requirements include exposure of the sensor to the sources shown in Table 6-2 and the distances beyond which the detectors must not produce false alarms. Such requirements represent a compromise between the false alarm problem and the state of the art of sensor technology. For example, a flashlight must not be a false alarm stimulus to the sensor, no matter what the distance. The detector technology reflected by Table 6-2, however, cannot distinguish between a large real fire and an incandescent frosted light closer than 25 mm (1 in.). As the technology improves, the distances decrease, and such changes are reflected in detector requirements.

Other sources of false alarms that must be considered include chopped light, combinations of sources, and the muzzle flash associated with firing weapon systems. Chopped light is the emission from a potential false alarm source that is suddenly interrupted by an object passing between the source and sensor. An example is sunlight that suddenly hits a sensor when a vehicle hatch is opened (or that suddenly is cut off from a sensor by a hatch being closed). Combinations of sources occur frequently in combat vehicles and have produced false alarms. Because of the different distances at which each source must not produce a false alarm, requirements are set at the greater distance for the combination source. For example, in Table 6-2 the requirement for the combination of an incandescent clear glass light and a flashlight (MX 991/U) would be 225 mm (9 in.) for a small fire. Muzzle flash from weapon systems presents a difficult challenge to those charged with setting or complying with the false alarm requirements for sensors. The cost of testing to determine the source-to-sensor distance at which detectors are immune to false alarms can be prohibitive, and this cost is compounded by the need to test sensors throughout their field of view. Consequently, requirements frequently specify testing at two distances with the results being recorded. Such results provide information to vehicle designers and users regarding whether there is a problem. The designer could then, if necessary, provide additional masking or filtering for the sensor to reduce the effect of the muzzle flash or move the sensor to a location from which the muzzle flash could not be seen. Muzzle flash is virtually the same as the flash from a hydrocarbon fireball. The greatest IR radiation peak is at a wavelength of 3.0 μm with secondary peaks at 2.2 and 4.4 μm for a 155-mm M2 artillery weapon (Ref. 19)

6-2.1.4 Discrimination

Discrimination is the capability of a detector to respond to a hydrocarbon fire and not respond to the high-intensity, short duration emissions caused by penetration of aluminum or steel armor by kinetic or chemical energy ammunition (Ref. 5).

As discussed in subpar. 4-1.2.3, gunners will continue to fire at a combat vehicle until they see evidence of a kill. Consequently, multiple penetrations of a combat vehicle are almost as likely as a single penetration. Automatic fire detection and extinguishing systems that incorporate nondiscriminating detectors will respond to the first penetration without regard for whether hydrocarbons were encountered, and extinguishant will be expended. If the vehicle survives the first penetration, extinguishant may not be available to respond to a subsequent penetration that does encounter hydrocarbons. As a result, the probability of the vehicle or crew's surviving the second or subsequent penetrations is reduced. Potential solutions include a "backup" extinguisher equivalent in capacity to the first shot, discriminatory sensors, or a combination of both.

The advantage of backup bottles compared to discriminatory detectors occurs when first one and later a second penetrator encounter hydrocarbons. A system with backup bottles has the capability to extinguish both resulting fires. Such a system, however, is at a disadvantage when there are fires resulting from any third, or subsequent, penetration because there is no extinguishant remaining. Other disadvantages include the additional space required for bottle storage and the increased probability the bottles will be hit. The disadvantage of a fire extinguisher bottle being hit is not wholly apparent. In the only incident in Vietnam (DAN 336)* in which an extinguishant bottle was hit, nothing untoward happened; the shaped-charge jet apparently stopped at the bottle** and did not continue into the vehicle. Thus the bottle apparently saved the vehicle from further damage in that incident. The only "bad" result was that the bottle was not available if there had been a subsequent hit.

The ability of a detector to discriminate provides several advantages that enhance the capability of the vehicle to fight and survive. Crew performance is enhanced, aside from the damage and shock of a nonfire-producing penetration, by not also having to cope with an extinguishant-rich environment during a combat engagement. The crew's continued ability to engage the enemy contributes to survivability, which is also enhanced by the retained extinguishant capability. Discriminatory detectors provide other advantages because they make no additional claim on the scarce internal volume of a combat vehicle.

A system incorporating both discriminatory detectors and backup bottles offers maximum fire-extinguishing capability. Its application is most appropriate if the risk of a penetration-induced hydrocarbon fire is high and the survivability of the vehicle is sufficiently critical to offset the increased extinguisher volume and increased cost.

The value of discriminatory detectors and backup bottles was indicated in studies that compared alternative fire-extinguishing systems (Refs. 20 and 21). The studies compared the cumulative probability of survival of alternative extinguisher systems for the M992 Field Artillery Ammunition Support Vehicle (FAASV) given one, two, and three penetrations of its armor. These studies were based upon a vulnerability assessment performed at the US Army Ballistic Research Laboratory (BRL) in which shotlines were passed through every square inch of the presented area of the vehicle at aspects every 30 deg around and above the vehicle to establish the probability of hitting ammunition, fuel, or hydraulic fluid. The vehicle was assumed to have a full basic load of ammunition 10% of the time, half full 80%, and with no ammunition 10% of the time. A fire was assumed to occur in either the engine compartment and/or the crew and ammunition compartment if either fuel or hydraulic fluid was hit, and an explosion was assumed to occur if ammunition was hit. Fire detection and extinguishing systems were not assumed effective against ammunition explosions but were assumed 100% effective against a fuel or hydraulic fluid fire. Averaging all the shotlines produced a probability of 0.66332 of encountering no energetic material, of 0.2276 of encountering ammunition, of 0.0465 of igniting a fire in the engine compartment only, of 0.0320 of igniting a fire in the crew compartment only, and of 0.0307 of igniting fires in both the engine and crew compartments. The vehicle probability of survival given one, two, or three hits is shown on Fig. 6-2 for no fire protection, for a single-shot AFES in each compartment, and for a two-shot AFES

*The document acquisition number (DAN) refers to files in the Survivability Information and Analysis Center (SURVIAC) described in par. 4-12.

**No fire resulted in this incident. The four crewmen were all wounded—probably three by spall and the fourth by the blast damaging his eardrums. None of the wounds were attributed to the fire extinguisher bottle or its contents (DAN 336).

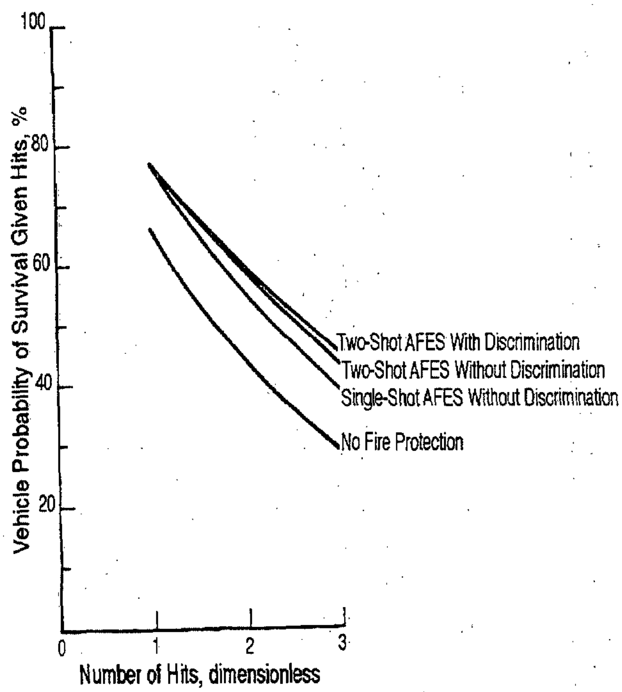


Figure 6-2. Probability of Vehicle Survival Given Multiple Hits for Three AFES Configurations (Ref. 21)

in the crew compartment and a one-shot AFES with a one-bottle manual backup in the engine compartment. This last alternative was conducted with nondiscriminating and discriminating detectors in the crew compartment. The plots in Fig. 6-2 show that the addition of extinguishers and use of discriminating sensors increases the probability of vehicle survival of subsequent hits. Unfortunately, the studies from which these data were derived did not consider a system with discriminatory sensors but no backup bottles. Consequently, there was no direct comparison between backup bottles and discriminatory sensors.

In subpar. 2-2.1.2 the differences in flash intensity and duration between steel and aluminum armor when penetrated by a shaped-charge jet and other penetrators were briefly discussed. The type of armor and/or hull material used by a particular vehicle incorporating a MIL-S-62546 sensor requires specific features in the sensor wiring harness, i.e., the connector pin assignment code. This information is provided to assist the detector designer in designing logic for detector discrimination and in facilitating the required interchangeability of detectors between steel-armored and aluminum-armored vehicles.

6-2.1.5 Durability

An optical fire detector should function flawlessly in the environments experienced by and in the combat vehicle. The reliability requirement in MIL-S-62546 for sensors is not less than 100,000 h between failures. The physical environment experienced by the combat vehicle includes temperatures as low as −51°C (−60°F) and as high as 125°C (257°F), vibration, shock, temperature shock, salt fog, fungus, sand, dust, humidity extremes, and electromagnetic interference. The vehicle environment is the nominal 28-V dc military vehicle electrical system. Response requirements, however, must be met at voltages from 16- to 30-V dc. Sensors must not produce false alarms if the input voltage decays, and they must not be damaged by voltages up to 40-V dc. Detectors must withstand reverse polarity and direct shorts without damage (Ref. 4). Finally, they must function following immersion in diesel fuel, water, a pressurized water jet, or salt fog.

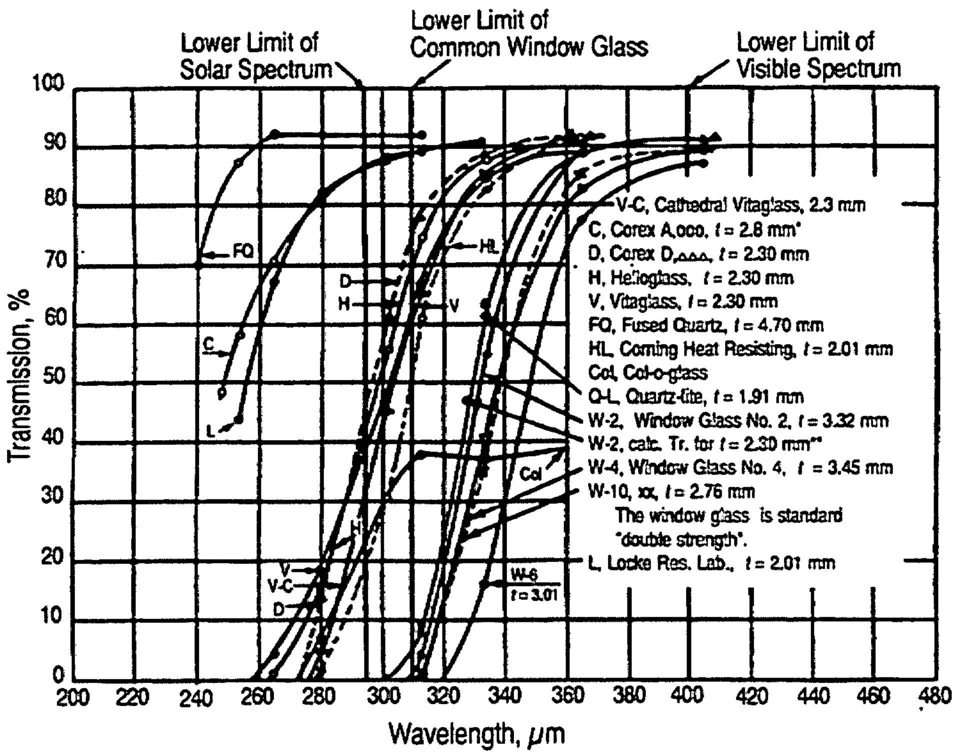
6-2.2 TYPES

All currently used emr sensors, i.e., UV, visible light, and IR, use the same basic physical phenomena to function. The materials used in these sensors differ because of the different reactions of these materials to emr of different wavelengths.

6-2.2.1 Ultraviolet Fire Detectors

Ultraviolet radiation sensors function similarly to visible light and infrared sensors. UV sensors differ primarily in the materials used; the materials are sensitive to UV radiation rather than IR or visible light radiation. Many materials are opaque to UV radiation, especially many types of glass, as shown in Fig. 6-3. Thus the types of glass that can be used to make or protect UV radiation sensors are limited (Ref. 22). On the other hand, the UV-opaque glasses can be used to filter out unwanted UV radiation, such as sunlight. The designer has a choice of both glass filters, which can remove radiation of undesirable wavelengths, and transparent shields, which can protect the sensing element from dust and other contaminants and still permit transmission of radiation of desired wavelengths. Fig. 6-3 shows that even in 1929 designers had a good selection of glasses that were transparent or opaque to different wavelengths of light. This selection has undoubtedly increased in the succeeding years. UV radiation causes photochemical change in many materials that can reduce the useful life of items using those materials. Because UV radiation causes fluorescence in some materials, its presence can be detected. UV radiation can be readily absorbed by many gases and other materials. This phenomenon can limit the distance at which UV sensors are useful, but it is also useful in enabling detectors to discriminate between a nearby fire and solar radiation. UV sensors are used in military equipment such as the LM2500 gas turbine engine on DDG class destroyers and in the F-14D, F-15, F-16, F-18, and F-22 aircraft as light-off monitors in afterburners. UV sensors are not often used alone in military equipment; they are sometimes used in conjunction with IR sensors to discriminate better between fire and solar radiation. UV sensors are used primarily in industrial applications.

UV sensors currently use a Geiger-Mueller-type output (Refs. 23 and 24). A Geiger-Mueller device contains a cath-



*The mean thickness *t* of the sample that, since these glasses are handblown, often varies 0.5 mm in the samples. This variation can cause a variation of 6% in UV radiation transmission.
**Calculated transmission of thicknesss equals 2.30 mm of Window Glass No. 2.

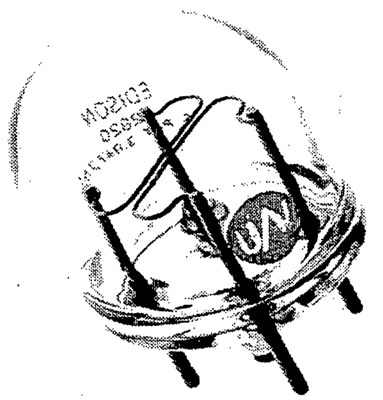
Figure 6-3. Ultraviolet Spectral Transmission Through Various Window Glasses When New (Ref. 22)

ode and an anode separated by a dielectric. A voltage is placed across the cathode and anode. The cathode is made of a material that emits electrons when irradiated by UV radiation. The dielectric becomes excited when irradiated by that same wavelength, and/or by the electrons emitted by the cathode, and acts as a photomultiplier to increase the number of free electrons. These free electrons travel to the anode and reduce the voltage between it and the cathode in a sudden burst. The abrupt voltage change is detected by the Geiger-Mueller circuit as a single count. The frequency of these counts is a measure of the quantity of radiation received. All the current UV sensors used in fire detection are based upon these phenomena. The design of different manufacturers' sensors varies with the shape of the anode and cathode, the selection of anode material, the dielectric in the cell, and the configuration of the cell. There are also differences in the logic element of the detector and in features such as self-testing devices and contamination resistance features. Examples of detectors of some competing manufacturers follow.* This technology is continually changing, so each designer should contact manufacturers to learn what features are available before selecting a specific device to use.

6-2.2.1.1 Omniguard® UV Detectors of Armtec

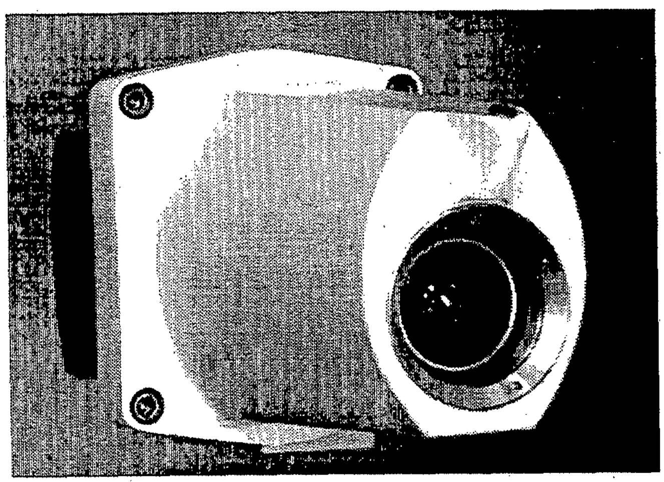
Armtec produces a line of detectors based upon its Edison® solar blind UV sensor tube; Fig. 6-4 shows an early version, and Fig. 6-5 shows an Omniguard® Model 652 UV Fire Detector. This device has a conical field of view with up to 70 deg of off axis area coverage. Fig. 6-6 shows the detection distances for the Model 652 detector for a 0.093-m^2 (1-ft^2) gasoline fire; the average response time is 1 s if the flame is close enough to achieve sensor saturation. The time constant is 60 ms. The Model 652 detector responds to emr in the wavelength range of 0.19 to 0.26 μm. This sensor will respond to fuels that produce UV upon combustion, such as diesel fuel and other hydrocarbon liquids, alcohols, acetone, hydrazine, wood, hydrogen, and plastics including epoxy. Detector response will be affected by wind, smoke, and angle of detection. Detection distances for combustion of some materials are given in Table 6-3.

*Descriptions of specific devices do not constitute Government endorsement of the devices; they are merely to illustrate some of the features available.



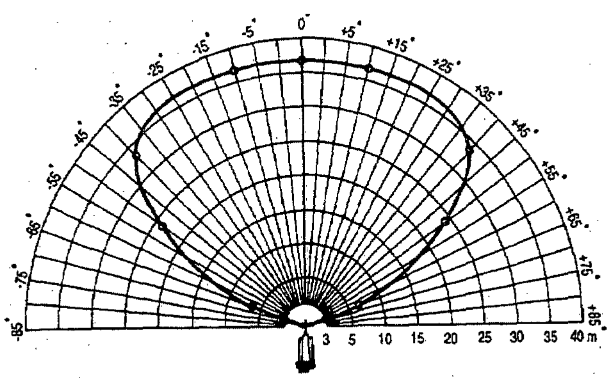
Courtesy of Armtec/Ragen, Inc.

Figure 6-4. Edison® UV Detector Tube



Courtesy of Armtec/Ragen, Inc.

Figure 6-5. Omniguard® Model 652 Ultraviolet Fire Detector



Distance, m (ft)		Maximum Included Angle, deg
3.05	(10)	150
7.62	(25)	140
24.38	(80)	110
33.53	(110)	90
36.57	(120)	30

Courtesy of Armtec/Ragen, Inc.

Figure 6-6. Series 650 Fire Detector Horizontal Performance Envelope (Cone of Vision)

TABLE 6-3. TYPICAL ARMTEC UV/IR FIRE DETECTION DISTANCE

FUEL	FIRE	DETECTION DISTANCE
DF-2	0.305 × 0.305 m (1 × 1 ft) pan	9 m (30 ft)
Gasoline	0.305 × 0.305 m (1 × 1 ft) pan	13.7 m (45 ft)
JP-4	0.305 × 0.305 m (1 × 1 ft) pan	13.7 m (45 ft)
Methane	152 × 229 mm (6 × 9 in.) sheet flame	7.6 m (25 ft)
Wood	0.305 × 0.305 m (1 × 1 ft) exposed area	8.2 m (27 ft)

Courtesy of Armtec/Ragen, Inc.

6-2.2.1.2 Det Tronics AOi® Ultraviolet Sensor by Detector Electronics

Detector Electronics produces a line of UV detectors that use its patented tube, shown in Fig. 6-7(A), mounted in the housing, shown in Fig. 6-7(B) (Ref. 23). The Det Tronics UV detector cone of vision is shown in Fig. 6-8. These devices respond to irradiation in the wavelength range of 0.185 to 0.245 µm. Shown in Fig. 6-8 are the count rates—in counts per second (cps)—for distances at which standard, i.e., 0.3- × 0.3-m (1- × 1-ft) pan, gasoline flames are set for calibrating the device. The sensitivity of this device to a gasoline flame is shown in Fig. 6-9.

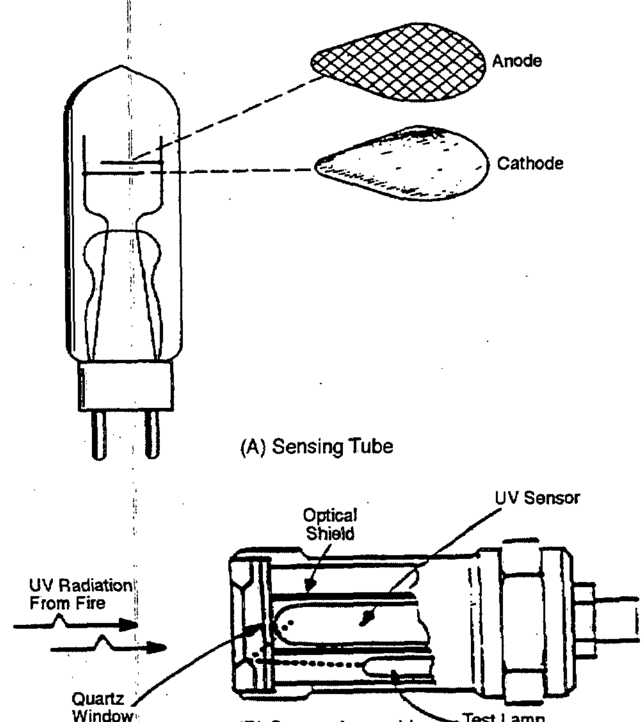


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Figure 6-7. Geiger-Mueller-Type Sensor (Ref. 24)

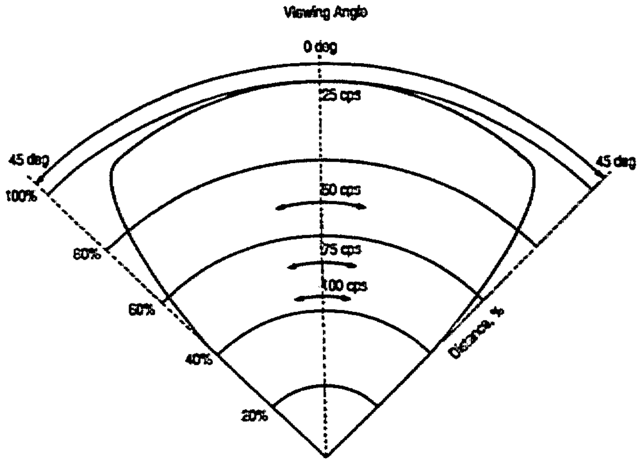

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Figure 6-8. UV Fire Sensor Cone of Vision (Ref. 25)

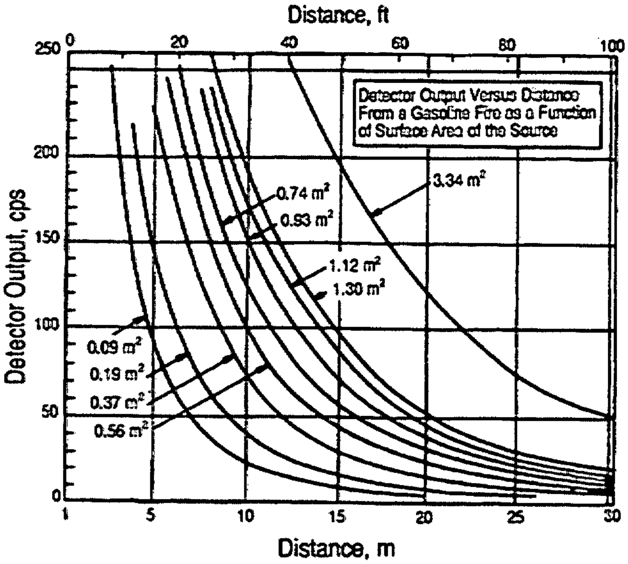

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Figure 6-9. UV Dectector Sensitivity to a Gasoline Reference Fire (Ref. 25)

The Det Tronics detectors have a standard self-test element to establish whether the sensor is functional. This functionality is primarily a matter of lens cleanliness. There is also an optional device, a detector air shield, that can maintain a flowing air curtain over the lens to preclude deposit of contaminants. (Ref. 26) Typical response to an intense UV source is less than 25 ms. Systems are available for applications in which response times of less than 10 ms are needed.

6-2.2.2 Infrared Fire Detectors

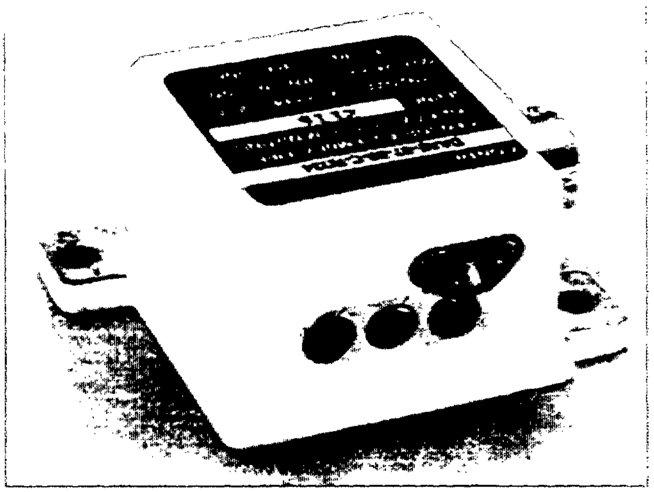
The most commonly used detectors for combat vehicle applications are the infrared (IR) detectors. In the past IR detectors have been unsuitable for general applications due to the number of IR radiation sources that can be found in nature and thus create a tremendous false alarm problem. Improvements in the ability to discriminate between the radiation from a fire and the radiation from other sources, however, have resulted in the IR detector becoming very reliable. IR is detected by either an optical sensor or a thermopile; thermopiles are described in subpar. 6-3.3.1. Optical IR detector systems normally use sensors that have been designed to respond to a specific IR frequency. By adding a second or third sensor element each tuned to a different frequency and/or with a different filter, it is possible to improve the ability of the system to distinguish fire conditions from extraneous blackbody radiation. Since most nonfire stimuli do not radiate in all of the spectral bands monitored, false alarm susceptibility has been greatly reduced.

6-2.2.2.1 Dual Spectrum® Infrared Sensors

The Santa Barbara Research Center (SBRC) Model PM-34 Dual Spectrum® Discriminating IR detector monitors radiation in two spectral bands to detect intensity above preestablished levels and uses a third IR sensor to provide other fire signature information. The two spectral bands are ones in which radiation is emitted by hydrocarbon fires but not by most nonfire stimuli. The sensors will respond to an explosive fire in 2 ms. (Ref. 27)

6-2.2.2.2 HTL Optical Fire Sensor Assembly

The HTL Optical Fire Sensor Assembly (OFSA), shown in Fig. 6-10, combines two narrow band optical sensors, one visible and one IR, and a narrow thermopile. Two of the



Courtesy of HTL/Kin-Tech Division, Pacific Scientific.

Figure 6-10. Dual IR Sensor Plus a Thermopile Sensor Assembly

optical sensors are photodiodes with filters. One senses radiation at a nominal wavelength of 0.6 μm with a bandwidth of ±0.05 μm, the other at a nominal wavelength of 0.9 μm with a bandwidth of ±0.05 μm. These two signatures establish a sensed blackbody temperature which is used to discriminate between fire and nonfire emanations. The thermo-pile has a filter, which views the radiation present at a nominal 4.3 μm with a bandwidth of ±0.5 μm and senses radiation from carbon dioxide. The HTL OFSA senses radiation in these three bands, processes these data electronically, and signals when a fire involving a hydrocarbon is present. It will detect explosions within 2 to 4 ms from receipt of radiation generated by a hydrocarbon explosion. A fire-extinguishing system (Ref. 28) controlled by this OFSA has passed both the discrimination and fire detection tests in a live-fire system test and thus meets the requirements of MIL-S-62546A. This HTL OFSA is used in the M992 FAASV (Ref. 29).

6-2.2.3 Combination UV and IR Detector

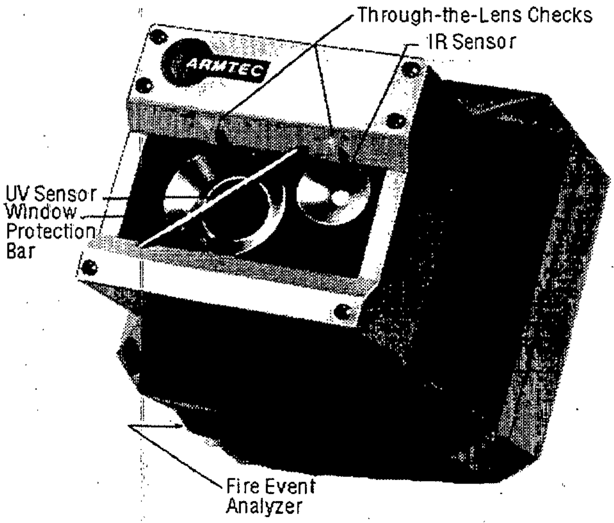
Combination detectors have been developed that incorporate both IR and UV sensors; thus they discriminate between a nearby fire and sunlight or many other stimuli by requiring that both heat and IR signature be present. The IR sensors are optical types or thermopiles. The IR sensor has a high signal-to-noise ratio but reacts to background radiation. The thermopile is not generally sensitive to X rays, lightning, or arc welding. The UV sensors are usually Geiger-Mueller types. Because each type of fire has its own unique signature and, therefore, a distinctive ratio of UV or heat and IR, most false alarm signals can be screened out by making the combination detector sensitive to this ratio of signals.

6-2.2.3.1 Omniguard® Model 750

Omniguard® Model 750 by Armtec Fig. 6-11, combines a UV sensor and a thin-film thermopile. The thin-film thermopile, senses the narrow band of the carbon dioxide spike at an approximate wavelength of 4.3 μm, and the UV sensor senses at a wavelength of 0.22 μm, as shown in Fig. 6-12, which is above that of solar radiation reaching the surface of the earth. These sensors provide an excellent means by which to discriminate between fire and solar radiance. Through-the-lens checks, which provide a self-test capability, are provided for both the IR and UV sensors. The proprietary logic system Fire Event Analysis (FEA) by Armtec is performed within the Omniguard® detector assembly to ensure discrimination against nonfire radiation sources by establishing that the ratio of UV to IR is within the range representative of a hydrocarbon fire (Ref. 30). The typical overall response time is 150 ms for a saturating signal.

6-2.2.3.2 Spectrex Optical Fire Detector

Spectrex provides a dual spectrum UV and IR detector that monitors a UV wavelength beyond that of solar radiation reaching the surface of the earth and the IR wavelength emitted by carbon dioxide. For a fire signal to be given, this IR radiation must have flickers (Ref. 31). This detector can signal a hydrocarbon fire in 5 ms.



Courtesy of Armtec/Ragen, Inc.

Figure 6-11. Combination UV-IR Flame Detector, Omniguard ® Model 750 (Ref. 30)

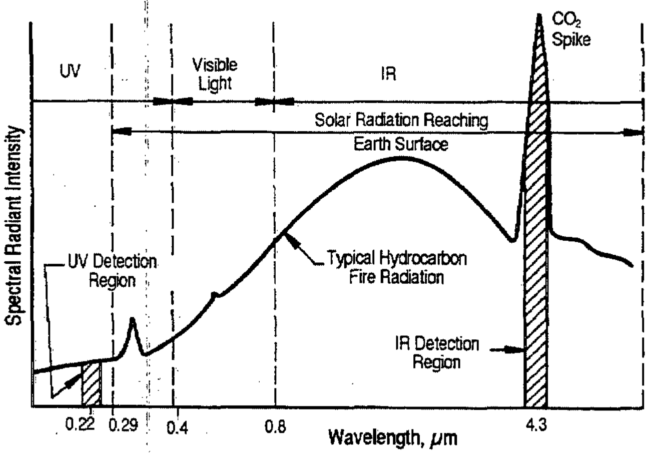


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Figure 6-12. Typical Hydrocarbon Fire Emission Spectrum Showing Detection Regions of Omniguard® Model 750 (Ref. 30)

6-2.3 APPLICATION

As discussed earlier in this chapter, a number of reliable, efficient, and quick-responding optical detectors exist for use in suppression systems for combat vehicles. The IR and UV sensors are capable of responding in the few-millisecond range. The IR sensor has the fastest response time of all the sensor types, and its IR sensor response time should be in the 4- to 6-ms range. The necessity to discriminate between emr signatures can increase the response time of this sensing system to a range of 9 to 150 ms with an average somewhat greater than 30 ms (Ref. 32). All three types of detectors are susceptible to certain extraneous stimuli;

thus they can give false alarms. The IR and combination UV and IR detectors can be designed with built-in tests or to be checked manually. Of the three types of detectors, the combination IR and UV has the lowest false alarm rate. The multiple IR detector also has a low false alarm rate.

The disadvantages of the optical detectors follow:

1. Susceptibility to opaquing of their windows by oil, dirt, and other contaminants. (During travel-worthiness tests of the AFES planned for use in the M60A3, the engine compartment optical sensors had to be cleaned after a mean of 82 km (51 miles) of travel. The minimum distance traveled before dust opaqued the lens was 14 km (9 miles). For optical sensors mounted within the crew compartment, the mean travel distance before cleaning was necessary was 137 km (85 miles). The minimum distance was 16 km (10 miles) (Ref. 33).)

2. Restricted fields of view, particularly in engine compartments or other crowded compartments

3. Selective absorption of emr by smoke, vapors, and other airborne materials, which reduce radiation intensity.

The most commonly used type of detector in US ground combat vehicles is the dual IR detector, such as the Dual Spectrum® PM-3C detector. The M1 MBT uses the PM-3C dual spectrum IR detector. The M2/M3 Bradley fighting vehicles and the US Marine Corps (USMC) amphibious assault vehicle (AAV)7A1 (Ref. 34) use the PM-34C dual spectrum IR detector and the necessary electronic controls to sense a fire and dispense halon fire extinguishant. Most currently produced LAV-25s, but not those of the USMC, use a Dual Spectrum® PM-34CBEH optical IR detector with a discrimination feature.

6-2.3.1 Number Required

The number of optical sensors required is governed by the field of view and range of each individual sensor; the space to be monitored, masking of space by objects, and location of extraneous radiation sources within the compartment; needs for redundancy of coverage; and potential sources of obscuring materials within the compartment.

Each sensor has a specific field of view and range, an example of which is shown in Fig. 6-6. Both of these characteristics are built into the sensor optics, and these optics may or may not allow adjustment. The range is vitally important if the fire detection system is expected to distinguish between "small" and "large" fires. The space to be covered has to include not only the locations of combustible-fluid-containing objects but also the locations combustible liquids can spray or flow and collect. When the view of some location that can contain combustible fluids is masked by some object, another sensor may be required to cover the masked area. Also some provision must be made to disseminate materials or gases that can reduce the sensitivity of the sensors and thereby reduce their range of coverage. When an object that can emit radiation in the wavelength to which the sensor will respond is located within the field of view of a specific sensor, either the object has to be masked or the field of view must be changed to avoid that object. Redundancy of sensor coverage must be provided to assure complete coverage given normal operational failure of, or battle damage to, individual sensors or their wiring. The number of sensors used in combat vehicles varies considerably. See Fig. 6-13 for sensor locations in the M1 MBT engine compartment and Fig. 6-14 for the locations in the BFV crew compartment.

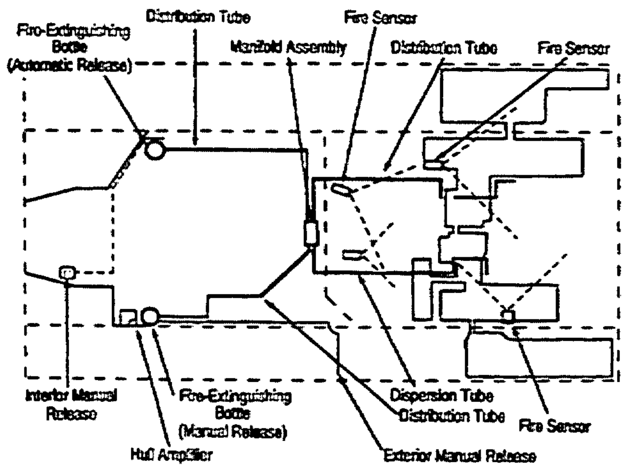
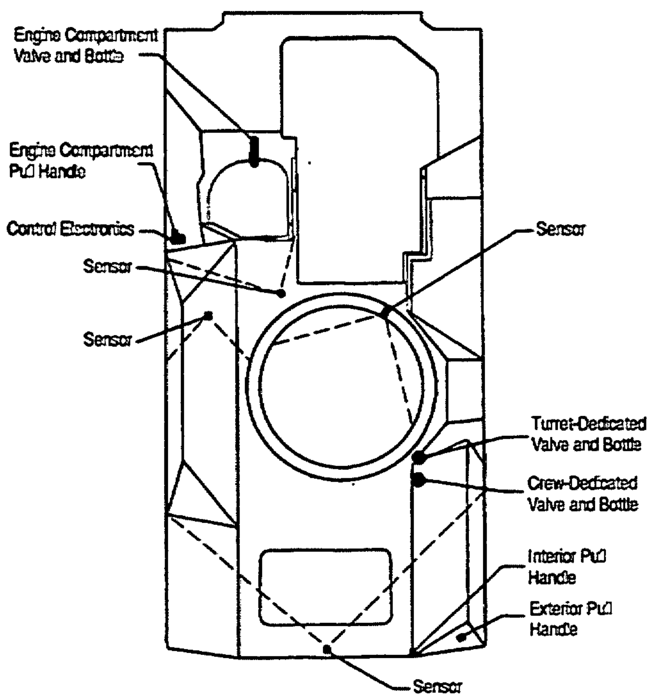


Figure 6-13. Fire Suppression System of the M1 MBT Engine Compartment (Ref. 35)



Courtesy of FMC Corporation.

Figure 6-14. Fire Suppression System for A1 and A2 Configurations of BFVs M2 and M3

6-2.3.2 Location Selection

The same factors that govern the number of sensors to be used affect selection of the locations of the sensors. Locations are selected also to minimize cleaning and maintenance efforts, potential ballistic damage, contamination of the windows and/or obscuration, effects of hot spots, and exposure to potential sources of false alarms.

When selecting mounting locations, the designer must assure that all potential fire locations are covered. The M1 MBT requirements specified that detectors must view a minimum of 95% of each compartment. In the initial design of the fire detector coverage for the M1 MBT, three sensors were placed in the engine compartment. The air intake and its large filter were not considered vulnerable to a hydrocarbon liquid fire and therefore were not covered by the sensor arrays. Unfortunately the designers did not consider that these filters do an excellent job of removing hydrocarbon liquids from the air passing through and that after a period of time these combustible liquids accumulate therein. There have been several instances in which such accumulations led to sustained fires in these filters. Subpar. 4-2.3.2 records such an incident.

Specifically, the field of view of a sensor should not be oriented through opened hatches. During the development test program, a sensor was mounted in the M60A3 driver's compartment so that when the hatch was open and the main gun fired, the sensor would falsely alarm. To solve this problem, a visor was placed over the sensor to obscure its view of the main gun (Ref. 36). During the development testing of the AFES for the M1 MBT, a false alarm was caused by the muzzle flash from a nearby gun (Ref. 29).

Sensor locations should be selected and reviewed when the vehicle has all contents fully stowed and all crewmen present so that all obstructions are identified. Also sensors should be placed high within the compartments so that added objects will not obscure their view.

6-2.3.3 Standardization

The objectives of standardization follow:

1. Reduction of acquisition costs by obtaining a large quantity of a single model
2. Reduction of replacement stockage requirements
3. Reduction of training requirements
4. Reduction of maintenance and repair labor
5. Enhancement of the capability to replace existing units with newer units that have upgraded capabilities.

The technique used to standardize fire detectors is to establish a single, standardized mount design, which is a common size and uses a standard fastener. In addition, a single, common electrical power and signal connector with standardized signals and pin assignments must be used.

6-3 THERMAL DETECTORS

This paragraph introduces thermal fire detectors that can be used in combat vehicles. Brief introductions of the actual types of thermal detectors, including continuous thermal detectors and thermocouples, are given. Most thermal detectors are thermocouples or thermistors, but there are also pneumatic devices and resistance thermocouple detectors (RTDs). The relative ranges and gains of most of these are shown in Fig. 6-15. The thermistor has the highest gain, and the thermocouple, the largest range. The RTD is in between.

6-3.1 CONTINUOUS THERMAL DETECTORS

Several different continuous thermal detectors (CTDs) are used in fire detection systems for combat vehicle applications. These detectors include the thermistor, thermocouple, eutectic salt, and pneumatic types. These detectors are normally used to protect engine compartments. The continuous fire detector is a long capillary tube filled with a temperature-sensitive material, and it senses a temperature change along its entire length (for overtemperature)—called "averaging" mode—and/or somewhere along part of its length (for flame or spot temperature)—called "discrete" mode. The sensor tube can be strung about the hazardous area, such as inside the engine or cargo compartments of a vehicle, so that it is highly likely that the heat generated by a fire would transfer through at least some portion of the sensor tube. Most CTDs provide an analog electrical signal, but the pneumatic detector furnishes a pressure that is converted to a digital electrical signal at the connection to the controller. Signal connectors are normally provided at each end of the sensor tube. These detectors, except for the pneumatic type, are generally connected in a loop with each end being connected to the control unit, which monitors the thermally responsive property of the sensing element. If the loop is severed, both sections can still function. The following subparagraphs present brief details of the operation of each type of thermal detector.

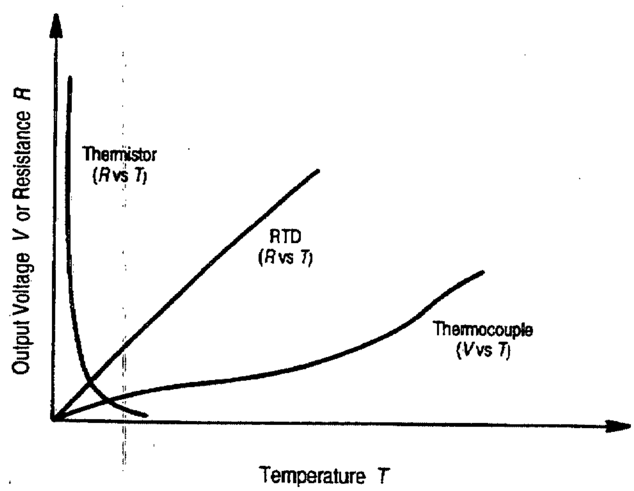


Figure 6-15. Comparative Outputs Versus Inputs for Thermistors, Resistance Thermocouple Detectors (RTD), and Thermocouples (Ref. 37)

6-3.1.1 Types

6-3.1.1.1 Thermistor-Type Continuous Detector

The thermistor-type detector has a capillary tube filled with a semiconductor or thermistor material in which one or more electrical conductors are embedded. The material, which has a negative temperature coefficient, reduces the electrical resistance between the conductors when it is heated and increases the resistance when it is cooled. Fig. 6-16 shows a thermistor-type continuous detector called Firewire® (Ref. 38), which is used in fire detector systems for engine compartments. This detector is manufactured for three basic temperature ranges by varying the filling material (and for intermediate temperatures for customized installations) and will react to temperatures as indicated in Fig. 6-17. Firewire® not only senses changes in resistance but also changes in capacitance, which increases as temperature increases, to make it less susceptible to false alarms. The connector design includes a hermetic seal to eliminate contamination by dirt and/or moisture.

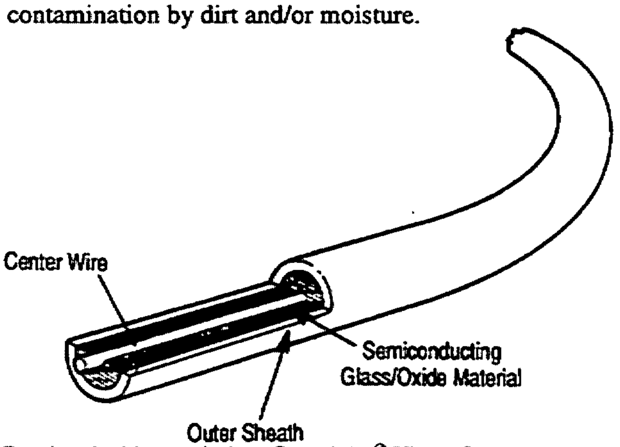


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Figure 6-16. Graviner Firewire® (Ref. 38)

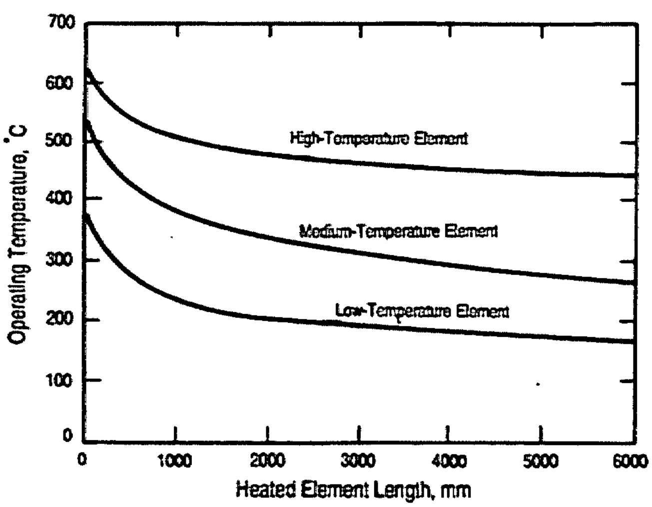

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Figure 6-17. Typical Temperature Ranges for Graviner Firewire® (Ref. 38)

Another version of a continuous thermistor cable (Ref. 39) uses a family of manganese oxide thermistors to provide sensors that operate in the six different temperature ranges shown on Fig. 6-18. In a thermistor-type detector system, a control unit monitors the resistance and signals the alarm when the resistance drops to the preset value that corresponds to the predetermined alarm temperature. Because the element is essentially an infinite number of thermistors in parallel, the resistance of the system is a function of the length of element heated and its temperature. The output is a nonarithmetic average temperature indication weighted to the high-temperature areas. Even if the cable is severed, such a loop system is still able to sense temperature increases because each end of the cable is connected to the control unit.

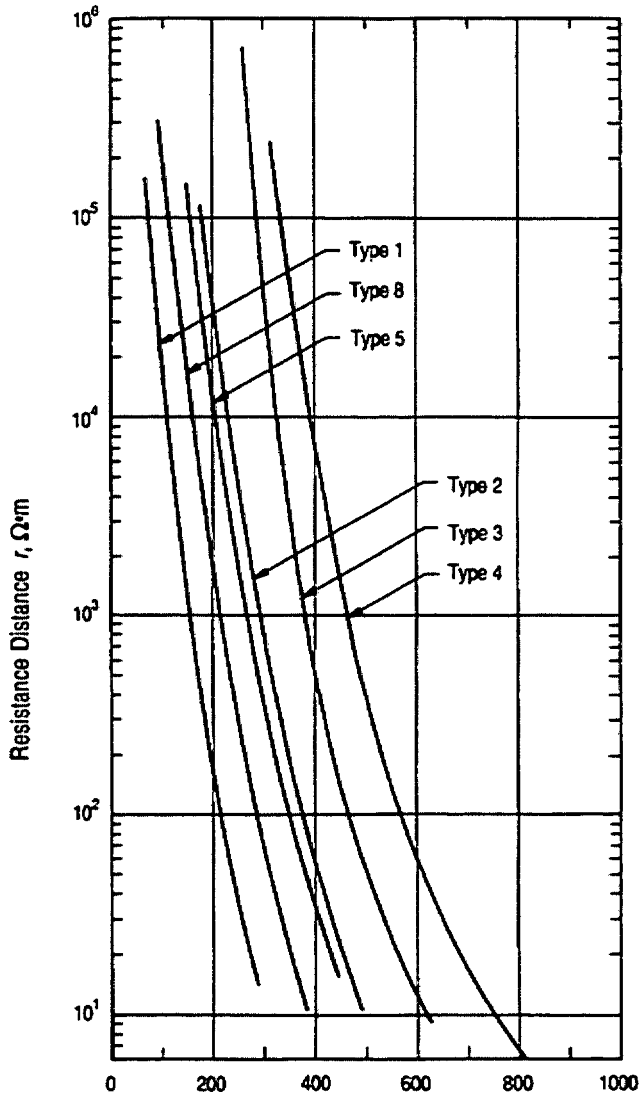

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Figure 6-18. Family of Curves From Armtec Continuous Thermistor Sensor Elements (Ref. 39)

6-3.1.1.2 Continuous Thermocouple Cable

The continuous thermocouple transducer cable shown in Fig. 6-19 consists of a protective stainless steel outer sheath within which chromel and constantan wires or chromel and alumel wires are embedded in a closely packed ceramic powder that has a high negative temperature coefficient. When heat is applied to the sheathing, it is transferred to the packed ceramic powder insulation, the electrical resistance of this insulation decreases so that temporary thermocouple junctions are formed at "hot spots". The output of the hot-test signals the temperature. When the heat source is removed, the cable returns to its original state. This cable generates a millivolt output proportional to the highest temperature in contact. The cable is not damaged by exposure to a temperature up to 899°C (1650°F) and has a nominal low operating temperature of 0°C (32°F). The sheath of the cable has an expected life of 20 years. The weight is 0.037 kg/m (0.4 oz/ft). The minimum bending radius is 12.7 mm (0.50 in.). The output voltage is +0.6 mV dc at 0°C (32°F) to +68.7 mV dc at 899°C (1650°F) (Ref. 40).

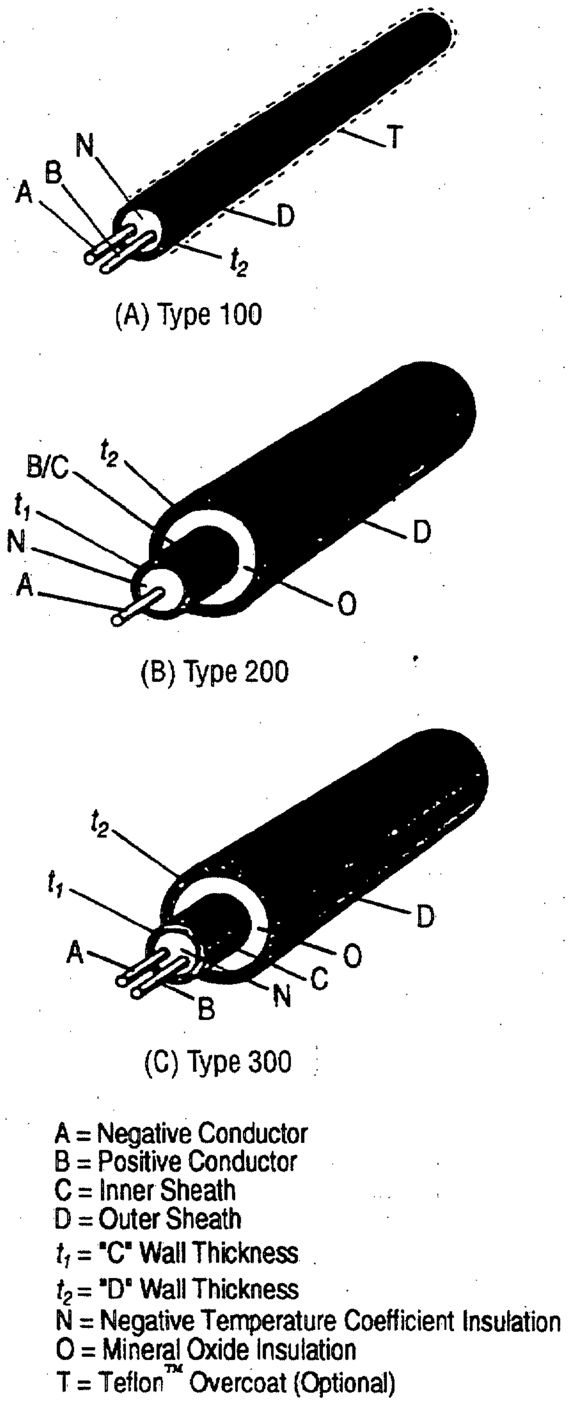


Figure 6-19. Continuous Thermocouple Cable (Ref. 40)

6-3.1.1.3 Eutectic Salt Continuous Detector

The eutectic device, as shown in Fig. 6-20, has the capillary filled with porous insulators impregnated with a eutectic salt that melts at the desired alarm temperature (Ref. 41). When the salt melts, it conducts electrical current and becomes a low resistance path, and it changes from a very high to a very low resistance over a very narrow temperature range. An alternating current potential must be used to operate the detector element because direct current will cause metallic plating to deposit on the insulator and result in permanent shorting of the detector. The melting salt cre-

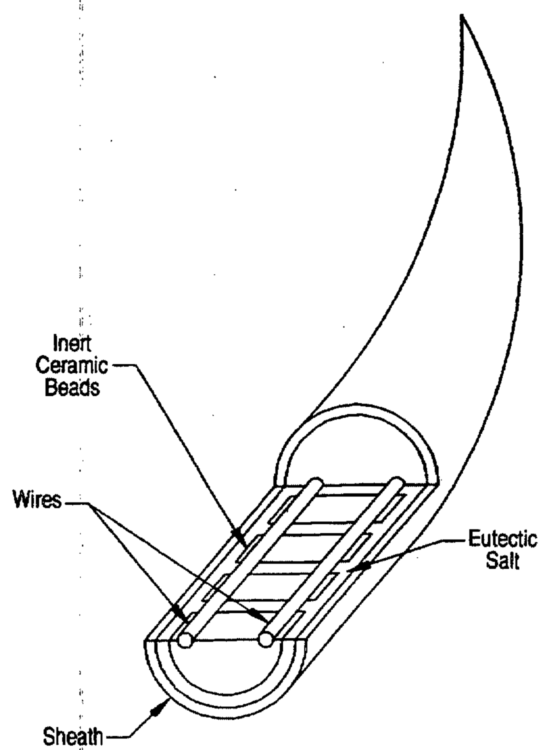
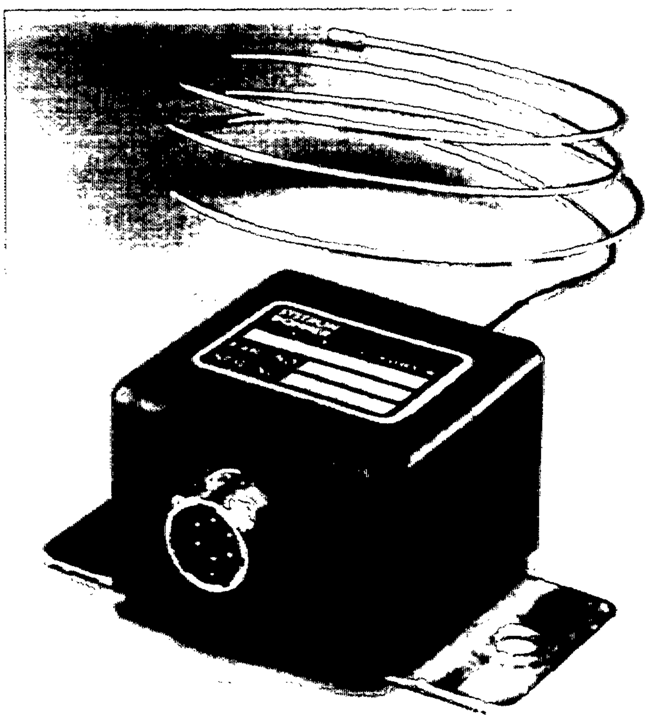


Figure 6-20. Eutectic Sensing Element (Ref. 41)

ates a very sharp switching action; therefore, the detector operates at a discrete temperature, which is virtually unaffected by the length of the element being heated. This device is essentially a fixed-temperature device that is non-averaging, i.e., the eutectic salt detector is discrete mode functioning only. Kidde-Graviner has a family of eutectic sensors developed for nominal alarm values from 102°C (215°F) to 332°C (630°F); there are presently 12 alarm temperatures. This manufacturer also has a hybrid detector, which combines the eutectic and thermistor features.

6-3.1.1.4 Pneumatic Continuous Detector

Two variants of the pneumatic overheat and fire detector, one of which is shown in Fig. 6-21, consist of a sealed stainless steel tube, or capillary, pressurized with helium, that contains a titanium wire saturated with hydrogen and wrapped in a molybdenum spiral (Ref. 42). When the entire sensor tube is subjected to low-level heat, the helium expands and thus increases the internal pressure of the tube, which triggers the overtemperature alarm for an averaging function mode, also called the "all point" mode. This pressure is dependent on the volume of gas heated and thus directly on the length of element heated. As a result, the detector will provide an arithmetic average of the temperatures of the element. Lengths of this detector cannot be connected in series as some of the other continuous detectors can, so these detectors are generally built to a specific length for an application. If more than one detector is desired in an area, they are wired in parallel. The core material is a selected metal hydride, which will desorb into hydrogen and



Courtesy of Systron Donner.

Figure 6-21. Systron Donner Model 808-DRV Pneumatic Continuous Detector

the metal. The hydrogen remains adsorbed on the titanium until it is heated above a critical desorption temperature; then it will outgas heavily and provide a "discrete function mode".

There are many designs available for different all point and discrete settings depending on the exact requirements of a specific installation. Fig. 6-22 is a specific example of a performance curve for a typical fire detector used in the engine compartment of commercial or military aircraft. When the entire detector is heated to 260°C (500°F), the pressure in the sensor increases to approximately 345 kPa (50 lb/in.^{2}), which closes a switch that signals an alarm condition. If a much shorter length of sensor tube, e.g., 152 mm (6 in.), were heated to 538°C (1000°F), sufficient hydrogen would be released to provide the same internal pressure in the sensor, and the alarm would also be signaled. A void space is maintained between the outgassing material and the capillary wall by a spiral wrap of molybdenum. The spiral wrap on the titanium core wire provides a passage for the helium and/or hydrogen if the outer sheath collapses onto the core when flattened or crushed during twisting, bending, or mishandling. This wrap makes the sensor tube resistant to the wear and handling it would experience in the field (Ref. 42). When outgassing occurs, a pressure buildup is transmitted along the capillary to a pressure switch at one end, which then signals the alarm. Once the detector has had a chance to cool, the hydrogen is readsorbed in the titanium. The reduction in internal pressure allows the alarm switch to return to its normally open position and thereby rearm the circuit. The volume of actual outgassing of the hydrogen is so great that it is almost independent of the length of the element. A digital output is provided by the responder end of this assembly, which contains two snap action diaphragms. The set pressure within the sensing tube is 111.5 to 192.6 kPa (16.17 to 27.93 lb/in.^{2}). One diaphragm is attached to the alarm switch, which closes normally open contacts when subjected to an internal pressure of 241 to 586 kPa (35 to 85 lb/in.^{2}), depending on the set alarm point. The other diaphragm is attached to the integrity switch, which opens normally closed contacts when the internal pressure drops below 110 to 193 kPa (16 to 28 lb/in.^{2}). The integrity switch signals the crew when the pneumatic thermal detector is inoperable. These switches cannot be readjusted after the detector leaves the factory. The reaction points and the detector response are established by flame test to be within specifications before the detectors are delivered. The sensitivity will not change even though the set point could shift slightly. This sensor is subject to malfunction if the capillary is ruptured. This failure could be a loss of integrity or a reduction in the sensitivity of the sensor, such as could occur given a ballistic perforation that results in a small hole in the sheath.

MIL-F-7872 requires a fire signal when 150 mm (5.9 in.) of cable is exposed to a flame at 1100°C (2012°F). A pneumatic detector can be set to provide such a signal and has done so in 5 s.

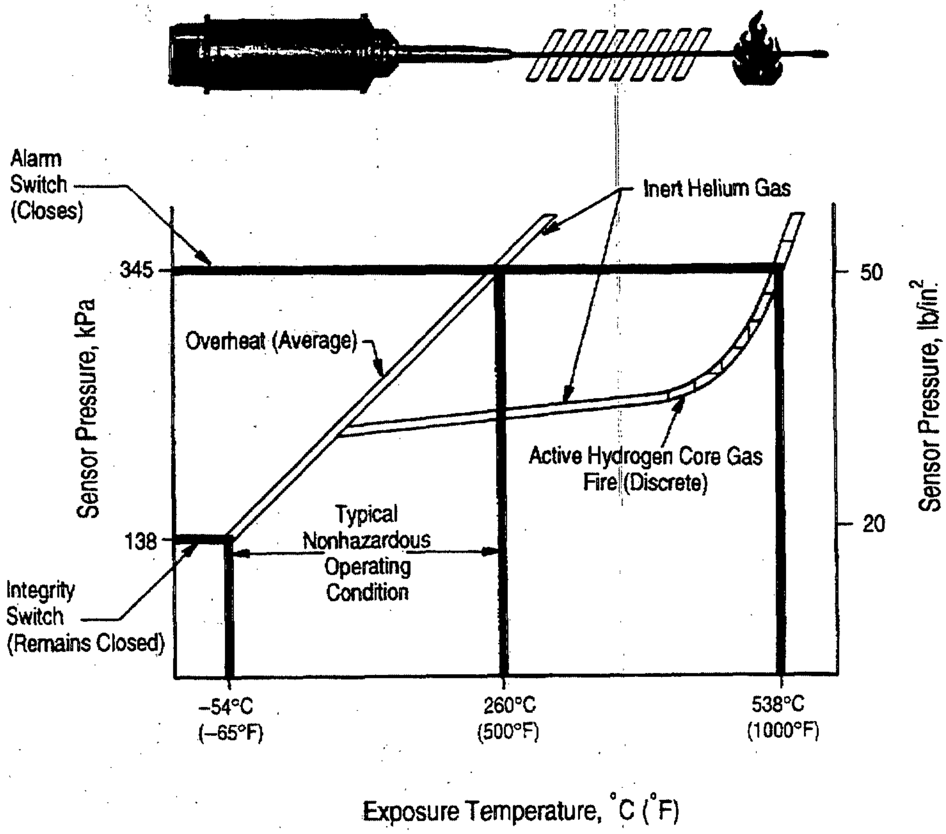


Figure 6-22. Typical Pneumatic Sensor Performance Curve (Ref. 42)

This pneumatic sensor can be fabricated to have its discrete function occur over other temperature ranges, and the values shown in Fig. 6-23 are the approximate temperatures required to generate an alarm for given exposure length. They are not intended or implied to be a specification (Ref. 43).

6-3.1.2 General Characteristics of Continuous Thermal Detectors

6-3.1.2.1 Response Time

The response time for all CTDs is long in comparison to optical detectors, which respond in milliseconds. In tests of two thermistor-type (Systems A and B) and one thermocouple-type (System C) CTD of the fire detection and extinguishing system of the Small Unit Support Vehicle (SUSV) M973 (Ref. 44) in which a propane torch was used to apply heat to a short section of the sensor cable, the responses in three trials were

1. System A: 82 s, 28 s, and 26 s for a mean of 45 s
2. System B: 18 s, 18 s, and 46 s for a mean of 27 s
3. System C: 24 s, 18 s, and 16 s for a mean of 19 s.

In some engine burn tests in that same program, the responses in three trials were

1. System A: No alarm, 46 s, and 34 s

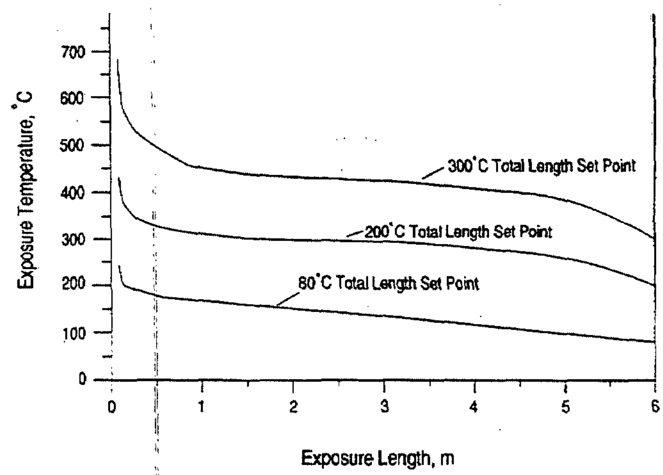


Figure 6-23. Typical 6-m Long Pneumatic Detector Performance (Ref. 43)

2. System B: No alarm, 44 s, and 34 s
3. System C: 32 s, 24 s, and 24 s
4. System D, a pneumatic-type CTD: No alarm, 48 s, and 32 s.

See subpar. 6-3.1.1.4 for discussion of pneumatic-type CTDs and subpar. 6-3.1.3.2 for more information on this test program.

6-3.1.2.1.1 Thermistor-Type Detector

Because the thermistor cable must increase in temperature before alarm output will be generated, thermistor detectors have an inherently long response time. The typical response time for a continuous loop thermistor detector is about 5 s; a 30-s response time is not unusual (Ref. 38).

6-3.1.2.1.2 Continuous Thermocouple Cable

The time constant—i.e., the time required to reach 63.2% of the final voltage for the temperature sensed—of the continuous thermocouple cable is comparable to a conventional, ungrounded thermocouple of the same diameter. This would be a shielded thermocouple with a sheath diameter of 2.5 mm (0.1 in.). The time constants graph in subpar. 6-3.2.2 indicates an approximate time constant of 10 s for a bare thermocouple with a sheath diameter of 2.5 mm and a time constant of 15 s for a shielded thermocouple with a sheath of the same diameter.

6-3.1.2.1.3 Eutectic Salt Detector

In a flame test the response time of this type of detector would probably be faster than that of the thermistor-type detector (which is approximately 5 s) because the short immersion length in the flame need not be heated as high as the averaging thermistor element. The response of a eutectic salt detector without air movement across the sheath versus temperature is shown in Fig. 6-24.

6-3.1.2.1.4 Pneumatic Continuous Detector

A typical pneumatic detector responds to a 152-mm (6-in.) long thermal input at 1100°C (2000°F) in 5 s. Once the fire source has been removed, it will return to a normal condition in approximately 30 s. (Ref. 42)

6-3.1.2.2 False Alarm Rejection

The causes of false alarms for each type of CTD are discussed in the following subparagraphs. The methods used to reduce false alarms include elimination of the causes, use of discriminating circuits, and redundant systems.

The potential sources of false alarms for CTDs are objects that become hot in use, such as the combustor can of the turbine engine of an M1 MBT or the exhaust manifold of a diesel engine. The CTDs should be routed so they are not in contact with or close enough to be affected by hot spots, and maintenance personnel should be continuously alert to assure that the CTDs are not inadvertently moved to such locations.

In general, all continuous thermal detectors rely upon convective heat transfer for averaging functioning and upon flame transfer for discrete functioning. They must be located where flames can reach them, or the fire will not be detected expeditiously. With CTDs, failure to alarm is as great a problem as false alarms. The electric CTD used in the A-10 aircraft reportedly failed due to shorting and/or chafing of the thermal cable. Sixty-seven of 87 unscheduled maintenance actions on the fire detection system were reported to be due to that cause. This chafing problem was later traced to an improperly designed mounting device. With installation of properly designed clamps and Teflon® insulators, the problem has disappeared. (Ref. 45).

6-3.1.2.2.1 Thermistor-Type Detector

A detector system that senses resistance and signals an alarm when the resistance drops below a preset value is subject not only to failure but also to giving false alarms if the detector element becomes shorted. Such a short could result from impact by a shaped-charge jet, KE projectile, fragment, spall, or chafing during normal operations. Dirt and/or moisture in connections is also a major potential cause of false alarms. To eliminate the problem of false alarms, a discriminating circuit is used in the control system, which will test for a short circuit condition and, given such a condition, will prevent the false alarm. Typical discriminating circuits currently used not only will prevent a false alarm but also will convert the false warning mode of failure to an "inoperative" failure signal.

The Firewire® (Ref. 38) system provides two parameters for fire detection. In a fire condition, the resistance between the central electrode and the sheath drops, and the capacitance rises. If the resistance and capacitance do not change simultaneously, the signal is treated as a false alarm, and no extinguishers are activated. The electronics provide a built-in self-test. If the resistance is out of tolerance, a fault is indicated, and fire signals are ignored until the fault is corrected. This setup assures positive fire detection and discrimination between a fire and a fault. If both ends of the cable are connected to the controller when the cable is cut, each segment of the cable remains functional.

6-3.1.2.2.2 Continuous Thermocouple Cable

The continuous thermocouple cable is subject to false alarms when electric currents are induced in the wires. Since the wires are installed within a stainless steel sheath, the probability of inducing electric current in the wires is low. Cutting the cable by ballistic action can be readily noted by loss of continuity; however, cutting the wires or shorting them does not render the thermocouple inoperative. Also, if both ends of the cable are connected to the controller, each segment of the cut thermocouple cable remains functional.

6-3.1.2.2.3 Eutectic Salt Detector

The eutectic salt detector is prone to false alarm problems when it is shorted. The electronic control monitors the resistance, and a low resistance condition is interpreted as a fire. Since the rate of resistance change of the melting salt approaches that of a short circuit, distinction between a short circuit and a fire condition is difficult. Consequently, a short circuit discriminator becomes quite complex, and discrimination may be unreliable. False alarm problems can be reduced by the use of redundant detector loops, which inherently provide electrical short circuit discrimination and thus reduce the need for actual discrimination circuits.

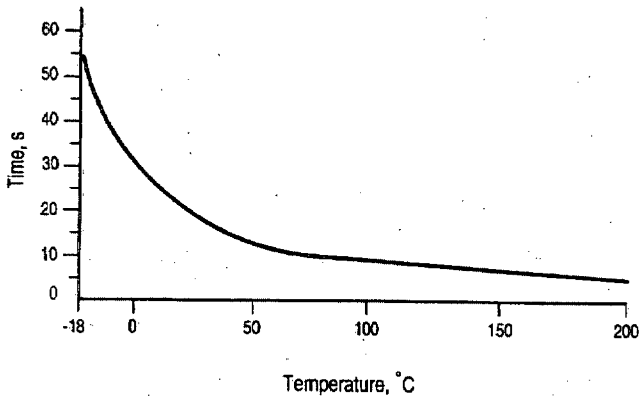


Figure 6-24. Typical Eutectic Response Times Without Air Movement Across Sensors for a Specified Alarm Temperature of 204° C (400°F) (Ref. 41)

6-3.1.2.2.4 Pneumatic Detector

The pneumatic detector is prone to false alarms only when the electrical interface wires are shorted to each other without shorting to ground by saltwater, moisture, or other contaminants. The detector design has minimized such problems with contamination. The only other way a false alarm could be generated would be to short the electrical power to the alarm circuit.

6-3.1.2.3 Sensitivity

The sensitivity of the various types of CTDs to fires and fire stimuli is discussed in the subparagraphs that follow. A common cause of degradation of sensitivity for all CTDs is for the cable or tube to become coated with a mixture of oil and dust, which can reduce heat transfer to the cable or tube. This reduction of heat transfer increases the time required for the sensor to heat. This problem is alleviated by proper cleaning and maintenance. Another common cause of sensitivity degradation is moisture or other contaminants in the electrical connections. This contamination can be prevented by proper sealing of the electrical connectors. A third potential cause for sensitivity degradation is a CTD installed too low in an engine compartment so that liquids collected in the bilge contact the CTD. The corrective action for this problem is to install the CTD high enough so that increased levels of bilge liquids or sloshing of liquids cannot contact the cable or tube.

6-3.1.2.3.1 Thermistor-Type Detector

Thermistor-type detectors respond to temperatures anywhere in the range of 124 to 1093°C (255 to 2000°F). The thermistor material is selected for the temperature at which the detector is to operate, and the temperature thresholds for alarms are individually preset. When this temperature threshold is exceeded, the alarm is triggered. The gain on thermistors is quite high, as shown in Fig. 6-15, so heating of even a short portion of the cable length results in a considerable inverse change in overall resistance (Ref. 37). Loss of sensitivity in a thermistor-type CTD can be due to moisture collecting within the electrical connector. This type of loss can be prevented by having an effective seal in the connector. In some cases, use of lug connectors with a proper locking device on the fastener assures a good electrical connection. Sensitivity can be maximized by selecting a CTD with the greatest gain at the temperature selected for system activation.

6-3.1.2.3.2 Continuous Thermocouple Cable

The sensitivity or accuracy of the continuous thermocouple cable in detecting a desired temperature is ±14 deg C (± 5 deg F). The repeatability is ±0.6 deg C (±1 deg F) after thermocycle to 538°C (1000°F), and the drift is similar to that of a mineral-insulated thermocouple.

In a series of tests for the SUSV program (described in subpar. 6-3.1.3.2) to establish the effects of contaminants in the electrical connections of a continuous thermocouple cable, the contaminants tested did not affect the capability of the cable connected to the controller to signal a fire or cause a false alarm. The contaminants tested included distilled water, tap water, saltwater, Jet A-1 fuel, antifreeze (50% ethylene glycol and 50% water), and dirty grease. Only when there was so much contaminant that the thermocouple-controller circuit was incomplete and an open circuit signal was caused was the fire detection system affected (Ref. 46).

6-3.1.2.3.3 Eutectic Salt Detector

This type of detector requires that when the eutectic salt melts, it operates as a conductor with a low resistance path and, in effect, acts as a switch that can change from a very high resistance to a very low resistance over a narrow temperature range of approximately 6 deg C (10 deg F).

6-3.1.2.3.4 Pneumatic-Type Detector

The pneumatic continuous detector has both an averaging and discrete mode of operation. In the averaging mode the detector has a fixed volume containing pressurized helium. If the pressure exceeds a desired value, a diaphragm snaps. The sensitivity of the detector in the averaging mode of operation is governed by Charles' and Boyle's laws in which the volume is constant, or $P_2/P_1 = T_2/T_1$. Therefore, there is a linear change in pressure P with a change in temperature T. For the discrete mode of operation, the increase in pressure depends upon the desorption of hydrogen from titanium hydride, which starts at approximately 399°C (750°F). The snap point of the diaphragm can be adjusted to ±10% of the desired temperature.

6-3.1.2.4 Durability

All of the CTDs currently available are designed to be rugged and corrosion, vibration, and shock resistant. Some detectors used in military equipment have already demonstrated their capability to meet the environmental requirements found in military specifications.

Some of these CTDs have been used in aircraft long enough to have established a mean-time-between-failure (Ref. 45). For an 11-yr period from 1972 through 1982, the pneumatic detector of Ref. 42 showed a mean time between false alarms of 803,800 h for single-loop pneumatic systems installed on Boeing 727 engines. This same detector has logged over 200 million flight hours in military aircraft with an average mean-time-between-failure in excess of 100,000 operating hours (Ref. 45).

The pneumatic CTD has a characteristic that is unlike any of the other types of CTDs: It is dependent upon trapped gases to expand or desorb in order to generate the pressure that provides a fire signal. Thus losing integrity of the sensor tube should affect its capability to function. To warn the crew when the sensor tube loses integrity, i.e., loses its internal helium pressure, an integrity check is provided. When the internal pressure drops below its nominal 34.5 kPa (5 psig), a snap action diaphragm snaps open and causes a warning lamp to light.

MIL-F-7872 (Ref. 47) requires that where detachable sensing elements of a control unit break, the break will not cause the system to become inoperative and that if one or more breaks occur, those portions of the sensing element still connected to the control unit shall retain the ability to detect and signal a fire. Other requirements in Ref. 46 include that such breaks will not cause false alarms. To establish that the pneumatic CTD meets these requirements, a series of tests (Ref. 48) in which breaks were made using five different techniques was conducted:

1. Cutting the sensor tube with tube cutters
2. Shearing the tube with diagonal-cutting pliers
3. Severing the tube by impact with a 7.92-mm bullet
4. Shearing the tube with a hammered blunt rod
5. Flexing the tube until a fatigue failure occurred.

All of these severing techniques tended to close the sheath and obtained at least a partial seal, which was minimal for flexing to fatigue, but these techniques simulated most of the damage that this sensor tube would be expected to receive in combat or normal operations. The blunt, high-speed penetrator and the shaped-charge jet were almost simulated by the flexing-to-fatigue failure because for that failure the sheath did not effectively block the gas flow passage (Ref. 49).

These tests did not show that puncture of the sensor tube results in loss of the averaging function, but the crew did receive warning that tube integrity was lost. On the other hand, these tests indicated that if the sensor were severed, a fire could be sensed if it contacted the tubing at least 305 mm (12 in.) from the cut. This phenomenon is due to the great quantity of hydrogen desorbed shortly after a high-temperature flame contacts the tubing. The sensor would not be fully operational, i.e., it would signal a fire, and that signal would be lost after the hydrogen leaks out through the cut. This leakage of hydrogen, however, can take considerable time, as was demonstrated by the tests in which the tube was cut with a hammered blunt rod. The alarm switch opened very quickly after the fire was removed from the tube, but the integrity switch remained closed and indicated appropriate pressure for 12 min. The switch would have remained closed longer if the sheath had not been cut further by the test personnel (Ref. 49).

6-3.1.3 Application Suitability of Continuous Thermal Detectors

6-3.1.3.1 CTD Installation

Because thermal detectors do not have as fast a response as the optical detectors, they are not well-suited for systems designed to extinguish flash fires, such as combustible liquid spray fireball fires in crew compartments. For vehicles designed to preclude the occurrence of hydrocarbon liquid spray fireballs (discussed in Chapters 2 and 4), however, CTDs could be appropriate for crew compartments if overtemperature is the primary concern. CTDs are also ideal for installation where there is a very high ambient temperature, a dirty environment, and a risk of fluid spills and where the equipment can withstand flash fires, such as in the engine compartment. Continuous thermal detectors can be routed away from high-temperature equipment, such as turbine engine combustor cans, to avoid the false alarms caused by those objects. Detector cables can also be strung about the hazard area and across the airflow patterns so that it would be highly unlikely for a fire to exist and not have the resulting hot gases come in contact with the thermal detector. Thermal detectors such as the Graviner* Firewire®, which is a semiconductor thermistor type of detector, and the Systron Donner pneumatic detector are routinely used in the engine compartments of combat vehicles. These detectors are routed within the engine compartment and in conjunction with their associated control electronics and fire extinguishers create very efficient and responsive fire suppression systems. Fig. 6-25 is a schematic drawing of the Firewire® detector, control electronics, and the fire suppression system as installed in a typical combat vehicle.

6-3.1.3.2 Comparative Tests of Several CTDs

The US Army has lost nine M973 SUSVs to fires, most of which occurred in the engine compartment. By the time the occupants realized there was a fire, the fire had developed too far to be extinguished with the onboard, portable extinguishers. A series of tests was performed at the US Army Cold Regions Test Center to evaluate candidate fire detection and extinguishing systems for the M973 SUSV (Ref. 44).

The systems furnished for this program included three thermistor-type CTDs, one thermocouple type, and one pneumatic type. All five of these sensors can function with a discrete mode, and all except the thermocouple cable can function in an averaging mode. Generally speaking, the thermistor- and thermocouple-type sensors obtain their dis-

*Use of the fabricator's name does not constitute Government endorsement of the products.

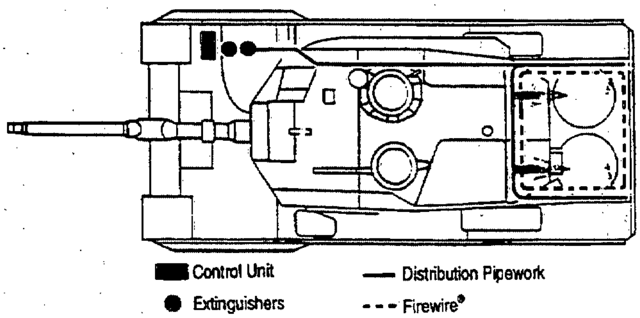


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Figure 6-25. Typical Firewire® Installation in Combat Vehicle (Leopard II) (Ref. 38)

crete function mode through the choice of the insulation material between the core wire and sheath or between the dissimilar core wires. The pneumatic-type sensor obtains its discrete function mode through the choice of core material and the gas it adsorbs. Initially, all five of the detector systems furnished were factory set to respond to a temperature better suited for a steel-hulled vehicle than for a fiberglass-reinforced, plastic-hulled vehicle. Most of these factory set systems were not capable of having the response temperature changed, although one system, the thermocouple-type CTD, was modified at the request of TACOM to provide the capability to readjust its response temperature set point. The SUSV fire detection and extinguishing systems were tested for their response at a desired reaction temperature within the range of 204 to 232°C (400 to 450°F). Three of the systems could function in the discrete mode or could be set to respond within the desired temperature range, and these three systems performed superbly. The other two systems could not be reset in the available time to function in the discrete mode within that temperature range. These two systems did not perform satisfactorily because they were not originally designed for this application, not because they were incapable of adequate performance. After modification of the set point temperatures, these two systems were retested and performed satisfactorily.

6-3.1.3.3 Lessons Learned

The lessons learned from that SUSV program follow:

1. Discrete functioning is preferable to averaging functioning for CTDs, and CTDs must be designed and fabricated to function within the desired temperature range.
2. CTDs should not be installed in locations that require significant labor to access for maintenance. In this case the engine had to be removed before the CTD could be installed or removed.
3. CTDs, except for the Systron Donner pneumatic detectors*, should be grounded, and they should not have a floating ground such as a sheath because accidental grounding of the sheath can affect sensor performance.
4. CTDs should be rugged enough to prevent electrical shorts of the CTD circuit if the cable is accidentally twisted.
5. The design of the mounting system is very critical.
6. Excessive slack in the CTD cable can lead to breakage (Ref. 44).

Another lesson learned is that more thorough guidance must be given by designers when a fire detection system is needed. Particularly, the desired temperature range in which the device is to function should be specified, or sufficient information on the desired application should be given so that the sensor system supplier can establish the necessary temperature range.

6-3.2 THERMOCOUPLES

A thermocouple is another thermal sensing device that can be used to detect a fire. Thermocouples are simple, rugged, and inexpensive. They have a slower response than the other combustion- or temperature-sensing devices already covered, but the response of a thermocouple can be fast enough to protect an engine compartment. A thermocouple is a point temperature measuring device unless a continuous thermocouple cable is used.

6-3.2.1 Basic Functioning

In 1821 Thomas Johann Seebeck discovered that when wires of different conductive materials are joined and the connected point is heated, an electric current flows in the wire circuit. This fact also means that if the circuit were broken at other than the heated connection, there would be a voltage across the open ends of the wires. All dissimilar metals exhibit this effect, but certain combinations of metals produce a greater current or voltage than others given the same thermal input to the connected point. This connected point is called a thermocouple junction.

Every connection of dissimilar metal wires is a thermocouple, but if connections are made at locations that are not exposed to great temperature variations or that are exposed to known or constant temperatures, only the purposely exposed thermocouple will produce the electrical output significative of a temperature change. When a reference junction is added to the circuit, the output voltage of the system is a function of the difference in temperature between the thermocouple and the reference junction. Normally this reference temperature is that of an ice water bath, which is 0°C (32°F). Leads can be attached to this thermocouple-reference junction array by using an isothermal block, which in essence provides two more thermocouples, the outputs of which cancel each other. The ice water bath reference junction can be replaced with an electronic ice point, which provides a voltage equal to that which the reference junction would produce. The voltage produced by this combination thermocouple-reference junction and lead wire array can be converted to a temperature by referring to a temperature-input versus voltage-output relationship, which is peculiar to the thermocouple materials used.

*The pneumatic detectors are at above ground potential and are not referenced to sheath ground. They are monitored differently than transistor-type electrical units.

6-3.2.2 Thermocouple Types

The six most commonly used thermocouple material combinations are shown in Table 6-4, and the temperature-voltage relationships for these six thermocouple types are shown on Fig. 6-26.

Chromel is an alloy of 90% nickel and 10% chromium. Alumel is an alloy of nickel that contains approximately 2.5% manganese, 2% aluminum, and 1% silicon. Constantan is a copper-nickel alloy that differs for the various thermocouple types. One of the constantan alloys is 55% copper and 45% nickel.

Type E (chromel/constantan) may be used at temperatures up to 871°C (1600°F) in an inert, mildly oxidizing or reducing atmosphere. Type E thermocouples are recommended for use in subzero applications. Type J (iron-constantan) is recommended for reducing atmospheres only, and Type K (chromel-alumel) is recommended for use in clean oxidizing atmospheres. Types R (platinum-platinum, 13% rhodium) and S (platinum-platinum, 10% rhodium) have high resistance to oxidation and corrosion. However, hydrogen, carbon, and many metal vapors can contaminate these types, so they should be used only with nonmetal sheaths. Type T (copper-constantan) is recommended for use in mildly oxidizing or reducing atmospheres and is suitable for use where moisture is present. (Ref. 37)

The thermocouple junction can be bare or shielded, as shown in Fig. 6-27. Bare thermocouple junctions, shown in (Figs. 6-27(A) and (C), can be either butt-welded or beaded. Shielded thermocouples can be either grounded to the shield, as shown in Fig. 6-27(B), or insulated from it, as shown in Fig. 6-27(D). The bare thermocouples have a faster response but are more susceptible to damage than the shielded. When the shield is grounded, the thermocouple is less subject to noise pickup. Shielded thermocouples have time constants, i.e., the time required to reach 63.2% of the final output given a step change in input, approximately 1.5 times those of bare thermocouples. The time constant of a bare thermocouple is given versus the wire or sheath diameter *D* in Fig. 6-28.

TABLE 6-4. THERMOCOUPLE MATERIALS (Ref. 37)

TYPE	POSITIVE	NEGATIVE
E	Chromel	Constantan
J	Iron	Constantan
K	Chromel	Alumel
R	Platinum	Platinum, 13% Rhodium
S	Platinum	Platinum, 10% Rhodium
T	Copper	Constantan

Source of information Omega Engineering, Inc. Used with permission of Omega Engineering, Inc., Stamford, CT 06907.

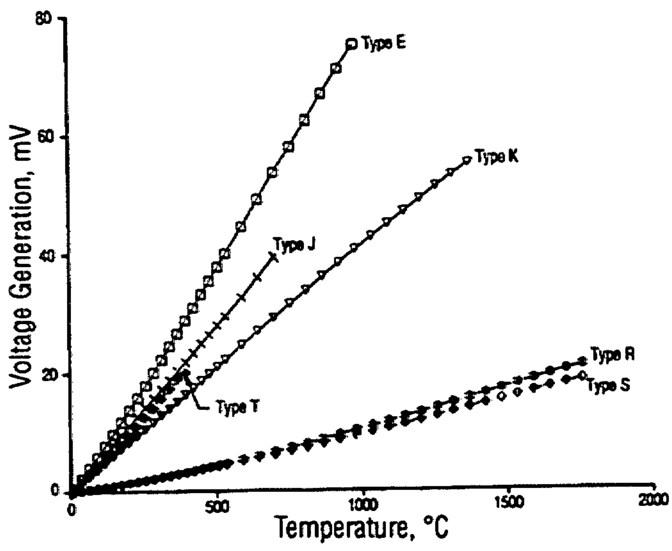
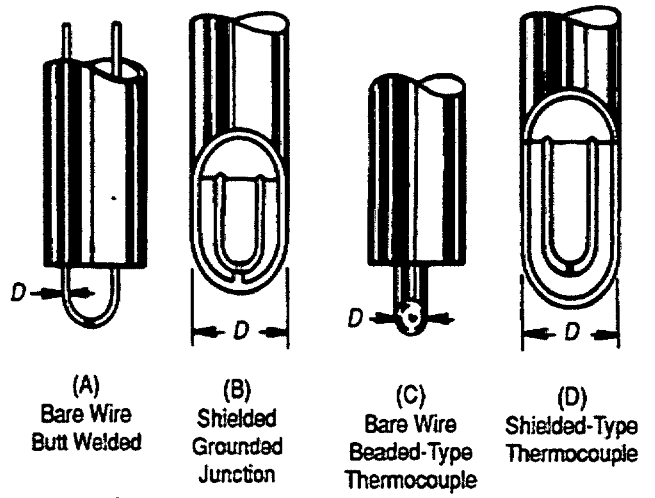


Figure 6-26. Typical Thermocouple Temperature and Voltage Ranges (Ref. 37)



D = diameter

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Figure 6-27. Thermocouple Sensing Elements (Ref. 37)

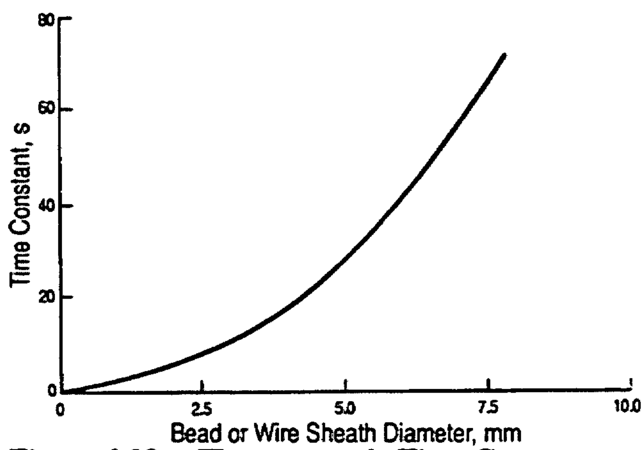

Figure 6-28. Thermocouple Time Constants (Ref. 37)

6-3.2.3 Application Suitability of Thermocouples

6-3.2.3.1 Reduction of Noise

Tree switching, analog filters, integration, or guarding techniques can be used to prevent receipt of noise from external sources. Tree switching is a method of organizing thermocouple channels into groups. Each group has its own main switch and a tree switch capacitance. Without tree switching, every channel can contribute noise directly through its stray capacitance, but with tree switching, groups of parallel channels are in series with a single tree switch capacitance. This technique greatly reduces cross talk in a large data acquisition system caused by reduced interchannel capacitance.

An analog filter can be used directly at the input of a voltmeter to reduce noise; however, this filter causes the voltmeter to respond more slowly to step inputs.

Integration is a technique used to average noise over a full line cycle and thus eliminate power-line noise and its harmonics.

Guarding is used to reduce interference from any noise source common to both high- and low-measurement leads. The guard is a floating metal box that surrounds the entire voltmeter circuit. The box and the connected shielding surrounding the thermocouple wires shunt interfering currents.

Another way to reduce noise pickup is to use twisted pairs of thermocouple extension wires.

6-3.2.3.2 Performance Degradation Problems

Most thermocouple measurement errors can be traced to one of the following sources:

1. Poor junction connection
2. Decalibration of thermocouple wire
3. Shunt impedance and galvanic action
4. Thermal shunting
5. Noise and leakage currents
6. Physical damage to the thermocouple.

6-3.2.3.2.1 Joint Connection

A good thermocouple occurs where there is an intimate, secure junction of the two materials. Acceptable thermocouples can be obtained by silver soldering or welding. Welding is the better method, but care must be exercised because the wires can be degraded by overheating. Any welding fluid or the atmosphere in which the welding is performed can result in diffusion of extraneous materials into the weld that change its characteristic voltage versus temperature. Poor welds can result in an open connection; these, however, can be readily detected. Commercial thermocouples are usually produced on special machines that use capacitance discharge techniques.

6-3.2.3.2.2 Decalibration

If the characteristics of the thermocouple have changed so that the electric current or voltage generated for a given temperature input is no longer within the tolerance allowed, the thermocouple has been decalibrated. Decalibration can be caused by overheating, cold working the wires, or by introducing contaminants into the junction. This type of malfunction cannot be as readily detected as the open junction.

6-3.2.3.2.3 Shunt Impedance and Galvanic Action

Shunt impedance results when the thermocouple wire insulation fails and thus creates alternate electrical circuit paths. Galvanic action occurs where wire insulation materials react with moisture to generate an electric current or voltage, which may exceed the current or voltage generated by the thermocouple.

6-3.2.3.2.4 Thermal Shunting

A thermocouple generates a specific current or voltage when the temperature of the dissimilar material junction is raised or lowered. Therefore, factors that affect the heat transfer between the material from which the temperature is being sensed and the thermocouple alter the temperature indicated. These factors include a drain or addition of heat energy from the thermocouple junction through thermally conductive paths or from thermocouple extension wires to extraneous heat sinks or sources.

6-3.2.3.2.5 Noise and Leakage Currents

The effects of noise were discussed in subpar. 6-3.2.3.1. The introduction of stray dc inputs into a thermocouple circuit results in an erroneous output.

6-3.2.3.2.6 Physical Damage to the Thermocouple

Physical damage to a bare wire thermocouple can result in a short to the case, which can introduce stray electrical inputs, stray thermal inputs, or additional dissimilar metal junctions of an intermittent nature. Damage to a thermocouple sheath can produce thermal or electrical shorts.

6-3.2.3.3 Advantages and Disadvantages

The advantages of using thermocouples follow:

1. They are self-powered.
2. They are simple.
3. They are rugged.
4. They are inexpensive.
5. There is a wide variety from which to choose.
6. They can cover a wide temperature range.

The following are the disadvantages:

1. Their response is slower than that of diodes.
2. They are nonlinear.
3. A reference junction or subsystem is required.
4. The output is not as stable as that of other types of temperature transducers.
5. Their gain and, therefore, sensitivity are not as great as those for other types of temperature transducers, e.g., thermistors.

6-3.2.3.4 Recommendations

Overall, thermocouples could be used to detect a fire in a combat vehicle. Each thermocouple would detect the presence of a high temperature at a selected discrete location;

therefore, several thermocouples could be required to cover a given compartment. Thermocouples would provide a simple, rugged, and inexpensive system that would have a slightly slower response than the continuous thermal detectors already discussed.

6-3.3 THERMOPILE

A thermopile is a number of thermocouples wired in series so that the voltage produced is additive. Some fire detectors made in the US use a thermopile to establish that heat is present when IR radiation is sensed by optical sensors, as discussed in subpar. 6-2.2.3.

6-3.3.1 Thin-Film Thermopile

Armtec Industries offers a thin-film thermopile, which can be made in different geometries for specific applications. The constituent bismuth alloy and antimony alloy thermocouples are connected in series with the cold junctions in contact with an electrically nonconductive, but thermally highly conductive, mass of beryllium oxide (BeO) that essentially keeps the cold junctions at ambient temperature. The hot junctions are coated with black, oxidized metal for high-speed performance or with black organic oxide for maximum spectral flatness. These hot junctions view the potential fire site through a window that filters out all but a desired narrow band of wavelengths of radiation, and this window can be faceted to provide a wider range of view. The thin-film thermopile generates a voltage. In an example in which the ambient temperature is 20°C, an object at 0°C would produce −1.93 mV, and an object at 200°C would produce 45.58 mV in a PS-15 thermopile, which has 28 hot junctions and a time constant of 20 to 40 ms (Ref. 50). Armtec is developing a thermopile better adapted to combat vehicles that will have a time constant of approximately 10 ms. Armtec thermopiles are currently used in intrusion detectors for indoor and outdoor surveillance. Thin-film thermopiles with similar characteristics are also manufactured by other suppliers.

6-3.3.2 Russian Thermopile

The Russians use a thermopile, similar to that shown in Fig. 6-29, for the sensing element in their combat vehicles (Ref. 10). This Russian thermopile consists of 15 chromel/constantan thermocouples wired in series. The ambient temperature junctions are embedded in a block of transparent plastic within the housing. Such a device should increase the voltage output over that of a single thermocouple by almost a factor of 15. This device does not produce a voltage proportional to absolute temperature; it produces a voltage when the exposed beads are subjected to flame and the embedded beads are at the temperature of the plastic mass. The plastic does not heat very much or very rapidly even though the housing is exposed to flame; thus the sensor is used to detect a sudden increase in temperature. Depending upon the voltage needed to trigger the controller, the multiple beads would tend to improve the sensor response by providing a usable signal sooner, i.e., before they have been raised to the flame temperature, and the device would not need power to operate. The chromel and constantan wires are 0.41 to 0.43 mm (0.016 to 0.017 in.) in diameter, and each bead is approximately 1.35 mm (0.053 in.) in diameter (Ref. 10). There is reason to believe that this device is being used as a heat flux sensor. See subpar. 8-2.1.3.3 for a description of heat flux sensors.

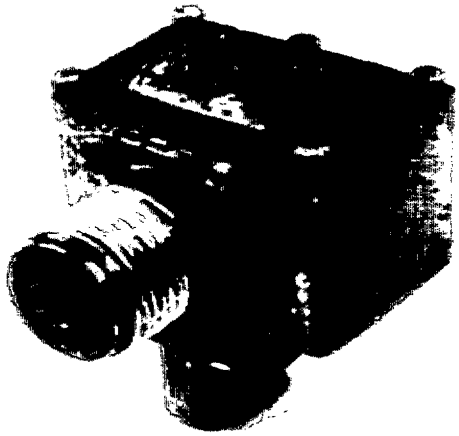

Figure 6-29. Typical Thermopile Sensor Used in Russian T-55 MBT

6-4 OTHER DETECTORS

6-4.1 PENETRATION DETECTOR

A continuous wire grid system, which was designed to sense combat vehicle hull penetrations by exploding mines, was successfully demonstrated on a landing vehicle tracked personnel (LVTP) 5A1 vehicle (Ref. 51). Discharge of a shaped charge upward into the hull of this vehicle usually results in a fuel cell being punctured and fuel being injected into the vehicle. The fuel mixes with air and becomes an ignitable mixture. This system is used to prevent or extinguish the fire that could result. The continuous wire system, as illustrated in Fig. 6-30, was installed in the vehicle, as shown in Fig. 6-31, and consisted of a network of wire grids laminated between two sheets of a glass fiber. These wire

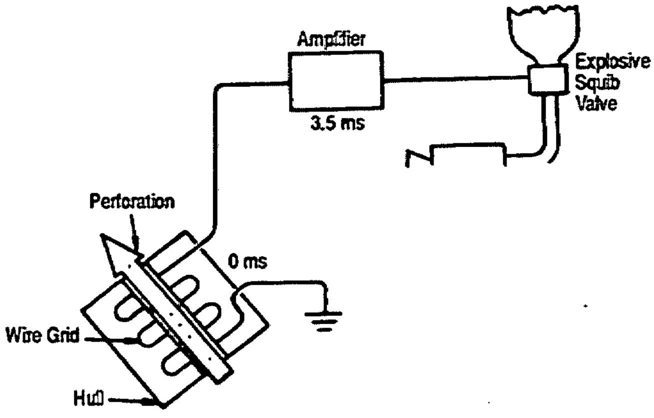

Figure 6-30. Wire Grid Detector (Ref. 51)

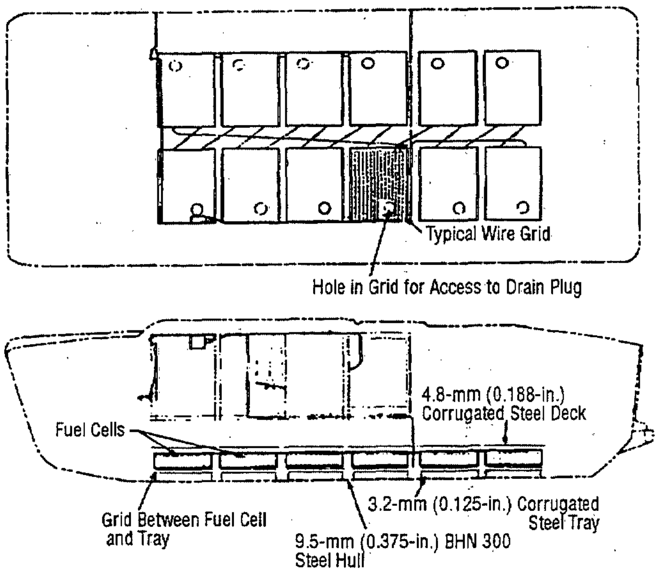

Figure 6-31. Continuous Wire Grid System of LVTP 5A1 (Ref. 51)

grid assemblies were connected to silicon-control-rectifier (SCR)-type amplifiers, which, when activated, supplied a current to one or several squib valves that released a fire suppressant into the vehicle. The system was activated when the grid circuit was opened, i.e., when a wire was broken after the grid screen was perforated. When the hull was perforated by a shaped charge, the system response time from detection of the perforation to a level sufficient to actuate the amplifier was established experimentally at 1.5 to 2.75 ms. Total system response time including the time required by the SCR amplifier to produce an output signal to the squib firing circuit was 3.5 to 4.0 ms after initiation of the blast.

This system has been shown to be very reliable and to have a fast response. The response time of the wire grid system compares favorably with that of the optical detector systems and is much faster than that of the thermal detectors. Detection of fire and release of the fire suppressant requires that one of the wires be broken, so the typical obscuration and false alarm problems involved with optical detectors are obviated.

In tests of the APC M113 and M113A1 AFES in the 1969-1972 period, the penetration detection system that had been proven on the LVTP 5A1 performed well (Refs. 11, 12, and 52). The penetration detector also reacted to penetration by a 14.5-mm armor-piercing incendiary bullet as well as to penetration by a shaped-charge jet (Ref. 11). The penetration detector was placed on the personnel side of the fuel cell in the M113 rather than on the hull side as in the LVTP 5A1. This placement rendered the penetration detector of the M113 more subject to accidental damage than that of the LVTP 5A1.

The major disadvantage of the wire grid system is that since the system is a positive-type response requiring the breaking of a wire, the system will not respond to fires initiated by impacts or penetrations that do not break a wire, initiated by penetrators that impact an area of the vehicle not equipped with wire grids, or resulting from fuel line leaks or breaks. All of these fire conditions would not be detected by the wire grid system but would be detected by either optical or thermal detectors. Another problem associated with the wire grid system involves accidental or inadvertent damage or breaking of a wire by personnel or other noncombat-related situations that would result in the system actuating and releasing the fire suppressant into the vehicle (Ref. 11). This potential problem can be overcome, or at least the probability of occurrence can be reduced, by proper protection of the wire grid.*

The wire grid system to protect the areas of a vehicle vulnerable to projectile, fragment, or shaped-charge impact combined with either an optical or thermal detection system to protect the other areas of the vehicle and to provide overlapping coverage appears to be a practical and effective way to provide fire detection coverage.

6-4.2 SMOKE DETECTORS

Smoke detectors currently in use are based upon one of two basic phenomena: (1) photoelectric, which is due to the scattering of infrared radiation by combustion products or (2) a change in the passing of a current between the anode and cathode that follows the ionization resulting from exposure to a radioactive source.

6-4.2.1 Photoelectric Smoke Detector

6-4.2.1.1 Photoelectric Smoke Detector Used in Cargo Aircraft

The Systron Donner** photoelectric smoke detector operates on the Tyndall effect. Thus in simple terms the smoke detector is a particle detector. As such, an alarm occurs when reflectance of these particles reaches a preset value whether the particles are smoke, moisture, or dust. There are two versions of this type of detector, i.e., draw-through and free convection.

The sensitivity of the detectors in light transmission T_{305} percentage—defined as the percentage of light falling on a photoelectric cell through a 305-mm (1-ft) distance occupied by smoke particles—is 94 to 96% T_{305} for the draw-through detector and 80 to 90% T_{305} for the free convection detector. (Ref. 53) The operating temperature range for both

*This wire grid penetration detector is reputed to have been field tested in SEA and rejected as being too susceptible to fatigue or accidental damage, but no records of such testing could be found. Similar "problems" were encountered at both FMC Corporation and Aberdeen Proving Ground but were "solved" at both places and the wire grids then performed excellently. Thus the author of this handbook recommends reserving judgment on the results of the reputed field tests until records of that work can be found and assessed

**Identification of this supplier does not constitute Government endorsement of the specific proiduct.

devices is –30 to 70°C (–22 to 158°F), and the nonoperating temperature range* is –55 to 70°C (–67 to 158°F). The input voltage range for both is 18.0 to 32.2 V, and these devices draw less than 50 mA. The volume requirements for both devices are 102 × 178 × 76 mm (4 × 7 × 3 in.), and their masses are 610 g (1.34 lb) and 550 g (1.21 lb), respectively.

The draw-through detector has an optimum response time of 30 s and can be mounted anywhere the sampling line and pump can draw enough air to ensure that the maximum system response time is 60 s. The Systron Donner draw-through-type smoke detector has an opto-electronic response time of less than 2 s. The time to alarm is a function of how long it takes to get the concentration of smoke to the optical "chamber" to trigger the alarm. During six tests with smoke at 86.9% T_{305} and flow at 0.000142 m^3/s (0.3 ft^3/min), the alarm times were between 2.53 and 6.71 s.

Mounting of the free convection detector is recommended to be in the same compartment as the hazard. For optimum performance this detector should be located close to the ceiling with the perforated cover fully exposed to the ambient air. The system response time should again be approximately 30 s.

A photoelectric smoke detector has been used in the cargo bays of some Boeing, McDonnell Douglas, and Fokker aircraft. The detector (Ref. 53) has three modes of operation: off, armed, and test.

The detector can provide three possible signals: armed mode light on or off, test mode light off, and test mode light blinking.

In the armed mode, if the alarm light is off, the detector is signaling that smoke is not present above the threshold set. If the alarm light is on, the detector is signaling that there is smoke present above the threshold.

In the test mode, if the alarm light stays off, the detector is indicating a malfunction. If the alarm light blinks on and off at a 5-Hz rate, the device is indicating that there is a buildup of dust either in the sensing labyrinth or on the optics or that smoke is present at less than the alarm level.

Moisture caused a problem for cargo aircraft smoke detectors because they would alarm after being cooled in flight and then subjected to high-humidity air on the ground. This problem was corrected by the addition of a heater block which is designed to keep the sensing portion of the smoke detector above the dew point in humid environments.

The possibility of detecting smoke while operating in dusty environments, such as on ground vehicles, by using these detectors would have to be demonstrated. The Systron Donner smoke detector, however, has been tested to par. 46, "Dust Test", of Underwriters Laboratories standard UL 268 (Ref. 54) with no false warnings. This result is attributed to the patented labyrinth design, which houses the smoke-sensing elements. A fail-to-test condition did eventually occur, and when the unit was cleaned (a simple operation), it operated properly again.

*Nonoperating (storage) temperature range is the range of temperatures to which the device can be subjected and remain functional, but the device does not have to function throughout the entire range.

6-4.2.1.2 Photoelectric Smoke Detector Used in Commercial Buildings

Barksdale* fabricates a photoelectric—light-scattering principle—smoke detector (Ref. 55) that has a normal sensitivity of 3.3% per 305-mm (1-ft) obscuration. This value translates to 96.7% T_{305} in the rating system used in subpar. 6-4.2.1.1. The photoelectric smoke detector is available with and without a bimetallic strip heat detector, which trips at 57°C (135°F). This smoke detector uses natural convection scanning and is quicker to react to smoke than the ionization-type sensor described in the next paragraph. When the particles are in the range of 3 to 10 µm, the device has the optimum reaction. The bimetallic strip heat detector assures that both heat and smoke are present before the detector signals a fire.

6-4.2.2 Ionization Smoke Detectors

An ionization smoke detector contains a small quantity of radioactive material that ionizes the air in a sensing chamber and makes the air conductive. This conductivity permits a current flow through the air between an anode and a cathode in the chamber. Smoke particles that enter the chamber attract the ions and reduce the effective conductance (Ref. 56). The detector notes the decrease in current flow by using a Wheatstone bridge-type circuit.

Ionization smoke detectors can react to particles in the range of 0.1 to 3 µm and thus are quicker to react to a flaming fire than the photoelectric sensor described in subpar. 6-4.2.1.2. The ionization detector is more sensitive than the photoelectric; the sensitivity of the ionization detector is 1.5% per 305-mm (1-ft) obscuration, or 98.5% T_{305} transmission. The ionization smoke detector is not as sensitive to dust as the photoelectric smoke detector, but excessive dust deposits can reduce its sensitivity.

6-4.3 VARIOUS GAS DETECTORS

Not too many years ago miners carried canaries down into mine shafts to establish whether or not the air was breathable. Canaries have now been replaced with many devices that can determine why the air is not breathable. Small devices can detect the presence of carbon monoxide and other noxious gases, they can determine breathability of air by the percentage and partial pressure of oxygen and they can determine whether a combustible or explosive mixture of vapors exists in the air (Ref. 56). Use of devices similar to these could permit monitoring of the air within the crew and engine compartments so that an incipient fire situation or smoldering fire could be discovered and preventive action taken before a fire flames.

In general, small, portable devices are available that can

*Identification of this supplier does not constitute Government endorsement of the specific product.

detect various gases, but they would have to be modified for use in combat vehicles.

6-4.3.1 Noxious Gas Detectors

Small, portable devices are available to detect carbon monoxide (Ref. 57). The sensor is an electrochemical polarographic cell. Samples are drawn past a porous tetrafluoroethylene membrane. Carbon monoxide is electrooxidized to carbon dioxide in proportion to the partial pressure in the sample area. The electrical signal that results from the ensuing electrolysis is temperature compensated and amplified to drive the meter. The response is 90% complete in less than 30 s. This detector can detect carbon monoxide to one part per million (ppm). The operating temperature range of the instrument is 0 to 40°C (32 to 104°F) and the relative humidity range is 5 to 95%. It was designed for use in normal civilian working areas and would require more engineering and testing before it could be used in a combat vehicle. There are several materials that can cause a false indication of carbon monoxide; these materials and their effect upon the reading by the device are given in Table 6-5.

6-4.3.2 Oxygen Detector

The capacity of the air to supply the necessary oxygen could be established rather than the presence of asphyxiant gases. A human's lungs require oxygen to be available at a partial pressure of at least 13.3 kPa (1.93 lb/in.^{2} or 100 mm Hg) (Ref. 58).

A family of instruments is available that directly senses oxygen by a galvanic cell containing a gold anode and a lead cathode in a basic electrolyte (Ref. 59). This electrolyte is on one side of a fluorocarbon-polymer diaphragm, and the air sample is on the other side. Oxygen diffuses through the diaphragm and initiates an oxidation reduction reaction that generates an electric current proportional to the partial pressure of the oxygen. These devices are accurate to ±0.3% oxygen at constant temperature and pressure over a range of 0 to 25% oxygen. They reach 90% of full response in 20 s over the temperature range of 0 to 40°C (32 to 104°F) and within 3 min over the temperature range of –18 to 0°C (0 to 32°F). The relative humidity operating range is 10 to 90%, and the operating temperature range is 0 to 40°C (32 to 104°F) or –18 to 40°C (0 to 104°F) if calibrated at the temperature of use.

6-4.3.3 Combustible Vapors and Their Potential Hazards

If the coolant air leaving the engine compartment were monitored for combustible vapors, incipient combustion could be detected prior to ignition. An engine fire due to nonballistic causes could be prevented if the combustibility of the air in the engine compartment were monitored and appropriate action were taken if required to lower the oxygen concentration or cool the compartment.

There are many devices available to establish the existence of a combustible or explosive mixture of fuel vapor and air. One instrument uses the catalytic action of a heated platinum filament in contact with the sample of gases (Ref. 60). The filament is heated to operating temperature by an electric current. The gas sample in contact with the filament burns and thus raises the temperature of the filament proportionately with the amount of combustible in the sample. This filament is in one leg of a Wheatstone bridge, which provides a signal proportional to the temperature of the filament. This device can be calibrated with any desired combustible gas or vapor and can provide a signal at any point between 0 and 100% of the lower explosive limit (LEL) of the combustible vapor used for the calibration.

There are some limitations with this equipment. Silanes and silicones and other compounds containing silicon can rapidly "poison" the platinum filament. Leaded gasoline vapor can also "poison" the filament. Atmospheres deficient in oxygen—less than 10%—may not indicate the proper concentrations of combustible gases, but that omission would not be important since such atmospheres do not support fire.

TABLE 6-5. INTERFERENTS FOR CARBON MONOXIDE DETECTOR (Ref. 57)

INTERFERENT	INTERFERENT CONCENTRATION, ppm	SENSOR RESPONSE ERROR, ppm
Ammonia	100	–4
Benzene	17.7	0
Carbon dioxide	5000	–4
Carbon disulfide	14.5	+2
Chlorine	5	0
Dimethyl sulfide	4.5	+2
Ethylene	50	+100
Freon 12	1000	–2
Hexane	500	–2
Hydrogen	500	+70
Hydrogen cyanide	42	+30
Hydrogen sulfide	40	+170
Isopropanol	50	+40
Mercaptan		
ethyl	4.4	+6
methyl	5	+7
Methane	50,000	–3
Methanol	50	+130
Nitric oxide	100	+260
Nitrogen dioxide	100	+80
Sulfur dioxide	150	+30

A version of the combustible vapor detector can sense molecular oxygen (Ref. 56). The time to 90% of full response for this device is 15 s within an ambient temperature range of 0 to 40°C (32 to 104°F), the normal operating temperature range of the instrument. The accuracy of this detector is ±3% for oxygen at consistent temperature and pressure and ±3% LEL for the combustible gas. The operating humidity range is 10 to 90% relative humidity. This device was designed for use in a normal civilian work area (Ref. 61). Further engineering and testing are needed before this device could be installed in a combat vehicle.

Devices are available with sensors that determine the presence of oxygen, combustible fuel vapors, and carbon dioxide (Ref. 62).

6-5 EXAMPLES

6-5.1 LEOPARD II MAIN BATTLE TANK

The fuel explosion and fire protection system for the Leopard II main battle tank is shown schematically in Figs. 6-25 and 6-32. Included are the detectors, control unit, and extinguishers. The engine bay system is shown in Fig. 6-25, and the crew bay system in Fig. 6-32. Infrared radiation is sensed in the crew bay by four sensors located fore and aft. Under noncombat operating conditions the control unit operates the extinguisher system only if simultaneous signals are received from at least two detectors, whereas under battle conditions the control unit can operate multiple extinguishers upon receipt of a detection signal from only one detector.

The fire detection and extinguishing system for the engine compartment of the Leopard II uses the Firewire® thermistor-type continuous thermal detector. Firewire® is an automatically resetting unit routed through the engine compartment. This detector signals a warning at the control unit if the temperature in the fire zone exceeds a set maximum operating temperature. The warning is cancelled automatically if the temperature subsequently drops below the set maximum operating temperature. See subpar. 6-3.1.3 for discussion of continuous thermal detectors.

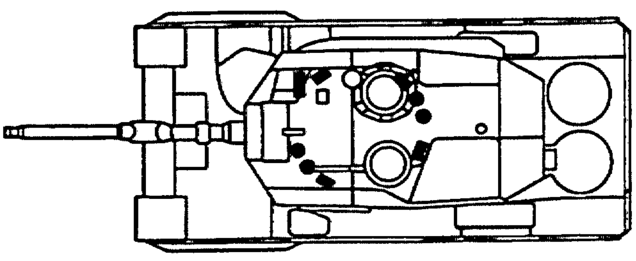

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Figure 6-32. Leopard II Crew Bay Fire Detection and Suppression System (Ref. 63)

6-5.2 BRADLEY FIGHTING VEHICLES

The fire suppression system for the Bradley fighting vehicles is shown in Fig. 6-14. This system has a dual spectrum infrared sensor system in the crew compartment but no fire detection system in the engine compartment.

6-5.3 MBT M60A3

From 1981 through 1987 a product improvement program was conducted for the M60A3 MBT that included an AFES, shown in Fig. 6-33, used optical sensors. Many tests of the system were performed (Refs. 64 through 68), and several interesting conclusions were drawn from this program. The independent evaluation report (Ref. 13) concluded that engine compartment optical sensors get dirty often and easily and will not function properly when dirty and that their locations made them difficult or hazardous to clean. Subsequently, a thermal detection system was evaluated for the engine compartment. An AFES was not fielded for the M60A3 due to its phaseout from the active Army.

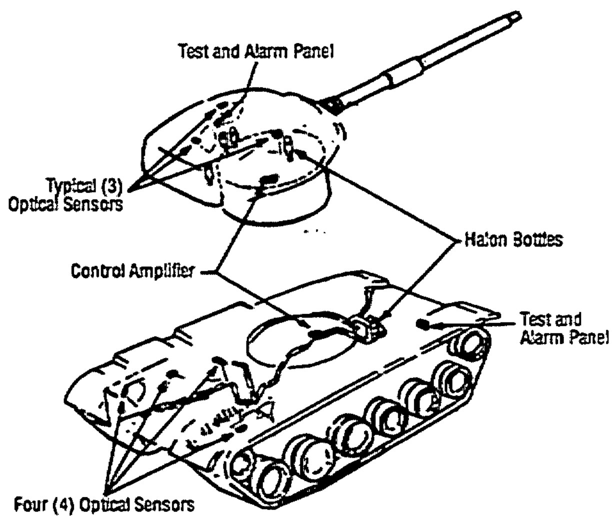

Figure 6-33. Fire Detection System Designed for the M60A3 MBT (Ref. 13)

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CHAPTER 7
EXTINGUISHING AGENTS AND SYSTEMS

Fire extinguishants and their uses and hazards are discussed. The extinguishants are given in order of their principal fire-extinguishing phenomenon. Extinguishants for a deep-seated cellulosic, such as rubber or wood, or combustible metals fires are described. Both active and passive fire-extinguishing systems are presented. The principal components of each type of system are discussed. The use of handheld extinguishers is described. System design features, such as the distribution system, the automatic control system, and the means of activation, are covered, and the basic design and design objectives given.

7-0 LIST OF SYMBOLS

a, b, c, d = converted empirical constants in Table 7-4, J/(g·K)
C_p = specific heat at constant pressure, J/ (g·K)
$\overline{C_p}$ = mean of the specific heats at the initial and final temperatures, J/(g·°C)
$C_{p_{PA}}$ = specific heat of potassium acetate and water solution, J/(g·K)
$C_{p_{T_1}}$ = specific heat at initial temperature, J/(g·°C)
$C_{p_{T_2}}$ = specific heat at final temperature, J/(g·°C)
C_t = latent specific heat of transformation, J/g
$conc$ = concentration of potassium acetate, % wt
d = diameter of nozzle orifice, mm
FP_{PA} = freezing point of potassium acetate and water solution, °C
H_f = heat of formation, J/g·mol
H_{f_i} = heat of formation of i^{th} substance, J/g·mol
H_{f_j} = heat of formation of j^{th} product, J/g·mol
i = electric current, A
i = substance involved in reaction, dimensionless
j = product of reaction, dimensionless
l = total number of substances or products, dimensionless
l = distance between nozzle and conductor, mm
MW = molecular weight, g/mol
MW_c = molecular weight of carbon dioxide, g/mol
MW_E = molecular weight of extinguishment, g/mol
MW_i = molecular weight of i^{th} substance, g/mol
MW_j = molecular weight of j^{th} product, g/mol
MW_O = molecular weight of oxygen, 31.9988 g/mol
MW_W = molecular weight of water, g/mol
m = mass of substance, g
m_C = mass of carbon dioxide, g
m_i = mass of i^{th} substance, g
m_j = mass of j^{th} product, g
m_O = mass of atmospheric oxygen, g
m_W = mass of water vapor, g
N_E = number of moles of extinguishant in 1 kg, mol
n = number of moles of subscripted material, mol
n_c = number of moles of carbon dioxide, mol
n_E = number of moles of extinguishant, mol
n_O = number of moles of oxygen, mol
n_p = number of moles of residual products, mol
n_W = number of moles of water, g
Q_c = heat involved in chemical change, J
Q_h = quantity of heat flowing into a system, J
Q_t = quantity of heat required for transition, J
q = heat involved, J
T = temperature, K or °C
T_f = final temperature, °C
T_i = initial temperature, °C
T_p = plateau temperature, °C
T_0 = ambient temperature, °C
v = voltage between conductor and earth, V
ΔT = change in temperature from initial to final value, deg C
ρ = specific resistance of water, Ω·mm

7-1 INTRODUCTION

The following paragraphs describe the phenomena involved and identify the agents available to extinguish a fire by (1) excluding oxygen or fuel from the reaction, (2) chemical intervention, and/or (3) cooling the reactants below their ignition temperatures. Typical extinguisher devices and systems are also described, and examples of existing fire extinguisher systems for vehicles used by the various services of the armed forces and pertinent civilian organizations are presented.

7-1.1 GENERAL

To reduce logistics requirements, the United States (US) Army prefers to stock a single fire extinguishant, which is intended to extinguish most types of expected fires. When each vehicle is designed, a specific extinguishant is selected and specified for use in the onboard fire-extinguishing equipment. This selection is based upon the state of the art of fire-extinguishing systems and upon existing design requirements. Because fire-extinguishing system design is based upon vehicle requirements as well as extinguishant characteristics, the specified extinguishant is used until a vehicle modification order is issued to change the extinguishant designation.

Fire-extinguishing agents, or extinguishants, used in combat vehicles must effectively extinguish fires from the combustibles therein, particularly from the hydrocarbon fluids used as mobility fuels, hydraulic power fluids, and lubricants. Explosives, both low explosives, e.g., gun propellants, and high explosives, e.g., warhead fillers, are not usually extinguishable because the reaction rate of many explosives is too fast for most practical extinguisher systems, the explosives contain sufficient oxygen to combust, and/or it is difficult to place the extinguishant on the burning propellant. Currently, the best method to protect the vehicle from the reactions of explosives is proper magazine design, as described in subpar. 7-3.2.1.1. For hydrocarbon fluids the primary agents that will be discharged within compartments of the vehicle should not affect occupants, equipment, or cargo since use of some agents can generate toxins, asphyxiants, or irritants for humans, and some agents or their by-products will corrode, coat, short out, or otherwise affect critical equipment. On the other hand, some secondary agents may be needed to extinguish combustion of materials for which the primary fire-extinguishing agents are not effective. Secondary extinguishants may be necessary and should be provided in portable extinguishers for electrical fires, liquid hydrocarbon pool fires, deep-seated cellulosic fires, and combustible metal fires.

Knowledge of fire-extinguishing agents and detection and suppression systems is important in the design of combat vehicles. Vehicles should be designed using appropriate fire prevention principles, and personnel must be trained in the use of the fire prevention systems because crew and vehicle survivability may depend upon the crew's knowledge of extinguishment techniques, especially during combat.

The flammability principles discussed in par. 2-2 provide a sound basis for a discussion of fire extinguishment principles and the desired characteristics of extinguishing agents. The phenomena involved in fire extinguishment may be divided into two basic categories, namely, (1) chemical mechanisms and (2) physical mechanisms. The chemical mechanisms capture free radicals or use oxygen in a mildly exothermic or, hopefully, endothermic process. The physical mechanisms insert a barrier between the reactants and the reaction, dilute the oxidizer or the fuel, or cool the reaction below the temperature needed to sustain the fire.

For vaporized fuel and either a physical mechanism or chemical mechanism extinguishing agent, the extinguishing properties may be represented graphically, as illustrated for diesel fuel vapor and water vapor in Fig. 7-1. The left side of the flammability envelope shows the upper and lower limits of flammability, whereas the balance of the flammability envelope exhibits the efficacy of the extinguishing agent. The tip of this envelope on the right (commonly referred to as the "flammability peak") denotes the added quantity of extinguishing agent or concentration required to prevent combustion, i.e., to inert,

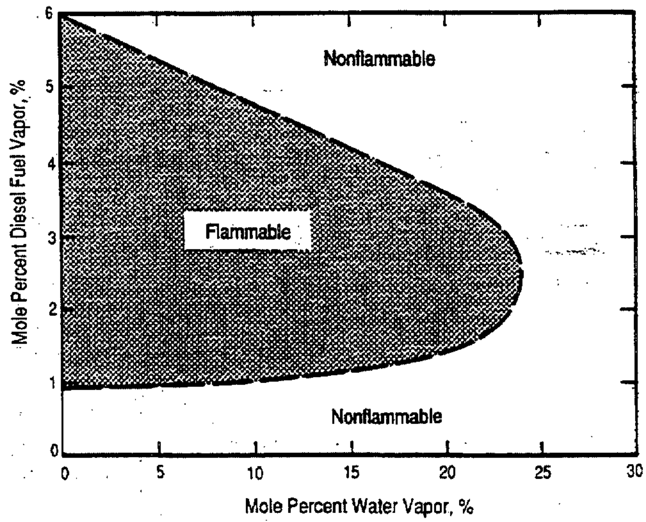


Figure 7-1. Flammability Envelope Illustrating Influence of Water Vapor on Diesel-Fuel-Vapor-Air Mixture Flammability

for all fuel-air extinguishant concentrations. As an illustration, reported values of the flammability peak for physical-acting agents with hydrocarbons typical of mobility fuel vary from about 24% for added water vapor (Ref. 1) to about 45% for added helium (Ref. 2). Reported values for chemical intervention agents with similar hydrocarbons vary from 4.2% for added Halon 1202 (dibromodifluoromethane) to about 18% for added Halon 121 (chlorodifluoromethane) (Ref. 3).

7-1.2 PAST EXPERIENCE

The US Army Safety Center (USASC) data (Ref. 4), described in subpar. 4-1.1, also provide information on the effectiveness of the vehicular fire-extinguishing devices, as shown in Table 7-1. The extinguishant used in the M1 main battle tank (MBT) and the M2/M3 Bradley Fighting Vehicles (BFV) was Halon 1301. The extinguishant used in the other vehicles was carbon dioxide. To be rated effective, the extinguishant has to extinguish the fire without reignition. The vehicular fire-extinguishing provisions include both fixed fire-extinguishing systems and portable extinguishers. The data for onboard systems in Tables 7-1(A) and (B)* indicate that overall the fire-extinguishing devices provided were at best 44% effective, systems using Halon 1301, which include portable extinguishers, were approximately 45% effective, and systems using CO_2 were approximately 43% effective. Automatic Halon 1301 systems were 28% effective, and manual initiation Halon 1301 fixed systems were 24% effective. Note in Table 7-1(C) that of 212 incidents in which the means of final fire suppression was given, in only 124, i.e., 58%, did the onboard fire-extin-

*The data given are too sparse for this to be other than an indication.

guishing system extinguish the fire. Thus there were 88 incidents reported in which onboard portable extinguishers or fixed fire-extinguishing systems (FFESs) either were not used or were not effective. As described in Table 7-1(C), of the 212 incidents for which data are given, onboard portable extinguishers were effectively used in 79 of the incidents to accomplish or finish extinguishment of the fire and other means used in 2 incidents for a total of 38% extinguished manually by crewmen. In 14 incidents the fires self-extinguished, and in 3 incidents the vehicle was totally destroyed. However, in 69 incidents (33%) a fire department had to extinguish the fire using a great volume of water. These data indicate that in 56% of the fires successfully extinguished—38 using manually activated FFESs and 81 using portable fire extinguishers or other means—the crewmen were actively involved.

The data from Southeast Asia (SEA) given in Table 4-2 provide another indication of the effectiveness of the fire-extinguishing systems previously discussed; 26 incidents are included (Ref. 5). Halon 1301 was used in the

TABLE 7-1. FIRE EXTINGUISHER SYSTEM EVALUATION (Ref. 4)

A) Effectiveness of Onboard Fire Extinguisher Systems or Equipment

VEHICLE*	FFES AUTOMATIC INITIATION		FFES MANUAL INITIATION		PORTABLE	
	NUMBER OF TIMES INITIATED	NUMBER OF TIMES EFFECTIVE	NUMBER OF TIMES INITIATED	NUMBER OF TIMES EFFECTIVE	NUMBER OF TIMES USED	NUMBER OF TIMES EFFECTIVE
M1 MBT	22	7	20	5	20	16
M2 and M3 BFV	3	0	1	0	7	5
M60 MBT			66	14	53	35
M48 MBT			4	2	3	2
M113 APC			8	1	14	7
M88 TRV			34	14	14	9
AVLB, CEV, and DIVAD			8	2	3	1
M109 and M110 SPH			0	0	4	4
Totals	25	7	141	38	118	79
Effectiveness, %	28		27		67	

*APC = armored personnel carrier
TRV = tracked recovery vehicle
CEV = combat engineer vehicle
SPH = self-propelled howitzer

(B) Effectiveness of Extinguishant in Onboard Systems or Equipment

EXTINGUISHANT	FFES AUTOMATIC INITIATION		FFES MANUAL INITIATION		PORTABLE		ALL ONBOARD	
	NUMBER OF TIMES INITIATED	NUMBER OF TIMES EFFECTIVE	NUMBER OF TIMES INITIATED	NUMBER OF TIMES EFFECTIVE	NUMBER OF TIMES USED	NUMBER OF TIMES EFFECTIVE	NUMBER OF TIMES USED	NUMBER OF TIMES EFFECTIVE
Halon 1301	25	7	21	5	27	21	73	33
CO_2	0	0	120	33	91	58	211	91
Halon Effectiveness, %	28		24		78		45	
CO_2 Effectiveness, %	Not Applicable		27.5		64		43	
Total Incidents	25	7	141	38	118	79	284*	124
Overall Effectiveness, %							44	

*Each fire-extinguishing system usage is considered a separate event. Thus if an automatically initiated system fails to extinguish a fire and the manually initiated backup system also fails and then the portable extinguishers are used, these three attempts are treated as three incidents.

(cont'd on next page)

TABLE 7-1. (cont'd)

C) Extinguisher Used for Final Suppression of Fire

VEHICLE	NUMBER OF INCIDENTS	NOT REPORTED	SELF-EXTINGUISHED	FIXED FIRE EXTINGUISHER AUTO	FIXED FIRE EXTINGUISHER MANUAL	PORTABLE	OTHER	FIRE DEPT	VEHICLE DESTROYED
M1 Tank	39	3	2	7	5	16	0	6	0
M2 and M3 BFV	9	1	1	0	0	5	0	2	0
M60 Tank	88	8	3	*	14	35	0	28	0
M48 Tank	5	0	0	*	2	2	0	1	0
M113 APC	40	7	6	*	1	7	1**	15	3
M88 TRV	38	2	0	*	14	9	0	13	0
AVLB, CEV, and DIVAD	8	0	0	*	2	1	1†	4	0
M109 and M110 SPH	6	0	2	*	0	4	0	0	0
Totals	233	21	14	7	38	79	2	69	3
	212 incidents in which data are given			124 incidents total using onboard fire-extinguishing equipment					

*no automatic fixed fire extinguisher system

**used snow

†used water from a garden hose

armored reconnaissance/airborne assault vehicle (AR/AAV) M551, and CO_2 was used in the other vehicles. In the six M551 fires the fixed fire extinguisher system was used in two cases (Document Acquisition Numbers (DANs) 463 and 1532) without success, and portable extinguishers were used in two cases (DANs 670 and 1532) with success. In addition, one fire (DAN 632) self-extinguished after burning all the available fuel (wire insulation in the battery box). In the sixth incident (DAN 1550) the propellant exploded upon jet impact and destroyed the vehicle. In the 20 incidents* involving vehicles containing CO_2 fire extinguishers, portable extinguishers were used seven times (DANs 228, 301, 381, 607, 671, 728, and 1709) but were successful only three (DANs 607, 671, and 728) of those times. In four other incidents other means were used to extinguish the fires, i.e., water in two (DANs 1666 and 1668), a wool blanket in one (DAN 432), and dirt thrown by a shovel in the other (DAN 1709). In the other nine incidents no extinguishment method was listed, but four fires (DANs 117, 169, 756, and 1682) self-extinguished.

In two incidents involving two field artillery ammunition support vehicles (FAASVs) in Southwest Asia (SWA) (Ref. 6), both vehicles were lost. The first incident occurred in mid-March 1991. The vehicle, carrying a full load of ammunition, was on a test drive in Iraq after being repaired. The ambient temperature was approximately 32°C (90°F). A fire started in the engine compartment. The fixed Halon 1301 system, described in subpar. 7-5.1.1.6, temporarily extinguished the fire, but the fire later reignited. Due to the large amount of ammunition in the vehicle and to the 1st Armored Division Artillery policy to evacuate burning tracked vehicles immediately, the crew initiated the fixed fire-extinguisher system and evacuated the vehicle. The vehicle burned for approximately 30 min; then the contents exploded. The second incident occurred in mid-April 1991 while the division was redeploying from Iraq to Saudi Arabia. The ambient temperature was 43 to 49°C (110 to 120°F), and the FAASV had been traveling for over 10 h. The fire is believed to have started in the crew compartment; it was probably due to an electric short in the blower section of the ventilation system. It was reported that a bag of clothing was in contact with the blower motor and that the short ignited the bag of clothing. Only the driver and vehicle commander were in the vehicle. The vehicle commander was looking out of one of the hatches and reported that he did not detect the fire until it was burning well. (The sand and dust were very thick and probably prevented the commander's detecting the fire earlier.) Both men evacuated the vehicle. They reported that the automatic Halon system activated but did not extinguish the fire. The vehicle later exploded. In both incidents there was not enough of the vehicles left after the explosions to verify the cause of the fires or the performance of the fire extinguisher systems.

*The vehicles were MBTs M48A3 and APCs M113A1. These vehicles had fixed CO_2 fire-extinguishing systems for the engine compartments and portable CO_2 extinguishers in the crew compartment.

The author of this handbook can only concur with the policy of the 1st Armored Division Artillery. Halon 1301 is not the extinguishant of choice to suppress fires in hot diesel engines effectively because the fires will readily reignite as soon as the Halon dissipates, nor is Halon 1301 the extinguishant of choice to fight a fire in a bag or pile of clothes. This is a Class A fire that requires liquid cooling. In addition, Halon 1301 is not able to prevent heated solid gun propellant from combusting. A vehicle designed to carry such a quantity of explosive must be better able to withstand the ignition of its contents. (See subpar. 4-6.4.1 for such a design technique.) A better analysis should be made of the fire-extinguishing or fire suppression needs of this vehicle, and a more appropriate total protection system provided.

7-1.3 TECHNIQUE FOR AGENT COMPARISON

The following method is offered to provide a means to compare the performance of potential fire-extinguishing agents. Only the cooling effect, the generation of diluents, and the removal of atmospheric oxygen by the extinguishant are considered. A case is hypothesized in which 1 kg of the extinguishant is injected into a volume that is at a temperature of 177°C and at constant sea level pressure. The heat that various extinguishants can absorb and the mass of diluents, i.e., water vapor and carbon dioxide, generated are calculated in subpars. 7-2.1.1, 7-2.2, 7-2.2.5, 7-2.3.1, 7-2.3.1.2, 7-2.3.2, 7-2.3.4, and 7-5.1.3.4.3.

The effects of these thermal and chemical processes can be estimated using the following equations:

1. To heat or cool a substance in a single state, i.e., solid, liquid, or gaseous, the quantity of heat Q_h required is

$$Q_h = \overline{C}_p \cdot m \cdot \Delta T, \text{ J} \tag{7-1}$$

where

Q_h = quantity of heat flowing into a system, J
$\overline{C}_p$ = mean of the specific heats at the initial $C_{p_{T_1}}$ and final $C_{p_{T_2}}$ temperatures, or

$$\overline{C}_p = \frac{1}{2}\left(C_{p_{T_1}} + C_{p_{T_2}}\right), \text{J/(g} \cdot \text{°C)}$$

m = mass of substance, g
ΔT = change in temperature from initial T_i to final value T_f, or $\Delta T = T_f - T_i$, deg C.

2. For a change in state of a substance, i.e., melting or freezing to change between solid and liquid states or vaporizing or liquefying to change between liquid or gaseous states or subliming or solidifying to change directly between solid and gaseous states, the heat Q_t required is

$$Q_t = \overline{C_t} \cdot m, \text{ J} \tag{7-2}$$

where

C_t = latent specific heat of transformation, J/g
Q_t = quantity of heat required for transition, J.

3. For a chemical change, the heat Q_c involved is

$$Q_c = \sum_{j=1}^{l}\left(\frac{H_{f_j}}{MW_j}\right) - \sum_{i=1}^{l}\left(\frac{H_{f_i}}{MW_i} \cdot m_i\right), \text{ J} \tag{7-3}$$

where

Q_c = heat involved in chemical change, J
H_f = heat of formation, J/g·mol
MW = molecular weight, g/mol
l = total number of substances or products, dimensionless
MW_i = molecular weight of i^{th} substance, g/mol
MW_j = molecular weight of j^{th} product, g/mol
m_i = mass of i^{th} substance, g
m_j = mass of j^{th} product, g
H_{f_i} = heat of formation of i^{th} substance, J/g·mol
H_{f_j} = heat of formation of j^{th} product, J/g·mol
i = substance involved in reaction, dimensionless
j = product of reaction, dimensionless

The mass of diluents generated and atmospheric oxygen consumed comes from evaluating the chemical process:

$$n_E\text{E} + n_O\text{O}_2 + q \Leftrightarrow n_p\text{P} + n_W\text{H}_2\text{O} + n_c\text{CO}_2 \tag{7-4}$$

where

n = number of moles of subscripted material, mol
E = extinguishant (carbon based)
O_2 = oxygen
P = residual product
H_2O = water
CO_2 = carbon dioxide
q = heat involved,* J.

The number of moles of extinguishant in 1 kg N_E is

$$N_E = \frac{1000}{MW_E}, mol \tag{7-5}$$

where

MW_E = molecular weight of extinguishant, g/mol.

*When the process is endothermic, q is positive; when the process is exothermic, q is negative.

The mass of atmospheric oxygen m_O removed is

$$m_O = N_E \frac{n_O}{n_E} \cdot MW_O, \text{ g} \quad (7\text{-}6)$$

where

MW_O = molecular weight of oxygen, 31.9988 g/mol
n_O = number of moles of oxygen, mol
n_E = number of moles of extinguishant, mol.

Similarly, the mass of water vapor generated m_W is

$$m_W = N_E \frac{n_W}{n_E} \cdot MW_W, \text{ g} \quad (7\text{-}7)$$

where

MW_W = molecular weight of water, g/mol.

The mass of carbon dioxide m_C is

$$m_C = N_E \frac{n_C}{n_E} \cdot MW_C, \text{ g} \quad (7\text{-}8)$$

where

MW_C = molecular weight of carbon dioxide, g/mol.

While evaluating fire extinguishants, the designer must keep in mind the objectives of extinguishing fires. The first objective is to preserve life, and to do this, air temperature must be kept below approximately 60°C (140°F). The second objective, when a soldier's life is not endangered, is to preserve the usefulness of equipment, e.g., aluminum, which is now widely used for US vehicles, must be kept below approximately 177°C (350°F), plastics or composites, below approximately 123°C (254°F), and steel, below approximately 538°C (1000°F). Thus a useful goal for extinguishants is to operate over the temperature range of –54°C (–65°F) to 177°C (351°F); beyond that the environment is either too cold for practical operations or aluminum equipment has been heated beyond salvage. For effective extinguishment of deep-seated celluosic fires (such as bags of clothing), heat must be transferred out of the burning materials. The time required for heat transfer is directly proportional to the heat transfer coefficient. Heat transfer from a hot solid to a gaseous coolant is an extremely slow process. For example, the heat transfer coefficient for air is very low; as shown in Table 5-1, it is in the range of 1.14 to 57 W/(m^2·K). The heat transfer coefficient for a liquid coolant such as water, however, is in the range of 284 to 17,000 W/(m^2·K). The cooling effect of an extinguishant from 21°C (70°F) ("room temperature") to 177°C (351°F) is evaluated in this handbook.

7-2 AGENTS

Although the following agents are divided into three classes, (1) oxygen and/or fuel excluders, (2) chemical intervention agents, and (3) cooling agents, some agents exhibit multiple fire-extinguishing mechanisms that overlap these classes. Some blends, e.g., wet powders, exhibit all three mechanisms. Accordingly, each agent has been classified in Table 7-2 according to its dominant mechanism.

7-2.1 OXYGEN OR FUEL EXCLUDERS

The agents in this subparagraph function primarily by blanketing the burning fuel with a layer of inert gas (or liquid), by diluting the surrounding air with an inert gas, or by inserting a barrier between the oxidizer and the fuel. Thus sufficient oxygen and/or fuel for sustained combustion do not reach the combustion zone.

For several fire extinguishants, Fryburg (Ref. 7) provided a measure of the relative volume percentage needed to render a fuel-air mixture nonflammable. A vertical glass tube, 1.80 m long and 50 mm in diameter, was prefilled with a mixture of gaseous fuel and air containing a given percentage of gaseous diluent. The mixture was considered flammable if a flame, ignited by passing a small alcohol flame across the bottom, propagated the full height of the tube. Table 7-3 contains properties of the diluents tested as well as the minimum percentage by volume of each that rendered a methane (CH_4)-air mixture nonflammable. The investigators concluded that the following are the factors by which the noncombustible diluent gases—argon (Ar), helium (He), nitrogen, water vapors, and carbon dioxide—rendered the mixture nonflammable:

1. Reduction of the oxygen content of the air (which primarily affects the upper limit of flammability)
2. Thermal capacity of the diluent
3. Thermal conductivity of the diluent.

The relative inerting effects of argon, nitrogen, and carbon dioxide are related to their relative specific heats. The difference in performance of Ar and He is related to their relative thermal conductivities. Water, however, would perform differently because of potential cooling due to change in state. The halocarbons, carbon tetrachloride (CCl_4), or Halon 104, and dichlorodifluoromethane (CCl_2F_2), or Halon 122, showed a "greatly enhanced aptitude for provoking [fire] extinction" (Ref. 7).

TABLE 7-2. DOMINANT FIRE-EXTINGUISHING MECHANISM OF AGENTS

CLASSIFICATION OF AGENTS		
OXYGEN OR FUEL EXCLUSION	CHEMICAL INTERVENTION	COOLING
Carbon Dioxide Nitrogen Vitiated Air Noble Gases Steam Foams Surfactants Copper Powder	Halons Alkali Metals Hydrated Salts Carbonates Phosphates	Water Alumina

TABLE 7-3. DILUENTS TO RENDER A SPACE NONFLAMMABLE (Refs. 7, 8, 9, 10, 11, 12, 13, and 14)*

SUBSTANCE	SYMBOL OR FORMULA	DENSITY AT nbp OR TEMPERATURE INDICATED AND 1 atm	NORMAL BOILING POINT (nbp)	SPECIFIC HEAT AT 25°C	THERMAL CONDUCTIVITY AT 27°C	MOLECULAR WEIGHT	LATENT HEAT OF VAPORIZATION	VOLUME % NEEDED TO RENDER A SPACE NONFLAMMABLE FOR METHANE (CH_4)	
		g/mL	°C	J/(g·K)	W/m·K	g/mol	kJ/mol	AT 25°C[7]	AT 67°C[7]
Argon	Ar	0.001784[9] at 0°C	−185.4[8]	g 0.519[9]	0.01781[9]	39.948[9]	6.5[8]	51	N/Avl
Helium	He	g 0.0001785[9] ℓ 0.8081	−268.9[9]	g 5.197[9]	0.1499[9]	4.0026[9]	5.97[10]	38.5	N/Avl
Nitrogen	N_2	g 0.0005798[9] ℓ 0.9604	−195.8[8]	g 1.038[9]	0.02598[9]	28.0134[9]	5.6[8]	38	N/Avl
Water	H_2O	0.00058[12]	100[9]	g 5.040[9]	0.0181[9]	18.0153[9]	40.62[11]		29.1
Carbon Dioxide	CO_2	g 0.001977[9] at 0°C triple point is −56.6°C at 5.2 atm	subl −78.5[8]	g 0.875[9]	0.01660[9]	44.01[9]	subl 25.23 (See table of thermodynamic properties of CO_2 in Ref. 9.)	25	27.1
Carbon Tetrachloride, Halon 104	CCl_4	g 0.006879 ℓ 1.586720[9] at 20°C	76.8[9]	ℓ 1.030[13]	0.01036[9]	153.81[9]	29.6[9]	11.5-12.2	N/Avl
Dichlorodi-fluoromethane, Halon 122	CCl_2F_2	g 0.00701[9] ℓ 1.311[9] at 25°C	−29.79[9]	0.607[9]	0.09665[9]	120.91[9]	19.97[9]	11.5	N/Avl
Inergen™	Mixture[14] N_2 50 ± 5% Ar 40 ± 4% CO_2 8 ± 1% H_2O 0.5% by weight maximum	15 MPa (2175 lb/in.²) maximum container pressure at 21°C (70°F)[14]	N/App	N/App	N/Avl	N/App	N/App	N/Avl	N/Avl

g = gas
subl = sublimation
N/App = not applicable
ℓ = liquid
v = vaporization
N/Avl = not available

*Superscripts in parentheses indicate the number of the reference from which the data were extracted, e.g., (9) = Ref. 9.

7-2.1.1 Carbon Dioxide

Carbon dioxide (CO_2) is an inert, colorless, odorless gas at normal ambient temperatures; however, it may be stored as a liquid in pressurized containers at approximately 5.69 MPa at 21.1°C (825 psi at 70°F). When released to flow through a nozzle into a large space, liquid CO_2 stored in a pressure vessel at 5.69 MPa and 21°C (825 lb/in.^{2} and 70°F) will decrease in temperature to –78.8°C (–110.02°F). At standard atmospheric pressure it will flash to a mixture of gas (72%) and solid CO_2 (28%). No longer subjected to a high pressure, the liquid changes to gas as it flows through the nozzle. The energy required to accomplish this change in state, i.e., the latent heat of vaporization of 15.82 kJ/mol, comes from the CO_2. Some of this energy is generated by lowering the energy level of the molecules, i.e., by lowering the temperature from 21 to –78.8°C, and the remainder is generated by the change in state of some of the liquid to a solid. The change in state provides the latent heat of fusion of 8.33 kJ/mol. This isenthalpic process for changes in pressure and the resulting temperature and state of CO_2 are shown graphically by a temperature-entropy chart or an enthalpy-entropy chart (Mollier diagram). These charts are available in standard reference texts such as Ref. 15 or through the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York, NY.

The mechanisms by which CO_2 extinguishes fire include (1) reduced flame temperatures resulting from the high heat capacity of CO_2, which is caused by dilution effects, and from energy absorbed during vaporization of the CO_2 snow, (2) blanketing of the burning material with the inert CO_2, and (3) cooling liquid fuel surfaces to below their flash points by contact with the cold gas and solid particles. The minimum concentration of added CO_2 needed to prevent ignition of all possible diesel fuel-air mixtures ("flammability peak") is about 28% (Ref. 2).

The cooling effect of CO_2 can be estimated by using a hypothetical case in which 1 kg of liquid CO_2 stored in a container at 21°C and 5.69 MPa is discharged through a nozzle into a large chamber that is kept at 177°C at atmospheric pressure. The liquid CO_2 will flash to 280 g of solid and 720 g of gaseous CO_2, which are at –78.8°C. The latent specific heat of transformation C_t is equal to the latent heat of transformation H_t kJ/mol divided by the molecular weight *MW*. By using the values from Table 7-3 and substituting into Eq. 7-2, the energy (heat) absorbed Q_t by the solid CO_2 when subliming to a gas is

$$\begin{aligned} Q_t &= (H_t/MW)\cdot m \\ &= (25.23\ \text{kJ/mol}/44.01\ \text{g/mol})\cdot 280\ \text{g} \\ &= 160.5\ \text{kJ}. \end{aligned}$$

By using Eq. 7-1, the energy absorbed by the resulting 1000 g of gas by heating it from –78.8 ($C_p \approx 0.761$ J/g·°C) to 177°C (C_p = 0.938 J/g·°C) is

$$\begin{aligned} Q_h = {} & [(0.761\ \text{J/g}\cdot°\text{C} + 0.983\ \text{J/g}\cdot°\text{C})/2] \\ & \times (1000\ \text{g})\cdot[177°\text{C} - (-78.8°\text{C})] \\ = {} & 217.3\ \text{kJ}. \end{aligned}$$

The total heat energy absorbed from the air in the chamber is $Q_t + Q_h$, or 160.5 kJ + 217.3 kJ = 377.8 kJ.

Most agents that are used in the gaseous state are stored as liquids. The fact that CO_2 can be stored and transported as a liquid at normal temperatures is advantageous when substantial quantities of inert gas may be required for extinguishing purposes since the volume of gaseous CO_2 at normal ambient temperature and pressure is almost a thousand times larger than that of its source liquid at the same temperature. A strong bottle is required to store CO_2 for a vehicular application; this bottle must be able to contain the CO_2 at approximately 20.7 MPa (3000 psi), even though the probable storage pressure is 5.69 MPa (825 psi) at 21°C (70°F).

Carbon dioxide is not effective against deep-seated Class A fires, nor is it effective to cool heated metal. Once it has vaporized, CO_2 is quickly convected away from any exposed fire or from a vehicle engine that requires a high flow rate of coolant air. Carbon dioxide is excellent for extinguishing a fire when it first ignites, but is very poor for extinguishing a sustained fire. It cannot be projected from a distance as a liquid such as water can. Because CO_2 is an asphyxiant, it cannot be safely used in a confined space occupied by humans. Also firefighters should not enter a "cloud" caused by release of CO_2 (The "cloud" is actually condensed water vapor, which is visible; the CO_2 vapor is not visible.) because they can breathe enough CO_2 to lose consciousness and possibly be asphyxiated.

Carbon dioxide is electrically nonconductive; hence it can be used on Class C fires as well as on Class B and on Class A fires burning on an exposed surface. Because CO_2 can decompose into CO and O_2 at temperatures above 1700°C (3100°F), it cannot be used on a Class D fire.

7-2.1.2 Oxygen-Depleted (Vitiated) Air

When a fuel-air mixture undergoes complete combustion, the final mixture contains carbon dioxide, water vapor, and nitrogen. All of these gases are inert and hence cannot support combustion. In the practical case of engine combustion, the combustion products also contain smaller amounts of carbon monoxide, unburned fuel and other pollutants, and unused atmospheric molecular oxygen. A properly adjusted gasoline engine uses approximately half of the available atmospheric oxygen; the exhaust gases are primarily nitrogen, water vapor, and carbon dioxide with some carbon monoxide and nitrogen oxides. A turbine engine uses approximately 20% of the atmospheric oxygen; hence the exhaust gases include approximately 16% oxygen as well as the other gases. A diesel engine uses approximately 10% atmospheric oxygen at idle to approximately 65% atmospheric oxygen at maximum power; therefore, its exhaust gases contain approximately 7 to 18% oxygen. Also there are nitrogen, water vapor, and carbon dioxide and some carbon monoxide, sulfure oxides, and nitrogen oxides. Whenever some of the fuel is not completely burned, there are soot, small particles of carbon, and fuel vapors. Mixed in with these exhaust gases are some lubricating oil and some contaminants from the mobility fuel and/or their combustion products.

Those gases that do not contain sufficient oxygen to support sustained combustion*, i.e., < 14% oxygen by volume, can be used to prevent fires by diluting atmospheric oxygen or to extinguish fires by blanketing the fire and diluting the flame reactants. Such gases can also serve to a lesser extent as cooling agents. The vitiated air probably contains unburned fuel vapor, soot, and greater-than-atmospheric proportions of water vapor and carbon dioxide. The minimum concentration of vitiated air required to prevent ignition of all possible fuel-air mixtures ("flammability peak") depends upon the completeness of combustion and the fuel-air ratio of the mixture burned to form it, and only the spark-ignition engine removes atmospheric oxygen reliably. If vitiated air can be obtained reliably, as a diluent the percentage used will be somewhere between added water vapor (24%) and added nitrogen (42%), both by volume. The water vapor when condensed and the soot could present a problem in vehicle components.

The principal disadvantage of vitiated air from piston engines is its pollutant and high heat content. Such an inerting agent could foul the systems being inerted. This problem would not necessarily be the case with gas turbine engines. They, however, do not use sufficient atmospheric oxygen, and their exhaust gases support combustion. An exhaust gas inerting system was explored for potential use on the B-52 aircraft but was rejected when development personnel found that exhaust gas formed sulfurous acid (H_2SO_3), which attacked structural members (Ref. 16).

7-2.1.3 Nitrogen

Nitrogen is an odorless, colorless, inert gas at normal ambient temperatures. It constitutes 78% of the atmosphere. It liquefies at −195.8°C (−320.4°F) at atmospheric pressure and can be stored and transported as a liquid in vacuum-jacketed or other insulated vessels. At ambient temperatures it is commonly stored and transported as a compressed gas in high-pressure cylinders. It is commercially available in both forms at reasonable cost.

In extinguishing or inerting applications liquid molecular nitrogen (LN_2) usually is used only to provide a source of gaseous molecular nitrogen (GN_2). Gaseous nitrogen extinguishes fire primarily by diluting oxygen but also by reducing flame temperatures through energy absorption. The minimum concentration of nitrogen required to be added to air to prevent ignition of all possible diesel fuel-air mixtures ("flammability peak") is about 42% by volume (Ref. 2). In tests of nitrogen inerting of aircraft fuel cell ullage, the overpressures resulting from the detonation of a 23-mm high-explosive incendiary tracer (HEIT) projectile were compared to ullages similarly protected by Halon 1301. The comparisons are shown in Fig. 7-2. Part of the explanation given in Ref. 17 for these results is that with a test chamber volume of 757 L (200 gal), the 23-mm HEIT detonation would consume approximately 2% of the available oxygen.

Nitrogen is used in C-5A aircraft to inert the fuel cell ullages and to extinguish fires in 12 unmanned spaces including leading edges of wings, wheel wells, underfloor cargo compartments, leading edges of engine pylons, power transfer units, and dry bays of wings. Fire in any of these spaces is sensed by separate continuous thermal detectors that energize alarm lights on the flight engineer's nitrogen fire suppression panel. The flight engineer then arms and activates the appropriate fire suppression valve (Ref. 16).

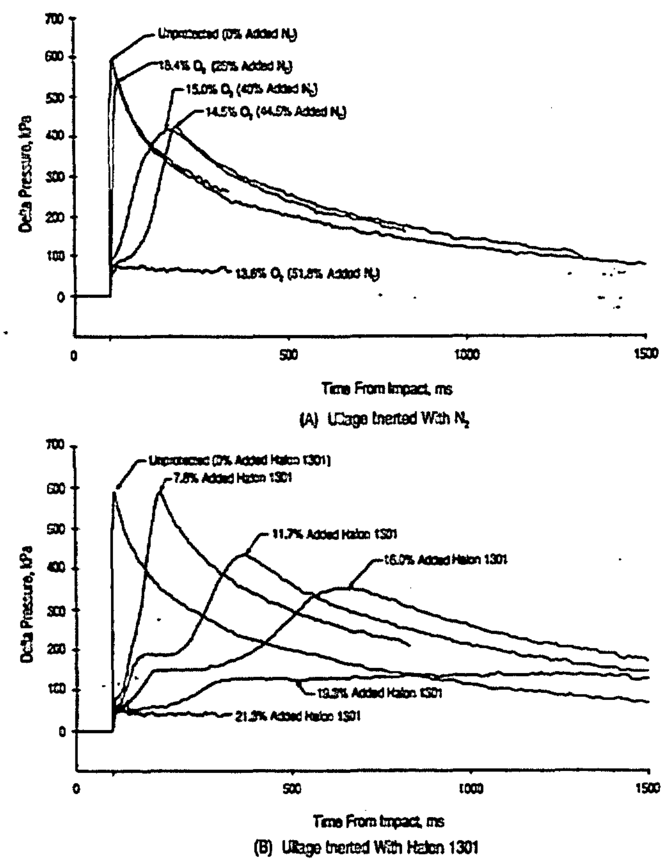


Figure 7-2. Overpressure Resulting From Combustion in Ullage of Fuel Cell Containing JP-4 Given a 23-mm HEIT Projectile Detonation (Ref. 17)

*"Insufficient air to support sustained combustion" does not mean that there will be no combustion. If there are multiple ignition sources, such as the incendiary mixture from an armor-piercing incendiary (API) projectile or the burst of a high-explosive incendiary (HEI) projectile, combustion within a restricted volume may not be sustained; there may be sufficient products from the multiple unsustained combustions to overpressurize the restricted volume container. This overpressurization has occurred within some aircraft fuel cell ullages hit by API or HEI projectiles.

The use of GN_2 as an extinguishant for engine nacelle fires has been considered but not selected.

The chief disadvantage of using GN_2 in extinguisher or inerting applications is the requirement for expensive, heavy, high-pressure storage vessels and ancillary equipment.

The chief disadvantage of using LN_2 in extinguisher or inerting applications is the requirement for expensive thermally insulated vessels and ancillary equipment. Another disadvantage is that liquid nitrogen surfaces exposed to air become oxygen enriched. Thus, given sufficient exposure time, the stored LN_2 can pose hazards equivalent to those of liquid oxygen (LOX). This phenomenon occurs because the liquefaction temperature of LN_2 (–195.8°C) is lower than that of LOX (–183.0°C). Hence a portion of the atmospheric oxygen can condense on the LN_2 surface.

Early in the space program, engineers attempted to utilize the great quantities of liquid nitrogen available as a by-product from the liquefaction of air to obtain liquid oxygen. The LN_2 was plumbed to the top of large liquid propellant engine test stands and released through nozzles when a fire occurred. When released, the LN_2 quickly vaporized, and the GN_2 was rapidly dispersed by convection induced by the violent oxygen-rocket propellant fire, which effectively removed the nitrogen before it could affect the combustion.

7-2.1.4 Noble Gases

There are only three nonradioactive elements that have been found to be chemically inert: helium, neon, and argon, which are among those commonly referred to as noble gases. Each of these is an odorless, colorless, inert gas at normal ambient temperature. The temperatures at which they liquefy at atmospheric pressure range from –269°C (–452°F) for helium to –185.4°C (–301.7°F) for argon. Neon is the most expensive of these three gases and offers no advantages over the other two.

Helium is used as an inerting gas when its low molecular weight and/or its complete chemical inertness are appropriate. It constitutes only 0.0005% by volume of the atmosphere, so it is normally obtained from limited supplies of helium-rich natural gas. It can be stored and transported as a liquid in vacuum-jacketed or other insulated vessels. At ambient temperatures it is commonly stored and transported as a compressed gas in high-pressure cylinders. The minimum added helium concentration required to prevent ignition of all possible diesel fuel-air mixtures ("flammability peak") is about 45% (Ref. 2). Helium affects the human vocal system and reduces the effectiveness of verbal communication.

Based on relative availability and cost, argon seems to be the most practical choice as an extinguishant in this group. Other than its complete chemical inertness, however, its characteristics are similar to those of nitrogen, which is more abundant and less expensive than argon. Argon constitutes 0.93% by volume of the atmosphere, whereas nitrogen constitutes 78%. Argon liquefies at –185.4°C (–301.7°F) at atmospheric pressure and can be stored and transported as a liquid in vacuum-jacketed or other insulated vessels. At ambient temperatures it is commonly stored and transported as a compressed gas in high-pressure cylinders. The minimum added argon concentration required to prevent ignition of all possible diesel fuel-air mixtures ("flammability peak") is estimated to be similar to that for added nitrogen, i.e., about 40 to 45%. The physical advantages and disadvantages of using argon as an extinguishant are the same as those of gaseous nitrogen.

An agent that includes a noble gas is Inergen™, which is a mixture of nitrogen (50 ± 5% by weight), argon (40 ± 4%), carbon dioxide (10 ± 1%), and water (0.5% maximum). Inergen™ is stored in the gaseous state at 15.2 MPa (2205 lb/in.^{2}) in a thick-walled bottle. Approximately a 34% concentration of Inergen™ is required to extinguish a fire (Ref. 14).

7-2.1.5 Water Vapor (Steam)

Vaporized water (steam) functions solely as an inert gas during extinguishing and inerting applications. It dilutes oxygen in the region of the flame by blanketing the fuel, and it lowers flame temperatures by dilution. The minimum added concentration required to prevent ignition of all possible hydrocarbon fuel-air mixtures ("flammability peak") is about 24% (Ref. 1). A plot of Gibbs' free energy versus temperature (Ref. 18) indicates that water would probably decompose near 4177°C (7551°F), which is much higher than the temperature reached in combat vehicles fires.

Unless steam is available as a by-product from another operation, such as a waste heat recovery system, the equipment and energy required for its generation would be difficult to justify for military vehicles. Another disadvantage of using steam is the requirement that all exposed surfaces be above the boiling point of water, 100°C (212°F), to prevent condensation. Additionally, in the design and application of steam extinguishing systems, precautions must be taken to protect personnel from steam burns (Ref. 19).

7-2.1.6 Foams

Aqueous foams suppress fires by forming a blanket over the fuel to reduce or prevent the escape of fuel vapor into the combustion zone above the fuel surface. This action not only excludes fuel vapor but also provides cooling of the fuel. For air foams, which are like soap bubbles containing air, the water, encapsulating agent, and/or other additives serve as the extinguishing agent. If the trapped gas is nonreactive, e.g., carbon dioxide, the efficacy of the aqueous foam is enhanced relative to that of an air foam (Ref. 11).

Aqueous foams represent a major class of extinguishants. Their types range from air bubbles mechanically foamed from water containing a foaming agent through bubbles foamed with an inert-gas blowing agent to air bubbles made with a fluorinated surfactant that spreads across the fuel surface beneath the foam as an inert liquid film (Refs. 10 and 20 through 22). Other types of extinguishing foams include nonaqueous liquids foamed with nonaerobic blowing agents, but apparently these have been used only in laboratory studies (Ref. 23).

In addition to the identity of the liquid, gas, and foaming agent in foams, other foam properties that may be varied include the expansion ratio (volume of foam per volume of liquid), drainage time (time to bubble collapse), and critical shear stress (foam stiffness). One or more additional components may be added to the foam to enhance its effectiveness. These components include surfactants and halogenated extinguishing agents adsorbed on powders, dry powders, or adsorbents (Refs. 20, 24, and 25).

Foams are arbitrarily classified as (1) low-expansion foam, expansion ratio up to 20:1, (2) medium-expansion foam, expansion ratio from 20:1 to 200:1, and (3) high-expansion foam, expansion ratio from 200:1 to 1000:1 (Ref. 22). Foams are typified by protein-based foams having expansion ratios ranging from about 3:1 to about 20:1 and by synthetic detergent foams having expansion ratios ranging up to 1000:1 (Refs. 20 and 21). The low-expansion foams are used primarily to blanket pool fires, to exclude fuel vapor, and to provide cooling. Medium-to-high expansion foams are well suited to fill cavities and enclosures and thereby exclude fuel vapor and provide cooling (Ref. 22).

Foams containing a fluorinated surfactant are characterized by their ability to form a continuous, self-healing film of surfactant over the surface of liquid fuels and thus retard fuel vaporization. Foams of this type are referred to as aqueous film-forming foams (AFFF) and film-forming fluoroprotein (FFFP) agents. AFFF, also known as "light water", consists of synthetic substances that are basically detergents, some of which are fluorinated materials. FFFP is composed of protein and film-forming fluorinated surfactants, which exhibit a fuel-shedding capability, i.e., if the foam becomes coated with fuel, the foam sheds the fuel readily. AFFFs and FFFPs can be used in conjunction with dry powders without reaction problems (Ref. 22), but the foams and their water carriers will trap the dry chemicals away from the flame.

Adsorbents, such as bentonite, in conjunction with foams, have been used only in airdrops on forest and brush fires (Ref. 26). Foams are excellent for extinguishing pool fires, but are not practical to extinguish a fireball. Once a fire has been extinguished, the foams do not cool hot metal objects as effectively as water. Foams, particularly protein foams, contaminate the fire site and present a problem in postfire cleanup. The greatest advantage of using a foam to extinguish a pool fire is that the foam will film over the liquid fuel surface and form a barrier between the fuel and the air. Foams do not enhance the capability of water to extinguish a Class A fire.

7-2.1.7 Surfactants

Surfactants are chemicals dissolved in water that reduce the surface tension of the water. Surfactants thus increase the ability of water to obtain an intimate contact with solid materials; surfactants are referred to as "wetting agents". Thus they increase the rate at which heat can be transferred. Water with a minute quantity of surfactant additive can better soak into fabrics and can enter small passages between solid blocks.

Surfactants are nonionic, anionic, or cationic. Nonionic surfactants, such as Triton X-100®, generate foam, are a mild irritant to man, but are noncorrosive to metals. Anionic surfactants, such as Duponol®, are detergents and are alkaline. Hence they can irritate skin and eyes and attack some metals, especially aluminum or magnesium. Cationic surfactants, such as quaternary ammonium salt, emulsify fats and kill germs, are acidic, and hence can irritate skin and eyes and attack some metals. Three surfactants that have been used for fire extinguishing are Sorbit ACH®, a mono and dibutyl naphthalene sodium sulfonate (anionic) wetting agent used in fire extinguishers; Triton X-100®, an alkylated aryl polyether alcohol (nonionic) wetting and dispersing agent also used in firefighting; and RN-200®, an alkyl-aryl sulfonate (anionic) detergent and wetting agent used as a water spreader for fires (Ref. 27).

When water containing a surfactant is applied to an ignited oil-film-covered pool of water, the surfactant/water solution spontaneously pushes the layer of burning fuel vapor away from the point of application and thereby provides a flame-free region on the pool surface (Ref. 28). Thus the fire is either diminished in size or extinguished. Practical applications of this phenomenon have not been developed. Some additional benefits from surfactants are given in subpar. 7-2.3.1.3.

Both surfactants and foaming agents provide a layer over the fuel. With only a surfactant this layer is thin, but with a foaming agent the layer is thicker and consists of bubbles with inert material that not only inhibits the rising of the fuel vapor into the air but also insulates the fuel. All foaming agents contain surfactants.

7-2.1.8 Copper Powder

When blown onto burning lithium, magnesium, or other combustible metals, copper powder or flakes melt and alloy with the molten metal on the surface of the combusting metal (Ref. 29). This alloy forms a skin on the surface of the molten base metal, which prevents further combustion. Copper powder is the basic ingredient in Navy 125S®, which is used for combustible metal fires. (See subpar. 7-2.4 for the fire extinguishants effective on combustible metal fires.)

7-2.2 CHEMICAL INTERVENTION AGENTS

The chemical intervention class of extinguishing agents appears to function by interfering with the free-radical (molecular fragments and/or atoms) chemical chain reactions discussed in par. 2-2 as opposed to extinguishing agents that use physical means, such as cooling, diluting, or providing a barrier, to extinguish a fire.

A major disadvantage of chemical intervention agents is that the most effective agents form potentially toxic combustion or pyrolysis products. Some solid agents, however, can serve as free-radical traps without developing combustion or pyrolysis products (Ref. 30).

Not all chemicals tested as extinguishing agents are included in the following subparagraphs. Only those that have been shown to, or may be expected to, have practical potential as agents are included.

Examples of chemical intervention agents are the halons, e.g., bromotrifluoromethane ($CBrF_3$), which is known as Halon 1301, and the dry chemical powders, e.g., potassium bicarbonate ($KHCO_3$). Typically, these materials decompose when exposed to heat and provide some inert diluents and some molecules that attract and trap free radicals and ions.

If 1 kg of potassium bicarbonate ($KHCO_3$) powder at 21°C were blown into a confined volume maintained at 177°C the powder would heat to 170°C and lower the average temperature by absorbing energy from the volume. The $KHCO_3$ would then decompose and lower the average temperature of the volume greatly by absorbing more energy. The temperature of the decomposition products of $KHCO_3$ would then increase to 177°C, and they would absorb additional heat energy. The decomposition process follows this formula:

$$2KHCO_3 + q \rightarrow K_2CO_3 + H_2O + CO_2.$$

By using the values in Table 7-4* and Eqs. 7-4 through 7-8, this process is expected to provide a cooling effect and result in the removal of approximately 0.844 MJ of heat energy from the volume; it consumes the 1 kg of $KHCO_3$ and generates 690 g of K_2CO_3, 220 g of CO_2, and 90 g of H_2O.

*The specific heat C_p of $KHCO_3$ is not available in any literature searched to the date of writing including the reference database of the National Institute of Standards and Technology (NIST) and Defense Technology Information Center (DTIC) database. Therefore, for this example, the constant average value of 0.9022 J/(g·K) is assumed because $KHCO_3$ is close in molecular structure to K_2CO_3 and Na_2CO_3. This approximate value of C_p for $KHCO_3$ could be used in Eq. 7-1 as a "first guess" to compute the heat required to raise the temperature from T_i to T_f. Because the multiple crystalline (solid) states of $KHCO_3$ are not stable, a single value or an equation for the C_p of $KHCO_3$ is not truly valid. Empirical data and experimentation are required to verify any engineering calculations.

Having appropriate values for the specific heat of the materials involved is essential to computing the heat involved in this process. Some values for specific heat, which vary with the state and temperature of the substance, are tabulated in Table 7-4. In some instances more appropriate values of specific heat C_p are needed. Empirical fit equations for specific heat are given in Ref. 9 and Ref. 33. These equations are in the form

$$C_p = a + bT + cT^2 + d/T, \text{ J/(g·K)} \qquad (7\text{-}9)$$

where

C_p = specific heat at constant pressure, J/ (g·K)
a, b, c, d = converted empirical constants in Table 7-4, J/ (g·K)
T = temperature, K.

Because the equations are empirical, the coefficients are valid only over the range of temperatures from which they were derived.

7-2.2.1 Alkali Metal Salt Powders

Alkali metal salt powders are an important class of extinguishants, and their role in extinguishing flames has been studied extensively (Refs. 7, 25, 30, 35, and 36). Their extinguishing effectiveness is proportional to the surface area of the powder (The powder must be ground into fine particles.), and it increases as alkali metals of higher atomic weights are employed. Hence the extinguishing effectiveness increases in this order: lithium, sodium, potassium, rubidium, and cesium. (Francium has the highest atomic weight but is radioactive.)

The formation of decomposition products, such as the carbon dioxide produced by pyrolysis of a carbonate powder, contributes to flame extinguishment; however, the dominant mechanism by which alkali metal salt powders extinguish flames appears to be the interruption of the free-radical chain reactions. Also it has been suggested that flame opacity caused by powders also provides cooling by shielding the fuel from thermal radiation (Ref. 25). Salts such as carbonates and tartrates, which decompose readily, are especially effective (Ref. 30). Sodium bicarbonate ($NaHCO_3$) and potassium bicarbonate ($KHCO_3$) are the most commonly used alkali metal salt powders.

A minor disadvantage of solid extinguishing agent powders is the residual extinguishing agent that often remains in the general area of the fire incident and that can result in damage to fine machinery and a need for cleanup following the incident.

TABLE 7-4. PROPERTIES OF DRY CHEMICALS AND PRODUCTS THEREOF (Refs. 9, 31, 32, 33, and 34)

(A) PROPERTIES

SUBSTANCE	SYMBOL OR FORMULA	MOLECULAR WEIGHT, g/mol	DENSITY, kg/L AT 25°C	MELTING POINT, °C	BOILING POINT, °C	HEAT OF FORMATION, kJ/mol	GIBBS FREE ENERGY, kJ/mol	LATENT HEAT OF TRANSITION**, kJ/mol	SPECIFIC HEAT C_p, J/(g·K) AT 25°C
Calcium Chloride	$CaCl_2$	110.99[9]†	c* 2.16	772	≈1940	−795.8 at 13°C	−748.1	Hm 28.5 Hv 235	c 0.6953 at 127°C c 0.7826 at 727°C
Magnesium Sulfate Heptahydrate	$MgSO_4 \cdot 7H_2O$	246.49[9]	c 1.67	150, $-6H_2O$[9]		−3388.71	−2871.9		c 1.5107[33]
Magnesium Sulfate Monohydrate	$MgSO_4 \cdot H_2O$	138.39[9]	c 2.445[9]		200, $-H_2O$[9]	−1602.1	−1428.8		c 0.9977 at 9°C[33]
Magnesium Sulfate	$MgSO_4$	120.37[9]	c 2.66	d 1124[9]		−1262 at 21°C	−1147	Hm 14.6	c 0.7593 at 8°C[33] c 0.9281 at 23-99°C
Ammonium Dihydrogen Phosphate or Monoammonium Phosphate (MAP)	$NH_4H_2PO_4$	115.03[9]	c 1.803 at 19°C		d 190	−1145.07	−1210.56		c 1.2338
Ammonia	NH_3	17.04[9]	ℓ 0.6175 at 15°C +7.2 atm g 0.6818 at nbp	−77.75 −74[9]	−33.35 −30.9[9]	−45.9 at 4°C	−16.4	Hm 5.652 Hv 23.35	g 2.0921 g 2.2723 at 127°C g 3.3151 at 727°C
Phosphorus Pentoxide	P_4O_{10}	283.88[9]	c 2.30	340	360 subl	−3009.9 at 89°C	−2773.3	Hm 34.3[31] Hv 95.0[31] Hs 106.0[31]	c 0.7458 c 0.9168 at 127°C c 1.1836 at 327°C
Potassium Acetate	$KC_2H_3O_2$	98.15[9]	c 1.57[9]	292[9]		−724.7[9]			c 1.14 at 20°C[32] c 1.74 at 40°C c 2.90 at 100°C
Potassium Hydrogen Bicarbonate	$KHCO_3$	100.12[9]	c 2.17	d 170[9]		−963.2	−863.6		0.9022††
Potassium Carbonate	K_2CO_3	138.20[9]	c 2.29	901	d to K_2O and CO_2	−1150.2 at 21°C	−1064.5	Hm 27.6	c 0.8280 c 0.9272 at 127°C c 1.3672 at 727°C
Potassium Monoxide	K_2O	94.20	c 2.32 at 20°C	d 881		−363.2 at 21°C	−3221		c 0.8885 c 0.9713 at 127°C c 1.2049 at 727°C

(cont'd on next page)

TABLE 7-4. (cont'd)

SUBSTANCE	SYMBOL OR FORMULA	MOLECULAR WEIGHT, g/mol	DENSITY, kg/L AT 25°C	MELTING POINT, °C	BOILING POINT, °C	HEAT OF FORMATION, kJ/mol	GIBBS FREE ENERGY, kJ/mol	LATENT HEAT OF TRANSITION**, kJ/mol	SPECIFIC HEAT C_p, J/(g·K) AT 25°C
Potassium Hydroxide	KOH	56.11	c* 2.044	406 360.4±0.7[9]	1323	−424.7 at 4°C	−378.9	Hm 8.6 Hv 142.7 Hs 192	c 1.1567 c 1.2773 at 127°C c 1.4019 at 327°C ℓ 1.4812 at 800-1000°C
Carbon Dioxide	CO_2	44.01	g 1.975 at 0°C c 1.512[31]†	−78.44 subl		−393.52 at 5°C	−1394.39	Hm 8.33 Hv 15.82 Hs 25.23	g 0.761 at −73.3°C[13] g 0.8437 g 0.9389 at 127°C g 1.2340 at 727°C ℓ 2.052 at −50°C[13] ℓ 2.847 at 4°C[13] ℓ 5.652 at 23°C[13] ℓ 35.67 at 30°C[13] c 4.494 at −78.8°C[33]
Hydrogen Oxide	H_2O	18.0153[9]	ℓ 1.000 at 4°C	0.00	100.00	−292.72 −285.83 −241.84	−237.14 −228.61	Hm 6.009 Hv 40.66	c 2.0599 ℓ 4.2159 g 1.8651
Aluminum Oxide	Al_2O_3	101.96[9]	c 3.97[9]	2015±15[9]	2980±60[9]	−1676.0	−1582.3	Hm 111.0	c 0.7763 c 0.9424 at 127°C c 1.2237 at 727°C
Copper	Cu	63.546[9]	8.92[9]	1083.4[9]	2567[9]	0	0	Hm 0.206 Hv 4.727	c 0.3846 c 0.4510 at 727°C ℓ 0.4937 at 1727°C[9]
Nitrogen	N_2	28.0134[9]	g 0.001506[9] ℓ 0.8081 at −195.8°C	−209.86[9]	−195.8[9]	0	0	Hm 0.0257 Hv 0.1991	g 1.040 g 1.044 at 127°C g 1.161 at 727°C
Carbonic Acid (Aqueous Solution)	H_2CO_3	62.03[9]				−698.73 at 25°C[9]	−623.42 at 25°C[9]		
Oxygen	O_2	31.9988[9]	g 0.001429 at 0°C[9]	−218.4[9]	−182.962[9]	0	0		

*State: c = crystalline or solid, ℓ = liquid, g = gaseous
**Heats of Transition: Hm = melting, Hv = vaporizing, Hs = subliming
†Reference for data is Ref. 34 unless otherwise indicated by the superscript reference number in parentheses.
††See footnote to subpar. 7-2.2.

subl = sublimation
nbp = near boiling point
d = decomposes

(cont'd on next page)

TABLE 7-4. (cont'd)

(B) COEFFICIENTS FOR EQ. 7-9

SUBSTANCE	STATE*	CONSTANT a, J/(g·K)	CONSTANT *b*, J/(g·K)	CONSTANT *c*, J/(g·K)	CONSTANT *d*, J/(g·K)	TEMPERATURE RANGE, K
Calcium Chloride	c(33)**	0.6371	1.455×10^{-4}	0	0	273-1055
Magnesium Sulfate Heptahydrate	c(33)	1.5107	0	0	0	291-319
Magnesium Sulfate Monohydrate	c(33)	0.9977	0	0	0	282
Magnesium Sulfate	c(33)	0.9281	0	0	0	292-372
Ammonia	g(33)	1.6451	1.547×10^{-3}	0	0	300-800
Phosphorus Pentoxide	c(33) g(33)	0.2317 1.0848	1.609×10^{-6} 0	0 0	0	273-631 631-1371
Potassium Carbonate	c(33)	0.9052	0	0	0	296-372
Potassium Monoxide	c(9)	0.7062	2.843×10^{-4}	0	0	273-1373†
Carbon Dioxide	g(33) g(9)	0.9830 0.7320	2.605×10^{-4} 5.039×10^{-4}	0 -7.891×10^{-8}	-1.859×10^{4} 0	273-1373†
Hydrogen Oxide	ℓ(9) g(33)	2.601 1.909	1.665×10^{-3} 3.484×10^{-5}	0 3.122×10^{-7}	0 0	273-373† 300-2500
Aluminum Oxide	c(9) c(33)	1.072 0.9061	1.801×10^{-4} 3.681×10^{-4}	0 0	-2.9830×10^{4} -2.1440×10^{4}	273-1973† 273-1973
Copper	c(33) c(9) ℓ(33)	0.3582 0.2700 0.4938	9.626×10^{-5} 6.716×10^{-5} 0	0 0 0	0 -1.383×10^{4} 0	273-1357 273-1357† 1357-1573
Nitrogen	g(33) g(9)	0.9708 1.0097	1.494×10^{-4} 9.051×10^{-5}	0 1.942×10^{-8}	0 0	300-3000 300-3000†

*State: c = crystalline or solid, ℓ = liquid, g = gaseous
**Superscripts in parentheses indicate the number of the reference from which the data were extracted except for the temperature ranges estimated by the author.
†Estimated by the author.

7-2.2.2 Alkali Metal Salt Aqueous Solutions

The extinguishing effectiveness of water sprays is enhanced by the presence of dissolved alkali metal salts, but it is not influenced by the salts of other metals (Ref. 7). Table 7-5 presents a summary of the relative effectiveness of experimentally measured minimum masses of alkali metal salts in water in extinguishing gasoline pool fires. In these tests a jet of the aqueous solution struck a target above the pan fire, and droplets of various sizes splattered onto the gasoline surface.

As it does for alkali metal salt powders, the extinguishing effectiveness increases with increasing atomic weight of the alkali metal. It also increases with increasing oxygen content of the anion attached to the alkali metal cation. For example, 40% less potassium chlorate ($KClO_3$) solution than potassium chloride (KCl) solution is required to extinguish a gasoline pool fire, and 80% less potassium perchlorate ($KClO_4$) solution than potassium chloride solution is required. The extinguishing effectiveness also varies with the type of anion attached to the alkali metal cation. For example, the chlorate is more effective than the bicarbonate, which is more effective than the chloride, which is more effective than the carbonate.

TABLE 7-5. RELATIVE EFFECTIVENESS OF AQUEOUS SOLUTIONS OF ALKALI METAL SALTS USED TO EXTINGUISH GASOLINE PAN FIRES (Refs. 9, 31, and 35)

SALT	FORMULA	MOLECULAR WEIGHT, g/mol	MASS* OF SOLUTE PER LITER OF SOLUTION, g/L	FIRE EXTINGUISHED
Cesium Chloride	$CsCl$	168.36	134.7	Yes
Rubidium Bitartrate	$RbHC_4H_4O_6$	234.55	17.6	Yes
Chloride	$RbCl$	120.92	120.9	Yes
Carbonate	Rb_2CO_3	230.95	173.2	Yes
Potassium Bitartrate	$KHC_4H_4O_6$	188.18	14.1	Yes
Perchlorate	$KClO_4$	138.55	27.7	Yes
Dichromate	$K_2Cr_2O_7$	294.19	29.4	Yes
Hydroxide	KOH	56.11	33.7	Yes
Fluoride	KF	58.10	34.9	Yes
Citrate	$K_3C_6H_5O_7{\cdot}H_2O$	324.34	43.2	Yes
Anthranilate	$KC_7H_6NO_2$	175.22	43.8	Yes
Permanganate	$KMnO_4$	158.04	47.4	Yes
Butyrate	$CH_3{\cdot}CH_2{\cdot}COOK$	126.19	50.5	Yes
Gallate	$KC_7H_5O_5$	208.21	62.5	Yes
Iodate	KIO_3	214.00	64.2	Yes
Formate	$KCHO_2$	84.12	67.3	Yes
Acetate	$KC_2H_3O_2$	98.15	68.7	Yes
Bicarbonate	$KHCO_3$	100.12	70.1	Yes
Chlorate	$KClO_3$	122.55	73.5	Yes
Chloride	KCl	74.56	74.6	Yes
Nitrite	KNO_2	85.11	76.6	Yes
Tartrate	$K_2C_4H_4O_6{\cdot}{}^1\!/_2H_2O$	235.28	94.1	Yes
Iodide	KI	166.01	99.6	Yes
Oxalate	$K_2C_2O_4{\cdot}H_2O$	184.24	101.3	Yes
Carbonate	K_2CO_3	138.21	103.7	Yes
Lactate	$KC_3H_5O_3{\cdot}3H_2O$	182.22	109.3	Yes
Nitrate	KNO_3	101.11	111.2	Yes
Bromide	KBr	119.01	220.2	Yes
Bromate	$KBrO_3$	167.01	250.5	Yes
Phosphate	K_3PO_4	212.28	283.0	Yes
Hydrogen Sulfate	$KHSO_4$	136.17	680.9	No
Sodium Acetate	$NaC_2H_3O_2$	83.02	83.0	Yes
Nitrate	$NaNO_3$	84.99	255.0	Yes
Chloride	$NaCl$	58.44	274.7	Yes
Potassium Carbonate	$NaKCO_3{\cdot}6H_2O$	230.19	287.7	Yes
Dichromate	$Na_2Cr_2O_7{\cdot}2H_2O$	298.00	298.0	Yes
Lactate	$NaC_3H_5O_3$	112.06	392.2	Yes
Tartrate	$Na_2H_4C_4O_6{\cdot}2H_2O$	230.10	1380.6	No
Diphosphate	Na_2HPO_4		**	No
Triphosphate	Na_3PO_4		**	No
Silicate	$Na_2Si_3O_7$		40.0%	No
Lithium Acetate	$LiC_2H_3O_2{\cdot}2H_2O$	102.01	510.1	Yes
Chloride	$LiCl$	42.39	635.9	No
Nitrate	$LiNO_3$	68.94	689.4	No
Citrate	$Li_3C_6H_5O_7{\cdot}4H_2O$	281.98	845.9	No

*Least mass per liter of solution that extinguished fire.
**Saturated solution

7-2.2.3 Halogen-Containing Hydrocarbon Compounds

Hydrocarbons containing halogen atoms, i.e., fluorine, chlorine, bromine, or iodine, are commonly referred to generically as halons, *halo*genated hydrocarb*ons*. Many halons are proscribed by the Montreal Protocol of 29 June 1990 and subsequent US Government action. This class of compounds exhibits greater flame extinguishment effectiveness, particularly when used in a dilute quantity, than could be attributed to physical effects such as fuel blanketing or reduction of flame temperatures by dilution, by increased heat capacities, or by cooling. Extensive research has confirmed that this enhanced extinguishment effectiveness is a result of interference with the free-radical chain reactions proceeding within the flame (Refs. 3, 7, 30, 36, and 37). These studies have provided extensive tabulations of the relative effectiveness of various halons. Table 7-6 presents a summary of the relative effectiveness of halon agents (Ref. 3). The relative effectiveness of these agents may vary depending on the test conditions.

In the absence of extinguishants free radicals (molecular fragments and/or atoms) in the flame react among themselves to form more free radicals than are consumed in the various reaction steps. Hence the reactions proceed ever faster until all reactants are consumed. A popular explanation of the effectiveness of halogen-containing agents (Ref. 30) is that they are capable of producing relatively inert halogen-containing free radicals that compete with the more reactive free radicals and atoms in the flame. Thus the net rate of formation of excess free radicals is decreased, and the reaction rates decrease until with sufficient agent flame extinction is achieved. Table 7-7 compares the characteristics of selected halons to desired military characteristics (Ref. 3).

When halons are subjected to high temperatures such as those reached in ammunition fires, they can decompose and yield toxic gases. A study of the use of Halon 1301 (bromotrifluoromethane) as an extinguishant for enclosure fires indicated that the concentrations of halogen-containing pyrolysis products were less hazardous than the concentrations of fuel combustion products produced in the tests conducted for the study. It was also observed that the duration of the extinguishant discharge determined the amount of products formed (Ref. 38).

Resistance to pyrolysis varies among the halons, as illustrated by the "white rat" toxicity data of Table 7-8. Refs. 3, 37, and 39 describe a comprehensive experimental study of the toxicological effects of bromochloromethane and its pyrolysis products on guinea pigs. The pyrolysis studies were conducted with various heat sources including an illuminating gas flame and gasoline, ethyl alcohol, and wood fires. This conclusion was reached: "Under ordinary conditions prevailing in fires in well ventilated places, particularly in the case of incipient and small fires, the concentrations of Halon 1011 (bromochloromethane) and its thermal decomposition products may not endanger life on temporary exposure, but in small closed places such as vaults, closets, or small basement rooms, where the prompt exit of persons is not possible, there is danger." (Ref. 39).

7-2.2.3.1 The Search for Halon Replacements and/or Alternates*

At the time this handbook was written, halons containing chlorine and/or bromine were being phased out of use as refrigerants, solvents, pressurants, and fire extinguishants. Potential alternative materials for use as fire extinguishants were being evaluated for their ozone depletion potential (ODP), global warming potential (GWP), toxicity hazard, and fire-extinguishing capability. The ODP was evaluated as a function of chlorine and bromine content. The model for this evaluation was being upgraded to include molecules containing iodine. Evaluation of global warming potential is dependent upon computer models that are still being developed. The toxicity hazard was evaluated using two different measures. One measure established the lethal concentration of the vapor(s) of the agent in air, which is defined as the concentration at which half of a number of rats exposed for four hours die, the LC_{50}. The other measure, which is the cardiac sensitivity threshold (CST), is established using dogs exposed to vapors until irregular heartbeats develop. Both of these measures are controversial. The LC_{50} criterion is better suited for evaluating the hazard in a production plant, and the CST criterion has been questioned for the applicability of dogs' reactions to humans' reactions. The preliminary criterion for fire-extinguishing capability has been the cup burner test, in which the volume percentage of the extinguishant in air needed to extinguish a heptane fire is established (Ref. 14).

*"Replacement" denotes a fire extinguishant that is chemically similar to halons; "alternate" denotes a fire extinguishant that is not chemically similar to halons, e.g., water, carbon dioxide, or a powder such as potassium bicarbonate or monoammonium phosphate (Ref. 40).

TABLE 7-6. MINIMUM CONCENTRATION OF HALONS REQUIRED FOR INERTING ALL CONCENTRATIONS OF HEPTANE IN AIR (Ref. 3)

COMPOUND NAME	COMPOUND FORMULA	MINIMUM CONCENTRATION FOR INERTION VOLUME, %
Dibromodifluoromethane	CBr_2F_2	4.2
Tribromofluoromethane	CBr_3F	4.2
2-Bromo-1,1,1-trifluoropropane	$CF_3CHBrCH_3$	4.9
1,2-Dibromotetrafluoroethane	$CBrF_2CBrF_2$	4.9
Tetrafluoro-1,2-diiodoethane	CF_2ICF_2I	5.0
Dibromomethane	CH_2Br_2	5.2
Pentafluoroiodoethane	CF_3CF_2I	5.3
3-Bromo-1,1,1-trifluoropropane	$CF_3CH_2CH_2Br$	5.4
Ethyl Iodide	CH_3CH_2I	5.6
Bromopentafluoroethane	CF_3CF_2Br	6.1
Methyl Iodide	CH_3I	6.1
Bromotrifluoromethane	$CBrF_3$	6.1
Ethyl Bromide	CH_3CH_2Br	6.2
1-Bromo-2,2-difluoropropane	$CH_2BrCF_2CH_3$	6.3
2-Bromo-1-chloro-1,1-difluoropropane	$CClF_2CHBrCH_3$	6.4
Dibromofluoromethane	$CHBr_2F$	6.4
1,2-Dibromo-1,1-difluoroethane	$CBrF_2CH_2Br$	6.8
2-Bromo-1,1,1-trifluoroethane	CF_3CH_2Br	6.8
Perfluoro(ethylcyclohexane)	$C_6F_{11}C_2F_5$	6.8
Perfluoro(1,3-dimethylcyclohexane)	$1,3\text{-}C_6F_{10}(CF_3)_2$	6.8
Perfluoro(1,4-dimethylcyclohexane)	$1,4\text{-}C_6F_{10}(CF_3)_2$	6.8
Trifluoroiodomethane	CF_3I	6.8
1-Bromo-2-chloroethane	CH_2BrCH_2Cl	7.2
2-Bromo-1-chloro-1,1-difluoroethane	$CClF_2CH_2Br$	7.2
Perfluoro(methylcyclohexane)	$C_6F_{11}CF_3$	7.5
Perfluoroheptane	C_7F_{16}	7.5
Bromochloromethane	CH_2BrCl	7.6
Bromodifluoromethane	$CHBrF_2$	8.4
1,1,2-Trichlorotrifluoroethane	$CClF_2CCl_2F$	9.0
Bromochlorodifluoromethane	$CBrClF_2$	9.3
Hydrogen Bromide	HBr	9.3
Methyl Bromide	CH_3Br	9.7
2,2-Difluorovinyl Bromide	$CF_2{=}CHBr$	9.7
Perfluorobutane	C_4F_{10}	9.8
1,2-Dibromo-2-chloro-1,1,2-trifluoroethane	$CBrF_2CBrClF$	10.8
1,2-Dichlorotetrafluoroethane	$CClF_2CClF_2$	10.8
Carbon Tetrachloride	CCl_4	11.5
2-Chloro-1,1,1-trifluoropropane	$CF_3CHClCH_3$	12.0
3-Chloro-1,1,1-trifluoropropane	$CF_3CH_2CH_2Cl$	12.2
Chlorotrifluoromethane	$CClF_3$	12.3
Hexafluoroethane	CF_3CF_3	13.4
Dichlorodifluoromethane	CCl_2F_2	14.9
Chloroform	$CHCl_3$	17.5
Trifluoromethane	CHF_3	17.8
Chlorodifluoromethane	$CHClF_2$	17.9
Octafluorocyclobutane	C_4F_8	18.1
Hydrogen Chloride	HCl	25.5
Carbon Tetrafluoride	CF_4	26.0

TABLE 7-7. COMPLIANCE OF SELECTED HALONS TO MILITARY CHARACTERISTICS (Ref. 3)

MILITARY CHARACTERISTICS	METHYL BROMIDE (HALON 1001)	CARBON TETRACHLORIDE (HALON 104)	BROMOCHLORO-METHANE (HALON 1011)	BROMOTRIFLUORO-METHANE ((HALON 1301)	DIBROMODI-FLUOROMETHANE (HALON 1202)	BASIS OF COMPARISON
The agent shall be suitable for use in combating fires of Classes B and C.	Approximately twice as effective as carbon tetrachloride	Comparator (Baseline)	Approximately 1 3/5 as effective as carbon tetrachloride	Approximately twice as effective as carbon tetrachloride	Approximately twice as effective as carbon tetrachloride	Laboratory data (Ref. 3)
The agent shall not be more toxic than carbon tetrachloride.	5 times as toxic as carbon tetrachloride	Comparator (Baseline)	Approximately 1/2 as toxic as carbon tetrachloride	1/28 as toxic as carbon tetrachloride	1/2 as toxic as carbon tetrachloride	Approximate lethal concentration (Ref. 13)
The agent shall be suitable for use at temperatures from 71° to −54°C (160° to −65°F).	Suitable	Solidifies at −22°C (−7.6°F); requires winterization	Suitable over entire temperature range	Suitable over entire temperature range; more effective than dibromodifluoromethane at −54°C (−65°F)	Suitable over entire temperature range	Cold chamber tests
The agent shall not deteriorate when transported or when stored for up to five years under any climatic conditions.	Stable under storage conditions	Stable under storage conditions	Stable under storage conditions	Higher stability than methyl bromide or carbon tetrachloride because of fluorine content	Higher stability than methyl bromide or carbon tetrachloride because of fluorine content	
The agent may be produced in quantity within reasonable cost limits and with existing production facilities.	In commercial production	In commercial production	In commercial production	Produced by fluorination processes as used for the production of freon-type refrigerants	Produced by fluorination processes as used for the production of freon-type refrigerants	
The corrosive effects of the agent shall not be greater than those of standard carbon tetrachloride fire extinguisher fluid.	Noncorrosive to common metals	Slightly corrosive (negligible when inhibited by traces of CS_2); most corrosive to aluminum under aqueous conditions	Slightly corrosive; most corrosive to aluminum	Noncorrosive to common metals	Anticipated to be noncorrosive to common metals	Laboratory data (Ref. 3)
The agent shall be a nonconductor of electricity.	Nonconductor	Nonconductor	Nonconductor	Nonconductor	Nonconductor	As a class, all of these agents are non conductors.

TABLE 7-8. APPROXIMATE LETHAL CONCENTRATION FOR SELECTED HALONS (Ref. 3)

AGENT	FORMULA	HALON	APPROXIMATE LETHAL CONCENTRATION			
			NATURAL VAPOR		VAPOR PYROLIZED IN IRON TUBE AT 800°C	
			mg/L	ppm	mg/L	ppm
Bromotrifluoromethane	$CBrF_3$	1301	5075	800,000	86	14,000
Carbon Tetrafluoride	CF_4	14	3220	512,000	3220	512,000
Bromochlorodifluoromethane	CF_2ClBr	1211	2200	324,000	52	7,650
Dibromotetrafluoroethane	CF_2BrCF_2Br	2402	1340	126,000	17	1,600
Carbon Dioxide	CO_2	—	1180	100,000	1200	102,000
Perfluoromethylcyclohexane	$C_6F_{11}CF_3$	GK(M)	1165	81,000	117	7,500
Ethyl Bromide	C_2H_5Br	2001	660	148,000	75	16,500
Dibromodifluoromethane	CF_2Br_2	1202	470	54,000	16	1,850
Chlorobromoethane	CH_2ClBr	1011	340	65,000	20	4,000
Dibromochlorotrifluoroethane	$CClFBrCF_2Br$	2312	285	25,000	8	700
Dibromodifluoroethane	CH_2BrCF_2Br	2202	190	20,700	110	12,000
Carbon Tetrachloride	CCl_4	104	180	28,000	2	300
Methyl Bromide	CH_3Br	1001	23	5,900	60	9,600
Methyl Iodide	CH_3I	10001	22	3,800	350	60,500

7-2.2.3.2 Halon Replacements

Evaluation of halon replacements is hindered by lack of a validated means to judge candidates. The NIST has documented procedures and criteria for replacements for Halons 1211 and 1301 (Ref. 41). There has not been a consensus, however, among the personnel selecting the halon replacements on how to predict the long-term effects of a material on either ozone depletion or global warming. Thus this halon replacement selection effort is in a state of flux at this time. NIST presented an exploratory list of replacements in Ref. 8. Some of the near-term replacements, which were under consideration in 1992, are described in Tables 7-9 and 7-10.

7-2.2.3.3 Halon Alternates

The lack of selected halon replacements has encouraged the review of previously used or discarded fire extinguishants. These include water, dry chemical powders, carbon dioxide, and other agents that lacked some of the favorable attributes of halons. NIST included halon alternatives in Ref. 8. Descriptions of the advantages and disadvantages of some of these alternatives are given, i.e., water in subpar. 7-2.3.1, carbon dioxide in subpar. 7-2.1.1, and dry powder in subpar. 7-2.2.

Both Spectrex and Kidde-Graviner are developing extremely fine dry chemical extinguishant generation devices. These devices burn a solid mass to produce a dust cloud of dry chemical, which probably contains potassium. These "dust" generators are cooled, usually with water, to preclude adding heat to the fire site. The dust produced floods the fire site. Once ignited, the "dust" generator must burn to completion. At this time, no research has been performed on the reactions of humans to this extremely fine powder, which is reported to be micron size, that would be extremely difficult to keep out of the lungs of vehicle crewmen. The effects upon crewmen should be explored before such devices are installed in crew compartments of combat vehicles. (See subpar. 5-6.2.2 for discussion of particles this size.)

7-2.2.4 Halogen-Containing Nonhydrocarbons

Various halogen-containing nonhydrocarbon extinguishing agent candidates have been evaluated in research studies. These included gaseous aluminum chloride, sulfur hexafluoride, sulfuryl chloride, boron trifluoride, phosphorous trichloride, phosphorous oxychloride, trichlorosilane, and silicon tetrachloride (Refs. 3, 7, and 30). The volatile hydrogen halides were included with the halogen-containing hydrocarbons in subpar. 7-2.2.3. The candidate agents that appeared most promising also presented toxicity hazards; therefore, they are not recommended for use in the crew compartments of military combat vehicles.

TABLE 7-9. PRELIMINARY EVALUATION OF HALON REPLACEMENTS COMPARED TO THE TWO PRINCIPAL HALONS (Refs. 14, 42, 43, 44, 45, 46, 47, and 48)

TRADE NAME*	FORMULA	OZONE DEPLETION POTENTIAL (ODP), dimensionless	CONCENTRATION LETHAL FOR 50% OF EXPOSED POPULATION OF RATS (LC_{50}), %	CARDIAC SENSITIVITY THRESHOLD (CST), %		CUP BURNER (HEPTANE), vol %	PROPOSED DESIGN VALUE, %	PROPOSED FOR USE	GLOBAL WARMING POTENTIAL (GWP), dimensionless
				NOEL	LOEL				
Carbon Dioxide	CO_2					28		S, F, OC	
Halon 1301	CF_3Br	10.0-14.1[47]	> 80[47]	5	7.5	3	5.0-5.2**	F, OC-Baseline	0.80[43]
Halon 1211	CF_2ClBr	2.4-3.0[47]	8.5-10.0[42]	na	na	3.8		S, UC-Baseline	
FE-13™	CHF_3	0[46]	65	50	> 50	12	15.6	F, OC, UC	5.7[44]
FE-25™	C_2F_5H	0[45]	> 70	7.5	7.5	8.1	(2)	UC	0.58[43]
FE-232™	CF_3CHCl_2	0.02	3.2[42]	na	na	7.2[42]	9.0[42]	P	0.02[44]
FE-241™	CF_3CHClF	0.02[45]	23-29	2.5	2.5	6.4	(2)	UC	0.1[44]
FM 100®	CHF_2Br	0.19-1.1[47]	10.8	2	3.7	3.9-4.4	(2)	S, UC	
FM 200®	CF_3CHFCF_3	0[47]	> 80	7	9	5.8	7.9	F, UC	0.3-0.6[47]
PFC 410™	C_4F_{10}	0[48]	> 80	40	> 40	5.5	6.2	F, OC, UC	insignificant[48]
NAF SIII™	(1)	0.044[43]	32[43]		8.6	0.32[43]	8.6	F, OC, UC	0.1[43]

Notes: (1) Mixture of $CHClF_2$, 82%; CF_3CHClF, 9.5%; CF_3CHCl_2, 4.75%; and proprietary hyrocarbon, 3.75%.
(2) Rule of Thumb: Cup Burner Value + 20%
*Mention of proprietary substances does not constitute Government endorsement.
** The current Army design value for Halon 1301 is 7% concentration.
OC = recommended for use in occupied compartments
P = intended for use in portable extinguishers
UC = recommended for use in unoccupied compartments
S = streaming, i.e., a spray or stream
F = flooding, i.e., a mist or vapor
na = not available
NOEL = no observable effect level
LOEL = lowest observable effect level
Reference for data is Ref. 14 unless otherwise indicated by superscript reference number in parentheses.

TABLE 7-10. PROPERTIES OF HALON REPLACEMENTS (Refs. 8, 9, 14, 42, 43, 45, 46, 47, 48, and 49)

SUBSTANCE	FORMULA	MOLECULAR WEIGHT, g/mol	DENSITY AT 25°C, kg/L or g/mL	BOILING POINT, °C	LATENT HEAT OF VAPORIZATION, J/g	VAPOR PRESSURE, MPa	SPECIFIC HEAT AT 25°C AND 1 atm, J/(g·°C)	FREEZING POINT, °C	ABSOLUTE VISCOSITY AT 25°C, mPa·s
Halon 1301	CF_3Br	148.95[43]*	1.538[45]	–57.75[43]	118.8[43]	1.62 at 25°C[45]	g 0.469[9] ℓ 0.870[43]	–168[9]	0.159[43]
Halon 1211	CF_2ClBr	164.5[42]	1.7973[42]	–4[42]	123.4[42]	0.276 at 25°C	g 0.450[8]	–160	
FE-13™	CHF_3	70.01	0.6699[46]	–82.1	239.6	4.59 at 25°C[46]	g 0.737 ℓ 1.549	–155.2	0.083
FE-25™	C_2F_5H	120.02	1.2494[45]	–48.5	164.7	1.31 at 25°C[45]	g 0.800 ℓ 1.260	–102.8	0.145
FE-232™	CF_3CHCl_2	152.9[42]	1.4597[42]	27.9[42]	96.00[42]	0.0896 at 25°C[42]	ℓ 0.667[8]		
FE-241™	CF_3CHClF	136.5		–11.0	167.9	0.38 at 25°C	g 0.741 ℓ 1.130	–198.9	0.314
FM 100®	CHF_2Br	130.92	1.80[49]	–15.5	171.9	0.490 at 27°C[41]	g 0.455 ℓ 0.455	–145.0	0.280
FM 200®	CF_3CHFCF_3	170.03	1.427 at 20°C[47]	–15.2	133.0	0.405 at 21°C[47]	g 0.726 ℓ 1.102	–131.1	0.183
PFC 410™	C_4F_{10}	238.03	ℓ 1.517[48] g 0.009935[48]	–2	96.3	0.2896 at 25°C	g 0.804 ℓ 1.047	–128.2	0.0642[48] ℓ 0.324
NAF SIII™	See Table 7-9	92.9	1.20[43]	–38.3	225.6	0.95 at 25°C	g 0.67 ℓ 1.256	<–107.2	0.21 [43]
PFC-614	C_6F_{14}	338[48]	1.68[48]	56[48]	88.4[48]	0.31 at 25°C[48]			0.00069

*Reference for data is Ref. 14 unless otherwise indicated by superscript reference number in parentheses.

g = gas

ℓ = liquid

7-2.2.5 Other

Hydrated alkali metal salts of boron and silicon oxides including sodium metaborates, tetraborates, metasilicates, and homologues thereof are effective extinguishing agents whose mechanisms include cooling by latent heat of vaporization, dehydration, intumescence, and formation of an insulative char or foam.

An example follows of a hydrated salt that could be used to cool a fire by liberating moisture. Assume 1 kg of magnesium sulfate heptahydrate, $MgSO_4 \cdot 7H_2O$, (Epsom salts) was dispensed into a large volume in which there was a fire maintaining a temperature of 177°C. The Epsom salts would heat from 21°C to 150°C absorbing 195 kJ of heat. At 150°C the Epsom salts would lose 439 g of H_2O absorbing 1.361 MJ of heat. The 561 g of magnesium sulfate, $MgSO_4$, and the water vapor would heat to 177°C absorbing 37 kJ of heat. Then a gaseous coolant could be injected that would absorb a total of 1.593 MJ of heat and release 439 g of H_2O diluent. The $MgSO_4$ would readily absorb water when cooled and would eventually return to Epsom salts (Ref. 31).

The boron salts are active free-radical terminating agents, a property shared to a lesser degree by the silicate anions. Aqueous solutions of these agents offer enhanced extinguishing ability by both interruption of free-radical chain reactions and energy absorption by the solutions as they release their associated water and proceed to calcine and intumesce. Thus energy is absorbed as the solute undergoes calcining transformation from solute to hydrated crystalline solids to expanding viscoelastic, amorphous masses and finally to rigid, cellular foams. The only practical use made of borate solutions to date has been in airdrops on forest and brush fires (Ref. 50).

7-2.3 COOLING AGENTS

Any vaporizing liquid extinguishing agent can provide cooling, but many such agents also exhibit chemical intervention properties and prevent oxygen access to the fuel. Consequently, such agents (other than water) are assigned to one of those classes rather than the cooling agent class. Likewise, powders such as alkali halides or bicarbonates that function more as chemical intervention or oxygen-excluding agents than as cooling agents are not included.

7-2.3.1 Water

Water represents the most common and most available fire-extinguishing agent. Its properties are well suited for fire-extinguishing applications. It is chemically stable and nonflammable. It is the only completely nontoxic extinguishing agent known, and it does not produce toxic combustion products. Moreover, it possesses an unusually high latent heat of vaporization relative to most other potential extinguishing agents, and this property enhances its cooling effects. Water should not be used on fires near high-voltage (>10 kV) equipment until the electrical power has been turned off. US Navy (USN) personnel have recommended the use of a freshwater* mist to extinguish even electrical fires (Ref. 51). The shock hazard associated with using water to extinguish fires involving electrical equipment has been shown to be minor as long as the electrical voltage is low, the water is not highly electrically conductive, and/or the water is not a continuous medium (Ref. 52).

Water functions as a fire extinguishant primarily as a coolant. As it impinges on hot surfaces or mixes with hot gases or flames, the resulting steam dilutes the flame gases, reduces flame temperatures, and blankets the fuel. Thus oxygen is diluted, and flame temperatures are thereby reduced to the point of extinction (Refs. 30 and 53). One kg of water at 21°C sprayed into a large compartment containing a fire maintaining a temperature of 177°C would do the following:

1. Heat from ambient to the boiling point by absorbing 0.333 MJ
2. Boil by using 2.257 MJ
3. Heat the vapor from the boiling point to 177°C by using 0.144 MJ.

The sum of these heats is 2.734 MJ, and the water would provide 1000 g of water vapor diluent.

For deep-seated cellulosic fires, liquid water would be 5 to 13,500 times as effective in cooling hot solids, that is in quenching a deep-seated celluosic fire, than would gaseous coolants used as extinguishants. On the other hand, several extinguishants described herein could eliminate flames more effectively than water.

7-2.3.1.1 Forms of Fire Extinguishant Water

The form in which liquid water is used to extinguish a fire is important in the planning of usage and distribution systems. For example, water can be spurted onto a fire in the form of a jet. This method would deliver a high volume of water quickly, which would be excellent to extinguish a deep-seated Class A fire, such as clothing or a seat cushion, that requires primarily cooling to extinguish. A water jet can travel a long distance quickly: 9 m (30 ft) using a handheld 63.5-mm (2.5-in.) hose. A water spray, in the form of many droplets, can be directed onto a burning pool of hydrocarbon fuel (Class B fire) without spreading the fuel pool by splashing and can be delivered from approximately 4.3 m (14 ft) using a handheld 63.5-mm (2.5-in.) hose nozzle. A water mist, which consists of very small droplets (Sauter mean diameters of 10 to 200 μm**) of water, would have a very short delivery range, i.e., 305 to 610 mm (1 to 2 ft),

*As opposed to seawater, which is normally used on US Navy ships to fight fires

**These sizes were established using a Malvern particle size analyzer. This instrument uses laser photocorrelation spectroscopy to characterize particle size and distribution. For liquid particles the size is characterized as the Sauter mean diameter D_{32} in μm. The theory by which this characterization is accomplished is described in Ref. 54.

and would probably require some means other than residual momentum to travel from the nozzle. Finally, water vapor, steam, can be used as a blanketing agent, but steam can be pressurized and jetted a greater distance than a mist.

For liquid hydrocarbon fuel fires, a stream of water cannot be applied directly to the fire because it would scatter the burning fuel. Hence water must be applied to liquid hydrocarbon fuel fires as a foam, spray, or fog. In special cases a relatively strong, coarse water spray can be applied to shallow pools of viscous hydrocarbon fuels to achieve emulsification of water in the fuel. The formation of such a water-in-fuel emulsion enhances cooling of the fuel (Ref. 19). The use of water in the form of foam is discussed in subpar. 7-2.1.6.

Ideally, a spray should penetrate to the seat of the fire and extinguish it at its source. The effectiveness of a water spray, however, increases with increasing droplet surface area, i.e., decreasing droplet size, but the penetration of the spray into the fire increases with droplet size (Ref. 55). Accordingly, there is an optimum water droplet size for maximum fire-extinguishing effectiveness for any fire configuration. Experimental and mathematical studies have been conducted to optimize the mode of application of water sprays, the rates and duration of application, and the properties of the spray being applied (Refs. 56 through 60).

It has been observed in an incident of a burning liquid fuel flowing as a film, i.e., film-wise, on a solid surface that the size distribution of droplets in a water spray is not important. With deep pools of the same fuel, however, the extinguishing effectiveness of water sprays increases with droplet size (Ref. 60). It has also been observed that the required rate of application of a water spray to liquid fuel flowing film-wise on a solid surface increases with increasing burn time; hence the surfaces of solids are hotter. Also, when the water spray is directed into the surface of the burning fuel, the extinguishment is more effective than when the spray is used to form a shroud around the fire (Ref. 59).

The fire-extinguishing effectiveness of water sprays improves with inclusion of selected additives. The use of dissolved salts of alkali metals is discussed in subpar. 7-2.2.2. The viscosity of the water increases with inclusion of water-soluble thickeners, e.g., salts of carboxymethylcellulose or alginates (Refs. 50, 56, and 57). The advantage of thickened water is that such formulations are much slower to run off the burning surfaces; thus the cooling and fuel-blanketing efficacy of water is enhanced. Recommended viscosity increases range from 5- to 200-fold (Refs. 57 and 61). For a water-additive combination the viscosity can be increased by increasing the molecular weight of the additive. Also additives that cause water to gel have been studied (Ref. 57). It has been observed that the time to extinguishment decreases as the viscosity increases; hence water consumption is reduced (Ref. 62). Disadvantages of water thickeners include increases in friction losses in hoses and pipes, difficulty forming water fogs, and growth of algae.

One practical use of water-soluble thickeners has been in airdrops on forest and brush fires (Ref. 50). They are also used in a zero gravity environment (spacecraft) (Ref. 63) and in combat vehicles (subpar. 7-3.2.4).

Water treated with friction-reducing additives, in contrast with thickened water, has been tested by domestic firefighters. It has been observed that fire hoses deliver significantly more water and achieve better nozzle pressures when using such treated water, "rapid water" (Refs. 11 and 26).

7-2.3.1.2 Freeze Point Suppressants

When exposure of water-base extinguishants to freezing temperatures is anticipated, freezing point depressants (antifreeze) should be included in the water (Ref. 10). The most common such additive used in fire fighting is calcium chloride ($CaCl_2$) plus a corrosion inhibitor. Sodium chloride (NaCl) cannot be used because it is not as effective and is extremely corrosive. Another freeze point suppressant that could be used is potassium acetate ($KC_2H_3O_2$). To assure adequate storage stability, water used in military fire-extinguishing applications must also contain an antifungal additive.

Pure water freezes at 0°C, well within the temperature range in which combat vehicles must operate. Therefore, a freeze point suppressant must be available for use in winter in temperate regions and in arctic regions. Combat vehicles are expected to operate in temperatures down to –32°C (–25°F) and down to –54°C (–65°F) with winterization kits installed; these winterization kits are not supposed to include internal heaters.

The current freeze point suppressant used by the US Army is ethylene glycol ($C_2H_6O_2$), per MIL-A-46153 (Ref. 64). The lowest freeze point indicated in Ref. 64 for mixtures of $C_2H_6O_2$ and water is –51°C (–60°F) at 90% by volume. Ethylene glycol is toxic; a lethal dose for humans is about 100 mL. An antifreeze agent recommended by the National Fire Protection Association when connecting a fire water reservoir to a drinking water supply system is propylene glycol ($C_3H_8O_2$) (Refs. 10 and 65). Propylene glycol is nontoxic and is used as an antifreeze in many household and recreational applications. The lowest freeze point indicated in Ref. 10 for propylene glycol is –51°C (–60°F) at 40% by volume. Calcium chloride was selected for use in the explosive-activated linear fire extinguisher discussed in subpar. 7-5.2.6. The lowest freeze point indicated in Ref. 10 is –45°C (–49°F) for a solution of 0.591 kg of $CaCl_2$ per liter of water. The US Navy has developed a lithium chloride solution for fire extinguishers exposed to low temperatures, i.e., –54°C (–65°F) (Ref. 10). The antifreeze additive used in the portable water extinguisher installed in Trans World Airlines (TWA) aircraft (Ref. 66) is potassium acetate ($KC_2H_3O_2$). This freeze point suppressant is in the proprietary material designated GS-4™, which is nominally 50%

by weight potassium acetate plus corrosion inhibitors, and the remainder is water. The lowest freeze point indicated for this mixture is –60°C (–76°F), and its range is shown on Fig. 7-3. Information on these freeze point suppressants is given in Table 7-11, and a sample calculation of cooling capability using potassium acetate as a freeze point suppressant follows. These equations were taken from Ref. 67 and, where necessary, converted to SI dimensions.

For the freezing point of a potassium acetate and water solution FP_{PA},

$$FP_{PA} = (-0.167\,conc) + (-0.0206\,conc^2),\ ^\circ\mathrm{C} \tag{7-10}$$

where

conc = concentration of potassium acetate, % wt.

For the specific heat of a potassium acetate and water solution $C_{p_{PA}}$,

$$C_{p_{PA}} = 4.226 + 0.0006025\,T - 0.2833\,conc,\ \mathrm{J/(g{\cdot}K)} \tag{7-11}$$

where

T = temperature °C.

The process hypothesized is for the solution to heat to its boiling point, which is assumed to be 116°C (241°F) for a solution near that of GS-4™. The water then boils out and leaves potassium acetate in a solid state. The potassium acetate will heat to 292°C (558°F) at which temperature it will combine with atmospheric oxygen, and one of the intermediate products ($KHCO_3$) will decompose and produce end products, as shown in this chemical reaction:

$$2KC_2H_3O_2 + 4O_2 + q \Leftrightarrow K_2CO_3 + 3H_2O + 3CO_2.$$

Potassium carbonate (K_2CO_3) will continue to heat to 891°C at which temperature it will calcine:

$$K_2CO_3 + q \Leftrightarrow K_2O + CO_2.$$

If moisture is present, the potassium monoxide (K_2O) could combine with the moisture in this process:

$$K_2O + H_2O + q \Leftrightarrow 2KOH.$$

The relative effectiveness of candidate cooling-type extinguishants can be estimated by establishing the heat removed, the atmospheric oxygen consumed, and the diluent gases—carbon dioxide and water vapor—produced by a given mass of water plus the freezing point suppressant and by using the equations in subpar. 7-1.3. Material properties are given in Tables 7-4 and 7-11. The estimation must be broken down into steps that are established by a change of state of one of the substances involved or by chemical reactions. For a potassium acetate and water solution of a mass of 1000 g, the steps follow:

1. Raise the temperature of the solution from the initial temperature to the boiling point of the solution. (Assume the initial temperature is 21°C and the boiling point is 116°C.) To suppress the freezing point to –54°C (–65°F), a 94.5% GS-4™ solution is used. (The $KC_2H_3O_2$ concentration is 47.25% by weight, and water is 52.75% by weight.) A mean specific heat can be obtained from Eqs. 7-1 and 7-11; $\overline{C_p}$ = 2.9215 J/(g·K). The heat needed to raise the temperature of the solution is 278 kJ.
2. Boil off the water; establish the mass of water vapor produced by using the latent heat of vaporization of water: 2257 J/g. The mass of the water boiled off is 527.5 g, and the energy required is 1.191 MJ.
3. Raise the temperature of the water vapor and potassium acetate solution from its boiling point to 177°C. Therefore, 527.5 g of water vapor and 472.5 g of $KC_2H_3O_2$ are raised from 116°C to 177°C using 0.103 MJ of heat.

These calculations indicate that by using a solution of 1 kg of water and sufficient freeze point suppressant to obtain a –54°C freeze point, a cooling capability of 1.572 MJ as well as 528 g of water diluent are obtained. Most of this cooling effect is from boiling the water—the best way to cool hot solid materials.

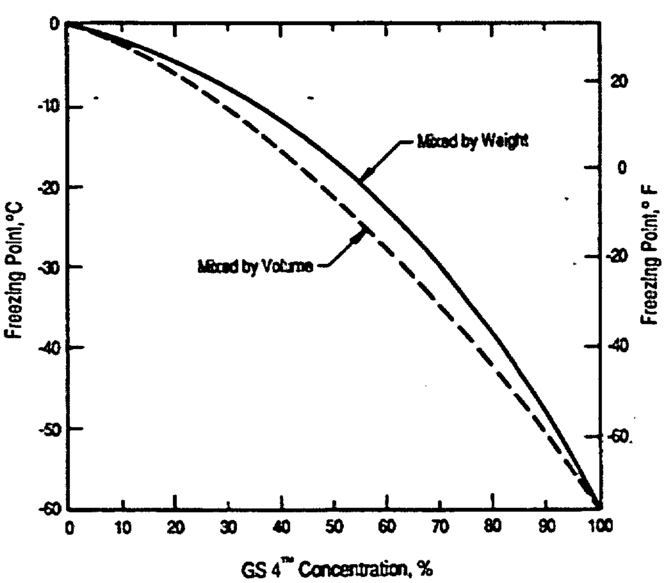


Figure 7-3. Freezing Point of Water—GS 4™ Solution (Ref. 67)

TABLE 7-11. DATA FOR WATER AND ITS FREEZE POINT SUPPRESSANTS

SUBSTANCE	FORMULA	MOLECULAR WEIGHT, g/mol	DENSITY, g/mL	TRANSITION TEMPERATURE, °C	HEAT OF FORMATION, J/mol	SPECIFIC HEAT, J/(g·°C)	LATENT HEAT OF TRANSITION, J/g	COMBUSTION OR DECOMPOSITION PRODUCTS
Water	H_2O	18.0153[9]*	c 0.913 at nmp[12] ℓ 1.000 at 4°C[12] g 0.0005799 at nbp[69]	nmp 0[9] nbp 100[9] d ≈ 4177[18]	g −241.8	c 1.925 at nmp[12] ℓ 4.186 at nbp[10]	f 333.2[10] v 5010.7[10]	H_2, OH, O_2
Ethylene Glycol	$C_2H_6O_2$	62.07[68]	ℓ .1088 at 20°C[9]	nmp −11.5[9] −12.6[69] nbp 197.5[68] 197.2[69]	ℓ −455.3[34]	ℓ 2.43[68] at 25°C g 1.56[68] at 25°C	f 181[9], 170[69] v 800[68,69]	H_2O, CO_2, CO
Propylene Glycol	$C_3H_8O_2$	76.11[9]	ℓ 1.0361 at 20°C[9]	nbp 189[9]	ℓ 485.7[34]		v 999.9[9]	H_2O, CO_2, CO
Calcium Chloride	$CaCl_2$	110.99[9]	c 2.15 at 25°C[9]	nmp 782[9] nbp >1600[9]	−795.8[34]	c 50.68 at 127°C [34]		
Potassium Acetate	$KC_2H_3O_2$	98.14[9]	c 1.57 at 25°C[9]	d 292[9]	−723.0[7]			$KHCO_3$, CO_2, H_2O, CO, KOH, KO_2

f = fusion ℓ = liquid c = crystalline or solid nmp = normal melting point
d = decomposes g = gas v = vaporization nbp = normal boiling point
*Superscripts in parentheses indicate the number of the reference from which the data were extracted, e.g., (9) = Ref. 9.

7-2.3.1.3 Surfactants and Foaming Agents

Some of the discussion of surfactants is given in subpar. 7-2.1.7.

When a fire involves a porous fuel, such as a fabric, the extinguishing effectiveness of water can be enhanced by the addition of trace quantities of a water-soluble surfactant (wetting agent). The normally high surface tension of water is thereby reduced substantially and allows increased penetration of the fuel mass. This "wet water" is normally used in fire situations in which the improved penetration allows water to reach remote or shielded regions within the fuel mass and/or promotes thorough soaking to provide improved extinguishment and cooling and thus prevent reignition.

7-2.3.1.4 Conduction of Electricity by Water

Previous efforts to quantify the conduction of electricity by water were intended to establish a safe distance from which firemen could project water without fear of electrocution (Ref. 10). Conduction in a water jet is a function of the diameter of the nozzle (which controls the diameter of the jet), the voltage of the electric source, whether the potential is between two conductors or from conductor to ground, the distance from the electric source to the fireman, and the impurities in the water. The form of the water is extremely important: A jet conducts electricity much more readily than a spray. The criterion used was the distance between the electrical source and the firefighter that was necessary to prevent 1 mA of current to flow. For example, with 115 V of alternating current (ac) potential to ground or a potential between two bare conductors of 230 V ac, a distance of 0.50 m (1.6 ft) is required for a 7-mm diameter nozzle, 1.00 m (3.3 ft) for a 18-mm diameter nozzle, or 2.00 m (6.6 ft) for a 30-mm diameter nozzle through which Seine River water was flowing, which had a specific electrical resistance of 360 Ω mm at 21°C (Ref. 52).

The specific electrical resistance of water varies from 10^7 Ω mm for highly purified water to 2 to 2.5 Ω mm for seawater. Potable water varies from 71 to 540 Ω mm. The current i that can flow through such a water jet path is

$$i = \frac{\pi d^2}{4} \cdot \frac{V}{\rho \cdot l}, \text{A} \qquad (7\text{-}12)$$

where

d = diameter of nozzle orifice, mm
V = voltage between conductor and earth, V
ρ = specific resistance of water, Ω mm,
l = distance between nozzle and conductor, mm.

When the water is in spray form, the current conducted by the spray is of the same order of magnitude as the leakage current because of ionization of the air surrounding the conductor (Ref. 52).

The relative electrical conductance of water with one mol of each of three salts can be obtained from data in Ref. 9. The three salts are sodium chloride (NaCl), the principal ingredient of seawater; calcium chloride ($CaCl_2$), a commonly used freeze point suppressant; and potassium acetate ($KC_2H_3O_2$), a freeze point suppressant that can meet the –54°C (–65°F) requirement. The ions released when these salts are in solution in water at 25°C and their equivalent conductances are Na^+, 50.9; Cl^-, 75.5; Ca^+, 120.0; K^+, 74.5; and, $C_2H_3O_2^-$, 48.0. From these ionic relative conductances, one mol of each salt in solution is: NaCl, 126.4; $CaCl_2$, 271.0; and $KC_2H_3O_2$, 122.5. A one-molar calcium chloride solution should have a little over twice the conductance of seawater, whereas a one-molar potassium acetate solution should have slightly less conductance than seawater.

Deposit of sufficient water in liquid form to bridge the gap between the conductors and the vehicle body would provide an electrical path, but such shorts should be handled by devices in the electrical circuits. In general, electrical power circuits that handle a high current flow are currently limited to 28 V dc, but in the future the voltage can be as high as 270 V dc in US combat vehicles. Circuits that have higher voltage, a maximum of 770 V in US combat-vehicles, have low amperages. Thus, the electrical systems in US combat vehicles should have little trouble if water mist were used as a fire extinguishant, even if freeze point suppressants were used also.

7-2.3.1.5 Use of Bulk Water

Bulk water is used to fight fires in US combat vehicles when local fire departments are available or when crew members pour water from water cans. Fire departments are not usually available in combat situations, but combat organizations often carry bulk water in supply vehicles. For example, the First Armored Division took water trucks to SWA to supplement the water trailers normally used (Ref. 70). Had emergency fire-fighting pumps, hoses, and nozzles been installed on those trucks, the FAASVs described in subpar. 7-1.2 that burned might have been saved. Installation of emergency fire-fighting pumps, hoses, and nozzles on bulk water carriers is recommended.

7-2.3.1.6 Use of Water Mist

In our technology-related society use of old-fashioned or simple items is highly suspect. This proposition is as true for fire extinguishers as it is for weapons or communications devices. Yet signal flags are part of the on-vehicle material (OVM), and bayonets are being issued to riflemen.

Both the knife and the flag have a use on the modern battlefield, and the Fort Hood crewmen (Ref. 71) had to pour water from a five-gallon can to extinguish a fire in the air filter of an M1 MBT, as described in subpar. 4-2.3.2. Water may be old-fashioned, but it is good for extinguishing fires. Also new ways can be found to use water. The objections to water are:

1. It freezes.
2. It conducts electricity.
3. It cannot extinguish a liquid pool fuel fire or a fireball.
4. It damages equipment.
5. It has to be cleaned up.

How valid are these objections? In 1977 Fielding, Williams, and Carhart (Ref. 72) suggested the use of water in mist form to extinguish fires in US nuclear submarines. They assumed that the electricity could be turned off in the fire area, and they calculated that water could cool fire temperatures of 1725°C to 1075°C, at which the flames would extinguish. They suggested that freshwater, as opposed to seawater, would not conduct electricity and would cause less damage to equipment, particularly in the form of a mist. They pointed out that the water mist was not toxic and would in fact remove smoke and toxic fire products from the air. (Nuclear submarines do not have a freeze problem.) They suggested that the submarine be made less susceptible to fire through identification of all flammable materials and their replacement as completely as possible with "firesafe" materials. They also suggested that a water mist fire-extinguishing system be developed for use in nuclear submarines. The US Navy started a program to develop this system.

In this Navy program water mist systems designed to blanket a compartment by spraying from the ceiling extinguished pan fires of hexane, diesel fuel, and lubricating oil (Ref. 73) as well as Class A fires of a stack of waxed paper milk cartons and other similarly difficult to extinguish Class A fires (Ref. 74).

A similar water mist system was suggested for commercial aircraft cabins to provide the passengers time to escape in the event of fire following a crash. Programs are being pursued in both the United Kingdom (UK) (Ref. 75) and the United States (Ref. 76) to demonstrate and evaluate this concept. In both efforts the washing of pollutants, such as hydrogen chloride (HCl), carbon monoxide (CO), particulates (primarily carbon), hydrogen cyanide (HCN), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), out of the air has been documented, as shown on Fig. 7-4 for carbon monoxide and Fig. 7-5 for HCl. The capability of water mist to remove contaminants from air is no surprise because "wet scrubbers" have long been used to remove particulates and SO_2 from smokestack smoke. Babcock and Wilcox (Ref. 78) state that wet scrubbers remove up to 99% of particulates and 85% of SO_2. What is surprising is that use of a water mist also reduces the amount of CO_2, as shown on Fig. 7-6, that infiltrates from a fire just outside into the cabin (Ref. 77). Researchers have established that soluble gases, e.g., HCl and SO_2, are readily absorbed by water sprays, that the concentration of gases having intermediate absorption rates, e.g., HCN and NO_2, can be reduced by water sprays of the proper droplet size and volume, and that gases with low absorption rates, e.g., CO and CO_2, are essentially unaffected by water sprays.

Research efforts in the UK established that the water mist droplet size is extremely important (Ref. 75). If the droplets are too large (≥200 μm), they do not absorb or adsorb the contaminants as effectively. If the droplets are too small (<5 μm), they cannot be filtered out by the normal human breathing apparatus, i.e., probably by the mucus that is secreted by the olfactory cells. These smaller droplets can carry dissolved or trapped pollutants into the lungs. Therefore, mist nozzles must be designed to produce droplets between these two sizes. Ball et al (Ref. 79) showed that nozzle design and pressure affect droplet size the most, as shown in Fig. 7-7, and that the flow rate of the water does not necessarily affect droplet size. In addition, they experimented with superheating and gas pressurizing to control

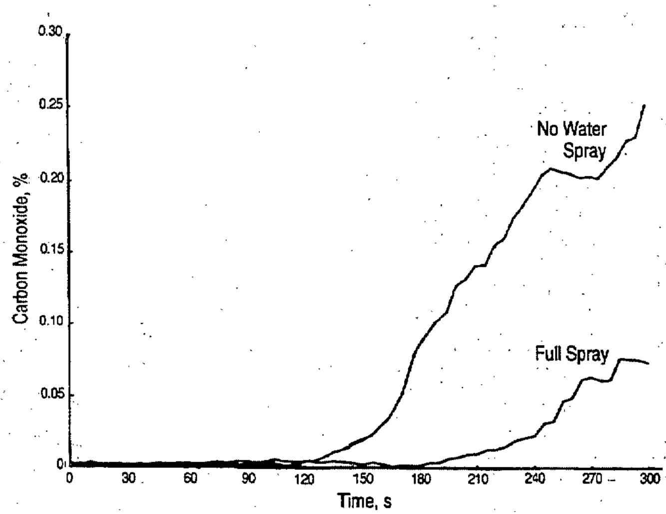


Figure 7-4. Difference in Carbon Monoxide Buildup Due to Water Mist Scrubbing (Ref. 77)

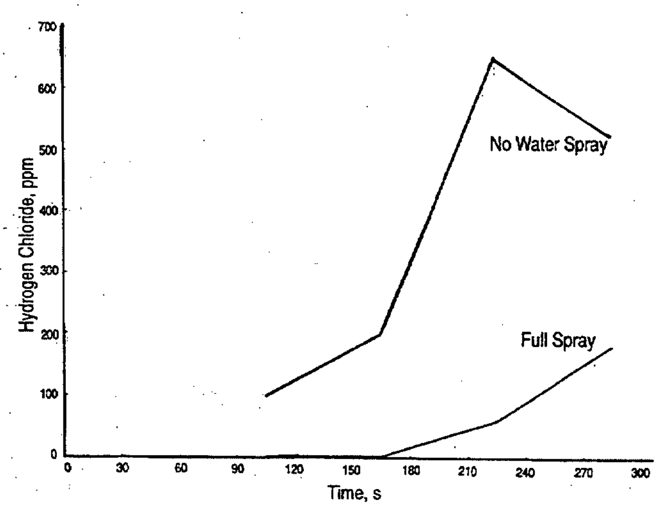


Figure 7-5. Difference in Hydrogen Chloride Buildup Due to Water Mist Scrubbing (Ref. 77)

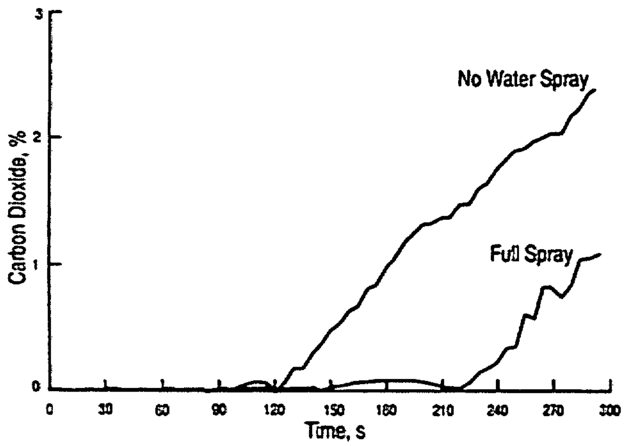


Figure 7-6. Difference in Carbon Dioxide Buildup Due to Water Mist Scrubbing (Ref. 77)

water droplet size. Superheating raises the temperature of the stored water prior to its flowing through the nozzle, and its effect upon droplet size is shown in Table 7-12. Although it effectively reduces water droplet size, superheating also reduces the capability of the water to absorb heat. Thus superheating is appropriate where quick blanketing of a space is desired but not where a fire is to be cooled in order to be extinguished. Pressurizing droplets by absorbed gas was also evaluated. Carbon dioxide dissolved in the water and stored at room temperature, 15°C (59°F) in this case, and at a pressure sufficient to keep the carbon dioxide in solution did not greatly affect droplet size, as shown in Table 7-13. More evaluation of water mist formation is necessary.

How effectively water mist reduces the air temperature in an aircraft cabin subjected to the effluents from an external JP-4 fire that is 18.3 m (60 ft) from the thermocouples was demonstrated by Marker (Ref. 77). Note on Fig. 7-8 that the air temperature was measured at a location 2.1 m (7 ft) above the deck and rose to approximately 165°C in 300 s in a test in which there was no water spray in the cabin but rose to only 58°C from 38°C in 300 s in a test in which there

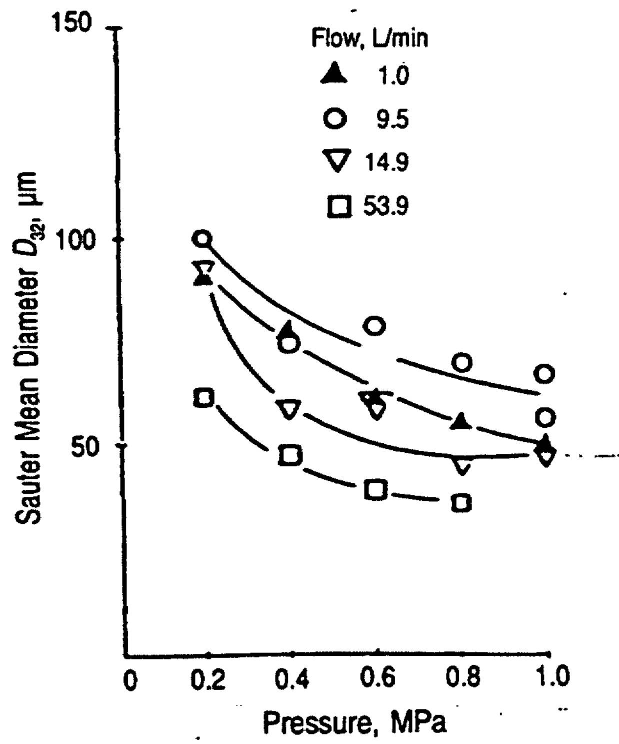


Figure 7-7. Effect of Water Pressure on Droplet Size for Various Flow Rates (Ref. 75)

was a full water spray within the cabin. There was no attempt to extinguish the fire—the intent was to lower the cabin temperature to enable people to escape from the fire. There were 324 nozzles mounted along the cabin.

Ball, Smith, and Spring (Ref. 75) and Smith (Ref. 79) demonstrated the capability of three different water spray nozzles that produce water mists of three different droplet sizes to reduce the temperature rise, as measured by twenty-eight thermocouples, within a test chamber in which there was a 457- by 457-mm (18- by 18-in.) Avtur (Jet A-1) fire. The tests were compared by summing the temperature increases for the 28 thermocouples from ambient temperature T_0 to a plateau temperature T_p. The summed excesses of

TABLE 7-12. EFFECT OF SUPERHEATING ON WATER DROPLET SIZE (Ref. 75)

RESERVOIR STORAGE				DROPLET SIZE D_{32}, Volume %	
TEMPERATURE		PRESSURE			
°C	(°F)	MPa	(psig)	< 10 µm	100-200 µm
15	(50)	2.00*	(290)*	1.5	52
150	(302)	0.50	(72.5)	46 ± 26	32 ± 8
180	(356)	1.00	(145)	31 ± 29	29 ± 10

*pressurized with GN_2

Notes: Equipment used was a 5-L suppressor with a 75-mm outlet valve.
Droplet size analyzer was 2 m from the outlet valve.

TABLE 7-13. EFFECT OF DISSOLVED CARBON DIOXIDE ON WATER DROPLET SIZE (Ref. 75)

AMOUNT OF CARBON DIOXIDE IN THE WATER, g/L	RESERVOIR STORAGE PRESSURE, MPa	(psig)	DROPLET SIZE D_{32}, µm
0	5.49	(791)	98 ± 11
200	5.49	(791)	89 ± 10
0	8.00	(1160)	76 ± 14
200	8.00	(1160)	73 ± 5
300	8.00	(1160)	81 ± 10

Notes: Pressurized with nitrogen
Equipment used was a 6-L suppressor with a 38-mm outlet valve.
Droplet size analyzer was 1 m from the outlet valve.

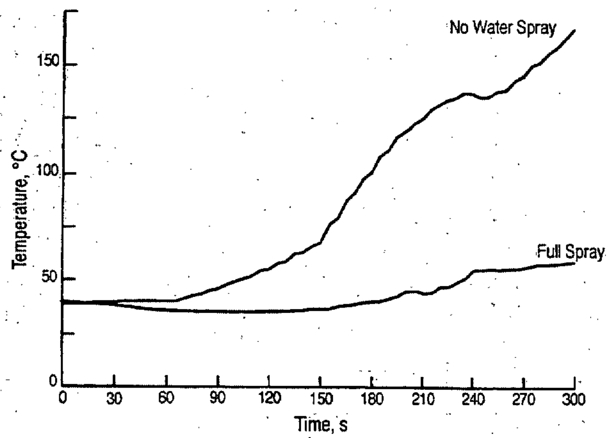


Figure 7-8. Temperature Increase With and Without Water Mist (Ref. 77)

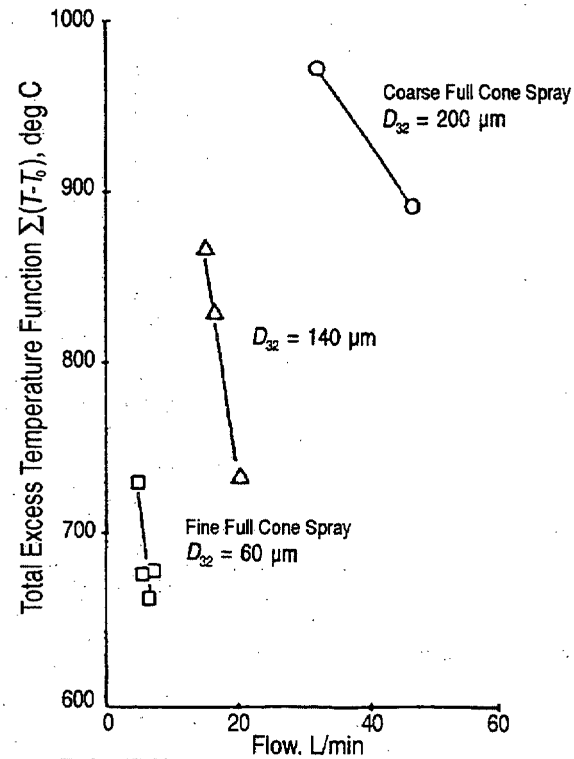


Figure 7-9. Effect of Water Flow Rate on Heat Absorption (Ref. 75)

temperatures above ambient are referred to as the total excess temperature function $\Sigma(T_p - T_0)$. The total excess temperature function was approximately 1300 deg C without any water spray. Note on Fig. 7-9 that a full cone spray of coarse droplets (D_{32}-200 µm) caused the total chamber excess temperature function to be approximately 970 deg C at a water flow rate of approximately 31 L/min and approximately 890 deg C at a water flow rate of approximately 47 L/min. Similarly, with a full cone spray of fine droplets (D_{32} = 60 µm), the total chamber excess temperature function was approximately 725 deg C at a water flow rate of 4 L/min or approximately 665 deg C at a water flow rate of approximately 7 L/min. The water mist in this program was designed to reduce the chamber temperature, not to extinguish the fire. These efforts were for a system that would maintain a habitable condition within an aircraft cabin until passengers could evacuate.

A different use of a fine water spray was developed by other researchers. Papavergos (Ref. 80) modeled a fine water spray system to replace a Halon 1301 system used to extinguish well head (gas flare) fires as well as pool fires and shuttle (Channel Tunnel) fires. Several practical fire suppression situations were examined, and fixed water spray systems were designed and verified experimentally in a scaled test fixture. Papavergos concluded (1) that water sprays have the ability to extinguish liquid fuel fires, (2) that this extinguishment is accompanied by enhancement of the environment through smoke scrubbing, effective cooling, and absorption of water-soluble acid gases, (3) that the quantities of water used were significantly less than those used by a conventional water deluge (Thus the concerns of water damage were also reduced.) and an order of magnitude less than the quantity a similar Halon system would use, and (4) that the fine water spray system offers substantial cooling of the surrounding solid materials, whereas Halon 1301 does not.

While reevaluating the objections to a water fire-extinguishing system presented at the beginning of this subparagraph, the reader will find the following:

1. Water will freeze, but just how cold will the interior of a combat vehicle be allowed to become? Antifreeze can be used in the water, as described in subpar. 7-2.3.1.2.

2. Freshwater is not an effective conductor of electricity. A high-amperage electric current cannot flow from its normal circuit without quickly destroying the shorted circuit; therefore, such circuits are equipped with circuit breakers. A high-voltage electric circuit has to be

contained to prevent arcing through normal atmospheric contaminants; this containment is already done in the electronic components of combat vehicles. Combat vehicles use a low voltage, 28 V dc or 77 V dc, for circuits that use high amperage. Even if a freezing point suppressant were used that could lower the electrical resistance of water almost to that of seawater, a water mist would not pass enough current to endanger a crewman spraying a fire. Ballistic damage has a high probability of rendering electric components inoperable, and most electric subsystems must be encased in sealed enclosures anyway. Any problems presented by the use of a water spray, which in many ways is no worse than a high-humidity smog, are solved either by the normal packaging requirements of the electrical components or by improved circuit breakers, or their equivalent.

3. Water mist systems can extinguish liquid fuel fires and fireballs.

4. A water mist without additives will not damage equipment within a combat vehicle any more than normal environmental moisture would.

5. Water from a mist extinguisher would not require any more cleaning up than rain or snow inside a combat vehicle would. Water, in liquid form, would collect in the bilge of the vehicle and could be drained overboard.

In addition, when effective passive fire suppression techniques are used in a combat vehicle, there should be no fires that water, in mist or spray form, cannot extinguish.

7-2.3.2 Alumina Powder

Powdered aluminum oxide (Al_2O_3), alumina, is the extinguishant of choice for use in military aircraft. Alumina was selected because it is chemically inert, whereas potassium bicarbonate is slightly acidic and monoammonium phosphate is slightly basic. Alumina has a specific gravity of 3.97, a hardness of 9 mohs, and other properties that are listed in Table 7-4. The heat-absorbing capability of alumina over the temperature range that concerns armored vehicle designers is due to its solid-state energy-absorbing ability when used as a fine dust. By using Eq. 7-1 and the values in Table 7-4 for C_p at 25°C and 127°C, the heat-absorbing capability of 1 kg of aluminum oxide, when heated from 21°C to 177°C, is determined to be 134 kJ. No diluents would be released, but there would be a problem of cleaning up the alumina afterward.

7-2.3.3 Perfluorinated Carbon Compounds

Volatile perfluorinated compounds (fluorocarbons) are assigned to the cooling agent class because their dominant extinguishing mechanism appears to be reducing flame temperatures to the point of flame extinction via increased heat capacity effects. The volatile fluorocarbons appear to be physiologically inert and when mixed with oxygen will support life, i.e., provide habitable atmospheres but will not support combustion (Ref. 61). As is true of the halons, however, their pyrolysis products are potentially toxic. It was concluded that the use of fluorocarbons as extinguishants would not be feasible (Ref. 61), but with the pending elimination of halons, these compounds are being reevaluated. PFC 410™, for example, has Environmental Protection Agency (EPA) approval (Refs. 14 and 17). Due to the long atmospheric lifetimes of PFCs, however, their use is limited to applications in which no other solution exists.

7-2.3.4 Other

The use of aqueous diammonium phosphate as an extinguishant has been proposed and studied. Apparently, this agent produces a residue that functions as a fireproof barrier (Ref. 26).

Monoammonium phosphate ($NH_4{\cdot}H_2PO_4$, referred to as MAP) powder is effective on Class C as well as Class A and Class B fires. It is referred to as the ABC powder because it can be used on all three types of fires (Ref. 26). If 1 kg of pulverized MAP at 21°C were injected into a space containing air at 177°C, heating the MAP to 177°C would take 193 kJ of heat. If MAP were heated to 190°C, it would decompose following the process $4NH_4{\cdot}H_2PO_4 + Q_c \rightarrow 4NH_3 + 6H_2O + P_4O_{10}$ and would emit 148 g of ammonia (NH_3) and 617 g of phosphorous pentoxide (P_4O_{10}). The ammonia can explode in air, is corrosive, and is toxic to breathe, and P_4O_{10} is an irritant to skin, mucous membranes, and eyes (Ref. 31).

7-2.4 EXTINGUISHANTS FOR COMBUSTIBLE METALS FIRES

Combustible metals that may be used in combat vehicles include magnesium, lithium, aluminum, titanium, and uranium. There are other metals that can burn, such as sodium and potassium, but they are not normally used in combat vehicles. Aluminum, titanium, and uranium usually will not burn in solid form in air without added heat unless they are powder. Magnesium and predominantly magnesium alloys can generate sufficient heat to sustain combustion in air. These have been considered for road wheels for combat vehicles. Lithium, which can generate sufficient heat to sustain combustion, may be used in some of the newer electric batteries for combat vehicle systems. Fire extinguishants for both magnesium and lithium have special requirements. Most currently available fire extinguishants recommended for extinguishing magnesium fires will not adhere to a vertical surface. The effectiveness of Navy 125S® (Ref. 81) to extinguish a lithium fire has been verified in tests. Navy 125S® has also been checked to extinguish fires of magnesium, sodium, potassium, titanium, and aluminum and is apparently equally effective in extinguishing fires of these materials. Navy 125S® is a copper powder that melts when exposed to the metal fire and forms a noncombustible alloy with the melted combustible metal. This alloy covers the surface of the base metal and extinguishes the fire. This process does not produce noxious products.

7-3 EXTINGUISHERS

The prime requirement for a fire-extinguishing or suppression system is that it effectively extinguish and/or suppress the fires that can occur within a combat vehicle. Active and passive fire-extinguishing systems are covered in this handbook. Handheld extinguishers are also discussed. Many fire extinguisher systems dispense fluids that reduce the percentage of atmospheric oxygen present or interrupt the combustion reaction chemically and thus prevent or at least reduce the probability of reignition by either ignition sources already present or ignition sources resulting from additional ballistic impacts. The period of time this reignition preventative is present is a function of the type of extinguishant used as well as the airflow through the compartment.

7-3.1 ACTIVE SYSTEMS

The system used in the crew compartment to counter a threat-induced mobility fuel mist or hydraulic fluid mist fire must react and function in milliseconds to prevent burns to crew members; therefore, such a system must be automatic. Fast response of an extinguisher system is not only dependent on fast detection of the initial fire but also on the fast release of the extinguishing agent. The majority of fire-extinguishing systems found in combat vehicles consist of either an optical or thermal fire detection system, a control electronics package, and a suppressant distribution system. Fig. 7-10 shows the fire-extinguishing system used in the amphibious assault vehicle (AAV) (personnel) Model AAV 7A1 (Ref. 82) as well as the locations of the fuel storage and engine. This particular system uses optical fire detectors to sense the fire and a fire extinguishant distribution system consisting of three bottles that project the extinguishant (Halon 1301) into the troop compartment. One of these bottles distributes the agent through a unique discharge tube that is directed aft along the starboard side of the crew compartment, as shown in Fig. 7-11.

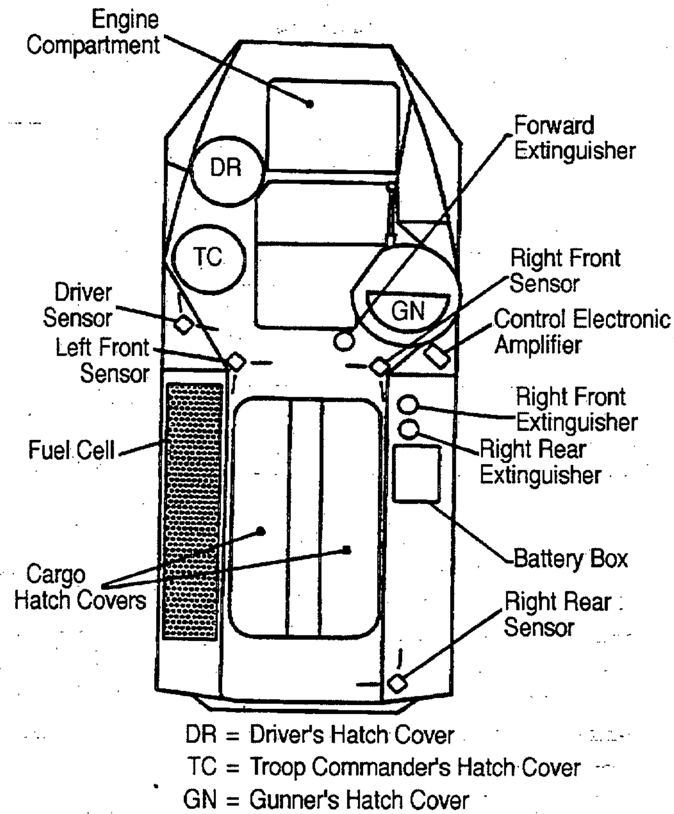


Figure 7-10. AAV 7A1 Automatic Fire Sensing and Suppression System (Ref. 82)

In typical applications the distribution system consists of one or more storage bottles of extinguishing agent (depen-

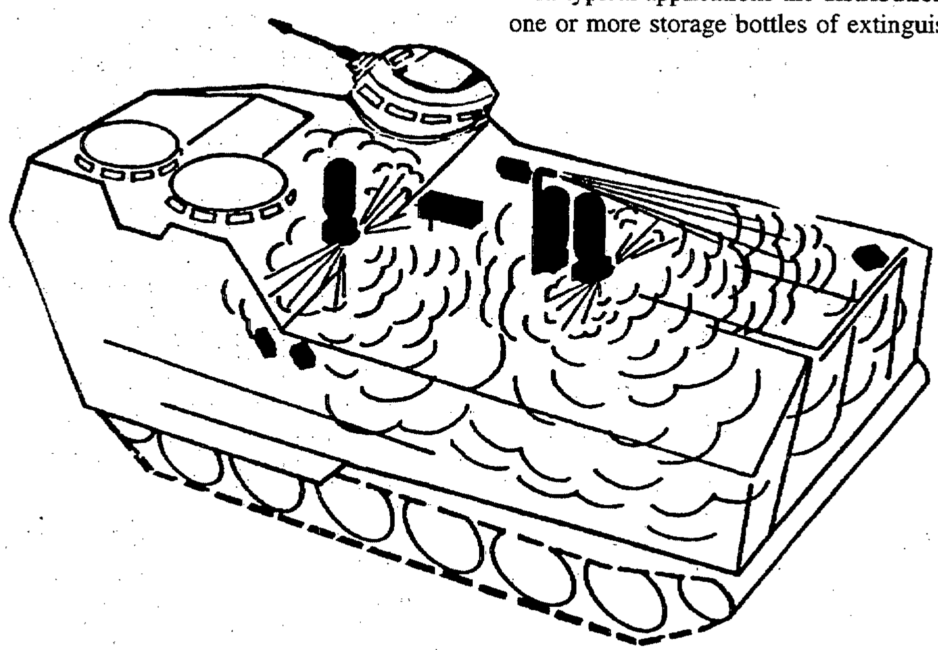


Figure 7-11. AAV 7A1 Halon Dispersement

dent on system requirements) and a distribution piping network that applies the extinguishant at strategic locations. The effectiveness of the system is highly dependent on the response speed of the quick-release valves, which can be of several types and designs including solenoid and squib valves. In this paragraph the various active fire-extinguishing systems are introduced including single and multiple container systems, single-outlet systems and multiple-outlet systems. Typical fire extinguisher component and system configurations found in current combat vehicles are presented in par. 7-5.

Courtesy of HTL/Kin-Tech Division, Pacific Scientific, Duarte, CA.

Figure 7-12. Typical Solenoid Valve and Bottle Assembly

7-3.1.1 Fast-Acting Valves

Fast-acting valves such as solenoid and squib valves are used in fire-extinguishing systems. Brief descriptions of each type are presented including descriptions of the ancillary equipment, valving and piping. Operational details are also presented. A typical solenoid valve and bottle assembly is shown on Fig. 7-12.

7-3.1.1.1 Solenoid

A solenoid valve uses an electrical coil that moves a core to open the valve port(s). The solenoid-actuated valve is most commonly used in fire-extinguishing systems because of its quick response and capability for reuse. One type of solenoid valve, shown in Fig. 7-13, consists of a cylindrical plunger with redundant elastomeric seals that holds pressure and seals an agent storage bottle port. The plunger is locked in place using a mechanical latching system. To operate the valve, the solenoid coil is activated; the coil pulls the ring off the lock mechanism and thereby allows the plunger to be

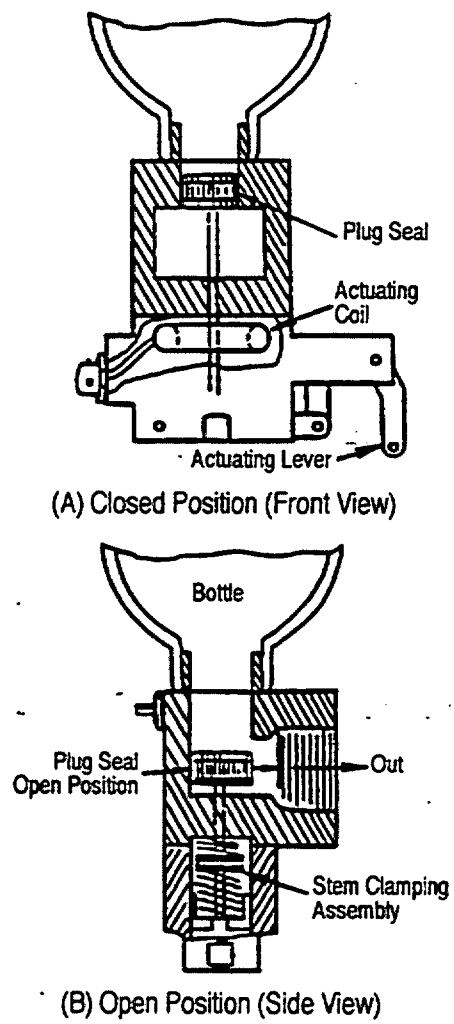
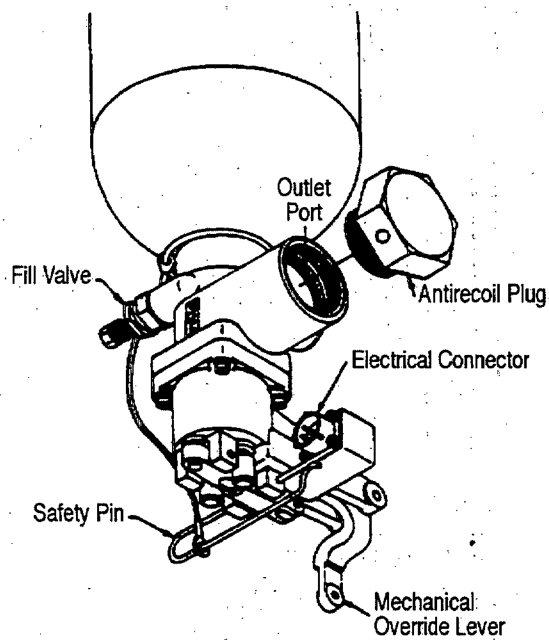


Figure 7-13. Solenoid Valve Schematic (Ref. 82)

pushed down by the bottle pressure to release the extinguishing agent. The particular valve shown in Figs. 7-13 and 7-14 has a valve response time of less than 10 ms. This valve design also has a manual release lever to allow manual backup activation by the crew if the automatic actuation of the fire-extinguishing system should fail or vehicle power not be available. The valve has been tested at vehicle temperature extremes of –54 to 71°C (–65 to 160°F) with little degradation in the response times.



Courtesy of Marotta Scientific Controls, Inc., Montville, NJ.

Figure 7-14. Marotta Scientific Controls, Inc., Valve With Mechanical Override

7-3.1.1.2 Squib

A squib valve uses some type of explosive squib or charge to open the valve. Squib valves are not resettable and often are not reusable. One type of squib valve that is used in vehicle fire-extinguishing systems is the protractor valve, which is shown schematically in Fig. 7-15. This valve has a diaphragm seal that closes off the bottle opening and is supported by a trapdoor. A small explosive charge referred to as the "protractor" is contained within the package and, when activated, physically pushes a pin to unlatch the trapdoor. Once the trapdoor has been moved, the bottle pressure tears open the unsupported, prescored rupture disk or diaphragm. This particular design uses nonfragmenting rupture disks and protractor and thus prevents any fragments from discharging with the extinguisher agent. The metal-to-metal seal provided by this valve design virtually ensures a leakproof system while in storage, yet valve response times are approximately 3.1 ms. This valve design also has a manual release lever built into the valve to allow manual backup activation.

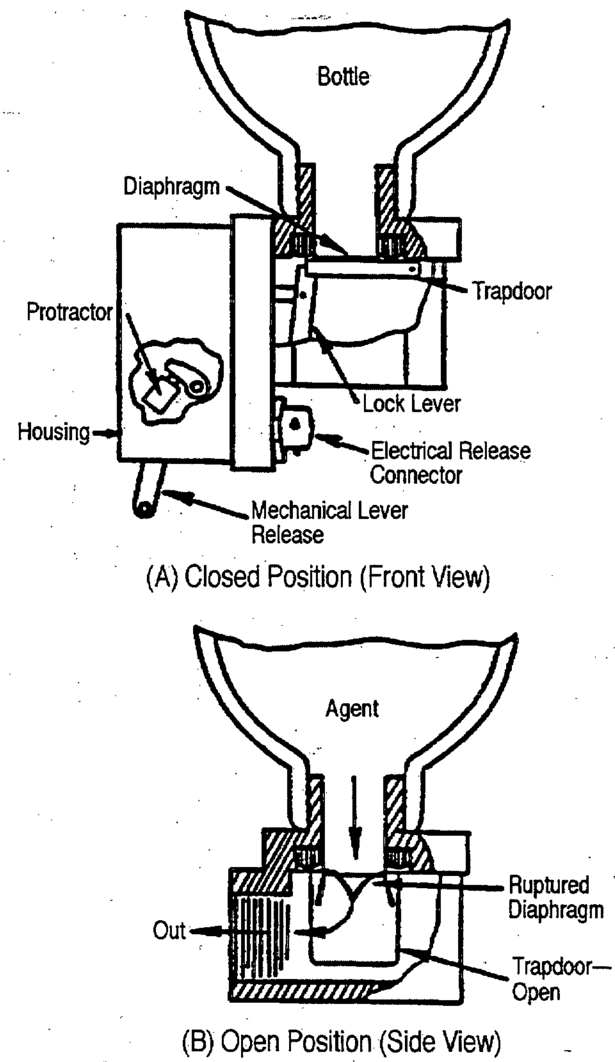
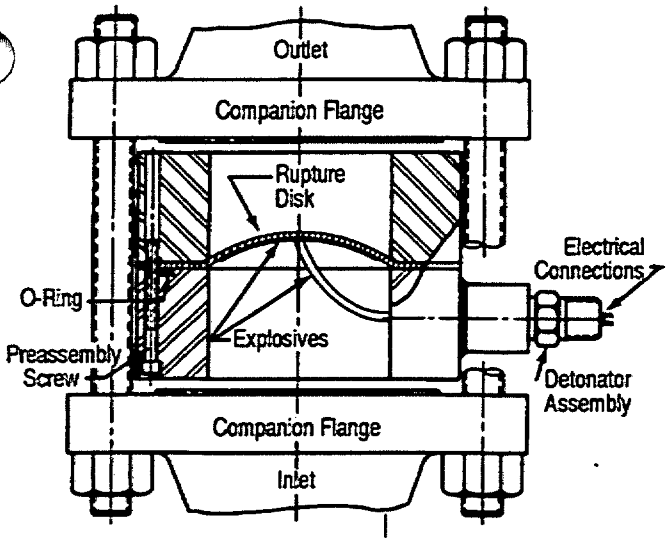


Figure 7-15. Protractor Valve Schematic (Ref. 82)

A second type of squib valve that is used in quick-release situations is the explosive-actuated deluge valve shown on Fig. 7-16. This valve uses a prescored rupture disk, a specially designed explosive charge fixed to the rupture disk, and a detonator assembly. The valve is attached to the extinguishing agent bottle or source and the rupture disk is used to seal the port. When it senses a fire, the electronic control sends a signal to the detonator assembly, which actuates the squib. The explosive charge forces the rupture disk to fail and thus allows the extinguishing agent to flow into the distribution network.

The Russians use a squib to drive a sharp, hollow punch through a diaphragm to start the flow of extinguishant into a distribution manifold; the system in which this valve is used is described in subpar. 7-5.1.3.4.1.

The decision to use a single explosive-actuated valve to supply an extinguishing agent manifold or smaller, individual systems, each with an individual squib valve, has to be



Fike Metal Products, Division Fike Corporation, 704 South 10th Street, Blue Springs, MO 64013, Technical Brochure Catalogue No. 7387-5, Copyright 1992.

Figure 7-16. A10 Series Deluge Valve (Ref. 83)

made based on a number of factors such as system effectiveness, logistics, system survivability, and cost in dollars, space, and weight penalties. Use of a single valve supplying a manifold is the most economic approach from a standpoint of dollar cost and weight savings. From a survivability standpoint, however, the single-valve system is very vulnerable and in danger of not functioning. If the valve fails to open due to an equipment failure or a projectile hit, a catastrophic fire could occur. The smaller, individual systems provide a higher level of survivability because if one system is lost for whatever reason, the remaining systems will still be operational and will release the extinguishing agent given a signal from the controller.

7-3.1.2 Manual Valves

Mechanically actuated valves are used in manual fixed fire-extinguishing systems or as manual overrides in automatic fire-extinguishing systems. The bottle and valve assembly shown in Fig. 7-13 has a mechanical lever that allows a crewman to pull a lanyard to actuate the valve manually should the automatic system fail to operate or electrical power not be available.

7-3.1.3 Other Valves

In addition to the distribution valves (solenoid, squib, or manual), there are a number of other valves and fittings that are incorporated into a fire-extinguishing system. The agent storage bottles are normally fitted with a fill valve for recharging. Many bottle designs are equipped with a pressure relief valve that will open and vent should the pressure in the bottle exceed a preset limit. These types of relief valves will reseat and make a complete seal. Thus they maintain pressure at an acceptable level. Another type of relief device is a rupture diaphragm that will fail at a certain pressure and release the entire contents of the bottle. These disks are normally designed to be replaceable. The valves used on US Army ground vehicles use the rupture disk approach.

7-3.1.4 Bottles

Fire-extinguishing systems for combat vehicles use high-pressure bottles to store the agent. These storage bottles have a quick-response valve to release the agent. Typically, the storage bottles are Department of Transportation (DOT) 3A or 3AA1800 nonshatterable steel bottles (Ref. 84), as shown in Fig. 7-12. The number and size of bottles used in an extinguishing system vary based on application rates, size of the fire expected, the compartment volume, vehicle weight and space limitations, and the criticality of the area being protected, i.e., the more critical the compartment, the higher the level of protection required.

Use of multiple agent bottles is a valuable system survivability factor. If the system has only a single bottle and that bottle is disabled by a projectile hit or by a component malfunction such as a valve failure, the entire extinguishing system becomes inoperative. With multiple bottles the system would still provide fire protection with extinguishant from the remaining bottle(s). Current fire-extinguishing systems are designed using multiple bottles of agent, and the control electronics are designed to check the continuity and pressure of the bottles of agent systematically. The system may include a pressure switch to monitor the pressure of the agent. When the pressure in the bottle is low because a previous activation or a leak has left it empty, the controller selects an alternate bottle.

7-3.1.5 Linear Fire Extinguishers

The US Air Force (USAF) has sponsored the development of linear fire extinguishers for use in aircraft void spaces (Ref. 85). These extinguishers are basically a tube filled with an extinguishant and either a linear explosive charge to rupture the tube and disperse the extinguishant or a small charge to pressurize the tube and force the extinguishant out a series of nozzles. One extinguishant used is water containing calcium chloride as a freeze point suppressant; however, liquid, gas, or powder can be used. These devices have performed successfully in tests. (See subpar. 7-5.2.6 for more information on these devices.)

A similar device was tested at Ballistic Research Laboratory (BRL) to suppress combustion of exposed grains of M30 solid gun propellant (Ref. 86). The tests performed were preliminary in nature, and water was used but without a freeze point suppressant. The extinguisher consisted of a plastic container filled with water containing an AFFF agent, 15 to 25% by volume, with an immersed linear explosive, Primacord®*. The water-foaming agent solution was dispersed extremely quickly by the explosive charge—

*Product of Ensign-Bickford Company, Simsbury, CT.

the extinguishant travelled 1 m in 6 ms in one test and 2 m in 34 ms in a second test. This technique extinguishes a fire of exposed propellant grains very effectively as long as the aqueous solution is delivered quickly. Finnerty hypothesized that delivery was so fast that the water reached the propellant and extracted heat directly from the grains; the water was not vaporized by the hot products of combustion.

The program described in Ref. 86 should not be confused with the program described in Ref. 87, in which the extinguishant was dispersed by the shaped-charge jet or a third program described in Ref. 88, in which the fire extinguishant was sprayed onto the burning propellant. In neither of the latter programs was the fire extinguished, although the violence of the combustion was somewhat reduced.

7-3.2 PASSIVE SYSTEMS

Passive fire extinguisher systems do not require an electric and/or mechanical controller or a human operator to activate them. In general, passive systems are either threat or fire activated. These systems include design features that inhibit the ignition or propagation of fires and remove combustibles or ignition sources from critical or susceptible regions by relocation or compartmentalization.

Threat-activated passive systems include powdered fire extinguishant layers, double-walled fuel cells, and water-gel subsystems. In World War II the "wet Shermans" had double-walled ammunition racks that contained a mixture of water and glycerine to mitigate the fires that ignited when the ammunition was hit (Ref. 89). These passive systems function when the threat, either the jet of a shaped charge or the penetrator of a kinetic energy projectile, perforates the passive system and causes the stored fire extinguishant to disperse.

Other types of passive fire protection systems reduce the transfer of heat from a fire (intumescent paints or coatings), reduce the probability of combustibles meeting ignition sources, reduce the ignitability of combustibles, and/or provide safe collection locations for combustible fluids. Several of these systems provide compartments in which combustion can occur without causing critical damage.

The best passive means by which to reduce the damage from a fire if a hit passes through or affects munitions or mobility fuel are to design and/or locate the munition magazine so that explosions therein will not affect the vehicle or crew (described in par. 4-6), to locate and/or design the fuel cells so that there will be no fuel fires within critical compartments (described in par. 4-3), and to use ancillary power systems that do not include the hazards of the current hydraulic fluid systems (described in par. 4-4).

7-3.2.1 Hazardous Materials Stowage

Vehicle design features can provide passive protection from hits by kinetic energy (KE) projectiles or shaped charges. The three most hazardous items carried in combat vehicles are the munitions, mobility fuel, and hydraulic fluid. The munitions and mobility fuel can be rendered nonhazardous to personnel and critical equipment by relocating the fuel cells or magazines and by redesigning their compartments and/or containers. There are several methods that can be used to render hydraulic fluid nonhazardous.

7-3.2.1.1 Munitions Stowage

The most probable source of fire and/or explosion from munitions is the solid propellant used to launch the larger projectiles by either gun or rocket motor. Somewhat less hazardous is the high-explosive warhead, which may not detonate upon projectile impact. Incendiary fillers, such as triethylaluminum (TEA), and some chemical munitions, such as white phosphorus smoke, are hazardous. These munitions become less hazardous when they are stowed in magazines with blowout panels that direct the products of explosion or combustion away from critical vehicle compartments such as the crew compartment. This redirection of the products of explosion has been accomplished on the M1 series main battle tanks, as shown on Fig. 4-29 and described in subpar. 4-6.2.2.2. The bulk of the main gun ammunition in these MBTs is carried in a bustle magazine that is separated from the crew compartment by explosion-resistant doors that are normally closed. This bustle compartment has blow-away panels that vent the products of explosion of the munitions outward to the atmosphere. A small number of main gun rounds are carried in a hull compartment similarly equipped with a compartmentalizing door and a blow-away panel that vents into the engine compartment. There are provisions within the crew compartment for only three rounds in the M1 or two in the M1A1. These are low in the vehicle below the gun breech in a location that is not likely to be hit when the vehicle is in hull defilade, and for the 120-mm-gunned M1A1 and M1A2 crewmen are instructed to place KE cartridges, but not high-explosive antitank (HEAT) cartridges, in this ready rack. (See subpar. 4-6.4.1 for a detailed discussion of ammunition stowage.)

Another vehicle that demonstrated this type of munitions stowage design was the Advanced Survivability Test Bed (ASTB) vehicle (Ref. 90), which is discussed in subpar. 7-5.1.1.5. For this vehicle the most hazardous munitions were the tube-launched, optically tracked, wire-guided (TOW) missiles. Missiles not in the launchers were stowed either in a magazine over the left rear sponson or in the rear of the vehicle bilge as shown on Fig. 4-32(A). The 25-mm cartridges were stowed in antifratricide trays, and most were used as an additional buffer between the TOWs and the troop compartment, as illustrated on Fig. 4-32(B).

A possible means to reduce the explosive effects within magazines was demonstrated by Finnerty (Ref. 86). He explored the use of explosively launched fire extinguishant to reduce the combustion of exposed propellant grains. This could be adapted to prevent fire propagation among combustible cased cartridges. Another means, devised by Ball

(Ref. 55), is to inject water into specific cartridge cases. Both of these techniques, however, require much more development. A third means is to combine the antifratricide intumescent cylinders tested by Mescall and Macione (Ref. 91) (The intumescent cylinders must be supported by metal cylinders as described by Cox (Ref. 92).), and the hinged rear of the magazine described by Walker (Ref. 93) to obtain a secure propellant or cartridge stowage area. Subpar. 7-6.4 describes some additional innovations in ammunition stowage.

If a flamethrower is mounted on a combat vehicle, means other than pressurized bottles of gelled fuel should be used to project the liquid incendiary. The flamethrower shown on Fig. 4-34 used a turbine-powered pump to project the liquid incendiary. Such a flamethrower presents a much smaller hazard to the vehicle and occupants than the pressurized metal bottles used previously by the US Armed Forces (described in subpar. 4-6.2.2.4).

7-3.2.1.2 Mobility Fuel Storage

Mobility fuel is carried in metallic, plastic, or composite fuel cells. Threats that penetrate combat vehicles are shaped-charge jets or massive KE penetrators and cause severe damage; therefore, self-sealing fuel cells have been ineffective and have not been used in US ground combat vehicles. Further, because the effects of the threat would probably result in cored perforations in fuel cell walls, aircraft-type self-sealing cells of conventional construction would not prevent fuel loss in combat vehicles.

In most current US combat vehicles, e.g., the M1 and M1A1 MBTs, the BFVs, most of the M113 APCs, and the M60 MBTs, the fuel cells are within either the crew or engine compartment. In the M113A3, as shown on Fig. 4-2, and the ASTB vehicle, the main fuel cells were mounted on the rear in external fuel cells.

The M113A3 external fuel cells were tested using either shaped charges or 14.5-mm API projectiles (Ref. 94). A 51-mm (2-in.) thick spacer was used between the fuel cell and the hull in the 14.5-mm API tests, but no spacer was used in the shaped-charge tests. In the two shaped-charge tests in which the jet traveled through the fuel and then entered the troop compartment, fuel did not flow into the troop compartment because the shaped-charge slugs plugged the holes in the hull, as shown in Fig. 4-41.

The ASTB external fuel cells were similar to those of the M113A3, Fig. 4-2, but these fuel cells were more fully tested (Ref. 95). In only three of the 27 tests described in Refs. 94 and 95, did the slug interfere with fuel flow from the fuel cell into the troop compartment. Thus the slug cannot be depended upon to prevent fuel flow into the vehicle from an external fuel cell. In these tests a 76-mm (3-in.) thick, gravel-filled barrier was necessary to eliminate fuel flow into the troop compartment after shaped charge perforation. (Thinner barriers, i.e. 50.8 mm (2 in.) thick, were not as effective.)

In the BFVs the largest presented area of the main fuel cell is on the hull bottom. This could leave a large area vulnerable to land mines projecting a jet or flyer plate upward. In tests of the Landing Vehicle, Tracked, Personnel (LVTP) 5A1, fuel cells between the hull and the deck were susceptible to perforation by such a threat (Ref. 96). The deck plates above these cells should be firmly secured to prevent personnel injury; the potential for injury caused by loose deck plates is described in subpar. 5-2.2.3.1 (Ref. 97).

Another technique used to render fuel cells less hazardous is to install a double-walled fuel cell with a fire extinguishant within the hollow wall. This technique is described in subpar. 7-3.2.3 and Ref. 98.

Another source of mobility fuel in the crew compartment is the hydrocarbon-fuel-fired troop compartment heater that is currently used. This heater is described in subpar. 4-8.2.3 as being inappropriate for use in the troop compartment. Tests of the automatic fire-extinguishing system (AFES) for the M60A3 (Ref. 99) indicated that the currently used troop compartment heater could be a hazard because it can rupture when impacted by a penetrator or fragments and thus introduce a combustible fluid, e.g., DF-2, into the crew compartment. A different source of troop compartment heat should be used or the current heater should be placed in a separate compartment.

7-3.2.1.3 Hydraulic Fluid Systems

Hydraulic fluid power systems are hazardous because they generally contain a flammable fluid in pressurized containers or lines, i.e., fluid sprayed from a ruptured line can produce a flammable mist. If a hydraulic fluid container is metallic, rupture of the container can be violent and can produce not only a mist or spray but also metallic fragments, which can be hazardous secondary projectiles. Tests of the AFES for the M60A3 (Ref. 99) indicate that the presence of a hydraulic reservoir and accumulator in the crew compartment, even when filled with fire-resistant hydraulic fluid MIL-H-46170, can be a hazard because once again a combustible fluid is introduced into a sensitive compartment. In many of these tests the reservoirs shattered or cracked until reservoirs of a less crack-sensitive material were used.

There are several ways to reduce these hazards. Finnerty (Ref. 100) successfully surrounded a fluid-filled reservoir with a mild steel box (to stop the fragments) and a powdered-extinguishant-filled honeycomb panel (to extinguish the mist fire) to reduce the hazards. Another technique is to use a truly noncombustible hydraulic fluid, such as MIL-H-53119, which can be quite expensive, or a water-based hydraulic fluid that does not use a combustible freeze point suppressant.

Because most of these high-pressure reservoirs are made of high-strength materials that are crack sensitive, an overwhelming threat will rupture a fluid container. A smaller threat, however, should not cause damage beyond the area perforated. Use of noncrack-sensitive materials or constructions in this application is recommended. Fluid container fragmentation caused by small projectiles can be eliminated by use of a filament-wound container. Filament-wound fuel cells have proved to be crack resistant, as demonstrated in Refs. 101 and 102. In the programs described in these two references, as well as in several other test programs, filament-wound fuel cells containing hydrocarbon mobility fuel or water consistently withstood hydraulic ram pressure loads caused by fully tumbled 14.5-mm bullet impacts at velocities of approximately 960 m/s (3149 ft/s) and suffered only the entrance wound, which was approximately bullet size; steel drums of 208 L (55 gal) capacity under the same conditions were torn wide open. In the B-1 aircraft program Artz (Ref. 103) fired a caliber .30 armor-piercing (AP) bullet through a filament-wound pressure bottle pressurized with nitrogen to 9.38 MPa (1360 psig) to establish whether or not the bottle would explode; it did not. Again, the damage to the bottle was restricted to the bullet-sized punctures.

Another technique to reduce the hazard from hydraulic fluid is to use an electric motor to rotate the turret or open the troop compartment door. There is at least one incident in the USASC database, however, in which the power cable for an M2 Bradley was not reinstalled properly after some vehicle maintenance, the insulation abraded, and an electrical short produced a fire. Therefore, a change to electric actuation is a change to a different hazard. If there is a change, the electric system must contain circuit breakers, or the equivalent, to preclude damage from hazardous shorts.

Another way to eliminate these hazards is to use pneumatic actuation. In the late 1950s The Marquardt Company developed pneumatic control systems for some applications in which nuclear radiation precluded use of electric or hydraulic power, as described in subpar. 4-4.1.2 and Ref. 104. One of the subsystems described is a pneumatic temperature sensor and a pneumatic actuator that controlled the metering of fuel through a regulator to maintain a constant temperature at the inlet to a turbine engine. A second pneumatic temperature sensor and actuator interacted with the fuel regulator to account for differences in the engine inlet air temperature. The pneumatic actuators developed were larger than hydraulic actuators for the same application and they were not spongy in operation. Also rotary pneumatic motors could be used. Pneumatic systems have not really been developed because hydraulic systems are better known and commonly used for high-power applications.

7-3.2.2 Powdered Fire Extinguishant Layer

Powdered-fire-extinguishant-filled panels were developed for use in small naval craft by Ciba-Geigy. This panel has the trade name Fire-Lam™ and is referred to as a powder pack. A version was tested for aircraft application by the Engineering Physics Department of the Royal Aircraft Establishment (RAE) (Ref. 105). As shown in Fig. 7-17, Russian 23-mm armor-piercing incendiary tracer (APIT) projectiles were fired through the leading edge of a simulated aircraft wing made of 6 SWG L 70 light alloy (English Number 6 Standard Wire Gauge is 4.9 mm (0.192 in.) thick; L 70 is an aluminum alloy), through an array of three 51-mm (2-in.) outside diameter (OD) aluminum fuel pipes, and into a fuel cell containing Avtur (English equivalent of Jet A-1) fuel at a temperature of 14°C (57°F). The APIT projectile was activated by the leading edge cover so that the fuel pipes and front face of the fuel cell would be exposed to a cloud of burning incendiary particles. (It was established that the incendiary particles and fuel from the pipes and/or cell would merge to produce a fire within 8 ms.) Upon impact with the simulated aircraft wing, the APIT projectile was relatively intact, the projectile windshield was in pieces, and spall was present; thus all of these could impact the pipes and the Fire-Lam™ panel. The fuel pipes were empty in Test 1, filled with unpressurized Avtur in Tests 2 and 3, and filled with Avtur pressurized to 138 kPa (20 psig) in Test 4. The impacted face of the fuel cell was a self-sealing construction made to withstand 12.7-mm projectiles; therefore, only a moderate quantity of Avtur was expected to spray backward into the leading edge space.

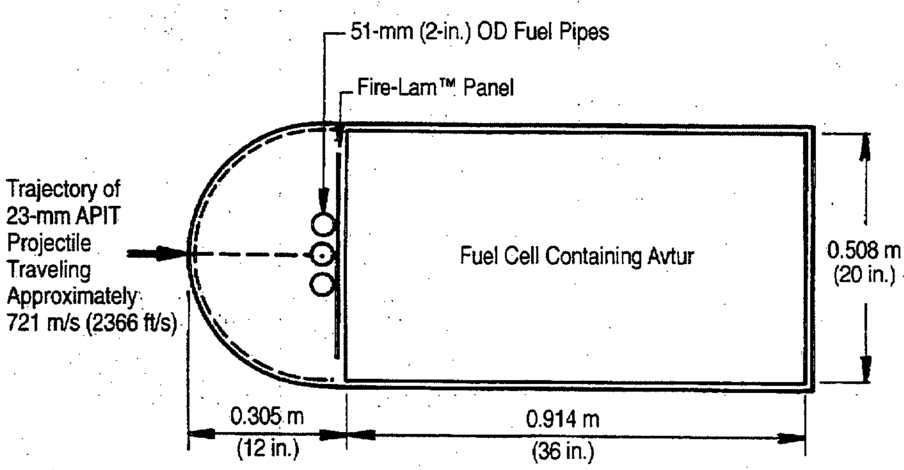


Figure 7-17. Installation for Fire-Lam™ Tests (Ref. 105)

The Fire-Lam™ panel, approximately 3.2 mm (0.125 in.) thick, was filled with a powdered extinguishant (Ref. 106). This powdered extinguishant could be potassium cryolite, potassium bicarbonate, sodium bicarbonate, an ammonium phosphate, or potassium bicarbonate urea (Ref. 106); but it was probably the latter, specifically Monnex®* (Ref. 107). Extinguishment was obtained in 11, 104, 72, and 60 ms in Tests 1 through 4, respectively (Ref. 105).

In the mid-1970s the US Army Air Mobility Research and Development Laboratory funded a program by Bell Helicopter to establish the capability of powder-filled panels to protect a helicopter fuel cell from the nearby detonation of a 23-mm HEIT projectile. Pedriani (Ref. 108) described the excellent effectiveness of this device.

In the mid-1980s Ciba-Geigy closed its California facility, and powder packs were no longer readily available for testing in the United States. To enable Government laboratories and contractors to continue testing, McNeilly (Ref. 109) described techniques used to produce similar powdered-fire-extinguishant-filled panels.

The capability of powdered-fire-extinguishant-filled panels or plastic bags in layers to extinguish flash fires of hydraulic fluid and mobility fuel has been demonstrated. Finnerty (Ref. 100) used either panels filled with Monnex® or powdered potassium bicarbonate in aluminum honeycomb 3 to 25.4 mm (0.118 to 1.0 in.) thick with aluminum foil faces or the powder in plastic bags held by wire screening. The tests used these powder-filled panels on both sides of containers of gasoline and of fire-resistant hydraulic fluid per MIL-H-46170 (Ref. 110) or hydraulic fluid per MIL-H-6083 (Ref. 111). In the gasoline tests in which 25.4-mm (1-in.) thick powder-filled panels were used, the potassium bicarbonate extinguished the fire in slightly less time (150 ms) than the Monnex® (200 ms) in a single test of each. In MIL-H-6083 hydraulic fluid tests, a 3.2-mm (0.125-in.) thick powder-filled panel containing potassium bicarbonate reduced the resulting flash fire from 363 to 231 ms. In tests with hydraulic fluid per MIL-H-46170, a 25.4-mm (1.0-in.) thick powder-filled panel containing potassium bicarbonate reduced the resulting flash fire from 820 to 165 ms. These tests provided a preliminary evaluation of the effectiveness of powder-filled panels. More work should be done to define fire-resistant hydraulic reservoir design features better.

In tests of four fuel cells and one fuel hose impacted by a shaped-charge jet, 12.7-mm (0.5-in.) thick plastic bag packets of Purple K** were used to extinguish combustion of heated DF-2 diesel fuel (The bulk temperature of the fuel was above its flash point.) carried or expelled from an internal fuel cell into a simulated troop compartment (Ref. 112). The Purple K packets were emplaced on the fuel-containing objects so that the jet projected the powder in the same path as the diesel fuel. The powder packets were not the only survivability enhancement feature used, but the "fire-out" times were 81, 59, 65, 8, and 55 ms. In a second program (Ref. 98) that used double-walled fuel cells containing Purple K in the hollow walls or jacket, much more heated diesel fuel was projected into the test fixture. The fire-out times for two tests that used a 25.4-mm (1.0-in.) thickness of Purple K were 132 and 210 ms, and for one test that used a 12.7-mm (0.5-in.) thickness of Purple K, the fire-out time was 102 ms. In the high frame rate motion pictures taken of these tests, the Purple K was seen to be projected from the jacket in a single large clod. This clod traversed the test fixture and then broke up into a cloud of powder after impacting the far wall of the fixture. Fire extinguishment started after the return of this cloud, so the fire-out time increased considerably. If there had been objects on which the clod could have impacted sooner, the fire-out times probably would have been significantly reduced. Again, these eight tests are too few to provide any more than an indication of the potential of fire-extinguishant-filled packets.

7-3.2.3 Double-Walled Fuel Cells

In the late 1970s the BRL sponsored two series of tests at the Terminal Effects Research Activity (TERA), located at New Mexico Technical University, Socorro, NM, of jacketed fuel cells to establish the feasibility of their use in the M113 APC (Refs. 113 and 114). The jackets tested were either strapped on (in the early tests) or integral (in the later tests) to the fuel cells and provided an extinguishant thickness of 19.1 mm (0.75 in.) or 25.4 mm (1.0 in.). The extinguishants tested were water, water with 50% ethylene glycol, bromochloromethane (Halon 1011), and dibromodifluoromethane (Halon 1202). The fuel cells contained DF-2 at ambient temperature. These tests were not as definitive as they could have been because the simulated fuel cells were improperly made: The seams were exceptionally weak. They did show, however, that the filled jackets would reduce hydraulic ram damage to the fuel cell at the jet impact location and that the jacketed fuel cell showed promise in reducing fires.

In 1987 a more definitive program was conducted (Ref. 98) in which double-walled fuel cells were tested. These fuel cells contained heated diesel fuel, and the hollow walls contained a liquid (water, water with high-expansion foam (HEF) or AFFF, water plus AFFF and propylene glycol, or bromochloromethane) or a pulverized (Purple K) or granulated (monoammonium phosphate) solid. The conclusions from this program follow:

1. Jacketed fuel cells are more hydraulic ram resistant than unjacketed fuel cells; see subpar. 4-8.1.3. Figs. 4-38 and 4-39 illustrate that the fuel cell wall at the jet exit, as seen through the large hole in the outer jacket wall of the

*A product of Imperial Chemical Industries (ICI) of America, which is a carbamic powder formulated from the reaction product of potassium bicarbonate and urea.

**Purple K is a product name of siliconized potassium bicarbonate with a small amount of purple dye coined by personnel in the US Navy. The K is for the potassium; the purple dye was added to discourage personnel from using the material in food preparation.

fuel cells used for Tests 3 (Fig. 4-38) and 5 (Fig. 4-39), has a smaller hole than the fuel cells used for Tests 2 (Fig. 4-38) and 4 (Fig. 4-39) do. This difference in hole size was probably caused by the inertia of the jacket filler, i.e., the fire extinguishant, to which the impulsive loads were passed; the fuel cell wall was subjected to a simple impact, not to an impact plus a pressure loading around the impact location as was the outer jacket wall.

2. The fire extinguishants that performed best were water, bromochloromethane (Halon 1011), and Purple K. The fire-out times for the water tests were 85, 36, 77, 35, 41, 90, and 105 ms, the fire-out time for the bromochloromethane test was 49 ms, and the fire-out times for the Purple K tests were given in subpar. 7-3.2.2. The water tests included those with 25% HEF or AFFF concentrate. In all of these tests the filler thickness was 25.4 mm (1 in.), and the water was heated to approximately the temperature of the diesel fuel, which was at or above its flash point. Granulated fire extinguishant is not recommended because the granules have a low surface-area-to-mass factor, nor are the water additives HEF and AFFF recommended because mist or spray fireballs do not provide a surface the additives can cover. (These additives form a layer over the surface of a burning fuel pool and prevent fuel vapor from leaving the surface to mix with the air and burn. This situation does not exist with a fire fueled by a mist or spray.) To prevent burning of pooled fuel, subpar. 7-3.2.8 provides a description of the use of the bilge.

This survivability enhancement technique shows great promise. More work should be done to develop and verify this technique.

7-3.2.4 Water Gel Subsystem

Gelled water was initially developed for the National Aeronautics and Space Administration (NASA) for use in spacecraft. A small plastic bag containing gelled water could be used to put out a fire even under zero gravity conditions (Ref. 63). These gelled water bags were either to be thrown like a bean bag or applied by hand like a wet rag.

Zabel (Ref. 95) demonstrated that gelled-water-filled plastic bags, when penetrated by a shaped-charge jet, very effectively reduced the duration of fireballs. Gelled water displays the same quenching characteristics as liquid water but tends not to flow. This tendency reduces the potential leakage from vertically emplaced water layers. These gelled* water bags were incorporated in the ASTB vehicle (Ref. 90).

One potential problem found during tests of the ASTB vehicle was the presence of algae in the gelled water. Hence the gelled water bags should be sterilized and/or a bactericide or algaecide should be added to the water to prevent growth of these organisms.

Also there is a concern that the water might freeze. In Test 11 of Ref. 95 a 51-mm (2-in.) thick layer of water-filled (no gel) plastic bags was installed just inside the simulated aluminum hull where the external fuel cell was mounted. A similar 51-mm (2-in.) thick layer of ice cubes in plastic bags was installed adjacent to the hull where the shaped-charge jet exited the test fixture. There was no sustained fire within the test fixture after a shaped-charge jet perforated the fuel cell and then the test fixture. The fireball at the entry wall lasted 9 ms, and that at the exit wall, 18 ms. Both fireballs were primarily from the aluminum hull simulants. Fireball durations for a similar test (Test 9) without the water and ice cubes were 30 ms at the entry wall and 32 ms at the exit wall. These times indicate that the ice suppressed aluminum flash less effectively than water but was significantly better than air.

A gelling agent will not reduce water vapor pressure, so the water can still evaporate from the gel. The gel can harden when its temperature is below the freezing point of water, but when the temperature of the gel is raised above its melting point, the water remains gelled. This gelled water expands at temperatures below its freezing point, as ice does.

7-3.2.5 Intumescent Paints and Coatings

Intumescent materials react at relatively low temperatures, swell while reacting, and then present a low thermal conductivity to heat. Intumescent materials are generally hydrated solids and binders that, when exposed to fire, (1) melt while absorbing heat, (2) become viscoelastic and liberate gases, usually water and/or carbon dioxide, which cause the solids to swell and form a closed cell foam that increases the heat transfer path and decreases the thermal conductivity of that path and (3) burn, dehydrate, and/or char (pyrolize) while absorbing heat. Usually it is the binders that burn and they are phenolic resins, epoxies, polysulfides, neoprenes, and/or water-glass-based film materials. Polysulfide, when used as a binder, or iron sulfide, when used as a filler, liberates oxides of sulfur (SO_x) that are toxic, and when they combine with atmospheric moisture, they can form sulfuric acid (H_2SO_4), which can damage electronic components. Sometimes fibers, including glass or ceramic fibers and mineral wool, are added to reinforce the char. Asbestos was used, but it usually is not considered at present.

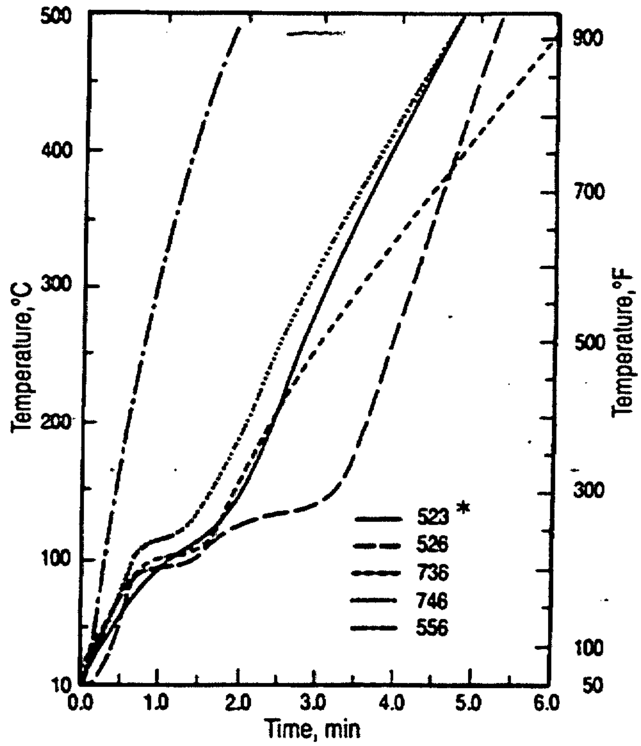
When intumescent materials react, the temperature sequence of the various components is very important. The acid-organic polyol must melt prior to or during esterification so that when the polyol decomposes through dehydration (forming a carbon-inorganic residue), the released blowing agent and the evolution of other nonflammable gases cause the carbonizing mass to foam. One of the purposes of the organic amine or amide, such as urea, melamine, dicyandiamide, and urea formaldehyde, is the

*The gelling agent used was Carbopol™ 934, a product of B. F. Goodrich. From 1.8 to 2.2% by weight of Carbopol™ was added to water. Then, to bring the pH to between 7 and 8, sufficient ammonium hydroxide was added while the solution was stirred continuously until gelled.

release of gases—including CO_2 and NH_3—that physically cause the fused organic mass to bubble or foam. If a phosphoric acid is used, amides and amines act as dehydrating agents to promote phosphorylation and enhance the conversion of the carbon in the polyol to char. In addition to the gases from amides and amines, a halogenated organic material or other suitable material generally is included. These materials release a large volume of gases that form bubbles which result in the characteristic foam of an intumescent system. Although water vapor and carbon oxides also may be released during dehydration and thermal decomposition of the polyol, these gases will function as blowing agents only if they are released at the proper time, i.e., after melt but before solidification occurs. Thus to assure sufficient gas is released at the proper point in the reaction, blowing agents with predetermined decomposition temperatures are employed, e.g., chlorine-containing paraffins, which release HCl over a temperature range of 160 to 350°C, or melamine, which releases ammonia, low molecular weight hydrocarbons, and carbon oxides between 300 and 350°C. Hydrated salts contain their own blowing agent, water vapor. As the reaction nears completion, gelation and finally solidification occur.

The binder ensures a continuous and uniform structure throughout the coating system and helps to ensure a uniform foam structure. It essentially holds the intumescent system and the inert fillers together. It can be a thermoplastic resin or a convertible resin that hardens by oxidation, by polymerization, or by reaction with hardening agents. The resin film, however, must not be so inflexible that it interferes with intumescence. The binder must also incorporate the expected properties of a coating system: (1) it is stable for long periods in its preapplication state, e.g., storage in a can, (2) it is noncorrosive, (3) it is easily applied, (4) it presents an aesthetically pleasing appearance, and (5) it is resistant to soiling, water, ultraviolet (UV), and other environmental effects. For combat vehicles the binder must also render the coating wear or abrasion resistant.

When subjected to flame, intumescent material begins to react from the exposed surface inward. The temperature of the substrate (the layer of material the intumescent coating is to protect) versus time is shown in Fig. 7-18. The four active formulations (523, 526, 736, and 746) displayed in Fig. 7-18 contain sodium metasilicate, each with a different binder. The first two (523 and 526) also contain borax. The resulting graphs indicate that intumescent coatings can be tailored to the application. In all of these tests the original intumescent coating was approximately 2 mm (0.079 in.) thick. After the reaction, the expansion was 2 to 9 times the original thickness. In tests described in Ref. 115 for Formulation 526, an initial thickness of 1.50 mm (0.059 in.) expanded to a char 3.61 mm (0.142 in.) thick. The density of the unaffected coating was 0.730 g/mL and of the char, 0.202 g/mL. The material intumesced at 118°C (244°F) in



Formulation	Binder	Filler	Fiber
523	Polysulfide Epoxy	Sodium Metasilicate	Glass
526	Neoprene	Sodium Metasilicate	Glass
736	Foundrez/Epoxy	Sodium Metasilicate	Glass
746	Flexible Epoxy	Sodium Metasilicate	Glass
556	Neoprene	Syloid (SiO_2)	Glass

Figure 7-18. Substrate Temperature-Time Histories for Actual Intumescent Formations (Ref. 115)

51 s. The postintumescent effective thermal conductivity was approximately 83.7 mW/(m·K) [0.0484 Btu/(ft·h·°F)]. The vapors given off are water and carbon dioxide. When the binder is neoprene, hydrogen chloride (HCl) is also given off.

Intumescent materials should not be used in the crew compartments of combat vehicles because they emit noxious gases. They would protect the equipment but not the crewmen. On the other hand, intumescent materials could be effective in engine compartments and are effective in ammunition magazines, as described in subpar. 4-8.4.2. Another potential use for intumescent materials is the exterior of the vehicle in order to reduce the effectiveness of Molotov cocktails and "liquid fire", which are described in subpars. 1-4.1.2.3 and 2-3.1.3. A third use is as an antifratricide device in a magazine to prevent the burning propellant charge of one cartridge from igniting another, as described in subpar. 4-6.4.1 (Ref. 91).

7-3.2.6 Other Impedimenta

Combat vehicles must carry munitions for crew-served and individual weapons; tools, spare parts, and supplies for maintenance; water, rations, and personal equipment for crew members; communications equipment and supplies; and much other impedimenta to enable the crew and vehicle to remain in the field in operational status for extended periods. This impedimenta can be used to shield and/or prevent fires by proper selection and vehicle design. Test 10 of Ref. 95 demonstrated that water quenches aluminum flash and the hydrocarbon fireball when a shaped-charge jet passes through an external fuel cell below the fuel level, the aluminum hull, the water container, a spall curtain, and then into the troop compartment. Similarly, when a water container was replaced by a box of loose 5.56-mm cartridges, the box of cartridges apparently trapped much of the hydrocarbon fuel, but only the cartridges whose metal cases were perforated by the jet contributed to the fireball (Tests 13, 14, 15, 17, and 18 of Ref. 95).

Impedimenta could safely trap armor flash and/or spall and combustible fluids carried in the wake of a shaped-charge jet or KE penetrator. Loss of these impedimenta is preferable to loss of the vehicle and/or its occupants. When combustible fluids or combustible metal flash are trapped by impedimenta, usually within a storage compartment, the conditions within the compartment do not ordinarily foster ignition.

7-3.2.7 Fire-Retardant Materials

Fire-retardant materials are used primarily to reduce the probability, or delay the inception, of ignition. These materials eventually burn in a conflagration and may produce toxic fumes while burning or smoldering. Both of these phenomena should be considered when the decision is made whether or not to specify the use of fire retardants.

When the most hazardous combustibles—solid propellant of large munitions, mobility fuel, and hydraulic fluid—are rendered less hazardous by location, compartmentalization, or other means, fire-retardant materials can be helpful. Any fire retardant used within a compartment to be occupied by humans must not produce noxious products.

7-3.2.8 Bilge

The bilge, the portion of the vehicle between the hull and the decking, is the lowest compartment in a combat vehicle, and unconfined liquids collect inside it. It is often used to stow hazardous materials because the location is less apt to be fired upon when the vehicle is in hull defilade. Designers should note, however, that the bilge is highly vulnerable to land mines, particularly those with shaped-charge warheads directed upward.

The tests of bilge fires discussed in Ref. 112 demonstrated that a bilge covered with well-secured flooring and partially filled with heated diesel fuel is not prone to support combustion. In these tests, the decking plates had finger holes, and the decking was not hermetically sealed. Therefore, it can be assumed that as long as the admittance of air into the bilge is reasonably restricted, there is a good probability the bilge contents will not sustain combustion. Obtaining a liquid seal would in fact be counterproductive since the leakage of combustible liquids must be able to drain past the decking into the bilge. These tests also established that heated diesel fuel will wick up through reticulated foam, other open-celled foams, rags, and Explosafe®* and provide combustible vapors at the upper surface of such wick-like items when they are exposed to air. Items that could become wicks should not be stowed in the bilge.

As was demonstrated in tests by Cosgrove et al (Ref. 96) and explained by Stoll and Chianta (Ref. 97), the decking must be secured to the vehicle to prevent explosions that occur underneath the vehicle from throwing the decking and bilge contents upward, which then injure or kill the occupants.

7-3.2.9 Other Passive Concepts

When planning the incorporation of fire suppression techniques in combat vehicles, the designer must start with a thorough evaluation of the hazard(s) to be reduced, the effectiveness of the survivability enhancement devices or concepts that can be used, and the limitations imposed by other vehicle requirements. The hazards can be divided into the combustibles present and the threats that can ignite them. The effectiveness of the survivability enhancement devices or concepts can be judged by whether they will (1) prevent a combustible material from being in a combustible form, (2) separate the combustible material from the ignition sources at least for the time required to obtain ignition, and/or (3) suppress any combustion that has occurred or reduce the effects of that combustion until effective extinguishment can be accomplished. When evaluating the limitations, the designer must always consider cost, weight, time, and the status of the vehicle. For vehicles being planned or designed but not yet in production, there is much more latitude in which to incorporate survivability enhancement concepts than there is for vehicles currently being used by troops. Retrofits of existing vehicles should be much less complex than a complete rebuild, and such retrofits should be limited to replacement of components, addition of some items, and minor vehicular reworking.

7-3.2.9.1 Fuel Cell Confinement

A plastic or elastomeric cell provides excellent containment of fuel, but such a cell cannot withstand the hydraulic ram forces resulting from a ballistic impact, especially at access ports or fuel line connections. By confining a plastic fuel cell within a metallic structure so that the plastic cannot expand beyond its elastic limit, a well-sealed, ballistic-resis-

*Explosafe®, a void filter material made of expanded aluminum foil, is a product of Explosafe Ltd of Canada.

tant fuel cell can be obtained. Such a combination can be used in retrofits as well as in initial designs.

When a fuel cell in an existing vehicle is diagnosed to be a hazard because it is located where it can be easily hit and because fuel cell failure can result in loss of vehicle and crew, that fuel cell might be rendered less hazardous by the addition of a confining wall. Work recorded in Ref. 112 demonstrated that a steel confining wall can be added to reduce the hazard to a small, easily extinguishable fire. Also the addition of a spall curtain, a layer of fire-extinguishant filled packets or panels, and removal of potential ignition sources could preclude a fire. Such a retrofit is eminently practical, could be relatively inexpensive, and could be performed by third echelon maintenance personnel.

7-3.2.9.2 Fuel Cell Material and Configuration

Prior to 1959 fuel cells for armored vehicles were made of carbon steel. Since then, fuel cells have been made of aluminum, stainless steel, nylon, polyethylene, and a composite of fiberglass and resin. Plastic is a particularly tempting material for fabricating a fuel cell. It is relatively inexpensive, and rotary molding can produce fuel cells relatively inexpensively that have a homogeneous thickness without built-in weaknesses, such as seams. It is not yet known, however, what material properties are needed or how to specify the control of these properties. Also plastics will not capture secondary missiles, such as the slugs from shaped charges.

Refs. 95, 112, and 116 describe a total of 40 tests with six different elastomeric fuel cell materials: nylon 6, nylon 12, cross-linked polyethylene, Hytrel®, Pebax®, and a conventional, crashworthy, self-sealing material per MIL-T-27422 (Ref. 117). None of these sealed when perforated by a shaped-charge jet. At ambient temperature only the polyethylene did not crack, but hydraulic ram did split it when a weld in the confining box failed. Twenty-six tests were performed with nylon 6 rotary-molded fuel cells. Containing diesel fuel at ambient temperature, these cells usually cracked, i.e., ruptured beyond the extent of the jet puncture, and thus provided a larger opening for fuel leakage. When these cells contained heated diesel fuel, three of the eighteen cracked. (Plastics are usually less crack sensitive when heated.) Laboratory personnel who examined the material from a cracked cell concluded that it contained no visible voids, whereas the material from the uncracked cell did. The probability that small voids in the plastic will reduce its propensity to crack is remote. More research is needed to establish (1) the properties needed to obtain desired performance and (2) better control of fabrication to obtain the desired properties, or the fuel cell design should assure that even with cracked or fractured fuel cells, there will be no gross dissemination of fuel.

Because heated fuel is not desirable (It is more easily ignited than cool fuel.) and fuel at ambient temperatures could be used, fuel cell materials that have more desirable properties at temperate ambient temperatures could be selected. To date, polyethylene appears less prone to cracking at temperate temperatures, but it is combustible. Before such a material selection is made, the material properties at the lower environmental temperatures, i.e., temperatures down to –54°C (–65°F), must also be considered.

US Army helicopters use crashworthy, self-sealing fuel cells made to the requirements of MIL-T-27422, which specifies that the cell does not have to seal when the threat cores a hole, i.e., when self-sealing material has been physically removed from the fuel cell. This removal occurs when an armor-piercing incendiary bullet or a high-velocity fragment perforates the self-sealing material. These missiles have sharp edges that act like a cookie cutter when perforating the elastomeric material. Conventional, self-sealing materials achieve a mechanical seal by having material that has been punctured by a pointed, tapered or ogival missile reform to close the perforation. A shaped-charge jet, a plug or spall from metallic armor, or a fragment from a KE penetrator can core the self-sealing construction and thus prevent the construction from sealing.

7-3.2.9.3 Reticulated Foam Within a Combustible Fluid Container

To preveent the explosion of fuel vapors and air in the ullages of aircraft fuel cells, reticulated foam was placed within the fuel cell (Ref. 118). Holten (Ref. 119) estimated that reticulated foam reduced the hydraulic ram loadings by approximately 20% given a hit by a 23-mm HEIT below the fuel level. Cosgrove et al (Ref. 96) attributed smaller fireballs from shaped charges to the use of reticulated foam within the fuel cells. Those shaped-charge jets, however, were traveling upward through partially filled fuel cells; thus the reticulated foam could well have filtered out fuel moving radially outward from the jet wake. See subpar. 4-8.3.2 for a detailed discussion of tests of reticulated foam used in the LVTP-5A1.

Finnerty (Ref. 100) found that a hydraulic fluid reservoir containing reticulated foam produced smaller fireballs in tests than did similar reservoirs without the foam. This result occurred in one test recorded in the referenced report and again in a reiteration of that test performed after the report was written. On the other hand, Zabel (Ref. 98) found no benefit from reticulated foam within a fuel cell given a horizontal shaped-charge jet passing through the fuel-wetted reticulated foam, again in two similar tests. Zabel noted some "sparklers" in the test fixture that were visible in high-frame-rate motion pictures of these two tests; these indicated more potential ignition sources, probably caused by the foam particles burning. Similar sparklers were mentioned by Braadfladt (Ref. 120) in a reference to tests performed with Explosafe® (expanded aluminum foil) within the fuel cell. (Such "sparklers" prolong the existence of an ignition source.)

7-3.2.9.4 Ullage Explosion Protection

Aircraft, both fixed and rotary wing, contain fuel cells in their fuselage and/or wings that are of construction light enough to need ullage explosion protection. The early metallic external fuel cells also needed ullage explosion protection; however, the filament-wound, external fuel cells made for the F/A-18 and several large helicopters are required to be strong enough to withstand the explosion of a propane-air mixture. These filament-wound fuel cells also withstand the hydraulic ram loadings from impacting tumbling 14.5-mm APIT bullets (Ref. 101).

While developing effective ullage explosion protection, designers tried many passive techniques. These techniques are described by McCormick et al (Ref. 121). In addition, active techniques were tried, which were the forerunners of the active fire suppression systems used today in the crew compartments of combat vehicles. Before the optical detection system was as well developed as it is currently, these active systems did not prove effective in fuel cell ullages.

Ground vehicles have an advantage over aircraft because there is not as great a need for weight reduction. Further, since ground vehicles are exposed to direct hits by larger threats, they are inherently stronger. Therefore, fuel cells of combat vehicles should be designed and fabricated to be strong enough to withstand ullage explosions and hydraulic ram loadings. Specific ullage-inerting devices should not be needed. Fuel cells should be tested in their normal installation to prove their design.

7-3.3 HANDHELD EXTINGUISHERS

Handheld fire extinguishers provide the capability for crewmen to extinguish fires that are not appropriate for a fixed fire-extinguishing system, i.e., fires that fixed fire-extinguishing systems cannot extinguish because of the location of the fire or the fixed fire-extinguishing system capability, or because the fire is external to the vehicle. In addition, handheld fire extinguishers are a morale booster because they represent a capability for the crewmen to react to a hazardous situation when all else fails. These portable fire extinguishers are described in Ref. 122.

7-3.3.1 Types

A number of handheld fire extinguishers have been designed for limited use against small fires and are currently used in ground vehicles, aircraft, and a variety of other applications for which personnel are available to fight small fires. The use of lightweight and effective handheld fire extinguishers is a critical part of ground vehicle survivability because controlling or extinguishing a fire in its initial stages prevents its escalating to an uncontrolled fire that can consume the entire vehicle. Handheld extinguishers have been in use for a number of years and are available in a variety of sizes and contain a variety of agents. Extinguishing agents such as the halons, water, copper flakes, carbon dioxide, and dry chemical powders have been demonstrated to be effective against a number of different types of fires.

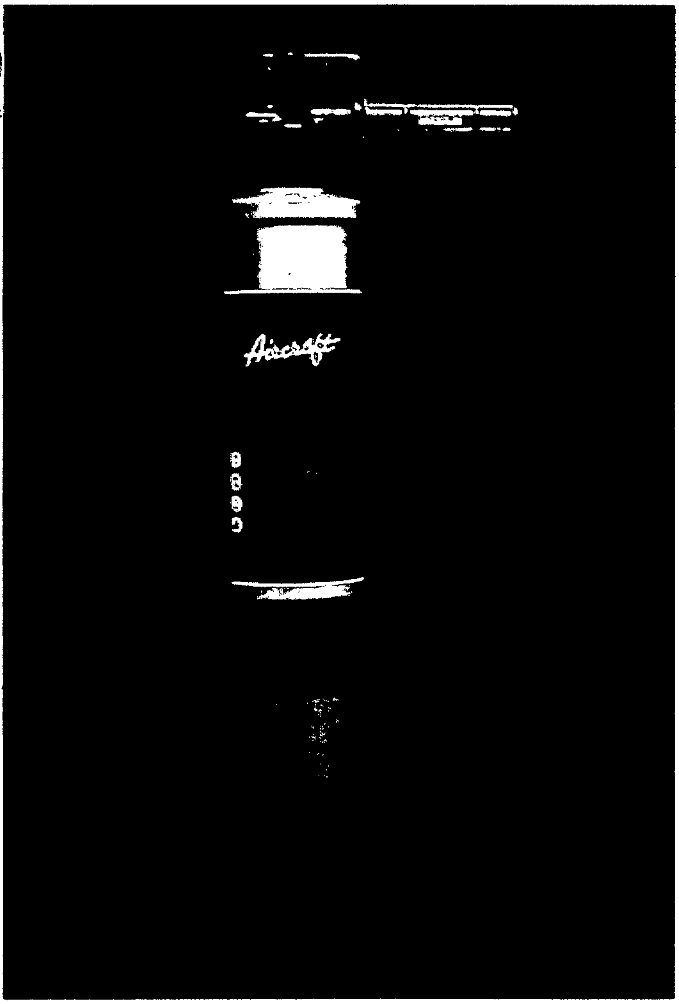
7-3.3.2 Uses

The selection of handheld extinguishers should match the extinguisher and extinguishing agent to the specific fire hazard, e.g., using AFFF for fuel pool fires but not for electrical fires. Factors affecting the selection of the type of extinguisher, such as the ease of use for the available personnel and the physical environment in which the extinguisher will be used are discussed in this subparagraph.

Selection of a handheld fire extinguisher should be based on a number of factors including size, type of extinguishing agent, space and weight limitations, ease of operation, and cost. Most handheld extinguishers are relatively easy to use and do not involve any more operations other than to point the container outlet at the fire, pull a pin, and either depress a lever or squeeze a handle to release the agent. The size of the extinguisher depends on the available area in which the crew member has to operate and on the size of the fire that the individual is expected to extinguish. Selection of the extinguishing agent is a bit more complex because of the nature of the fire and the fact that certain agents work well against certain material fires but will not extinguish all types of fires. For example, carbon dioxide is effective against fires involving flammable liquids and electric sparking within a closed space but is not effective against combustible metal fires or deep-seated fires of ordinary combustibles, such as paper, textiles, and hazardous solids.

Water was the first extinguishant used in portable extinguishers. It is still in use today, but is not as common. Today water extinguishers use carbon dioxide cartridges rather than the reaction of soda in water to pressurize the extinguisher bottle. Water very effectively extinguishes cellulosic fires, e.g., burning wood or paper, but it is not desirable for fires involving electric discharges until after the electric circuits have been interrupted. One source of fires in commercial aircraft is that passengers throw cigarettes into the wastepaper containers in the rest rooms. This type of fire is difficult to extinguish using either dry chemicals or carbon dioxide. Halon 1301 was also ineffective in extinguishing this type of fire; water, however, is excellent in this situation. Airlines install a Federal Aviation Administration (FAA)-required Halon 1301 fire extinguisher in the rest rooms, and some install a portable, water-type extinguisher in the vicinity of the rest room for such situations. Trans World Airlines (TWA) has used this setup and has encountered little or no problem in the use and maintenance of the portable extinguishers (Ref. 66). These portable extinguishers, shown in Fig. 7-19, use small carbon dioxide cartridges to pressurize the bottle when the extinguisher is to be used and use GS-4™ (potassium acetate) to lower the freezing point of the water to −40°C (Ref. 123). These 1.6-kg (3.5-lb), water-type extinguishers have a range of over 6 m (20 ft) and will flow for 30 to 45 s.

Dry chemical, portable extinguishers have been used since 1928, and they are more effective against flammable liquid fires than against cellulosic fires. Only one, monoam-



Courtesy of Kidde-Graviner Ltd, Berkshire, England.

Figure 7-19. Portable Fire Extinguisher, Water Type

monium phosphate, is rated for cellulosic fires, and it performs marginally. Most dry chemicals are also usable against fires involving electric discharges. These dry chemicals, their relative effectiveness, and the types of fires for which they are recommended, are tabulated in Table 7-14. These extinguishers are usually pressurized by nitrogen or dry air. The 0.9- to 2.3-kg (2- to 5-lb) dry chemical, portable fire extinguishers have a range of 1.5 to 6 m (5 to 20 ft) and will discharge for 8 to 10 s (Ref. 124).

For Class B and Class C fires, a 1.1- to 2.3-kg (2.5- to 5-lb) carbon dioxide, portable fire extinguisher has a range of 0.9 to 2.4 m (3 to 8 ft) and a discharge time of 8 to 30 s.

Most of the dry powder* extinguishants currently in use—graphite, sodium chloride, "G-1 powder" (screened, graphitized, foundry coke plus an organic phosphate), "Met-L-X" powder (sodium chloride base with additives), "Na-X" (sodium carbonate base with additives for sodium fires), foundry flux (mixture of potassium chloride, barium chloride, magnesium chloride, sodium chloride, and calcium fluoride), and many others listed in Ref. 125—are not truly usable for a combustible metal fire on or in a combat vehicle. Boralon™, a mixture of trimethoxyboroxine (TMB) and Halon 1211 or 2402 (Ref. 126), is not acceptable because of potential ozone depletion and for toxicity reasons. The best candidate to extinguish combustible metal fires in combat vehicles is Navy 125S® (Ref. 81), which is basically copper flakes. Both Ansul and Amerex are currently producing, on a small scale, portable extinguishers containing Navy 125S® for the US Navy, which have a 13.6- or 113.4-kg (30- or 250-lb) capacity. If there is a need for smaller combustible metal, portable fire extinguishers, they can be made. The existing units are pressurized with argon. This type of extinguisher has been listed by Underwriters Laboratories, Inc., for Class D lithium fires (Ref. 127) and is being evaluated for Class D magnesium fires (Ref. 128).

Portable extinguishers are most often used against sustained fires from a heated fuel or on a heated object. The prime objective in such cases is to cool the heated fuel (which is often solid such as a bag of clothing, electric wire insulation, paper, or wood) and/or the heated surroundings. Normally the greatest cooling effect is obtained by vaporizing a liquid extinguishant; the latent heat of vaporization of water is 2254.8 J/g. For heat transfer between a solid—the heated metal or the burning wood, plastic insulation, or cloth—and a fluid—the extinguishant, the most significant determinant is the coefficient of heat transfer. Several representative coefficients are given in Table 5-1. If a liquid extinguishant droplet impacts a hot engine block, the coefficient of heat transfer will be approximately 250 times that of cool gaseous extinguishant vapors passing by that same engine block. Thus when liquid droplets of extinguishant hit a hot piece of metal or hot fuel, that hot metal or fuel loses some of the heat required to vaporize the extinguishant. Large droplets of water can be physically held from a hot piece of metal by the steam flashed from the droplet. In this case, many smaller droplets impacting the hot piece of metal would cool the metal more quickly than would fewer larger droplets. If the extinguishant vaporizes enroute, as Halon 1301 would, which has a boiling point of –57.7°C (–71.9°F) and a latent heat of vaporization of 118.8 J/g; the heat required would be taken from the air within the compartment. This air would regain some of that heat from the heated engine unless the cooled air were forced out of the compartment by the coolant air flowing over the engine. This fact explains why engines remain hot and reignite fuel when either Halon 1301 or carbon dioxide is used to extinguish an engine compartment fire, i.e., Halon 1301 and carbon dioxide cool the hot air in the engine compartment instead of the hot engine.

*The convention is to call the Class B-Class C fire extinguishants "dry chemical" and to refer to the Class D—combustible metal fire—extinguishants as "dry powder".

TABLE 7-14. DRY CHEMICAL USAGE IN PORTABLE EXTINGUISHERS (Ref. 124)

DRY CHEMICAL	FORMULA	RELATIVE EFFECTIVENESS AGAINST FLAMMABLE LIQUID FIRES	PRODUCES CORROSIVE PRODUCTS	NATIONAL FIRE PROTECTION ASSOCIATION CLASS RATINGS*
Sodium Bicarbonate	$NaHCO_3$	1 (baseline)	no	B, C
Monoammonium Phosphate	$NH_4H_2PO_3$	1.5	corrosive	A, B, C, **
Potassium Chloride	KCl	1.8	most corrosive of these	B, C
Potassium Bicarbonate	$KHCO_3$	2.0	no	B, C
Potassium Carbamate†	$KHCO_3 \cdot NH_2CONH_2$	2.5	no	B, C

*Not to be used on wet high-voltage equipment
**Leaves sticky residue
†Product of the reaction of potassium bicarbonate and urea

7-3.3.3 Selection Guidance

Handheld fire extinguishers are a necessity. They provide the best means to extinguish special fires and the most effective means to combat fires that the fixed fire-extinguishing system does not attack. Fixed fire-extinguishing systems are designed to combat hydrocarbon fuel mist or spray fires at specific locations within an enclosed space. They do not always extinguish and prevent the reignition of fires in ventilated spaces, particularly liquid pool fires, electrical fires, combustible metal fires, smoldering fires in bedding, fires in the air filters of engines, burning uniforms, fires of externally stowed gear, etc. Handheld extinguishers can extinguish these fires. Handheld extinguishers can also be used when the automatic system fails or has been expended.

Portable fire extinguishers should be provided to extinguish the following types of fires:

1. Electrical
2. Slow-burning combustibles, such as paper or clothing
3. Hydrocarbon liquid in either the crew or engine compartment
4. Combustible metals, if present
5. Fires not completely extinguished by the primary system
6. Deep-seated fires, such as occur in rubber tires or track pads.

For these combustibles four basic extinguishant types are needed: a general-purpose extinguishant usable in electrical fires such as dry chemical, a cooling agent such as water, a special Class D extinguishant for combustible metals, and a persistent cooling and inerting agent.

Dry chemical or a liquid halon alternate is recommended over carbon dioxide for automatic systems in unoccupied compartments because either can be used to extinguish electrical fires. These extinguishants can be used in manual extinguishers because they can be thrown farther than carbon dioxide and thus allow a crew member to fight a fire from a greater distance. Expended, but unconsumed, dry chemical can have an effect should the fire reignite. Personnel using extinguishers of all types tend to use 10 to 100 times the quantity of extinguishant needed (Ref. 30); gases dispense, water evaporates, but powder lingers. There may be a cleanup problem because much of the powder or its products remain until removed by mechanical means, particularly if the powder cakes in oil, hydraulic fluid, fuel, or other liquids.

All combat vehicles carry water for the crew, usually in 19-L (5-gal) cans strapped or stowed on the vehicle somewhere. The *Combat Lifesaver Course, Medical Tasks* manual stresses the need for potable water (Ref. 129). Installation of a drinking water reservoir in combat vehicles is highly advisable. The water could be used for drinking, washing, and other purposes. Providing a small pump at the bottom of the drinking water reservoir and a small hose with a spray nozzle and valve combination could satisfy some of the need for a water-type extinguisher, but such a system would be limited to use only in the crew compartment.

Water is recommended over other coolant-type extinguishants for use in occupied compartments because it presents fewer problems during and after use. Potable water can be used in mist form even on electrical fires, but the electricity should be turned off because the water will eventually pick up contaminants and become conductive. Additives to the water such as AFFF and HEF are not recommended by fire-fighting specialists unless there is a hydrocarbon liquid pool fire. Water in mist form is highly effective against most fires; deep-seated cellulosic fires, however, require a spray or jet of water. A rechargeable, portable fire extinguisher, such as that shown in Fig. 7-19, equipped with a selectable mist-spray-jet nozzle would provide an excellent tool for fighting slow-growth Class A, Class B, or Class C fires within the vehicle. The water mist can also flush noxious materials out of the air and reduce the hazard of smoke inhalation, as described in subpar. 7-2.3.1.6.

The combustible metal extinguishants need further study. Many of those listed in Ref. 125, such as graphite and sand, are intended to be shoveled onto the burning object to cut off the source of oxygen. Navy 125S® is highly effective and presents a means to extinguish the fire without burying the burning object. The deep-seated plastics/rubber fire extinguishants need further study. At present, the only available extinguishant for burning rubber is water (Ref. 130); formerly Halons 1211 and 2402 were recommended (Ref. 131). Water with surfactants performs well. Fortunately, small portable extinguishers should provide the fire-extinguishing capability needed for both of these types of fires, a Navy 125S® (copper flake) extinguisher for combustible metals and a water extinguisher for burning rubber.

7-4 SYSTEMS

Two basic approaches have been used to improve fire survivability. One approach is to prevent the fire from igniting. The other is to extinguish the fire before the vehicle or its occupants are affected. Elements of both approaches must be incorporated into the approach used in a combat vehicle.

7-4.1 GENERAL SYSTEM OBJECTIVES

The preferred approach is to prevent a fire from igniting by primarily passive means. The combat vehicle should be designed or modified to have the most hazardous materials located where they are not apt to be hit or where, when hit, their explosion and/or combustion products cannot seriously affect the vehicle or its crew. This approach includes design features that would reduce potential ignition sources, eliminate potential combustibles, separate combustibles from ignition sources, and reduce the availability of oxygen where fires could occur. The potential for ignition of combustibles is reduced by this approach to a fire survivability system. All potential catastrophic fires should be reduced to slow-burning or smoldering fires extinguishable by crew members. This system should, in turn, be backed up by fire extinguishers.

The approach that seeks to extinguish fires before the vehicle or occupants can be affected depends primarily upon an active fire-extinguishing system. Ideally, this system would sense an incipient fire and activate an appropriately sited fire extinguisher to extinguish the fire as soon as it ignites. This active system depends upon sensors that can react extremely quickly, a controller that can discriminate between a fire and other phenomena and activate the appropriate fire extinguisher, the fire extinguisher and its distribution system being sited to deliver extinguishant to the fire extremely quickly and effectively, and an extinguishant that will quickly end the combustion. Additional protection is achieved if the fire extinguishant acts as an inertant and prevents reignition of the fire for the period of time necessary for heated parts to cool down and combustible materials to be removed or if the extinguishant cools the fuel and fire site.

7-4.1.1 Crew Compartment

Regardless of whether an active or passive system is used, the design objectives for the crew compartment are the same. The prime objective is to assure that the personnel are not killed or seriously injured by fire effects or fire suppression. Secondary objectives include that the equipment within the crew compartment remains operable or at least that the vehicle is repairable and recoverable. Since current fire-extinguishing systems are ineffective in suppressing gun or rocket solid propellant chemical reactions, use of protective magazines is imperative. Therefore, the most hazardous combustible to be treated by the fire-extinguishing system is hydrocarbon mist or spray of either the mobility fuel or hydraulic fluid.

Preferably, liquid hydrocarbon containers should not be located in the crew compartment. These containers must be designed and fabricated not to rupture grossly when hit. Also the locations of the liquid hydrocarbon containers are important; however, the threat that can reach these containers and puncture them will probably have enough energy to produce a sizable spray within the crew compartment. An appropriately designed passive system would assure that only a short-duration fireball could occur rather than sustained combustion. This passive system, described in subpars. 7-3.2.1.2 and 7-3.2.1.3, would probably involve strengthening and confining the hydrocarbon container, compartmentalization, and a threat-released fire extinguishant layer.

An active fire-extinguishing system would have optical sensors viewing the compartment from several aspects and several nozzles covering the regions the hydrocarbon spray could reach. The distribution lines should be relatively short to minimize the response time of the system. Since Halon 1301 does not travel well in air (Gases do not travel well in other gases.), sufficient Halon 1301 must be used to flood the region of potential combustion. This requirement could also be necessary for an alternate for Halon 1301 if it were gaseous when released. Flooding the region of potential combustion requires rapid employment and dispersion of more Halon 1301 than would be required if the extinguishant could travel in a more dense form. A system that achieves total flooding is used also because the location of the fire is unpredictable. Halon 1301 is preferable to Halons 1211 and 2402 which are more toxic and do not work well in total flooding applications, and to carbon dioxide, an asphyxiant for which a gas mask is not effective. Dry fire extinguishants such as potassium bicarbonate would be effective but would tend to irritate the eyes and breathing passages of occupants. Water mist is an attractive alternate; see subpar. 7-2.3.1.6.

7-4.1.2 Engine and/or Cargo Compartment

The presence of hydrocarbon liquids in the engine compartment cannot be avoided. Objects within this compartment can withstand more heat energy than people or other heat-sensitive objects within the crew compartment can. In addition, extinguishants can be used within the engine or cargo compartment that are not recommended for use within crew compartments. The primary design objective here is to limit fire damage to the burning or charring of the surface of the more susceptible items such as electric wire insulation and rubber fuel or hydraulic fluid hoses.

Within the engine compartment the presence of continuous ignition sources makes inerting the compartment of major importance in order to prevent reignition of the combustibles. Also engine cooling requirements usually result in an extremely high airflow within the engine compartment. The extinguishant should be selected from among the more persistent agents, i.e., dry chemicals such as potassium bicarbonate, liquid Halon alternates, and water. Neither Halon 1301 nor carbon dioxide is sufficiently persistent to render the engine compartment effectively inert for the time necessary for liquid hydrocarbons to drain to a safe location, such as a covered bilge, particularly because the airflow through the engine compartment quickly removes the Halon 1301 or carbon dioxide.

The quantity of extinguishant to be dispersed by a fire extinguisher should be sufficient to inert the entire compartment and cool heated objects. Liquid extinguishants tend to vaporize when they contact the heated surfaces present in the engine compartment. These liquids will continue to vaporize over a period of time and thus provide longer term inerting than gaseous extinguishants do. Liquid extinguishants, especially water, also cool the compartment and thereby reduce the probability of reignition.

Cargo compartments are similar to engine compartments because there are no occupants; hence greater freedom is allowed in selecting the extinguishant. Cargo compartments differ from engine compartments by the absence of high coolant airflow and heated surfaces, which absence can reduce the probability of reignition. Also cargo compartments are more able to maintain inertion and therefore less likely to have reignition. Cargo compartments do not necessarily contain liquid hydrocarbons, but they could contain explosive or incendiary cargo. Again, rendering the atmosphere within these compartments inert is advisable. The engineer should assure that whatever means are used to inert the compartments will not produce toxic products because they can leak into the crew compartment.

For both engine and cargo compartments, if the cargo is not energetic, the fire-extinguishing system can have a slower response than the crew compartment system. Methods for stowing energetic materials are described in subpar. 4-6.2.

7-4.1.3 Fire-Extinguishing System Survivability

To assure the survivability of vehicle and crew, the fire-extinguishing system must also survive. The survivability of vehicle systems and their components has historically followed the A, B, C, D, and E of survivability design: Armoring the vehicle, Burying critical components behind other items, Concentrating many of the critical components, which presents less area to hostile threats and allows armoring of the clustered components with less weight from armor, Duplicating to maintain functions if a component is damaged, and Eliminating combustible materials from within the vehicle.

1. *Armoring*. In the case of a fire-extinguishing system for a combat vehicle, the vehicle will already be armored. This armor provides protection from small arms fire and from high-velocity fragments produced by high-explosive shells. Within the vehicle protection from objects that have perforated the vehicle armor cannot be expected, but protection of the fire-extinguishing system components and electrical harnesses from spall and ricocheting particles of the penetrator can be provided.

2. *Burying*. Burying critical components is an efficient method used to improve the survivability of a fire-extinguishing system by making use of the inherent shielding the vehicle and its components offer. The strategic positioning of critical components, such as the control devices and electrical harnesses, behind other components in the vehicle so these items provide protection from spall impacts and blast loads will result in a higher survivability factor for the fire-extinguishing system.

3. *Concentrating*. The technique of concentrating the critical components in a particular area is another method used to reduce the vulnerability of a system. On the other hand, concentration without any other survivability enhancement, such as armoring or burying the concentration of components, may increase the vulnerability of the system because all of the critical components are now next to each other and are susceptible to a single hit.

4. *Duplicating*. Duplicating the critical components is one of the most effective methods used to improve the survivability of a fire-extinguishing system because it provides a level of redundancy that allows the system to operate if a portion of the system is lost or fails. The use of multiple, parallel-wired fire detectors improves response times and assures that even if a detector is lost, the system will operate with the remaining detectors. Redundancy in the agent distribution system requires either multiple bottles of agent connected to the same distribution piping network or complete, identical redundant systems (bottles, valves, and piping) covering the same area. The use of complete, identical redundant systems provides a higher level of survivability; however, it is a more expensive technique in both material costs and vehicle space and weight penalties.

5. *Eliminating*. If a flammable or combustible is not absolutely necessary on a vehicle, it should be eliminated. This elimination should be done during the design phase of the vehicle and carried forward on a mission-by-mission basis. The principle is that the less there is to burn, the less likely there will be a fire and the easier any resultant fire will be to extinguish.

For an active fire-extinguishing system to function properly, control lines must remain intact, and several system components must be functional. These systems should be fail-safe in all aspects and should be as simple as possible to avoid incurring a higher than desired failure-to-alarm rate. The possibility of losing components to ballistic or accidental damage must be considered. In a significant number of vehicle tests, active fire-extinguishing systems failed to function because ballistic damage severed an electric wire, damaged a valve, or destroyed a controller.

7-4.2 GENERAL SYSTEM DESCRIPTION

Fire-extinguishing and prevention systems generally are either active or passive. The two are similar in some respects. Any complete fire-extinguishing or prevention system, active or passive, must be designed to limit gun or rocket propellant combustion and/or to divert the blast and products of detonation so such effects will not affect the vehicle or its crew. The M1 and M1A1 MBTs have separate magazines for the main gun cartridges, except the few rounds in a basket on the turret floor. These magazines are separated from the crew compartment by sliding doors that are normally closed. The magazines are designed to withstand the impulse from detonation of a single warhead therein, and each magazine has a blow-away panel to vent the quasi-static pressure generated by such detonation either to the outside or into the engine compartment. This is a passive means to prevent the effects of such a chemical reaction from affecting the crew or the vehicle. This is an example of a passive technique used on a combat vehicle that has active fire-extinguishing systems in both the crew and engine compartments.

7-4.2.1 Active Systems

Active fire-extinguishing systems sense combustion and react to extinguish that combustion by the discharge of an extinguishant. These systems have sensors that detect parameters symptomatic of combustion, a controller that follows a set logic to signal extinguisher valves to open, electrical wiring, controls, and indicators, and extinguishant distribution plumbing including nozzles. In general, an active system for the crew compartment uses optical sensors and has an extremely fast response. An active system for an engine or cargo compartment can use optical or thermal sensors and have a slower response. Active systems can usually be activated manually when combustion is detected.

The advantages of an active system follow:

1. The system can react to combustion that occurs accidentally, i.e., for reasons other than ballistic impact, such as the failure of a hydraulic line within the engine compartment.
2. The system is on standby and requires only actuation to be put into use quickly.
3. An automatic system does not require a crewman to activate it.

Disadvantages of an active system include the following:

1. The system is subject to damage that can prevent its functioning. Some active systems can be turned off manually by crewmen and thus may not be available when needed.
2. The system is predirected to cover regions in which fires are anticipated to occur and cannot be redirected to cover other regions in which combustion may actually occur.
3. The system is subject to false alarms.
4. The system is currently limited to one or two activations. It cannot respond to multiple (>2) fire events.
5. The system may have expended its extinguishant or be inoperable when needed.
6. An active system requires maintenance and periodic checking to assure it is functional.

7-4.2.2 Passive System

A passive fire suppression system is present where the vehicle has been systematically designed and fabricated to minimize the probability of ignition, the effects of combustion, and the probability of a fire becoming sustained. The most hazardous combustibles (explosives, mobility fuel, and hydraulic fluid) must be removed from the crew compartment to the maximum extent possible. The explosives must be stowed where they cannot affect either crew or vehicle given a hit and subsequent reaction. Mobility fuel cells must be strong enough to resist gross rupture and be provided with threat-released fire extinguishant panels or jackets where they are most likely to be hit. A passive fire extinguisher system, such as a double-walled fuel cell, requires that the system suffer ballistic damage in order to function. In most ways, passive systems are less likely to malfunction given ballistic damage. Mobility-fuel-fired troop compartment heaters might be replaced with electric heaters and/or with hot air heated by the engine. It is foolish to remove most of the mobility fuel from the troop compartment and then pipe some back into a heater to wait to be hit. Hydraulic power systems should use a truly nonflammable fluid or be replaced with electric or pneumatic systems. Engine and cargo compartments should use insulation or intumescent coatings to minimize the effects of fires. The bilge should be covered to prevent gross influx of air. Bilge cover plates should allow leaked liquids to collect under them. Inherent in passive systems is the probability that some combustion will occur. These systems are designed to reduce the intensity of such combustion or to localize it so that the crew can extinguish it with portable fire extinguishers. The concepts of passive systems are described in subpar. 7-3.2 and elsewhere in this handbook.

Advantages of the passive approach include the following:

1. The system is always on-line and cannot be turned off.
2. The system requires little maintenance. However, checks must be made to assure that the troops have not nullified the passive concepts, e.g., by careless placement of flammable objects or pressurized containers.
3. The system is not subject to false alarms.
4. A properly designed passive system can protect many regions within the vehicle.
5. The system usually has lower life cycle costs than an active system, particularly for new designs.

The disadvantages of passive systems include the following:

1. If jackets are used, as they are for jacketed fuel cells, inspection of the fire extinguishant is difficult.
2. Personnel are not familiar with passive fire prevention techniques; therefore, until they gain confidence in the passive system, it should be backed up with an active system, at least a manually activated one.
3. Personnel unfamiliar with passive protection techniques may inadvertently neutralize a passive device.
4. The passive device may not be activated by accidental fires.

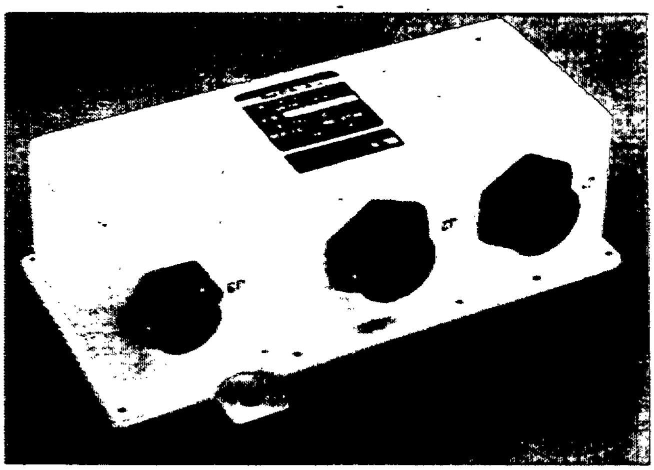
7-4.2.3 Logic Followed by Current US Army Active Fire-Extinguishing Systems

The following is a brief description of the logic followed by the automatic fire-extinguishing systems (Ref. 132) used in the latest US Army combat vehicles, such as the FAASV and some armored systems modernization (ASM) vehicles.

The optical fire sensor assembly (OFSA) per MIL-S-62546A responds to optical radiation from exploding or combusting atomized or vaporized hydrocarbons and energizes the fire-extinguishing system within 3 to 4 ms, depending on the optical sensor type, when an energy level equal to or greater than the large fire threshold is reached. The optical fire sensor systems are intended for use in combat vehicles, crew and squad zones, and other compartments, such as engine spaces. System standardization assures maximum interchangeability between various vehicle families. These systems are designed to protect against the potential danger of detonations, deflagration, and slow-growth fires caused by the presence of highly combustible fuels or other liquid hydrocarbons or flammable debris.

The fixed fire extinguisher per MIL-V-62547 and described in subpar. 7-3.1.1.1 is designed to be used with the module, standard electronic control (MSEC). It includes an integral pressure switch to indicate when the extinguishant pressure drops below a preset limit, i.e., 2.52 to 2.76 MPa (365 to 400 lb/in.^{2}), and an agent flow switch to confirm successful extinguishant discharge after receipt of an activation signal. This information is used by the MSEC to determine extinguisher availability and whether extinguisher backup is required (See subpar. 7-4.4.2.). The extinguisher can be operated automatically, electrically and manually, or mechanically and manually. The system usually operates as a two-shot, two-extinguisher-per-shot system. (Current systems in the M1 MBT or the BFV are single shot.)

The order of priority of the extinguishers in the system is 1 (highest), 2, 3, and 4 (lowest). Extinguishers are considered available when pressure/flow switch and solenoid continuities are sensed by the MSEC in accordance with MIL-M-62545, shown in Fig. 7-20 and connected as shown on Fig. 7-21. The MSEC follows the extinguisher activation logic shown on Fig. 7-22. Within 2 ms of receipt of a large fire signal from an OFSA or an electrical-manual activation signal from the test and alarm panel, the MSEC applies extinguisher drive signals to the two highest priority, available extinguishers. An extinguisher is not considered to be available for 8 to 10 s after the MSEC has supplied a drive signal to it. If flow indications are not received within 38 ms of the start of the drive signal for either or both of the extinguishers chosen initially, the MSEC provides automatic backup to select and apply drive signal(s) to the next highest priority extinguisher and check its flow in turn. After the MSEC begins extinguisher activation, it ignores OFSA large fire signals for 0.5 s and electrical-manual activation signals for 4 to 6 s. If the MSEC finds no available extinguishers when a large fire signal is present, it sequentially applies an extinguisher drive signal to each extinguisher (with not more than 2 ms between consecutive drive signals). This drive signal application is done on the possibility that extinguishers indicated as unavailable may in fact be usable. The MSEC does not apply subsequent drive signals until extinguisher availability is again indicated, as shown on Fig. 7-22.



Courtesy of HTL/Kin-Tech Division, Pacific Scientific, Duarte, CA.

Figure 7-20. Standard Electronic Control Module

7-4.3 DISTRIBUTION SUBSYSTEM

A fire extinguishant distribution subsystem is needed only by an active fire-extinguishing system. The distribution subsystem is used to provide fire extinguishant at the site of the fire. Passive systems using threat-dispersed fire extinguishants automatically broadcast the extinguishant where the threat would cause a fire. The critical determinants for distribution subsystem design are the overall system response requirements and the type of extinguishant used.

7-4.3.1 Within the Crew Compartment

The design of the fire extinguishant distribution subsystem within the crew compartment is influenced by the system response requirements; the type of extinguishant used; the locations of sources of combustible hydrocarbon fluids; the size, location, and shape of the compartment and the items within that can block or divert flow; the location and direction of airflow from the ventilation system or compartment heater; and the location, size, and number of extinguishers. The flow of an extinguishant, particularly one that flashes from liquid to gas (as Halon 1301 does), must be through nozzles. These nozzles and the rest of the plumbing and reservoir are designed to maintain a back pressure on the extinguishant to prevent its flashing to a gas before reaching the nozzle. Were the extinguishant to become gaseous before reaching the nozzle, the flow rate would be greatly reduced. These nozzles must be optimized for each application.

Because of the complex geometry of crew compartments, the extinguishant must travel a relatively long distance from its release point to the fire. An extinguishant that must travel in gaseous form, such as Halon 1301, is quickly slowed down by the air within the compartment because each molecule quickly loses momentum when colliding with the air molecules. If the extinguishant is in mist (liquid) or powder (solid) form, the individual particles are significantly larger than the air molecules; therefore, many collisions are required to reduce the

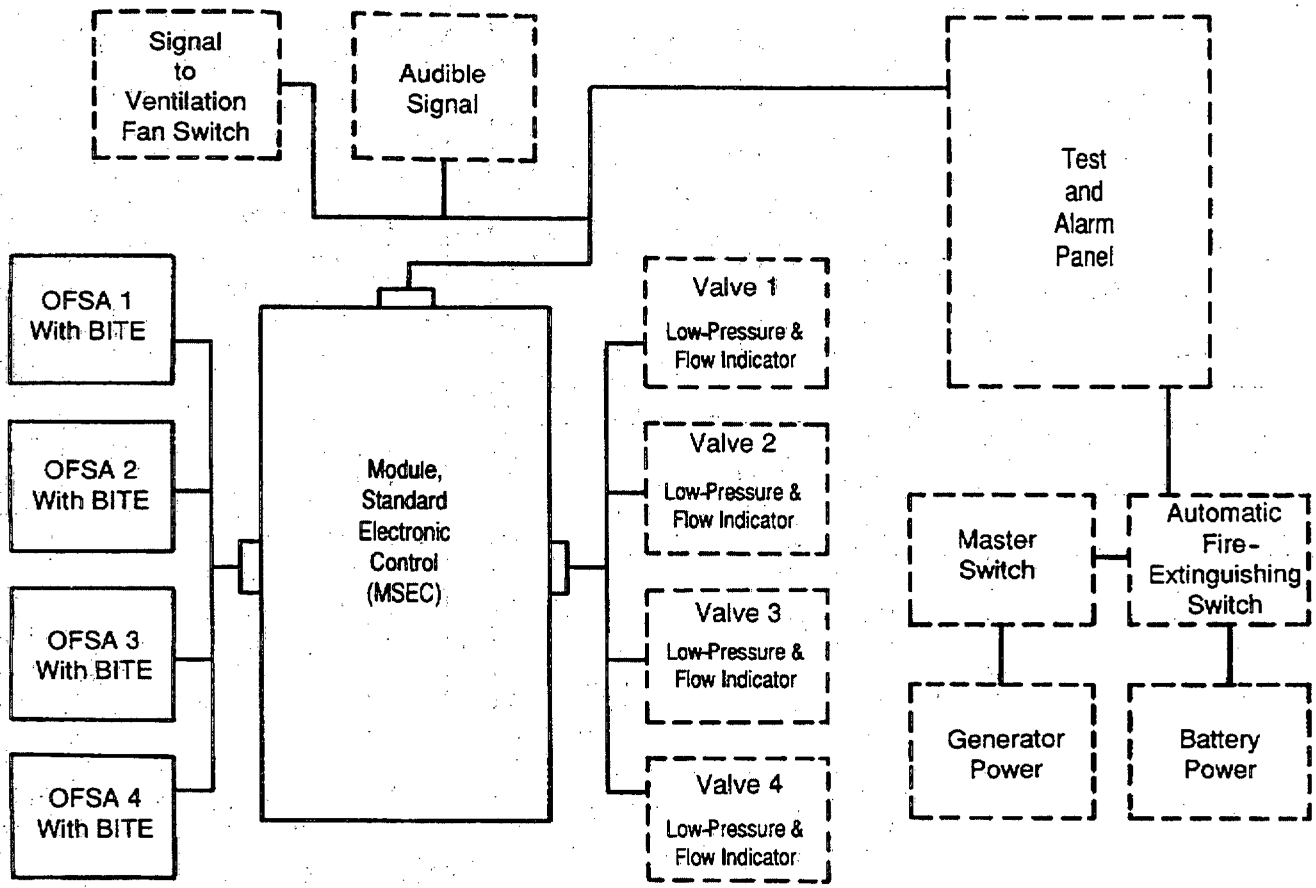


Figure 7-21. Block Diagram of Typical AFES Configuration (Ref. 133)

directed momentum of the extinguishant particles. Thus extinguishant in mist or powder form maintains its momentum to travel farther and more rapidly than extinguishant in gaseous form, and fire extinguishers projecting a mist or a powder are said to have a greater reach than those projecting gas. Extinguishers with the greatest reach, however, are those that project a liquid stream. Liquid can also be projected as a spray, i.e., with larger particles than a mist.

A gaseous discharge from a nozzle will billow outward radially to cover a greater volume in a shorter time than a mist or powder discharge. This fact is important to inerting the interior of a compartment quickly. Mist and powder billow radially more than a jet. A spray can be made to expand to the same dimensions as a mist, but the particles will be much larger. Usually use of a jet or spray is reserved for nozzles being manipulated manually, not for those of an AFES. For an AFES to be effective, the nozzles used must be selected for the application and positioned to direct the extinguishant where it is needed.

Current vehicle AFESs use Halon 1301. Halon 1301 is released as a liquid but flashes to a gas. A submerged jet of gaseous Halon 1301 in air loses speed rapidly; therefore, distribution of Halon 1301 beyond the nozzle is influenced by convection of the airflow within the compartment. These air currents are also dependent upon the compartment ventilation system and the crew compartment heater as well as on the halon distribution system. In one M113 AFES test catastrophic results occurred when the halon distribution system was disrupted by the test charge detonation displacing an extinguisher bottle. Thus the Halon 1301 was not projected as planned. (This incident is described in subpar. 5-2.2.3.3.) Halon 1301 functions by flooding the crew compartment rather than by being a stream projected into the combustion region. Because there is a system response requirement of no further detectable combustion after 250 ms, Halon 1301 has to be released quickly; therefore, the length of piping between the bottles and the nozzles and restrictions of the flow passage are minimized. In most of the current crew compartments, no distribution systems are used. Halon 1301 is ejected from the valve at 5.2 MPa (750 lb/in.^{2}) through a nozzle into the air. An alternate for Halon 1301 would have to be evaluated to ascertain the design features needed for the distribution system.

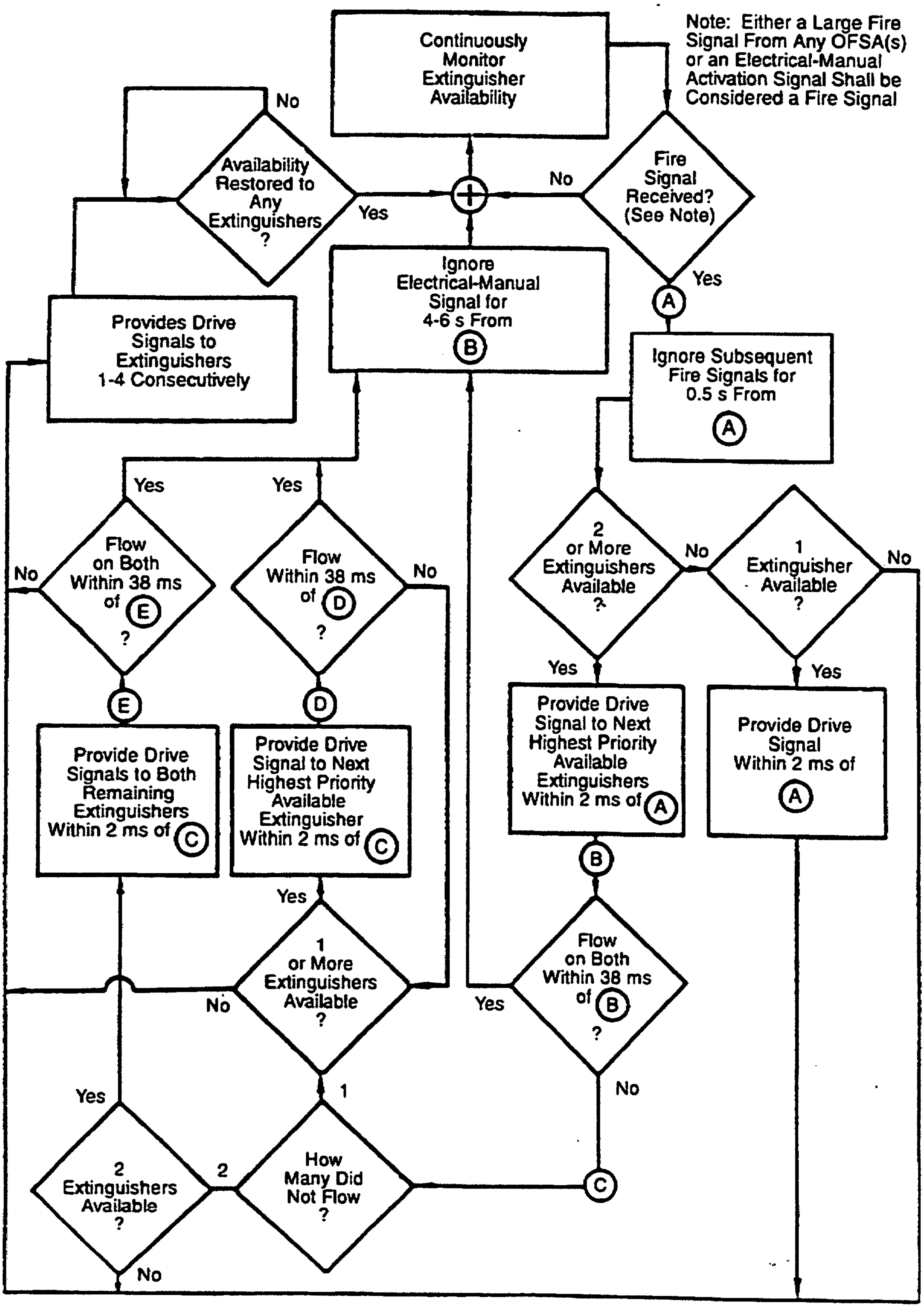


Figure 7-22. Extinguisher Activation Logic (Ref. 133)

7-4.3.2 Within the Engine and/or Cargo Compartment

The design of the fire extinguishant distribution subsystem within an engine and/or cargo compartment is influenced by the same factors as it is for the crew compartment. The main differences are the high coolant airflow for the engine, the high heat of the engine, the system response requirement, and the choice of extinguishant. The system response requirement for an unoccupied compartment allows more time than it does for an occupied compartment. The choice of fire extinguishant is no longer determined primarily by human exposure, so other fire extinguishants can be used. Although the prime means of extinguishing combustion is still by flooding the compartment, the cooling effects of the extinguishant are also important. Distribution of the extinguishant is helped by being able to use liquid or powder extinguishants. The liquid extinguishant could be water; the powder extinguishant could be potassium bicarbonate. Both liquid and powder extinguishants have better throwing capabilities. They are also more persistent and thus result in a longer period of compartment inertness.

Engine compartments are different from crew compartments because there is much less unoccupied space and there is a much higher airflow. (The higher airflow is required to cool the engine.) This higher airflow affects extinguishant distribution and must be considered. Engine compartments can withstand hydrocarbon spray fireballs and short-duration small fires. Fires are less easily detected by optical detectors, because engine components that are densely packed into engine compartments are in the way. Thus fires often exist longer in engine compartments before the extinguisher system is activated. This delay results in greater heating of items within the compartment. For these reasons, it is more important that the extinguishant used in the engine compartment be more persistent than the one used in the crew compartment and that this extinguishant be capable of cooling the heated items. Due to its normally hot environment, extinguishers are usually not located within the engine compartment unless they must be there to obtain the desired performance, such as the linear fire extinguishers described in subpar. 7-3.1.5. The extinguishants would not necessarily be distributed by plumbing but could be explosively launched as described by Finnerty (Ref. 86), who used a short length of Primacord® to disperse water from a plastic bottle to extinguish combustion of solid propellant grains on a tray; however, such explosive and liquid-filled devices would have to be protected from the engine heat.

Passive fire protection techniques have been demonstrated (Ref. 98) that include a double-walled or jacketed fuel cell. Again the threat distributed the fire extinguishant (Water, Halon 1011, and potassium bicarbonate were successfully tested.) into the region in which the hydrocarbon mist fireball existed.

7-4.4 AUTOMATIC ELECTRONIC CONTROL SUBSYSTEM

The development of rapid response and reliable fire detectors, both optical and thermal, has made totally automatic fire-extinguishing systems possible for combat vehicle applications. The advances in detector response time, false alarm immunity, and reliability, as well as those in development of the control electronics necessary to integrate the detectors and the agent-dispensing subsystems, have enabled designers to develop fire-extinguishing systems that respond and extinguish fires within milliseconds. The actual design and response criteria for the detectors are covered in Chapter 6. The automatic fire-extinguishing systems, such as the optical detection system used in the AAV 7A1, can sense a fire, sound an alarm, and dispense the fire-extinguishing agent in 12 to 15 ms (Ref. 82). Tests were performed on an AAV 7A1 vehicle in support of the live-fire tests in which a rocket-propelled grenade (RPG) -7 warhead was fired into the vehicle through the exterior armor and the fuel cell and caused a fuel mist deflagration in the crew compartment. The time necessary to contain the fireball ranged from 27 to 52 ms, and the time necessary to achieve total suppression varied from 45 to 225 ms. Posttest inspections of mannequins placed in the vehicle showed no evidence of burning of either the mannequins or their clothing. These extremely fast suppression times show the efficiency with which the AFES detects and extinguishes a fire—before catastrophic results can occur.

Since current automatic fire detection and extinguishing systems are so reliable and can be designed to be nearly false alarm proof and yet can respond in such a short time, automatic systems currently are used in combat vehicles to assure protection from combustible fluid spray fires. The demonstrated ability of these systems to extinguish fires in milliseconds definitely outweighs any problem that could arise with false alarms. Automatic systems are subject to ballistic or accidental damage that can render them inoperative; therefore, they should have fail-safe features and redundancy designed into them. At the time this handbook was being prepared, the main challenge for automatic fire-extinguishing systems was identification of a satisfactory alternate for Halon 1301.

7-4.4.1 One Shot, Two Shots, or N Shots

Current electronics and controls allow a designer to add a level of sophistication to fire-extinguishing systems and to design them to be either single shot or multiple shot. The multiple-shot extinguishing system enables a combat vehicle to continue operating with an available extinguishing system even after having sustained a hit that resulted in a fire. Certain fire-extinguishing systems, such as the Kidde-Graviner system (Ref. 134), utilize a multiple-shot electronics controller and are designed to function for up to three shots and use two suppressant bottles per shot. Combat vehicles can be expected to be hit more than once, so the design of the extinguishing system will be influenced by the need for vehicles to survive multiple hits. A multihit fire-extinguishing system requires multiple extinguishers to provide for the multiple shots; each valve and bottle are used for a single shot. (At the time this handbook was prepared, dual-shot extinguishers were under development but were not ready for vehicle application.)

The logistics of multishot fire-extinguishing systems do not pose any particular problem to the designer because the multishot system uses solenoid valves, which are excellent for high-pressure situations. Because the system uses a new bank of bottles for each shot, the vehicle should not have to lose its fire-fighting capability when the first shot is discharged.

7-4.4.2 Backups for Automatic Extinguishers and for Automatic Systems

Automatic extinguisher backup is a system that checks the presence of extinguishant within a bottle and electrical continuity to the valve and automatically sequences to an alternate bottle to assure that extinguishant flows into a preselected space. The presence of extinguishant is established by bottle pressure, and low bottle pressure is signaled to the crew.

Automatic extinguisher backup should not be confused with either a backup for the automatic system or system redundancy. There are two types of backup for an automatic system. One is used when the automatic system fails to activate extinguisher bottles, a manual activation handle or switch is provided (See subpar. 7-4.5.), and the other is used when the automatic system fails to extinguish the fire, either a manual system is provided or portable extinguishers can be used (See subpar. 7-3.3.).

Current fire-extinguishing system design incorporates a backup system for automatic fire-extinguishing systems. This backup system, however, has primarily been a manual backup so a crew member can discharge the extinguishing system should the automatic system fail to respond. Most of the current combat vehicle fire-extinguishing systems have very limited redundancy built into them because of the severe space and weight limitations placed on these extinguishing systems. The redundancy is usually limited to the agent storage bottles. As previously mentioned in this chapter, the use of redundant components whenever possible is strongly recommended, especially in regard to critical components, e.g., the detectors, control electronics, electric wiring, and distribution system. If limitations preclude the use of complete backup systems, the designer should assure that as a minimum, the fire-extinguishing system has a manual backup so the crew can activate the fire-extinguishing system should the automatic function fail. Another reason to have a manual backup is to allow the crew to trigger the fire-extinguishing system if vehicle power is lost. This capability requires the use of a backup battery to provide temporary power to the solenoids and other electronics if an electric-manual system is used.

7-4.4.3 Response Requirements

The response requirements for an automatic fixed fire-extinguishing system are based upon the combustible to be extinguished and the items to be protected from fire effects.

7-4.4.3.1 Hydrocarbon Fluids in Mist or Spray Form

When the combustible is a hydrocarbon mist or spray in personnel-occupied compartments, the fire-extinguishing system must respond rapidly enough to protect the crew. Currently, a system response that assures extinguishment within a crew compartment of all detectable combustion within 250 ms of threat impact is acceptable. The AFES must protect the crew from receiving second-degree burns. (A superior system requirement would be to preclude the occurrence of these fireballs by use of a passive system as discussed in subpar. 7-3.2.) Actually the requirement is to extinguish the fireball that results from a shaped-charge jet or high-velocity KE penetrator going through a combustible fluid container. This type of combustion does not have time to heat the compartment, the compartment walls, or anything within the compartment; therefore, the extinguishant has only the incipient "fire" to extinguish and does not have to cool surrounding objects. Crew compartments generally do not contain ignition sources other than those that are threat caused. Therefore, reignition is not as great a problem as it is within the engine compartment.

When a threat causes hydrocarbon mist or spray within an engine compartment, the response requirements are different. First, continuous ignition sources, such as the combustor can of the M1 MBT turbine engine, exist; thus the threat of reignition is continuous as long as fuel and oxidizers are present. Second, the items more susceptible to damage by fire are electrical cable insulation, rubber mobility fuel or hydraulic fluid hoses, and lighter weight engine components, although even these items can char a bit before becoming inoperable. The response time needed for the fire-extinguishing system is a function of the radial burning rate of the outermost layer of these items and the kindling temperature of that material. In this case, the heat generated by the fire rather than radiation from the fire causes damage. The fire-extinguishing system response can therefore be much slower and measured in seconds rather than milliseconds. The extinguishant, however, should be different also. In this case, reignition is a significantly greater problem. The compartment should be inerted long enough for the combustible liquid to drain into the bilge, and whichever components have been heated above the ignition point of the combustible fluid should be cooled. For some applications a response time of 15 s has been established for this engine compartment fire-extinguishing system, i.e., 10 s for fire detection (allowing for thermal detection) and 5 s for fire extinguishment.

7-4.4.3.2 Explosives, Low and High

When the combustibles are explosives initiated by penetration of a jet or high-velocity penetrator, the resulting chemical reaction is probably either a deflagration or a detonation. Fire-extinguishing systems do not exist that can react in time to halt these chemical reactions. Further, low explosives (solid gun or rocket propellants) are usually in a metallic or combustible case, which, even if perforated by the jet or penetrator, would prevent the bulk of any extinguishant from reaching the propellant grains. Extinguishment of propellant grain combustion must be accomplished by cooling (Ref. 86). Even when the propellant is in the form of a caseless cartridge, the extinguishant cannot cool more than the external surface of the propellant. Therefore, a fire-extinguishing system is not truly applicable unless it effectively reduces the probability of fratricide (a cartridge causing initiation or ignition of the explosives in an adjacent cartridge that would otherwise not be initiated or ignited) or the effects from the cartridge that the jet or penetrator initiated or ignited. A better survivability enhancement system for explosives is one that prevents fratricide so that the only cartridges to react are those directly impacted by the threat and vents the overpressures outboard. These systems are described in subpars. 4-6.2.2 and 4-6.4.1.

7-4.4.3.3 Other Combustibles

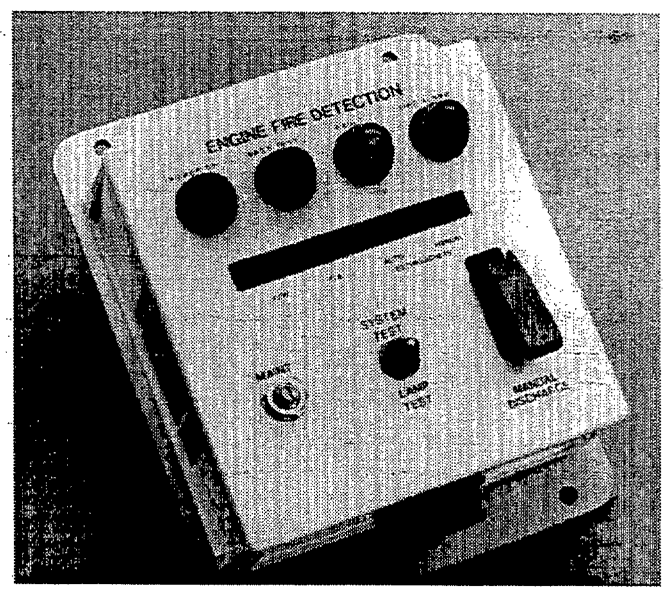
Other combustibles include wire insulation, clothing, paper, and other items that may be in the vehicle. Most of these are extinguished by cooling. These combustibles present a response problem when hydrocarbon fluids or gun or rocket propellants can be ignited. A slower response, such as is provided by a heat sensor or even a smoke detector, is adequate. Smoke detectors, however, have a problem of false alarms, particularly when weapons are fired or when dusty conditions prevail.

An AFES would probably not be used with these other combustibles. Extinguishment of the combustion of these items could be better decided and directed by a human using portable fire extinguishers, manual activation of a fixed fire-extinguishing system, or other means.

7-4.4.4 Built-In Test Equipment (BITE)

The use of built-in test equipment (BITE) to determine the status of the fire-extinguishing system is definitely an aid to the crew in reducing the time spent doing routine checks. BITE can be as simple as a gage that monitors system status such as pressure and moves a "flag" or needle to indicate a certain condition, or it can be as sophisticated as the automatic optical integrity system used (Ref. 135) to check a UV detector for loss of sensitivity caused by a dirty window or an electronics problem or failure. This type of BITE capability is required in MIL-S-62546. BITE should be designed and implemented to determine system status of the following components as a minimum: detector integrity (whether the detector is optical or thermal); electrical continuity of the control electronics and of the detectors; agent bottle pressures; and control unit status. There are a number of totally automatic BITE systems, which are used in current fire-extinguishing systems, such as the M992 FAASV engine bay test and alarm panel, illustrated in Fig. 7-23, which monitors a thermal wire sensor and two bottles (Ref. 136). A crew bay test and alarm panel, which appears almost identical externally to the engine panel, is designed to monitor four optical detectors, four bottles, and one amplifier (Ref. 137). The Kidde-Graviner control unit (Ref. 134) features a totally automatic BITE that displays system faults including detector faults, cable faults, extinguisher faults (low pressure or loss of electrical continuity), and control unit failure on an alphanumeric display located in the front of the control unit. The actual faults are displayed as a coded message. The crew bay test and alarm panel monitors the circuitry within the unit and isolates any defect of any module within the fire-extinguishing system and gives a diagnostic display.

As mentioned previously, some of the optical detection systems have automatic BITE, e.g., the automatic optical integrity test for UV detectors. Some of the infrared (IR) optical detection systems, e.g., for the M1 MBT and M2/M3 BFV, require the crew to use a separate test set. The fire-extinguishing system test set used to check out the dual spectrum IR detector (Ref. 138) contains all of the BITE electronics and controls necessary to perform checkout tests and to verify the results. The unit generates test and timing signals to the infrared radiation unit (which is used by the crew to test the optical detectors), provides the necessary threshold and logic circuits, drives



Courtesy of HTL/Kin/Tech Division, Pacific Scientific, Duarte, CA

Figure 7-23. M992 FAASV Engine Bay Test and Alarm Panel (Ref. 136)

the lamp indicators, and contains its own power source. The infrared radiation unit provides infrared radiation of the proper spectral bands and energy levels to determine whether or not the optical sensor is operating properly.

The majority of the BITE in use for testing the agent storage systems consists of system self-checks of the actual storage bottle. Because the majority of the current fire-extinguishing systems use a pressurized extinguishing agent, the crew needs to know the pressure in the extinguishant quickly and accurately. Extinguishers include a gage to measure the pressure of the agent as part of the valve. MIL-V-62547 valves (Ref. 139) use a temperature-coordinated pressure gage to measure bottle pressure because of the wide variations in pressure caused by bottle temperature. The gage uses a green "flag", which moves with temperature, and a black needle, which moves with pressure. This setup allows the crew to look for a black needle over the green background for a nominal status compared to having to read a pressure that would then have to be compared to a temperature versus pressure "go no-go" chart. Electrical continuity is continuously monitored between the controller and extinguishers. At the same time, the pressure switch in the valve relays information to the electronic controller so that if the pressure of the agent is very low, an indicator light will signal that service is required on that component, and the controller can select an alternate bottle.

System test and alarm panels should also be designed to include BITE capabilities so that the crew can test the operational status of any lamps or lights on the panel. In addition, the test panel should have a capability to perform a self-test to determine whether there are any faults in the electrical circuits and to check for electrical continuity in the wiring. The system designed by Spectronix Ltd (Ref. 140) for use in the engine compartment of an armored vehicle has integral BITE to determine the status of the lamps on the control box. The system automatically checks for electrical faults in the control box and performs a continuity check of the overheat detection wire used by the system to detect fires.

7-4.4.5 Test and Alarm Panel

The test and alarm panel should enable a crewman to see the vital information on the status of the fire-extinguishing system so he can tell at a glance that the system is operational. In a combat situation the crew does not normally have time to do any detailed system troubleshooting or interrogation. Ideally, a test panel should provide information only on the most critical components of the fire-extinguishing system: system power, detector status, agent bottle status, and control unit status. As previously mentioned, the Kidde-Graviner control unit (Ref. 134) features an alphanumeric display on its front panel. This alphanumeric display will show system faults including detector faults, cable faults, suppressor faults such as low pressure and empty status, and control unit failure. In addition, the control unit has a check of the test lamps and the alphanumeric display. The M992 FAASV crew bay test and alarm panel (Ref. 137) contains lamp test and system test functions. In addition, this unit has a built-in timer that keeps the extinguishing system active for three hours after the master power switch for the vehicle has been shut off.

7-4.5 MANUAL ACTIVATION

The following reasons may lead to selection of a manually activated fixed fire-extinguishing system:

1. The compartment and its contents are not overly susceptible to fire damage, so a slower fire-extinguishing system can be used.
2. False alarms have plagued an automatic control system.
3. The extinguishant can adversely affect crew and/or cargo.
4. The cost of this system is less.

In addition, backup or optional manual activation control features may be included in the automatic system. A detector system should provide a signal that a fire has been detected in a given location. This fire indicator is usually located adjacent to either an electric switch or a handle that is used to activate the fixed fire-extinguishing system. The fire extinguisher activation signal is transmitted through electric wire or through mechanical motion, i.e., a cable, rod, or shaft. In both cases the mechanism is subject to ballistic or other damage that can render the manual actuation capability of the fire-extinguishing system inoperable. Lack of a detector system in an unoccupied compartment can lead to fires not being detected. Data from the USASC, which is discussed in subpar. 4-1.1, yielded many instances of the commander of a second vehicle radioing the commander of the vehicle in front of him that the front vehicle is emitting smoke and apparently is on fire.

7-4.5.1 Electrical-Manual

An electrical-manual system is one that requires the crew member to initiate the extinguishing system by depressing or closing an electrical switch to activate the extinguishing system. This electrical-manual activation could be wired as an override to the logic system, i.e., the human must make the decision. A variation could be provided that connects the switch directly to the extinguishers by separate wires and provides a redundant means to actuate the fire-extinguishing system.

7-4.5.2 Mechanical-Manual

A mechanical-manual fire extinguisher initiation system uses a mechanical device such as a cable, rod, lever, or shaft to trigger the extinguishing system. Such an activation system could be used in lieu of or in addition to the electrical-manual activation system. In this system one or more handles are provided for crew members to use.

7-4.5.3 Placement of Activation Handles and Switches

Manual activation handles and switches for combat vehicles should be placed where crew members can reach them when there is an active fire. Redundant capability should be provided so that the crew can activate the extinguishers from inside or outside the vehicle. Manual activation capability should be independent of vehicle power. Handles and switches must be clearly labeled and positioned to minimize inadvertent activation. There was one USASC fire incident reported during which the driver evacuated without pulling the internal fire extinguisher handle located beside his seat. The fire became quite active; no one dared to climb into the vehicle to actuate the fire extinguisher. A redundant external handle would have allowed personnel to activate the fire extinguisher from outside the vehicle and thus greatly reduce fire damage.

7-4.6 ROLE OF HANDHELD EXTINGUISHERS

Handheld fire extinguishers are necessary in combat vehicles because they can be used for fires that automatic, semiautomatic, or passive fire suppression systems cannot or do not extinguish. Handheld fire extinguishers provide a fire fighting capability when the vehicle is not operative and when there are fires outside the vehicle.

Handheld fire extinguishers are needed to extinguish combustible metals fires, deep-seated fires, slow-burning fires such as cloth or paper, fires that a fixed fire-extinguishing system does not address because of location or extinguishant incompatibility, and fires that occur or persist after the fixed fire-extinguishing system has expended its extinguishant. For some vehicles handheld fire extinguishers will be the only systems available because there is no system installed or the extinguishant was not replaced. For a passive fire suppression system, appropriate handheld extinguishers are an excellent secondary system.

Handheld extinguishers containing a dry chemical or appropriate liquid extinguishant are recommended for fighting most liquid hydrocarbon fires because they can be used where there are sparking electric ignition sources. The dry chemical and liquid extinguishants have better carrying properties and can inert an area longer than a gaseous extinguishant such as Halon 1301 or carbon dioxide. The sparking electrical ignition source should be deenergized. A water-based extinguishant with AFFF or HEF added is recommended for fuel pool-type fires because it can provide a film on the surface of the fuel pool. A handheld extinguisher containing an appropriate Class D agent is one of the few means of fighting a combustible metal fire.

7-5 EXAMPLES

The current usage of fire-extinguishing systems is described in this paragraph. Examples of fire-extinguishing systems currently installed in vehicles are given.

7-5.1 COMBAT VEHICLES

7-5.1.1 Description of US Army Systems

Operational requirements and design guidance objectives are established for US Army equipment by the US Army Training and Doctrine Command (TRADOC). The operational requirements thus established for fire-extinguishing systems for current combat vehicles are:

1. *APC M113*. No requirements
2. *MBT M60*. No requirements for the original model. (A requirement for an AFES to be retrofitted has been cancelled.)
3. *MBT M1*. "...shall have an integral fire detection/suppression system for crew and engine compartments with a nontoxic extinguishing agent."
4. *BFV M2/M3*. "...must have a fire suppression system."
5. *FAASV M992*. "...shall start to extinguish fires within 200 ms."
6. *TRV M88A1E1*. AFES desired that extinguishes fires within 100 ms.

Current US Army combat vehicle fire-extinguishing systems described in the following subparagraphs are the M60 and M1 MBTs, the M2/M3 BFVs, and the M992 FAASV. In addition, the fire suppression system for the ASTB is described. See Table 7-15 for the characteristics of the fire-extinguishing systems.

7-5.1.1.1 M113 Armored Personnel Carrier

The M113 series APCs have a manual carbon dioxide FFES for the engine compartment. The 2.3-kg (5-lb) extinguishant bottle of the system is located in the crew compartment. There is no fire detection system, but there is a handheld extinguisher, also 2.3-kg (5-lb) carbon dioxide, in the crew compartment at the rear on the right wall.

7-5.1.1.2 The M60 Main Battle Tank

The M60 MBT has no fire protection for its main gun ammunition, which is stowed in the forward part of the hull beside the driver, in a turret bustle magazine, and in a ready rack on the floor of the turret basket. Mobility fuel is carried in two welded aluminum fuel cells located in the engine compartment, which is separated from the crew compartment by a fireproof bulkhead. The turret traverse is activated by hydraulic fluid pressure accumulated by the pump for the hydraulic system, which is driven by an electric motor.

The engine compartment is equipped with a fixed fire-extinguishing system with two external and one internal mechanical-manual activation handles and three 4.5-kg (10-lb) bottles of carbon dioxide in a two-shot system. No fire detection is provided for either the crew or engine compartment, but one handheld fire extinguisher containing 2.3-kg (5-lb) of carbon dioxide or 1.25-kg (2.75-lb) of Halon 1301 is provided for the crew compartment.

TABLE 7-15. US COMBAT VEHICLE FIRE SUPPRESSION SYSTEM CHARACTERISTICS (Ref. 141)

		SENSOR NUMBER AND TYPE	FFES TYPE	NUMBER OF EXTINGUISHERS TYPE AND WEIGHT	DISCRIMINATION	LARGE-FIRE/ SMALL-FIRE DETERMINATION	BITE	HANDHELD EXTINGUISHERS TYPE AND WEIGHT
M60 MBT Family	Crew	None	None	None	NA	NA	NA	1 CO_2 2.3 kg (5 lb)
	Engine	None	2 Shot, Manual	3 CO_2 4.5 kg (10 lb)	NA	NA	NA	None
M1/M1A1 MBT	Crew	4 Optical	1 Shot, Manual, or Automatic	1 Halon 1301 3.2 kg (7 lb)	No	No	No	Halon 1301 2 ea. 1.25 kg (2.75 lb)
	Engine	4 Optical	2 Shot, Manual, or Automatic	2 Halon 1301 3.2 kg (7 lb)	No	No	No	None
M113 APC Family	Crew	None	None	None	NA	NA	NA	1 CO_2 2.3 kg (5 lb)
	Engine	None	1 Shot, Manual	1 CO_2 2.3 kg (5 lb)	NA	NA	NA	None
M2/M3 BFV Family	Crew	4 Optical	1 Shot, Manual, or Automatic	2 Halon 1301 2.3 kg (5 lb)	Yes	No	No	Halon 1301 2 ea. 1.25 kg (2.75 lb)
	Engine	None	1 Shot, Manual	1 Halon 1301 3.2 kg (7 lb)	NA	NA	NA	None
M992 FAASV	Crew	4 Optical	2 Shot, Automatic	Halon 1301 4 4.5 kg (10 lb) or 6 3.2 kg (7 lb)	Yes	Yes	Yes	Halon 1301 2 ea. 1.25 kg (2.75 lb)
	Engine	Thermal	1 Shot, Manual, or 1 Shot, Automatic	2 Halon 1301 4.5 kg (10 lb)	NA	Overheat Warning	Continuity Check	None

NA = not applicable

7-5.1.1.3 The M1 Main Battle Tank

The M1 and M1A1 MBTs (The M1A1 is shown on Figs. 7-24 and 7-25.) have 4-man crews and a rear-mounted engine. The M1 and M1A1 MBTs have most of the main gun ammunition in two isolated magazines, one low in the hull and one in the turret bustle (See Fig. 4-29.). The turret bustle magazine is divided into two or three sections, dependent upon the caliber of the gun. There is a three-round ready rack below the main gun breech for the M1 and a two-round rack for the M1A1, which may or may not be used—the potential hazard from such use is described in subpars. 4-6.2.2.2 and 4-6.4.1. The mobility fuel is located in six rotary-molded, high-density, cross-linked polyethylene cells. Four fuel cells are located in the hull and are armor protected. Two of these four cells are adjacent to the crew compartment, i.e., one on each side of the driver. Fuel from these two cells must be pumped to one of the cells in the engine compartment. Steel bulkheads, 25.4 mm (1 in.)

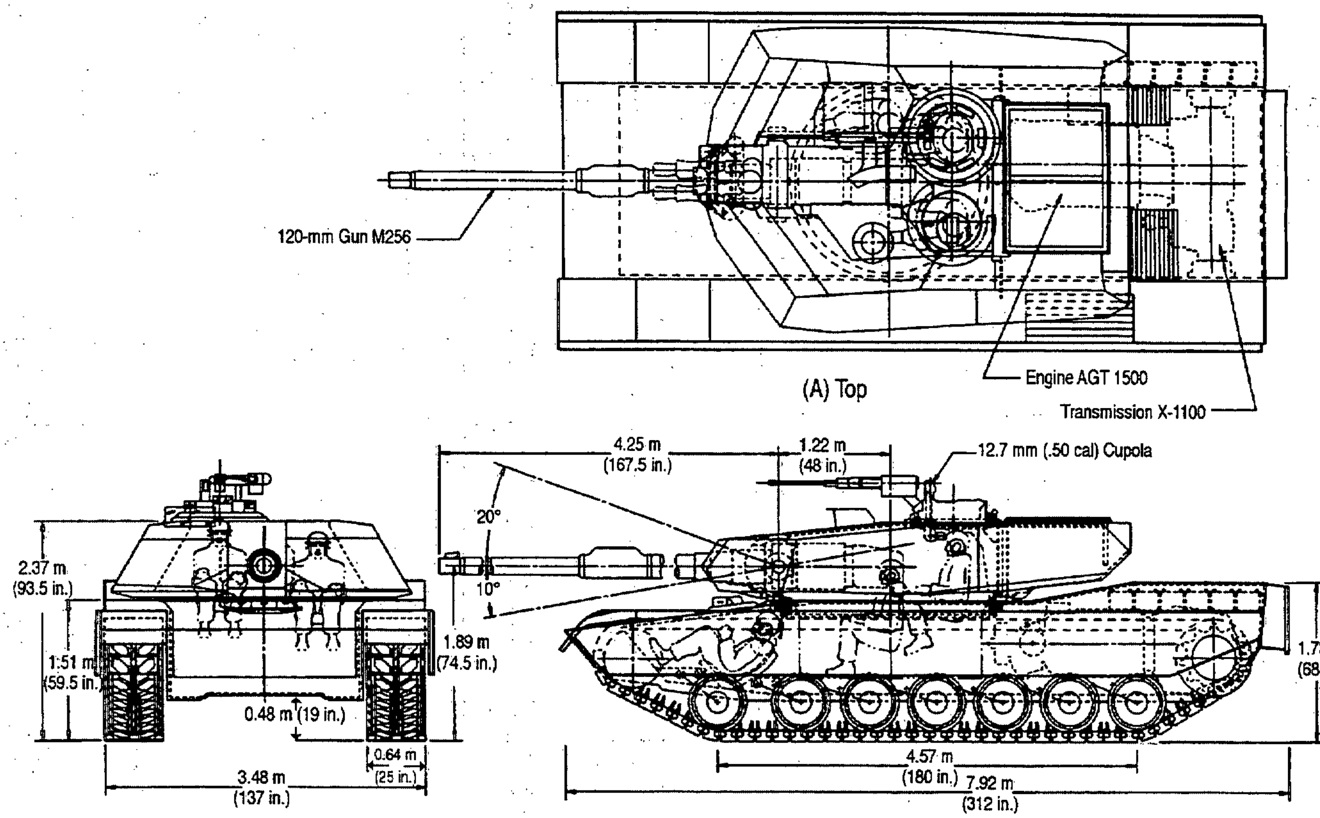


Figure 7-24. Line Drawing of M1A1 MBT

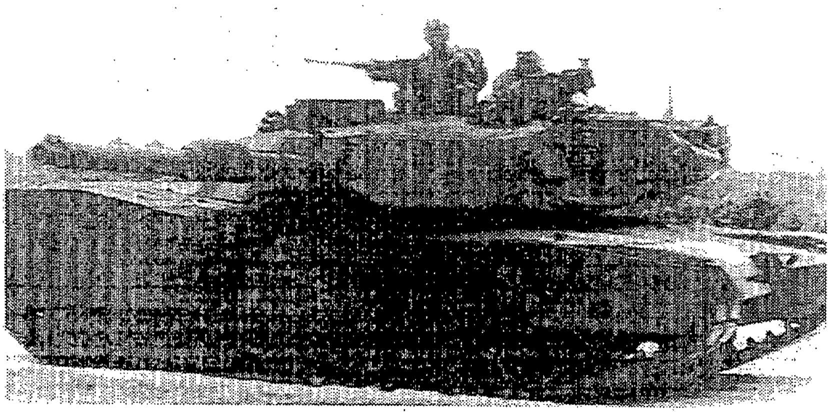


Figure 7-25. Photograph of M1A1 MBT

thick, separate these fuel cells from the driver. Two additional fuel cells are located in the sponson areas. All six of these fuel cells are interconnected so that a hole in any one can drain all cells down to the level of the hole. There is a hydraulic power system to drive the turret and to move the magazine doors.

The M1 and M1A1 MBTs have two automatic Halon 1301 fire-extinguishing systems, one in the crew compartment and one in the engine compartment. Four dual-spectrum, infrared sensors are used in each compartment. The crew compartment has an automatic, one-shot system, whereas the engine compartment has a two-shot system with automatic detection and activation of one bottle for the first shot. If a fire rekindles, the driver can release the second shot by actuating an electrical switch. This release will cause the engine to shut down, and after a built-in time delay, the second bottle will discharge. In addition, a manual discharge for the first shot in the engine compartment is provided for the driver at his station. An external handle, mounted on the left side of the hull, will discharge the second shot without the engine being shut down. The crew compartment system has one 3.2-kg (7-lb) Halon 1301 bottle, the engine compartment system has two. There are two portable 1.25-kg (2.75-lb) Halon 1301 fire extinguishers in the M1 and M1A1 MBTs.

7-5.1.1.4 Bradley Fighting Vehicles M2 and M3

The Bradley fighting vehicles (BFV) are aluminum hulled and have tube-launched, optically tracked, wire-guided (TOW) missiles, 25-mm cartridges, and other miscellaneous munitions stowed throughout the troop compartment. The M2A1 infantry fighting vehicle (IFV) is shown on Fig. 7-26, and the M3A1 cavalry fighting vehicle on Fig. 7-27. There are two rotary-molded nylon 6 fuel cells, both of which are in the troop compartment. The engine compartment is separated from the troop compartment by a 6.35-mm (0.25-in.) thick aluminum bulkhead. Considerable mobility fuel is heated by the engine and returned to the fuel cells—to the upper fuel cell in the M2 and M3 versions and to the lower fuel cell in the M2A1, M3A1, M2A2, and M3A2 versions. The personnel heater uses mobility fuel and is in the troop compartment mounted in a recess in the upper fuel cell. A hydraulic power system operates the rear ramp door. The hydraulic fluid reservoir, containing about 0.95 L (1 q) of fluid, is in the bilge near the door. The bilge under the engine is open, i.e., not covered with decking, but the bilge in the crew compartment is covered with decking.

The BFVs M2, M3, M2A1, M3A1, M2A2, and M3A2 have a single-shot AFES with manual backup in the crew compartment. The crew compartment system uses four opti-

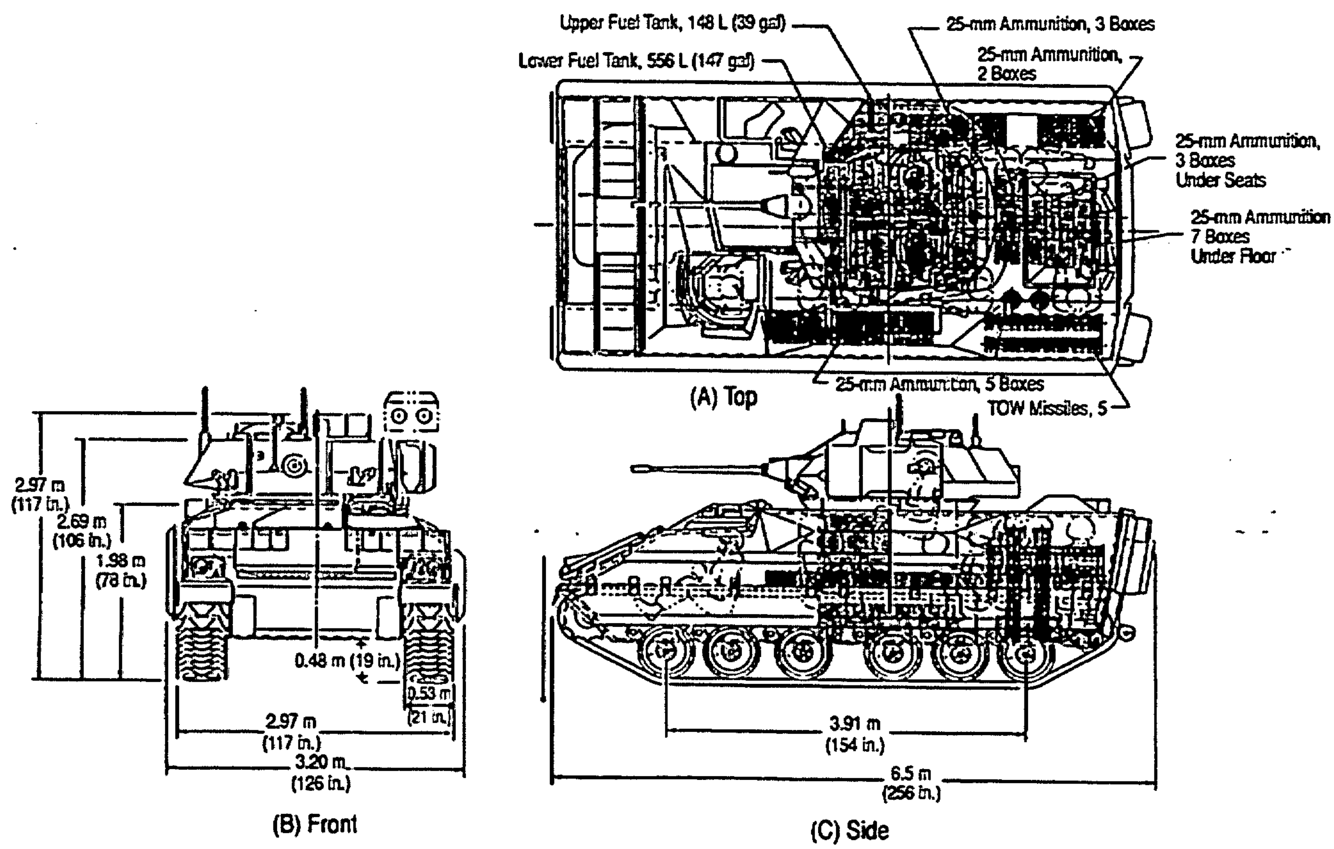


Figure 7-26. M2A1 Infantry Fighting Vehicle (IFV)

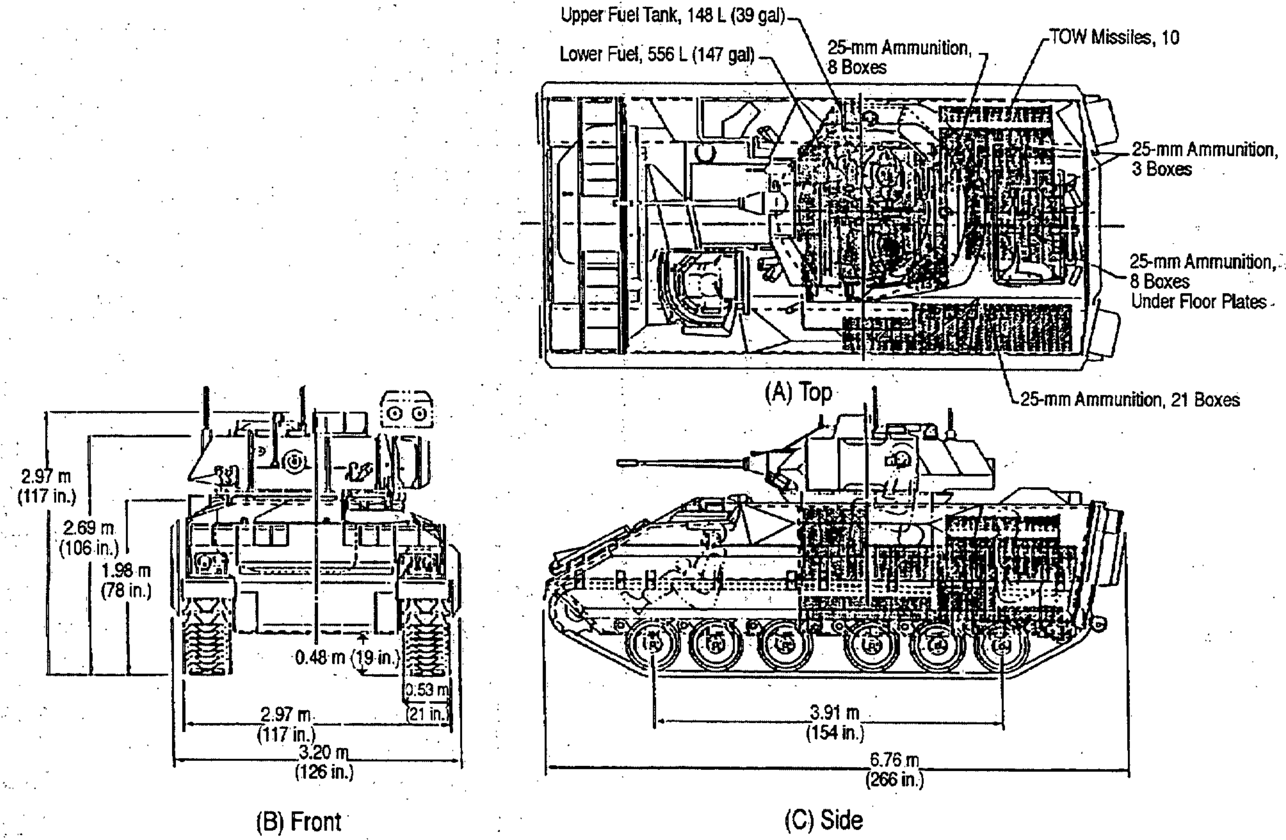


Figure 7-27. M3A1 Cavalry Fighting Vehicle (CFV)

cal sensors and two 2.3-kg (5-lb) bottles of Halon 1301. The manual engine compartment system has one 3.2-kg (7-lb) bottle of Halon 1301, which is located in the crew compartment next to the driver. There are two handheld 1.2-kg (2.75-lb) bottles of Halon 1301 in the crew compartment.

7-5.1.1.5 Advanced Survivability Test Bed Vehicle

The Advanced Survivability Test Bed (ASTB) Task Force was formed in 1986 to design, fabricate, and demonstrate alternate versions of the Bradley fighting vehicles with enhanced vehicle and crew survivability given overmatching threats. Both infantry fighting vehicle, Fig. 7-28, and cavalry fighting vehicle, Fig. 7-29, versions were made.

The ASTB had its stowed TOW missiles moved to an external magazine or placed in the bilge and had the 25-mm ammunition stowed in protected magazines or stowed externally (See Fig. 4-32.). The bulk of the fuel was stowed in external rear cells similar to those of the APC M113A3, shown in Fig. 4-2, with a smaller "get home" fuel cell in the engine compartment (Ref. 90). The troop compartment heater, fueled with mobility fuel, and the hydraulic fluid reservoir in the bilge, remained the same as in the Bradley.

The fire suppression system had the following passive and active features:

1. Most of the munitions were removed from the crew compartment.

2. The fuel cells were removed from the troop compartment, and where fuel cells abutted the troop compartment, entry of fuel into the troop compartment was restricted by an aggregate baffle. Hull flash and fireball were reduced by a gelled water baffle (Ref. 95).

3. The selectable automatic or manual fire extinguisher system covering the troop compartment consisted of four optical sensors, a controller, and two 4.5-kg (10-lb) Halon 1301 bottles. This setup was reconfigured from the BFV system by relocating sensors and bottles within the crew compartment to allow for differences in interior configuration. The fixed fire extinguisher system for the engine compartment was not changed from the BFV configuration.

4. The bilge under the engine compartment was covered with decking, but passages were provided to allow drainage of liquids into the bilge in order to provide a safe collection location for spilled liquids.

5. The effectiveness of a double-walled or jacketed fuel cell was explored and documented. These tests indicated that such fuel cells will eliminate fires in the engine compartment given a hit on the fuel cell (Ref. 98).

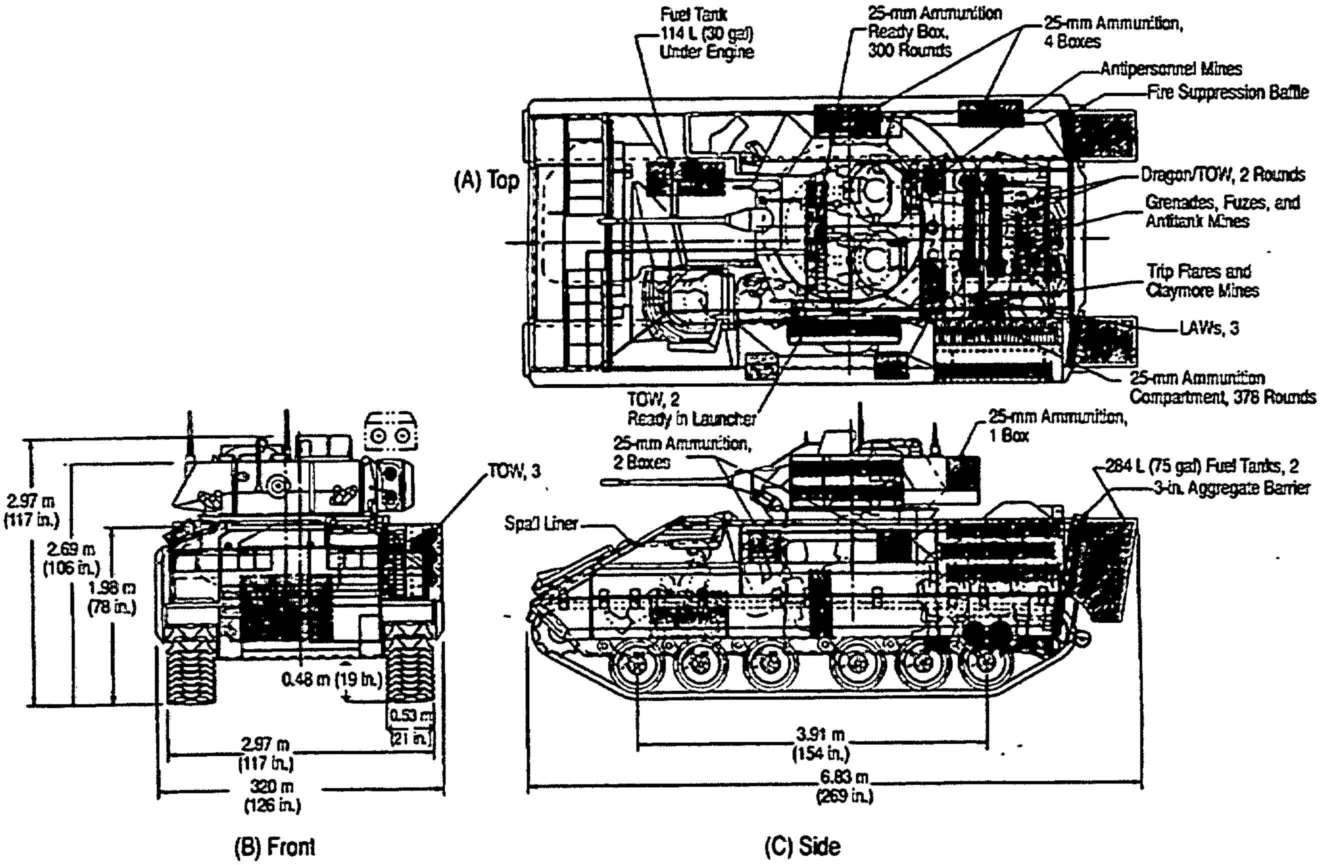


Figure 7-28. ASTB IFV Concept 163

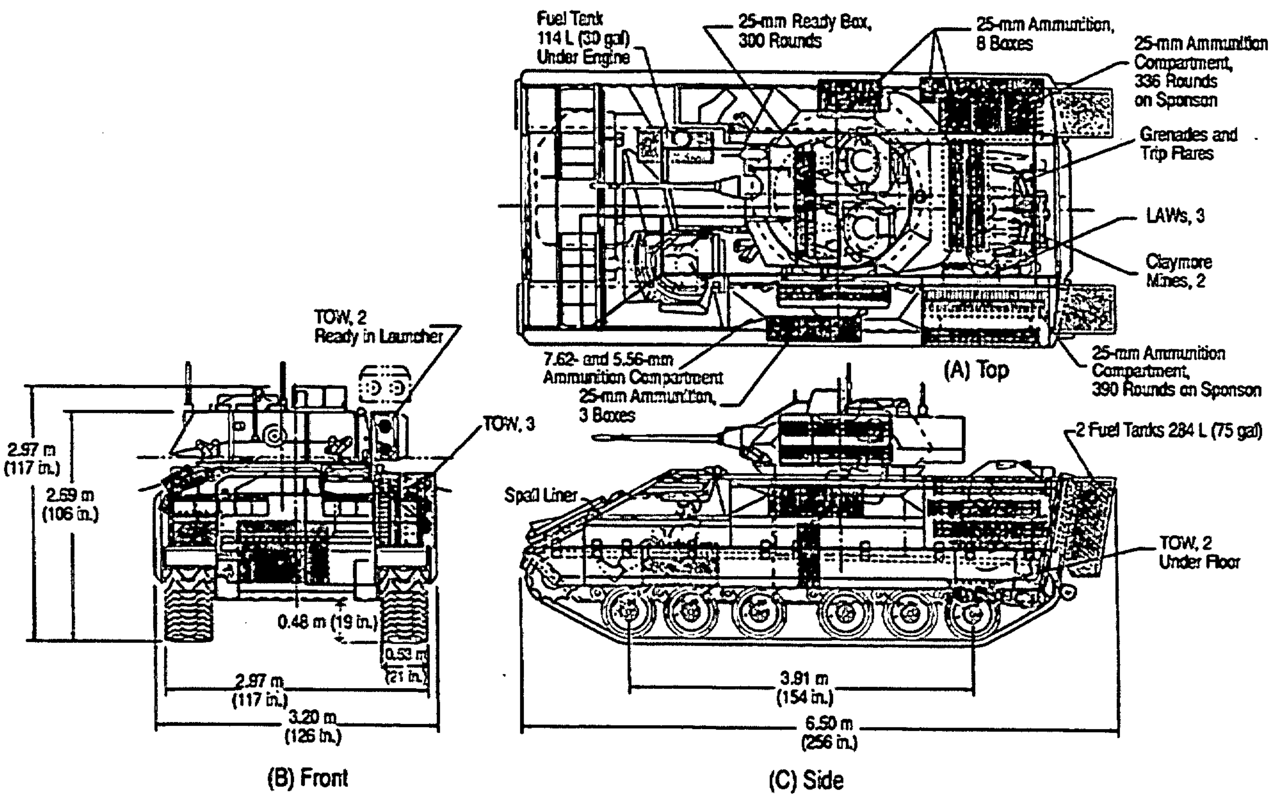


Figure 7-29. ASTB CFV Concept 165

7-5.1.1.6 Field Artillery Ammunition Support Vehicle M992

The M992 FAASV is an aluminum-hulled vehicle that carries ammunition for use in the M109, 155-mm, series of self-propelled howitzers. The chassis is basically that of the M109. The M992 has a crew of three and can carry five passengers. The artillery rounds are delivered via a conveyor to the M109. Ammunition handling within the FAASV can be mechanically assisted although crewmen still must place ammunition elements onto the conveyor belt, which uses hydraulic power. The layout of the ammunition and troop compartment is shown on Fig. 7-30. The FAASV is diesel powered and contains a fiberglass fuel cell that is located within the engine compartment and has a corner, protruding into the ammunition and troop compartment. A 3.175-mm (0.125-in.) plate separates the fuel cell from the ammunition and troop compartment. The hydraulic fluid accumulator, the reservoir, and a fuel-fed heater are in the ammunition and troop compartment. The auxiliary power unit (APU) is mobility fuel powered and is located above and behind the driver in a separate compartment.

The FAASV has an AFES for the ammunition and troop compartment that uses four optical sensors and provides two shots of Halon 1301. The halon is in four 4.5-kg (10-lb) or six 3.2-kg (7-lb) bottles, as shown on Fig. 7-31. The engine compartment has thermal detectors and a two-shot fire-extinguishing system, one shot is automatic and the second shot, manual. The engine compartment system has two 4.5-kg (10-lb) bottles of Halon 1301. For experiences of FAASVs in SWA, see subpar. 7-1.2.

The FAASV supports the M109 series SPH (155-mm cannon with separate-loading ammunition) and carries 90 conventional projectiles, 3 Copperhead cannon-launched guided projectiles or similar-sized projectiles, 99 propellant charges, and 104 fuzes. (Ref. 142)

7-5.1.1.7 Armored Reconnaissance and/or Airborne Assault Vehicle M551 (Sheridan)

The armored reconnaissance and/or airborne assault vehicle M551, shown on Fig. 7-32, has an all-welded aluminum hull and an all-welded steel turret with a titanium cupola. Power is provided by a liquid-cooled Detroit diesel Model 6V53T; 598 L (158 gal) of diesel fuel are carried in two aluminum cells, one along the starboard side of the crew and engine compartments and one across the vehicle in the engine compartment and adjacent to the firewall separating the two compartments. The main gun is the 152-mm gun/launcher M81, which fires the MGM-51A Shillelagh missile with combustible case cartridges. Combat cartridges are the HEAT-T-MP M409, WP M410, or canister M625A1 (beehive). Stowage is provided for 10 missiles and 20 cartridges. These missiles were too moisture sensitive to be used in SEA (Ref. 143), so additional cartridges were usually stowed in the spaces provided for the missiles.

The AR/AAV M551 was the first US combat vehicle to have a Halon 1301 fixed fire-extinguishing system. There is no fire-sensing system. The engine compartment has a manually activated FFES with a 1.5-kg (3.25-lb) bottle; the crew compartment has a manually activated FFES with a 3.6-kg (8-lb) bottle. In addition, there is a 1.25-kg (2.75-lb) portable fire extinguisher in the crew compartment.

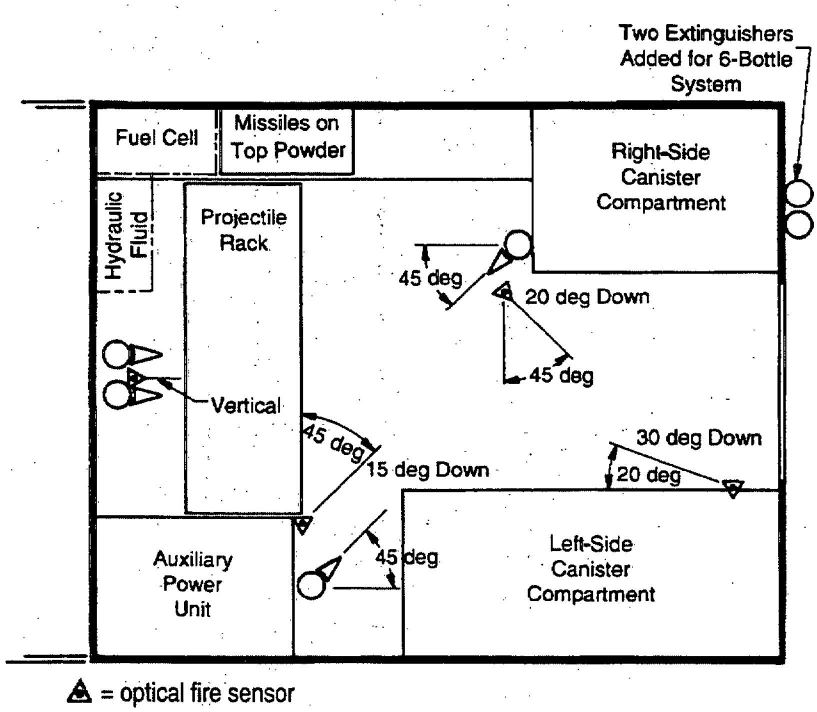
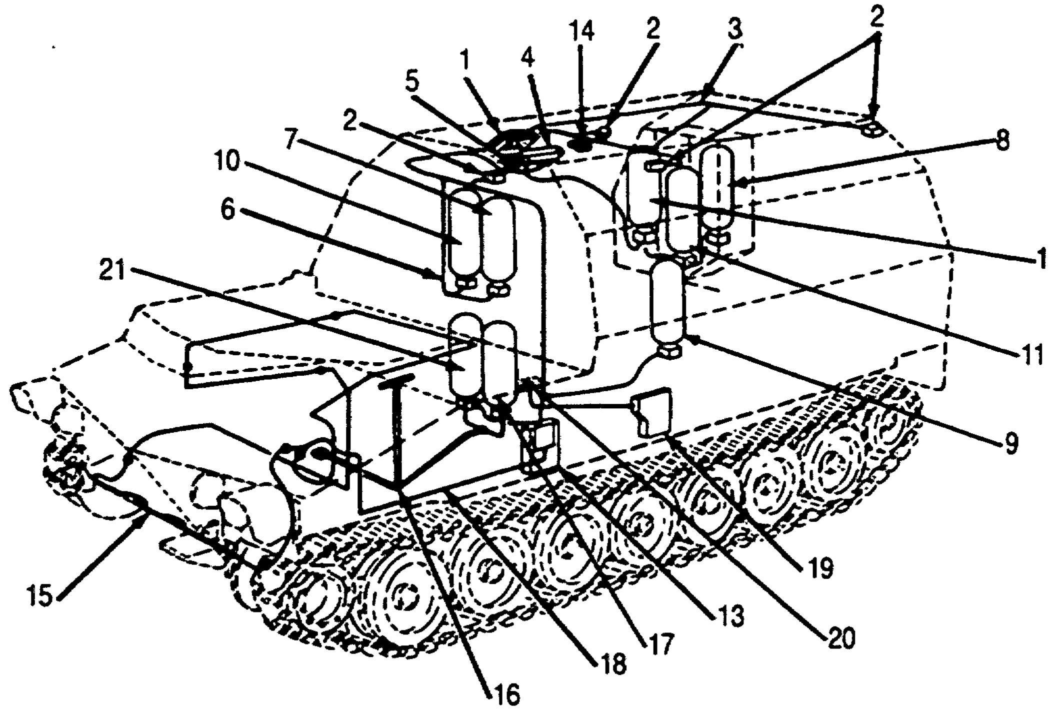


Figure 7-30. Layout of Ammunition Compartment Sensors and Extinguisher Bottles on the FAASV



Automatic Fire-Extinguishing System (AFES)

AFES Manual Discharge System MDS Components

Crew

1. Crew T/A* Panel
2. OFSA
3. OFSA Wire Harness W1
4. MSEC
5. MSEC Wire Harness W2
6. Ext Wire Harness W3
7. Crew Fire Ext No. 1
8. Crew Fire Ext No. 2
9. Crew Fire Ext No. 3**
10. Crew Fire Ext No. 4**
11. Crew Fire Ext No. 5
12. Crew Fire Ext No. 6

Engine

13. Engine T/A Panel
14. Remote Status Indicator
15. Thermal Detection System
16. Halon Distribution System
17. Engine Fire Ext No. 1
18. Ext Wire Harness W4

Manual

19. Lanyard Assembly
20. Lanyard Cable Pull Handle
21. Engine Fire Ext No. 2

*T/A = test and alarm
**Activated by either crew AFES/MDS

Figure 7-31. FAASV AFES

Two AR/AAV M551s were hit by RPG-2s in SEA in approximately the same location; the trajectories of the jets of these two warheads are shown on Fig. 7-33. In the incident described in DAN 1548, the jet passed through the driver and killed him, but the jet was absorbed by materials in the rear of the crew compartment without starting a fire. In the incident described in DAN 1550, the jet hit main gun rounds stowed in the missile area, and these rounds exploded and killed all four crewmen, as described in subpar. 4-6.1.3 (Ref. 5). These incidents illustrate the value of providing protected stowage in combat vehicles for main gun ammunition.

7-5.1.2 Description of US Marine Corps Systems

The United States Marine Corps (USMC) is responsible for the design and development of amphibious vehicles. The following descriptions are furnished for two USMC amphibious vehicles and the wheeled light-armored vehicle (LAV) 25.

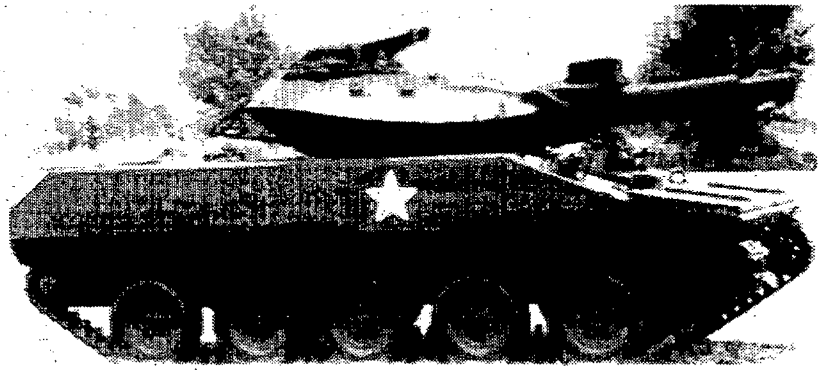
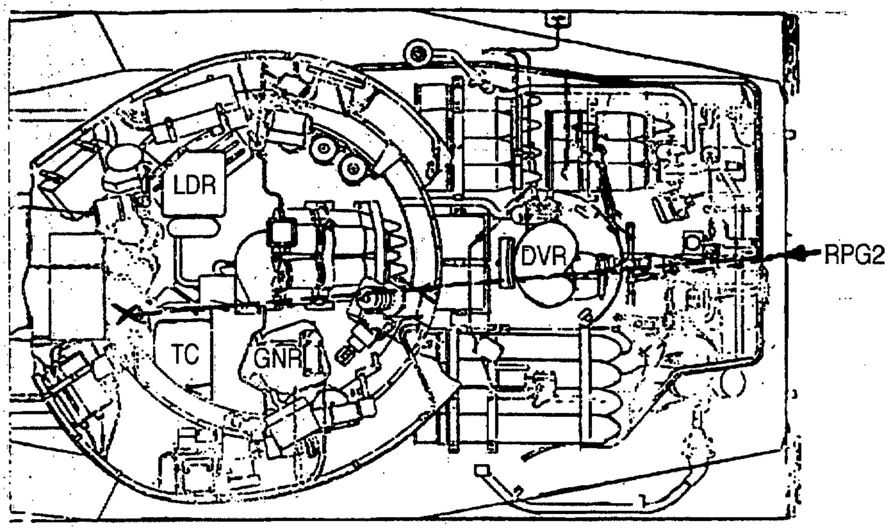
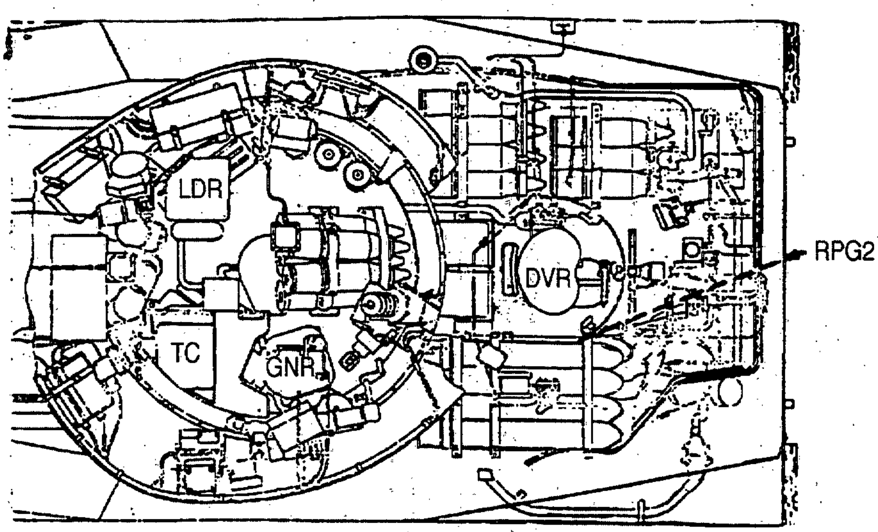


Figure 7-32. Armored Reconnaissance/Airborne Assault Vehicle M551



(A) RPG2 Hit on AR/AAV, DAN 1548

TC = Tank Commander
GNR = Gunner
DVR = Driver
LDR = Loader



(B) RPG2 Hit on AR/AAV, DAN 1550

Figure 7-33. Shaped-Charge Jet Trajectories in Two Incidents Involving AR/AAV M551 in Southeast Asia (Ref. 5)

7-5.1.2.1 Landing Vehicle, Tracked, Personnel (LVTP) 5A1

The Landing Vehicle, Tracked, Personnel (LVTP) 5A1, shown on Fig. 7-34, is no longer used by the USMC. It is, however, still in use by the Philippine Republic. The LVTP 5A1 is included primarily because of the early work done on an AFES that was designed and tested for but not incorporated into this vehicle. This AFES design was the basis for the first US Army AFES. The LVTP 5A1 is a steel-hulled, gasoline-powered vehicle. The gasoline is carried in 12 cells, eight of which are located in sections of the bilge directly under the troop compartment. Rubber-coated fabric gasoline cells were covered with a layer of elastomer to provide abrasion resistance (Ref. 144).

The primary threat was a beach mine with a shaped charge directed upward. A series of tests was conducted to demonstrate how effectively the AFES could counter this threat (Ref. 96) (described in subpar. 5-2.2.3.1). The AFES used optical fire detectors, but an intrusion detector—a grid of wires placed between the hull and the fuel cells to sense jet perforation and described in subpar. 6-4.1—was also tested. Government contractor personnel recommended the intrusion detector because they had false alarm problems with the optical sensor system. The fire-extinguishing system used two nozzles to flood Halon 1301 into the troop compartment if a perforation of the hull occurred. There were four halon bottles, each containing 4.5 kg (10 lb) of Halon 1301. In addition, the engine compartment had one nozzle connected to a bottle containing 7.9 kg (17.5 lb) of Halon 1301.

7-5.1.2.2 Assault Amphibian Vehicle (AAV) 7A1

The assault amphibian vehicle (AAV) 7A1, shown on Fig. 7-35, is an aluminum-hulled vehicle with a diesel engine. An automatic fire-sensing and suppression system (AFSSS) was approved for retrofit for the troop compartment. The AFSSS operation was demonstrated to be acceptable (Ref. 82) according to USMC validation test procedures (Ref. 145).

The AAV 7A1 has one fuel cell in the port (left) sidewall, shown on Fig. 7-10. The vehicle has a manual fire-extinguishing system in the engine compartment, and mechanical pull handles are located both inside and outside the vehicle at locations accessible to the crew. A portable 1.25-kg (2.75-lb) Halon 1301 fire extinguisher is installed in the vehicle.

The AFSSS has four discriminating optical sensors, an electronic controller, and three 3.2-kg (7-lb) Halon 1301 bottles with associated wiring and plumbing. The sensors are Dual Spectrum™ Infrared Optical Fire Sensors; described in par. 6-2. The electronic controller receives inputs from all four sensors. If any sensor(s) detects the flash of a penetration, the system goes into a delay mode

Figure 7-34. LVTP 5A1

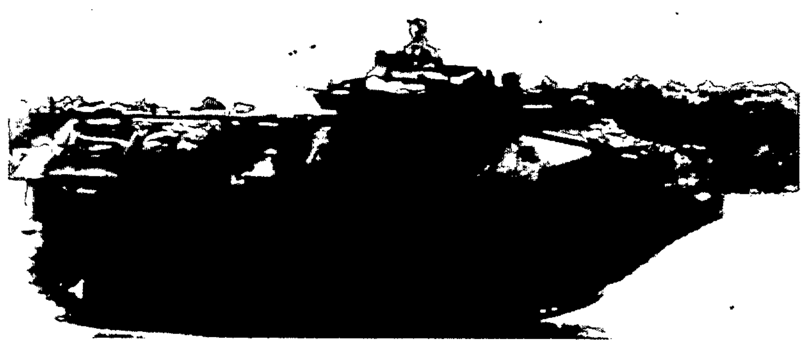


Figure 7-35. AAV 7A1

periodically to recheck the situation. Only when a sensor(s) detects a fire without any detection of the flash will extinguishers activate.

This system uses solenoid valves that have manual release levers which are connected to mechanical pull cables. Deflector nozzles are used on two bottles, and a discharge tube is used on the third; the halon will spray in the directions indicated on Fig. 7-11. The electrical wiring is sealed to protect it from salt fog.

7-5.1.2.3 Light-Armored Vehicle (LAV) 25

The USMC is acquiring the LAV 25, illustrated on Fig. 7-36, from General Motors of Canada. This vehicle is equipped with manual fixed fire-extinguishing systems in both the crew and engine compartments. It originally had a single-shot, two-bottle system furnished by Walter Kidde, but the system is now fabricated by Canadian subcontractors. Each 6.8-L (418-in.^{3}) aluminum bottle contains 4.1 kg (9 lb) of Halon 1301 pressurized to 4.1 MPa (600 psi). These bottles are actuated by any one of three cable pulls, i.e., from the driver's location, the troop compartment, or the vehicle exterior. Both bottles discharge with a single pull.

The USMC is currently considering retrofitting the LAV 25 to use a crew compartment system similar to that used in the AAV 7A1.

7-5.1.3 Description of Foreign Systems

Some information is provided on the fire protection systems in foreign combat vehicles, which include the West German Leopard II MBT, the English Chieftain MBT, Israeli combat vehicles, and Russian MBTs.

7-5.1.3.1 Leopard II Main Battle Tank

The West German Leopard II MBT uses the Deugra™ (Deutsche Graviner) fire-extinguishing system. The crew compartment has a two-shot automatic fire-extinguishing system using four IR sensors and four 3.2-kg (7-lb) Halon 1301 bottles. The second shot is available five seconds after the first shot has been used. The controller has three selectable modes of operation. In Mode 0 the system is off. In Mode I the system automatically operates when two or more sensors simultaneously signal a fire (peacetime mode). In Mode II the system automatically actuates when one sensor signals a fire (wartime mode). The one-shot fire-extinguishing system in the engine compartment has a Firewire™ thermal detector, an electric-manual controller, and one or more 1.6-kg (3.5-lb) bottles of Halon 1211.

The Leopard system requirements include the following items:

1. The fire-extinguishing system must recognize a fuel or hydraulic fire being initiated, signal the fire, and extinguish it before personnel suffer irreversible injury.
2. The combat value of the vehicle cannot be degraded.
3. Effectiveness of the fire-extinguishing system cannot be degraded by the nuclear, biological, and chemical (NBC) system or by normal vehicle ventilation.
4. When the vehicle suffers a hit that causes fuel, oil, or hydraulic fluid to burn, the pressures generated are not to cause ear damage and the temperatures are not to cause greater than first-degree burns.
5. The total time from an explosive atmosphere forming to total extinguishment shall be less than 150 ms.

The Canadian Leopard C1 MBT, armored reconnaissance

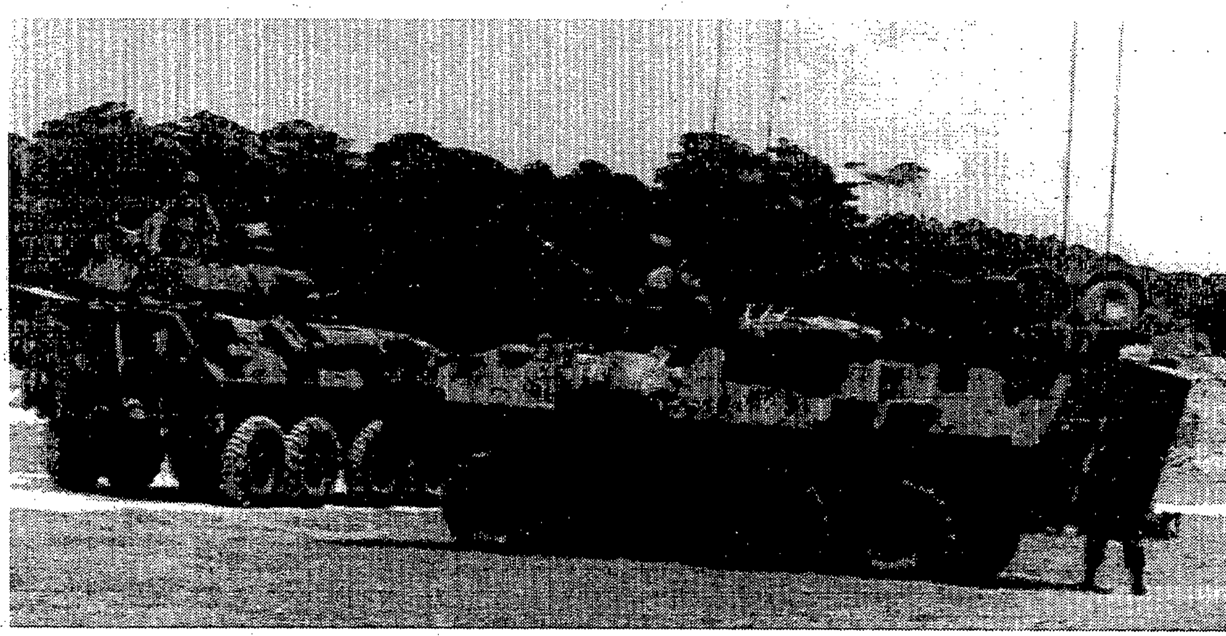


Figure 7-36. USMC Light-Armored Vehicles: Left, LAV 25 With 25-mm Chain Gun; Right, Logistics Variant

vehicle (ARV), AVLB, and armored engineer vehicle (AEV) have the Spectronix automatic fire-extinguishing system described in subpar. 7-5.1.3.3.

7-5.1.3.2 British Army Main Battle Tanks

The Chieftain is the British Army MBT fielded in 1963. The Challenger I is the MBT fielded in 1983 and used in Kuwait in 1991. The Challenger II is the upgraded MBT scheduled to replace the remaining Chieftains and Challenger I's.

The Chieftain MBT has the Graviner Firewire™ thermal system and Halon 1211 extinguisher bottles for fire protection of the engine compartment only, and it has water-jacketed, fiberglass magazines for the main gun ammunition. The fuel cells are plastic* cells in metal compartments. The turret power is electric, and there is no automatic or manual fixed fire-extinguishing system in the crew compartment.

The Challenger MBT also uses the Firewire™ continuous thermal wire detection system for the engine compartment with Halon 1211, but it has eliminated the water-jacketed magazines for the main gun ammunition. Rigid, rotary-molded* fuel cells are used (Ref. 147). Turret power is electric, and there is no fixed fire-extinguishing system in the crew compartment. Extended range fuel drums can be cantilevered off the rear of the Challenger II.

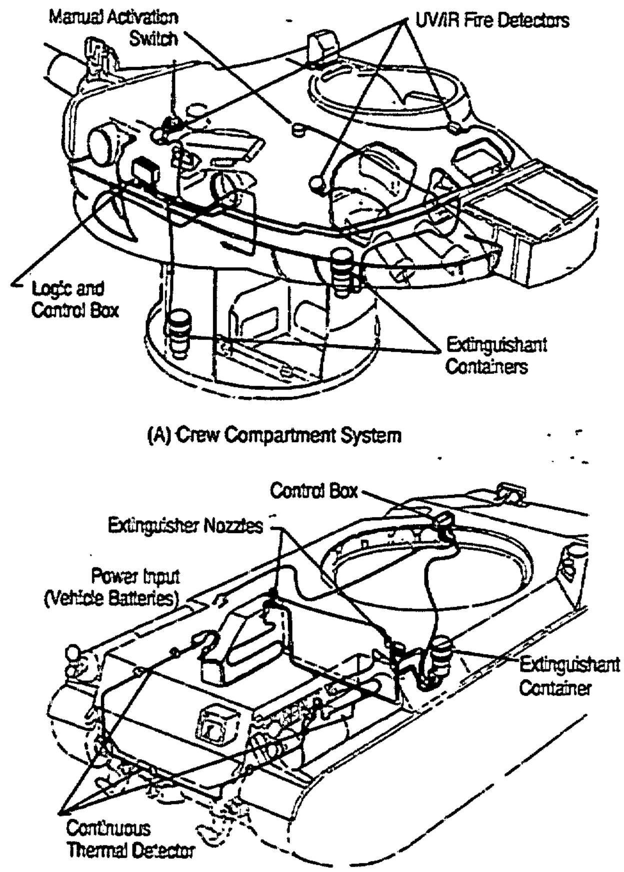
7-5.1.3.3 Israeli Combat Vehicles

Almost all Israeli combat vehicles are protected from fire of hydrocarbon liquids. This protection includes an AFES for the engine and crew compartments, as shown on Fig. 7-37. This fire-extinguishing system is also used in the Canadian Leopard CI MBT; the Spanish AMX-30 MBT and M109 SPH; the Greek Leonides MBT; the Austrian M60 MBT, M109 SPH, and Speyr 4K APC; and the Israeli M60 series MBTs, upgraded Centurion MBT, and Merkavas.

The crew compartment fire-extinguishing system, depicted on Fig. 7-37(A), is capable of detecting and suppressing all types of fires, small or large, slow or rapid growth, limited in area or widely growing, as well as fuel explosions, in combat or training. This system is designed to minimize the pressure increase resulting from an explosion to not more than 101 kPa (one atmosphere) and should prevent second-degree burns to uncovered skin. The optical detectors, three or more, are dual spectrum, i.e., UV and IR. Use of the UV, particularly in the spectral region of 0.16 to 0.26 μm, permits discrimination between most false stimuli and a hydrocarbon fire. A 6-ms response time from fire exposure to extinguishant valve actuation is desired (Ref. 148). The control unit has indicator lights for each of the four bottles that light when the bottle is discharged. Lights also indicate detection of a system fault and power "on". There is a selector switch for normal or combat modes of operation. BITE checks the lamps and the system. The normal mode of operation is that fire detection must be by at least two sensors. If the time between the two sensor detections is less than 30 ms, the system will actuate two bottles. If the time is greater than 30 ms, only one bottle will be actuated. In the combat mode of operation, a fire signal from one or more sensors causes activation of two bottles. The system resets itself to repeat the automatic modes of operation in five seconds. This system can also be operated manually (Ref. 149) by using switches that generate their own current. The bottles contain Halon 1301, and the size is selected to fit the vehicle.

The engine compartment system, as shown on Fig.

*These rigid fuel cells are rotary-molded, cross-linked polyethylene. These cells contain Promel™ molded polyamide fiber explosion suppression medium and are surrounded by Atomel™ molded polyamide fiber fire-retardant materials. These fuel cells, the Promel™ and Atomel™, and the rotary-molded, cross-linked polyethylene water reservoirs for the Challenger II are all made in England (Ref. 146).



Courtesy of Spectrex, Inc., Cedar Grove, NJ

Figure 7-37. Spectronix* Automatic Fire-Extinguishing System in the MBTs of Several NATO Countries and the Merkava MBT

*Use of product name does not constitute endorsement by the Government.

7-37(B), detects overheating and/or fire by using a continuous thermal detector of the thermistor type. The logic and control box monitors the sensor and signals an overheat condition (a flickering alarm light). When the signal is strong enough, the controller signals fire (steady on alarm light) and activates one of the two Halon 1301 bottles. The second Halon 1301 bottle is for manual actuation (Ref. 140).

The Merkava—Hebrew for war chariot—MBT has been designed with survivability of the crew in mind. This design includes placement of the engine forward and provision for ingress and egress low in the rear, and an all electric turret (Ref. 150). The Merkava III has rear-mounted fuel cells similar to those shown on Fig. 4-2, and it appears to have the ASTB type of spacers/baffles between the fuel cells and the hull (Ref. 151), which provide a rapid drain overboard when the fuel cell is perforated. These fuel cells provide protection to the ammunition magazine, which is installed low and at the rear of the hull. The 120-mm rounds are individually stowed in thermally insulated, antifratricide containers, which reduce the potential for cook-off if a fire starts (Ref. 150).

7-5.1.3.4 Russian Tanks

In Russia fire-extinguishing equipment is considered another means of tank defense (Ref. 152). During World War II hand-pumped fire extinguishers were used, but they were only slightly effective. Modern Russian tanks use fixed fire-extinguishing systems consisting of a controller, distribution system, and several extinguisher bottles that are either manually or automatically controlled or both.

7-5.1.3.4.1 T-54 MBT

The T-54 MBT was the first post-World War II tank to be produced by the Russians; its prototype was built in 1945 (Ref. 153). This vehicle has been upgraded while in use. The fire-extinguishing technique used in the T-54 is to smother the fire with carbon dioxide. Smothering internal fires would be effective only if the vehicle were sealed to prevent the intake of fresh air; therefore, an essential element of extinguishing the fire is to close the air intakes, which has to be done manually.

The Russian T-54 has a manually activated, fixed fire-extinguishing system that can selectively inject carbon

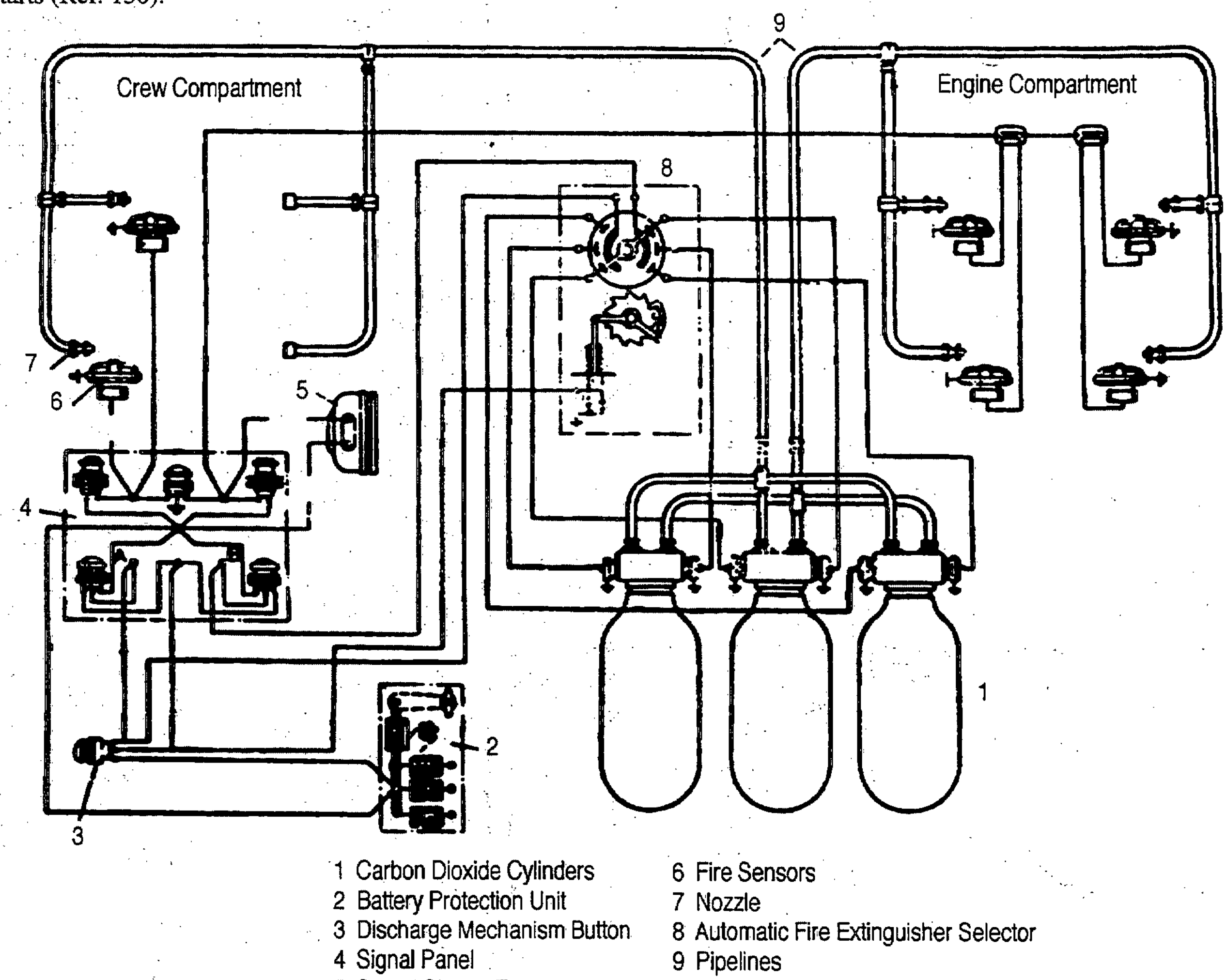


Figure 7-38. Fixed Fire-Extinguishing System for T-54 MBT (Ref. 154)

dioxide into either the engine compartment or the crew compartment (Ref. 154). This FFES, shown on Fig. 7-38, has three bottles, each containing 1.8 to 2.0 kg of carbon dioxide, located in the rear right corner of the crew compartment and adjacent to the engine compartment. Each bottle has a dual-outlet valve with a squib controlling each outlet that can be initiated separately or together in order to inject carbon dioxide into the engine compartment or the crew compartment or both simultaneously. All three bottles are plumbed to two manifolds. One manifold goes to the engine compartment, and the other manifold, to the crew compartment. Each manifold has four nozzle outlets. The FFES has a selector box that controls both the squib(s) to be initiated (hence the compartment to be flooded with carbon dioxide) and the bottle to be discharged. This system uses battery power throughout to operate the sensing and control devices.

The sensors used with this system are heat-activated switches. The sensing element is a cupped diaphragm (probably bimetallic) that straightens when heated and closes the contacts of a switch. When a cloud of carbon dioxide engulfs one of these fire sensors, the diaphragm snaps back and resets the sensor. There are four of these fire sensors located in the crew compartment, and four in the engine compartment. These fire sensors are wired to a control panel at the driver's location. The control panel has a signal light (visual alarm) for each compartment, which is energized when a compartment fire sensor activates. The engine detector subsystem also has an audible alarm. There is a button switch beneath each signal light that the driver must press to activate the FFES in the compartment in which the fire was detected.

When the fire is in the engine compartment, the driver can actuate the FFES. The driver must first stop the engine so that the carbon dioxide will not be expelled; also the tank commander and the loader must turn off the ventilation fans. The crew is instructed to remain within the tank and proceed with their duties.

When the fire is in the crew compartment, the driver and the loader must each press a separate button located at his station. The tank commander and the loader must open the hatches. After the fire is extinguished, the tank commander and loader start the ventilation fans, and the gunner opens the escape hatch. If permissible, the tank crew exits the tank and leaves the fans operating for three to five minutes. If exiting the tank is not possible, the crew members remain within the tank and don their gas masks. (Gas masks will not help against carbon dioxide but will help against smoke and many of the other products of combustion.)

When the driver or loader presses and releases his actuation button, the selector indexes the next bottle. This bottle may then be actuated. Each bottle requires 40 to 50 s to discharge fully. If there are fires in both compartments, the crewmen should start the flow of carbon dioxide into one manifold from one bottle and then start the flow from another bottle into the other manifold. They can have a bottle discharge into both manifolds simultaneously, but to obtain sufficient carbon dioxide in both compartments, a second bottle must be simultaneously activated.

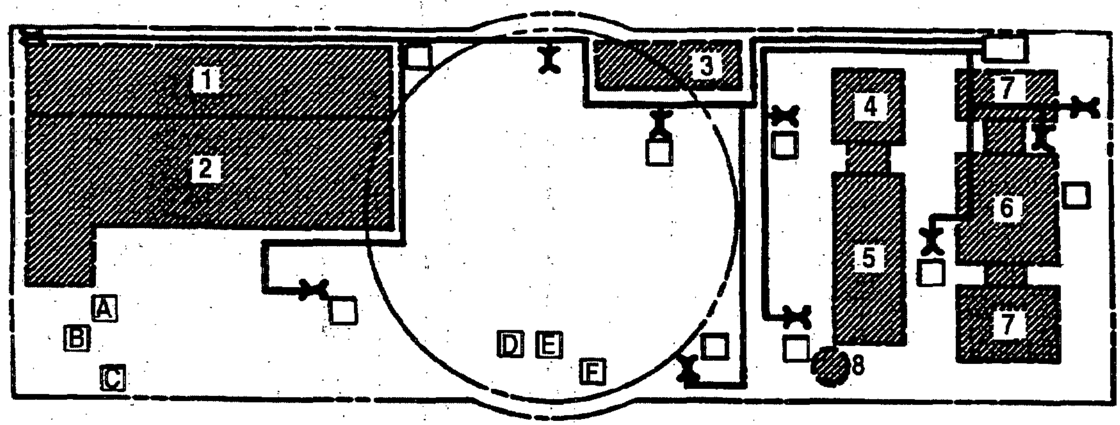
The T-54 MBT also has a portable fire extinguisher containing 1.5 kg of carbon dioxide that is located adjacent to the three FFES bottles.

7-5.1.3.4.2 T-55 MBT

The T-55 was developed in the 1950s to operate on thermonuclear battlefields (Ref. 155) and was introduced in 1958. One of the new features built into the T-55 was a way to seal the vehicle, which, with a positive internal air pressure, prevented entry of fallout into the vehicle. The fire-extinguishing technique was still to smother the fire. Since sealing the vehicle was still an essential element of the smothering technique, the automated sealing features of the fallout protection system were also used by the fire-extinguishing system.

The fixed fire-extinguishing system of the T-55 MBT is shown on Fig. 7-39. This FFES uses the same principles as that of the T-54, but much of the hardware has been changed. The fire extinguishant bottles, valves, and manifolding are the same, but they have been relocated within the engine compartment. The extinguishant has been changed from carbon dioxide to a liquid halon CH_3CH_2Br (ethylbromide or Halon 2001) pressurized by carbon dioxide. Instead of four nozzles within each compartment, there are nine nozzles in the crew compartment and six nozzles in the engine compartment. Some of these nozzles are directed at specific fire threats; the rest are used for general compartmental flooding. There are still four sensors in each compartment, but the sensor has changed from the bimetallic diaphragm switch to a 15-thermocouple thermopile (described in subpar. 6-3.3.2). The thermopile generates its own current and thus negates the need for battery power in the sensor circuits. The control logic remains the same, and the master control is still located at the driver location. The selector box of the T-54, however, has been incorporated into the driver's panel, and the control signals are now transmitted by relays to reduce the current flowing through the cables and to permit the incorporation of needed relays into the control system rather than depending upon the crew. All the vents are louvers, and fan circuits, which had to be closed or turned off by hand, are automated by using the fallout ventilation control circuitry. The switch used by the loader in the T-54 to provide an auxiliary means to actuate the crew compartment FFES was relocated so that either the tank commander or the gunner could operate it. There is no mention of an audible alarm for the FFES control system in the engine compartment. The master control box has a toggle switch that can select automatic or manual control. All components for the FFES and the fallout protection system are color coded red.

The fire-extinguishing system for the T-55 is also used in later Russian MBTs.



1 Fuel Tank and Ammunition Rack
2 Ammunition Rack and Fuel Tank
3 Fuel Tank
4 Transfer Case
5 Engine
6 Transmission
7 Brake and Steering Units
8 Fuel Filter

A Master Control Box
B Ventilator Control Box
C Driver's Relay Box
D Radiometric Protection Unit
E Distribution Relay Box
F Push Button
G Fire Extinguisher Bottles
H Manifold

Sensor □

Nozzle

Figure 7-39. Fire-Extinguishing System for the T-55 Tank (Ref. 155)

7-5.1.3.4.3 Other

The Russian fire extinguishant of choice has changed over the years. In World War II it was water. In the T-34 carbon dioxide was used, although it may have been in the form of carbonic acid (H_2CO_3). In the T-54 carbon dioxide was used. In the T-55 and T-62 MBTs Halon 2001 (CH_3CH_2Br) pressurized with carbon dioxide was used in the FFES. In the later tanks, T-64, T-72, and T-80, Halon 2402 ($C_2Br_2F_4$) is used, but the pressurizing gas is not known (Ref. 156).

Carbonic acid (H_2CO_3) is created when carbon dioxide is injected into water within a closed container. The contents of the container will be a solution of carbonic acid in water, and the ullage will contain both carbon dioxide and water vapor. The higher the pressure within the container and the greater the quantity of carbon dioxide injected, the higher the carbonic acid concentration. When this liquid solution flows from the bottle through a nozzle into a much larger space, the carbon dioxide bubbles out of the liquid, and the liquid jet rapidly becomes a spray. The conversion of H_2CO_3 into water and carbon dioxide is an endothermic reaction. The heat required for the conversion is calculated by using Eq. 7-3 and properties of the compounds. From Ref. 9, for H_2CO_3, $MW = 62.03$ g/mol and $H_f = -699.65$ kJ/mol; for H_2O in liquid form, $MW = 18.0153$ g/mol and $H_f = -285.83$ kJ/mol; and for CO_2 in gaseous form, $MW = 44.01$ and $H_f = -393.52$ kJ/mol. One gram of H_2CO_3 forms 0.29 g of water and 0.71 g of carbon dioxide. Substituting into Eq. 7-3 shows that Q_c is 330 J. This pressurized carbonic-acid-water solution is known colloquially as "fizz water", "seltzer water", or "soda water". It was the fire extinguishant used in handheld extinguishers by Russian tank crews in World War II. It works. The water spray rapidly cools the combusting materials. The carbon dioxide lowers the level of oxygen present in the combustion area, and the endothermic reaction absorbs some of the heat being generated by the fire. Further, the spray is a good way to project the water, penetrate the flames, and impinge upon the burning matter. Also the development costs of the device were nil because seltzer bottles were invented prior to World War I.

A similar device, with replacement carbon dioxide cartridges, is currently being used by airlines to extinguish fires in passenger aircraft. The appeal of this device is that the bottle is not pressurized until used. First, the carbon dioxide cartridge is screwed into the holder. This action punctures the seal at the top of the cartridge and thus injects the carbon dioxide into the water. Then the nozzle is pointed toward the fire, and the handle is depressed to spray the extinguishant on the fire.

Russian vehicles make extensive use of external fuel cells. This design provides a passive means of fire protection, particularly since these external fuel cells are often simple drums that provide enough fuel to reach the battle area and can then be jettisoned when the vehicle goes into combat. Later Russian tanks cantilever these fuel cells off the rear, as shown on Fig. 7-40, to preclude leakage due to gravity onto the rear deck of the tank.

Another passive fire protection technique used by the Russians is to stow some of the main gun ammunition in racks immersed within an internal fuel tank. *This apparently does not work well*, as is described in subpar. 4-6.2.1.

The Russian T-72 MBT, which mounts a 125-mm smooth

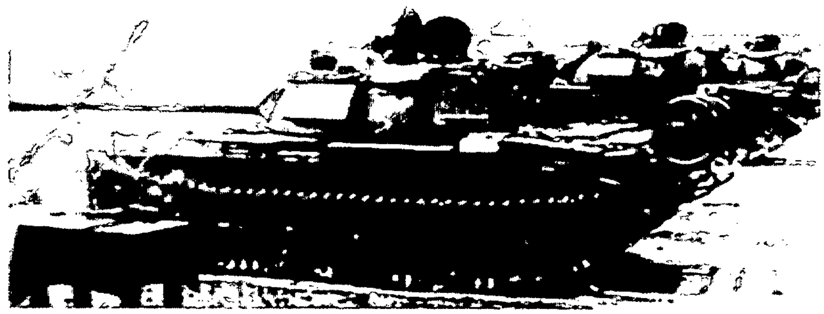


Figure 7-40. Russian T-55M MBTs Showing Jettisonable Fuel Drums

bore gun that fires separate-loading ammunition, carries 22 complete rounds in the autoloader carousel, which is low in the vehicle, and another 17 projectiles and 17 propellant charges. Of these propellant charges five are located in the turret (one in front of and two behind the commander's seat and one in front of and one behind the gunner's seat), and twelve propellant charges are located in the hull (one on the right-hand sidewall, three in the front rack, and eight in the center rack). Experiences in 1982 in Lebanon and in 1991 in SWA have shown that hits on the T-72 almost always produce catastrophic ammunition fires (Ref. 157).

The Russians provide fire-extinguishing systems for their armored personnel carriers and fighting vehicles similar to those for their tank systems.

The Russians' use of slow-response fire detectors, slow total flooding systems, and less than crew-friendly agents indicates their approach is to protect the vehicle, not necessarily the crew. Their current doctrine, however, does specify that the crews should evacuate the tanks once the crew compartment fire-extinguishing system is activated. Also the fire-extinguishing system shuts down the engine when the system is activated.

7-5.2 AIRCRAFT

In general, the threats faced by ground combat vehicles differ greatly from those faced by aircraft because ground combat vehicles can be made much sturdier. Some aircraft survivability enhancement concepts are directly applicable to ground combat vehicles, but some are inappropriate because of the heavier construction.

An excellent dissertation on the history and current status of active fire-extinguishing systems for aircraft was given by Hillman (Ref. 158). Hillman described the development of the active systems that preceded those for armored vehicles. A study in which both active and passive systems were evaluated to determine their ability to protect dry bays was described by LeBlanc (Ref. 159). LeBlanc compared an active Halon 1301 system to powder panels and to filler foam.

Aircraft use a number of passive and active fire suppression techniques. The primary threats against which aircraft are protected are the incendiary bullet, the high-velocity shell fragment, and the small high-explosive shell. The threat with which most Western aircraft are designed to cope is the Russian 23-mm HEIT projectile used by the ground-to-air automatic cannon. Protective concepts include

1. Fuel cell ullage fillers
2. Inerting systems for fuel cell ullages
3. Self-sealing fuel cells
4. Fillers for dry bays or void areas adjacent to fuel cells
5. Powdered fire extinguishant panels
6. Active fire-extinguishing systems.

McCormick et al reviewed these aircraft fire survivability techniques and evaluated their potential for use in combat vehicles (Ref. 121). Of the first five protective concepts listed, only powder-filled fire extinguishant panels were recommended for use in combat vehicles.

7-5.2.1 Ullage Filler Materials

Of great concern for aircraft is the fact that under some conditions the fuel vapors can form an explosive mixture with air in the space over the fuel in fuel cells. If air and an ignition source are introduced into that space, which is the ullage, the fuel-vapor-air mixture can explode and cause structural damage. To avoid this, reticulated foam (Ref. 118) was fully packed into the fuel cells. Later voids up to 30% were left in which explosions could occur without disastrous results to the fuel cells (Ref. 160). Currently, schemes include gross voided configurations in which up to 80% voiding is left—the foam is located only in the top of the cell. Reticulated foam initially had a problem of deteriorating, but that has been solved (Ref. 161).

In the United Kingdom a nylon material mat, called Promel™, is manufactured for the same function that reticulated foam performs in the US (Ref. 162). In Canada, an aluminum foil batting, called Explosafe®, was developed (Ref. 163). All three of these materials perform the task desired, i.e., they prevent ullage explosions when used properly.

Ullage explosions are of much greater concern in aircraft than in ground vehicles. Aircraft fuel cells are proportionally larger than those of combat vehicles, and the aircraft fuel cells and structures are of much lighter construction. The external, filament-wound fuel cells of aircraft can withstand ullage explosions. Fuel cells of combat vehicles can also be made strong enough to withstand the ullage explosions.

7-5.2.2 Inerting Systems for the Ullage

Another means of inerting fuel cell ullages is to introduce a material in gaseous form that will render the ullage explosion-proof by making it too fuel poor or too fuel rich for ignition. The first concept was to introduce an inert gas, either carbon dioxide or nitrogen, into the ullage. This worked, but a bottle system, which added weight to the vehicle, was needed. The second concept was to heat some fuel to vaporization so that the ullage became too fuel rich for ignition. This system introduced a potentially dangerous item, the heater, into the fuel cell, and the too-rich ullage could be a danger to the aircraft when the fuel cell was perforated. The next concept was to obtain nitrogen-rich air by removing oxygen through membranes. This would save the weight of bottles. This concept worked, but the filters could not obtain nitrogen-rich air fast enough to follow rapid aircraft altitude changes. A fourth scheme was to add Halon 1301 to the fuel to inert the ullage. This also works. Further, the Halon 1301 remaining in the fuel has been found to clean carbon deposits out of the combustor and engine.

McCormick et al (Ref. 121) did not recommend the use of any ullage-inerting concept, nor does the author of this handbook. Fuel cells for ground combat vehicles can be made strong enough to resist ullage explosions through the structural strength of metal cells, the structural support of plastic cells, or both. It is still advisable to incorporate a pressure-relief feature into the cell.

7-5.2.3 Self-Sealing Fuel Cells

The main reliance for eliminating fires in combat aircraft is upon passive suppression techniques rather than upon fire-extinguishing systems. Thus self-sealing fuel cells were used, as noted by General Ridgeway in 1945 (Ref. 164). In an airborne attack across the Rhine in 1945, the US 17th Airborne Division of the XVIII Airborne Corps lost 19 of 72 C-46s primarily by fire—these aircraft did not have self-sealing fuel cells. Only 13 of 476 C-47s were lost. The much better loss rate of the C-47s could not be attributed solely to the newly installed self-sealing fuel cells. There was such a graphic difference, however, in the response of these two aircraft to flak-hits; observers, including General Ridgeway, saw too many C-46s burst into flames to risk paratroopers in them again. For future drops Ridgeway decreed that the C-46s were to be reserved for resupply missions and that the paratroops were to drop from C-47s. The self-sealing fuel cells in the C-47s made those aircraft much less vulnerable to ground antiaircraft fire than the C-46s.

A self-sealing fuel cell conserves fuel that would otherwise leak out, which would leave less fuel for mobility. Crashworthy fuel cells were developed to prevent the gross spillage of fuel when aircraft, particularly helicopters, crash. Such crashes often resulted in fuel fires that killed personnel who otherwise might have survived. The use of crashworthy cells saves those lives. Combat helicopters use crashworthy, self-sealing fuel cells. A crashworthy construction usually withstands the smaller threats, such as 7.62-, 12.7-, and 14.5-mm bullets, better than simple self-sealing constructions.

In the United States there are three military specifications for elastomeric fuel cells used in aircraft:

1. MIL-T-6396 (Ref. 165) applies to internal, nonself-sealing fuel cells.
2. MIL-T-5578 (Ref. 166) applies to self-sealing and partially self-sealing fuel cells.
3. MIL-T-27422 (Ref. 117) applies to self-sealing and nonself-sealing crash-resistant fuel cells.

A crashworthy fuel cell full of water will not rupture when dropped from a height of 19.81 m (65 ft) onto a flat concrete surface. Crashworthy fuel cells were first made for use in racing cars.

A self-sealing cell will seal to the point of merely weeping a test fluid after being penetrated by the design threat. This seal must be made within 2 min of the bullet impact. There are several conditions under which a seal is not expected:

1. When the impact occurs within 76.2 mm (3 in.) of a corner
2. When the impact occurs on or within 50.8 mm (2 in.) of a metallic or nonmetallic item installed in the cell wall
3. When coring, i.e., physical removal of some of the rubber, occurs
4. When the projectile "slices" (makes a long cut) the fuel cell
5. When metallic pieces from the aircraft or the projectile are lodged in the self-sealing construction
6. When two or more perforations intersect.

Shaped-charge jets are known to core conventional self-sealing constructions (Refs. 112 and 116).

A preactivated self-sealing construction was demonstrated that provided a means to seal in most of the cases just discussed (Refs. 167 and 168). However, this construction has not yet been perfected for production (Ref. 169), nor has it been tested against a shaped-charge perforation.

7-5.2.4 Dry Bay and Void Space Fillers

Fuel does not burn well within a fuel cell, but it can burn very well in a dry bay or void space adjacent to a fuel cell if the fuel cell is penetrated. To prevent such dry bay or void space combustion, either the void space is filled with a noncombustible material or a layer of this material is placed adjacent to the fuel cell in the dry bay.

Such a void space filler is rigid polyurethane ballistic foam, which was first developed by NASA-Ames (Ref. 170) and is now produced commercially. Another void space filler is Atomel™, which is a fiber mat similar to Promel™ (Ref. 171).

Some rigid foam used to buffer plastic fuel cells in two tests using small shaped charges, 81-mm M28A2 warheads, did not appear to have a beneficial effect after the shaped-charge jet perforation (Ref. 112).

7-5.2.5 Powdered Fire Extinguishant Panels

Powder packs, fire-extinguishant-filled panels, were developed to extinguish aircraft fires (Ref. 105). These are discussed in subpar. 7-3.2.2.

7-5.2.6 Fire-Extinguishing Systems

One of the first tasks for AFESs is to detect incipient explosions within the ullage of a fuel cell and inject an extinguishant (Ref. 172). This task was not fully accomplished with the earlier systems because of response requirements.

Parker-Hannifin (Ref. 85) developed a reactive explosion suppression system for use in the ullage of an aircraft fuel cell. This system senses the detonation of a projectile and injects water in mist form to inert the ullage within approximately 10 ms. The key element of this device is the dispersion tube, shown on Fig. 7-41. This tube contains the extinguishant, i.e., water with calcium chloride freeze point suppressant, and a linear solid gun propellant explosive charge. Upon sensing a strong burst of light, the exploding bridgewire (EBW) is initiated, and this initiation in turn initiates a mild detonating cord (MDC) fuse, which in turn initiates the propellant cord and pressurizes the dispersion tube. The pressurized extinguishant forces the suppressant bladder to shear at the discharge orifices, which are located at several locations along the tube, and thus permits the extinguishant to flow into the ullage. The pressurizing propellant products of combustion are confined within the dispersion tube by the bladder, as shown on Fig. 7-42, because the pressurization is not sufficient to rupture the bladder a second time after ejection of the extinguishant.

The fire-extinguishing systems, both automatic and manual, currently used in aircraft are similar to those used in combat vehicles.

7-5.2.7 Fire-Resistant Fuels and Hydraulic Fluids

Fire-resistant fuels (FRF) were first developed to prevent catastrophic fires in aircraft after crashes. The development efforts employed both an emulsified fuel and an antimisting fuel. The antimisting fuel was also tested for ballistic impacts (Ref. 173). No fire-resistant fuels are in use in either aircraft or ground combat vehicles. In two series of tests aircraft using neat JP-5 or JP-5 containing 0.3, 0.2, or 0.1% of AM-1* antimist additive were hit by 23-mm APT-T or HEIT projectiles. The tests of neat JP-5 had five fires in six tests, and three of the fires were sustained. The tests of JP-5 with 0.1% AM-1 had two fires in two tests, and one fire was sustained. The tests of JP-5 with 0.2% AM-1 had three fires in four tests, and none of the fires were sustained. The

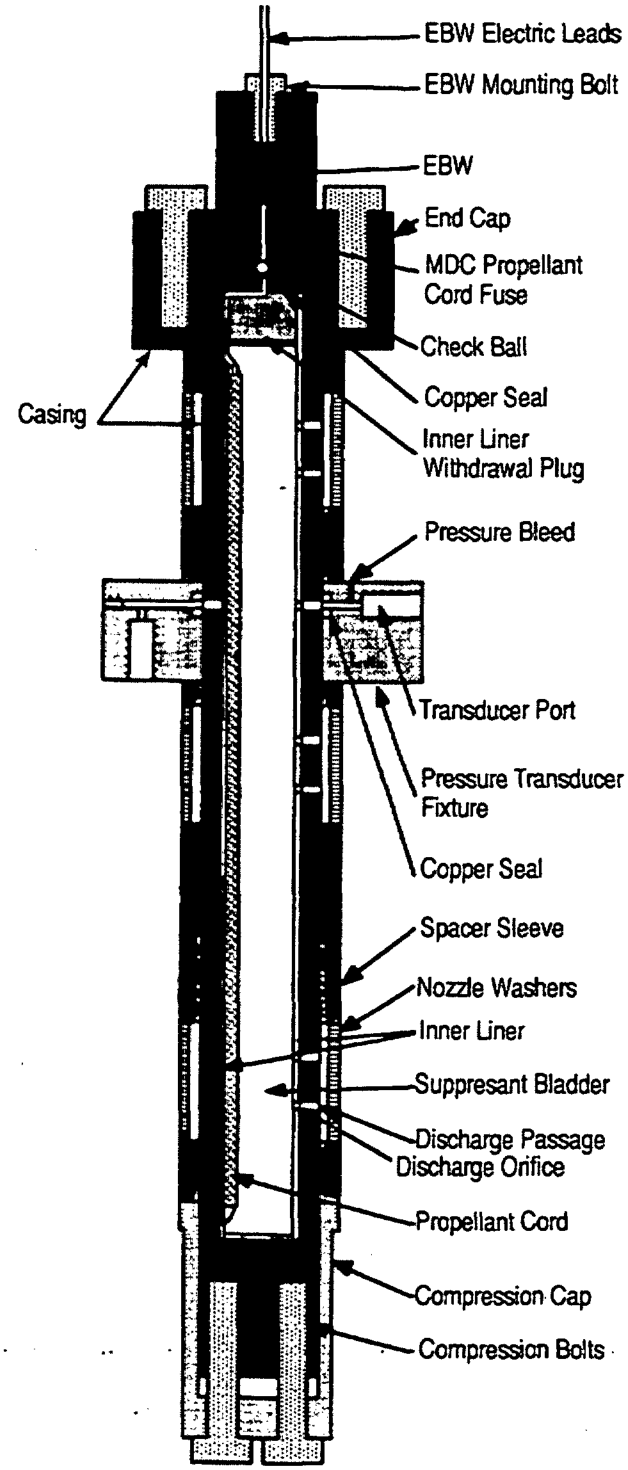


Figure 7-41. Explosive Dispersion Tube Schematic (Ref. 85)

*This antimist additive was a product of Conoco, Bartlesville, OK.

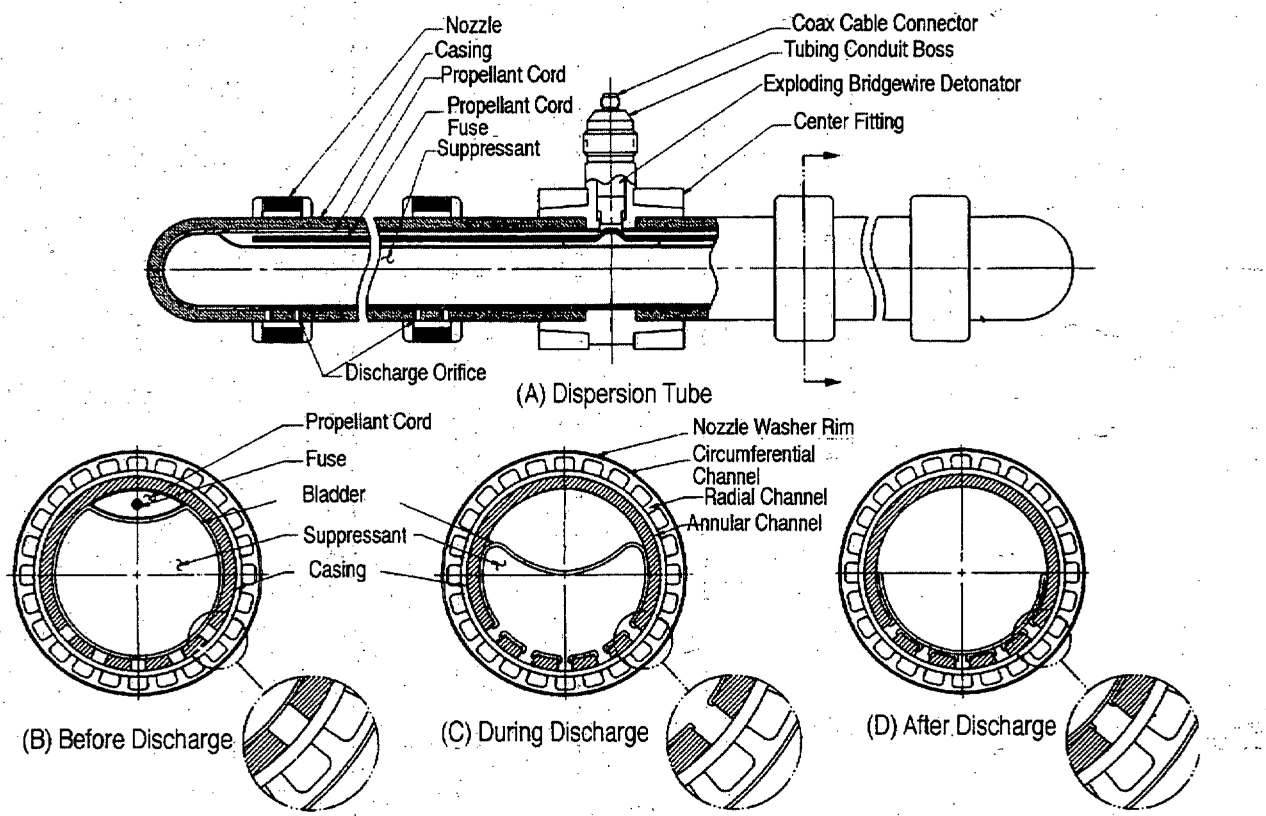


Figure 7-42. Dispersion Tube Bladder Functioning (Ref. 85)

tests of JP-5 with 0.3% AM-1 had three fires in eight tests, and none of the fires were sustained. (Ref. 174) In a series of seven tests lightweight, single-wall, ground combat vehicle fuel cells containing neat DF-2 or a water-DF-2 emulsion-type FRF were impacted by BRL precision 81-mm shaped-charge jets. Three tests with neat DF-2 all resulted in sustained fires. The tests of FRF had two fires in four tests, and none of the fires were sustained. All seven tests produced large fireballs. (Ref. 175) Thus tests of fire-resistant fuel in both aircraft and armored vehicle applications indicate that fire-resistant fuels can reduce the probability of a sustained fire but will not eliminate fireballs.

Fire-resistant hydraulic fluids were considered during competitions for the TFX airplane, which became the F-111. More recent development of fire-resistant and nonflammable hydraulic fluids is described in subpars. 3-3.1 and 3-3.2, respectively.

7-5.2.8 Adapting Aircraft Fire Prevention Concepts to Combat Vehicles

At least two aircraft fire prevention concepts have already been adapted to combat vehicles. These are the AFES and the powdered fire extinguishant panel. The reactive explosion suppression system described in subpar. 7-5.2.6 shows potential as a fire extinguisher in the engine compartment of a combat vehicle. Other concepts are being considered but have not shown applicability yet.

Fuel cell ullage filler materials have been tested but have not yet proven they effectively enhance combat vehicle survivability because ground vehicles are subject to direct hits by shaped-charge warheads and by much larger caliber projectiles than aircraft are. See subpar. 7-3.2.9.3. The same is true for other ullage-inerting concepts. It has been demonstrated that much of the impedimenta carried in combat vehicles can be used effectively as void space fillers (Ref. 95). Small arms ammunition, water, rations, and clothing are included.

Conventional self-sealing fuel cells are probably not appropriate for combat vehicles. Shaped-charge jets core such material, and sharp-edged KE penetrators or spall could do the same. Preactivated sealant constructions have not yet been developed to the point that they are effective against these threats.

Fire-resistant fuels and nonflammable hydraulic fluids have been considered for use in combat vehicles. The fuel would require considerable additional logistic efforts without an equivalent increase in survivability. Noncombustible hydraulic fluid, discussed in detail in subpar. 3-3.2, will certainly be a candidate for use in future combat vehicles.

7-5.3 SHIPS

Navy ships have always had a major problem with fire. In the days of sailing ships, a ship with tarred rigging, sails, and wooden masts and spars mounted on a dry wooden structure with black powder at each gun were pyres awaiting a match. Even with the advent of steam power and iron hulls, navy ships still had a major fire problem. In 1915 when the Germans lost the battlecruiser *Bluecher*, they learned that the magazines of a ship must be better protected. In 1916 the British learned the same lesson at Jutland when they the lost the battlecruisers HMS *Invincible*, HMS *Queen Mary*, and HMS *Indefatigable*, and almost lost the HMS *Lion** due to explosions in the propellant path from magazine to gun. The survivability enhancement concept used by the British was to place rubberized curtains along the propellant path so that when the propellant was ignited somewhere along the path, the fire or explosion would not travel to the magazine. The U.S. now uses a similar concept in the M1 MBT except that we use a sliding door to prevent the products of explosion from entering the crew compartment and provide a blowout panel to vent the resultant quasi-static pressure to the atmosphere.

In general, most of the facets of fighting fires aboard a ship differ from those in a combat vehicle. First, ships have ready access to copious quantities of the most effective extinguishant—water. All the ship needs is a pump and power for that pump to get more than enough seawater to extinguish shipboard fires, although it is not always possible to get the water where it is needed quickly enough. Second, ships are larger and have many occupied compartments rather than the one occupied compartment of a combat vehicle. Therefore, the compartment(s) involved in the fire can be evacuated, and the fire isolated. The Navy does share a concern with mobility fuel. Because of serious fires in the carriers USS *Forrestal* in 1967 and USS *Enterprise* in 1969, the fuel used for carrier aircraft was changed from JP-4 to JP-5, and the chemical washdown systems were converted to AFFF dispensers (Ref. 176). JP-5, with a flashpoint of 60°C (140°F), is much more difficult to ignite than JP-4, with a flashpoint near −18°C (0°F), and the AFFF floats a film over a pool of liquid hydrocarbon fuel to prevent free release of vapor. The Navy also started the use of the Twinned Agent Unit**, which dispenses Purple K powder or AFFF solution.

The following are other actions taken by the Navy to enhance fire survivability of aircraft carriers:

1. Redesign of munitions to make cook-off in a pool fire more difficult
2. Installation of Halon 1301 systems and heat and smoke alarms in avionics spaces
3. Installation of sprinkler systems and fire alarms around high-value spaces such as the combat information center or in combustible storage spaces such as the storage space for aircraft tires
4. Use of flame arrestors in cableways through bulkheads
5. Inspection of aircraft carriers by fire-fighting assistance teams.

The improvements for naval ships in general include the following:

1. Luminescent markers for egress routes to weather decks
2. Freshwater systems to compartments containing critical electronic equipment that saltwater would damage seriously
3. Removal of unnecessary furnishings and other combustibles from ships
4. Establishment of standards for fire spread capability of packaging materials
5. Installation of sprinkler systems for storage spaces containing high-value supply items in combustible packaging
6. Provision of lockers for overnight storage of in-use flammable liquids
7. Protection of aluminum superstructure with refractory felt insulation
8. Improved magazine sprinkler systems
9. Installation of fire-stops for cableways.

In addition, the Navy is researching modeling of fire-spread characteristics; studying toxicity, combustion, and pyrolysis; studying use of new and special materials; studying means to overcome smoke obscuration; and studying use of nitrogen pressurization to inert closed chambers. This last techhnique is used in submarines and could be of use in combat vehicles. Life is supported by the partial pressure of oxygen, whereas fire is supported predominantly by the percentage of oxygen. In a sealed environment, partial pressure and percentage of oxygen can be varied independently. It is possible to pressurize a sealed environment with an inert gas such as nitrogen to reduce the percentage of oxygen to a value below that needed to support combustion but still to maintain the partial pressure of oxygen so that the atmosphere is habitable for humans.

While exploring fire-extinguishing techniques, the Navy has established that pressurized containers of water and a very fine mist nozzle produced a system that is able to use only a few gallons of water to extinguish an oil fire. This ability was possible because the water uses heat energy as it vaporizes, as described in subpar. 7-2.3.1. The Navy has also recommended that potable water mist can be used to extinguish Class C fires.

*A mortally wounded Royal Marine Major within a magazine ordered the magazine flooded before the propellant in it could explode.

**This Twinned Agent Unit provides a firefighter with the capability to dispense either a liquid or a dry powder extinguishant. The Twinned Agent Unit has two hoses, two valves, and two nozzles. The firefighter selects which system to use based upon his assessment of the fire.

7-5.4 CIVILIAN EQUIPMENT

A good example of a civilian vehicle that has fire suppression problems similar to those in combat vehicles is the Caterpillar D10 tractor. The D10 is a diesel powered, tracked, off-road vehicle that tends to collect combustible debris around the engine. This debris can become impregnated with hydraulic fluid, oil, and/or fuel and create a potentially hazardous fire situation. Also a hydraulic fluid or oil line might fail and spray a combustible fluid onto the engine or exhaust pipe and cause a fire.

Caterpillar furnished an AFES as optional equipment. This system used a thermal sensor based upon the differential expansion of two dissimilar metals. The sensor was set to trip at approximately 193°C (380°F) and send an electric current through a solid-state electronic controller to a solenoid valve. The solenoid valve ported compressed gaseous nitrogen to a piston that drove a cutter through a diaphragm and thus liberated an extinguishant that flowed through nozzles onto preselected locations around the engine being protected (Ref. 177).

This system is of particular interest because of the development of selection criteria for extinguishants. The diesel engine is basically in the open; therefore, there is an abundance of atmospheric oxygen. The candidate extinguishants considered were Halon 1301, Halon 1211, Halon 2402, and the Class ABC dry chemical MAP. The fires anticipated could be Class A, B, C, or a combination thereof. This application nullified flooding performance of the extinguishant as an important selection criterion and elevated the throwing characteristics and the persistence as selection criteria. Thus the gaseous extinguishant Halon 1301 and the liquid flash-to-gas extinguishant Halon 1211 were not as desirable as MAP and Halon 2402. Between these two, Halon 2402 had better throwing characteristics, was a more effective extinguishant, and did not leave a difficult-to-remove residue.

Before the start of this development program, the Caterpillar fire-extinguishing system used Halon 1301. In this program MAP was considered and rejected; then Halon 2402 was selected. The Halon 2402 was found to be much more effective than Halon 1301 in requiring much less extinguishant to extinguish the fire and in inerting the region for a significantly longer time. Thus the incidence of reignition was reduced. This system consisted of components designed by Caterpillar including spray nozzles, actuation valves, bottles, heat sensors, and a solid-state electronic controller. The spray nozzles were designed to provide 0.91 kg (2 lb) per second of extinguishant per nozzle to the protected site. Because the tractor is open to the atmosphere, there was no danger that the operator would be in an enclosure with Halon 2402. This system is no longer used because of the restrictions on halons.

7-6 LESSONS LEARNED

The cases described in this paragraph present equipment design and usage from which we may learn lessons. At the very least they present concepts that should be examined further.

7-6.1 DESIGN CONCEPTS EXPLORED IN THE ASTB PROGRAM

In the ASTB program several design concepts were explored that showed potential to enhance combat vehicle survivability:

1. Relocate the most hazardous munitions out of the most critical vehicle regions.
2. Use less hazardous impedimenta, including the less hazardous munitions, to buffer the vehicle from the effects of the more hazardous munitions.
3. Separate the mobility fuel from the occupied compartment.
4. Use passive concepts, such as compartmentalization, confinement of fuel cells, use of gelled water, and collection of combustible liquids in the bilge, to preclude fast-growth fires or fuel fires and/or explosions within the occupied compartment.
5. Use passive concepts, such as double-walled or jacketed fuel cells, to preclude fast-growth fires or fuel-air explosions within the engine compartment.

7-6.2 DESIGN CONCEPTS USED IN FOREIGN TANKS

To increase the range of operation of their tanks, the Russians have used light-gauge metal exterior fuel cells since at least 1940, i.e., beginning with the KV-1 heavy tank (Ref. 178). At the present time, all the MBTs have two 200-L jettisonable external fuel cells (drums) at the rear, and three or four 95-L external fuel cells on the sponsons (Ref. 179). Thus the fuel used first, approximately half the fuel carried, is in external fuel cells. This design feature is a great savings in interior volume. The jettisonable fuel cells cantilevered off the rear are located where, when hit, the resulting fires would be neither in nor on the vehicle. The sponson fuel cells again would probably not contribute to fire damage within the vehicle. The Swedish "S" tank also uses sponson-mounted fuel cells (Ref. 180.) These external fuel cells added to the protection of the vehicle from shaped-charge attack. The use of jettisonable or sacrificial external fuel cells should be considered.

7-6.3 FULL-TIME AUTOMATIC FIRE PROTECTION

In some of the incidents described in the USASC data mentioned in subpar. 4-1.1, vehicles parked in a motor pool have caught fire when no one was present. Vehicles are too valuable to be lost to fire. Each vehicle should have a full-time AFES to protect it, and the system should be operable even when the vehicle power is off.

7-6.4 AMMUNITION MAGAZINE DESIGN

A study was conducted at BRL of techniques to reduce the effects of a shaped-charge jet hit on the propellant of the main gun ammunition of the M60 MBT. Four of the five approaches tested and reported in Ref. 181 are worthy of consideration. Other details cannot be included because the reference is classified.

An upgrade option that can be incorporated into either the M1A1 or M1A2 MBT is FASTDRAW, i.e., an autoloader with two carousel magazines, each of which has 18, 120-mm cartridges, located in the turret bustle. The two carousels are separated by an armored center web and have small access ports through which cartridges are fed to the gun. FASTDRAW would enable the crew to fire at a rate of 11.6 rounds/min. The improved isolation would decrease vehicle vulnerability, and the ammunition load would be increased by two rounds. (Ref. 182)

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CHAPTER 8
TEST AND EVALUATION FOR DESIGN VERIFICATION

The roles of testing and modeling in the design of a combat vehicle for fire survivability are discussed. Tests of existing or generic systems are used to develop computer models and mathematical models of the natural phenomena involved. The computer models are used to design and size vehicle systems for fire prevention and/or extinguishment. Tests are used to verify the performance of the system. Test results are also used when computer models are upgraded or verified. There are no computer models in existence written specifically to perform these tasks, but there are some computer models that can be modified to do so.

8-0 LIST OF SYMBOLS

C = concentration of extinguishant, mg/L
C = a calibration constant, (W/m²)/mV
e = sensor output, mV
$P_{d/h}$ = probability of damage given a hit, dimensionless
$P_{k/h}$ = probability of kill given a hit, dimensionless
Q = heat flux, W/m²
R = resistance, Ω
T = temperature, °C
T_{Li} = limit temperature, °C
V = voltage, V

8-1 INTRODUCTION

Combat vehicles are designed to perform certain tasks. This design evolves following a process specified in Department of Defense (DoD) Directive Number 5000.1 (Ref. 1) and DoD Instruction 5000.2 (Ref. 2). The three major decision-making support systems and their interactions that constitute this process are shown on Fig. 8-1. A mission need is identified in broad operational terms, which are progressively translated into system-specific performance requirements. Where new or modified equipment is needed, the performance and affordability of these material needs are thoroughly evaluated. The process is a phased series of steps, as shown on Fig. 8-2. The designs of combat vehicles have evolved over the years in many different forms. Requirements, both stated and implied, have multiplied; thus fitting them together in a single vehicle becomes a challenge. Further, installing an item to meet one requirement could hinder compliance with another. The Army cannot afford to fabricate a host of specimens to meet a single need and then try them out. In the early design stage the Army must be able to evaluate specific features in order to select those that, when assembled, can best meet all design requirements. To make this selection expeditiously and efficiently, the designer must be able to predict performance not only for the extremes of conditions in which the vehicle must operate but also for attack by weapons of hostile forces. For fire survivability the designer must assure that even when the vehicle is hit by an overmatching threat, the results will not be catastrophic.

Prediction of performance after ballistic attack can be

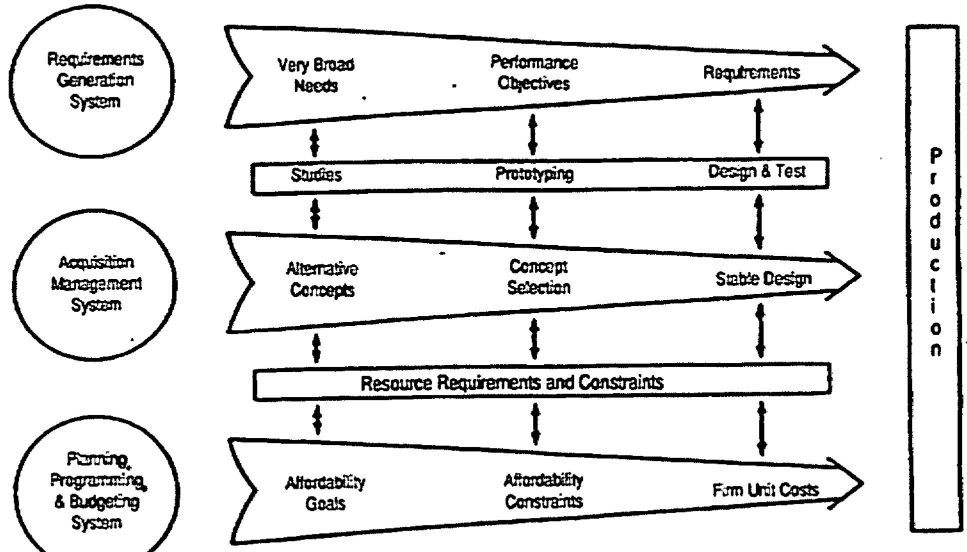


Figure 8-1. Major Decision-Making Support Systems and Key Interactions (Ref. 1)

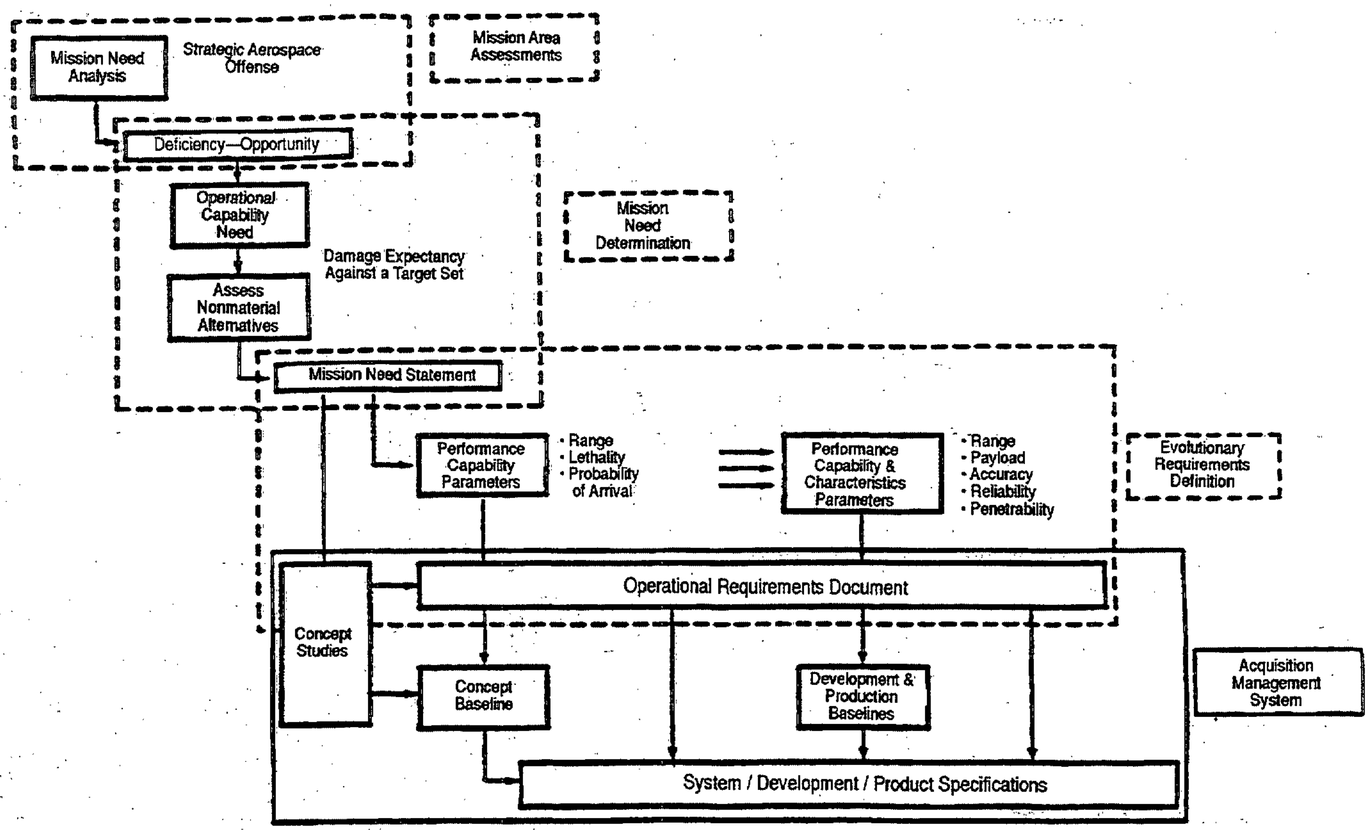


Figure 8-2. Requirements Generation System (Ref. 2)

based upon theoretical studies, upon experience in battle, and/or upon test data. Theoretical studies are the poorest source of performance data. Theory is best used to guide the design studies and test programs that produce the design data. Battle damage is also a poor source of design data primarily because detailed studies are not usually made of the resulting damage and its cause. The best source of data to guide survivability design is a well-planned test. The majority of tests performed are not generic; they are conducted with specific weapons used against specific targets. If detailed descriptions of the threat, target, test conditions and events, and the test results are documented, specific tests of specific items can be correlated with other tests to provide generic guidance. Then the battlefield data can be used for verification.

This chapter is not intended to instruct instrumentation personnel how to use pressure transducers, temperature-sensing devices, or the associated recording and playback equipment. The intent is to inform designers and program managers what types of instruments are available and what types of data can be obtained so they will know what to require from the instrumentation specialists. No attempt has been made to describe all makes and models of instruments, nor is the inclusion of a specific device to be considered an endorsement of that device. The equipment used in the specific instances described was often chosen because it was available at the laboratory or test site, not because it was the best device for the test. There are usually many models of devices that could perform the desired function(s) and many suppliers.

Which data can be obtained and which data are needed must be established. The following question could be asked: Which useful data can be obtained and documented without unduly increasing the test cost? As a minimum for each test or combat operation, we should have descriptions of the target and threat, the incident or test, and the events and results. The descriptions of the threat and target should be in sufficient detail for an independent evaluator to know what materials came in contact throughout the incident and the condition and strength of the materials and their spacings in order to evaluate penetration and ignition source generation, impact location, and threat trajectory. Other information is also needed, such as mass, shape, explosive content, fuze functioning details, target contents, parameters that affect ignition (such as combustible fluid bulk temperature and flash point), and which survivability enhancement features are present. The description of the incident or test should include impact velocity, impact obliquity, and weather conditions—i.e., ambient temperature, humidity, barometric pressure, and wind speed and direction. The description of test events includes (1) threat penetration into the target, which includes portions of the threat that may become separated, (2) spall generation, (3) locations, magnitude, and duration of the ignition sources generated, (4) sources and forms of the combustibles broadcast, (5) locations, ignition, and duration of fires, and (6) means needed to extinguish the fires. The test results should include perforations in the target and materials in front of and behind the target; functioning or malfunctioning of the threat; damage to the target, particularly damage affecting the ignition and combustion of the contents; functioning of any survivability enhancement device; other incidental damage, movements, or incidents that occurred; residual mass and the condition of threat remnants; residual mass and/or volume and locations of combustibles and extinguishants. This may seem like a lot of information from a "simple" test, but all of it is readily available and need only be observed and recorded, except for the flash point of the fluid, which can be determined and recorded. Motion pictures or videos are excellent methods of recording much of this information. Even a "simple" test is expensive, and the agency paying for it deserves this minimum for its money. Some tests involve obtaining more information and thus involve more complex instrumentation.

The next question is "What will be done with the information collected in these tests?". Some tests are intended to demonstrate the efficacy of a specific vehicle design to meet specific requirements. These requirements, however, may change. Very few combat vehicles remain unchanged over their service life, and the service life could be greatly extended over what is currently envisioned. The US Army could place tanks in depot storage in the same manner in which the US Navy "mothballs" ships. In the event of a major conflict, however, these tanks could be upgraded and then used in secondary theaters or for training and thereby allow the first-line tanks to be deployed to the most critical theater. Our M60A3 main battle tanks (MBTs) are still highly effective against most of the tanks in the world. These could be upgraded with additional parasitic armor and survivability enhancements in order to approach first-line tank status. Israel is still using upgraded US M4 tanks, and the Russians store T54/55 MBTs. One use of test data gathered from obsolete or obsolescent combat vehicles is to plan the upgrading of those vehicles. Another use is to plan the design and future upgrading of new vehicles. This handbook demonstrates that lessons learned with the British Mark I and Mark IV tanks in 1916 and 1917 are still applicable to tanks to be made tomorrow.

Computer models enable designers to predict the relative effectiveness of candidate techniques, but software for survivability enhancements would have to be developed. Although there is no existing software, computer models could be prepared to predict the life cycle cost of these survivability enhancement concepts in specific combat vehicles. Care must be taken, however, to assure that computer models will perform properly and will represent the "real world". Also care must be taken to assure that the mathematical models are correct and that the data used to develop these models are correct and represent the proper phenomena. Once all of these steps have been followed, valid vehicle designs or modifications can be selected.

The roles of testing and modeling in the design of a system follow:

1. Testing provides the data by which mathematical models can be developed of the phenomena involved in the functioning of a specific design under specific loadings, and it provides indications of the sequencing of these phenomena so that a logic flow can be prepared.
2. Computer models are prepared by establishing the logic flow and then the specific mathematical models needed in order to predict the phenomena observed. The parameters needed are selected from theoretical evaluation of the phenomena. These parameters must be amenable to quantification and determination in practical tests. These computer models are prepared and verified by additional tests.
3. Candidate survivability enhancement concepts are selected and their capabilities established by using the computer models. These concepts are incorporated into the design of test specimens.
4. Conceptual survivability enhancement features are tested for effectiveness. The results from these tests are used to verify and/or improve the computer model and to plan improvement of the survivability-enhanced design.
5. The design is modified, and qualification test specimens prepared and tested. The computer model is exercised to predict results.
6. Test results are compared to the computer-predicted results, and any differences explained. The test results are used to improve the computer model and to qualify the survivability-enhanced design.
7. The system design is incorporated into the vehicle design. A vehicle is then built and subjected to design verification tests. The computer model is exercised to predict the test results.
8. Design verification test results are evaluated to verify that the vehicle design meets the specified requirements. These test results are also used to check and improve the computer model.

Throughout this process the computer model is checked and improved by factoring in the results of each test series and modifying the design of the vehicle or its components to improve the performance of the system. There is continuous interaction between tests, vehicle design, and predictions throughout the development process.

This chapter covers the test requirements and capabilities available, as well as the computer software available and the requirements for such software. Life cycle cost is needed to establish affordability. For a discussion of cost analysis, see par. 1-5.

8-2 PERFORMANCE PARAMETERS THAT CAN BE TESTED

The parameters that can be tested include pressure and temperature versus time, gas concentration, and extinguishing system event timing. To select instrumentation for these parameters, both the purpose for which the data are to be used and the environment under which the data are to be collected must be considered.

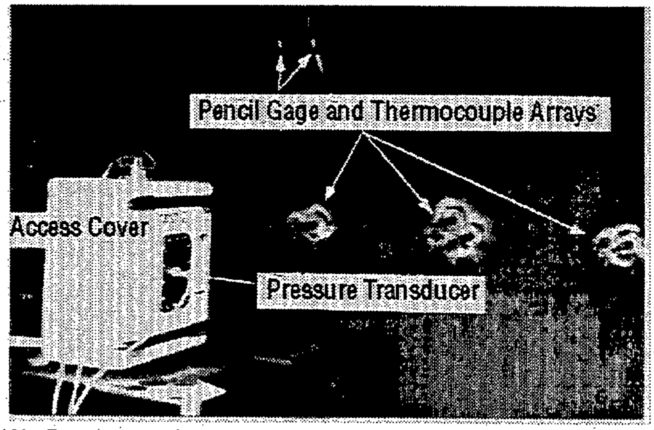
Pressure and temperature data are needed to evaluate the potential effects on occupants and equipment. The effects on occupants and equipment, however, are usually functions of impulse or heat flux received and often of the rate at which the impulse and energy are received. Specific impulse is the integral of pressure versus time; heat flux is the rate of change of heat energy per unit area. The gas concentration has to be established as that the eyes and lungs of occupants would receive. The vapor, mist, or particulate concentration that would affect vision should also be established.

Instrumentation must withstand the environment of a combat vehicle that sustains a ballistic impact. If the threat being tested has a shaped-charge warhead, the test vehicle or specimen is going to receive a severe impulse load from the blast of the shaped-charge warhead. At the least this impulse load will send shock waves through the vehicle and/or test fixture body. The impulse load may also cause the vehicle and/or test fixture to displace abruptly (Ref. 3). Blast pressure gages installed as shown on Fig. 8-3(A) have been destroyed by "whiplash" when a test fixture was displaced approximately 152 mm (6 in.) when loaded by the blast from a shaped charge. These gages were relocated on a separate stand that was not subjected to the blast load.

In general, these tests are to determine what happens when a given threat hits a given target in a selected location. The relative effectiveness of candidate design "X" can be established by comparison of the results from a baseline test to those of configuration "X".

This paragraph addresses testing combat vehicles or their components that contain combustibles for fire survivability and vulnerability when subjected to the terminal effects of battlefield threats. The types of battlefield threats that are most probable to cause fire within a combat vehicle are shaped-charge warheads, high-velocity kinetic energy projectiles, and land mines.

An example of such a situation is an aluminum armored vehicle to which the threat considered is a shaped-charge warhead from a shoulder-launched, rocket-propelled weapon. The shaped charge is presumed to detonate on contact with the outer surface of the vehicle at a standoff of 2 1/2 cone diameters. Most fin-stabilized, rocket-propelled, high-explosive, antitank (HEAT) projectiles are traveling at a relatively low velocity at impact; hence the greatest warhead effect against the vehicle is obtained from the jet formed by the shaped charge. This jet has a velocity of approximately 7620 m/s (25,000 ft/s). The projectile, if it is a Russian rocket-propelled grenade (RPG)-7, has an impact velocity of



(A) Pretest Picture of Pencil Gages and Thermocouples Affixed to Fixture Walls and Piezoelectric Transducer Mounted in Fuel Cell Access Plate

(B) Pencil Gage Showing "Whiplash" Damage After Test

Figure 8-3. Inappropriate Test Instrumentation Location (Ref. 3)

approximately 294 m/s (965 ft/s) (Ref. 4). The velocity of the shaped-charge jet is primarily from the detonation of the warhead alone; the residual velocity of the projectile is only a minor contributor to the total velocity of the jet. Thus a statically fired shaped charge is an adequate simulation of this threat. When a HEAT projectile is fired from a tank gun, the velocity at impact is approximately 914 m/s (3000 ft/s); the blast and fragments from such a threat would significantly contribute to the damage to the target, particularly for lighter armored vehicles.

The fragmentation from the HEAT projectile body would have a primary velocity that is directed radially. For normal impacts (0 deg obliquity), only where the projectile has an impact velocity approximately that of the tank gun projectile would any casing fragment impact near the hole in the target surface created by the jet. Also that fragment would most probably be from the base of the projectile and would have a comparatively low forward velocity. This base fragment velocity would be the difference between the projectile velocity at impact and the velocity imparted by the charge detonation, which would be in the opposite direction, and these fragments would be of a comparatively large size (approximately that of the hole produced by the jet). Thus these base fragments should be unable to penetrate the armor of the vehicle. The other projectile casing fragments would most probably not penetrate through the vehicle armor either. These fragments will impact the target when the trajectory to target surface angle is acute, as shown on Fig. 8-4 by an M28A2 warhead at 45-deg obliquity (Ref. 5). The behind-the-armor effects probably would be produced by the jet. Actual vehicle armor should be simulated, if not used, in the tests.

For light US combat vehicles the armor might be one or two thin steel plates and then a thicker aluminum plate. For an aluminum armored vehicle that has spaced steel exterior armor plates, the jet from an RPG-type warhead could produce a 25-mm (1-in.) diameter hole in the aluminum armor protecting the fuel system component. This jet would readily perforate the fuel system component and the fuel and most of the internal components of the vehicle in the path of the jet, and the jet could exit the vehicle through the opposite side. This action was demonstrated repeatedly in the tests conducted for Kanakia and Wright (Ref. 6) and those conducted by Zabel (Ref. 3).

Where the jet passes through a fuel cell, a fuel spray follows the jet and enters the vehicle as a mist, as shown on Fig. 8-5. This mist is readily ignitable, but the strongest ignition source is produced by the subsequent impacts of the jet with aluminum components within the compartment, including the far wall of the vehicle. Ignition of this fuel mist and/or vapor and air mixture within the compartment results in a fireball, the heat from which can severely injure the occupants. Additional fuel can flow into the compartment through the jet perforation and any ruptures in the fuel cell, as shown on Fig. 8-6 (Refs. 3 and 7). Hydraulic ram pressures, which

Figure 8-4. Jet Entry Hole and Fragment Impacts From Static-Fired M28A2 Warhead Placed at 45-deg Obliquity to a Heavy-Walled Fuel Cell (Ref. 5)

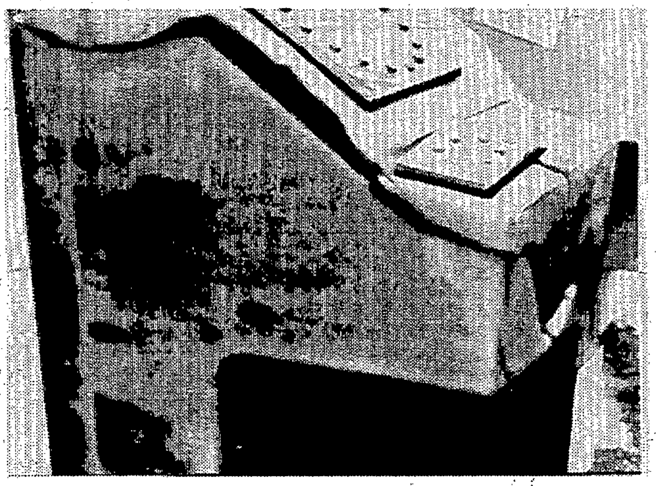
(A) Jet Passage and Fuel Mist Following Jet From Fuel Cell

(B) Fuel Spraying Out of Fuel Cell From Ruptures Both in Front and Rear

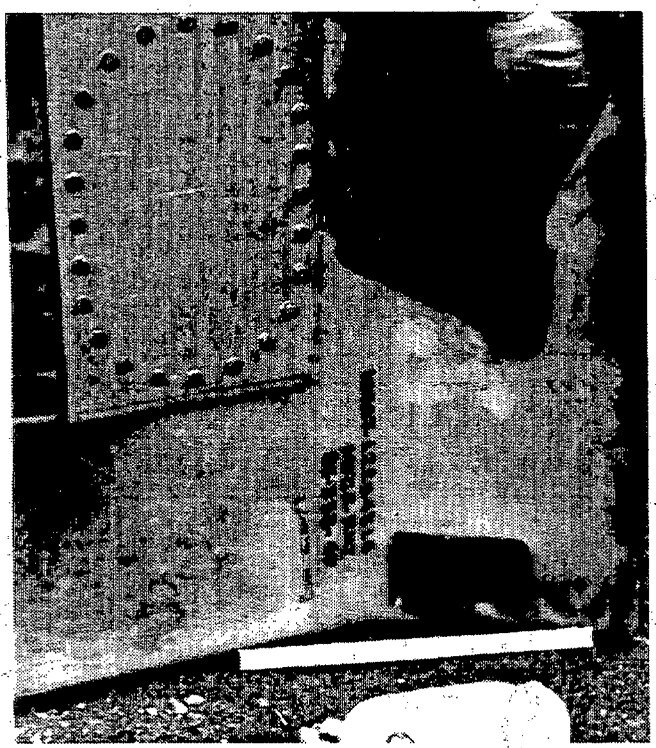
Figure 8-5. Test of Actual Fuel Cell (Refs. 3 and 7)

oscillate by apparent expansions and contractions, produce fuel sprays where the fuel is forced through ruptures in the fuel cell (Refs. 8 and 9). This fuel can vaporize and ignite from the heat of the earlier flash fire; with air being continuously input into the compartment, combustion within the chamber can be sustained. Occupants in the path of the jet would be wounded, possibly mortally, by the jet, and occupants near the path of the jet could be hit by spall. These and any other occupants could receive severe burns. All could receive damage to eardrums, as described in par. 5-3. The unburned liquid fuel can collect in the bilge, and if there is sufficient air, a pool fire could result that could render the vehicle irreparable. Although it is of less importance at this time, perforation of the fuel system components can also result in loss of mobility.

Items of interest to measure in this example are the hydraulic ram pressures in the fuel cell, the shock or blast pressures within the test fixture (troop compartment), and the tempera-



(A) Cracks in Fuel Cell: Front and Right Side



(B) Damage to Rear Surface of Fuel Cell

Figure 8-6. Damage to Fuel Cell Shown in Fig. 8-5 (Refs. 3 and 7)

ture within the test fixture. In some cases strain gages can be placed on metal fuel cells to provide information for designers, and accelerometers can be used to record gross vehicular, or test fixture, reaction to the blast and/or impact. (The test fixture in which the gage shown in Fig. 8-3 was mounted weighed over 1200 kg (1.3 tons) and was moved 100 to 150 mm (4 to 6 in.) by the blast of the warhead.) Also pictorial recordings of the events within the test fixture should be obtained. Obtaining samples of the gases within the test fixture requires greater sophistication of both test and instrumentation.

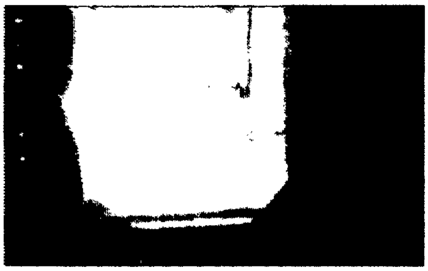
8-2.1 PRESSURE AND TEMPERATURE TIME HISTORY

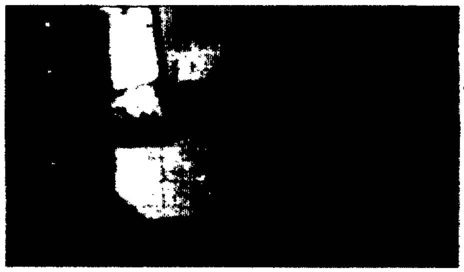
The two most important parameters to establish for fire survivability are pressure and temperature versus time. The hydraulic ram pressures versus time or their integral (impulse) should be established so the designer will know the loading to be expected within a fuel cell. The impulse loadings transmitted through air onto the walls of a magazine are a function of the type of chemical reaction of the explosive contents. Similarly, the air or shock pressure loading on the walls of an engine compartment or the upper portion of a fuel cell in contact with the ullage can be highly impulsive where an explosive fuel-vapor-air mixture ignites, as indicated in subpar. 8-2.4.1.3. In addition, the shock pressure versus time of a threat passing through a troop compartment must be known in order to establish the effects on personnel, as described in subpars. 5-3.4.3 and 5-4.4. The need to establish temperature buildup versus time is described for human incapacitation in subpar. 5-2.2 and is described for design of fire-sensing subsystems in subpar. 8-3.4. This need to establish temperature versus time was also described in subpar. 4-8.4.2, in which the differential heating of the magazine walls given gun propellant combustion resulted in buckling of the magazine doors. There is a great need to know the changes in both pressure and temperature versus time and, since the rate of combustion of various materials can be affected by either pressure or temperature, to know the relationship of the rate of change of pressure and temperature to the temperature and/or the pressure.

8-2.1.1 Hydraulic Ram Pressure Versus Time Recordings

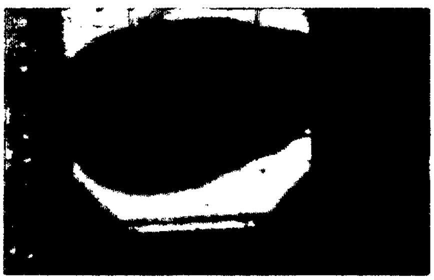
Hydraulic ram is a phenomenon that increases the damage to a liquid container upon penetration by a high-velocity threat. There are very few data available, however, by which hydraulic ram can be characterized, particularly when the threat is a shaped charge. Over the years pressure transducers have become sturdier and have a faster response. In 1957 a Photocon pressure transducer was used to measure the hydraulic ram resulting in the liquid oxygen (LOX) feed line of a large liquid propellant rocket engine when the flow through the main oxidizer feed valve was suddenly stopped (Ref. 10). The pressure transducer had to be protected from the low temperature (–183.0°C (–297.4°F)) of the LOX by use of a jacket normally used for protection from heat. A liquid was forced through the jacket to maintain the transducer temperature within the operable temperature range. The transducers successfully measured the LOX pressure variations when a series of twisted bourdon tube transducers used previously had failed to measure the pressures and had also failed to survive.

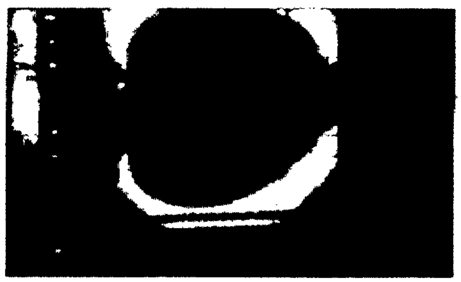
More recent pressure transducers that use piezoelectric crystals have a faster response, are smaller, and can better withstand impulsive pressure changes. In 1974 Kistler piezoelectric transducers were used to measure the hydraulic ram pressures within a liquid, which resulted from the impact of a severely yawing 14.5-mm armor-piercing incendiary tracer (APIT) bullet (Refs. 8 and 9). Fig. 8-7 is a sequence of frames from a high frame rate motion picture that shows the passage of this bullet through the liquid and the first hydraulic ram pressure oscillation. The pressure transducers were mounted in fittings at the end of the steel tubes seen in the center of the test fixture. Each transducer was approximately 152 mm (6 in.) from the anticipated bullet trajectory. A typical pressure recording is shown in Fig. 8-8.


Fr. 3, $t = 0.0006$ s


Fr. 5, $t = 0.0011$ s


Fr. 8, $t = 0.0018$ s


Fr. 25, $t = 0.0056$ s


Fr. 40, $t = 0.0089$ s

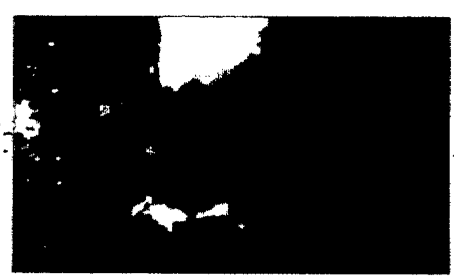

Fr. 61, $t = 0.0136$ s


Fr. 99 $t = 0.0220$ s.


Fr. 136, $t = 0.0302$ s


Fr. 154, $t = 0.0342$ s


Fr. 290, $t = 0.0664$ s.


Fr. 425, $t = 0.0944$ s.

Notes: 1. The pressure transducers are in hermetically sealed fittings at the ends of steel tubes and can be seen in Frame 3.
2. These photographs were made by a HyCam at the rate of 4500 fr/s.
3. Fr. = frame

Figure 8-7. Hydraulic Ram Buffering Test (Ref. 9)

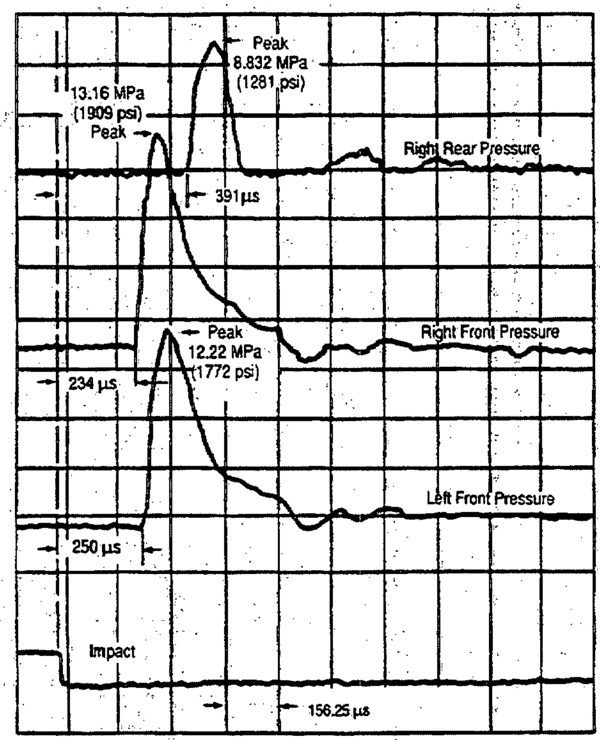


Figure 8-8. Typical Recordings Made With Pressure Transducers Configured as Shown on Fig. 8-7 (Ref. 9)

In 1982 recordings of hydraulic ram pressures generated by fully tumbled 14.5-mm APIT bullets were made successfully by using either piezoelectric pressure transducers or underwater tourmaline blast pressure transducers. Water was contained within aluminum-lined, fiber-wound external fuel cells, and the bullets impacted at a fully tumbled attitude. Pressure 3, shown in Fig. 8-9, was measured 1.041 m (41 in.) from the impact location with a PCB Model 102A03* piezoelectric pressure transducer mounted in a bulkhead at the nose of the fuel tank. Pressure 4 was measured at a bulkhead at the tail of the fuel cell approximately 3.2 m (11 ft) from the impact location. The pressures measured using a PCB Model 138A underwater blast transducer 146 mm (5.75 in.) from the impact location are as shown on Fig. 8-10 (Ref. 11). The biaxial strain gage recordings on Fig. 8-10 are both saturated.**

*Use of equipment by PCB Piezotronics, Inc., or other manufacturers does not constitute endorsement by the US Government.

**The filament-wound, composite fuel cell being tested was grossly delaminated under the biaxial strain so that the layer of material on which the gage was mounted was no longer stressed.

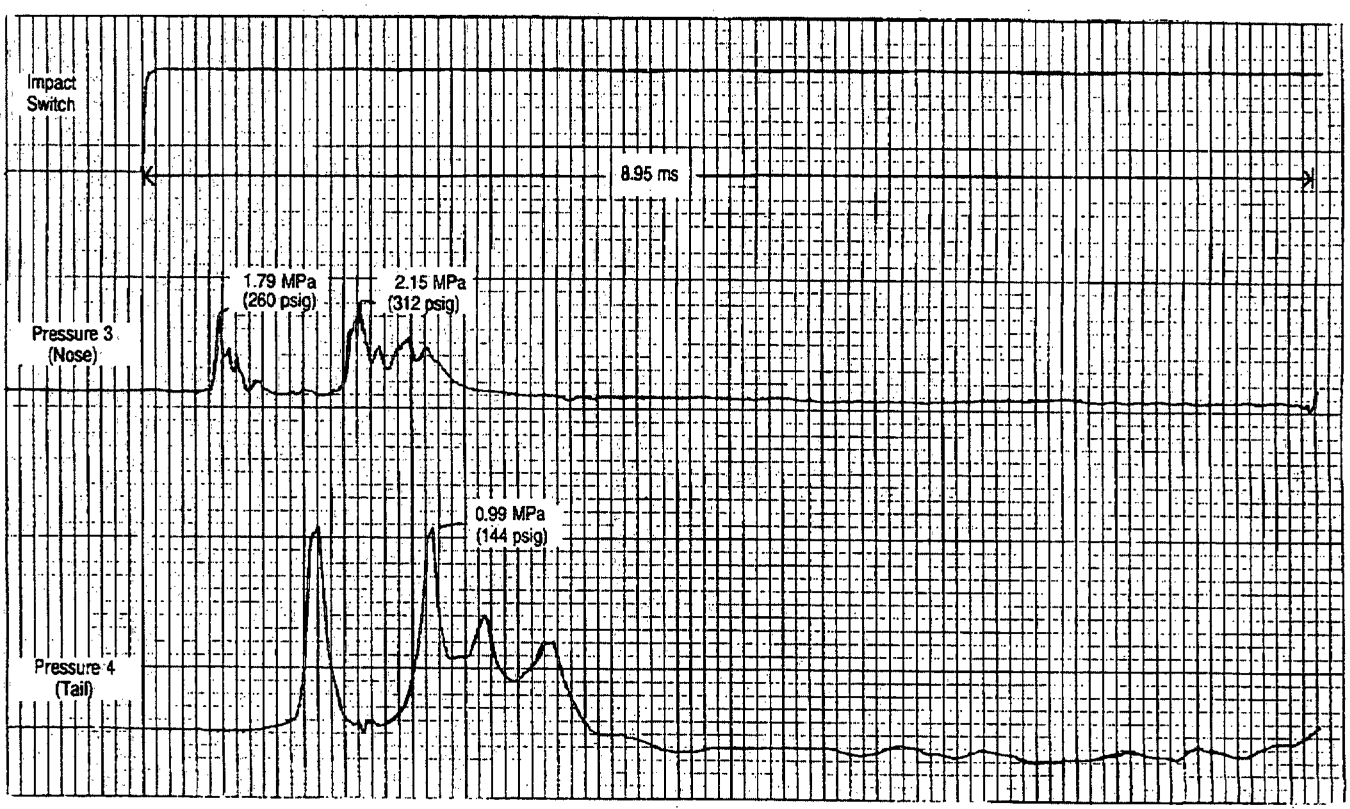
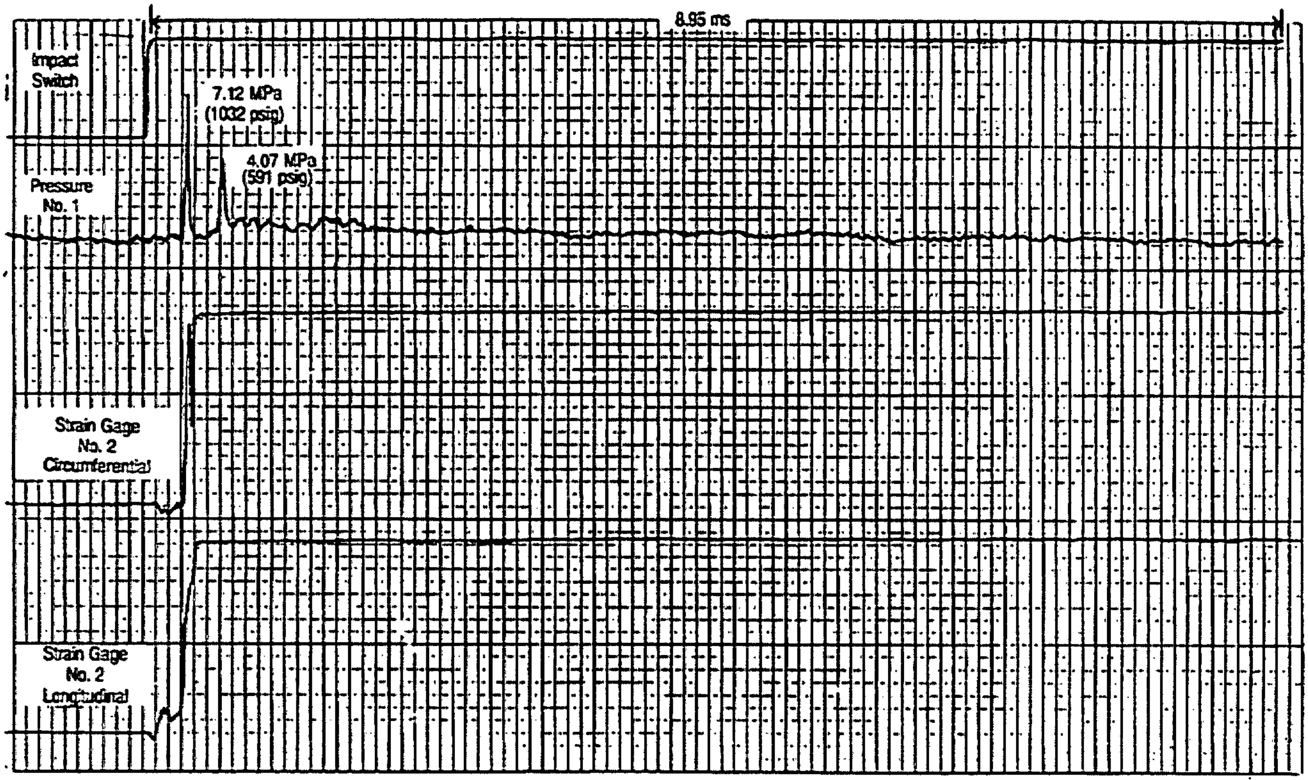


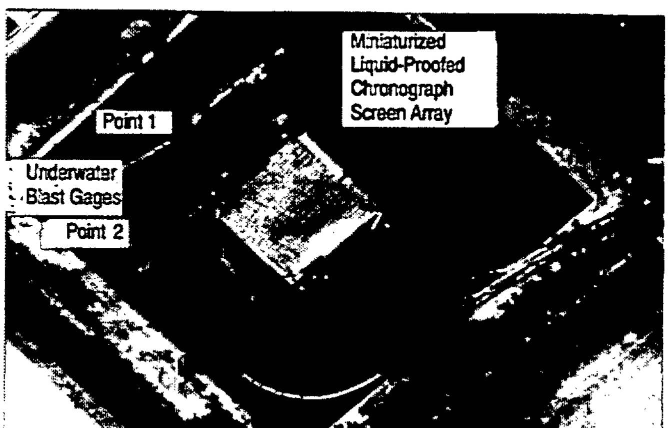
Figure 8-9. Hydraulic Ram Pressures Recorded Using a PCB 102A03 Piezoelectric Pressure Transducer (Ref. 11)



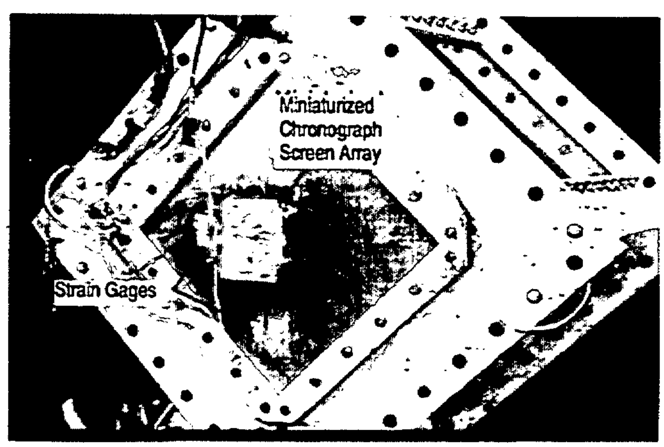
(Orthogonal strains from a nearby biaxial strain gage are also shown.)

Figure 8-10. Hydraulic Ram Pressure From an Underwater Blast Transducer (Ref. 11)

In another program (Ref. 12) a 7.78-g (120-grain) steel fragment simulator impacted a fuel cell with a thin aluminum face at 1585 m/s (5200 ft/s). The cell contained JP-5, water, or methanol. Hydraulic ram pressures on the inside of the face were measured with PCB Model 138A underwater blast gages, shown in Fig. 8-11(A). These gages were cemented to the interior fuel cell wall with an elastomeric cement. Biaxial strain gages were attached to the exterior surface of that fuel cell wall, as shown in Fig. 8-11(B), in opposite quadrants on the same fuel cell wall. The miniature chronograph screen arrays seen on Fig. 8-11 were an attempt to ascertain fragment simulator velocity immediately before and after perforation of the aluminum sheet. This attempt was not successful primarily because of the difficulty maintaining interscreen distances accurately. The interior screen array had been fuel proofed with spray-on epoxy (Ref. 12) The pressure and strain recordings shown on Fig. 8-12 are typical of the pressure on the inside of the



(A) Internal Surface of the Front Face of the Test Fixture



(B) Front Face of Test Fixture

Courtesy of Southwest Research Institute.

Figure 8-11. Strain Gages on External Surface and Underwater Blast Gages on Internal Surface of Fuel Cell Fixture (Ref. 12)

front face and the strain in the rear face. The underwater blast gages were located at Points 1 and 2, 51.3 mm (2.02 in.) and 113 mm (4.45 in.), respectively, from the impact location; the liquid for the test shown was water.

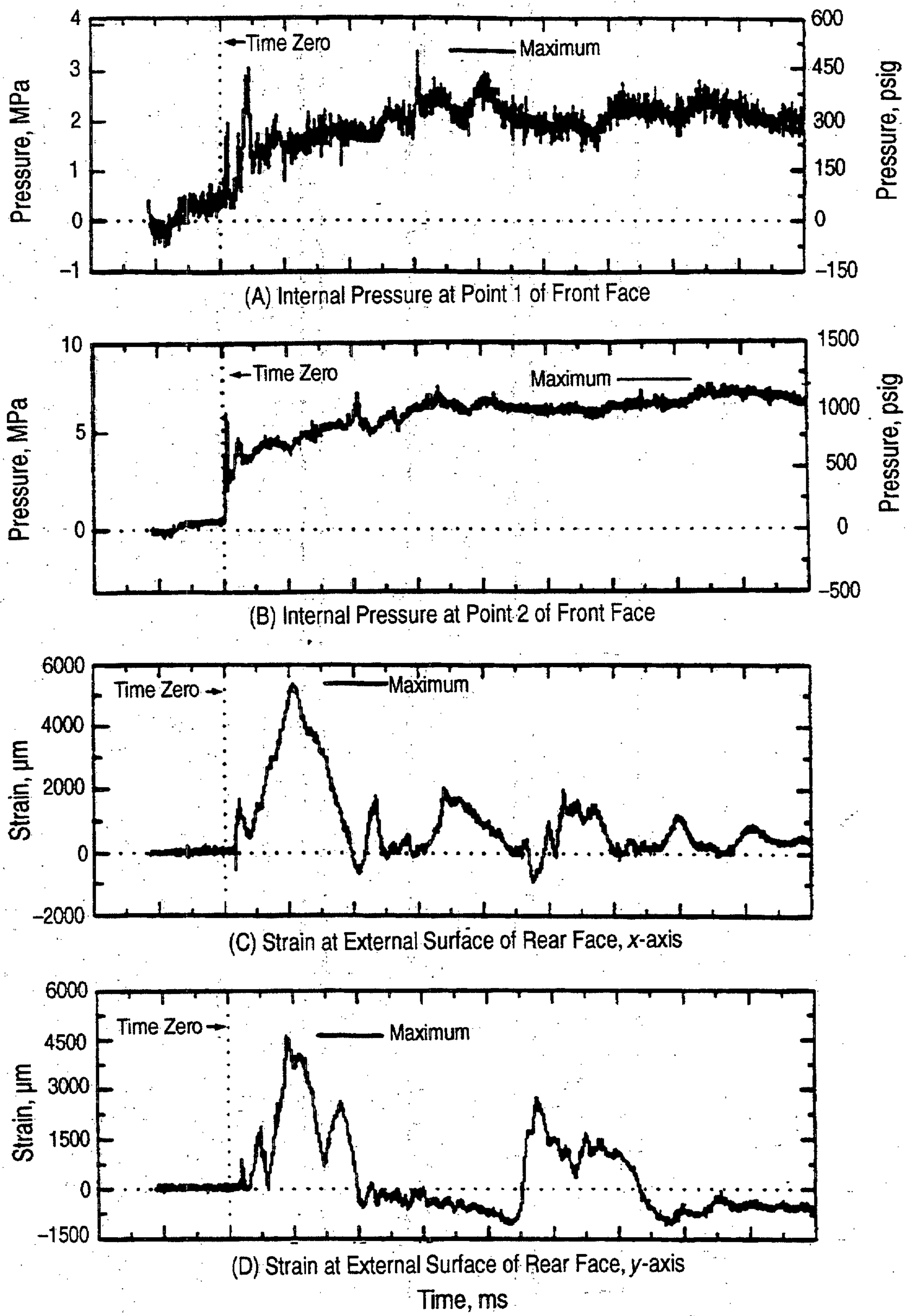


Figure 8-12. Hydraulic Ram Pressures Recorded Using Underwater Blast Gages Cemented to an Aluminum Wall With a Biaxial Strain Gage on the Outside (Ref. 12)

Hydraulic ram pressures caused by shaped-charge impacts can also be measured. The hydraulic ram pressures on the jet exit wall of the fuel cell were measured in a series of shaped-charge shots (Ref. 3). Initially, the pressures, shown on Fig. 8-13, were measured using Susquehanna underwater tourmaline pressure transducers attached to the fuel cell walls. The transducers, however, were physically disassembled by the very strong impulse. These tourmaline transducers were replaced by a PCB ballistic transducer first (designed to measure gun chamber pressures) and a PCB Model 102A03 piezoelectric pressure transducer later. These transducers were usually emplaced in the access port cover on the fuel cells as seen on Fig. 8-3(A). The hydraulic ram pressures measured by the piezoelectric pressure transducers varied from 46.9 to 78.5 MPa (6803 to 11,384 psi). In three of these tests the shaped-charge slug did not enter the fuel cell. The hydraulic ram pressures recorded for these three tests had a low of 46.9 MPa (6803 psi), a high of 52.2 MPa (7679 psi), and a mean of 48.5 MPa (7126 psi). In 13 tests the slug and the jet entered the fuel cell. In these tests there was a low of 47.9 MPa (7034 psi), a high of 78.5 MPa (11,384 psi), shown on Fig. 8-14, and a mean of 64.9 MPa (9408 psi). No good correlation could be found between peak pressure and distance from jet exit to pressure transducer. The plots shown on Figs. 8-13 and 8-14 were made by recording the pressure versus time data on a magnetic tape recorder, then digitizing the data, and documenting it on paper by using an X-Y plotter. These same pressure-time plots can be recorded from an oscilloscope by using a camera. For the test results shown in Fig. 8-14 a PCB piezoelectric pressure transducer was emplaced in the access port cover on the jet exit side of the fuel cell. The jet exit was approximately 305 mm (12 in.) from the pressure transducer diaphragm. The second pressure peak shown is due to the addition of reflected shock waves, but such pressures are too variable to be used for design. With knowledge of these impulsive loads a designer can better design a liquid container to prevent gross rupture when a shaped-charge jet impacts it.

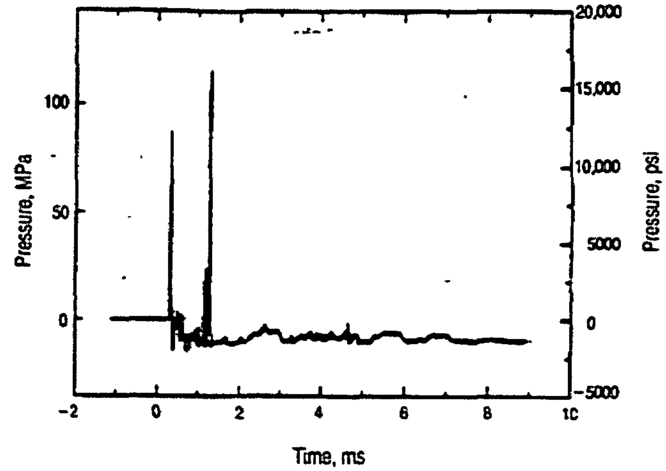
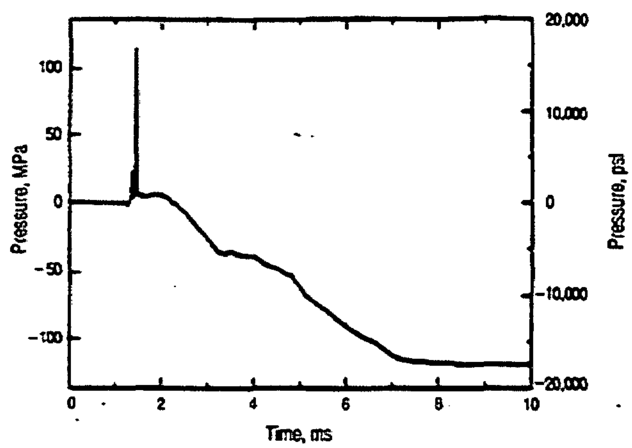


Figure 8-14. Hydraulic Ram Pressures in a Fuel Cell Impacted by a Shaped-Charge Jet Measured With a Piezoelectric Pressure Transducer (Ref. 3)

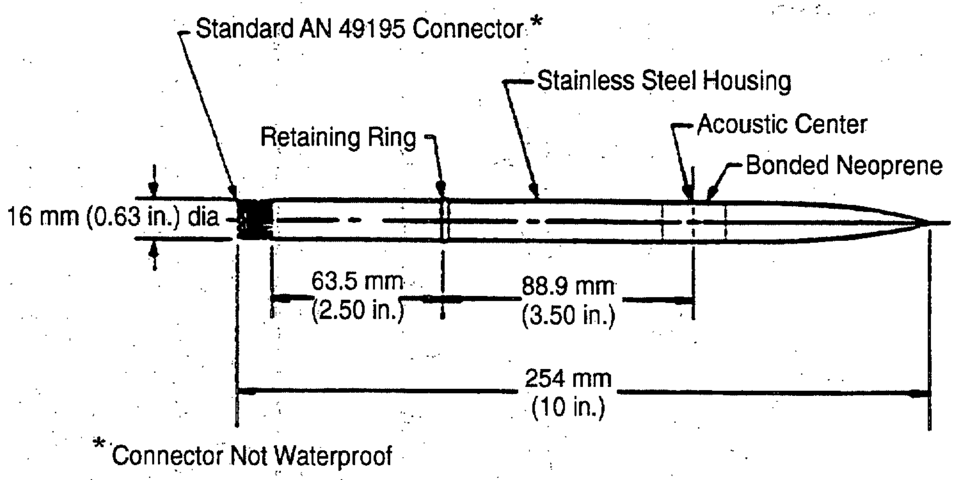


Pressures recorded after the first 2 ms are often not accurate. The underwater pressure transducer was cemented to the inside surface of the fuel cell on the jet entry side approximately 102 mm (4 in.) from the jet impact point.

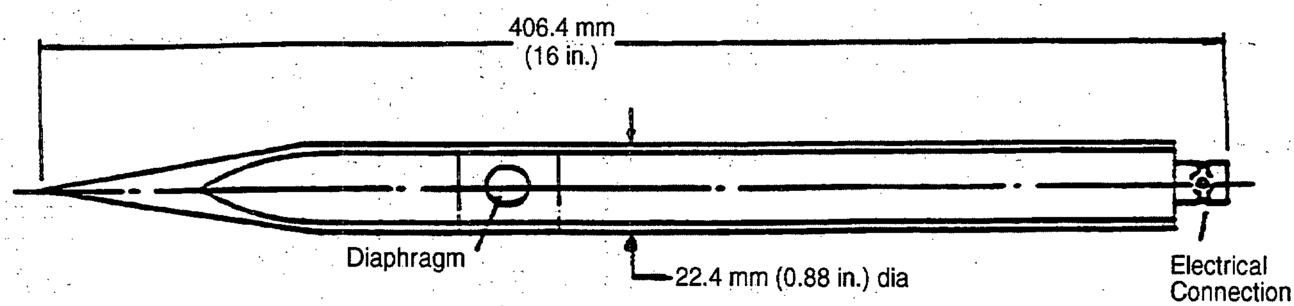
Figure 8-13. Hydraulic Ram Pressures From a Shaped-Charge Jet Passing Through a Fuel Cell Measured With an Underwater Pressure Transducer (Ref. 5)

There are many means available (Some of these are shown on Fig. 8-15.) by which to acquire these data and document them. The underwater blast gage in Fig. 8-15(C) proved to be too delicate for hydraulic ram determinations when shaped-charge jets pass through fuel cells; however, a device that should be sturdy enough for this purpose is currently being developed (Ref. 16). The underwater tourmaline transducers, which were disassembled by the turbulence incident to jet-liquid interactions, were easily reassembled and functioned properly afterward.

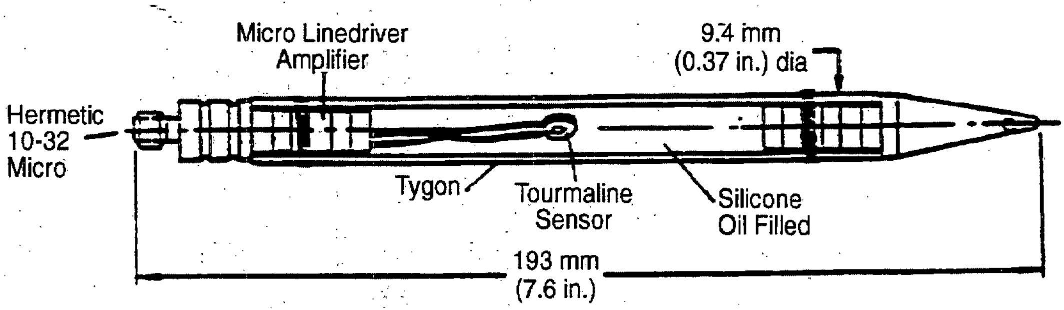
On occasion, the effect of hydraulic ram can be assessed by the posttest condition of some hardware within the fuel cell, as shown in Fig. 8-16 by the crushed the fuel feed line within an integral wing fuel cell.



(A) Celesco LC-33 Blast Pressure Transducer (Ref. 13)



(B) Model 137A, Series Free Field Blast Pressure Probe
(Former Susquehanna Model ST-7 With Built-In Source Follower) (Ref. 14)



(C) PCB 138A, Series Underwater Tourmaline Blast Pressure Transducer
(Former Susquehanna Model No. PHI-7) (Ref. 15)

Figure 8-15. Pressure Transducers

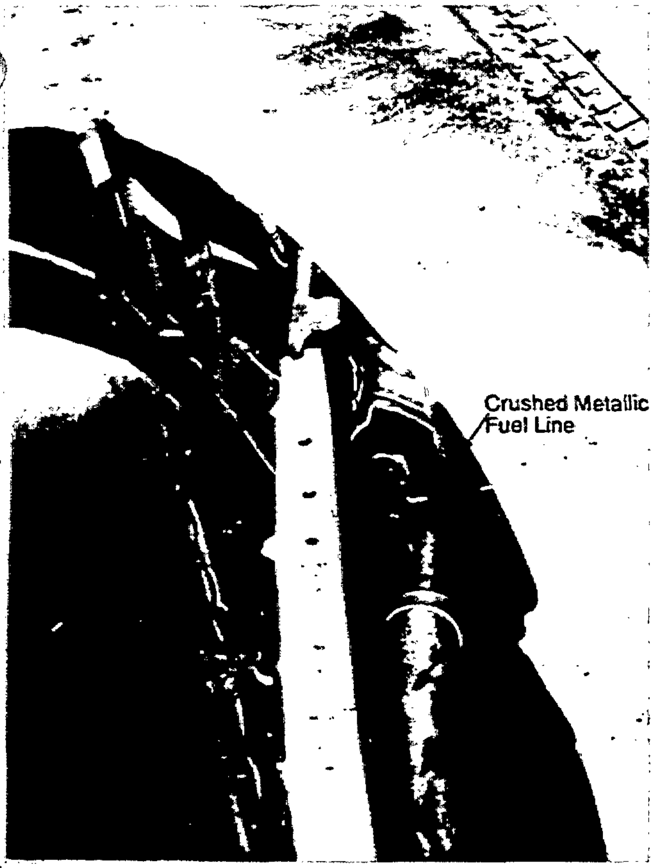
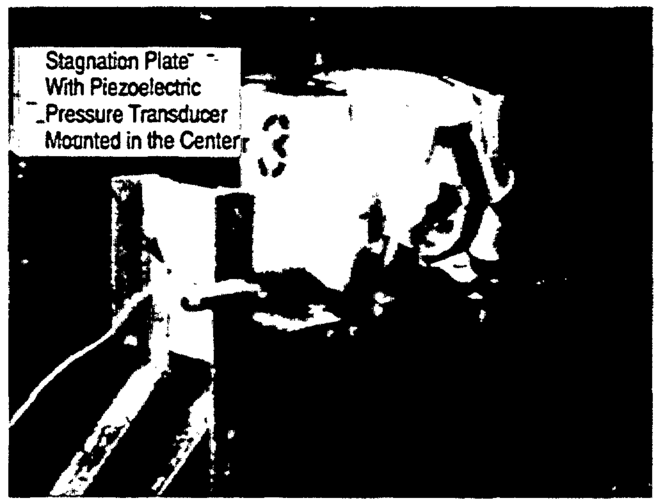


Figure 8-16. Collapsed Fuel Line Within Aircraft Wing Integral Fuel Cell (Ref. 17)

Note: The instrumentation is protected from blast by a metal shield (1). The pressure transducer mount (2) has a separate ground base (3) from the box (4) simulating the vehicle.

(A) Isolation of Air Shock Transducer



(B) Relation of Air Shock Transducer to Test Fuel Cell

Figure 8-17. Piezoelectric Pressure Transducer Mounted in Stagnation Plate for Test Fixture Air Shock Pressure Determinations (Ref. 18)

8-2.1.2 Air Blast or Shock Pressure Versus Time Recordings

The use of piezoelectric pressure transducers has greatly improved the fidelity of blast or shock wave pressure measurements in air. Oscilloscope photographs of the shock pressures from the passage of a shaped-charge jet through a test fixture are Fig. 5-15 (Ref. 3). Pencil gages were used, either Celesco Model LC-33 blast pressure transducers (Fig. 8-15(A)) or PCB Model 137A free field blast pressure probes (Fig. 8-15(B)). These gages are somewhat limited because the gage has to be directed toward the source of the shock wave. Otherwise the fidelity of the pressure being sensed decreases, and the gage will not sense a true side-on pressure. This orientation requirement means that the shocks from reflections, which can be seen on Fig. 5-15, may be greater or lesser than those recorded depending upon the direction from which they came.

To alleviate this orientation problem, a piezoelectric pressure transducer can be centered in a stagnation plate, shown in Fig. 8-17. This type of device senses the normal component of all incident pressures, as illustrated in Fig. 5-17, for effective pressures received by a crewman's ears. A good rule of thumb is that the stagnation plate should provide the distance of approximately ten transducer diaphragms from a flat surface in the plane of the diaphragm and in all directions around the diaphragm to assure the sensing of the dynamic (stagnation) pressure.

8-2.1.3 Recording Temperature Versus Time

Heat is a nebulous quantity to measure. Heat is not measured; the effect that heat has on an object, i.e., the temperature of the object, is measured indirectly by the volume a fluid fills or by pyrometers, which measure the voltage across a dissimilar metal junction, the electrical resistance of a material, or the emitted light. All of these phenomena take time to become evident and do so through a finite volume. Also that volume will not be at a single temperature throughout; therefore, a measured "temperature" should be the average of the temperatures throughout the volume. The test instrumentation shown in Fig. 8-3(A) uses five thermocouples to attempt to obtain a mean temperature. Changes in the measured "temperature" take time to occur. This time is a function of the nature of the heat transfer that takes place, the area through which this heat transfer is occurring, the thermal capacitance and mass of the material being heated, the difference in temperature between the heat source and the material, and the loss of heat from the material. There are three processes for heat transmission: radiation, conduction, and convection. Convection is the transfer of heat by the combined mechanisms of fluid mixing and conduction. (Ref. 19) Heat transfer by radiation is faster than by conduction (Radiant heat transfer occurs at the speed of light.), but radiant heat transfer is a function of the difference between the absolute temperatures of the donor and acceptor each taken to the fourth power. There must be a great difference in absolute temperatures, as described in subpar. 5-2.1.2.1.1, before this means of heat transfer is greatly effective. Most of the heat transfer addressed in this handbook is by conduction. To measure heat transferred by conduction, either a voltage generation device, i.e., thermocouple, or a change of resistance device, i.e., a thermistor, can be used. The volume change device, i.e., thermometer, and other devices, such as a bimetallic probe or coil, have been omitted because they are not suited to high-speed recording. The thermocouple is usable over a greater range of temperatures with which the engineer is concerned than the thermistor; see Figs. 6-15 and 6-26. To obtain a very fast response, a bare, butt-welded thermocouple (Fig. 6-27(A)), a beaded type with a small head (Fig. 6-27(C)), or a thin film thermocouple (described in subpar. 6-3.3.1) is needed. The smaller the bead, however, the finer the wire. Thus fabrication is more difficult, and the fine wire provides an extremely sensitive device that is highly subject to being damaged. A pyrometer is useful when temperatures are too high to use thermocouples.

There are many types of temperature-sensing devices, but for most recording of temperature in tests, an engineer need consider only two, the thermocouple and the thermistor. Heat flux sensors have been used to determine whether sufficient heat is received by a body at a given location to cause a burn, but this device is essentially a specialized use of a thermocouple.

8-2.1.3.1 Thermocouples

There has been much controversy about whether a thermocouple has as fast a response as a piezoelectric pressure transducer. It does not, but is that fast a response for temperature needed when designing a combat vehicle for fire survivability? For what purposes is the information needed? These purposes are

1. To establish the potential hazards to occupants
2. To select or design fire sensors for the troop compartment, the engine compartment, and vehicular magazines
3. To establish which items need fire-retardant or thermal insulation coverings
4. To establish the expected duration of operation of specific components given a fire in their compartment
5. To establish the rates at which specific materials, e.g., mobility fuel, hydraulic fluid, and explosives, will heat in either sustained vehicular operation or the event of vehicular fires.

To select fire sensors or detect heat inputs into magazine walls, time in the seconds or even minutes range can be used. A faster device such as an intrusion or penetration detector (break wire device) (See subpar. 6-4.1.) can be used to detect penetrations that may cause a fire. The time response requirement for fire-retardant insulation, for the operational times of components, and for the rate of burning of materials is also in the seconds range. Therefore, for all practical purposes, thermocouples provide an adequate response. They are described in subpar. 6-3.2. Thermocouples are inadequate for immediate detection of a hydrocarbon fireball that may cause crew burns if sustained.

The main advantages of a thermocouple are that it is simple, rugged (compared to other temperature-sensing devices), and can cover an extensive temperature range. The main disadvantage is that a thermocouple is slow compared to a piezoelectric pressure transducer but so are most other temperature-sensing devices. An important advantage is that thermocouples can be easily fabricated by the technicians at a test site using a simple welding device. A thermocouple responds to temperature wherever junctions are formed, usually only at the bead. In a large target it is necessary to employ a large number of thermocouples, each with its own recording device. On the other hand, temperature is a point phenomenon and is subject to change whenever heat sources and/or heat sinks vary, and even when the heat source and heat sink each remain constant, the "temperature" of a single body will vary within the body.

8-2.1.3.2 Thermistors

Another temperature-sensing device that can be used is a thermistor or THERMal resISTOR. A thermistor is a ceramic material (a semiconductor) whose electrical resistance changes with temperature (Ref. 20). Thermistors, like thermocouples, are used in bridge circuits to provide an error signal that is a measure of the temperature to which the thermistor is exposed. Thermistors have a greater gain than thermocouples; that is, the change of signal with change of temperature ($\Delta R/\Delta T$) is greater than it is for a thermocouple ($\Delta V/\Delta T$) where R = resistance, T = temperature, and V = voltage. The temperature range of the thermistor, however, is correspondingly smaller (as shown on Fig. 6-15). Also the output of the thermistor versus temperature is not as linear as that of a thermocouple. The time response of the thermistor is approximately the same as that of a thermocouple; again, a volume of material must have heat transferred into or out of it for its average electric resistance to change. A thermistor is more delicate than a thermocouple, i.e., the thermistor can be more easily damaged by heat as well as by mechanical impact. Thermistors cannot be fabricated easily, especially not by technicians at a test site. Thermistors require more knowledgeable and/or experienced instrumentation personnel than thermocouples to obtain valid temperature determinations. Thermistors are recommended where temperature must be established more precisely.

8-2.1.3.3 Heat Flux Sensors

Heat flux sensors have been used to quantify the heat received by an animal that resulted in a given burn, and they are being used in current tests to establish the potential for a person to receive a burn. There are four basic variations of heat flux sensors that are most often used. These types are shown on Fig. 8-18. These sensors must be selected based upon several factors; the mode of heat transfer, the temperature range involved, the heat transfer rate, and the time involved are probably the most important factors in this application. The important application for the purposes of this handbook is to establish the probability of a crewman's being exposed to enough heat to receive a skin burn. The modes of heat transfer involved in this application are radiation, convection, conduction (when a hot droplet of liquid impacts), and/or the combination of the three when a fireball of burning liquid spray engulfs a person. This is a much more complex situation than most heat flux applications. The greatest challenge is to calibrate the heat flux sensor to account for the total heat flux. Calibration is usually accomplished by a combination of measurement and analysis.

The capacity element of the slug-type heat flux sensor, Fig. 8-18(A), is a heat-receiving mass that is usually in the form of a copper cylinder and the outer surface has been blackened to increase its absorptivity. This slug is embedded in thermal insulation and has a thermocouple embedded in the center of the unexposed, or inner, face. The heat flux Q is proportional to the rate of rise of the slug temperature. Slug-type sensors are generally inaccurate because of the practical difficulty in insulating the slug perfectly from its surroundings. The slug-type sensor is good for short duration heat flux inputs and has a very fast response, but its use is restricted to applications whose total test time is in milliseconds. This type of sensor is useful for establishing transient heat transfer but is not capable of measuring steady state heat flux.

The thin foil- or membrane-type heat flux sensor, which is illustrated in Fig. 8-18(B), is usually a constantan membrane attached on its periphery to a copper mass, and a copper lead is attached to the center of the membrane. The thermocouples are the junctions of the constantan and copper at the center and around the periphery of the membrane. The thermocouple output is a function of the differential temperature between the center (hot junction) and the periphery of the membrane (cold junction), which is a function of the heat flow from the membrane to the sink (the copper mass). The sensory output can have a range of 0 to 10 mV. Sensors have been manufactured that can measure up to 34.05 MW/m^2 (3000 Btu/(ft^2·s)). Continuous time-varying measurements can be made easily. A 63% response time is in the range of 50 to 500 ms. Most thin foil sensors are limited to a temperature range of −45°C to 230°C. Water-cooled sensors are also available.

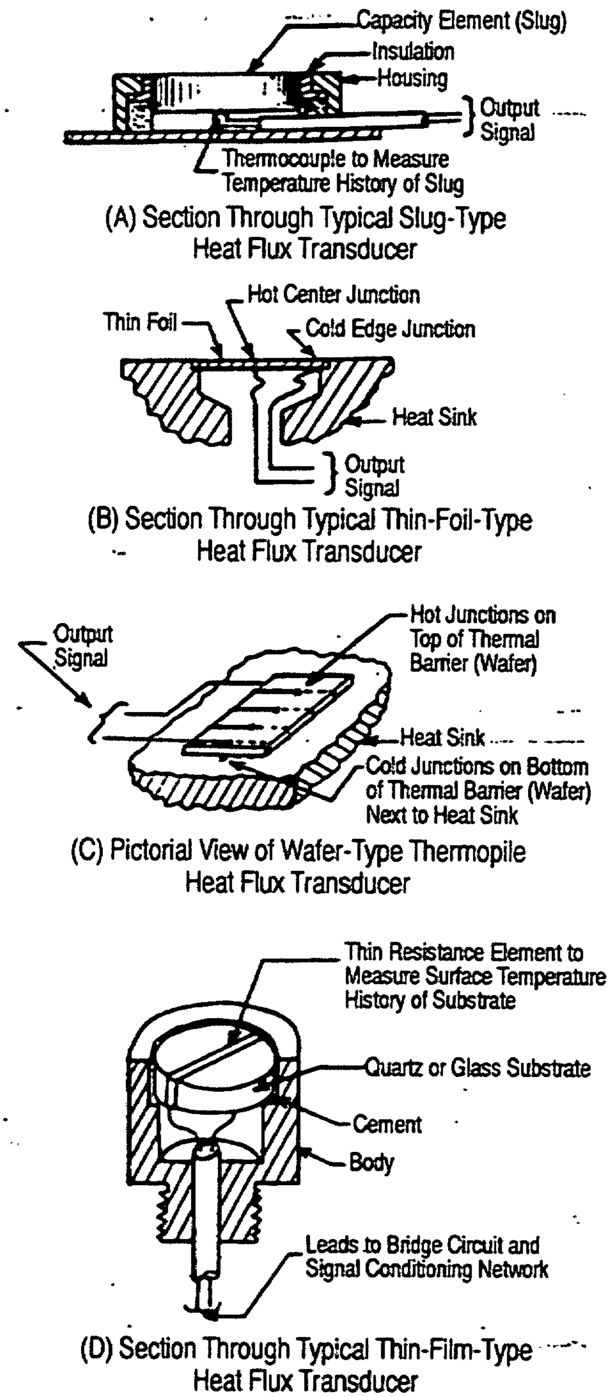


Figure 8-18. Heat Flux Sensors (Ref. 21)

The thermopile-type sensor is shown in Fig. 8-18(C). The hot junctions are exposed to the heat, and the cold junctions are buried in the heat sink below the thermal barrier. The thermopile output voltage is proportional to the heat flux. This type of sensor is ideal for measurement of low convective heat transfer rates from low-temperature gases. Both water-cooled and uncooled types of sensors are available. Heat flux rates from very low to 227 kW/m² (20 Btu/(ft²·s)) can be measured with a 63% response time ranging from 250 ms to several seconds. The maximum operating temperature is 180°C (356°F).

The thin-film sensor, Fig. 8-18(D), has a thin, resistive, temperature-sensitive film deposited on a quartz or glass substrate. The electrical resistance of the film varies proportionally with surface temperature. The temperature can be related to heat flux through a complex computer analysis. This device has a very fast response. The usable temperature range is dependent upon the film material used.

All of these heat flux sensors must be calibrated to provide a heat flux Q in terms of

$$Q = Ce,\ \mathrm{W/m^2} \tag{8-1}$$

where

C = calibration constant, (W/m²)/mV
e = the output of the thermocouple, mV.

The thin-film heat flux sensor is better adapted to establishing transient flux.

8-2.2 GAS CONCENTRATION

Measurement of gas concentrations during full-scale testing is intended to serve several purposes. These data are crucial to evaluate the toxic hazards due to the products of a fire inside a combat vehicle. Such hazards are related to the concentrations of the important chemical species (generally gases), the toxicities of these species, and the time of exposure of the subjects. The detection of lethal gases, as well as those that might produce toxic effects other than lethality, e.g., sensory or pulmonary irritation, is necessary. These gases may be produced by either pyrolysis or combustion of the substances burning or by the extinguishant itself. Of secondary importance is the measurement of fuel vapors which may contribute to continued burning or subsequent reignition. Devices that sample the air from within the vehicle on a fairly timely basis are described in subpar. 6-4.3.

It is not necessary to analyze all of the products of a fire; in fact, it is nearly impossible to do so. It is most important to characterize those products that pose a risk to life or to the appropriate functioning of the individuals in the vehicle. Animal subjects are often used in an effort to assess the effects of the combination of toxic products rather than to attempt to model, i.e., predict, the biological effects based solely on chemical analyses. The sampling of gases and aerosols from a fire environment creates unique problems that must be solved to assure that the chemical species (and their concentrations) do not change during the sampling process. An extensive survey of this subject is given in the American Society for Testing and Materials (ASTM) E 800, *Standard Guide for Measurement of Gases Present or Generated During Fires* (Ref. 22). In many cases, specially designed sampling probes and instrumentation are required for the unique environment of a fire. Transport of reactive gases, e.g., hydrogen chloride, through long sampling lines is discouraged. A fire or explosion in an enclosed vehicle presents some additional problems due to the likely pressure buildup. Sampling lines, vessels, and other test equipment must be designed to withstand these stresses. A fire in a combat vehicle is an obvious and immediate problem. The hazards from toxic gases resulting from such a fire may not be so obvious, however, because of low concentration and/or lack of odor. Development of gas monitors for use in vehicles during actual operation may be advisable.* For example, there are small, commercially available detectors for carbon monoxide that sound an alarm at low levels (generally 400 ppm), which could be hazardous if breathed over long periods of time.

8-2.2.1 Fuel and Extinguishant Vapors

The presence of volatilized fuel or unburned hydrocarbons in a vehicle after a fire or munition impact poses a threat of further fire or explosion. Although these vapors are generally not lethal or even acutely toxic, their measurement indicates the possibility of a hazard to the crew from fire or explosion. Today there are instruments available to determine selected gas concentrations inside vehicles.

Measurement of fuel vapors can be accomplished by atmosphere sampling and common laboratory analytical techniques, such as gas chromatography. Such techniques are the same as those described for hydrocarbon vapors in subpar. 8-2.2.2. The data must be compared with the combustibility limits for the type of hydrocarbon vapors, and consideration given to the likelihood an ignition source is present.

Release of a fire extinguishant should be measured in real time or by periodic sampling and followed with analysis by gas chromatography or mass spectrometry or other techniques. Presence of certain extinguishing agents within a given concentration range may preclude a fire from reigniting. However, the possible toxic effects of the extinguishant and its pyrolysis by-products will need to be identified.

8-2.2.2 Fire By-Products

Some of the by-products of a fire are potentially toxic, perhaps even lethal in large doses. Thus analyses of these species (generally gases) are crucial to evaluation of the

*Such monitors could be integrated with the nuclear, biological, and chemical (NBC) system, but basically the monitoring and altering of the content of the air within a combat vehicle is an environmental—air conditioning—problem, not a chemical warfare one.

survivability of an individual to these fire by-products. Different types of chemical reactions, even with the same material, do not necessarily produce the same products. For example, detonation of RDX produces 0.6 moles per kg of CO, 6.6 moles per kg of CO_2, 0.8 moles per kg of NH_3 (ammonia), and 3.1 moles per kg of H_2O (Ref. 23), whereas deflagration of RDX produces 8.0 moles per kg of CO, 5.5 moles per kg of CO_2, 2.8 moles per kg of NH_3, and 8.0 moles per kg of H_2O (Ref. 24). In an enclosed environment such as a combat vehicle, the toxic effects of the gases may be exerted over relatively long periods of time because the occupants are confined within the vehicle. These toxic effects are dependent on both the concentration of the species and the time of exposure of the subject; therefore, it is necessary that the toxic gaseous species be identified and that their concentrations as functions of time during and after a fire be determined. With this information an assessment of the toxic hazards due to these species can be made, as was done in Ref. 25 for Halon 1301.

Specialized sampling and analysis systems exist for many of the common fire by-products, including carbon monoxide, carbon dioxide, hydrogen cyanide, hydrogen halides (HCl, HBr, and HF), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbonyl sulfide, organic aldehydes, and hydrocarbons, as well as oxygen, water, and nitrogen. In some cases continuous or semicontinuous analysis of the particular gas of interest may be obtained; in other cases, however, only intermittent analyses are possible. Each sampling and analysis system has its advantages and disadvantages for application to any particular fire scenario.

Table 8-1 has been abstracted from ASTM E 800, *Standard Guide for Measurement of Gases Present or Generated During Fires* (Ref. 22). It contains a summary of the methods of sampling and analysis for the gases of primary concern in fires. The table contains references to sections in the text of the standard that contain further discussion. The following information is intended to supplement that provided in the standard and to include discussion of the unique situation of fire in a combat vehicle.

Many analytical techniques can be used to analyze the fire by-products of interest, provided that interferences, such as further reactions within the sampling system, are taken into consideration and that the appropriate ranges of concentrations are accommodated. The most critical aspect of measurement of fire by-products is sampling. (See Section 5, "Sampling", in ASTM E 800 for a detailed discussion of the problems of sampling fire atmospheres.)

Listed in Table 8-1 are the two basic modes for sampling fire atmospheres, batch and continuous. Batch refers to a sample obtained over some period, whether it is 30 s or the entire run. Continuous refers to a continuous measure of the concentration of the species for the duration of the experiment. These two modes may be further subdivided into remote and direct sampling. Remote sampling entails a transfer line from the point of sampling to the point of collection for analysis; this type is preferable for a large fire or explosion in a confined space. Direct sampling can be represented by a collector directly in the fire atmosphere; this type is advisable for collection of reactive gases, such as the hydrogen halides. Thus sampling gases from a test fire environment in a combat vehicle may include the following:

1. Remote continuous analyzers may be used to measure selected nonreactive and noncondensable gases. For example, commercially available, nondispersive infrared instruments are very useful for measuring carbon monoxide or carbon dioxide. When this type of analyzer is available, it would be the preferred choice.

2. Remote batch analyzers that entail noncontinuous sampling and laboratory analyses, e.g., gas or solution chromatography with an automatic or semiautomatic sampling system, may be used for most of the gases of interest, e.g., CO, CO_2, HCN, hydrocarbons, and aldehydes. Gas chromatography can also be used in conjunction with direct grab sampling. This type of instrumentation is commonly available in laboratories and is applicable to a broad range of chemical species. However, it has a significant disadvantage because many samples must be obtained in order to be able to describe a concentration-time curve. Other specific types of analysis of batch samples may include titration, calorimetry, and ion-selective electrode methods, which are listed in Table 8-1.

3. Several types of direct batch sampling probes are available that permit collection and holding of a sample of the atmosphere with essentially no sampling line ahead of the collector. One type involves solid soda lime, or caustic solution, sampling tubes, which are referenced in Section 7.3 of ASTM E 800. This type is particularly useful for sampling reactive gases, such as hydrogen halides, that might be lost due to reaction or condensation in sampling lines. Subsequent analyses usually involve titration or ion chromatography. The other type of direct batch sampling is a "grab" sample of the atmosphere. This generally consists of an evacuated bulb, a plastic bag, or a gas-tight syringe to collect a known volume of the test atmosphere. Subsequent analyses might be conducted using gas or liquid chromatography. All of these batch methods require multiple samples in order to describe a concentration-time curve. In practice, a tester would set up many samplers in the same location inside the test environment and actuate valves remotely in order to activate each sampler at a precise time during the experiment.

Measurement of the gases present during a fire in a simulated combat vehicle is a difficult task. Stainless steel sampling probes have to be located at key sites within the volume of the "vehicle". Numerous probes may be necessary at each site in order to analyze all of the key gases for an extended time period. Several different types of analyzers are necessary to provide the appropriate characterization of the gases of interest. It is impractical and unnecessary to attempt to analyze all of the gases produced in a fire; however, it is essential to characterize properly the important

TABLE 8-1. SUMMARY OF ANALYTICAL METHODS FOR FIRE GASES (Ref. 22)

METHOD*	SPECIES**	SAMPLING MODE†	INTERFERENCES/LIMITATIONS
Gas Chromatography	CO, CO_2, O_2, N_2 HX HCN Hydrocarbons Aldehydes	Batch Batch Batch Batch Batch	No single column will resolve all four species. Not commonly used See Ref. 21. Suitability to mixtures of hydrocarbons depends on calibration. See Ref. 21.
Ion Chromatography	X NO_2, NO_3	Batch, solution Batch, solution	Specific detector and conditions required Specific detector and conditions required
Infrared	CO, CO_2 HX HCN SO_X Hydrocarbons	Continuous or batch Continuous Continuous Continuous Continuous	Continuous mode usually limited to analysis of one species; batch mode not limited Technique under development Technique under development †† Not very accurate for mixtures of hydrocarbons
Ion-Selective Electrodes	X CN	Batch or continuous, solution Batch or continuous, solution	Cyanide, sulfide, and other halides can interfere; each electrode specific to that species Cyanide, sulfide, and other halides can interfere; each electrode specific to that species
Electrochemical Methods: Oxidation Conductometric Amperometric Chemiluminescent	CO HX HCN NO_X HCN Acrolein	Continuous Continuous, solution Continuous, solution Continuous Batch, solution Batch, solution	Relatively slow Nonspecific Interference from H_2S Large sampling volumes Limited to low concentrations Limited to low concentrations Determines total acid gas component, i.e., anything that will remove or pick up proton in solution
Titrimetric Procedures	HX HCN	Batch or continuous, solution Batch, solution	Not commonly used Intereference from halide ions
Gas Analysis Tubes ("pull tubes")	CO, CO_2, O_2 HCl HCN	Batch	Only semiquantitative; HCl tube very limited

*This list is not exhaustive.
**X = halide (F, Cl, Br, I)
SO_x = sulfur oxides (SO_2, SO_3)
NO_x = nitrogen oxides (NO, NO_2)
†"Batch" refers to a sample obtained over some period (whether it be 30 s or the entire run). "Continuous" refers to a continuous measure of the species' concentration for the duration of the experiment. "Solution" means that the species must be absorbed into solution in order to be measured.
††No remarks

toxic by-products. The key gases depend somewhat on the materials and products exposed to the fire (as detailed in previous chapters). In all fires measurement of carbon monoxide, carbon dioxide, and oxygen has become routine and necessary. In many fires measurement of HCN is essential. Likewise, analysis of HCl, HBr, and HF must be done when their presence is suspected based on the types of materials being burned or the possible by-products from the extinguishant being used. Analyses of specific aldehydes, hydrocarbon vapors, nitrogen and sulfur oxides, carbonyl sulfide, etc., may be undertaken as deemed necessary, but they are too expensive for most routine experimentation.

8-2.3 EXTINGUISHING SYSTEM EVENT TIMING

For test and design personnel to develop a fire-extinguishing system, they must be able to relate events that have occurred with the threat, the test specimen, the combustion reactions, and the fire-extinguishing system. All of these events or reactions must be established for their time of occurrence relative to each other. Instrumentation must be selected that has the capability to discern the nature of the event and its relative time of occurrence.

8-2.3.1 Threat Functioning

Usually the test and design personnel know how threats function and what target response can be expected; however, test personnel should always verify that the threat has functioned as expected and be able to relate threat effect to target response. Sometimes the threat does not function as expected, and threat malfunction must be diagnosed. Most threats are of foreign manufacture and often cannot be disassembled to establish whether they are properly fabricated and assembled. Many of these threats have been acquired by one government agency and have been passed through other agencies before being received by the user. In one instance, a number of 14.5-mm APIT cartridges were received that were reputedly unmodified, and none appeared to have been modified. Several of these cartridges were used in tests, all functioned properly, and the chronograph system used established the expected near-muzzle* velocities. In the test to establish the reaction of an external fuel cell for the FA-18 aircraft to the impact of a "fully tumbled" 14.5-mm bullet, the target performed as expected, but the chronograph system indicated a much slower than desired muzzle velocity. The "tumble" was not "full" enough. Examination of witness sheets, emplaced to monitor the tumbling of the bullet, showed that the bullet was accompanied by many small particles part of the way to the target. Some of these particles were recovered and examined for chemical composition because the test personnel thought there was a possibility that the propellant of this foreign cartridge might have been defective. The chemical analysis of these particles was surprising—the particles were a carbohydrate, resembling breakfast cereal. The test conductor remembered that personnel at the government agency which had furnished the cartridges had a policy to fill the space between the propellant and the bullet of off-loaded cartridges with Cream of Wheat. Therefore, all remaining cartridges were examined for propellant loads, i.e., the bullets were pulled and the propellant charges weighed and examined. Approximately eight off-loaded cartridges inadvertently had been included in a shipment of fifty 14.5-mm cartridges. However, sufficient instrumentation had been used, including witness sheets, to establish just what had happened, and this diagnosis, or at least the identification of an abnormality and the gathering of evidence, took place a few minutes after the test was performed (Ref. 26). Test personnel must be alert to any abnormality or discrepancy and must check such at the time of the test.

In another program intended to establish the capability of antimisting fuel to resist ignition or sustained combustion, the reaction of the target fuel cell and the fuel to the impact of a 23-mm high-explosive incendiary tracer (HEIT) projectile seemed remarkably subdued. The tests were performed to simulate an attack aircraft receiving a ground-to-air antiaircraft projectile hit as the aircraft was climbing after a strafing run. The test installation is shown in Fig. 8-19. The chronograph system mounted on the muzzle of the main gun showed that the projectile was at the desired velocity. One of the test technicians noticed that some bright object had come from the target area and landed over by the wind machine. After the area was declared safe, he investigated and discovered that the object was a sizable part of the body of the projectile. This identification led to a further evaluation of the subdued projectile-target interaction, which proved to be caused by an unsuspected projectile weakness. (Ref. 27) This test demonstrates that observant test personnel, who check out unusual happenings and bring them to the attention of the test director, are a form of instrumentation that is extremely valuable. It also shows that remnants of the threat are themselves a reliable indicator of threat performance. The fragments shown in Fig. 8-20 were all collected during this same series of tests. Fragments shown in Fig. 8-20 show that two different mechanisms were involved in their formation. Fragments on Fig. 8-20(B) were formed by a normal detonation of a 23-mm HEIT projectile. The fragment shown on Fig. 8-20(C) was formed when the projectile failed mechanically after it hit a hard object and then split or mushroomed. Fragments on Fig. 8-20(A) show evidence of both failure mechanisms; they were failing mechanically and then apparently explosively when the charge detonated. For this dual failure to occur, the mechanical failure had to occur before the fuze delay ended, but the mechanical breakup of the projectile was not complete enough to disrupt the explosive train. Thus failures of the threat to function properly can be diagnosed from examination of projectile fragments.

*The velocity established using a chronograph screen array is not the velocity of the projectile as it passes through the plane of the muzzle of the weapon; it is the velocity established near the muzzle.

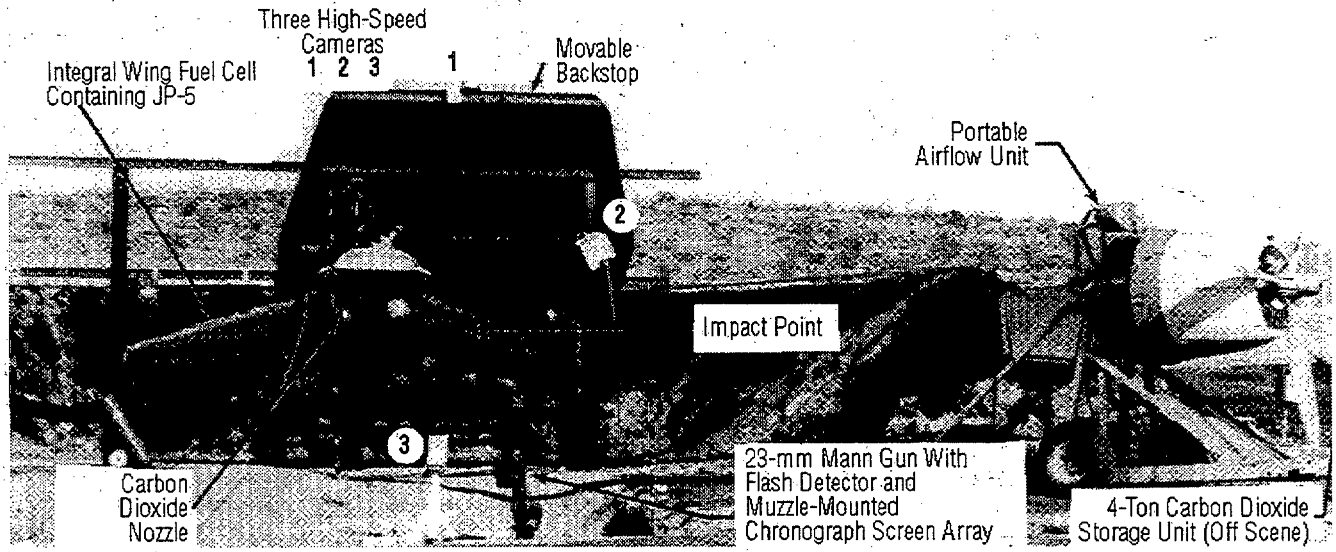


Figure 8-19. Installation Showing Test Specimens, Mann Gun, and Wind Machine (Ref. 27)

Proper threat functioning can be observed from viewing motion pictures, from recordings of blast gages or light sensors, or from target damage. Time of arrival of a projectile impacting a target can be obtained from an impact switch or an event timer.

8-2.3.2 Target Response

The target response can be established by use of strain gages, pressure gages, high-frame-rate motion pictures, and posttest examination. Data from strain and pressure gages can be recorded on a high-speed recorder. An example of establishing the target response is on Fig. 8-5(B), which clearly shows that the fuel cell failed when a large piece broke out of the rear surface before the fuel cell was thrown off the shelf on which it was mounted (Refs. 3 and 7). Abnormalities in, or abrupt cessation of, strain gage or pressure data (e.g., the extraneous blip on Fig. 5-15(B)) or signal saturation (e.g., the strain gages on Fig. 8-10) can provide indications of the time at which some phenomenon occurred, such as an impact by an extraneous object (the first example) or when the target failed (the second example).

8-2.3.3 Combustion

The time and location of ignition is probably best shown in high-speed motion pictures. The duration of the resulting fire is better shown on real-time motion pictures or videos unless the fire is of short enough duration to be recorded completely on the higher frame rate films. Recordings of temperatures can be of great value, particularly when smoke obscures the motion pictures. Infrared film or videos can be used when smoke precludes other methods.

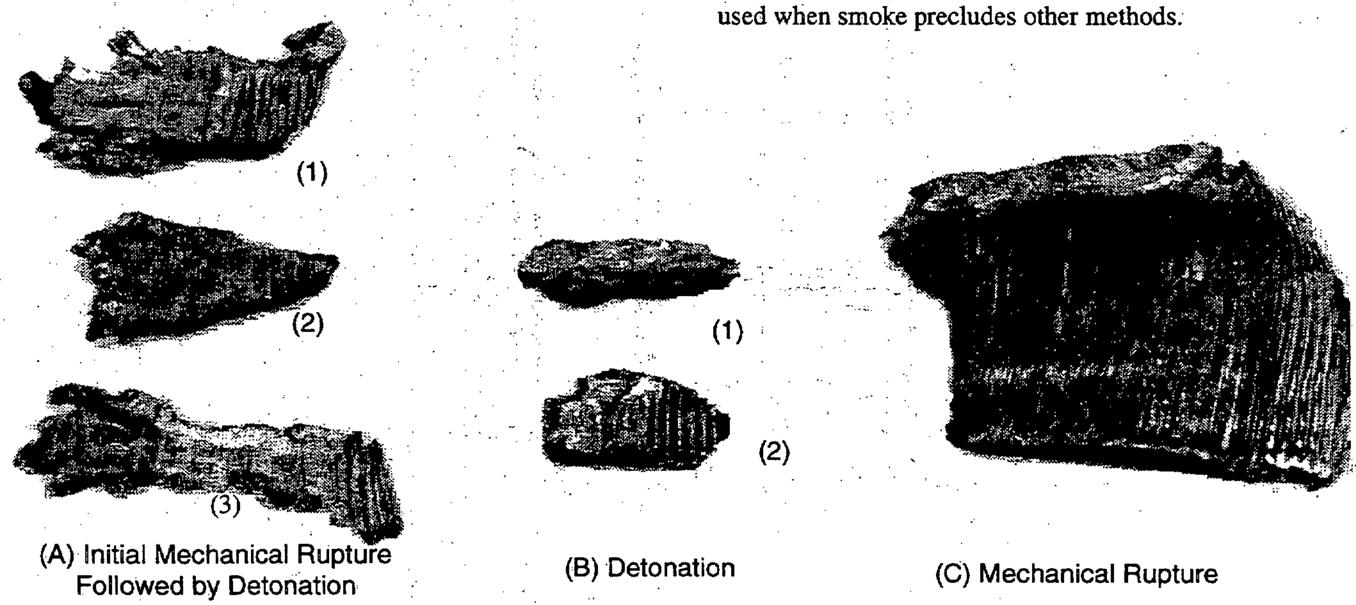


Figure 8-20. Fragments Showing Different Rupture Modes (Ref. 27)

8-2.3.4 Extinguisher System Performance

Extinguisher system performance can be obtained by recording sensor outputs, light or other electromagnetic radiation (emr) from selected locations, control signals to valves, extinguisher pressure, and temperature at selected locations, all recorded versus time. Motion pictures can also show extinguishing events, but smoke will often obscure some scenes or locations.

8-2.3.5 Correlation

The two main sources of information are the motion pictures or videos and the recordings of electronic information; such as pressures, temperatures, strain, or emr versus time. These can be correlated by recording the threat time of impact by means of a switch that the threat closes. The time of impact is time zero and is recorded with the electronic data, as shown on Fig. 5-15 or on Fig. 8-12 on which time zero is indicated by a series of dots and/or in the motion pictures by having the switch energize a lamp that is visible in the motion pictures. For example, the Hycam® provides a time correlation feature. Other cameras may not.

8-2.4 ANCILLARY DATA

The reactions of materials to various loadings can be understood and modeled mathematically when the phenomena can be visualized. By knowing the sequence of actions and reactions from beginning to end (but particularly in the beginning), the designer can deduce the causes and change specific design features in order to alter the results.

The types of equipment used currently are either photographic or electronic. Photographic equipment can provide still or motion pictures, whereas electronic equipment can provide real-time videos or a series of still pictures taken at a very rapid rate (image converters). Flash X-ray equipment is mentioned because it may be used in tests involving ignition and combustion. The X rays do not effectively record combustion and can complicate the use of other equipment that can record combustion or the use of other instrumentation, but flash X-ray photographs are often desired because they provide information not otherwise obtainable, such as close-in velocity determinations, impactor attitude at impact and breakup, and projectile fragmentation patterns.

Ballistic tests of combat vehicles or their components are usually costly enough to warrant redundancy in the equipment used to obtain pictorial data. Such redundancy need not be two identical means; it can include different equipment viewing the test from different aspects.

8-2.4.1 Recording of Rapidly Occurring Events

Rapidly occurring events can be recorded using either photographic or electronic equipment. Both types of equipment are being improved rapidly. Some of the specific equipment described is obsolescent or perhaps obsolete; however, equipment that can produce at least equivalent results is available.

With the more rapidly occurring events the needs of the recording equipment may drive the test sequence. For example, when using a high-frame-rate motion picture camera such as a Hycam® to obtain motion pictures at or over 5000 frames per second (fr/s), the camera must be framing pictures at the desired rate before the event occurs. Thus a switch that can trigger the event after sufficient film has been expended for the camera to have reached the proper framing rate is provided within the camera. Thus, the camera is not only an observer of events but also the sequencing driver.

8-2.4.1.1 Photographic Equipment

A great variety of photographic equipment is available to record rapidly occurring events. This type of equipment can provide a sequence of photographs that can be viewed with a projector on a screen, with a motion analyzer on a viewing plate, or as a series of photographs. The development of color film of ASA 400 or better and the greater strength of Mylar-based film have eliminated the need to consider black and white motion pictures. Color film provides far superior pictures, especially for the analysis of ignition and combustion processes.

The cameras range from the Beckman-Whitley Model 200 Simultaneous Streak and Framing Camera (Ref. 28), in which 35-mm film is placed on the inside surface of a rotatable drum and achieves frame rates from 10,000 to 8,800,000 fr/s, through the Hycam® (Ref. 29), which uses reels of 16-mm film at framing rates to 11,000 fr/s, to the Locam (Ref. 30), which frames 16-mm film at framing rates to 500 fr/s. These three cameras have been selected to illustrate the range of photographic equipment available; no attempt has been made to describe all available makes and models of cameras.

The Beckman-Whitley Model 200 supports a relatively short length of film on the inside surface of a relatively large drum. This 35-mm film is approximately 3 to 23 frames long. The drum is rotated at a very high speed. The camera functions by either opening a slit for a streak picture and/or rotating a prism for framing pictures. The streak picture, Fig. 8-21, simply shows the rate of change of the quantity of light entering the slit. The framing photographs, Fig. 8-22, show a series of pictures taken at a high rate of speed. The photographs in these two figures were taken at the same time and show a nonelectric blasting cap, i.e., the booster for a 23-mm HEIT projectile, detonating. The framing rate of this camera (Ref. 28) is very high, from 10,000 to 8,800,000 fr/s. The camera is driven to speed via a pneumatic turbine before the lens is opened and uses one of five basic plug-in framing modules and one of three mirror turbines to provide the frame rate desired. Test procedures are sequenced so the lens is open for the event that is to be recorded.

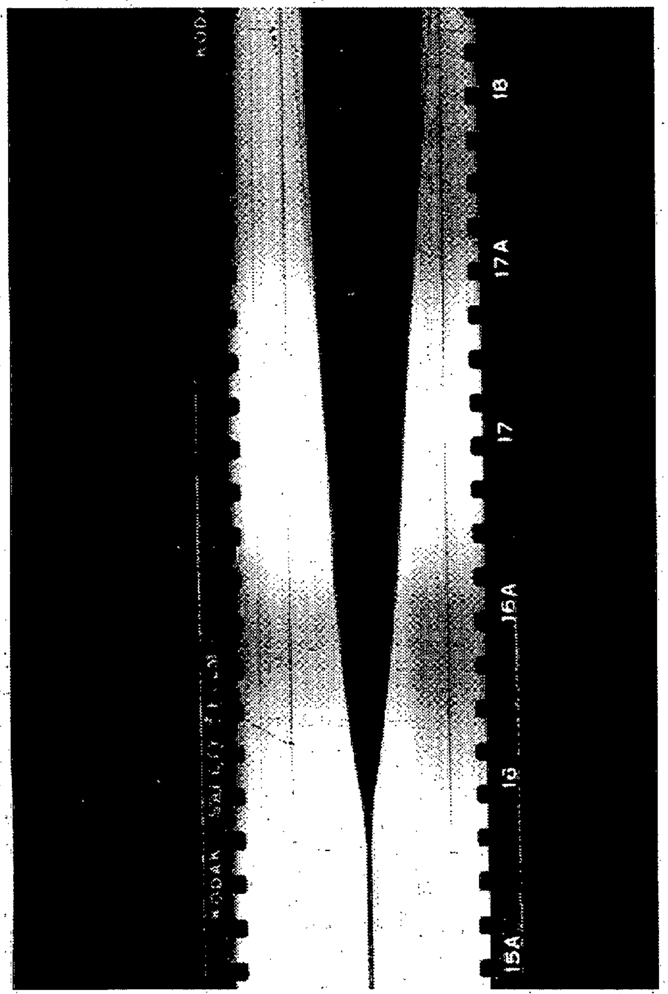
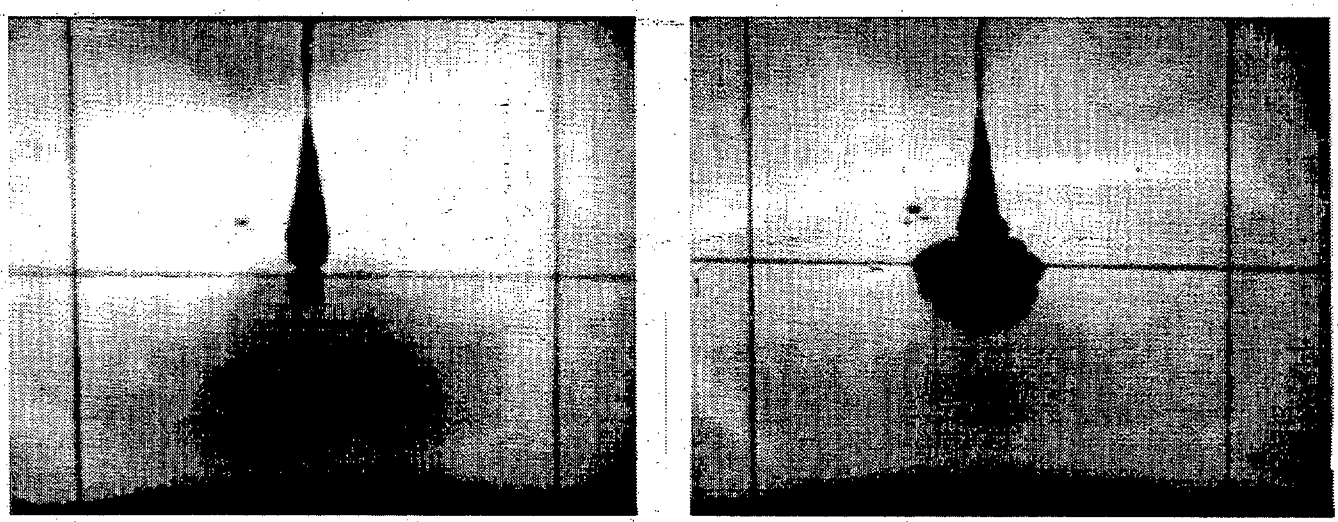


Figure 8-21. Streak Picture of Booster for 23-mm HEIT Projectile Detonating

The Hycam® uses a rotating prism and a segmented shutter to frame pictures on film. The film is fed from one reel to another. The camera is powered electrically and uses a high current. (This high-current requirement, if not taken into account, can affect other electrically powered instruments. The power cable to the Hycam® should be isolated from other circuits.) The framing rate achieved is from a combination of reel size, power setting, and time of operation (See Fig. 8-23.). The camera requires time to come up to speed, so considerable footage will not contain photographs taken at the desired filming rate. For full-frame photographs the maximum frame rate is 11,000 fr/s (Ref. 29). Thus when a high framing rate is desired, the largest reel must be used, i.e., 122 m (400 ft), and the camera must pass most of the film past the lens just to get up to speed. To assure the event is sequenced to occur at the proper time, a switch within the camera can be set to close after a desired length of film is on the take-up reel. This switch closure can be used to trigger an event such as discharge of a gun or initiation of a blasting cap. Selected frames from a motion picture taken by a Hycam® using a frame rate of 1000 fr/s are shown in Fig. 8-24. When operated at a high frame rate (over 4000 fr/s), the Hycam® cannot be stopped to save film. Three reel sizes can be used in a Hycam®, 30 m (100 ft), 61 m (200 ft), and 122 m (400 ft). A Hycam® has a rated minimum rate of 20 fr/s, but it has somewhat poorer resolution that is caused by using a rotating prism. Thus it does not operate as well below a framing rate of 100 fr/s as either a Locam or a standard motion picture camera.

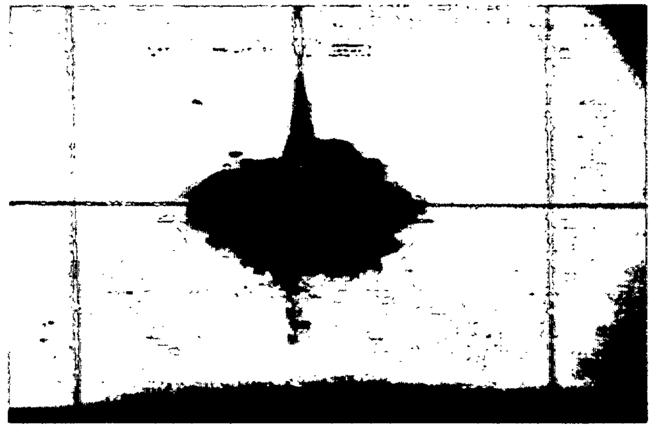


(A) Frame 1 (B) Frame 2

Figure 8-22. Frames of Detonation of the Booster of a 23-mm HEIT Projectile

(cont'd on next page)

(C) Frame 3



(D) Frame 4

Figure 8-22. (cont'd)

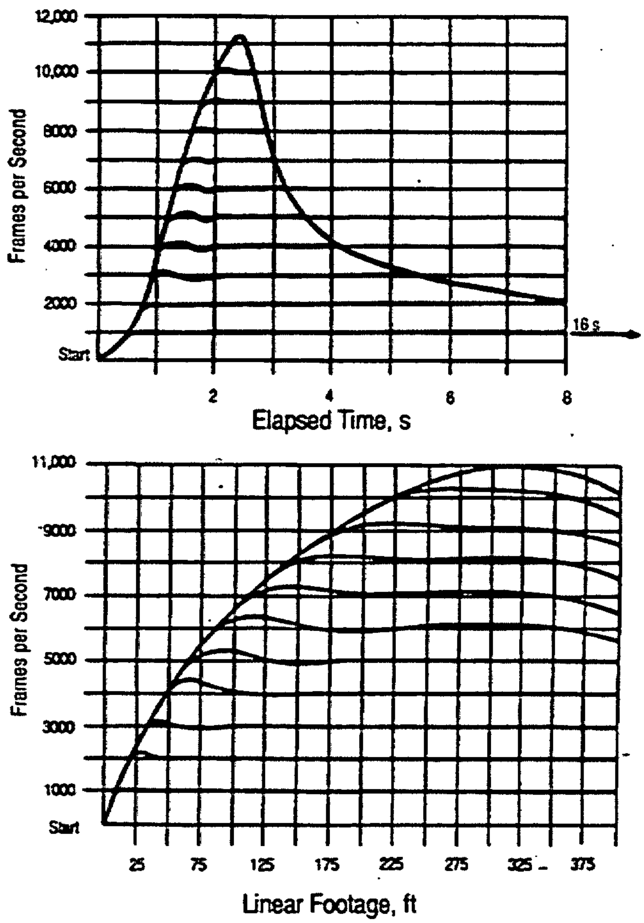
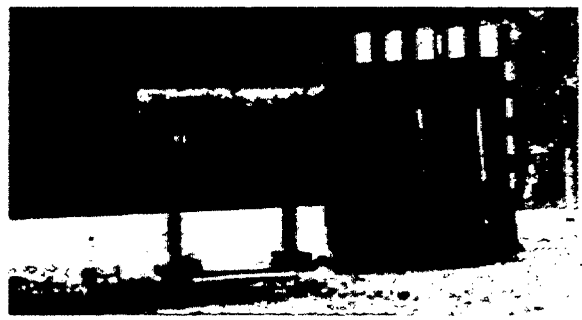


Figure 8-23. Framing Rate Versus Elapsed Time and Linear Footage for Hycam® Using a 122-m (400-ft) Reel (Ref. 30)



(A) Frame 1

(B) Frame 2

(C) Frame 3

Figure 8-24. Three Sequential Frames From Motion Picture of Test No. 1 of Ref. 5

The Locam is a variable rate motion picture camera with a minimum framing rate of 16 fr/s and a maximum framing rate of 500 fr/s. Locams can be operated at the standard rate of 24 fr/s. They are shutter cameras, which direct light from the scene directly onto the film rather than use light reflected by a prism (Ref. 30).

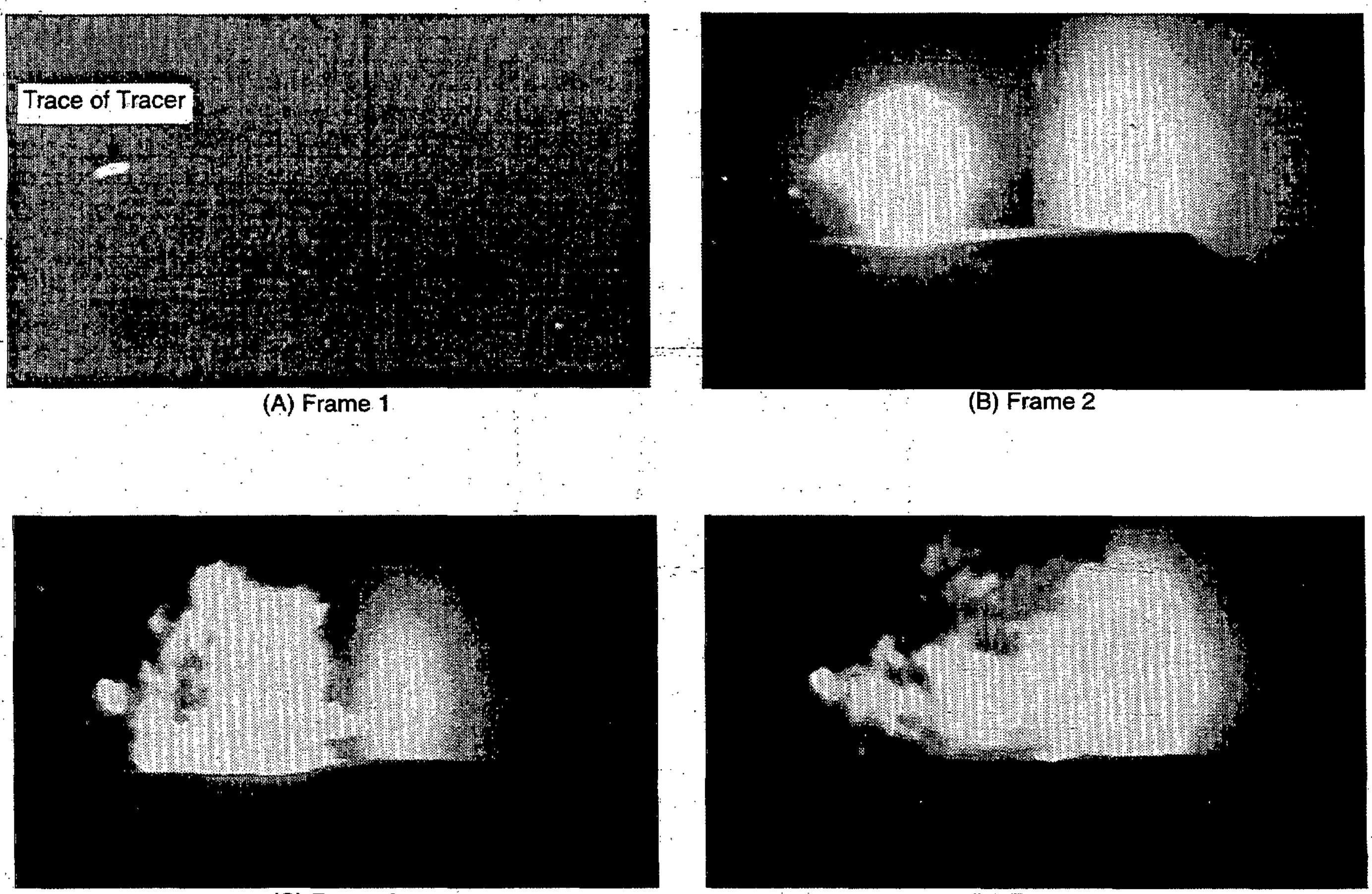
Both Hycams® and Locams have small lights that flash at preset rates near the edge of the film to provide timing pips. Some Hycams® also have a second light, which can be flashed on the other film edge to provide a time correlation with some outside event such as projectile impact on the target. This time correlation light must be triggered by an external signal.

Each frame of a framing camera is a picture made by the deposition of light over a short period of time. Items that do not move during that period of time appear as sharp images; items that do move appear as a blur. Fig. 8-25 is from a motion picture taken by a Fastax (an earlier design of the Hycam®) at a rate of 8000 fr/s. The short bar of light seen in Fig. 8-25(A) is the burning tracer of a 23-mm HEIT projectile that traveled approximately 114.3 mm (4.5 in.) during the time light was impregnating the film to produce the frame. The higher the framing rate, the shorter the dwell time for making a single picture. This shorter dwell time not only "freezes" motion but also increases the requirement for light from the subject.

If the subject is not self-illuminated, high frame rate motion pictures require additional illumination to activate the film. When the dwell time is shortened, the light must be more intense to obtain proper film activation. In southern Texas or Arizona the sun is an adequate source of light for framing rates of approximately 2500 fr/s for much of the year. If more light is needed, banks of photo flood lights or sequenced banks of flash bulbs have been used successfully. A problem with banks of photo flood lights is that they heat the subject. The flash bulbs heat the subject less, primarily because they provide light for a shorter period of time. A tank searchlight was found to add a half f-stop of light. Additional illumination for Fig. 8-22 came from an exploding bridgewire spread evenly through a Fresnel lens. Some subjects are self-illuminating, such as the detonating 23-mm HEIT projectile in Fig. 8-25.

High-speed photography is a fairly costly operation in funds, time, and labor. Time is required to develop the films and there is no instant playback. Excerpts from high frame rate motion pictures can be converted to video tapes for documentary purposes.

When flash X-ray radiographs are desired, the test instal-



(A) Frame 1

(B) Frame 2

(C) Frame 3

(D) Frame 4

Figure 8-25. Sequential Pictures of a 23-mm HEIT Perforating a Stainless Steel Target

lation is more complicated because the cameras and their film must not be in the X-ray beam. Flash X-ray radiographs are made in order to "see through" the opaque cloud of combustion and combustion products, e.g., Fig. 8-26*. (The fragments and the rearward ejected tracer can be seen readily in the radiograph, whereas the light and products emitted by the detonation would prevent an observer from seeing the fragments, as shown on Fig. 8-22.)

8-2.4.1.2 Electronic Equipment

The image converter was an early version of electronic equipment used to make a series of sequential pictures at a very fast rate. Fig. 2-12 is a series of pictures showing a steel fragment perforating a titanium sheet that was taken using an image converter. Basically, the image converter reproduced this same scene five times approximately 20 ns apart. The limitation on this device was that five frames were the most that could be made. Also the scene had to be backlighted using a xenon light source to overcome the flash generated by the impact of the steel fragment on the titanium target. (Fig. 2-11 is a similar set of pictures of a fragment impacting an aluminum sheet taken by an image converter.)

Figure 8-26. Flash X Ray of Static Detonation of a 23-mm HEIT Projectile (Ref. 31)

*This flash X ray is a double exposure. First, the intact projectile was x-rayed. Then the detonating projectile was superimposed by being x-rayed on the same plate a desired number of microseconds after initiation.

At present the only video system capable of making the equivalent of high frame rate motion pictures with full frame pictures is the Spin Physics (Eastman Kodak) Models EKTAPRO 1000 (1000 fr/sec) and SP 2000 (2000 fr/s), but these produce black and white pictures only. These pictures are recorded on magnetic tape, and each point is recorded in linear analog as one of 256 shades of grey. These can be played back in pseudocolor at the normal 30 fr/s using a pseudocolor generator in which each shade of grey has been assigned a color from yellow to red to blue or combinations of these. This color assignment produces a video scene similar to that of a colorized video tape of an old black and white motion picture.

Eastman Kodak is working on an image intensifier system that magnifies light up to 40,000 times with an electronic gating (equivalent to shutter speed) of 1 μs, which can be recorded on a high-speed data tape traveling at approximately 6.35 m/s (250 in./s). This tape provides an equivalent of a 10,000 fr/s of motion picture in black and white. Again this can be colorized using the pseudocolor generator for playback. This device would not require as much light as the other system.

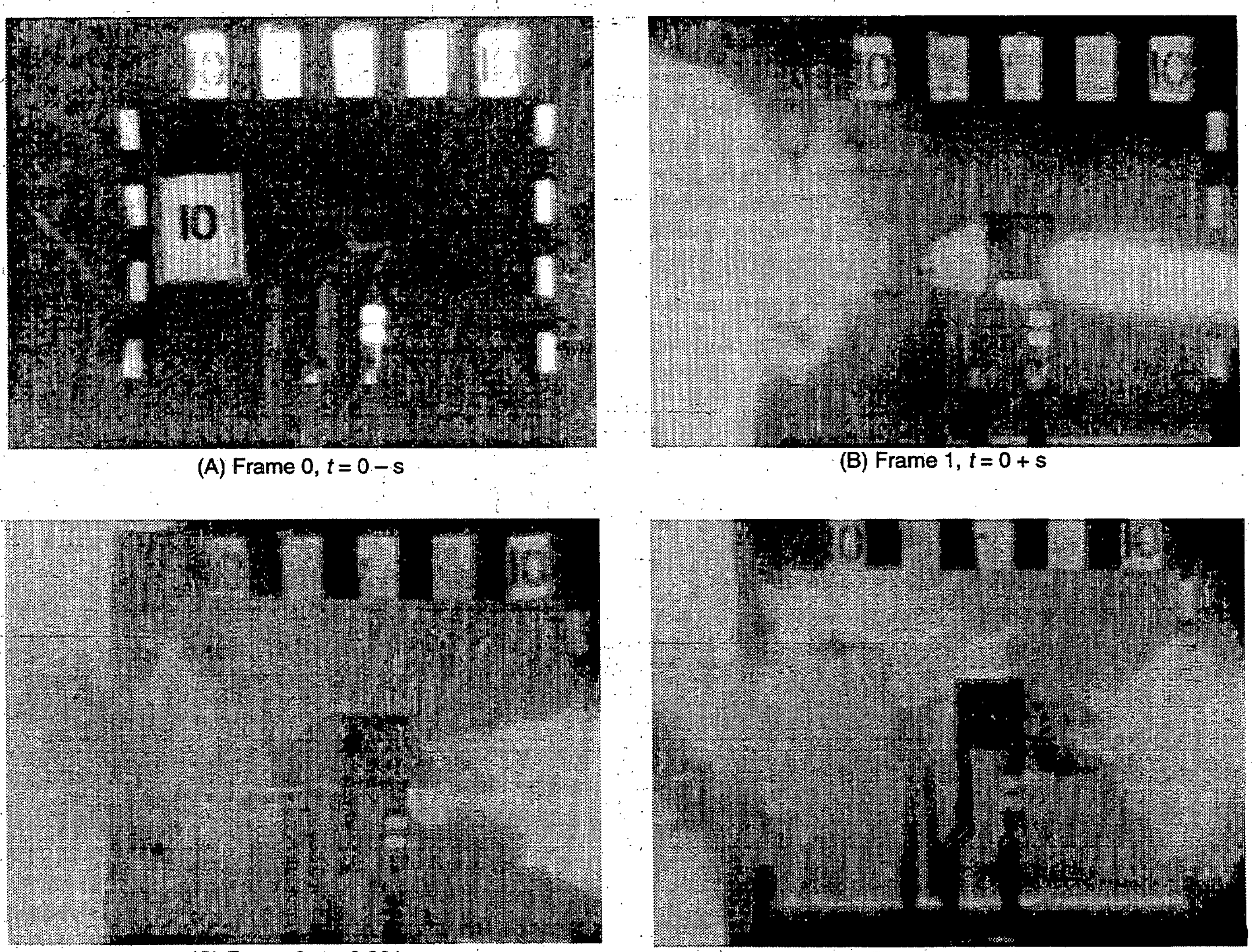
8-2.4.1.3 Examples of High-Frame-Rate Motion Pictures

The motion pictures described in this subparagraph were originally made in color, but the excerpts shown are in black and white. Two examples are shown to illustrate important points.

In 1985 P. H. Zabel (Ref. 3) was tasked to adapt aircraft fuel cell survivability techniques, such as those shown effective for helicopter fuel cells (Ref. 32), to lightly armored ground vehicles and to demonstrate their enhanced survivability. The first phase of this task was to review the then current state of the art of lightly armored vehicle fuel cell vulnerability. Even more important than the written reports were the motion pictures that had been made during those tests. Those motion pictures, some frames of which are shown in Fig. 2-17, clearly showed that the main source of combustible fuel was the mist produced when the seams of the fuel cells split. Those motion pictures also showed that the jet exiting the vehicle produced the ignition sources that ignited the fuel mist. Braadfladt (Ref. 33) had demonstrated that the actual fuel cells did not split at the seams when hit by a shaped-charge jet. Thus, in the program reported in Ref. 3, care was exercised to fabricate fuel cells that would be more representative of actual fuel cells. In this example the high frame rate motion pictures that had been taken to establish the relative characteristics of combustion of neat and fire-resistant diesel fuels later provided the means to detect fuel cell weaknesses and to establish combustible fuel mist and ignition source meeting. From these, design changes produced the successful survivability enhancement demonstration of fuel cell confinement in Ref. 3, as is described in subpar. 7-3.2.9.1.

A second example of the value of high frame rate motion pictures is from Ref. 18. In this program double-walled or jacketed fuel cells were examined in fair detail. One question that arose was "Why does the dry powdered fire extinguishant, Purple K, take approximately twice the time to extinguish the fire ball as does water?". The answer is shown in Fig. 8-27, an extract from the high frame rate motion picture taken of Test 10 of Ref. 18. The dark object seen traveling from the fuel cell, Fig. 8-27(C), to the far wall of the test fixture is the Purple K launched as a single clod. This clod impacts the far wall and then travels back into the center of the test fixture as a cloud of powder, Fig. 8-27(H). Extinguishment occurs as this cloud passes back through the fireball. Therefore, in an actual vehicle with many objects located within the engine compartment, such as an engine, tubes, wires, and many other assorted objects, this clod of fire extinguishant would have been broken up into a cloud of powder long before reaching the far wall. Hence extinguishment in an actual engine compartment should have been much more rapid than in the empty test fixture.

High-frame-rate motion pictures provide extremely valuable answers to what occurred and when it occurred. Sometimes these answers can verify the adequacy of the test installation, as happened when Zabel (Ref. 34) provided a thin window of 6.25-mm (0.246-in.) acrylic over the fuel cell ullage containing an explosive fuel vapor-air mixture when firing a 23-mm HEIT projectile into the fuel cell, Fig. 2-8. An observer had complained that the window was too thin and was blown away by the projectile detonation, which allowed external air to mix with the ullage vapor and thus resulted in the explosion. Later examination of the Hycam® motion picture, Fig. 2-8(J), showed that the ullage vapors had started burning and that combustion was well beyond the explosion stage before the window ruptured, Fig. 2-8(L). In short, the window was not ruptured due to fragment impact; the ullage explosion ruptured the window, which admitted air that



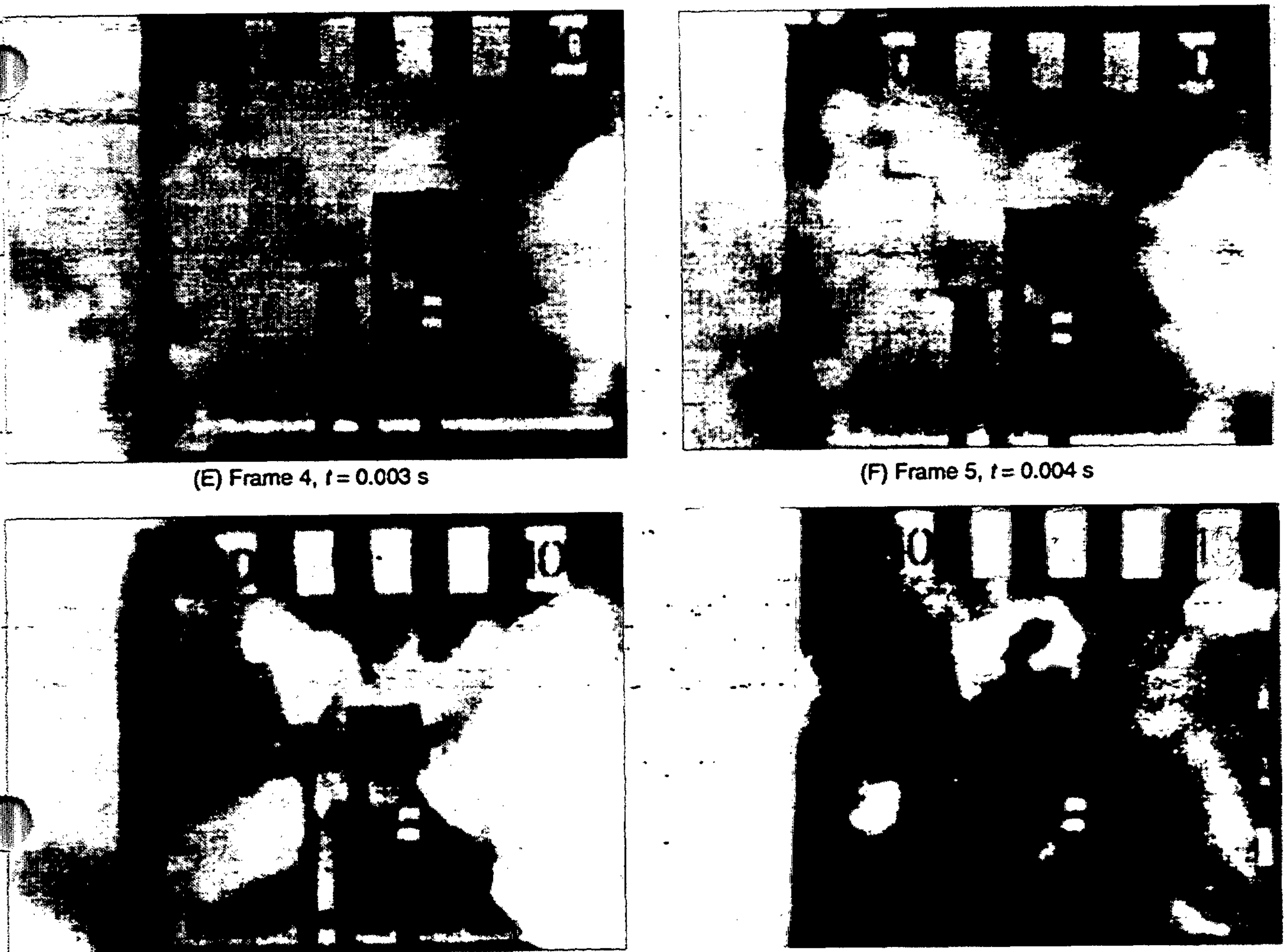
(A) Frame 0, $t = 0-$ s

(B) Frame 1, $t = 0+$ s

(C) Frame 2, $t = 0.001$ s

(D) Frame 3, $t = 0.002$ s

Figure 8-27. Fire Extinguishant Purple K Dissemination (Ref. 18)



(E) Frame 4, $t = 0.003$ s

(F) Frame 5, $t = 0.004$ s

(G) Frame 19, $t = 0.018$ s

(H) Frame 47, $t = 0.046$ s

Figure 8-27. (cont'd)

enabled the ullage vapors to explode. These motion pictures not only justified the test installation—the window was strong enough to resist extraneous phenomena prior to the ullage explosion—but also led to a better understanding of the explosive potential of ullage vapors.

For the tests of the double-walled or jacketed fuel cells (Ref. 18) in which the majority of the tests resulted in initial fireballs only, motion pictures taken at a framing rate of 1000 fr/s were needed to establish the fireball-out time in milliseconds.

When definitive numerical data are lacking for heat generation, for example, a crude measure of relative heat generation can be determined by noting the color of combustion and the intensity and duration of light generation. Caution should be used in attempting to relate test series performed by different organizations using this technique, but this comparison can provide a crude measure of correlation within a single test series or of tests performed during a short period of time by the same organization.

8-2.4.2 Documenting Overall Test Events

The adage that a picture is worth a thousand words is not only correct but possibly an understatement of the value of a picture. A fact to remember is that tests conducted for one purpose today may provide the answer to a different problem five, ten, or fifteen years from now. Hopefully, we learn as we work. Often, much can be learned from earlier work if it is known just what was done with which instrumentation, facilities, and fixtures. Terminology changes. Pictures provide much better understanding of past events or earlier equipment than volumes of text. These pictures can be still photographs, motion pictures, videotapes, or other media of recorded pictorial details. The general setup of tests or the general layout and composition of equipment can be seen in still photographs. For example, Fig. 8-28 shows the instrumentation and four cameras used as well as the test fixture and terrain of the tests documented in Ref. 3. Also note that in Fig. 8-24 there was no concrete pad; the test fixture itself was depended upon to catch leaked fuel, and a large, heavy

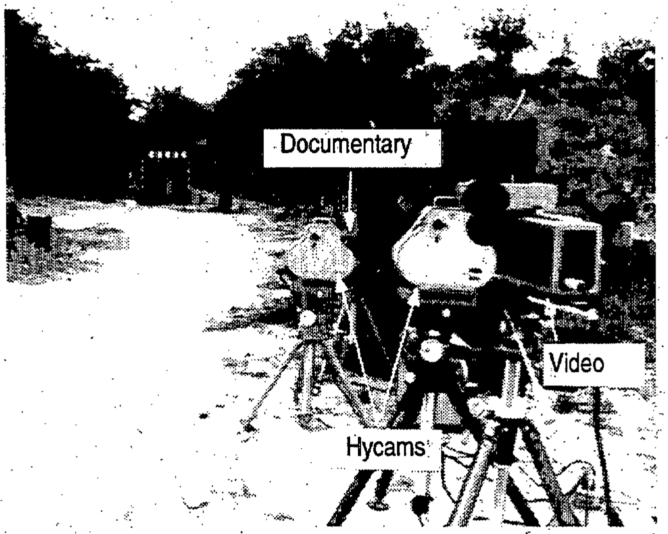
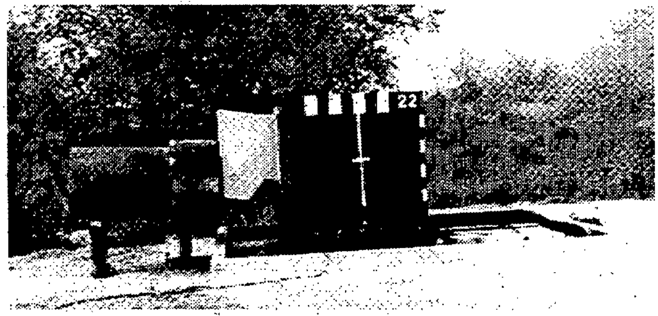
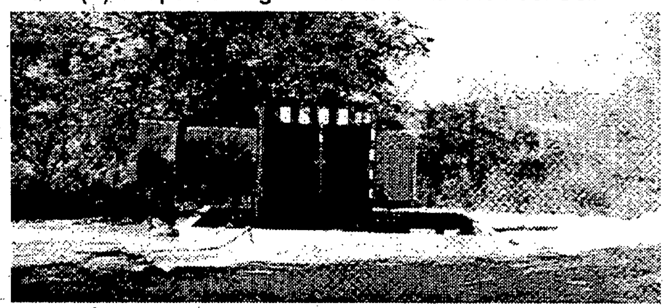


Figure 8-28. Test Site Installation (Ref. 3)



(A) Shaped Charge in Contact With the Fuel Cell



(B) Shaped Charge on Opposite Side of the Test Fixture From the Fuel Cell

Note: The shaped charge was enclosed in the large fragment trap to the left. The concrete pad had a large sump pump on the far side to capture leaked fuel.

Figure 8-29. Installation for Testing (Ref. 5)

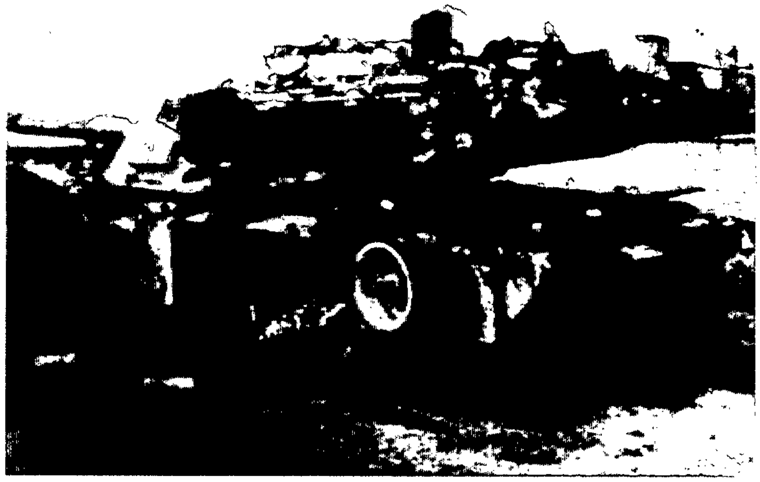
pipe was used to capture fragments from the M28 HEAT warhead. Fig. 8-29, a test subsequent to Ref. 3, shows that a test pad had been constructed to capture leaked fuel and that the fragment trap for the warhead had been reinforced. Details that the author of a test report did not deem worth stating can be established from photos taken before, during, and after tests.

Documentary motion picture (24 fr/s) or video (30 fr/s) recordings are of great value in establishing overall test events and results. The presence or absence of sustained combustion can be noted. The locations at which ignition occurred can be established and those sites checked to find the probable causes.

8-2.4.3 Value of Photographs

Not only tests but also accidents, newspaper articles, and combat records can provide important information when still photographs are analyzed. Fig. 8-30(A) is of an M1A1 MBT that was hit by a large antitank guided missile (ATGM) in Southwest Asia (SWA) early in 1991 (Ref. 35). The missile hit the tank on the right side, above, and slightly forward of the front right road wheel. The jet entered the front right fuel cell and ruptured it and dispersed the fuel around the front of the vehicle and the rear of the turret. (The tank was apparently traveling with the turret facing rearward.) Noting the blackened surfaces of the front of the hull and the rear of the turret and the statement of the photographer, MAJ Spencer, that "the vehicle was dripping with 'black oil'", the author believes that the front right fuel cell was ruptured and that although a flash fire followed, the fire self-extinguished before the ammunition in the turret bustle could ignite. (In several tests, the author has seen diesel fuel draining down the wall of a test fixture after a shaped-charge jet perforated a test fixture and sprayed the fuel within the fixture. The resulting fireball either self-extinguished or was extinguished. After the test, the blackened diesel fuel was found to have coated the inside of the fixture and in some places to run down the wall and drain into the bilge. The author has also picked up 5.56-mm ball cartridges off the floor of a test fixture, which had been thrown out of an ammunition box perforated by the shaped-charge jet, and found the cartridges usable. The flash fire just did not have time to heat the fixture, the cartridges, or the fuel to a reaction temperature.) The damage done to the vehicle was from the blast, the jet perforation, and the hydraulic ram incident to jet passage. The driver was killed, probably by the jet, but the jet did not exit the far side of the vehicle.

Fig. 8-30(B) is of the left side of the turret of a Bradley fighting vehicle (BFV) hit by the same type of missile that hit the M1A1. This photograph shows that the tube-launched, optically tracked, wire-guided (TOW) launcher, which is mounted there, was removed, but since there are no obvious impacts from fragments of either the TOW warhead or missile motor, it can be assumed that either the TOW launcher was in the firing position (unlikely) or that the warhead blast of the incoming missile merely blew the TOW launcher and its missiles away without causing a detonation of the warhead or motor of either TOW. MAJ Spencer stated that both the vehicle commander and the gunner were killed (probably by the jet). However, the jet did not perforate the far wall of the vehicle, nor did it start a fire or cause ammunition to explode. Neither vehicle was irreparably damaged, even by the hit of such a large weapon. Figs. 8-30(A) and (B) illustrate that a significant amount of information can be obtained from evaluation of such photographs.



(A) M1A1 MBT After Impact

(B) Bradley Fighting Vehicle Turret After Impact

Courtesy of MAJ C. Spenser, North Carolina Army National Guard.

Figure 8-30. Vehicles Impacted by Large HEAT Warheads in SWA

8-2.5 OTHER ASPECTS OF FIRE SURVIVABILITY TESTING

There are other aspects of fire survivability testing that require planning and preparation. Inherently these tests often result in fires. The test specimens are often expensive and therefore should be designed and fabricated or prepared not to be destroyed in a single test should a fire result. Also test facilities must have backup systems to extinguish fires. Sometimes the threat used will require special operations to assure safety; usually the mobility fuel must be trapped and disposed of safely after the tests. The fire-extinguishing agents must not add to the safety problems, and the test fixture contents should not present hazards that are not representative of those of the actual vehicle. The selection of appropriate extinguishants, training of fire-fighting crews, and preparation of test fixtures are necessary for protection of the test facility.

8-2.5.1 Fire Extinguishant Selection

Selection of a backup fire extinguishant to safeguard test assets must be based upon the following:

1. The type of fire to be fought
2. The effectiveness of the agent under the conditions of the test
3. The hazards associated with the agent that are intensified by the test conditions
4. The effects of the agents on cleanup and on preparation for the next test
5. The availability of equipment needed in order to use the agent.

Some gaseous extinguishing agents, such as carbon dioxide or Halon 1301, cannot be depended upon to extinguish a fire and then inert the fire site unless the fire is in a space that can effectively exclude the surrounding atmosphere. If the fire is deep-seated and/or smoldering—as in multilayered fabrics, multipiece wooden objects, or cushioning mats—or if metallic objects have been heated or if there are other ignition sources present, these inerting agents must remain in place long enough for the heated objects to cool or the ignition sources to be eliminated; otherwise reignition will occur. If the volume containing the fire cannot be effectively closed to the atmosphere, the inerting agent may be ineffective in any case. This closure to the atmosphere need not be complete. The small holes made by a shaped-charge jet or a KE penetrator will probably not be large enough to admit sufficient air for sustained combustion. If hatches or doors are blown open or a significant hole is made in the vehicle wall, however, sufficient air will probably be available to sustain combustion. Ventilators or air blowers that introduce air into the compartment in which a fire has started should be shut off until after the combustion is extinguished and there is no probability of reignition.

A cooling agent, such as water, extinguishes a fire more effectively, particularly if the fire is deep-seated or there are nonelectrical ignition sources. Of all the fire extinguishants available, the one that has the lowest cost, presents the lowest hazard or contamination, and is usually most effective is water. The latent heats of vaporization, specific heats, and boiling points of water and two of the liquid halons are given in Table 7-3.

The US Navy has explored the use of water mists to extinguish oil fires. In such a form water could be used very effectively within a test specimen or fixture. The water mist would not only be an excellent coolant, it would also lower the oxygen percentage as the water droplets vaporize. Equipment within the vehicle would have to be able to withstand the high humidity, but so does equipment used in the tropics. After extinguishing a fire with water mist, the extinguishant would present no greater hazard than is encountered in a sauna, and the water mist will have removed many noxious materials. See subpar. 7-2.3.1.6 for discussion of the use of water mist as an extinguishant.

The US Navy has found that water mist can be used to extinguish Class A and Class B fires (Refs. 36 and 37). Their work was on a fixed fire extinguisher system intended for use in submarines. This system was designed to flood a 6.1× 6.1 × 2.7 m (20 × 20 × 9 ft) test compartment with a water mist areal flow rate of 2.037 L/min·m² (0.05 gal/(min·ft²)). Newly ignited Class A and Class B fires were extinguished; deep-seated Class A fires were not. Freshwater was recommended for Class C fires but not tested (Ref. 38). The principal fire-extinguishing mechanism was cooling, but the smothering mechanism was of great benefit. Work on this system was stopped in 1986 for lack of funding, and portable systems were not explored.

In several test programs (Refs. 32, 34 and 39), a fixed, high-flow carbon dioxide system, illustrated in Fig. 8-31, was used successfully to blow out a fire at the exposed surface of a mobility-fuel-filled target impacted with a simulated superquick-fuzed* 23-mm HEIT projectile. In these tests the aircraft engine (shown in Fig. 8-18) used to force an 80-km/h (50-mph) airflow over the test fixture had to be shut off before the carbon dioxide could be used, and the carbon dioxide had to be used before the fire became deep-seated or had heated the surrounding structure. This carbon dioxide system required a considerable investment of funds and preparation. The system had a 3630-kg (4-ton)** storage bottle connected with buried high-pressure steel pipe to the CARDOX® fog nozzles seen on Fig. 8-31 directed toward the test specimen. Each nozzle was controlled by a solenoid valve operated from the control trailer. The carbon dioxide blew out the fire if used promptly, or the fire became sustained. The storage bottle was behind the berm and hidden from view by the portable airflow unit seen on Fig. 8-19. This carbon dioxide system was backed up with a light water system, which was used when the fires, particularly pool fires under the test specimen, were sustained.

*This particular foreign projectile does not have a superquick fuze. The personnel at the test organization modified the delay fuze so that it functioned in approximately 20 μs, which is almost superquick. This modified fuze was used only in the tests described in Ref. 34. In the tests described in Ref. 32, a striker sheet was used in order to have the delay fuze function where a superquick fuze would have functioned.

**This specifies the mass of carbon dioxide that the vacuum-insulated bottle can contain.

Figure 8-31. Installation Showing Carbon Dioxide Piping and Fog Nozzles Positioned to Extinguish JP-5 Fire (Ref. 39)

When a fuel cell is perforated, the fuel above the perforation flows out in liquid form. This fuel pools within test fixture compartments or below the test specimen or fixture unless provisions have been made to drain it elsewhere. If ignited, a fuel pool provides enough heat energy to destroy or at least distort almost any test specimen or fixture. Once a fuel pool has started to burn, the most effective extinguishing system is one with light water. Therefore, a light water fire-extinguishing system is necessary for tests involving mobility fuels.

Light water is water containing 3 or 6% aqueous film-forming foam (AFFF) concentrate. This additive forms a foam or film that will float on the surface of the fuel and provide a barrier that separates the fuel from the air. This concentrate is introduced into the water stream via an eductor or similar metering device located between the pump and the nozzle. A fire hose should be equipped with an adjustable spray or fog nozzle, which can also form a jet. The light water should be sprayed on the fire to form a foam barrier on the surface of the fuel (Ref. 40). If the water were used in a stream, the jet would break up the foam or film barrier on the fuel surface and could spread the fire by splattering burning fuel droplets.

Because the AFFF additive is basically a detergent, it can clean oil or fuel off the test specimen or fixture; however, it can also cause the test specimen or fixture to corrode or rust. Therefore, after the fire has been extinguished, the flow of light water and AFFF concentrate should be stopped and the fire hose flushed out with water only. This water can also be used to cool the test specimen and fixture and to flush the foam off the fixture and test site.

The residual mobility fuel must be collected and prevented from soaking into the ground. The concrete pad shown in Fig. 8-29 under the test fixture is a method of collecting the fuel. This pad has a raised rim of concrete and a sump in the rear to prevent escape of released fuel.

If electrical discharges are present, dry chemical extinguishants are recommended. Water should not be used unless the electric circuit is opened.

In tests involving depleted uranium (DU) penetrators, there is another problem. All detectable uranium and/or uranium oxide must be removed and packaged for indefinite storage. For DU penetrator tests the entire target area is usually enclosed, and the air within pumped out through a filter to provide a negative pressure differential between the outside air and the air within the test fixture. This procedure assures no loss of radioactive particulates. Due to the ballistic impact, some of the DU becomes an aerosol. This DU aerosol must be filtered out, and the filters prepared for storage. For example, if a dry chemical extinguishant were used, that dry chemical powder would have to be collected. Such an operation involving filtering down to one-micron-size particles is very expensive in time, labor, and filters (which include long-term storage). The requirement of such a clean-up operation caused a six-week delay in a test schedule in a program in which personnel mistakenly assumed that Halon 1301 could extinguish any fire that would occur within the target. When the halon system failed to extinguish the fire, the backup system was used. The backup extinguishant chosen was dry chemical powder, which was required to be used in large quantities during the test. (The fire finally became retarded enough that the burning items could be physically removed and allowed to smolder elsewhere.) In this incident, water could have been collected more easily, but the water itself would have had to be collected in drums. This collection of water would have posed a disposal problem if a great amount of water were used to extinguish the fire, unless the water had evaporated. (In the test cited the fire was within a particleboard dummy covered by a cloth uniform. A piece of DU was embedded within the particleboard. Application by a person wearing proper breathing apparatus of a small amount of water, either as a jet or a spray, at the correct location could have quickly extinguished the fire without spreading radioactive contaminants.)

8-2.5.2 Fire-Fighting Crews and SOPs

When tests with the potential for fire are being conducted, a fire-fighting crew should be designated and trained to fight any fires that may occur. Untrained personnel often take the wrong action (Ref. 40) and may expose themselves to hazards unnecessarily. Fire-fighting crews should be trained and clothed in appropriate gear before the test.

Appropriate standard operating procedures (SOPs) should be prepared and distributed before the test. These SOPs should assure that any fire is attacked promptly in a manner that does not endanger the fire-fighting crew, and the crew should be trained in the SOPs. The fire-fighting crew should be familiar with the test site, or someone familiar with the test site should accompany them.

The fire-fighting crew should be trained how to approach a fire safely. Fire fighters should not approach a liquid fuel fire from downwind or downhill—the burning liquid or noxious fumes may travel toward the crew. They should not enter a cloud where carbon dioxide has been dispersed. The white cloud is actually moisture condensed from the air, but it also contains a great deal of carbon dioxide, which has diluted the oxygen the fire fighter needs to breathe. A gas mask is of no use in a carbon dioxide cloud; the oxygen just is not there in sufficient quantity. The SOP should clearly state when fire-fighting personnel should enter an area containing a fire and what areas should be avoided. These procedures, however, should not unnecessarily limit the fire-fighting crew's access to the area. An example of unnecessary limitation of the fire-fighting crews was the requirement during a test that a single-shot Mann gun have its screw-on breech removed before the test site could be entered. (There is no way a single-shot Mann gun can fire a second shot without a second round being loaded.) There are many procedures such as these that untrained personnel either do not know or will not remember in the excitement of fighting a fire.

8-2.5.3 Preparation of Test Specimen and Fixture for a Fire

Special test equipment within the test fixture and the specimen should be installed so that such equipment will not be lost as a result of a fire. This is particularly applicable to such items as remote television or video cameras, which may be the principal means of letting the test controller know the status of an internal fire.

Care should be taken not to introduce combustibles unnecessarily into the test fixture. For example, a dummy used to represent a crewman within a combat vehicle should be no more combustible than the crewman himself. The human body is approximately 78% water, and this water must boil out before the body can sustain combustion. A dummy made of papier-maché, particleboard, or cloth and plywood would present a fire hazard that a human body would not. Fires within these materials could become deep-seated and would present a reignition problem not representative of a human body. Use of styrofoam would be worse because its fumes would be toxic. For tests of combat vehicles in which the crew is to be represented sufficiently well to establish wound probability, low-cost dummies should be used. A recommended filling for these dummies is gelled water.

Also simulating ammunition with plastic replicas is discouraged because solid plastic replicas are costly and thin plastic replicas are subject to heat damage and distortion. It is reasonable to exclude the explosive filler in ammunition from tests, but onboard munitions would be better represented by hollow metallic surrogates rather than solid plastic ones. Combustible cartridge cases would be better represented by fire-retardant-treated cardboard tubes that contain sand. These metallic or cardboard surrogates would provide witness devices that would "record" impacts by threats capable of igniting or initiating the normal onboard munitions. This simulation does not apply to live-fire tests in which the objective is to establish what will happen when a vehicle containing its normal combat load is hit.

8-3 MODELING

Computer models are used to make a preliminary evaluation of a design and can be used to establish the relative effectiveness of survivability enhancement devices. Such computer models are very valuable design tools. Currently available models, however, usually predict the probability of kill ($P_{k/h}$) or damage ($P_{d/h}$) given a ballistic hit in a particular location. These models use tables of kill and damage probability that have been generated by tests and/or by the best engineering estimates of knowledgeable personnel. The $P_{k/h}$ tables do not differentiate between the terminal effects that cause the kill; the tables indicate either a kill or no kill given a hit in a certain location. Thus they do not predict partial effects of fire.

There are computer models that predict the spread of fire and/or generation of toxic combustion products (Ref. 41). These models were developed for apartment buildings, but some have been adapted to naval ships. The models assume a sustained fire exists in one room, and then monitor heat buildup and flame spread. The generation and flow of toxic products are similarly predicted. Such a model, however, is of little use for a combat vehicle with two or three "rooms" at most and those "rooms" are usually separated by fire barriers. In fact, as has been established in many instances in the reports described in subpar. 4-1.1, the driver of a combat vehicle has difficulty realizing that there is a fire in the engine compartment of his vehicle, which may be only a few millimeters away on the other side of a fire wall.

There are computer models that predict the vulnerability of combat vehicles and the time required to repair battle damage. These models use prepared $P_{k/h}$ and $P_{d/h}$ tables as described previously. Usable with these models is a model called FIRESIM (Ref. 42). FIRESIM provides the capability to designate components to be flammable fluid locations or heat sinks, stowed ammunition, or components protected by a fire-extinguishing system. When these specific components are hit, the model provides logic to assess the type of kill that occurs or, in the case of components protected by the fire-extinguishing system, whether the kill is prevented. Again the user must input tables of probability of kill for each case. As Dr. B. E. Cummings (Ref. 43) pointed out in 1973, the greatest void is in the area of probability of kill predictions. Dr. Finnerty has prepared a tabulation of probabilities of sustained fires for combat-damaged vehicles in Ref. 8-44. FIRESIM is further described in subpar. 8-3.3.1.

A model that accounted for the incidence of fire separately from other terminal effects is the PARKed AirCraft (PARK AC) model (Ref. 45). The treatment of incidence of fire given a 23-mm HEIT projectile hit in or near a fuel cell was expanded (Ref. 46). PARK AC is further described in subpar. 8-3.3.2.

A computer model follows a series of logic operations in which decisions are based upon conditions, configurations, events, and/or circumstances. Sometimes empirical data are used to provide the probability of occurrence of given events. Often the decisions are based upon mathematical models of natural phenomena.

Several mathematical modeling techniques are used. One technique is to model phenomena that occur from theoretical concepts. This usually leads to an involved theoretical model of events that is partially hypothetical and involves inputs from handbooks which may or may not be truly representative. A second technique is to base a model upon empirical test or incident data. This usually requires a multitude of tests, the results of which are interpolated. These tests, however, are of specific designs that are not always applicable to new designs. A third technique, similitude modeling, is partially theoretical and partially empirical. In this method nondimensional Buckingham Pi terms are established that relate theoretical phenomena. When a good correlation has been established, an empirical fit to all applicable test data is made. This technique makes maximum use of all available empirical data and maximizes the utility of the empirical fit by using as many parameters as are applicable.

An example of data regression to provide a predictive equation is shown on Fig. 8-32 (Ref. 47). Impact velocities were from 59 to 3537 m/s (193 to 11,605 ft/s), and obliquities were from 0 deg to 80 deg. The total number of data points was 847. All materials were transparent, including laminates, homogenous materials, bullet-resistant glass, and polycarbonate. Projectiles included steel fragments as well as bullets. Residual velocities were from 2993 to 0 m/s (9820 to 0 ft/s). This similitude modeling approach is recommended for preparing mathematical models. See Ref. 48 for details on similitude modeling.

8-3.1 CREW INCAPACITATION

There is currently no computer model available that can predict fire casualties in combat vehicles. There are models that can predict casualties caused by bullet, fragment, or flechette impact, but these are for troops in the open and are not really for blast and not at all for burns, overheating, or noxious gas (smoke) inhalation. As part of an attempt to develop a usable model for predicting crew incapacitation, the Director of Live-Fire Testing, Office of the Secretary of Defense, has sponsored two crew casualty assessment workshops. The first workshop focused on the data available and testing techniques, whereas the second workshop focused on assessment methodology. In addition, the Joint Technical Coordinating Group for Aircraft Survivability (JTCG/AS) sponsored a workshop to establish the best usable component vulnerability, i.e., probability of damage given a hit ($P_{d/h}$), for use in aircraft vulnerability assessments. One of the panels was assigned "crew stations", which included all personnel aboard the aircraft.

8-3.1.1 First Live-Fire Crew Casualty Assessment Workshop

The first live-fire crew casualty assessment workshop was held at the Naval Submarine Base, Groton, CT, 18-19 October 1988. This workshop concentrated on establishing the availability of pertinent data and how such data could be obtained. Approximately 150 military, civilian, Government, industry, and medical representatives attended this workshop. The panels that covered the subjects most pertinent to this handbook were the working groups on burns, toxic gases, and blast/overpressure. (Ref. 49)

The burns working group reviewed the Knox burn model, which was derived from the tests described in subpar. 5-2.2.3.4. They also reviewed potential preventative measures

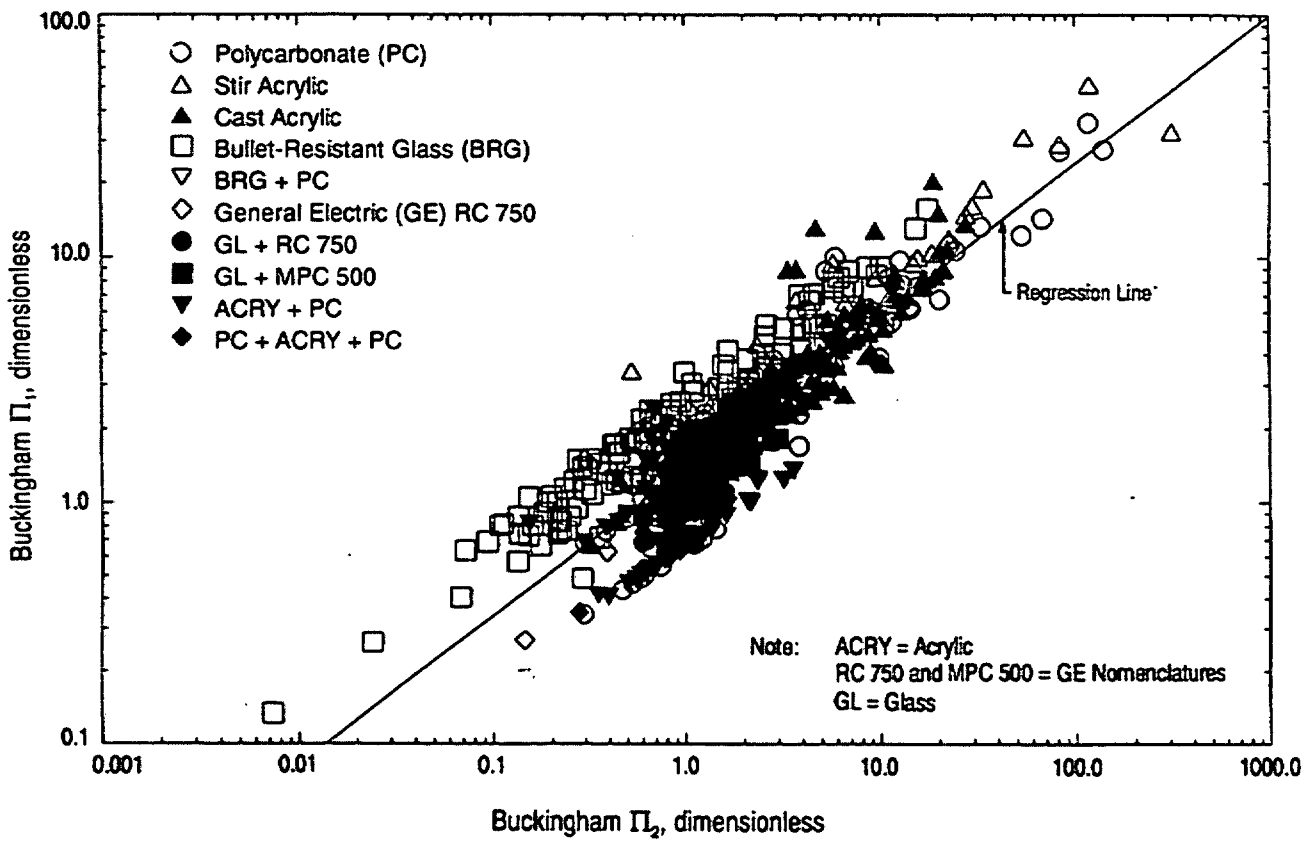


Figure 8-32. Regression of Test Data to Provide a Prediction Equation of Residual Velocity for Projectile Penetration (Ref. 47)

such as use of low-vulnerability ammunition, passive techniques to prevent gross dispersion of fuel within the crew compartment, and improved protective clothing. The incapacitating effect of burns was discussed, but no criteria could be agreed upon. The working group members agreed that data are available—most of which are presented in this handbook—but the data have not been collected into a single database. The best available instrumentation was discussed. Thermocouples appear to furnish the best available temperature instrumentation.

The toxic gases working group members agreed that most current work has been with the toxicity of individual gases rather than the degree of incapacitation caused by breathing the gases. They agreed that the degree of incapacitation should be explored. In a study performed by Knight, Schlichting, and Dougherty (Ref. 50), the mental and motor capabilities of six volunteers were evaluated after exposure to noxious gases. After being exposed to an atmosphere with a 12% oxygen content for 30 min, their mental capabilities (ability to perform mathematical computations) were noticeably impaired, but their motor capabilities (ability to pedal an exercise bike) were not.

The blast/overpressure working group reported that the greatest problem is that blast or overpressure within a military vehicle is never "clean", it is always accompanied by fire and fragments. Aside from this problem, good techniques are available for predicting "clean" blast effects, but just what a crewman has to be incapable of doing before he is considered incapacitated has not been defined.

A definition of incapacitation is needed for all three areas, i.e., burns, toxic gases, and blast/overpressure, singly and in combination.

8-3.1.2 Second Live-Fire Crew Casualty Assessment Workshop

The second live-fire crew casualty assessment workshop was held at Brooks Air Force Base, San Antonio, TX, on 29 October 1-November 1990. Again there were approximately 150 attendees, most of whom had attended the first workshop. The first order of business was to receive updates on the subjects of the first workshop. Then the workshop divided into three working groups: ground, sea, and air systems. For the final efforts the workshop divided into two working groups: (1) incapacitation assessment methodology and (2) integrated crew/equipment and integrated crew/ equipment weapon system vulnerability and lethality assessment methodology. (Ref. 51)

In the update for burns, some work had been done on predicting burns, but most of the work done had been on how to prevent burns. The Knox prediction methodology was still the best available. In the update for toxic gases, the only work reported was by the Navy. They still recommended the use of their oxygen breathing apparatus when fighting fires. The update for blast/overpressure reported that work in the field had continued.

For the ground systems working group, the personnel from the Live-Fire Test Organization at the US Army Ballistics Research Laboratory (BRL) described how they were conducting live-fire tests on Army ground equipment. The sea systems working group covered Navy damage control measures, which are more toward assuring that sufficient crewmen are available to fight fires to save the ship than protecting individual crewmen. (There is good reason for this: Loss of the ship is tantamount to loss of the entire crew.) The air systems working group pointed out that for most aircraft the crewmen could do little to affect casualty reduction. A crewman is fairly well fixed in place, much like other aircraft components, until the aircraft lands. (This is not correct for large aircraft such as the AC-130.) For aircraft crews the most important items are the capability of the crewmen to perform their duties and the time required for a wounded crewman to return to duty.

For the incapacitation working group, the greatest need found was for a series of definitions of "incapacitation". The working group members agreed that each service and many specialties require different definitions. There was agreement that a "human tolerance handbook" is needed.

For the methodology working group, the consensus was that each service should develop its own crew casualty assessment methodology.

8-3.1.3 Crew Casualty Assessment Reference System

The Office of the Deputy Director of Test and Evaluation/ Live-Fire Testing had a personal computer database directory prepared (Ref. 52) and distributed to Government and industry experts in crew casualty assessments. This directory describes available databases and instructs users where the data and/or models are located.

8-3.1.4 JTCG/AS Component Vulnerability $P_{d/h}$ Workshop

This workshop convened at Wright-Patterson Air Force Base, OH, in February 1991. The crew stations panel consisted of five individuals, all from private organizations. The consensus of this group was that the existing fragment or bullet impact methodology would have to be used to predict incapacitation, particularly for pilots. They believed that other types of wounds could not be assessed with the current state of assessment methodology (Ref. 47). The criteria for incapacitation, therefore, are still based upon the capabilities needed by an infantry rifleman to use his weapon and move on the battlefield.

8-3.2 EQUIPMENT DAMAGE

In existing vulnerability assessment models vehicular components are assessed for ballistic impact damage caused only by kinetic energy impacts. An aircraft or vehicle may be deemed lost due to blast or fire, but that is a yes or no decision. In PARK AC provision was made to assess heat and burn damage to rubber tires and canopies from nearby pool fires (Ref. 45) based upon aircraft burn tests at the Naval Weapons Center (NWC) (Ref. 53).

A fire damage computer model for a combat vehicle engine compartment would be a very useful design tool. Because such a model is not currently available, a model should be prepared with the following features. All vehicular components would have to be assessed to establish failure or malfunction modes due to surrounding combustion and/or heating. The contribution of each component to the available combustibles would have to be noted. Where high-energy combustibles such as mobility fuel, lubricating oil, or hydraulic fluid could be liberated, the circumstances by which such liberation occurs would have to be monitored. The effects of survivability enhancement devices, such as fire extinguishers or intumescent coatings, would have to be included. A probable scenario would be for a shaped-charge jet to penetrate a fuel line and thus liberate *X* L (*Y* gal) of JP-8, which would be assumed to ignite and burn. Given no specific extinguishment, that fuel could be assumed to liberate *XX* Joules (*YY* Btus) of heat energy. The probability of such ignition and combustion occurring would be based upon fire-extinguishing system and/or component performance. This heat energy could heat objects, ignite materials, or be lost to the external environment. The greatest value of this model would be to establish the relative efficacy of candidate survivability enhancement devices. Given specific component damage criteria, a heat transfer model, such as that described in subpar. 8-3.4, could be modified to provide an equipment damage model.

8-3.3 FIRE INITIATION

The two extant programs for predicting initiation or ignition of explosions or fires are FIRESIM (Ref. 42) and PARK AC, (Ref. 45). In addition, Dr. A. E. Finnerty (Ref. 44) has prepared a tabulation of predicted probabilities of sustained fires for combat-damaged vehicles based upon test data.

8-3.3.1 FIRESIM

FIRESIM (Ref. 42) uses the Monte Carlo technique to predict the probability of fire given a hit. Each flammable fluid container must be designated. These containers are fuel tanks, lines, and filters; lubricant locations such as oil pans, recoil fluid reservoir, etc.; hydraulic cylinders, reservoirs, and accumulators; as well as sinks where spilled fluids collect. Stowed ammunition is identified. For fluid locations the critical damage is perforation of the component, which causes the contained fluid to spill. Ignition of these fluids is treated separately. For the sinks the critical damage is perforation of the sink by the threat, which creates the possibility of ignition of any spilled flammable fluids that have collected there. For the stowed ammunition the critical damage is whatever causes that ammunition to detonate or ignite and cause the vehicle to suffer a catastrophic kill. This model does not determine what level of damage will cause this type of loss. Loss due to explosion is determined elsewhere and used in the vulnerability programs that use FIRESIM as input. In some vehicles fluid containers of a given type are interconnected; when one is punctured and the fluid spills, all those connected to it will also be drained. Included in the input data are arrays indicating into which sink fluid from each location drains. Fluid draining outside the vehicle should be treated as a separate sink.

The vulnerability of the combustible fluids is given as conditional probabilities of ignition given puncture or perforation of the fluid container. Two types of fires are addressed: (1) an immediate fire caused by the puncture of the container and (2) ignition of fluids spilled and collected in a sink but not ignited by earlier impacts. Type 1 fires depend on the vehicle, the threat, the fluid type, and the fluid location. Type 2 fires depend upon ignition of a fluid pool by a threat and are conditional upon the threat entering the compartment defining the sink. The probabilities of Type 2 fires can vary for each sink and the fluid in each sink. Thus there are two probabilities for fires in each sink, one if the sink contains fuel and a second if it contains only lubricating oil and/or hydraulic fluid.

Each sink is assumed to have one of two types of fire-extinguishing systems. The first type will discharge when there is a fire in its sink or in one of the locations draining into the sink. The second type will discharge whenever there is a perforation into the sink or a puncture of one of the fluid locations draining into the sink whether or not a fire is started. For both types of extinguishers, two probabilities for extinguishment are given. The first is the probability that a single charge of the extinguishant will extinguish a Type 1 (mist fireball) fire, and the second is the probability that a single charge of the extinguishant will extinguish a Type 2 (pool) fire. No distinction is made in either case for the type of fluid burning. It is assumed that the extinguisher will not extinguish an ammunition fire. Each extinguisher system can discharge up to n shots; n is an input to the program.

FIRESIM uses pregenerated tables of damage for predetermined shot lines. For a given shot line, if a combustible fluid container has been punctured, a random number is obtained and compared to the probability of a Type 1 fire for that container. If the random number is less than the probability of fire, a fire is assumed to occur. Similarly, penetration of a threat into a sink requires the random number check for a Type 2 fire.

FIRESIM requires damage prediction from the vulnerability model COVART or a similar vulnerability model as an input. FIRESIM does not predict fire ignition based upon the reaction of vehicular components to the threat; it uses user probability inputs and then figuratively flips a coin x number of times to decide whether a fire occurs or whether other events occur.

FIRESIM has the capability to predict casualties given kinetic energy (KE) missile impacts. The user must input the kill, wound, and injury criteria; FIRESIM just monitors how many vehicle occupants are hit by the penetrating threat and considers these occupants as additional components.

8-3.3.2 PARK AC

PARK AC (Refs. 45 and 46) is a computer model written to be operated independently rather than as an adjunct to another model, such as FIRESIM which is an adjunct to COVART. This model was prepared to establish which aircraft parked on an air base would survive a conventional weapons attack and how soon damaged, but repairable, aircraft would be available to fly a mission. Since fire and explosion are the two principal modes of destruction, they received special attention. PARK AC relates damage directly to either aircraft destruction or to the number of hours of repair time needed before the aircraft can perform another mission. Also PARK AC uses a Monte Carlo approach. Subroutines (S/Rs) that treat fire and explosion are presented.

S/R BLOW calculates the reaction of stowed ordnance to impact by a high-velocity fragment or a projectile. The criteria and databases for the chemical reactions of such an impact are given in Ref. 46. Similitude modeling of extensive test data produced reaction criteria that considered warhead casing thickness, projectile size, shape, velocity, and other parameters. S/R BLOW addresses both high-explosive-filled warheads and solid propellant rocket motors.

S/R PFYRE establishes the probability of ignition of a fire given a small high-explosive incendiary (HEI) projectile burst, the impact and subsequent initiation of an armor-piercing incendiary projectile, or the impact of high-velocity fragments on or near a fuel-filled component. The analog for this subroutine is described in Ref. 46 and is based upon data from more than 686 tests for small HEI projectile bursts. This subroutine takes into account the fuel tank ullage as well as adjacent dry bays. Fuel ignitibility is treated as a function of bulk temperature, air velocity, and impact location. Most of the survivability enhancement techniques used for aircraft fuel systems are considered, but fire-extinguishing systems are not.

S/R TYPETR establishes whether or not a projectile or fragment trajectory intercepts an explosive-containing or fuel-containing component or a component adjacent to a fuel tank. If a fuel-containing component is intercepted, the subroutine establishes whether the interception is above or below the fuel surface.

S/R LEAKS establishes which components are more flammable because of fuel leaks caused by earlier hits.

In addition, S/R PROJPN, which follows projectile penetration through aircraft components and other objects, checks for incendiary projectile activation as materials are perforated. If the fireball diameter of a high-explosive (HE) warhead is greater than a given aircraft dimension, either S/R PROJPN or DIRHIT can signal the destruction of that aircraft. S/R DIRHIT and FRDAMG can call S/R BLOW or PFYRE if either a projectile or fragment is able to initiate or ignite component contents.

An abbreviated version of PARK AC, called ENDGAM, has the capability to handle moving targets and was used to establish aerial bomb fragment hits on trucks in convoys or laagers or warhead fragment hits on an aerial missile. ENDGAM has been used in two projects at Southwest Research Institute, so it should be available for use. ENDGAM has been prepared for batch mode operation.

PARK AC has not yet been used. A moderate effort would be needed before it would be available for use. It uses modified combinatorial geometry for its target description and shot line generation. PARK AC was written for batch mode operation. Any updating of this program should provide user-friendly terminal operation.

8-3.3.3 Predictions of Probabilities of Sustained Fires for Combat-Damaged Vehicles

In Ref. 44 Finnerty provides the probabilities of a sustained fire within many different combat vehicles given hits with several types of threats. These probabilities are based upon both combat and test data and are for the vehicles as built. The only survivability enhancement device considered is the automatic fire-extinguishing system if it is installed in a vehicle as built. This report would provide an excellent database to establish the baseline vulnerability of these vehicles before other survivability enhancement concepts are incorporated. This work could provide the damage criteria for use in either FIRESIM or PARK AC.

8-3.4 FIRE GROWTH AND EXTINGUISHING

Considering the limited size of combat vehicles and that there is usually a fire wall or barrier between the engine compartment and the occupied compartment, fire growth is primarily concerned with the burning rate of the most combustible material ignited. In the engine compartment the most probable combustible is a hydrocarbon fluid, i.e., mobility fuel, lubricating oil, or hydraulic fluid. The hotter the fluid, the more rapid the combustion; therefore, as a fire progresses, the burning rate increases with increased fluid temperature. These materials are highly flammable in the mist state as well as in the vapor state and can explode. The most probable passages through which a fire in one compartment of a combat vehicle could enter another are via a bilge open to both compartments and openings made by the threat between the two compartments.

The most important result from a fire growth computer model is the ability to predict the rate of temperature rise of the compartment walls and of objects within the compartment. Temperature rise is a function of the heat added less the heat lost and of the specific heat of the materials heated. The heat added is controlled by the quantity and energy content of the material combusting, the quantity of oxygen available, and the rate of combustion, which is in turn a function of combustible temperature. The practical use for such a computation would be to establish design details for a fire-sensing and/or fire-extinguishing system or to establish the time to malfunction of components or the time of loss of compartment walls.

There are heat transfer models available that can be used for such computations. In these models the compartment and its contents are divided into nodes—either heat sources or heat sinks—that are connected by paths for conductive, convective, or radiative transfer of heat. Each heat sink has an individual mass and specific heat. Each heat source has a specific rate of heat generation, which can be fixed or variable. Each heat transfer path is based upon a single means of heat transfer, and each path should consider all factors affecting heat transfer, e.g., the effective film coefficient resulting from the clamp connection where two pieces of metal are bolted together.

The fire-extinguishing system would be incorporated in the heat transfer program by handling the temperature sensor(s) as additional nodes with logic provided to activate negative heat generators or oxygen depleters simulating the released extinguishants when appropriate temperatures are reached. Thus utility heat transfer computer programs could be used or modified to model fire growth and extinguishment within a compartment of a combat vehicle. To improve the predictions of such a model, better analogs of burning rates of materials as affected by temperature will probably be needed.

8-3.4.1 Model for Predicting the Performance of Halon Fire-Extinguishing Systems

Drzewiecki et al (Ref. 54) have prepared a model for predicting the flow of Halon 1301 through plumbing to extinguish a fire within a compartment. This model has been prepared for use on a personal computer and has been made specifically for the M1 and M1A1 MBTs and their Halon 1301 fire-extinguishing system. The model is divided into three phases: (1) computation of the time required to fill the distribution lines once the halon bottle valve has opened, (2) computation of the halon flow through each individual nozzle once the lines are filled and pressurized with halon, and (3) computation of the halon concentration within the compartment in specified control volumes given the outflow through the nozzles. The distribution line fill time is computed as an isentropic expansion process of the pressurizing nitrogen with the halon liquid flow being throttled by valve and line resistances. The halon flow out of each nozzle is modeled as a distribution network of an equivalent electric resistive-inductive circuit driven by a discharging capacitor. Halon concentration was treated as a bookkeeping problem of keeping track of the halon flowing into a space and the transfer of halon-air mixtures between adjacent spaces. The fire was assumed extinguished when a volumetric halon concentration of 6% was obtained. Throughout, electric analogs were made of the fluid flow. The heating of items within the compartment was mentioned but not included in the model. This model shows potential, but much more work should be done to generalize it for fire-extinguishing systems, fire extinguishants, vehicle compartments, and fire extinguishment methods.

This model has been made more user-friendly and has been checked by comparing its results with results from a live-fire test on an M1A1 MBT. The fluid flow computations have been checked by comparison with test results obtained by the Jet Propulsion Laboratory, Burbank, CA. (Ref. 55)

8-3.4.2 Fluid Flow Computations

Electric analogs are simple to use and are generally understood. The calculations, however, could be made using fluid flow rather than electric flow. Such computations should not be too complicated and would easily lend themselves to treat other extinguishants and other configurations of plumbing and compartments. An analysis using fluid flow parameters rather than an electrical analog was performed without benefit of a personal computer in 1966 to establish the design for an ignition system for a supersonic ramjet engine. (Ref. 56) In that system a pyrophoric liquid was forced from a toroidal reservoir through a burst diaphragm into a distribution system with multiple impinging jet nozzles that fed the combustion chamber of the engine.

Another such evaluation was made in 1965 (Ref. 57) to establish why attitude control engines for the Apollo spacecraft were meeting performance requirements on one test stand but not on another. The flows of oxidizer and fuel from reservoirs into the combustion chambers were calculated for 10-ms pulses and were shown to differ in magnitude and timing sufficiently to account for the difference in performance. The only causes for the differences in flow were the differences in the plumbing.

These two examples show that calculating the flows of different fluids in different plumbing are well within the state of the art. The use of personal computers should reduce the time required for these evaluations.

More recently, MPR Associates, Inc., has prepared FLONET™, a two-phase flow and pressure loss model to calculate the flow of Halon 1301 through the fire-extinguishing system plumbing of a Navy ship (Ref. 58). MPR also prepared TFHAL (Ref. 59) for the Naval Sea Systems Command, Fire Protection Division, a model for predicting the capability of the fire-extinguishing system of a Navy ship to function. This model has additional features that make it more generally applicable. These two models could be combined and adapted for use in combat vehicles.

8-3.4.3 Fire Extinguishment Predictions

Ewing et al (Ref. 60) performed a series of studies on the effectiveness of extinguishants. Concentrating on the use of dry chemicals, they studied the parameters affecting extinguishment, but they also studied liquids and gases. They took the extinguishment of heptane in a flat pan, conducted experiments, and by using a main frame computer, calculated the results with STANJAN®, a chemical reaction model. They have established the optimum particle size for several dry extinguishants, which are shown on Fig. 8-33, and verified these sizes in tests.

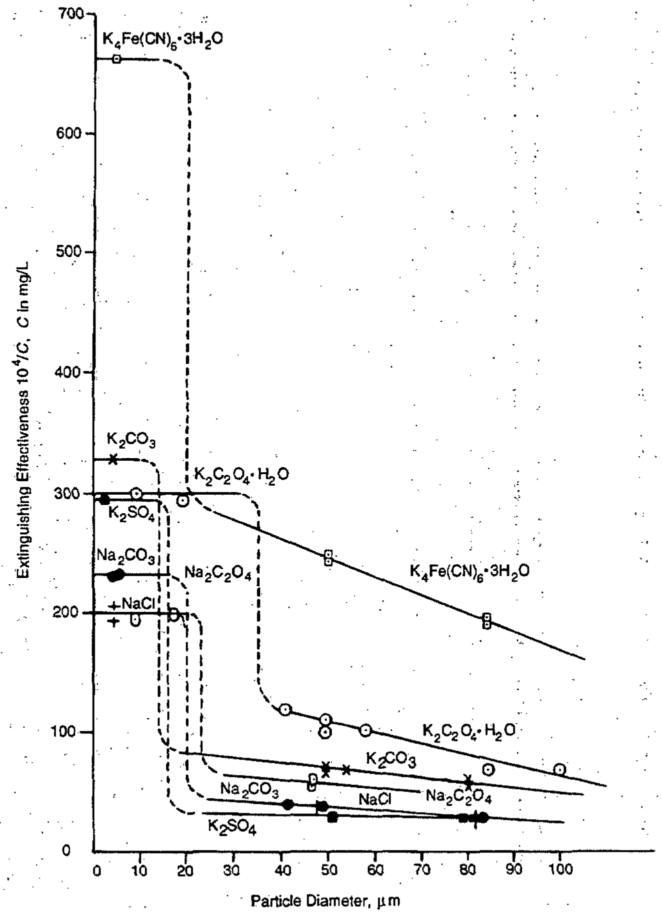


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Figure 8-33. Extinguishing Effectiveness Versus Particle Diameter for the Extinction of the *N*-Heptane Pan Fire (Ref. 60)

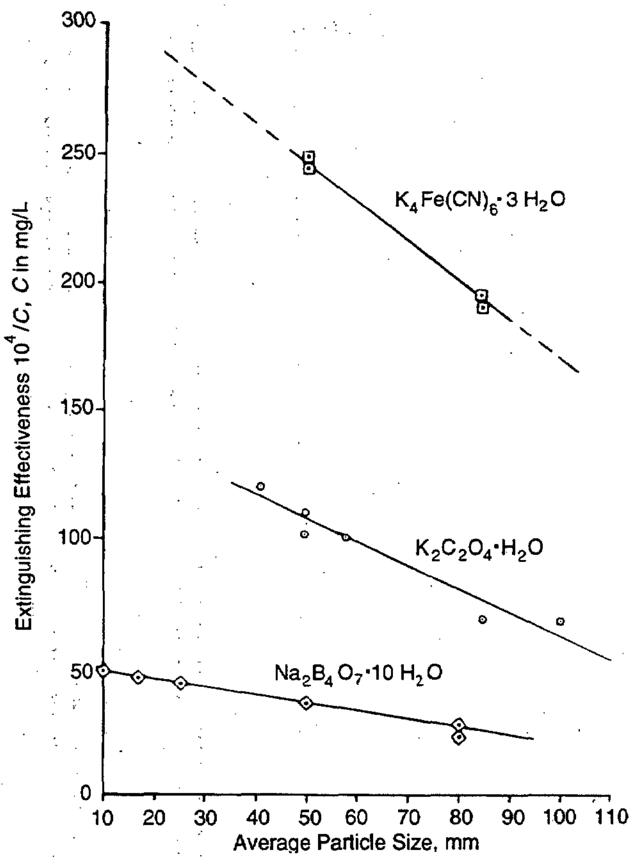

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Figure 8-34. Flame Extinguishing Effectiveness Versus Particle Size for Large Particle Sizes of Hydrated Extinguishants (Ref. 60)

Ewing et al (Refs. 60, 61, 62, 63, and 64) are propounding a hypothesis that thermal absorption is the principal mechanism in extinguishing flame. By their hypothesis flame is extinguished when sufficient heat is removed to allow the adiabatic flame temperature to fall below a limit temperature, T_{Li}. Their model is basically a heat balance in which the heat-absorbing capabilities of the extinguishant including changes of state, changes in temperature, and decomposition or disassociation are compared to the heat produced by the chemical reactions of the fuel. The model locates the concentration of extinguishant C needed to lower the temperature of the flame below the temperature needed to sustain combustion, i.e., T_{Li}. The effectiveness of some hydrated extinguishants is shown on Fig. 8-34. Ewing et al have shown that this methodology can predict the performance of halons, dry chemical extinguishants, and liquid extinguishants for both diffusion flames (the flames over a pool fire) and premixed flames (the flames of a gaseous fuel/air mixture in a chamber, e.g., the ullage of a fuel cell). They have compared analytical and experimental results using the extinction concentrations (mole percentage in air). If the experimental results were obtained from literature, the average differential between analytical and experimental results was ±16%. See Table 8-2 for comparisons. If they conducted the experiments, the average differential was ±7%. These predicted results, both experimental and analytical, are based upon extinction of flame, not upon cooling the fire site below fuel kindling temperature. Their analytical technique has been shown to apply to both Class A and Class B fires.

Ewing et al concluded that the primary fire extinguishment method involved is through cooling the flames. This conclusion is highly probable since the standard practice of fire-fighting personnel and of vehicle designers is to apply more extinguishant than is needed by factors of three, four, or five. Fristrom said 10 to 100 times (Ref. 65). Therefore, the cooling effect very probably is the most important for the physically acting agents.

TABLE 8-2. COMPARISON OF PREDICTED EXTINGUISHING CONCENTRATIONS WITH EXPERIMENTAL VALUES FROM LITERATURE (FINELY DIVIDED SOLIDS AND LIQUIDS) (Ref. 61)

EXTINGUISHING CHEMICAL SUBSTANCE	FUEL	EXTINCTION CONCENTRATIONS*, (mol % in Air)	
		PREDICTED THERMAL MECHANISMS	EXPERIMENTAL
Na_2CO_3	CH_4	0.65	0.53
$NaHCO_3$	CH_4	0.88	1.30
$KHCO_3$	CH_4	0.59	0.57
$AlCl_3$	CH_4	1.60	1.20
NaCl	CH_4	1.40	1.10
H_2O (mist)	nC_6H_{14}	5.20	5.00
Br_2	nC_6H_{14}	2.20	2.30
I_2	nC_6H_{14}	2.30	2.30

*Average differential ±16%

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GLOSSARY

6V-53. A diesel engine used in M113 family of vehicles.

8V-71 Detroit Diesel. An engine used in M109/M110 SP howitzers.

A

Acoustic Trauma. Injury caused by sound.

Added Concentration. The percentage of an inertant, such as nitrogen, carbon dioxide, etc., which must be added to air to assure that the fuel-air mixture is inert.

AGT-1500. An engine used in the M1/M1A1 MBTs.

Alveolus. Air cell of the lungs.

Anaerobic. Absence of free oxygen.

Antifratricide. Something or method that precludes explosion of one explosive-filled device from initiating a similar reaction in an adjacent explosive-filled device.

ASA Exposure Index or Film Speed. A measure of the sensitivity to light of the film and that is calibrated in accordance with American Standards Association (ASA) requirements. (This exposure index or film speed is used by a photographer to establish the aperture setting, exposure time, and artificial lighting requirements when taking pictures. A film may have different exposure indices or film speeds for daylight or artificial (assumed to be from tungsten) light. The higher the index, the less light needed for a proper exposure.)

Ataxia. Lack of normal coordination, especially inability to coordinate voluntary muscular movements.

B

Ballistic Damage. Damage to equipment resulting from the impact of bullets, projectiles, shaped-charge jets, fragments, blast, etc.

Battle Dress Uniform (BDU). Uniforms designed specifically for use in combat; the BDU in use is made of 50% cotton, 50% nylon, usually 237 g/m^2 of a 2:1 left-hand twill weave and usually with a camouflage pattern.

Bazooka. The early 59.9-mm (2.36-in.) antitank rocket launcher that resembled the "musical instrument" used by comedian Bob Burns. Burns called his instrument a "bazooka", and this name has stuck to the rocket launcher since World War II.

Beehive Projectiles. Nickname for antipersonnel (APERS) projectiles. Similar to the shrapnel projectiles, but the submissiles are flechettes rather than spheres. Beehive projectiles were used in Vietnam and were made for artillery rounds with 0.81-gram (12-grain) flechettes and for 2.75-in. (70-mm) folding fin aircraft rockets (FFAR) with 1.29-gram (20-grain) flechettes. The flechettes were all made of steel. Beehive projectiles do not project the flechettes forward; they merely release them.

Bronchoconstrictors. Substances that lead to constriction of the bronchial tubes, the portions of the windpipe that go to each lung.

Brownian Motion. The motion imparted to very fine particles held in suspension in a fluid and caused by impacts by molecules of the fluid.

Burn. A chemical reaction—fire—the rate of which is governed primarily by the heat applied to the fuel reacting. A fire can range from glowing combustion to a deflagration.

Burn, First-Degree. Abnormal reddening of the skin (erythema) without blistering; can be painful after several hours; typical example is sunburn.

Burn, Second-Degree. Abnormal reddening of the skin with blistering. Touching or pricking the skin in the burned area produces pain. Deeper layers of the skin have been damaged.

Burn, Third-Degree. Destruction of the full thicknesses of skin and often of deeper tissues including bone.

Burn, Fourth-Degree. At one time, used to describe a burn well into the muscle, possibly to the bone.

C

Candela (cd). Unit of luminous intensity in the direction of the normal.

Canister Rounds. Like large shot gun shells. The canister slugs are cylindrical steel missiles with a mass of 5.1 g or weight of 79 grains. These were used in World War II, Korea, and Vietnam by US forces and were fired primarily from antitank or tank guns for antipersonnel use. *See also* Beehive.

Carboxyhemoglobin. Compound formed by carbon monoxide and hemoglobin during poisoning by carbon monoxide.

Class A. Fires in ordinary combustible materials (wood, cloth, paper, rubber, and many plastics) that require the heat-absorbing (cooling) effects of water or water solutions, the coating effects of certain dry chemicals (which retard combustion), or the interrupting of the combustion chain reaction by halogenated agents.

Class B. Fires in flammable or combustible liquids, flammable gases, greases, and similar materials that must be put out by excluding air (oxygen), inhibiting the release of combustible vapors, or interrupting the combustion chain reaction.

Class C. Fires in live electrical equipment; safety of the operator requires the use of electrically nonconductive extinguishing agents. (Note: When electrical equipment is deenergized, extinguishers for Class A or B fires may be used.)

Class D. Fires in certain combustible metals (magnesium, titanium, zirconium, sodium, potassium, etc.), which require a heat-absorbing extinguishing medium that does not react with the burning metals.

Cold Work. Permanent strain produced by an external force in a metal below its recrystallization temperature.

Combat Development Test. Requirements for the Army in the field, or a study that contributes to such determination.

Combat Vehicle Crewman (CVC) Helmet or Uniform. Helmet or uniform developed especially for use by crewmen in combat vehicles. The helmet includes provisions for the earphones needed for the vehicular intercommunication and radio equipment.

Combustion. The continuous rapid combination of a substance with various elements, such as oxygen or chlorine, or with various oxygen-bearing compounds accompanied by the generation of light and heat.

Computer Model. The program necessary to perform series of operations on a computer. This program has a logic flow in which a series of logic steps and mathematical models are used to produce and document results from a specified set of inputs; thus a task is performed. *See also* Mathematical Model.

Cone Calorimeter. A laboratory device used to measure the rate of heat release of a material during combustion.

Cored. Cut or bored out, i.e., when a projectile cuts out some of the material, as an apple corer cuts out the core of the apple.

Count. The rate of ionic discharges (discharges per second) established by an ionic discharge instrument. (Refers to the frequency of ionic discharges detected by a Geiger-Mueller device.)

Cover. A location where terrain features prevent direct fire onto a vehicle or person.

D

Document Acquiston Number (DAN). A number used by the Survivability Information and Assessment Center (SURVIAC), Wright-Patterson Air Force Base, OH, to identify incidents in the Battle Damage Assessment and Repair Program database.

Defilade. Behind cover, i.e., behind a hill or mound that precludes impacts by direct fire weapons. *See also* Hull Defilade.

Deflagration. Very rapid combustion sometimes accompanied by flame, sparks, and/or spattering of burning particles. Although classed as an explosion, it generally implies the burning of a substance with self-contained oxygen so that the reaction zone advances into the unreacted material at less than the velocity of sound in the unreacted material. The term is often used to refer to the action of a high-explosive projectile, which upon impact with a target does not produce the usual effects of a high-order detonation. *See also* Detonation *and* Burn *and* Combustion *and* Explosion.

Detonation. An exothermic chemical reaction which propagates with such rapidity that the rate of advance of the reaction zone into the unreacted material exceeds the velocity of sound in the unreacted material, i.e., the advancing reaction zone is preceded by a shock wave. *See also* Deflagration *and* Burn *and* Combustion *and* Explosion.

Dust. Dust is finely divided material in solid form that can remain airborne for a significant period of time, seconds or minutes, after being agitated. *See also* Mist.

Dysfunction. Impaired functioning.

E

Elastomers. Rubber-like plastics.

Electric Arc. An electric discharge through air. The arcing between the anode and cathode of a spark plug is one example; lightning is another. When the insulation on an electric conductor is removed, arcing often occurs. Electric arcs produce ultraviolet radiation.

F

Fire Extinguishment. Using extinguishants to eliminate combustion whether that combustion is sustained or not.

Fire Prevention. Measures taken to preclude ignition of a fire or, if ignition does occur, to assure the combustion is not sustained.

Fire Suppression. Both fire prevention and fire extinguishment.

Fires, Large and Small. For specifying desired optical fire sensor performance, US Army Tank-Automotive Command has classified hydrocarbon fires as large or small. A large fire produces radiation similar to that produced by a 76-mm minimum depth of 840 cm^3 of diesel fuel DF-2 in a 130-mm diameter pan at a distance of 380 mm from the sensor being tested. A small fire produces radiation similar to that of the large fires, except that the distance to the sensor is 1200 mm.

Flak. Abbreviation for flugzeug abwehr kannone, which is German for aircraft defense cannon. Since during World Wars I and II, we in the US and United Kingdom (UK) were usually on the receiving end, Flak came to mean antiaircraft artillery fire.

Flammability Characteristics. The characteristics by which a material ignites and burns. These characteristics include the material melting point, the boiling point, the vapor pressure versus temperature, the kindling temperature or flash point, the specific heat, the thermal conductivity, the heat of combustion, and many other properties.

Flash Point. The lowest temperature at which combustion of fuel vapor can be achieved over a liquid surface. The flash point of a liquid is used to gage relative fire safety.

Fog. Vapor condensed into fine droplets large enough to scatter light and to obscure vision. Fog droplets range in diameter from 0.25 to 1.00 μm and remain suspended in air through Brownian motion. *See also* Mist *and* Spray *and* Vapor *and* Dust.

Free Radicals. Chemical species (molecules) that have unpaired electrons. These species are very energetic and chemically reactive and are capable of promoting and participating in chemical reactions, such as combustion.

Freon. Trade name belonging to E. I. Du Pont de Nemours and Company for halogenated hydrocarbons."Halon" is an industry name for the same materials.

Fresnel Lens. A succession of concentric rings, not necessarily circular, each of which is an element of a simple lens, assembled in proper relationship on a flat surface to provide a short focal length and used to concentrate light expanding from a point source into a relatively narrow beam. Named for Augustin Jean Fresnel (1788-1827), a French physicist who was a pioneer in optics. Fresnel lenses are made from plastic quite economically and can therefore be used in ballistics tests in which they will probably be destroyed.

Fuel. A generic term denoting a material that will combine with an oxidizer in a combustion process in which energy is generated. Fuel is used in three specific instances in this handbook: (1) Mobility fuels are mixtures of liquid hydrocarbons that are burned in internal combustion engines to propel vehicles, to produce electrical power, or to provide other stationary power needs, (2) Solid fuels are also used in explosive or pyrotechnic mixtures to fuel solid propellant rockets; to produce blast, light, or smoke; or to launch bullets or projectiles, and (3) Fuels for fires can be any combustible material.

Fuel Tank, Fuel Cell. In this handbook the fuel container in or on a combat vehicle is referred to as a fuel "cell" to preclude confusion with the heavily armored combat vehicle, the tank.

Fuse. An object that, when lit at one end, will burn at a fairly well-defined rate, dependent upon the combustible material used, to ignite some material at the other end—for military purposes usually either an explosive charge or an incendiary—a desired time later. The fuse functions by burning a filler, and the burn time is usually established by the length of the burning material. Fuse is also used for the device in an electrical circuit that melts when a predetermined amperage of current flows.

Fuze. An object used to initiate functioning of artillery projectiles, aerial bombs, and missile warheads, which have advanced so that simple, combusting fuses are no longer adequate. To differentiate the more elaborate initiation device from the burning fuse, the US military has adopted the convention of calling the more elaborate device a "fuze". The devices used to initiate these objects are often quite complicated. Fuzes can initiate on contact—called superquick—or after a finite delay following impact—delay. Fuzes can "sense" an object and initiate a short distance away—proximity. Fuzes can initiate a given time after firing—time. Fuzes can be mounted in the front (nose) or the rear (base) of the projectile.

G

Geiger-Mueller. A gas-filled ovoid chamber with an anode (fine wire) along the axis and the chamber wall as the cathode. When a quantum of radiation enters the chamber, the radiation impacting the gas molecules results in ionization of the gas. The electrons move to the anode and cause a change in voltage between the anode and the cathode. This change in voltage can be detected by an electronic instrument. When the frequency of radiation impacts is low, the instrument can count the number of impacts per unit of time. When the frequency is high, the instrument can measure the output current, which is proportional to the radiation intensity.

Grand Mal. Violent, epileptic-like seizures.

Ground Fault Interrupter. A very high-speed electronic circuit breaker.

H

Half f-Stop of Light. A camera with an adjustable lens provides several aperture diaphragm openings to control the amount of light entering the camera. These full-stop openings are usually designated f/2.8, f/4, f/5.6, f/8, f/11, f/16, and f/22. Each full-stop opening passes twice as much light as the f/number following; f/2.8 passes the most light, and f/22, the least. A half stop such as f/3.5 would be halfway between f/2.8 and f/4 in the quantity of light passed. Referring to a light source as providing a half f-stop of light means that the extra light on the object being photographed is equal in effect to opening the diaphragm a half f-stop.

Halon. Halogenated hydrocarbons that are used as fire extinguishants. The most common used in vehicles are Halons 1301 and 1211.

Heat Flux Calorimetry. Use of a heat-measuring device, calorimeter or heat flux sensor, to measure the rate of heat flow.

Heat Rejection. A term indicating that heat has been transferred from an object to a coolant. When cooling an engine, heat is "rejected" by the engine to the coolant liquid, which later "rejects" this same heat to the air flowing through the radiator. In air-cooled engines heat is rejected directly to the air.

Hemoconcentration. Thickening of blood that results when water is lost from the blood.

Histotoxic Anoxia. Tissue poisoning due to lack of oxygen.

Hull Defilade. A tank is in hull defilade when it is behind a mound and the hull is in defilade, so only the turret is exposed to direct fire from the front.

Hydraulic Ram. The conversion of kinetic energy to a pressure within a liquid. The kinetic energy can be that possessed by the liquid itself, as when flowing liquid is suddenly stopped, or that possessed by a moving object which enters the liquid, as a projectile or shaped-charge jet which enters a fuel cell.

Hydrolytic Stability. The fluid cannot absorb more water and change its properties when exposed to atmospheric moisture.

Hygroscopic. Readily absorbs and retains atmospheric moisture.

Hyperpyrexia/Hyperthermia. Higher than normal body temperature.

Hypoxia. Lowering of the oxygen content in the blood.

I

Ignition. The action by which combustion, burn, or fire is started. (Compare to initiation.)

Impedimenta. Supplies carried by individuals, military organizations, or vehicles.

Incus. *See* Ossicles.

Initiation. As applied to an explosive item, the beginning of the deflagration or detonation of the explosive.

Intumescent Coating. A coating that expands when exposed to the heat of flames and forms a char. The char has a low thermal conductivity and therefore reduces the heat transfer from the flames to the material protected. In short, reaction of the intumescent coating insulates the material on which it is placed.

K

Kinetic Energy Penetrator. A solid, very hard antiarmor projectile that impacts armor at a high velocity and uses kinetic energy (KE) to damage the target. In World War II these steel projectiles were called armor piercing (AP). Material advances led to hardened steel, tungsten carbide, and depleted uranium (DU) penetrators. To avoid higher than normal aerodynamic drag on the tungsten carbide penetrators (which had a smaller diameter than the gun tube), the bulk of the projectile was a low-density sabot, which was discarded upon muzzle exit. When the greater effectiveness of long-rod penetrators was appreciated, the penetrator was lengthened and fins were installed to obtain aerodynamic stability. These rounds are called armor-piercing, fin-stabilized, discarding sabot (APFSDS). Projectile velocities can exceed 1372 m/s (4500 ft/s).

L

Lean Limit. The smallest fuel-vapor-to-air mixture ratio at which sustained burning can occur.

Learning Curve. Manufacturers, particularly aerospace contractors, when estimating the cost of a product that is to be produced in quantity, use an exponential curve to estimate what the final product cost will be after their personnel have "learned" how to fabricate and assemble the item. These "learning curves" are based upon experience and are used to estimate labor costs.

Limp Home. The capability of the vehicle to move to a safe area after sustaining damage.

Live-Fire Tests. Tests of military equipment prescribed by Congress in 1986.

M

M1 Main Battle Tank (MBT). Called the Abrams for GEN Creighton Abrams. Turbine-powered and uses diesel fuel or JP-8, mounts 105-mm gun (M1A1 and A2 have 120-mm gun.), steel hull; has automatic Halon 1301 fixed fire extinguisher systems (FFES) in crew and engine compartments. The M1 and M1A1 have high-density polyethylene fuel cells.

M2 and M3 Bradley Fighting Vehicles (BFVs). M2 is the infantry version, and M3 is cavalry. Mount 25-mm gun plus tube-launched, optically tracked, wire-guided (TOW) missiles, diesel powered, aluminum hull, has automatic Halon 1301 FFES in the crew compartment and a manually activated Halon 1301 FFES in the engine compartment. The BFVs have rotary-molded nylon 6 fuel cells.

M48 MBT. Mounts 90-mm gun, except M48A5 mounts 105-mm gun. M48, M48A1, M48A2 were gasoline powered; M48A3, M48A5 were diesel powered with welded aluminum fuel cells and a steel hull. M67 was a flame thrower version. M48 armored-vehicle-launched bridge has M48 hull and engine.

M60 MBT. Mounts 105-mm gun, diesel powered, steel hull, manually activated carbon dioxide FFES in engine compartment, and has welded aluminum fuel cells. M60 armored-vehicle-launched bridge and M728 CEV use same chassis.

M109 and M110 SP Howitzers. Aluminum hull, diesel engine, and welded aluminum fuel cells. M109 has 155-mm howitzer; M110 has 203-mm (8-in.) howitzer.

M247 DIVAD (Sgt. York). Divisional air defense vehicle, now cancelled; used M48A5 hull and engine.

M728 CEV. Combat Engineer Vehicle. Has 165-mm demolition projector. *See also* M60.

Magazine Rifle. A rifle into which several cartridges can be loaded so that the user need not load each cartridge separately. The use of the magazine rifle permitted soldiers to fire from the prone position and greatly reduced their vulnerability and enabled them to fire more accurately at a much higher rate. Because these magazine rifles were loaded at the breech rather than the muzzle, the soldiers did not have to expose themselves to reload their weapons, and the use of spin-stabilized projectiles greatly increased the effective range and accuracy of the weapon.

Malleus. *See* Ossicles.

Mathematical Model. Mathematical models are a series of mathematical operations that convert input parameters into a desired output parameter. An example of a mathematical model relating the mass of a body m and the rate at which that body is being accelerated a by an unbalanced force F is $F = m \cdot a$. Mathematical models are components of computer models. *See also* Computer Model.

Military Stress Situations. Specific combat situations in which soldiers must function and for which specific manual and/or mental functions are required.

Mist. Liquid droplets greater in size than 1.0 µm but can be up to 5.0 µm. For these mist droplets the gravitational force is relatively small compared to air currents. Mist droplets will not remain permanently airborne by Brownian motion alone. *See also* Fog *and* Spray *and* Vapor *and* Dust.

Molotov Cocktail. An incendiary device consisting of a glass bottle that contains gasoline or another liquid fuel and an external igniter. In use, the external igniter, which is normally a gasoline- or oil-soaked rag, is ignited, and the device is thrown onto a target so the glass bottle breaks. Molotov cocktails were used by the Finns against Russian tanks in 1940 when the USSR invaded Finland. The Finns reputedly named these for the Soviet Foreign Minister, V. I. Molotov, stating that these cocktails were for the consumption of Molotov's emissaries, the Russian tankers.

Monobloc. Essentially one-piece armor. A single thickness of material, as opposed to multiple layers of possibly different materials with or without air gaps between layers.

Mothball. To "mothball" is to prepare an item of equipment for long-term storage and then to store the item. Some essential maintenance may be required during storage. Basically, the item is available, but some preparation will be necessary before the item can be used.

Mucosa. Mucous membrane.

N

Napalm. Gelling agent used with hydrocarbon fuel, such as gasoline, to make a thickened fuel for use in incendiary weapons such as a flamethrower, fougasse (a large incendiary land mine usually initiated by an observer), or aerial bomb.

Narcotic. Substance that in moderate dosage allays sensibility, relieves pain, and produces profound sleep; however, in greater dosage produces stupor, coma, and convulsions.

Nasopharynx. Upper part of the pharynx continuous with the nasal passages. The pharynx is the part of the alimentary canal between the cavity of the mouth and the esophagus (gullet).

Nuclear Hardening. Modifications made to hardware so it will resist the electromagnetic pulse (emp) effects of a nuclear weapon explosion.

O

On-Vehicle Equipment (OVE). Equipment stowed in or on the vehicle that are necessary for operation and/or maintenance of the vehicle, such as tools, weapon-cleaning tools, etc. These items are listed in the vehicular maintenance manual.

Order of Magnitude. An order of magnitude is a factor of ten, i.e., if one object is measured in tens of items and another in hundreds of items; thus the second object is said to be an order of magnitude greater than the first.

Ossicles: Malleus, Incus, and Stapes. Three bones, or ossicles, of the ear. The malleus, or hammer, is connected to the eardrum, or tympanic membrane. The stapes, or stirrup, is connected to the walls of the oval window at the entrance to the cochlea, or inner ear. The incus, or anvil, connects the malleus to the stapes.

Overpressure. Transient pressure that exceeds atmospheric pressure manifested in the blast wave from an explosion.

P

Plug. Part of a target cut out by a flat-ended projectile, much like a cookie cutter removes a circular piece of dough. The piece removed is called a plug and usually leaves the target with the same velocity as the residual penetrator.

Polargraphic. A method of qualitative or quantitative analysis based on current-voltage curves obtained during electrolysis of a solution with increasing electromotive force.

Pounder (pdr). The British designate their cannon by the weight of the high-explosive shell fired, e.g., the 25 pounder that had a caliber of 85 mm (3.35 in.).

Pour Point. The temperature at which a liquid has a low enough viscosity to flow.

Pressure Attenuator. A device to reduce pressure spikes.

Probit. Unit of measurement of statistical probability based on deviations from the mean of a normal frequency distribution.

Purple K. A trade name for a powdered dry chemical fire extinguishant consisting primarily of potassium bicarbonate but with a small amount of purple dye added.

R

Rack Setting. The position to which the rack is adjusted to obtain a desired diesel fuel injection rate.

Radiation Liner. A liner usually contiguous with the inner vehicular wall, which captures fast neutrons and gamma radiation.

Reflected Pressure. Total, or stagnation, pressure applied normally, i.e., perpendicularly, to a surface. In some instances "reflected" is applied to shock waves, i.e., waves that echo from various surfaces.

Reticulated Foam. An open cell polyether or polyester polyurethane foam used in the ullage of military aircraft fuel cells to preclude explosion of the fuel vapor and air. Also used in void spaces adjacent to fuel cells to preclude fires within. This material conforms to MIL-B-83054.

Rich Limit. The greatest fuel-vapor-to-air mixture ratio at which sustained burning can occur.

Rotary Molded. A fabrication process in which granules of a thermoplastic are taken above the melting point in a mold that is rotating about two orthogonal axes. The temperature is gradually lowered so that the plastic solidifies on the inside surface of the mold. This procedure produces a seamless, hollow part with a very constant thickness and very few built-in stresses. This process can be used with many materials including nylon, polyethylene, etc.

Rust Inhibitor. A component added to the fluid which provides a coating on steel or iron components that prevents atmospheric oxygen contact with the metal and thus prevents oxidation or rust from forming.

S

Sarin. A nerve gas, GB.

Seebeck Effect. Named for Thomas Johann Seebeck (1770-1831), an Estonian-born German physicist, who discovered in 1821 that an electric current flows between different conductive materials when two junctions of these different materials are at different temperatures in a circuit. This is the basis of a thermocouple circuit.

Shaped-Charge Jet. A shaped-charge or high-explosive antitank (HEAT) warhead is a chemical energy warhead that has a copper-lined, conical cavity in a high explosive. As the high explosive detonates, part of the copper liner is accelerated into a very fast-moving jet (jet tip velocity is approximately 7620 m/s (25,000 ft/s)), which is followed by the liner in the form of a slug. The slug is moving at approximately 244 m/s (800 ft/s). The shaped-charge jet applies an extremely high impact pressure on the armor.

Shot. Used in a tank commander's fire command for inert, kinetic energy (KE) projectiles. Also used in testing to describe a single event that uses either a KE or shaped-charge projectile.

Shrapnel. An artillery shell containing a large number of submissiles, usually lead balls, and a propelling charge that is exploded in air, usually by a time fuse or fuze, so that the balls are projected toward troops from above.

Slug. Rearmost portion of the metallic liner of the shaped-charge jet. This is the slowest moving portion of the jet, approximately 244 m/s. The slug may contain much of the liner.

Soman. A nerve gas, GD.

Spall. When a ballistic penetrator impacts a target, stress waves pass through the material and reflect backward from the far side of the target. When these waves combine with others in the target, the target material can fail in tension. When broken free, the target material is called spall. Spall can have a significant velocity, particularly from a shaped-charge jet impact. These particles are usually thrown outward from the side opposite that impacted by the penetrator or blast. In combat vehicles the spall is usually metallic.

Spall Curtains. Layers of ballistic fabric, bonded or unbonded, which are intended to trap spall.

Spall Liner. A spall-trapping lining contiguous with or spaced a short distance, e.g., 102 mm (4 in.), from the metallic wall that can emit spall.

Spectral Bands. Electromagnetic radiation forms a spectrum by frequency or wavelength with electric or radio waves at one end and cosmic waves at the other. Between these limits are heat rays including infrared and visible radiation, ultraviolet, X rays, and gamma rays listed in order from longer to shorter wavelengths. In several cases these designations overlap. The spectral bands are discrete sets of wavelengths or frequencies of radiation that are emitted by materials when heated. These spectral bands are peculiar to specific bonds between atoms.

Splash. Metal that flows from the target in the opposite direction from that of the impacting projectile.

Spray. A distribution of droplet sizes generally greater than 5.0 microns in diameter. Sprays are usually caused by mechanical action such as a ballistic impact on a liquid mass, a liquid being forced through an opening, or a liquid jet impacting an object. *See* Fog *and* Mist.

Squib Valve. A valve actuated by an electroexplosive device.

Stapes. *See* Ossicles.

Stick Grenade. German hand grenade, also called a "potato masher," had a handle; the US oval hand grenade was called a "pineapple" because of the deep serrations in the body. The ovoid grenade was thrown much like a baseball, whereas the stick grenade was thrown like a hatchet.

Straight Run Distillates. Those hydrocarbons that were inherently in the crude oil and merely boiled off and then condensed. Cracked distillates are those resulting from cracking or breaking up of longer chain hydrocarbon molecules.

Stoichiometric Mixture. A mixture of oxidizer and fuel in which both oxidizer and fuel are completely consumed in a chemical reaction to stable products, e.g.,

$2H_2 + O_2 \rightarrow 2H_2O$.

Subcaliber. A projectile smaller in diameter than the bore of the gun from which it was fired.

Synergism. Cooperative action of discrete agencies that causes a total effect greater than the sum of the effects taken individually.

T

Time Constant. A measure of the quickness of response of a device to a change in input. For the temperature-sensing devices, such as a thermocouple, the time constant is the time required for the device to reach 63.2% of its final voltage given a step change in temperature.

Tinnitus. Perceived buzzing, whistling, or ringing sound in the ear that does not correspond to real physical stimulation.

Trigeminal Nerve. Fifth, or trifacial, nerve is the largest cranial nerve. It is the great sensory nerve of the head and face and the motor nerve of the muscles of mastication.

Troland. A unit of retinal illuminance, the troland (td), is based on the fact that the light passing into the eye is proportional to the area of the pupil. The troland is the retinal stimulation provided by a source of 1 cd/m^2 viewed through a pupil of 1 mm^2. The troland value for the stimulus is given by $td = 1\ (cd/m^2) \times A(mm^2)$, where A = pupil area.

U

Ullage. The vapor space above the liquid level in a liquid container, such as a fuel cell. The ullage of a fuel cell contains air and fuel vapor. These can be in a combustible or explosive mixture or can be too lean or too rich for combustion.

V

Vapor. A substance in the gaseous state; vapor is molecular in size. *See* Fog *and* Mist.

Vapor Lock. Fuel flow in a line blocked by vaporized fuel.

Vehicular Survivability. The ability of a vehicle to endure ballistic hits or other damage and not lose crew members or be destroyed.

Venturi Principle. Fluid flow in a channel is restricted so that the rate of flow increases in order to lower static pressure on the walls of the channel.

VTA-903 Cummins. An engine used in the M2/M3 BFVs. This is a diesel, 8-cylinder, liquid-cooled engine.

W

Weeps. A very low leakage rate, more like a seepage than a drip or pour.

White Phosphorus. Pyrophoric material used as a filler in smoke grenades and projectiles.

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SUBJECT TERM (KEY WORD) LISTING

Agents, extinguishing
Agents, extinguishing, chemical intervention
Agents, extinguishing, physical-acting
Ammunition, hazards
Detectors, combustion, optical
Detectors, combustion, thermal
Electrical system, 12 V dc, design
Explosion, suppression
Extinguisher, handheld
Extinguisher, vehicle-mounted
Extinguishing systems, active
Extinguishing systems, passive
Extinguishing techniques, passive
Fire prevention
Fuel system, design
Hydraulic system, design
Incapacitation, crew, predictions
Materials selection, vehicle
Modeling, combustion and extinguishment
POL
System integration, AFES
System survivability

Custodians:
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