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MIL-HDBK-336-2
21 September 1983

MILITARY HANDBOOK

SURVIVABILITY, AIRCRAFT, NONNUCLEAR,

AIRFRAME-VOLUME 2

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DEPARTMENT OF DEFENSE
WASHINGTON 25, DC

MIL-HDBK-336-2
Military Handbook for Military Aircraft Nonnuclear Survivability

1. This standardization handbook was developed by the Department of Defense with the assistance of the Air Force Wright Aeronautical Laboratories (AFWAL/FIE) in accordance with established procedure.

2. This publication was approved on for printing and inclusion in the military standardization handbook series.

3. This document provides basic and fundamental information on military aircraft survivability design requirements and assessment methodology. It will provide valuable information and guidance to personnel concerned with the design and assessment of military aircraft. The handbook is not intended to be referenced in purchase specifications except for informal purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on military aircraft design techniques and assessment methodology. It is the intent to review this handbook periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions to Air Force Systems Command, Attn: ASD/ENESS, Wright-Patterson Air Force Base, Ohio 45433.

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FOREWORD

1. This is a four volume Military Handbook. The titles of the four volumes are:

a. Volume 1 - Survivability, Aircraft Nonnuclear, General Criteria

b. Volume 2 - Survivability, Aircraft Nonnuclear, Airframe

c. Volume 3 - Survivability, Aircraft Nonnuclear, Engine

d. Volume 4 - Survivability, Aircraft Nonnuclear, Classified, General Criteria

The information contained in volumes 1, 2, and 3 is unclassified to permit greater utilization and accessibility to the user. In areas where classified data is applicable, it has been incorporated into volume 4, and is referenced as such in the text of each volume.

2. This handbook has been prepared to provide military planners and industry with the information and guidance needed for the conceptual and detail design of the new aircraft where nonnuclear-survivability enhancement is to be integrated into the system. It is also structured to provide data and guidance for the incorporation of survivability-enhancement features into existing aircraft systems as a retrofit modification. Both fixed and rotary wing aircraft design information are contained in this publication. Figure 1 illustrates the role of this handbook in the design process. It is a task-flow diagram of the major elements involved in the development of new aircraft. The system requirements are initiated by the using command that defines the operational requirements and capabilities desired to perform specific combat missions. These requirements are studied by the appropriate service agencies in the form of conceptual (Phase O) design analyses. The optimum mission and performance parameters are defined, along with system/cost effectiveness comparisons of candidate conceptual design candidates. This is accomplished through an analysis to identify the mission-essential functions that must be performed in order to accomplish the specific mission objectives. With these functions defined, an analysis is conducted to identify the subsystem-essential functions that must be provided to perform the mission-essential functions. At the same time, an analysis is conducted to identify the hostile threat systems to which the aircraft system may be expected during the conduct of its operational mission. The results of these analyses are then used by the S/V engineer to conduct an evaluation of the various candidate survivability-enhancement techniques that may be used in the design concepts. This design handbook will be the basic source for identification of the basic principles and techniques that may be employed. It will also provide references to other information sources for more detailed and/or specialized data. The results of this analysis are summarized into recommendations for the development of candidate conceptual aircraft designs. As each candidate system is evolved, vulnerability and survivability assessment are conducted to evaluate the effectiveness of their individual S/V design features. As shown, this design handbook is used directly by the conceptual designers, vulnerability assessment analysts, and survivability assessment analysts in the design process. At the same time, design trade-off studies are conducted that evaluate the benefits and penalties associated with candidate system and subsystem elements. The results of vulnerability, survivability, and design tradeoff

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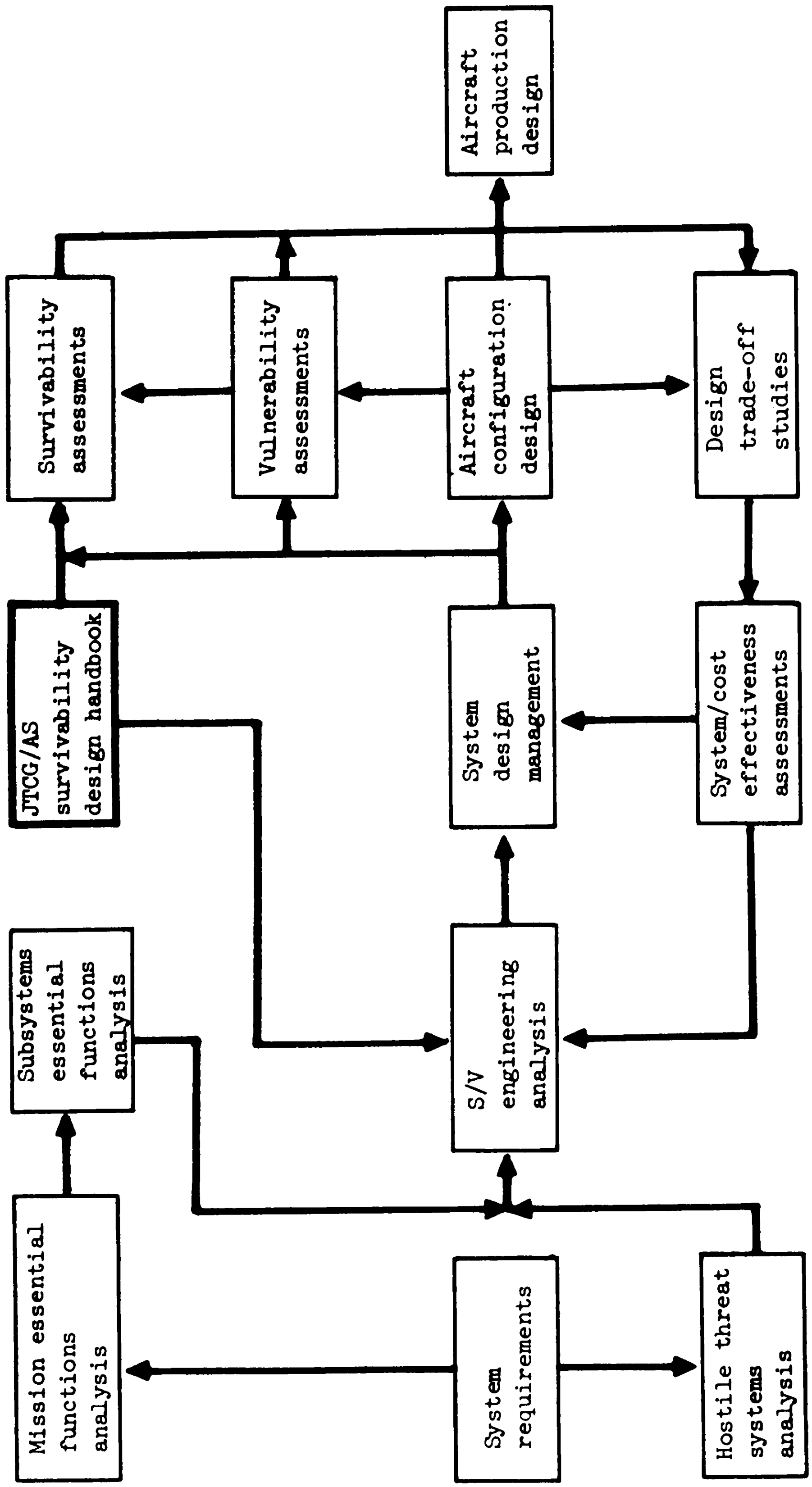

FIGURE 1. Handbook use in design process.

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studies are used as input data for system/cost effectiveness analyses, This evaluation provides the system design management and the S/V engineer with the overall system benefits and penalties for the various design concepts. It permits selection of the most effective combinations of survivability-enhancement features for the specific system applications, and identifies areas of. deficiencies or over design that may be improved. The process is iterative, and is continued until the most cost effective design concept is developed. It then becomes the baseline design for the production aircraft. The same process is repeated through the validation, full-scale development, production, and operational phases of the aircraft system.

3. Military aircraft survivability enhancement began in World War I with makeshift efforts by the pilots to provide themselves with some form of ballistic armor protection. This progressed from steel infantry helmets and stove lids fastened to the pilot seats to all-steel pilot seats 0.3-inch thick. In 1917, Germany designed an armored, twin-engine bomber, with 880 pounds of 0.29-inch steel plate armor located in sensitive areas. The British countered by installing steel seats and 0.50- to 0.625-inch nickelchrome steel armor around radiators, gas tanks and the aircrew in some of their aircraft. In the late 1930's, the United States began to install armor in some of their fighter aircraft. In World War II, the greatest threat against aircrews was fragments from antiaircraft artillery shells. The available body armor in 1942 was awkward and heavy; thus rejected. The need for lightweight armor led to the development in 1943 of fiberglass bonded into a laminate and called Doron, after Col. G.F. Doriot. Most of the body armor of WW II was Doron Type 2. The introduction and use of flak suits reduced casualties from 6.58 wounds per 1,000-man sorties to 2.29 wounds per 1,000-man sorties in 1943-44. None of the armor of this period was effective against API bullets, however. The aluminum nylon M12 vest was developed as an improvement over Doron and was field-tested in Korea. An all-nylon vest consisting of 12 layers of 2 x 2-inch basketweave nylon also developed was attractive because of its flexibility and effectiveness against mortar and shell fragments. Flat plate armored glass was incorporated into the windshields of combat aircraft as an added protection for the crew. Self-sealing fuel bladders and lines were developed for bomber and fighter aircraft during World War II and were credited with saving many of these systems. Some attention was also directed to the suppression of fuel fires in bomber aircraft. Balsa wood was installed around some of the voids in wing fuel tanks to prevent fuel leakage fires in those areas. The British experimented with fire extinguishing systems in the fuel tank areas of some of their multiengined aircraft. Considerable research on specific problems of aircraft protection and vulnerability was conducted during the war, with particular attention being directed to penetration of materials by bullets and fragments, and the effect of blast on aircraft structures. In 1948, the First Working Conference on Aircraft Vulnerability was held at the U.S. Army Ballistic Research Laboratory at the Aberdeen Proving Grounds, Maryland. The participants were recognized experts from the Air Force Air Material Command, the Army Ballistic Research Laboratory, Johns Hopkins University Applied Physics Laboratory, University of Chicago Ordnance Research, General Electric Engine Company, New Mexico School of Mines, the Navy Ordnance Explosive Group, and the Rand Corporation. The purpose of this meeting was to define the problem of military aircraft vulnerability and to identify the technology required to develop design improvements. Unfortunately, the excellent beginning

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initiated by this group was curtailed by the philosophy that all future wars would be fought with nuclear weapons. This idea continued through the 1950's and early 1960's where little attention was paid to nonnuclear survivability of military aircraft. During the Korean conflict, a limited revival of interest in nonnuclear survivability was experienced. The emphasis was primarily directed to fighter- and attack-type aircraft. The major survivability enhancement techniques were mainly improvements in armor and self-sealing fuel tank designs. The use of coordinated tactics in air-to-air combat with fighter aircraft became an area of interest to the Air Force and Navy that proved to be an important factor in the one-sided kill ratios enjoyed by the United States. Again, after this conflict, the emphasis of military aircraft design was directed to general nuclear war considerations that hampered research on nonnuclear survivability considerations.

The Army recognized the threat of small arms and light AA weapons to aircraft operating in direct support of forward area units, and in the late 1950's initiated action to develop protective measures for the aircrew and critical aircraft components against these threats. The Air Vehicle Environmental Research Team, consisting of technical representatives from the user and the appropriate technical service laboratories was formed, and they developed the original concepts for ballistic protection systems that were later employed in all Army combat aircraft. These concepts were also used in varying degrees by the USAF and Navy. These efforts led to the development of a new family of light weight armor materials, damage tolerant components, and major advances in fuel protection.

The employment of large numbers of U.S. aircraft in Southeast Asia, in the mid-1960's, resulted in an awareness of their susceptibility to hostile nonnuclear weapon systems. Helicopters were used for the first time in combat roles where exposure to enemy gunfire was commonplace. The large numbers of rotary-wing aircraft shot down or critically damaged by small-caliber weapons provided the motivation to conduct research and testing geared to providing improved survivability for these systems. Many of the design improvements were pioneered by this effort. The Air Force and Navy were also experiencing unacceptable aircraft losses and embarked on programs to analyze the problems and develop new means to modify the existing aircraft to make them more survivable. The use of reticulated foam inside fuel cells was one of the major improvements developed. Considerable advances were made in the field of armor materials. Ceramic composite armors were developed for protection against armor-piercing projectiles in an effort to obtain higher levels of ballistic protection with smaller weight penalties. Later in this conflict, when the sophistication of hostile weapon systems was raised to a level never before experienced, many new survivability enhancement methods were developed and employed. These included radar homing and warning systems (RHWS), electronic warfare countermeasures, infrared emission suppression methods for aircraft engines, evasive tactics against surface-to-air missiles, improved weapon delivery systems (missiles, smart bombs, etc), visual and aural signature reductions, tactics, and many other techniques.

The analytical capabilities for survivability assessment programs were expanded tremendously through the use of high-capacity, high-speed electronic computers,

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providing military and industry with valuable new tools. There occurred a rapid proliferation of computer models by each of the services and most of the airframe manufacturers. The military services recognized the need for an integrated effort to standardize the growing methodology and research and test programs. An organization was developed through triservice efforts to accomplish these objectives. It was designated as the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), with the charter signed by the Joint Commanders on 25 June 1971. Since that time, considerable progress has been made to implement interservice efforts to develop more effective and efficient methods to enhance aircraft nonnuclear survivability. The organization has maintained close liaison with each service activity to ensure that all survivability and vulnerability data and systems criteria are made available to developers for new aircraft. The JTCG/AS has accepted the responsibility for coordinating the aircraft survivability technology for high-energy laser weapons that are projected as the next major threat system in potential future conflicts. This activity has been pursued for the past several years. Rap id advances in survivability enhancement methods are being accomplished through numerous research programs. Considerable savings in manpower and resources are expected to be realized through the coordination of this new technology through the efforts of the JTCG/AS in the future. This publication will serve as the vehicle by which the analytical and design data will be dispersed to the S/V community. The fruits of the coordinated efforts are currently being enjoyed, as is evidenced by the significantly higher levels of survivability that have been incorporated into new military aircraft systems now entering service or in current development.

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1. SCOPE

1.1. General. This is the second volume in a four-volume design handbook for nonnuclear survivability of military aircraft. Each volume is structured to be used in conjunction with the other three volumes, as needed, in the design process. This volume contains specific subsystem design concepts, procedures, and other pertinent information. The information and design guidance contained in this volume is arranged in a manner to enhance its use in the conceptual design process, system research, design, test, and evaluation (RDT&E) programs, and existing aircraft modification programs where nonnuclear survivability features are required. Specific information pertinent to each subsystem is contained therein. This volume is arranged to permit the designer or analyst to select the specific area or subject of concern in the design or modification of an aircraft system and find the candidate design methods that may be considered for use. Table 1-1 is a matrix of the general survivability enhancement methods and the subsystems associated with military aircraft. The general applicability of the listed methods, for each subsystem, is indicated by a dot in the matrix. This serves as a preliminary check list for the user to ensure that all potential candidate survivability enhancement methods are considered. The use of this chart is an essential step in the process of selecting the most effective combination of survival enhancement features for the given aircraft design concept.

1.2. Application. The data contained in this design handbook have been arranged to support the development of both fixed and rotary wing military aircraft. Each has unique mission and performance characteristics that require specialized attention and design solutions. The subsystem design categories have been established with these considerations in mind. For example, the power train and rotor blade subsystems deal primarily with military helicopter applications, while the launch/recovery systems deal with those subsystem elements for both fixed and rotary wing aircraft landing gear systems and for those systems related to the assisted takeoff (launching) and deceleration (recovery) methods most used by the Air Force and Navy fixed-wing aircraft.

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TABLE 1-I. SURVIVABILITY ENHANCEMENT METHODS.

Aircraft Subsystems	Radar Cross Section (RCS) Signature	Infrared (IR) Signature	Visual Signature	Aural Signature	Redundancy/Separation	Damage Tolerance	Delayed Failure	Leakage Suppression/Control	Fire/explosion Suppression	Fail-Safe Response	Masking/Geometry/Armor	Laser Protective Techniques	Performance	Electronic Countermeasures/ Threat Detection	Decoys Chaff, and Aerosols	Lethal Defense	Mission Tactics
Configuration	●	●	●										●	●	●	●	●
Structures	●	●	●		●	●	●			●	●	●		●			
Personnel Stations	●		●		●	●			●	●	●	●		●			
Fuel Systems		●			●	●	●	●	●	●	●	●					
Propulsion Installations	●	●	●	●	●	●	●	●	●	●	●	●	●				
Power Train Systems				●	●	●	●			●	●	●					
Rotor Blade Systems	●		●	●		●	●			●		●					
Flight Control Systems					●	●	●	●	●	●	●	●					
Fluid Power Systems					●	●	●	●	●	●	●	●					
Environmental Control Systems					●	●	●	●		●	●	●		●			
Armament Systems					●	●				●	●	●					
Electrical Power Systems					●	●	●			●	●	●		●			
Avionic Systems	●				●	●	●			●	●	●		●			
Launch/recovery Systems						●		●		●	●						
Oxygen									●		●						
Armor						●	●				●	●					

● Indicates general applicability of a survivability enhancement method to a subsystem.

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2. REFERENCED DOCUMENTS

2.1. General. The documents in this section form a part of this handbook to the extent specified herein. This section contains a complete list of all references specifically referred to in these four volumes and those where additional information can be obtained.

2.2. Reference by Volume. Table 2-I lists the references by Volume number. Parentheses ( ) around a number indicates that the reference has been deleted.

TABLE 2-I. References by volume no.

Ref. No.	Volume Number 1	2	3	4
1	X			
2	X	X		
(3)				
4	X			
5	X	X		X
6	X			
7	X			
8	X			
9	X			
10	X			
11	X			
12	X			
13	X			
14	X			
15	X			
16	X			
17	X			
18	X			
19	X			
20	X			
21	X			
22	X	X		
23	X	X		
24	X			
25			X	
26			X	
27			X	
(28)				
29			X	
30		X	X	
31			X	
32		X	X	
33			X	
34			X	
35			X	
36			X	
37			X	
38			X	
39			X	
40			X	
41			X	
42			X	
43			X	
44			X	
45			X	
46			X	
47			X	
48			X	
49			X	
50			X	
51			X	
52			X	
(53)				
54			X	
55		X	X	
56			X	

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TABLE 2-10 References by volume no. (continued)

Ref. No.	Volume Number 1	2	3	4
(57)				
58			X	
59			X	
(60)				
61		X		
62		X		
63		X		
64		X		
65		X		
66		X		
67		X		
68		X		
69		X		
70		X		
71		X		
72		X		
73	X	X		
74		X		
75		X		
76		X		
77		X		
78		X		
79		X		
80		X		
81		X		
82		X		
83		X		
84		X		
85		X		
86		X		
87		X		
88		X		
89		X		
90		X		
91		X		
92		X		
93		X		

Ref. No.	Volume Number 1	2	3	4
94		X		
95		X		
96		X		
97		X		
98		X		
99		X		
100		X		
101		X		
102		X		
103		X		
104		X		
105		X		
106		X		
107		X		
108		X		
109		X		
110		X	X	X
111		X		
112		X		
113		X		
114		X		
115		X		
116		X		
117		X		
118		X		
119		X		
120		X		
121		X		
122		X		
123		X		
124	X			
125		X		
126		X		
127		X		
128		X		
129		X		
130		X		

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TABLE 2-I. References by volume no. (continued)

Ref. No.	Volume Number 1	2	3	4	Ref. No.	Volume Number 1	2	3	4
131		X			167		X		
132				X	168		X		
(133)					169		X		
(134)					170			X	
135		X			171		X		
136		X			172		X		
137		X			173	X	X		
138		X			174		X		
139		X			175		X		
140		X			176		X		
141		X			177		X		
142		X			178		X		
143		X			179		X		
144		X			180		X		
(145)					181	X			
146		X			182		X		
147			X		183	X			
148			X		184	X			X
149			X		185	X			
150			X		186	X			
151			X		187	X			
152			X		188	X			
153			X		189				X
154			X		190				X
155		X			191				X
156				X	192	X			
157				X	193	X			
(158)					194	X			
(159)					195	X			
160		X			196	X			
161	X	X			197	X			
162		X			198	X			
163	X	X			199		X		
164	X	X			200		X		
165	X	X			201		X		
166	X				202		X		

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TABLE 2-I. References by volume no. (continued)

Ref. No.	Volume Number 1	2	3	4
203		X		
204		X		
205		X		
206		X		
207		X		
208		X		
209		X		
210		X		
211		X		
212		X		
213		X		
214		X		
215		X		
216		X		
217		X		
218		X		
219		X		
220		X		
221		X		
222		X		
223		X		
224		X		
225		X		
226		X		
227		X		
228		X		
229		X		
230		X		
231		X		
232		X		
233		X		
234		X		
235		X		

Ref. No.	Volume Number 1	2	3	4
236		X		
237		X		
238		X		
239		X		
240		X		
241		X		
242		X		
243		X		
244		X		
245		X		
246		X		
247		X		
248		X		
249		X		
250		X		
251		X		
252		X		
253		X		
254		X		
255		X		
256		X		
257		X		
258		X		
259		X		
260		X		
261		X		
262		X		
263		X		
264		X		
265		X		
266		X		

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2.3 Reference by subject. Table 2-II lists the References by subject matter.

TABLE 2-II. References by subject matter

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elect. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
1	X																	
2	X																	
(3)	0																	
4	X																X	
5	X																X	
6	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		
7	X																X	
8																	X	
9																	X	
10																	X	
11																	X	
12																	X	
13																	X	
14																	X	
(15)																		0
16																	X	
17																	X	
18																	X	
19																	X	
20																	X	
21																	X	
22	X																	
23	X	X	X	X	X	X		X	X	X	X	X	X	X		X		X
24	X																X	
25					X													

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
26					X													
27					X													
(28)																		
29	X													X				
30				X	X													
31														X			X	
32					X			X	X				X					
33					X													
34					X													
35	X				X									X				
36					X													
37					X													
38					X													
39	X				X									X				
40	X													X				
41	X													X			X	
42	X													X				
43	X																	
44	X				X													
45	X				X													X
46					X													
47					X													
48					X													
49					X													
50					X													

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
51					X													
52					X													
(53)																		
54					X													
55					X													
56				X	X													
(57)																		
58				X	X													
59				X	X													
(60)																		
61	X	X																
62								X									X	
63								X										
64								X										
65								X										
66								X										
67								X										
68								X										
69								X										
70								X										
71								X										
72								X										
73	X							X									X	
74																X		
75	X						X	X						X				X

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
76					X													
77					X		X											
78					X		X											
79					X		X											
80					X		X											
81					X		X											
82					X		X											
83	X		X															X
84									X							X		
85								X	X									
86								X	X									X
87	X																	X
88	X																	X
89	X																	X
90	X																	X
91	X																	X
92	X																	X
93	X																	X
94	X																	X
95	X																	X
96	X																	X
97	X																	X
98	X	X				X												X
99			X															
100	X		X															X

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
101			X													X		
102																X		
103																X		
104																X		
105																X		
106																X		
107																X		
108																X		
109																X		
110	X				X							X		X				X
111																X		
112																X		
113																X		
114	X		X													X		
115				X													X	X
116				X				X										
117								X										
118												X				X		X
119												X						X
120												X						X
121												X						
122	X	X																
123		X														X		
124	X																	
125		X																

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
126		X																
127								X									X	
128	X																	
129	X	X																
130		X																
131		X		X													X	
132	X	X																
(133)																		
(134)																		
135					X	X												
136								X										
137								X										
138																X		
139	X																X	
140	X																X	
141	X																X	
142	X																X	
143	X																X	
144													X	X				
(145)																		
146														X				
147					X													
148					X													
149					X			X	X							X		
150					X													

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structure	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
151					X													
152					X													
153					X													
154					X													
155	X	X																
156	X				X	X	X											
157	X				X	X	X											
(158)																		
(159)																		
160								X										
161								X										
162		X	X	X						X							X	
163								X										
164	X							X									X	
165	X							X									X	
166																		X
167								X										
168								X										
169				X														
170							X							X				
171										X								
172				X														
173				X														
174				X														
175				X														

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TABLE 2-II. References by subject matter (continued)

Category / Ref. No.	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
176				X														
177				X														
178				X														
179										X								
180										X								
181	X																	
182		X		X												X		
183												X						X
184	X											X						
185	X																	X
186	X							X										X
187	X							X										
188												X					X	X
189		X														X		
190												X						X
191	X	X														X		X
192	X																	
193	X																	
194	X																	
195																	X	
196				X														
197			X															
198				X														
199												X						
200	X																	

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
201				X					X		X							
202											X					X		
203					X						X							
204																X		
205																		
206	X	X																
207																X		
208									X									
209																X		
210				X														
211									X									
212				X														
213		X		X														
214				X														
215																X		
216																X		
217			X															
218				X														
219																X		
220	X						X											
221		X																
222		X																
223		X																
224		X																
225		X																

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TABLE 2-II. References by subject matter (continued)

Ref. No. \ Category	General	Structures	Personnel (Crew)	Fuel	Propulsion	Power Train	Rotor Blades	Flight Cont.	Fluid Power	Envir. Cont.	Oxygen	Armament	Elec. Power	Avionics	Launch/Recov.	Armor	Computer Prog.	Threat Data
226		X																
227		X																
228		X																
229		X																
230		X																
231		X																
232		X																
233		X																
234		X																
235		X																
236		X																
237		X																
238		X																
239									X									
240								X										
241												X						
242																X		
243																X		
244															X			
245			X					X										
246	X						X											
247				X						X						X		
248																		
249																X		
250																		

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TABLE 2-II. References by subject matter (continued)

Category / Ref. No.	General Structures Personnel (Crew)	Fuel Propulsion Power Train	Rotor Blades Flight Cont. Fluid Power	Envir. Cont. Oxygen Armament	Elec. Power Avionics Launch/Recov.	Armor Computer Prog. Threat Data
251						X
252						X
253						X
254						X
255						X
256						X
257		X				
258	X		X			
259				X		
260						X
261		X				
262		X				
263					X	
264			X			
265		X				
266						X

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2.4. References by number. The following documents form a part of this handbook to the extent specified herein. Due to their large number, the documents are numbered consecutively.

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(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

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3. DEFINITIONS

3.1 General. For general aircraft nonnuclear survivability terms see MIL-STD-2089 (Reference 1).

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4. GENERAL SURVIVABILITY ENHANCEMENT METHODS

4.1 General. For each of the aircraft design disciplines, a wide variety of general survivability enhancement techniques are available for application to a specific aircraft system. The designer and system manager must evaluate the candidate methods available to determine the combination of techniques that will be the most effective for a given application. The choice may be limited by the specific requirements imposed by the procuring agency, which has conducted a selection of the candidate survivability enhancement methods during the initial system studies. The selection process must consider the impact of each candidate survivability enhancement method upon the system design factors, such as procurement cost, weight, maintainability, reliability, safety, logistics, system security, and life cycle costs. When considering general survivability enhancement techniques for an aircraft design application, priority should be given to those techniques that provide the greatest benefits for the least penalties. For example, combat damage tolerance, redundancy, and subsystem fail-safe response design features will generally be more system/cost effective than the use of heavy parasitic armor to obtain a given level of survivability against hostile nonnuclear threats. This section lists the general categories of techniques to the depth that is applicable for the majority of subsystems. Where more detailed information is applicable to one or a few specific design disciplines, it is included in the specific design areas contained in section 5 of this volume. The techniques described in this section are:

a. Minimized detection

b. Active countermeasures

c. Ballistic/laser protection

d. System operational factors

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4.2 Minimized Detection Passive Countermeasures. The hostile threat systems encountered during combat missions usually consist of a minimum set of functional elements for (1) target detection, location, and identification, (2) tracking, aiming and fire control, and (3) terminal effect kill mechanisms. The reduction in the efficiency of hostile threat system functions will enhance the survivability of the target system. The reduction of threat system target detection capability, through the use of onboard passive countermeasures, is addressed in this section. These techniques do not effect the vulnerability of the aircraft, rather, they operate in a way that increases survivability, of which vulnerability is only one element. Passive countermeasures for detection minimization are defined as the onboard unpowered equipment and components dedicated to the reduction of the capability of the hostile threat systems to detect, locate, and identify the vehicle as a target containing the countermeasures equipment. Several parameters exist that threat systems utilize in target detection, and are shown in Table 4-I.

TABLE 4-1. Target Detection Parameters.

Observable parameter	Sensor
Electromagnetic reflection	Radar
Thermal radiation	IR, spectral electromagnetic region, UV spectral region
Visual observability	Eyes, TV, LLLTV (visual EM spectrum)
Noise generation	Pressure waves, ears, mech/ electronic sound location systems
Electromagnetic Emission	ESM

Each of these parameters possesses a unique set of characteristics that are indicative of the target and are referred to as signatures. The methods generally used individually or in combination to reduce a threat system's detection capability include:

a. Reduction of target signatures below sensor thresholds

b. Masking of target signatures by minimized target/background contrast

c. Degradation of threat system sensors

d. Masking or biasing of the target signature to create threat system sensor errors

Methods used by threat systems generally include radar detection, infrared (IR) detection, visual detection, and aural detection. The type of detection method will be determined typically by the threat type, use, location, and the degree of threat system sophistication as indicated in Table 4-II. These are examples of threat systems and the general detection methods typically used.

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TABLE 4-II. Target Detection Methods.

Threat system	Typical detection Methods
Small arms thru 14.5 mm	Visual, aural
Antiaircraft guns, 20 mm thru 100 mm	Visual, aural, radar
Air-to-air guns (AAG)	Visual, radar
Air-to-air rockets (AAR)	Visual, radar
Air-to-air missiles (AAM)	Radar, IR, ESM
Surface-to-air missiles (SAM)	Radar, IR, ESM

4.2.1 Radar cross-section (RCS) signature. Radar detection is based on processing reflections of transmitted electromagnetic signals received from target surfaces. Radar cross-section (RCS) is the term used to denote the effective electrical size of a target as seen by a radar. Alternate designations, such as radar echo area and scattering cross section are used synonymously by different investigators. The detection range of a target is a function of the intrinsic parameters associated with a given radar and the magnitude of the reflected signal. The magnitude of the reflected signal is a function of the effective target radar cross-section area (signature). The units for RCS are those of area, typically square meters (Reference 110). Any method used to reduce the target cross section will reduce the range at which detection will occur. The techniques used to reduce the magnitude of the reflected radar signal by the target include:

a. Target geometry

b. Use of target construction materials that absorb a significant amount of the impinging transmitted electromagnetic energy

The radar cross section of a target is that area of the incident electromagnetic field at the target from which the energy must be removed and reradiated isotropically to provide the same signal power at the receiver as was obtained from the actual target, Note that this definition applies to both the collocation in space of transmitter and receiver antennas (monostatic radar) and the spatial separation of these antennas (bistatic radar). Space does not permit a lengthy discussion of the many intricacies of RCS here, but several general points are made on the subject. The RCS discussion is limited to the case of a monostatic radar against a distant target since this is where most RCS interest occurs. The distance provides what is known as far-zone RCS due to plane wave illumination. This should not be interpreted as meaning that echo reduction techniques have any such limitation. Indeed they apply as well to bistatic and short-range (near-zone) encounters, with some minor modification

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being necessary in a few cases. The most important point is that echo is not equivalent to physical area for the majority of reflecting geometries. As usual there are a few exceptions to the rule - the most widely known being the metallic sphere whose size is large in terms of illuminating wavelength. In this case, the radar cross section is equivalent to the shadow area (πR^2) as shown in Figure 4-1. Consider though, that much of the energy which strikes the sphere is scattered in directions other than back to the source; hence, only a small fraction of the energy which enters the spherical aperture is backscattered. In contrast to the sphere, if the aperture is filled by a flat plate with one square meter physical cross section, and is illuminated normal to its surface, a radar will receive a much larger echo since little of the incident energy is scattered in random directions. Thus, the effective echoing area is that of a sphere which is physically much larger than the plate. In the example shown in Figure 4-1 the flat plate of 1 m^2 physical cross section has a radar cross section of roughly 14,000 m^2 at a wavelength of 3 centimeters. By contrast a flat plate approximately 10 cm (4 in.) on a side has a radar cross section on the order of 1 m^2 at this wavelength. This relationship between physical and electrical size must be kept in mind since very small radar cross sections are discussed for vehicles that are physically quite large.

4.2.1.1 <u>Radar cross-section determination.</u> Except for simple geometric shapes, the determination of the effectiveness of radar cross-section minimization of the radar signature cannot be determined analytically. Therefore, radar cross sections are determined empirically by tests. Testing has been done on the test ranges and in anechoic (reflection-free) chambers. The results of testing have shown that satisfactory qualitative data can be generated using target scale models sized from full scale to as small as one-tenth scale. All have been used for cross-section determination with satisfactory results, so long as the critical dimensions of the scale model are not too close to the impinging signal wavelengths.

4.2.1.1.1 <u>Echo patterns.</u> Aircraft represent complex assemblies of reflecting elements. The reflections from these elements vary in relative phase as viewing angle changes. The total echo from the vehicle varies greatly with angle, particularly at short wavelengths. This is due to the constructive and destructive interference between the elemental reflections as they combine to form the total reflection. Figure 4-2 is a typical echo pattern of an aircraft as viewed by a microwave radar. The plot is relative echo area amplitude in decibels (dB) versus azimuth angle (in degrees) references to nose-on, where:

$$dB = 10 \log_{10} \frac{\sigma}{\sigma_o}$$

σ = ECHO AREA IN SQUARE METERS

AND σ_o = ARBITRARY REFERENCE ^{o} LEVEL IN SQUARE METERS

Immediately obvious is the large difference between peaks and nulls throughout the pattern, and the narrowness of the individual lobes. The narrowness of the lobes leads to the conclusion that the exact value of RCS at a precise viewing

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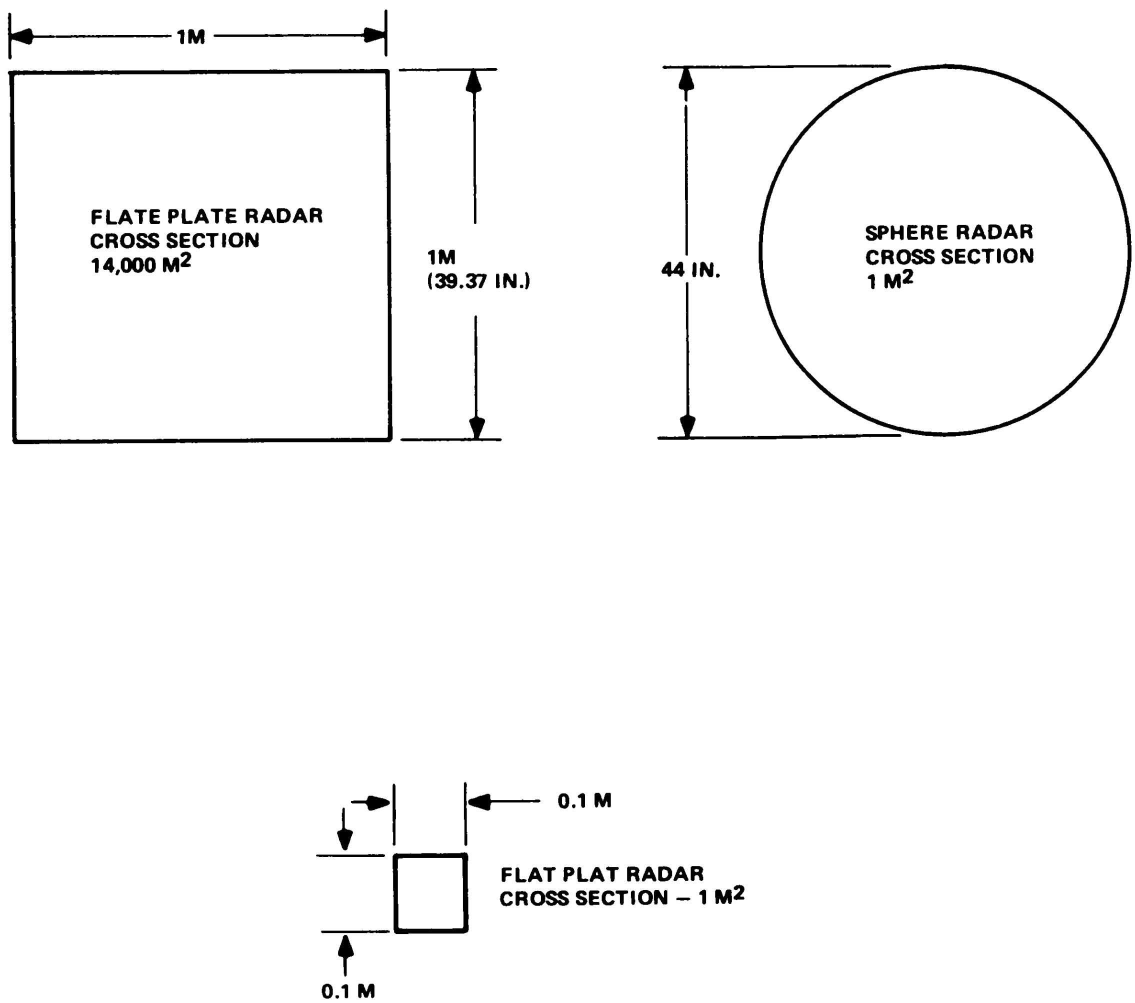

FIGURE 4-1. Radar cross section versus physical geometry.

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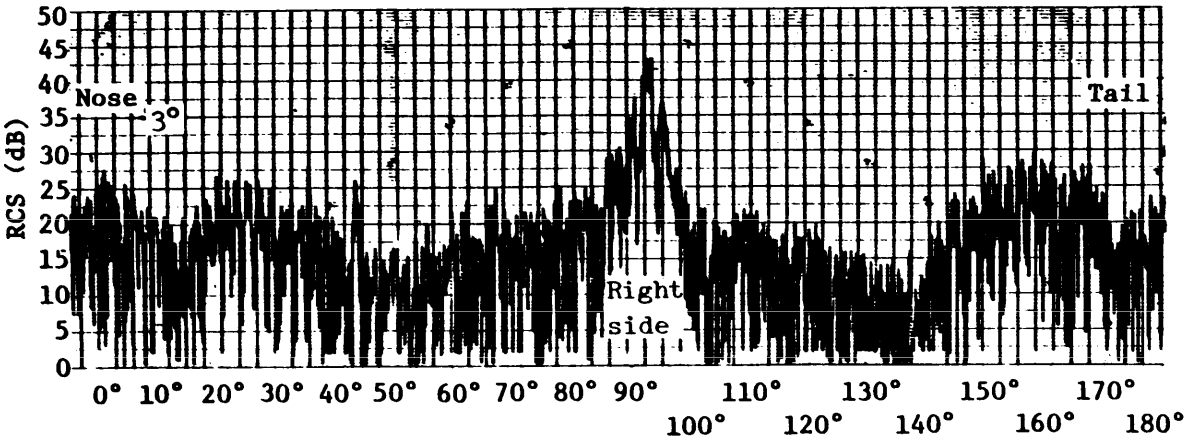

FIGURE 4-2. Typical aircraft echo patterns at microwave frequencies.

angle is of little consequence operationally, since neither could economically be determined to the extent required. Rather, statistical representation of the pattern has greater significance because probabilities of "seeing" a given value can be related to the general viewing angles. This observation has a major implication for RCS reduction, i.e., the concern must be for strong echoes which occur over broad angular regions rather than for narrow isolated peaks, because the probability of observing the peak to the extent of operational usefulness is small. A good example seen in the pattern of Figure 4-2 is the spike from the leading edge of the wing, which occurs at approximately 36 degrees. Though very large in amplitude, its width of less than 0.5 degrees makes this echo trivial to the camouflage problem, Radar cross section influences aircraft survivability in a hostile environment in two ways - it governs the size of the volume in which the hostile radar can detect or track the aircraft, and it determines the size, weight, complexity, and cost of electronic countermeasures intended to increase survivability.

4.2.1.1.2 Echo reduction. A second look at the RCS pattern reveals the existence of a much smoother curve upon which the fine lobes are superimposed. This smooth curve is large in amplitude over several broad angular regions, and represents the real basis on which most radars observe the aircraft. The sources of echo contributing to this smooth curve are the main concerns in reduction of RCS. For reasons to be discussed later, in most cases one's concern can be further narrowed to those sources of strong, wide-angle echo which are also broadband. The reasoning is simply that echo reduction involves

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aircraft structural design, and changes are expensive and hard to make. A vehicle is in the inventory for many years, and since enemy radar capability, especially operating frequency, is only predictable in a general sense, it follows that a design effective against any very limited frequency range would represent a monumental gamble. Thus, echo sources to be treated, and treatment methods as well, must be broadband to minimize possibilities for negating the echo reduction by simply changing radar frequency a small amount. This subject is discussed in more detail in Reference 110.

4.2.1.1.3 Radar Range. The influence on radar performance is seen through consideration of the simplified radar range equation:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

where

P_R = power received from the target (watts)

P_t = transmitted power (watts)

G = antenna gain (dimensionless)

λ = operating wavelength (meters)

σ = target cross section (square meters)

R = range to target (meters)

Since the receiver noise ultimately limits the minimum detectable signal Pr_{min}) we can see from the previous equation that maximum radar detection range is related to target cross section by:

$$R_{max} = k \sqrt[4]{\sigma}$$

where

$$k = \sqrt[4]{\frac{P_t G^2 \lambda^2}{(4\pi)^3 P_{r_{min}}}}$$

This means that a very large reduction in radar cross section is necessary to produce a useful reduction in detection range. Figure 4-3 is a plot of this function. The function applies when range is limited by radar sensitivity and not by radio horizon or terrain masking. Note that the plot is on a

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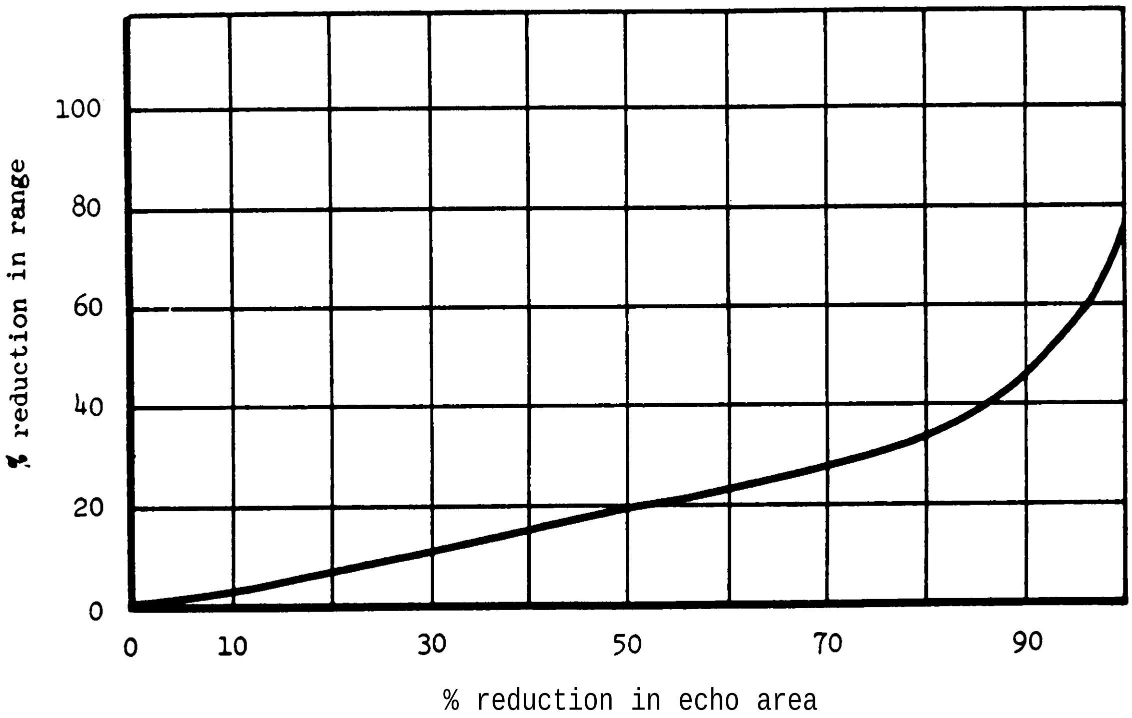

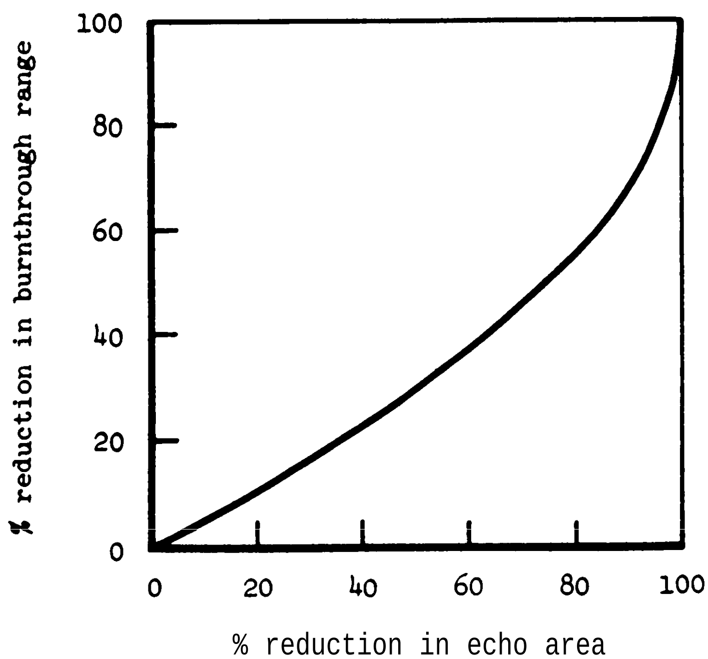

FIGURE 4-3. Effect of RCS reduction on radar detection range and burnthrough range.

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relative basis, since absolute values depend upon the radar and target parameters. A range reduction of 50% requires a cross section reduction of approximately 95%. Expressed in decibels, the latter is a reduction of 13 dB, which is the basis for the magic number frequently assigned as a performance goal for radar absorbent materials design. To reduce ranges to one-third of its normal value requires a 99% (20 dB) reduction in echo.

4.2.1.1.4 Signal Strength Levels. Cross sections have the dimensions of square meters or square feet, but cannot be identified directly from test data. Test data can only be interpreted in terms of signal strength levels; thus, the analytically known radar cross sections of some simple geometric shapes is used to calibrate the test radar return of signal strength levels. The aircraft model return signal data are then compared to the calibration model to indirectly establish its radar cross section. A discussion of radar cross section calibration is contained in Reference 146.

4.2.1.2 Radar cross-section passive source reduction. The reduction of radar cross section is accomplished by attenuation of the signal reflected back toward the radar receiver. Methods for reducing the magnitude of the signal reflected normally from the target surface included signal scattering and/or signal absorption as a result of the propagated signal interaction with the target surface.

The magnitude of signals reflected from a target surface are determined by the reflectivity and transmissivity characteristics of the surface, These characteristics are determined by the surface material characteristics and geometry in the signal impingement area. Surface geometries that do not attenuate the reflected signal include:

a. Large, flat surfaces that are normal to the impinging signal

b. Surface intersections that form concavities (reflectors)

c. Cavity-type anomalies that intercept smooth surfaces and contain internal reflection surfaces

d. Electromagnetically transparent surfaces with internal structure containing elements with reflecting surfaces facing the direction of the radar receiver

Techniques that reduce the reflectivity of critical surfaces include (1) the use of materials that absorb a significant part of the impinging signal, and (2) configuring the affected surface to a geometry that maximizes signal scattering. An additional classified discussion of passive radar cross-section reduction is contained in Volume 4 of this handbook.

4.2.2 Infrared (IR) signature. Aircraft survivability can be enhanced by minimizing aircraft detectability. In the IR spectrum, the enhancement of aircraft survivability through IR signature reduction is manifested primarily in the reduction of IR missile launch boundaries. If missile launch

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has occurred, then combinations of passive and active countermeasure techniques are required to negate or degrade IR seeker effectiveness. Over the last decade, aircraft IR signature reduction concepts have evolved in the following areas: (1) hot component masking; (2) hot component cooling; (3) surface treatments and coatings to control emissions and reflections; (4) mechanical air mixing to reduce exhaust gas temperature; (5) obscurants (aerosols) to mask the aircraft signature; and (6) fuel additives to modify the engine plume spectral signture. While most of the techniques derived from the above concepts have been applied to engine IR signature reduction, several have equally important applicability in the reduction of airframe IR signatures. For slower, low-flying aircraft, the major IR signatures, other than the engines and sun glint reflections, usually are the result of "hot-spots" generated by various subsystem operations. They include such items as gear boxes, oil coolers, hydraulic system reservoirs, etc. On rotary wing aircraft, the main rotor transmission can contribute to the IR signature. Special attention is required to suppress these signatures to an acceptable level. For high speed aircraft, aerodynamic heating can be a significant source of infrared emissions for specific portions of the detection spectrum. Special coatings and other techniques may be utilized to minimize the emissions. Additional information on aircraft engine infrared emission characteristics and suppression techniques is contained in Volume 3 of this handbook. In chapter 8 of Reference 110, the aircraft IR emissions sources are defined, the applicability of each related suppression concept explained, the impact of the suppression concept on aircraft performance characterized, and the aircraft detectability benefits identified.

4.2.3 Visual signature. In chapter 9 of Reference 110, a detailed description of observer-target-background psycho-physical relationships is presented so the reader may become acquainted with those attributes affecting visual detectability. These attributes are logically divided as to luminance (brightness), chromatic (color), clutter, and movement contrasts. One must first be familiar with the causes of detection before attempting optical signature reduction/control. A number of environmental aspects such as visibility, sun position, terrain reflectance, amount of cloud cover and other factors will significantly influence the performance of any camouflage system. Numerous environmental factors are identified along with some representative values which may be used in preliminary analyses. Sources are identified for obtaining the more detailed data necessary for a good engineering design. All pertinent technology is summarized as to its concepts, implementations, and test results. These signature control techniques are:

a. exhaust suppression (additives, engine redesign)

b. canopy glint reduction (flat plate designs, baffles, anti-reflection coatings)

c. a variety of paint and coating techniques (including pattern painting, countershading, search light/glint suppression)

d. active camouflage (discrete source YEHUDI and flood-lighting systems)

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4.2.3.1 Lighting systems. Night time combat operations are a special case where the effects of the aircraft's interior and exterior lighting systems must be considered as major sources of potential visual clues to enemy forces. Exterior lights should be masked from ground angles to the greatest degree practical while providing adequate safety for formation flying. The capability of anti-collision light installations to reflect moonlight or other light sources when not in operation should also be considered to minimize such occurrences. Interior instrument lighting systems must also be considered as potential sources of light visible to the enemy. Tests have indicated that this factor can be significant in visual detection of an aircraft. Care should be exercised to minimize the direction and intensity of instrument lighting for combat missions, and to minimize the interior reflective surfaces of the cockpit.

4.2.4 Aural signature. In chapter 10 of Reference 110, the concepts and physical quantities which are relevant to minimizing the unaided aural detection of aircraft by ground observers are described. A method of predicting the range at which a given aircraft can be heard by an average listener is presented. Predictions of the acoustic levels radiated to the ground by various aircraft noise sources, and the means to estimate the major contribution of each to the total sound pressure level propagated to the observer are given. These predictions are employed in an example which demonstrates the method used to reduce the acoustic levels propagated to a ground observer in a noisy background. Aircraft noise may be suppressed by use of the following techniques:

a. Design of propeller/rotor to minimize rotational and vortex vibrational amplitude (quiet operation).

b. Design of exhaust systems to suppress hot gas noise.

c. Improvement in aerodynamic laminar flow characteristics around the airframe.

d. Use of quiet power train systems to replace conventional gearing, i.e., "V" belts, quiet gearing.

e. Operation of engine at reduced power.

4.2.5 Other detection signatures. Consult Volume 4 for other classified detection signatures that should be considered in the conceptual design of an aircraft system.

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4.3 Active mission countermeasures. Action mission countermeasures consist of means of sensing and disrupting the enemy's use of the electromagnetic spectrum, or by destroying the threat by any means. The usual objectives of disruption or destruction are denial of enemy communications, sensing and guidance functions, especially for the purpose of increasing aircraft survival by preventing encounters, denying weapon launches, spoiling weapon aim or guidance accuracy, or denying fuzing. Means for denial of these functions include (1) real (e.g., decoy) or simulated real (e.g. electronic jamming) electromagnetic signals which interfere with enemy electromagnetic signal reception; or (2) maneuvers and tactics involving multiple aircraft which tax the capabilities of the sensing and guidance systems; or (3) anti-threat weapons (lethal defense). At the present time, the ECM signals occupy the frequency domain of threat sensors and communications, including radio frequency (RF), IF, and visible. Generally, active jamming and maneuvers are involved only after threat presence and identity are established. This is the function of electronic support measures (ESM) and premission intelligence. At the present time ESM occupies the frequency domain of the threat active and passive emissions, including RF, IR, UV and visible. With the exception of lethal defense, the text of this section was extracted verbatim from Reference 110. This document provides the basic design rules for observable and active countermeasures and was prepared by the Joint Technical Coordinating Group on Aircraft Survivability. Almost all of the introduction of that document is included in this document as it provides an accurate and convenient summary of the contents thereof.

4.3.1 Threat detection.

4.3.1.1 RF passive warning and identification. Chapter 11 of Reference 110 describes methods and techniques of radar, guidance and command/control signal interception, detection, and analysis as practiced for quick reaction, defensive countermeasures, and evasive maneuvers. Included are crystal video, superheterodyne, and instantaneous frequency measurement (IFM) receiving techniques. The threat identification portion describes identification of threat emitters by means of signal parameters such as RF, pulse repetition frequency (PRF) or pulse repetition interval (PRI), scan rate and modulation, and pulse width and rise time, as well as statistical signal analysis techniques for unique emitter separation in dense pulse environments.

4.3.1.2 RF active warning. The terminally guided missile is a growing threat to air superiority because of its potential to limit the free movement of aircraft. Chapter 13 of Reference 110 identifies the threat missiles, providing data relative to their characteristics, and discusses detection ranges and search times of active warning systems. Range and velocity resolution relative to signal processing is discussed in Reference 110. Antenna backlobe requirements are given in the general discussion of backlobe clutter, A discussion of range and Doppler ambiguities relates to the closing velocity of air-to-air and ground-to-air missiles. The chapter completes the overall discussion of RF action warning by addressing the areas of coherence and spectral purity, radar frequency tradeoffs, RCS, the complexity of processing, and the factors affecting choice of frequency.

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4.3.1.3 IR/optical/ultraviolet (UV) warning. Because of its classification, the description of these detection devices is included in Volume 4. Also see Reference 110, chapter 12.

4.3.1.4 Systems for location of active threat transmitters. Chapter 14 of reference 110 describes techniques that can be used in airborne systems to locate radiating transmitters. Primary consideration is given to systems that use direction of arrival (DOA) , time of arrival (TOA) , or differential Doppler (DD) measurements. For each measurement type, the different possible system configurations and computation algorithms are described. The error sources for each system are discussed and error analysis methods for computing the transmitter location accuracies are given,

4.3.2 ECM/onboard.

4.3.2.1 RF noise jamming, As ECM has progressed from art toward science, a variety of techniques for generating noise jamming signals have evolved. These techniques include direct noise amplification (DINA), FM by sine plus noise, pseudorandom noise, and digital noise. Considerable confusion exists with regard to the relative merits of the various noise techniques due to the difficulty of quantifying noise transients, nonlinear effects in nonideal components, and normalizing tests and data which include a human operator. During the past 5 years, substantial emphasis has been placed on the quantitative measurement of manual target detection and the tracking capability of a human operator in various ECM environments using displays associated with simulated scanning surveillance and tracking radars.

Chapter 15 of Reference 110 defines noise, describes techniques to generate signals which produce noise at the output of a radar IF amplifier, and summarizes the significant quantitative testing which has been performed. A short appendix is included in Reference 110 with some simplified rules of thumb for transient analysis.

4.3.2.2 RF deception jamming. Chapter 16 of Reference 110 is organized to provide information on deception ECM (DECM) techniques. In this chapter essential elements common to a basic technique and its variants, as well as special requirements for a particular variant, are identified and assessed. The essential elements include technique operation, victim system, anticipated effects and measured effectiveness, applicable ECCM, deployment requirements, and technical requirements for implementation. This last element has traditionally imposed a significant constraint on DECM technique development. Thus, it is particularly appropriate to identify the technology constraints on a technique-by-technique basis. The second section of this chapter cross--references the basic DECM techniques by generic type of victim system; monopulse, track-while-scan, conical scan, or by DECM objectives; delay detection, break track, and degrade intercept. This approach also provides a convenient method for summarizing the important aspects of each technique, which is accomplished in the section. The final section details the equations used to develop basic DECM requirements, such as jam-to-signal (J/S) ratio, power, gain, and isolation.

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4.3.2.3 Adaptive power management. Chapter 17 of Reference 110 describes the concepts and implementation methods of adaptive power management as applied to penetrating aircraft protection. It defines the problem, and provides a generalized solution to real time jamming control for optimally jamming the highest priority threat systems in the environment while maintaining efficient jamming against lesser priority threat systems. Adaptive power management is not a jamming modulation technique, rather it is a mechanism for applying fundamental jamming techniques in an organized manner to counter a relatively dense electronic enemy environment.

4.3.2.4 Infrared jamming. Chapter 18 of Reference 110 provides engineering details on IR radiation> detection, transmissions the spectral radiant intensity of an aircraft, scattering effects, and design parameters and requirements for incorporation of several jamming techniques.

4.3.2.5 Active optical countermeasures. Countermeasures against visual band systems are described in chapter 19 of Reference 110. A classified summary of the chapter is contained in Volume 4 of this report.

4.3.2.6 Communications countermeasures. Although GCI radar equipment may detect and locate approaching aircraft as they enter a defense area, it is not probable that the interceptor pilots will locate the penetrators if they are denied the necessary guidance data by the application of communications countermeasures. By the use of communications jamming equipment, therefore, it should be possible to increase the survivability of the penetrating aircraft by reducing the chances of counter attack by airborne interceptors. To effectively interfere with enemy communication.s systems, however, it is necessary to address a number of technical problems. Countermeasures equipment should be designed to minimize interference to friendly communications systems and allow for possible ELINT activity without compromising the effectiveness of the jammer system. Future equipment must be capable of countering all methods of transmitting voice or data link messages whether these methods involve simple AM or advanced spread spectrum techniques, Communications jammer design criteria are described in chapter 20 of Reference 110.

4.3.2.7 IFF countermeasures. Chapter 21 of Reference 110 describes techniques for jamming enemy IFF systems. A classified summary of that chapter is provided in Volume 4 of this report.

4.3.2.8 Fuze countermeasures. Applying the countermeasures to the fuze of an antiair weapon, the effectiveness of that weapon can be completely negated. Effective fuze countermeasure techniques require detailed knowledge of the threat to be countered and of the mission to be flown. Chapter 22 of Reference 110 describes the operating characteristics of most known fuze types and suggests areas of susceptibility. A general description of two Soviet fuze systems and their susceptibility to countermeasures is included.

4.3.3 Electronic countermeasures/expendable.

4.3.3.1 Chaff. Chaff is a general term used to refer to multiple radiation elements that scatter incident electromagnetic energy in all directions in an approximately uniform pattern. Chaff may consist of resonant dipoles

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which are roughly one-half the wavelength of the radar frequency, nonresonant streamers, or rope which are many wavelengths long, or special elements. In general, many resonant elements are deployed and each returns a signal to the radar where they are added vectorially to produce a signal whose amplitude and frequency vary with time. Chapter 23 of Reference 110 describes the pertinent chaff factors, including frequency responses, deployment requirements, and effectiveness against a variety of radar sets and missiles. The discussion on dispensing techniques includes electromechanical, pneumatic, pyrotechnic, rocket, and special considerations. The chapter concludes with a discussion of the various chaff materials that have been investigated, and a final paragraph on special chaff.

4.3.3.2 Aerosols. Chapter 24 of Reference 110 is an overview of the subject of light scattering based on the theorems of Rayleigh and Mie. The treatment emphasizes the development of controlled systems based on the utilization of light scattering principles. The concept of refractive index as a complex function is defined, followed by a brief description of the scatter of light by single spherical particles for the cases of small and large particles with real, complex, and so-called infinite refractive indices. The special case of diffuse reflectors is also included. This is followed by a consideration of the properties of aerosol clouds which includes the scattering properties of clouds, the attenuation of light by particulate clouds, methods of particle preparation and cloud generation, and aerosol cloud stability. The body of the chapter concludes with a description of applications of aerosol clouds to the defense or protection of aircraft and other military systems. Three appendixes have been added which define the scattering functions, list representative sources of light scattering computer programs, and indicate sources of aerosol materials. The chapter is limited by the relatively small amount of published information on aerosol applications to military systems. No attempt has been made to discuss the optics of long cylinders which play an important role in microwave defense, or in the scatter of thin platelets. The latter, together with the hollow microsphere, merit careful investigation when material weights are serious considerations. Throughout the chapter, the practical utility of light scattering technology is stressed. An effective technology must recognize the importance of adequate control of the major parameters, and particularly, the coordination of the systems with the micrometeorology of the environment.

4.3.3.3 Active expendable countermeasures. In recent years, the use of expendable countermeasures that employ active radiating devices has received considerable attention as a supplement to onboard countermeasures and passive expendable countermeasures. Active expendable countermeasures derive their primary utility from the fact that physical separation between the active expendable device and the penetrating aircraft permits the range between threat radar and active device to be shorter than that between threat radar and aircraft. Thus, the power requirements for the expendable ECM device are less than for onboard ECM. Also, the physical separation between aircraft and active ECM device permits real angle deception. An active expendable

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countermeasure usually requires the following four elements: (1) delivery vehicle, (2) dispenser, (3) payload, and (4) deployment. In chapter 26 of Reference 110, design and tactics considerations, and typical operating characteristics and conditions in each of these areas are discussed. In the final section of chapter 26, the methods for evaluating the cost-effectiveness of active expendable countermeasures are examined from a modeling viewpoint and from a flight-test viewpoint.

4.3.3.4 Optical and infrared decoys. Descriptions of optical and infrared decoys are provided by chapters 25 and 27 respectively, of Reference 110. Classified summaries of those chapters are included in Volume 4 of this report.

4.3.4 Lethal defense. Methods for suppressing enemy anti-aircraft weaponry generally include one of the following: aircraft mounted guns, missiles, rockets, or other guided munitions. Aircraft design implications to accommodate such armament are fully described in Reference 201.

4.3.5 Tactics/performance. Previous pages have described individual countermeasure techniques which can be used effectively against individual threat sensors. However, a battle rarely consists of an isolated confrontation between one type of offensive and defensive element. There will usually be an offensive force mix which requires the use of a combination of countermeasures or penetration aids. Chapter 28 of Reference 110 describes the rationale for penetration aid mix selection and recommends employment tactics. Chapter 29 of Reference 110 provides Navy countertactics against surface-to-air weapon systems. The development includes determining the impact of offensive force composition and countermeasures on defensive element capabilities. Defense reactions such as using alternate data sources and employing alternate tactics are postulated for each countermeasure/defensive element combination. Penetration aid mixes and employment tactics are developed and recommended by determining which countermeasures will complement each other to significantly increase mission success. Speed, altitude, and maneuverability are important aircraft performance parameters that tax the capabilities of threat acquisition and guidance systems, resulting in fewer weapons fired, and degraded weapon accuracy and kill probability.

4.3.6 Aircraft RF system integration. RF/ECM system performance is largely determined by the antenna system performance, which in turn is highly constrained by physical laws of electromagnetic and the presence of other RF devices. The aircraft environment and desired mission capabilities dictate requirements for the ECM antenna system. Chapter 30 of Reference 110 presents guidelines to aid ECM system engineers or program directors in choosing an antenna system. For specific antenna design, detailed references should be made to the bibliography provided. The goal of this chapter is to prevent engineers with little practical antenna design knowledge from choosing impossible antenna concepts and expecting unrealistic performance. Chapter 37 of Reference 110 provides the EW system engineer with the design and analysis tools necessary to achieve noninterfering, compatible operation between FCM (and other) transmitters and the other avionic receivers on the aircraft. In addition to system compatibility, the chapter also includes a discussion of

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system integration, whereby the integration of common functions among several equipments can be used to improve performance and/or to reduce costs. Compatibility is treated through a detailed analysis of the design factors that make up each of the three elements of the basic isolation equation; that is, the interfering signal power transmitted, the receiver susceptibility, and the isolation between them:

a. The power level of the transmitted jamming signal is set by the system requirements and cannot be lowered; however, all other related extraneous transmissions should be minimized or eliminated. Both design estimates and typical measurements for such unwanted transmissions as harmonics, intermodulation products, and thermal noise are given, as well as ways to minimize them.

b. Methods for calculating the susceptibility to noise interference are given for various types of receivers. While susceptibility is related to sensitivity of a receiver, it is not directly equivalent to the sensitivity and varies with the type of receiver and the type of interference. The signal distortion effects of repeater jammers are also analyzed.

c. Methods are given for calculating isolation, including the effects of near-field coupling, transmission around a curved fuselage, and coupling around corners and other obstructions. Methods are also given for increasing isolation in both new designs, and in existing installations. For the situation where adequate isolation cannot be achieved, noise cancellation techniques and various blanking methods are described. Procedures are given to establish minimum look-through times, and to calculate degradation due to the blanking duty cycle.

d. The chapter concludes by discussing the shared use of components such as general-purpose computers, transmitter exciters, and antennas to reduce avionics cost and size. The use of shared functions, such as modification of radars for passive threat detection, is also described.

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4.4 Ballistic laser protection methods.

4.4.1 Redundancy/separation. One of the basic methods to minimize aircraft losses is to provide duplicate, or redundant, systems to perform essential functions, This technique is also used for safety and reliability reasons. For survivability against hostile ballistic weapons, however, consideration must be given to adequate separation and mutual masking of redundant systems to minimize or prevent system failure or malfunctions from single or multiple hits from a given direction. All major subsystems may use this technique. For example, multiple engines, fuel sump tanks, and control linkages provide redundant systems that permit the aircraft to function when one system element has ceased to function after a projectile impact. The separation portion of this technique must be carefully evaluated for each application to obtain the most beneficial amount of inherent masking from structure and noncritical aircraft equipment. Masking can minimize or eliminate the need for parasitic armor that may otherwise be required to provide an acceptable level of survivability. The designer must consider not only the response of the system to the projectile impact, but also the secondary hazards that may also be initiated. These include fire, explosion, release of toxic or corrosive materials, spallation, and malfunction of related subsystems.

4.4,2 Isolation. In many instances, survivability of an aircraft can be increased by isolating a sensitive essential subsystem from areas of potential hazards that may readily be generated by a ballistic impact. Conversely, isolation of potentially hazardous materials such as fuel, munitions, oxygen, and high-pressure components in areas of low sensitivity should also be considered. In the first case, each subsystem should be examined to determine its most sensitive elements and the types of conditions that may cause it to fail, malfunction, or create a hazardous condition due to ballistic impact induced response. For example, flight control hydraulic lines should be isolated from areas where high-temperature gases would be liberated by ballistic damage. For the second case, fuel, lubrication, and hydraulic systems should be located in areas where leakage or vapors caused by projectile damage will not readily propagate to high-temperature ignition sources.

4.4,3 Damage tolerance. Two basic techniques have been developed to limit and/or minimize the primary and secondary damage mechanisms that can be generated by projectile impacts. Damage tolerance is an application of design techniques and appropriate material to construct essential structure and components in a manner to accept some degree of physical damage without impairing their capability to perform their functions. This is accomplished by providing redundant load paths, high-fracture-toughness materials, large-diameter and thin wall control rods, composite materials bellcranks and cable sectors, and high-temperature tolerance features. The majority of specific applications of this technique are contained in the structure> flight control, and fluid power design sections. It is one of the primary techniques that should be considered in the design process, since it can provide a significant degree of survivability improvement for the least weight and cost penalties.

4.4.4 Ballistic resistance. Ballistic resistance is a design technique to defeat the projectile's capability to penetrate the component. Material selection and construction features are primary considerations. The example

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of a current research effort to construct a damage-resistant transmission oil sump from dual-hardness steel armor material is an illustration of this procedure. It provides ballistic protection to the unit while acting as integral armor. Detailed examples of such techniques are contained in the appropriate subsystem design sections.

4.4.5 Delayed failure. The choice of construction or system operating media materials can have a significant influence in minimizing aircraft vulnerability to weapon effects. This consideration must be made early in the design effort to take advantage of such benefits. For structural elements and subsystem components that must retain their load-carrying integrity, high fracture toughness materials should be selected to prevent or limit crack propagation following damage from a projectile impact. Selection of transparency materials should be made to prevent or minimize shattering, spallation, and/or loss of essential visibility for the crew. Other considerations may be the selection of high–temperature-tolerant materials in areas where the component or structure may be exposed to fire or hot gas “torching” as a result of projectile hits. Within the crew areas, nonflammable, nontoxic, and non-smoke-producing materials should be selected to minimize secondary hazards from ballistic and HEL threat damage.

4.4.6 Leakage suppression/control, One of the most significant hazards that can be initiated by weapon effects/ballistic damage is the liberation of flammable, toxic, or corrosive fluids that are used for the operation of military aircraft. There are two basic techniques that can be used to prevent or minimize dangerous consequences that can develop from ballistic impact: leakage suppression and leakage control.

4.4.6.1 Leakage suppression. Leakage suppression is a technique that uses self-sealing materials designed to accept a degree of ballistic damage, and seal the damaged area with little or no leakage from the fluid container. This serves two basic purposes: (1) the fluid is retained for its intended use, and (2) suppression of the liberation of the fluid to areas where fire, toxic products, smoke, or corrosive reactions may be generated that could endanger the crew or normal operation of essential subsystems.

4.4.6.2 Leakage control. Leakage control is a technique that may be used to handle and direct liberated fluids or vapors in such a manner that danger to the aircraft and crew is minimized. This technique includes sealing of sensitive or ignition-producing areas, drainage provisions, flow diverters, and venting features.

4.4.7 Fire/explosion suppression. Fires and/or explosions are serious threats to aircraft survival. They can be initiated by direct or secondary weapon effects. Each is the result of a combustion process where three basic elements are present: oxygen, flammable material, and an ignition source. An explosion is a specific-form of a fire where extremely rapid burning of flammable vapors causes high gas pressures to be generated within a confined space. Suppression or prevention of fires or explosions requires either prevention of ignition or suppression of the flame-front propagation once ignition has occurred. For flammable fluids, such as jet fuel, hydraulic oil, and

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lubricating oil, ignition can be prevented by techniques that do not permit the ratio of fluid vapor and air that will support combustion to occur. Where there is excessive air in ratio to fluid vapor, an overly lean condition is said to exist. Where the ratio of fluid to air exceeds the combustion limits, an overly rich condition is present. Forced venting of leakage-potential areas is another method that can be used to remove combustible fluids and vapors to create an overly lean condition. Minimizing the spaces available for fire acts as a suppression technique when it will hamper flame propagation. Inerting vapor areas within fuel containers is an effective means of preventing fires and/or explosions. The use of a noncombustible gas, such as nitrogen, is one such technique. The use of reticulated (open pore) foam is a recently developed technique. It acts as a three-dimensional "screen" that prevents propagation of a flame front. For void areas external to fuel tanks, sponge-type plastic foam may be used to prevent ignition or propagation of fuel fires, Another technique is the use of a fire detection and activation suppression system. A sensor detects the ignition of the material within an area and transmits a signal to actuate the suppression device which, in turn, forcibly applies suppression material in time to prevent propagation of the flame front before it can develop into a sustained fire. Details on the techniques described herein are contained in Section 3.4 of this volume (Fuel System) since fuel systems constitute the largest portion of flammable materials in military aircraft.

4.4.8 Fail-safe response. Once the vulnerable subsystems and their components have been identified, their response to weapon effects must be analyzed. This analysis should examine the types and extent of damage that could be experienced, and should consider methods of preventing or minimizing identified unsafe or hazardous conditions. This is the basic objective of fail–safe response techniques as applied to survivability, and it may be integrated with reliability and system failure mode and effects analysis where similar factors are considered. The criteria for fail-safe response are similar for each of these specialties, with the major difference being the cause of initial failure. For survivability, it is the primary or secondary weapon effects; for reliability, it is material failure; and, for safety, it is a nonhostile, hazardous environment. An example of fail-safe response is the incorporation of an engine fuel control that will automatically position itself to a predetermined power setting if the throttle control linkage is severed. This technique can be applied to all subsystems, and is a technique to which each designer can apply his knowledge and ingenuity in providing fail-safe features with the least penalties. Other examples of this technique include:

a. The design of hydraulic accumulators that use high-pressure gas charging, with pressure-limiting valves or blowout plugs that will prevent explosive disintegration of the gas pressure section when exposed to fire or high temperatures

b. The design of essential gearboxes and bearings to operate for extended periods when loss of lubrication has been experienced

c. The design of multiple-load-path structure which provides fail-safe protection by preventing catastrophic failure when a load path is severed or severely damaged,

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4.4.9 Masking/geometry. The protection of aircraft personnel and flight/mission-essential components, when exposed to hostile weapon effects, is vital. Reduction of the effects of projectile impacts on the aircraft is a method to enhance survivability, and can be accomplished by a combination of techniques, including inherent masking, redundancy, separation, isolation, damage tolerante/resistance, leakage suppression, minimized detection, and the use of integral or parasitic armor if necessary. How these methods can be used, either independently or in combination, must be considered in the initial design effort to eliminate the need for, or to minimize the amount of, armor required to supplement the other techniques.

4.4.10 Armor. The structure, consumables, and components of an aircraft system can act as a barrier against weapon effects to protect personnel or flight/mission-essential components, The technique of inherent masking is to arrange elements in a fashion to obtain the most protection with the least penalties, and to incorporate the protection with the rest of the design requirements. For example, providing heavy structure around the crew station for crashworthiness considerations can, at the same time, provide some inherent masking against hostile threats from those directions that are likely to be experienced under combat operations. Similarly, less essential components or consumables can be judiciously placed to eliminate or minimize the amount of armor material or other techniques that would be required to achieve a given level of protection. Figure 4-4 and 4-5 show a representative design configuration where structure, noncritical components, and fuel act as inherent masking against a large segment of expected attack aspects. When using this technique, the designer must also consider the accessibility of the elements being masked. The gains in ballistic protection must be balanced against the time and effort required to maintain the aircraft in both peace time and combat operations to determine the most effective design configuration. The value of various aircraft structures and basic system components can be approximated by use of the penetration equations contained in Section 6.2 of this volume. These equations cover both solid and liquid materials. Taking advantage of inherent masking will minimize the amount of additional material, or armor, needed to defeat a specific hostile threat level.

4.4.10.1 Protection against high explosive threats. Criteria for armor protection against high explosive threats should be established during preliminary design. A predetermined range from the hostile gun system should be selected to represent the distance at which the majority of combat encounters would occur. This range establishes the baseline requirement for protection. Penalties incurred for protection at near muzzle velocities should also be examined to provide comparative data. Protection against the high explosive threat can be accomplished for relatively modest penalties. One important factor is to employ design features that cause delay fuze time to be minimized and cause projectile detonation in the least distance. When this can be accomplished, the resulting fragments and blast effects can be defeated with minimum aircraft penalties. There has been significant progress in the development of light weight armor materials and systems within the past few years. These advancements have indicated that high levels of ballistic protection can be achieved for reasonable weight and cost penalties.

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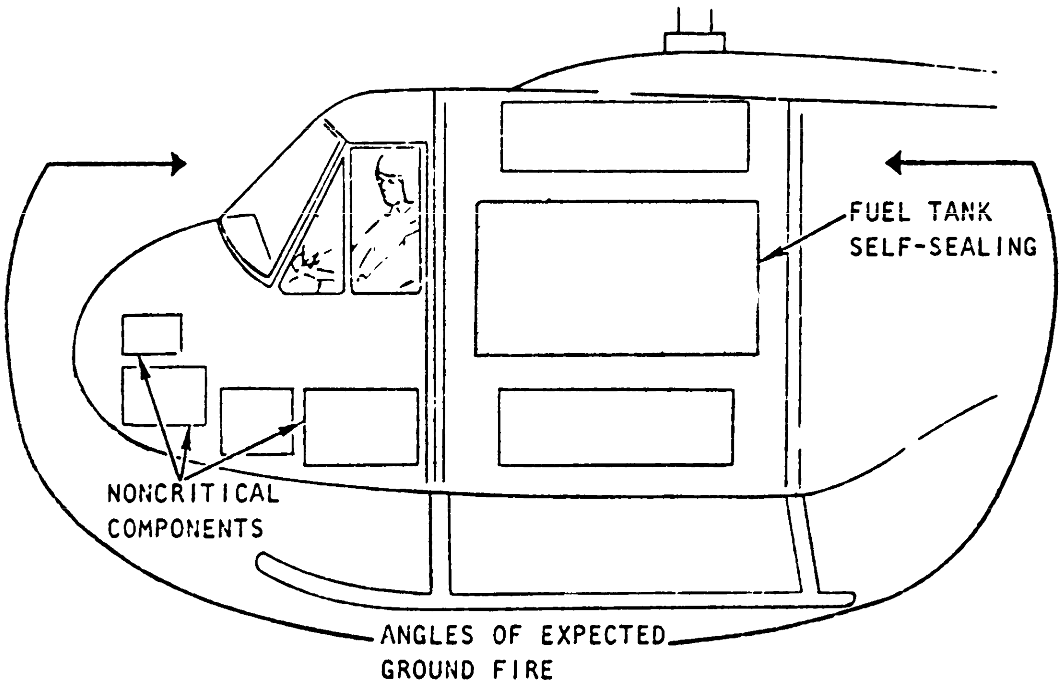

FIGURE 4-4. Inherent masking.

4.4.11 Laser protection methods. Most aircraft material are opaque to laser radiation. When a high energy laser beam impinges on the surface of an opaque material the surface heats rapidly. The rapid surface heating can be followed by one or more high temperature effects such as emission of intense visible light, melting, vaporization, charring, spalling, burning, tearing, or cracking of the material. When the high energy laser beam is maintained on a material for a sufficient length of time, a hole will be formed, allowing the high energy laser beam to impinge on internal aircraft components behind the hole. Secondary effects such as structural failure, ignition of fuels or other flammable materials, component kill or wounding of the crew can occur as a result of these primary or secondary effects. The state of the technology in the laser area is relatively new and is changing so rapidly that discussion of the threat and aircraft hardening techniques would be out-of-date before published. The user is referred to AFWL/PGV for device, beam and vulnerability details and to AFML/LPJ for details on passive hardening techniques and materials.

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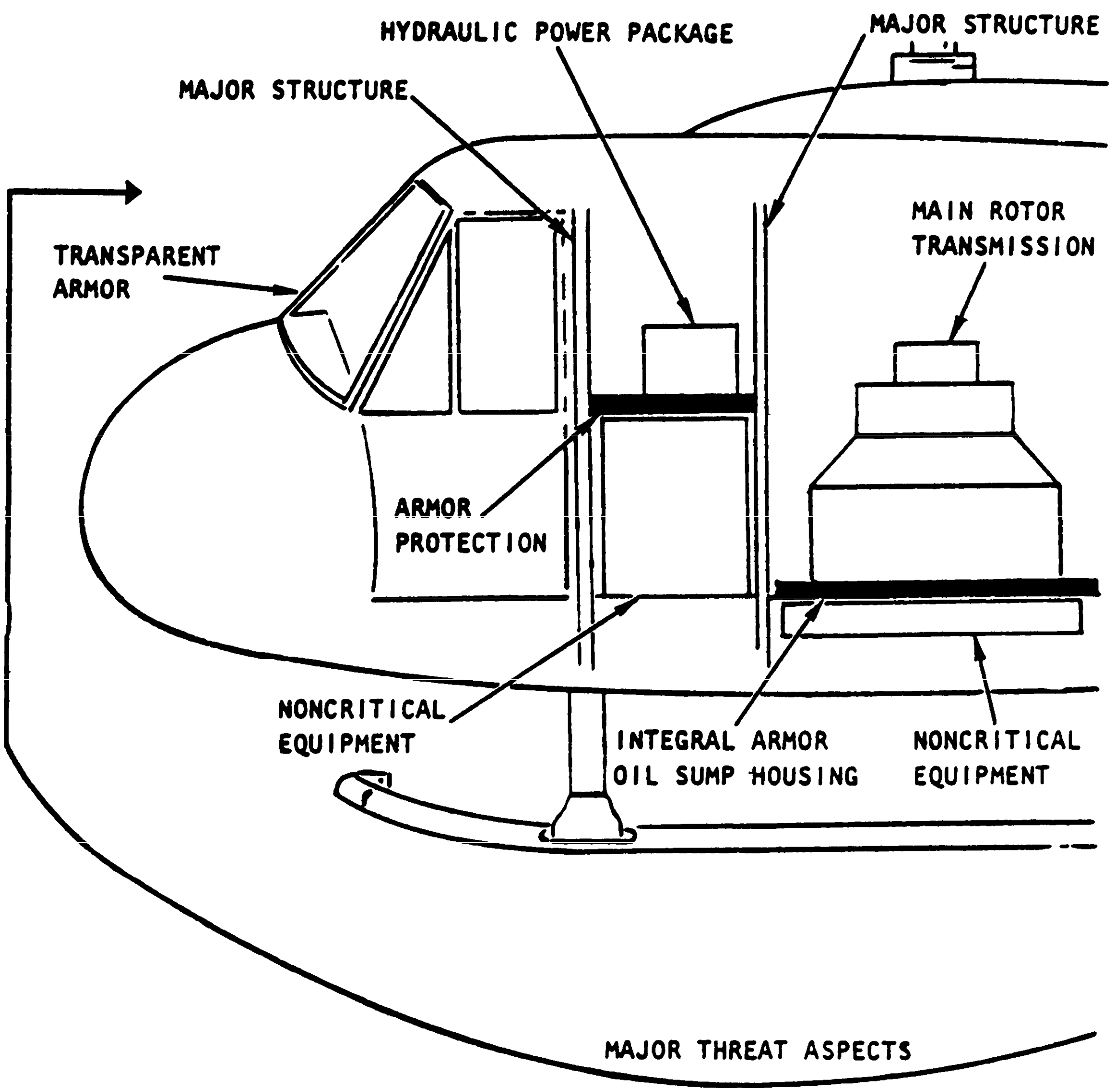

FIGURE 4-5. Masking and armor protection.

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4.5 System operational factors. One of the areas of growing concern in the design of new military aircraft, and for existing operational systems, is their "Cost of Ownership." This includes not only the acquisition costs of an aircraft system, but the operational costs as well. Over the past decade there has been a dramatic increase in the operational costs compared to the acquisition costs for military aircraft systems, focusing greater attention on those elements that are major contributors to operational costs during combat and peacetime operations. As the sophistication of a system increases, its operational costs rise dramatically. The S/V design engineer must consider the impact each survivability enhancement technique can have on the elements that affect this cost of ownership. These costs include repairability/maintainability, safety, logistics, and system reliability. Each of these subjects must be carefully evaluated during the design process to ensure that sufficient data is obtained for a valid system/cost effectiveness analysis that will provide the design manager with the proper information required to guide the system development. A survivability enhancement technique may be very effective against a particular hostile weapon effect, but impose such severe penalties for maintenance and logistics, that the total effectiveness of the system would be degraded to an unacceptable level. This section contains basic identification of the major areas of concern for most military aircraft systems. However, each individual system must be analyzed separately to ensure that the influence of each operational factor is properly considered.

4.5.1 Repairability/maintainability. The maintenance and repair of military aircraft systems is a major element of operational costs for both peacetime and combat missions. The normal peacetime repair and maintenance expenditures for a military aircraft can be affected by the types of survivability enhancement features incorporated into a system. These factors must be carefully considered in the design concept or modification design process. An S/V feature may be very effective against a particular hostile weapon effect, but impose such severe penalties on logistics, repair efforts, and maintenance man-hours, that it makes it too expensive from a life cycle cost standpoint. The designer and system manager must evaluate the impact of each S/V feature on the normal maintenance and repair factors for both operational base and depot level facilities. One of the areas of primary concern is the maintenance of aircraft structures to prevent corrosion. For nearly all types of military aircraft, corrosion control and repair accounts for approximately half of the total structural maintenance and repair efforts (Reference 122). Moisture accumulation or entrapment is one of the major contributors to the initiation and propagation of corrosion within an aircraft's structure. Primary attention should be directed to this factor in the selection and installation design details for all candidate survivability enhancement methods. Recent combat experience has revealed that significant efforts were required to repair battle damage on military aircraft (references 61 and 98). These studies indicate that appreciable reductions of repair times can be realized through the use of various techniques and proper consideration of their application in the design process. Studies have shown that structural repair is the most predominant factor in battle damage repair since it comprises the greatest total area of all the subsystems and has the least number of line replaceable elements. The highest repair time items (in man-hours) are castings and

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forgings that are not amenable to local area repair, and therefore require replacement. The major factor in calendar repair time for aircraft is the procurement time for replacement parts or components and specialty fasteners. Figure 4-6 shows an example of a process that may be used to incorporate battle damage repair considerations into an aircraft system.

4.5.1.1 Design criteria procedure. The candidate battle damage repair techniques (block 1) are used together with the damage mechanisms (block 2) of the specified hostile threat systems in the development of the aircraft system design concepts (block 3). In this step, the configuration designer is required to examine many different combinations of aeronautical arrangements, armament carriage, landing gear geometries, and other subsystems provisions. The subject criteria allow addition of considerations for battle damage repairability to be incorporated in the evolution of each aircraft system design concept. Each of these design considerations has an impact upon the size, weight, and/or cost of the candidate aircraft design concepts and upon the operational cost of ownership. Battle damage repairability can have a significant effect upon the initial and continuing costs, yet has not been adequately taken into account to date. It is to be noted that the original design to provide a high capability in this regard will also frequently yield side benefits in other system engineering disciplines, (as in safety, survivability, normal maintenance, and logistics) and could lead to marked improvements because of this synergism. The designer seeks to obtain the configuration most effective in meeting the specified operational purposes of the system for the least life cycle cost by selecting and evaluating various combinations of design features. The result of these efforts is the identification of the baseline design concept (block 4), being the one considered to have the highest percentage of desirable features. After selection of the baseline concept, detail design of the structure and subsystems is initiated (block 5). In this step, more detailed battle damage repair design techniques must be considered and evaluated (block 6). A failure mode and effects analysis (FMEA) must be conducted as part of the evaluation. This step aids in determining the collateral (or secondary) damage that may be experienced by other components through the failure, malfunction, or secondary hazard generated by the damage inflicted on the initial component. The evaluation process is iterative and is repeated until the most effective combination of design features is obtained. The production design of the aircraft system is the product of this process (block 7). As with other segments of the design program, the results of the design refinement with respect to battle damage repair should be documented, and validation tests and/or analyses conducted.

4.5.1.2 Documentation. The documentation of battle damage repair should include a relationship to the levels of hostile weapons effects considered so that operational effectiveness and cost of ownership of the aircraft system may be determined for the designated range of combat operations. Figure 4-7 shows an example, in the form of a representative summary, or repair factors that are considered significant. The factors shown include only the estimated man-hours (MH) and elapsed time (ET) estimated for the repair. They do not

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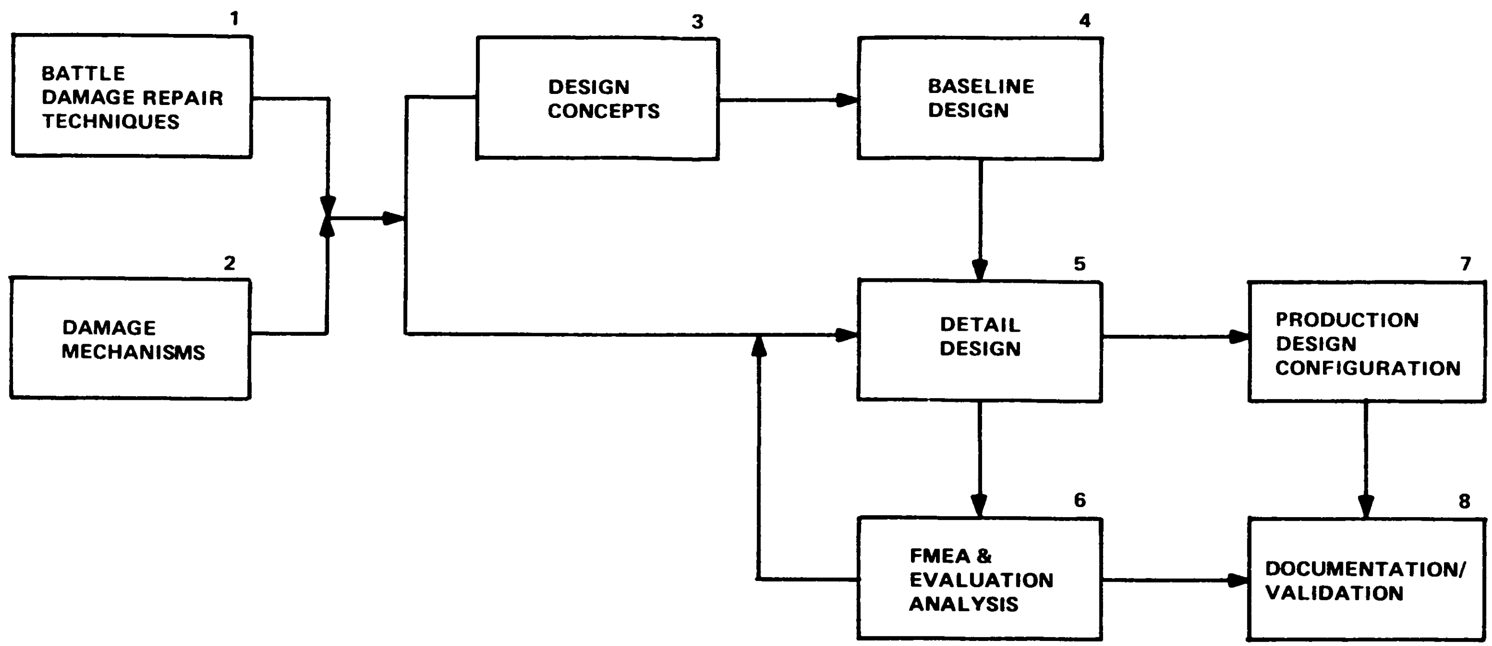

FIGURE 4-6. Battle damage repairability design criteria procedure.

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ACTION TAKEN	ESTIMATES			
	SEQUENTIAL		CONCURRENT	
	MH	ET	MH	ET
Damage Inspection (Total)				
Remove Parts for Access				
Repair in Place				
Remove and Repair				
Remove and Replace				
Function Test Part				
Reinstall Access Parts				
Corrosion Control				
Inspect Repair (Total)				
Function Test Subsystem				
Function Test Aircraft				
TOTALS				

FIGURE 4-7. Battle damage repair factors example.

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include the cost of materials and fabrication of repair parts. In the example, the action taken includes the following:

a. Damage inspection (total) - The total man-hours and elapsed time that is estimated to be necessary to inspect the general area for battle damage and for inspection of the damaged part(s) after access to it (them) and to the area that is surrounding it (them) has been gained.

b. Remove parts for access - The total man-hours and elapsed time to remove parts (i.e., panels, equipment, defueling, etc) to gain access to a damaged item for inspection and repair.

c. Repair in place - The man-hours and elapsed time required to repair the damaged part(s) in the aircraft.

d. Remove and replace - The man-hours and elapsed time required to remove a damaged part that is not repairable at the operational level and replacing it with a serviceable like item.

e. Function test part - The man-hours and elapsed time required to test a repaired or replaced part for proper functioning.

f. Reinstall access parts - The man-hours and elapsed time required to install those parts that had been removed to gain access to the damaged part(s) and to inspect the area.

g. Corrosion control - The man-hours and elapsed time required to treat a repaired area so that corrosion protection is maintained.

h. Inspect repair (total) - The man-hours and elapsed time required to perform an inspection of the repaired part(s) and the complete reassembly of the system.

i. Function test subsystems - The man-hours and elapsed time required to perform a required functional test of a subsystem where a damaged part has been repaired or replaced.

j. The estimate developed for each item may be identified by a work unit code (WC), and is applicable to the average damage that may be sustained as a result of each type and size of hostile weapon effect. The results of the analysis are essential to the determination of the cost of ownership and operational readiness and availability of the aircraft systems in combat.

The validation of estimated battle damage repair efforts may be included in part four of a specific aircraft system specification, and would correspond directly to a repair requirement in part three of the specification. The type of validation, demonstration, and/or analysis would be determined by the procuring agency during development of the documentation requirements for the system.

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4.5.2 Safety. System safety features for all aircraft should be carefully integrated and evaluated with survivability enhancement techniques, because the majority of safety and survivability techniques are mutually com-elementary. This is especially valid for protection against hazardous environments that can be created by either hostile or nonhostile actions. These include protective techniques for fuel or hydraulic fluid, fire or explosion suppressions crew protection against toxic fumes or smokes fail-safe structure design, redundant subsystems/components, etc. Of particular concern is crashworthiness for those aircraft that can sustain an accident where the crash forces are within a survivable level for the crew. This has been proven to be highly successful in reducing the number of casualties and injuries sustained by crew and passenger personnel in those aircraft where crashworthiness features have been incorporated. The basic principles for this technology are contained in Reference 205. This publication contains general and detail requirements for system crashworthiness that includes airframe design, occupant retention, cargo and equipment retention, post crash emergency escape provisions, and post crash fire prevention requirements and design techniques.

4.5:3 Logistics. One of the significant items in the system operating factors of a military aircraft is the cost of its logistical support. These include the cost of providing replacement parts and/or consumables required for peacetime and combat periods, special equipment for inspection, repair, or replacement, and the number and level of support personnel associated with specific design features. For candidate and competitive survivability enhancement features, their impact upon logistical costs must be considered and evaluated to determine the effect upon the total life cycle cost of the aircraft system. An area of special concern is the necessary costs of fuel, lubricating oils, and other petroleum based products. When the total lifetime operation of an aircraft system is considered, small changes in fuel consumption rates can result in significant variations in the life cycle costs. Careful attention to these factors in the evaluation of candidate survivability enhancement features is recommended.

4.5.4 Reliability. High reliability of military aircraft systems is required to maintain an acceptable operational readiness rate for peacetime and combat missions. This level of reliability must be provided with reasonable acquisition and logistical support costs. These factors must be considered in the selection and design of survivability enhancement features for military aircraft. The primary concern is the capability of the survivability feature to perform its designated function over its programmed useful service life. At the same time, the design feature must not adversely affect the reliability of other components or subsystem which could be susceptible to such conditions. For example, foam materials may be installed around a fuel tank to fill the cavity between the tankage and the fuselage skin. Care must be exercised to ensure that the foam does not act as a moisture trap that could cause corrosion of the structure and its fasteners. Each design configuration must be evaluated individually to identify the most effective combination of design features that will provide the most effective and operationally acceptable aircraft system.

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5. SYSTEM SURVIVABILITY ENHANCEMENT DESIGN

5.1 General. The survivability enhancement of an aircraft system requires careful attention and consideration in the initial design concept development process. This is the area in which the most beneficial combination of survivability design features may be incorporated into the aircraft system for the least penalties. To accomplish this objective, the S/V engineering requirements must be integrated together with those for mission profiles and performance, range, operations, safety, reliability, maintenance, logistics, etc. The configuration and subsystem design engineers must be provided the essential information on these items in a timely fashion to permit systematic evaluation and selection of the techniques most applicable to the individual aircraft system concepts and the hostile nonnuclear threat systems to which it is expected to be exposed. This section contains information and guidance on specific survivability enhancement techniques and indications of the factors related to weight, volume, and costs that must be evaluated in terms of an aircraft's system effectiveness and cost of ownership, which are major factors in the life cycle costs of a system. The information contained in this section has been selected to be representative of both fixed and rotary wing type aircraft used by each of the three major military services.

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5.2 Configuration Design. The initial design of an aircraft system begins with the establishment of the basic criteria for the operational mission it is to perform, and the natural and man-made environments that it is expected to encounter. Other constraints, such as maximum allowable weight, size, or cost may be imposed, to stay within the limits of allowable service resources and/or to be competitive with another type weapon system capable of performing the same basic mission or destroying a hostile force with different technology. A military aircraft design concept development process consists of generation of many different airframe and subsystem arrangements that are evaluated against each other. As certain concepts are selected, refined, and re-evaluated, survivability enhancement features must be part of the process to ensure that the most effective mixture of enhancement features are identified. Just as the aerodynamic, performance, weight, basic structure loads, vibration and flutter characteristics are analyzed to determine their adequacy for the established system criteria, so must the survivability characteristics be evaluated, An operational mission analysis of the aircraft system is necessary to establish the basic encounter conditions with the full range of anticipated hostile nonnuclear threats. The capability of these hostile systems to detect, identify and initiate weapon launch or activation must be carefully considered. The candidate survivability enhancement techniques that may be used to degrade the hostile systems capability must be established and evaluated for possible incorporation in each design configuration. At the same time the basic candidate nonnuclear protection techniques must also be identified and considered. The following are the basic techniques that should be considered as candidate methods in a new aircraft system design.

5.2.1 Minimized detection. Consider the methods most appropriate for each specific design concept to minimize detection by the defined hostile threat systems. The primary objective should be to obtain the most effective minimum observable first, through basic geometry and subsystems arrangements, before using those techniques that impose higher weight and cost penalties. For detailed and classified information on detection reduction methods, consult the JTCG/AS Countermeasures Design Handbook, Reference 110, Chapter 7.

5.2.1.1 Radar cross section. Consider structural shaping to produce minimum radar signatures in an aircraft design concept. Other radar signature reduction techniques, such as radar absorbent materials (RAM), ECM, chaff, aerosols, etc. , should be considered as candidate methods.

5.2.1.2 Infrared signatures. Identify the potential sources of infrared (IR) signatures, for the wavelengths established for the specific aircraft system, and evaluate the available candidate methods to suppress the IR signatures to acceptable levels. Engine IR signature suppression is described in volume 3 of this publication and should be considered by the aircraft system configuration designer. Other potential sources of IR radiation are from “hot spots” where heat is generated by operation of subsystem components such as rotary wing main rotor transmissions, and power trains, lubrication oil heat exchangers, and aerodynamic heating of the structure. Consideration for placement of these items within the airframe during the conceptual design phase can eliminate or reduce the amount of insulation, maskings or cooling flow techniques required to reduce the radiation to an acceptable value. Consult Chapter 8 of

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Reference 110 for the most current information on these methods. Sunlight glint from aircraft transparencies or other highly reflective surfaces can be sources of IR detection and tracking by threat systems. For systems designed for employment against such threats, consider concepts with minimum transparent and reflective areas. Where such areas cannot be avoided, use flat surfaces to the extent practical to minimize the angles of detection for the threat system.

5.2.1.3 Visual detection.

5.2. 1.3.1 General provisions. The majority of combat aircraft losses in the Southeast Asia conflict was due to hits from optically directed weapons firing nonexplosive projectiles, In many cases, the enemy tactic was to aim a barrage at the visual signatures of the aircraft even before the vehicle itself could be observed. This was especially experienced on fixed wing jet aircraft that emitted engine smoke trails. The reduction of this observable smoke signature is described in volume 3 of this specification. The configuration designer should consider the use or specification of jet engines with no visible smoke emissions. As with the IR glint signatures, the amount of transparencies and reflective surfaces should be minimized to prevent or minimize the visual detection of an aircraft from optically operated hostile threat systems. The use of flat transparencies should be considered in those military aircraft systems required to fly at low altitudes and speeds to accomplish their missions. Under closely controlled conditions camouflage is an effective means to reduce visual detection by minimizing the visual contrast of the aircraft with its background. The patterns and colors used for this are therefore highly dependent upon the terrain and seasonal changes in its background. Standard bright identification markings and paint with a glossy finish are also reflective and are visible for a considerable distance, both in sunlight and in moonlight. Lusterless camouflage paint should be used for the overall aircraft, with low-contrast paints for the necessary aircraft markings, except where gloss colors are required for compartment cooling. Research has also indicated that for static conditions, well chosen simple camouflage patterns are more effective than poorly chosen complex patterns. Temporary camouflage coverings, or paint, may be used to mask those transparencies not essential for specific missions. Nighttime combat operations are a special case where the effects of the aircraft’s interior and exterior lighting systems must be considered as major sources of potential visual clues to enemy ground forces. Exterior lights should be masked from ground angles to the greatest degree practical while providing adequate safety for formation flying. The capability of anticollision light installations to reflect moonlight or other light sources when not in operation should also be considered to minimize such occurrences. Interior instrument lighting systems must also be considered as potential sources of light visible from the ground. Tests have indicated that this factor can be significant in visual detection of an aircraft, Care should be exercised to minimize the direction and intensity of instrument lighting for combat missions and to minimize the interior reflective surfaces of the cockpit. When viewed directly, the exhaust glow of turbine engines can be seen readily at nighttime. For aircraft with primary missions at night, consideration should be given early in the design process to the probable viewing angles and methods of making each engine glow from the enemy.

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5.2.1.3.2 Rotary wing aircraft. To minimize visual detection of Army helicopters flying NOE, and at the same time not compromise IR requirements, it is recommended that they be painted with MIL-L-46159 (Reference 258) "IR paint" OD in color. Using this paint with a grind of O on the rotor blades has revealed some rotor blade aerodynamic performance reduction. Therefore, it is recommended that if this paint is used on the blades it have a grind of 6 to minimize this aerodynamic problem. If this grind is not available the blades should be painted with MIL-L-19538 (Reference 246) black paint. Field testing has determined that pattern painting of Army helicopters does not reduce their visual detectability when they are flying NOE in a typical temperate zone environment. Maintenance and unit markings on Army helicopters should be kept to a minimum. When absolutely necessary, they should be as small as possible and preferably painted on with lusterless black paint (Reference 246). Conspicuous markings should be oversprayed for combat missions. Other factors to be considered are:

a. The sunglint from helicopter canopies and windows has been established as an important visual detection cue. This is especially true at the extended ranges where other factors such as noise, size, shape, etc., do not play an important part in detection. Flat plate canopies and windows, if properly designed, have been found to be a viable approach in reducing this important visual detection cue. However, there are some internal reflection problems associated with this approach that dictate that this approach be studied carefully before being applied. See Reference 128.

b. In rotary wing aircraft, rotor blade “flicker” detection has been found to be higher with two blade configurations over those with four or more main rotor blades. Consider the use of multiblade configurations as a signature reduction method.

c. Helicopter rotor heads are a significant source of reflected light as well. Consideration should be given to finishes that will minimize or subdue such reflective surfaces. Rotor blade tip markings also provide a degree of visual clues, but elimination or muting of such markings must be evaluated closely with personnel safety factors.

5.2.1.4 Aural signatures. For certain aircraft systems, aural detection may be an important factor in its survivability capabilities. The primary sources for noise are listed in Table 5-I together with the general techniques that may be used to reduce their intensity. Some of the approaches to noise reduction result in reducing aircraft performance to the point that the aircraft and its parts would be scarcely moving. The degree of allowable aircraft noise depends on the ambient noise level of the listener and the distance of allowable detection. Only the noise above the level need be reduced. Thus, there is always a tradeoff between noise reduction and vehicle performance. This does not imply, however, that two vehicles with the same performance must produce equal noise. Quite the contrary, judicious and intelligent application of noise reduction techniques to an aircraft design not requiring high performance results in a design with surprisingly low noise level compared to so-called conventional designs. Consult volume 4 of this publication for classified information on this subject.

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TABLE 5-I. Noise Sources and Reduction Methods.

Type	Source	Control of Spectrum	To Reduce Intensity
Rotational	Propellers and Rotors, Fans, Compressors Turbines, etc.	RPM No, of Blades	Decrease RPM, Increase Diameter, Decrease Shaft HP, Increase No. of Blades
Combustion	Combustors, Pistons	No. Cylinders, RPM	Decrease Shaft HP, Muffle
Jet	Turbulent Mixing of Jet Exhaust	Exit Velocity Exit Diameter	Decrease Velocity, Decrease Thrust, Muffle
Aerodynamic	Wing Vortex, Boundary Layer, Wake, Cavities, Vibrating Panels	Velocity Characteristic Length,	Decrease Velocity, Eliminate Cavities Use Highly Damped Panels

5.2.1.5 Other detection signatures. Consult Volume 4 for other classified detection signatures that should be considered in the conceptual design of an aircraft system.

5.2.2 Passive protection. Configuration arrangement can be used to enhance the survivability of an aircraft system for modest or no appreciable penalties. The basic methods are:

a. Redundancy and separation of critical components or subsystems.

b. Component concentration together with natural masking and/or armor shielding.

c. Hazardous material location/containment,

d. Battle damage repairability.

5.2.2.1 Redundancy/separation. Many of the major subsystems of an aircraft cannot be designed to be completely protected against the total range of enemy weapon effects with existing technology, In these cases, duplication of the subsystem function is a method of achieving a practical, higher degree of survivability. In most cases, duplication is also made for reasons of aircraft safety and reliability, and provides the basis for integrating the requirements with each of these design specialties at the same time. Where redundancy is used for safety and reliability reasons to prevent injury, aircraft damage, and mission failures, separation and mutual masking of the

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redundant systems must also be considered for survivability against weapon effects:

a. Figure 5-1 illustrates the basic concept for redundancy, separation, and mutual masking of rotary-wing aircraft engines. The two engines are located on opposite sides of the fuselage with structure and equipment between them. This provides a natural barrier that minimizes the probability of single- or multiple-projectile hits from one direction.

b. Figure 5-2 shows a similar separation and mutual masking of a fixed-wing aircraft. This basic technique should be considered for each of the flight or mission-essential subsystems. These include flight controls, engines, fuel feed and supply, crewmembers, electrical power, hydraulics, and armament circuits.

c. Figure 5-3 shows an example of tandem seating of pilot and copilot for rotary- or fixed-wing aircraft. Armor material on the back of the pilot's seat serves two purposes. It protects the pilot from ballistic projectiles from the rear quarters and also provides frontal protection to the copilot.

d. Figure 5-4 shows an example of side-by-side seating. Separation between pilots is limited for small aircraft. Structural masking or armor between the seats can provide protection that will reduce the chances of simultaneous injury of pilot and copilot from hostile threats from the side.

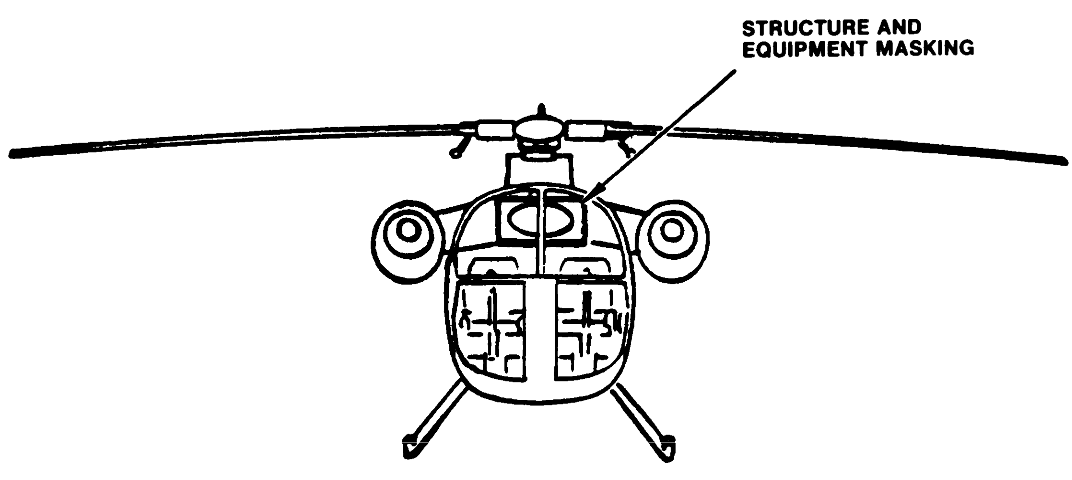

FIGURE 5-1. Engine redundancy/separation and masking on rotary-wing aircraft.

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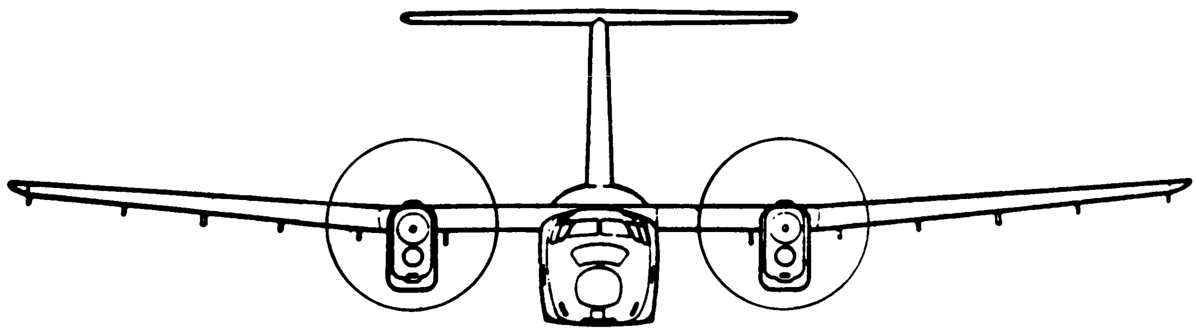

FIGURE 5-2. Separated and masked engines on fixed-wing aircraft.

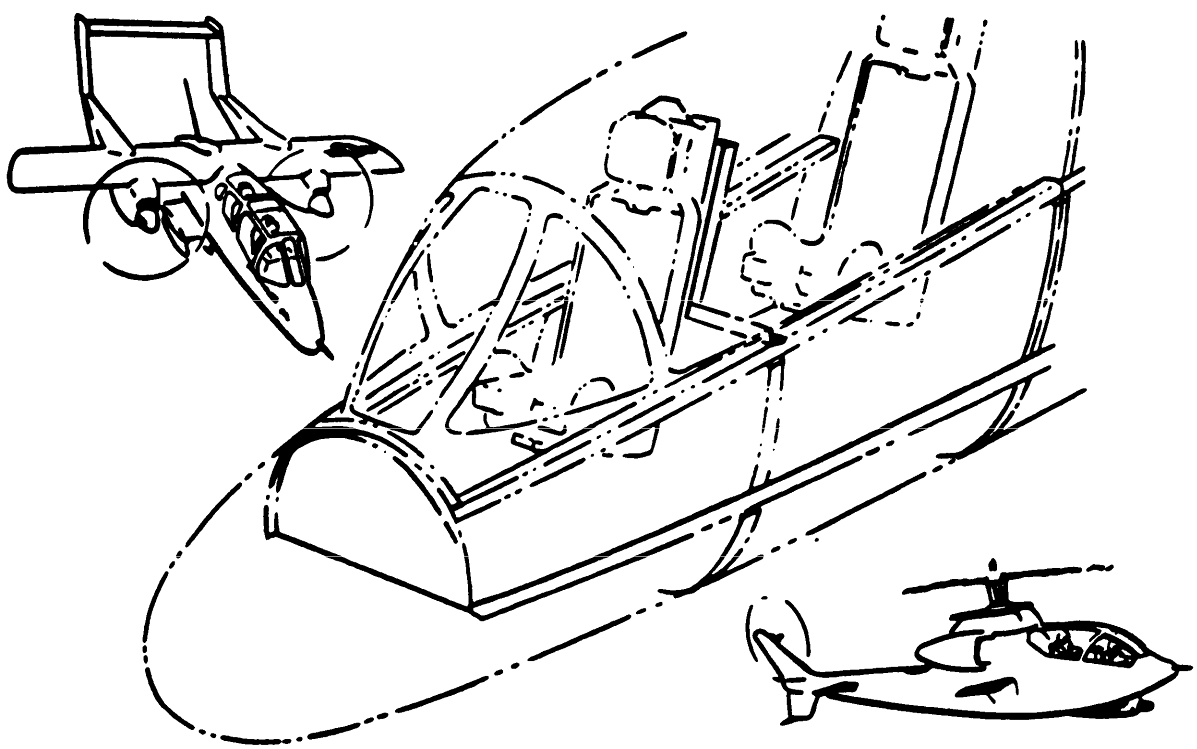

FIGURE 5-3. Redundant pilot tandem seating arrangement.

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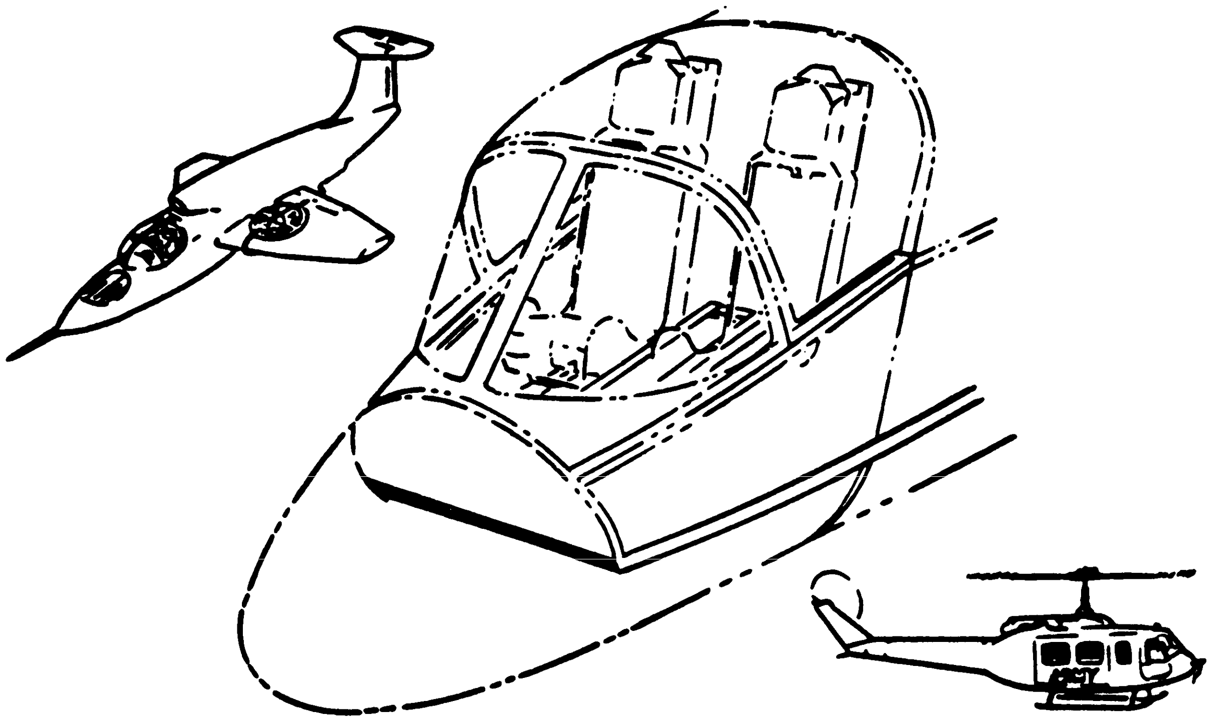

FIGURE 5-4. Redundant pilot side-by-side seating arrangement.

5.2.2.2 Component concentration and shielding. Compact grouping of critical components serves to reduce the overall vulnerable area of vehicle subsystem where they may be more effectively shielded or located to present the least vulnerable aspect to the hostile threat environment. A major objective of this technique is accessibility and maintenance requirements. The ease of accessibility should be in the same order as the frequency of servicing or replacement action. See Figure 5-5 for an example of component concentration in a ground attack aircraft.

5.2.2.2.1 Shielding. Shielding is important for the protection of aircraft critical components from hostile nonnuclear ballistic effects. There are two basic forms of shielding: inherent and armor. Inherent shielding consists of positioning the various components and elements of the aircraft with noncritical or less critical elements or areas in locations that “mask” the more critical elements or areas from the ballistic threats. Where inherent shielding, or other passive design techniques are not feasible or practical, armor should be considered for shielding the critical items. Each of these techniques will have certain benefits and penalties for the specific application and as such must be examined and compared during the initial design phase to obtain the most efficient, practical, and survivable configuration. Ignoring this procedure can result in aircraft vulnerability problems that may prove to be highly difficult, costly, or impossible to rectify when the aircraft is in production and/or service. Consider the placement of the major aircraft elements, such as engines, heavy structures fuel tankage, landing gears, etc., to achieve shielding of the critical elements from the prominent hostile ballistic

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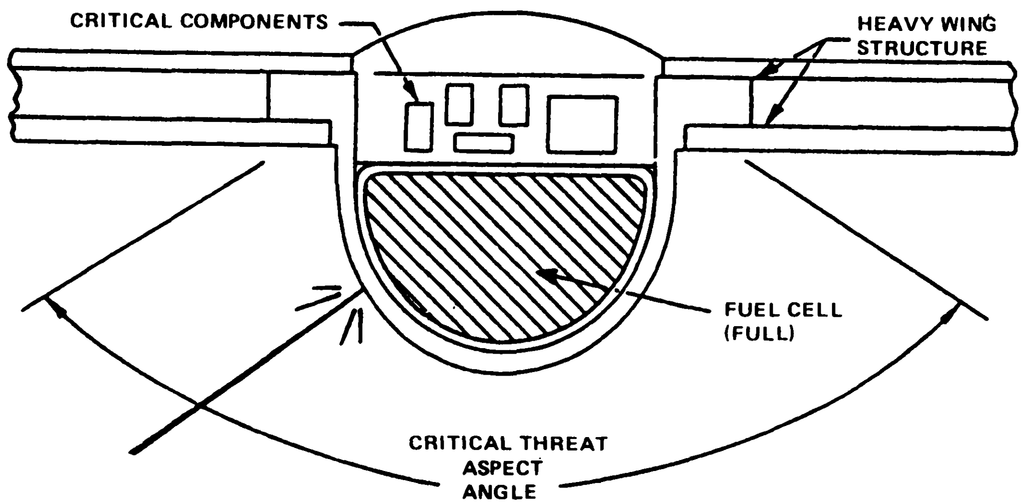

FIGURE 5-5. Component concentration technique, ground attack aircraft.

threat aspects. For example, in a ground attack aircraft design, the basic threat aspects may be from the bottom and sides. Placement of critical control elements in the upper portion of the aircraft, above heavy structure or other elements would provide inherent shielding. See Figure 5-6 for an example of this technique. In existing aircraft, inherent shielding usually can be achieved through relocation of relatively small critical components into areas where more inherent shielding is available. Use caution in applying this technique to ensure that the relocation does not expose an equally or more critical component or that the relocation does not result in a higher vulnerability of the connection circuitry between other portions of the same subsystems, the damage or failure of which would be critical to the operation of mission or flight essential functions,

5.2.2.2.1.1 Concentration. In many design areas, there are types of equipment that do not lend themselves to being designed to withstand weapon effects. Control valves, filters, pressure transducers, and gages are examples of such elements whose integrity may be vital to continued flight or mission completion. Consideration should be given to miniaturization and concentration of such subsystems within the aircraft configuration to minimize their exposure to hostile threats and the amount of HEL shielding or armor that would be required to protect them. Figure 5-7 shows an example of an integrated hydraulic system package that incorporates the reservoir, pump, filter, and control valve. The amount of armor or shielding is thereby minimized and, for the protection required, imposes a lower weight and cost penalty than a conventional installation where the system is “spread out” through the airframe and thus has interconnecting lines that are quite vulnerable and add to the problem.

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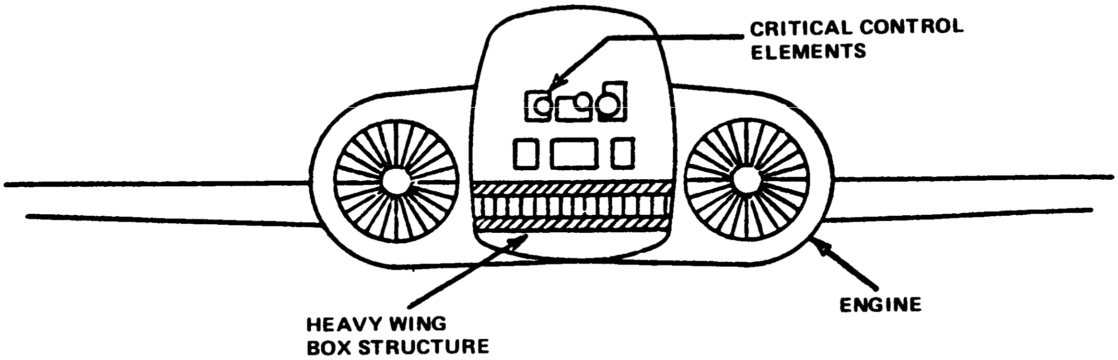

FIGURE 5-6. Inherent shielding for critical elements.

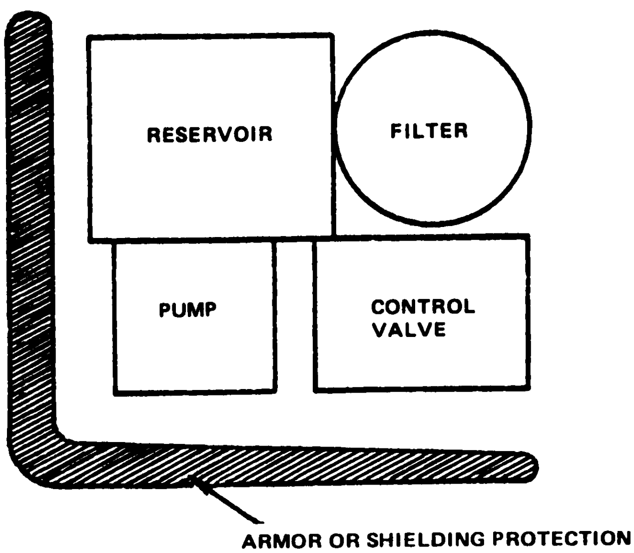

FIGURE 5-7. Concentration and shielding concept.

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5.2.2.3 Hazardous material placement/containment. Consideration should be given to the placement of hazardous materials (such as fuel, munitions, hydraulic fluid, lubrication oil, oxygen systems, and batteries) within the design configuration, and to their response to weapon fire. Provisions should be considered for rapid jettisoning of such material if containment of their response is not feasible. The consequences of their response or liberation upon the vulnerability of personnel and/or flight/mission-essential elements should be examined. Fire and/or explosion potentials of flammable fluids must receive special attention, since they generally are the major volume of such material:

a. Fuel tanks should be located so that leakage from ballistic damage will not migrate to the interior of the aircraft or to potential ignition sources such as hot engine sections, hot bleed air lines, or electrical equipment. Particular attention should be paid to the location of fuel tanks adjacent to the inlet ducts of jet engines. Massive fuel leakage ingested by the engines is capable of causing rapid engine failure and destruction. Carefully consider the benefits and penalties for such installations and the protective measures that would be required to prevent or minimize the consequences of fuel cell damage from hostile weapon effects.

b. Batteries should be located in areas where their corrosive acid will not affect personnel or essential elements.

c. Explosives, such as ammunition, rockets, and grenades, should be located so as to minimize injury or damage to the crew or equipment if struck.

5.2.3 Configuration design repairability/maintainability. One of the areas of growing concern in the design of new military aircraft is the “cost of ownership.” This covers the life cycle costs for operations, maintenance, repair, and support. As new weapon systems become more sophisticated and expensive, the cost of ownership rises rapidly. In recent years, the cost of operation and support of new systems has been found to exceed the acquisition cost of the system itself. Particular attention must be directed to this situation by the S/V design engineer, since the selection of the survivability enhancement methods for a system can have a significant effect on both the acquisition costs and the ownership costs.

5.2.3.1 Battle damage repair design concept. Recent combat experience has shown that considerable maintenance effort, costs, and time have been expended for repair of battle damage on aircraft. Research and analysis indicate that significant reductions in such expenditures can be avoided in future aircraft by application of certain criteria in the design process. This procedure provides the guidance by which the criteria may be incorporated into an aircraft system preliminary design and subsequent subsystem detail designs. The application of this procedure also requires consideration of the impact of design for ease of battle damage repair upon other system engineering specialties (safety, normal maintenance, reliability, logistics, survivability, etc.), and the resulting cumulative influence upon total system effectiveness and life

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cycle costs. The basic principles discussed herein have been developed from the research and analysis of battle damage repair actions on a number of aircraft types. As newer and more advanced types of aircraft structure and subsystem components and materials are developed, battle damage potential and repairability of these new elements must be determined and verified. Effectiveness of the new aircraft system may be seriously impaired in a combat situation if these aspects are inadequately considered. Analysis indicates that employment of these principles will also provide significant savings of manpower and materials for normal peacetime maintenance and repair.

5.2.3.1.1 Preliminary design. Preliminary design is defined as that portion of the design process where the basic aircraft system concept is established. This includes the fundamental geometric and aerodynamic shape of the airframe and placement of major subsystem elements such as aircraft engines, fuel tankage, armament, crew stations, equipment bays, landing and launching gear etc. It is during this process that major design features may be incorporated that will enhance the battle damage repairability of the system, many of which will also provide a more maintainable and repairable aircraft for peacetime operations. It is highly desirable that the aircraft system concept be developed with these objectives in mind. The following are systems engineering and design guidelines that have been developed through the research and analysis of battle damage repairs implemented on a wide range of aircraft damaged by hostile ballistic weapon effects. Each is to be considered on an individual basis for the specific weapon system of interest, as they will vary with each system, just as the most effective combination of design features applicable to the operational conditions of the aircraft system will vary. It is the responsibility of the designer to assess the preferred combination for his particular case.

5.2.3.2 Threat aspects and damage mechanisms. The predominant directions of impact for each potential hostile weapon system should be established. The type, size, and striking velocity of hostile weapon penetrators or HEL weapon effects should be determined so that the characteristics of potential damage mechanisms may be determined. For high-explosive projectiles and missile warheads, the blast impulse characteristics should also be determined so that their effect upon the aircraft system may be assessed. The aircraft design concept should be developed with the damage-producing characteristic of the hostile systems being used as a guide in the basic arrangement of the structure and subsystems to minimize repairs. The preceding data should also be used for the detail design of structure and subsystems.

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5.3 Structures. Aircraft structures are considered to consist of the basic airframe, which includes the fuselage, empennage, and fixed (non-rotating) wings. All major load attachments for elements such as launch and landing gear, engine pylons, armament, and external stores are also included in this category. The airframe is, in general, susceptible to damage from non-nuclear weapon effects, such as ballistic impact by nonexplosive projectiles and fragments from externally detonated missile warheads, internal and external blast effects together with fragment impacts, and high-energy laser weapon effects. Secondary weapon effects, such as internal fires and explosions, hydrodynamic ram effects, liberation of corrosive materials, and high-temperature gases, must be considered in the selection and design of aircraft features for survivability enhancement. An airframe is designed in accordance with References 222 thru 238. There are, however, specific aircraft design considerations (crashworthiness, repairability, secondary hazards, and operational readiness) that can significantly influence the effectiveness of the system. These considerations must be taken into account in the initial design phase to select the basic structural type, or combination of types, that will provide the most survivable and effective system configuration. The survivability of structural elements of the airframe is derived from their tolerance and/or resistance to threat-generated damage. This survivability is referred to as its passive defense capability. Designer ingenuity, subsystem integration, and the application of passive defense measures are the keys to a survivable aircraft weapon system.

5.3.1 General design considerations. Aircraft structure can be damaged bv the primary or secondary damage mechanisms that may be caused by threat effects. An understanding-of the basic damage mechanisms of nonnuclear threat environments is essential in initial structural design efforts. These are blast effects from detonation of high-explosive projectiles or warheads, penetration by projectiles, continuous rods or fragments, and secondary thermal effects caused by the blast or penetration and/or incendiary materials that are a part of the threat mechanism. Fuselage, wing, and empennage are the major components of fixed-wing aircraft construction. For rotary-wing aircraft, additional sensitive structures include the main and tail rotor assemblies, and the tail boom. Basic design considerations for all of these are:

a. For survivability of external blast, use multiple load-path design to avoid concentrated load-carrying members, the failure of which would result in significant loss of control or performance. Utilize multiple shear-type joints for primary load path structural attachments and members, which will permit yield in bearing absorption of blast energy. Avoid designs that will allow crushing of critical structural areas needed for control or performance when subjected to blast effects that would otherwise have been survivable.

b. Internal blast effects caused by detonation of a high-explosive projectile within the vehicle or by the detonation of an explosive mixture in a vehicle cavity is the primary threat to structures.

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High-impulse pressures are generated that are capable of causing immediate loss of aircraft. To minimize damage, design those interior compartments that have little possibility of accumulating explosive mixtures from other sources (i.e., fuel, hydraulics) to be as large as possible to give blast gases room to expand with resulting pressure reduction, and to reduce the number of shock wave reflecting surfaces. Eliminate, to that extent possible, all dry bay type of cavities that might develop explosive mixtures due to fuel cell damage, hydraulic line or reservoir damage, etc. Consider filling those cavities that cannot be eliminated with rigid foam or some other device to reduce the danger of explosion. Give special attention to compartments where liquids such as fuel, hydraulic oil, and water are carried. Internal blast effects are generally considerably more destructive with liquids present than when the compartment is empty. Where aerodynamic requirements dictate use of countersunk (flush) fasteners for structural skin attachment, use such types that require a force that equals tensile strength of fastener body to pull fastener head through skin. This consideration will significantly reduce the probability of large skin area loss due to internal blast effects. Avoid the use of large continuous skin panels, particularly in critical structural areas, unless pads to limit crack propagation are used to reduce the possibility of large skin area loss from blast effect or slipstream forces.

c. Probability of current aircraft design structural catastrophic failure from penetration by fragments or small high-explosive projectiles is extremely slim. However, continuous rod warhead effects are more hazardous. Use multiple load path structural design to avoid single major load-carrying members whose failure from a penetration would cause significant loss of control or performance. Use crack arrestment techniques to prevent spread of penetration damage from aircraft operating loads.

d. Secondary thermal effects from weapon effects, such as burning internal fuel, hydraulic oil, ammunition, oxygen fires, or hot gas "torching" from damaged engine, may cause structural damage or failure. Where fire and/or explosion suppression techniques cannot be used, consider shrouding or compartmentizing critical areas to limit damage to primary structures. Avoid the use of magnesium for or near major structural members, particularly in fire or heat-critical areas.

5.3.1.1 Material selection. When selecting aircraft structure material, it is important to use those with good fracture-toughness qualities to prevent and/or minimize crack propagation. The critical plane strain-stress intensity factor (K_{1c})used in the field of fracture mechanics as a fracture index. The metallics material type, heat-treat condition, and gain direction are variables that influence its capability to resist crack growth. Fracture mechanics is a relatively new technical discipline and, as such, must rely upon physical tests rather than pure analytical means to determine the crack

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resistance of specific structural designs after ballistic damage. For data on fracture toughness and crack propagation of high strength materials, see Reference 129. Composite materials usage in structural applications has been increasing and, under many conditions, may be substituted for metallics with savings of weight and cost with improved ballistic damage tolerance. Typical composites used in aircraft include: Fiberglass, Boron, and Kevlar. Composites used termed as advanced composites include:

a. Graphite - Epoxy/polymide

b. Boron - Epoxy/polymide

Polymide elements are used for higher temperature applications. For additional information and data on advanced composites, consult Reference 130.

5.3.1.2 Construction configuration. Three basic types of construction can be used for aircraft structures: thin skin/stringer, sandwich, and sculptured plate. The selection of construction type for each major structural element (i.e., fuselage, rotary wing, fixed wing, empennage, and tail rotor) must consider the type and level of damage by ballistic effects that can be tolerated.

a. Thin skin/stringer construction provides more ballistic damage tolerance than other types of construction when ductile, high-fracture-toughness materials are used. Multiload-path construction should be used to allow fail-safe response of the structure if damaged. Wide, large-area stringers, frames, and longerons should be used in preference to heavy-section small-area types that can lose a larger percentage of load-carrying capability when struck by threat effects. Attachments for the transfer of high loads should be designed for adequate strength following ballistic damage to permit safe recovery of the aircraft under combat maneuvering conditions.

b. Sandwich construction includes fabrication by bonding of face sheets to an inside core. Honeycomb construction is one of the most widely used types of sandwich construction. Fiberglass or plastic material laminates are examples that have been under recent development and use. Selection of the basic material for sandwich construction must consider the strength remaining in the load-carrying elements when subjected to single- and multiple-projectile impacts and overpressure. Composites, such as boron filaments bonded with epoxy resins in both sandwich and layered configurations, have been under research and development for new aircraft structure, since they offer high strength-to-weight ratios that are needed for higher performance requirements. Graphite fibers are also under development as a new construction material.

c. Integrally stiffened (metallic sculptured plate) structure is fabricated as one piece of material by mechanical, electrical, or chemical means. Material removed is to leave relatively thin walls integral with heaver stiffening lands and attachment sections.

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This type of construction is generally used for highly loaded panels or “shell-like” applications. This type of construction should be used with discretion due to the potential danger of extensive crack propagation and/or the limited combat area repairability characteristics. Experience with sculptured plate construction has shown that projectile/fragment damage has required the replacement of major structural elements where such damage levels in skin/stringer and sandwich-type construction were easily repaired.

5.3.1.2.1 Design guide. A design guide that is of assistance in the development of structural construction configuration and material usage can be found in Reference 126. This design guide contains specific data for:

a. Structural battle-damage prediction

   1) Ballistic impact and penetration
   2) Blast damage (internal and external)
   3) Hydrodynamic ram damage

b. Structural residual strength capability

c. Typical design application and trade studies

In addition, methodologies are presented for vulnerability analysis and assessment.

5.3.1.3 General design repairability/maintainability. The materials and construction types selected for the airframe structure should consider the extent of damage that can be experienced from the hostile weapon effects. An analysis of the candidate structures should be conducted to evaluate the extent of damage for each and the amount of effort and cost that would be required for repair. Where the extent of repair is beyond the operational unit’s authorization or capability, consideration should be given to an airframe design that will permit removal and replacement of a section of the airframe that is directly interchangeable with the same section on all of the same model aircraft. For sections of the airframe that may be damaged by high-explosive projectiles and small missile warheads, where there is a reasonable probability of aircraft recovery, they should be designed to be removable and replaceable with a minimum of maintenance effort. The use of special tools and fixtures should also be avoided. The use of major structural section interchangeability will permit effective cannibalization to ensure that the greatest number of aircraft can be maintained in operational readiness during peacetime and combat operations. This concept will also minimize the number of damaged aircraft that must be disassembled, crated, and shipped to an aircraft rework facility for repair. The following factors should also be considered:

a. The basic airframe design should also be designed to permit minimum effort for access for inspection to those areas most susceptible to damage. The structural provisions for electrical cabling and fluid

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(fuel, hydraulic oil, etc) lines should be designed for rapid access, inspection, repairs and/or replacement. The placement of hazardous materials should be such as to minimize the creation of secondary damage mechanisms, and to limit the propagation of further damage.

b. The selection of an aircraft structure type of construction and materials should consider the time, skill level, special tools, and facilities required to effect battle damage repair. The types of fasteners used in structural designs should be held to a minimum so that the stock of repair fasteners may be minimized. In areas of critical fastener locations in major structural elements such as forgings, castings, sculptured plates, etc, provisions should be provided to permit the use of oversized or larger fasteners where battle damage may distort the original fastener hole. In structural areas where the greatest number of ballistic damage occurrences are expected, standard repair designs should be developed that may be prefabricated and maintained in a combat area rapid repair kit to permit repairs in the minimum length of time. Such predesigned and prefabricated repair concepts should consider the types and sizes of hostile threat damage mechanisms to which the aircraft may be exposed. The structure should also be designed to limit the propagation of damage following that initially sustained. Techniques such as crack stoppers, high-fracture-toughness materials, and multiloadpath designs should be considered. Careful consideration should also be given to the selection of materials and protective coatings so that adequate corrosion control may be maintained following repair of battle damage.

c. The use of nonmetallic (composite) structure should be carefully analyzed to establish the means by which ballistic damage may be repaired under operational maintenance conditions. Where damage may be experienced that is beyond the capability or authorization of the operational maintenance unit, provisions should be made for rapid removal and replacement of the damaged section.

d. Recent experience with damaged boron fiber composite structure has revealed a potential problem and hazard. The destruction of the composite by impact liberates a large quantity of the fibers that can split into small “needles.” These needles can penetrate the clothing and skin of repair personnel and cause great discomfort and possible infection. Battle damage repair concepts for this type of structure should consider such possibilities and examine means to minimize their occurrence and consequences.

e. Nonflush repairs should be blended or faired with the skin by chamfering or with aerodynamic filler, where necessary, as shown in Figure 5-8.

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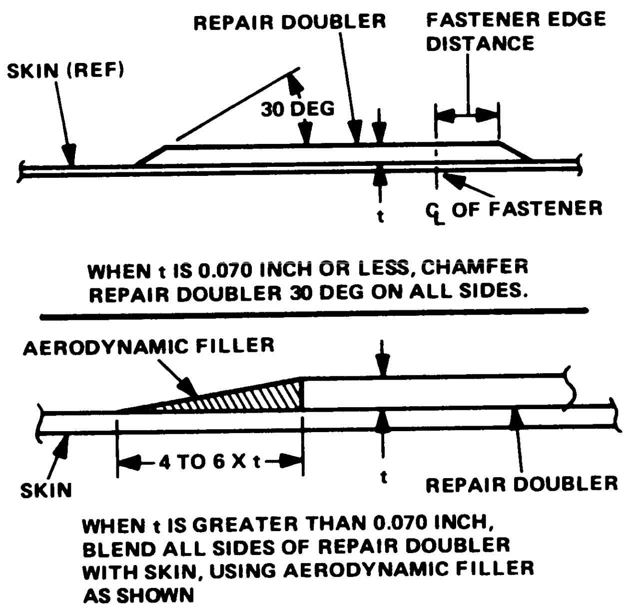

Figure 5-8. Blending nonflush repairs.

f. Repair instructions should be simple and easily understood by maintenance personnel in the combat zones. Figure 5-9 through 5-13 show examples of repair concept illustrations that would provide maintenance personnel with the type of repair information that does not require a high degree of technical skill or education. This type of approach also lends itself to a method of utilizing prefabricated repair components for different levels of structural damage. It has an advantage over conventional repair methods in that significant savings in man-hours and calendar repair time may be realized.

g. Extensive damage can be sustained by aircraft structures from the indirect effects of enemy gunfire. Forced or crash landings can be caused by damage to flight-essential subsystems. Consideration should be given to design concepts that will permit easy removal and replacement of major structural elements to facilitate rapid combat area repair and return of the aircraft to operational status. Interchangeability of major structural sections should also be considered to permit rapid repair by cannibalization of damaged aircraft.

5.3.1.4 Crashworthiness interrelationships. Structural, survivability design features must be fully integrated with crashworthiness considerations. This includes multiload-path and fail-safe features as well as considerations for natural “masking” of vital components and personnel from threat effects.

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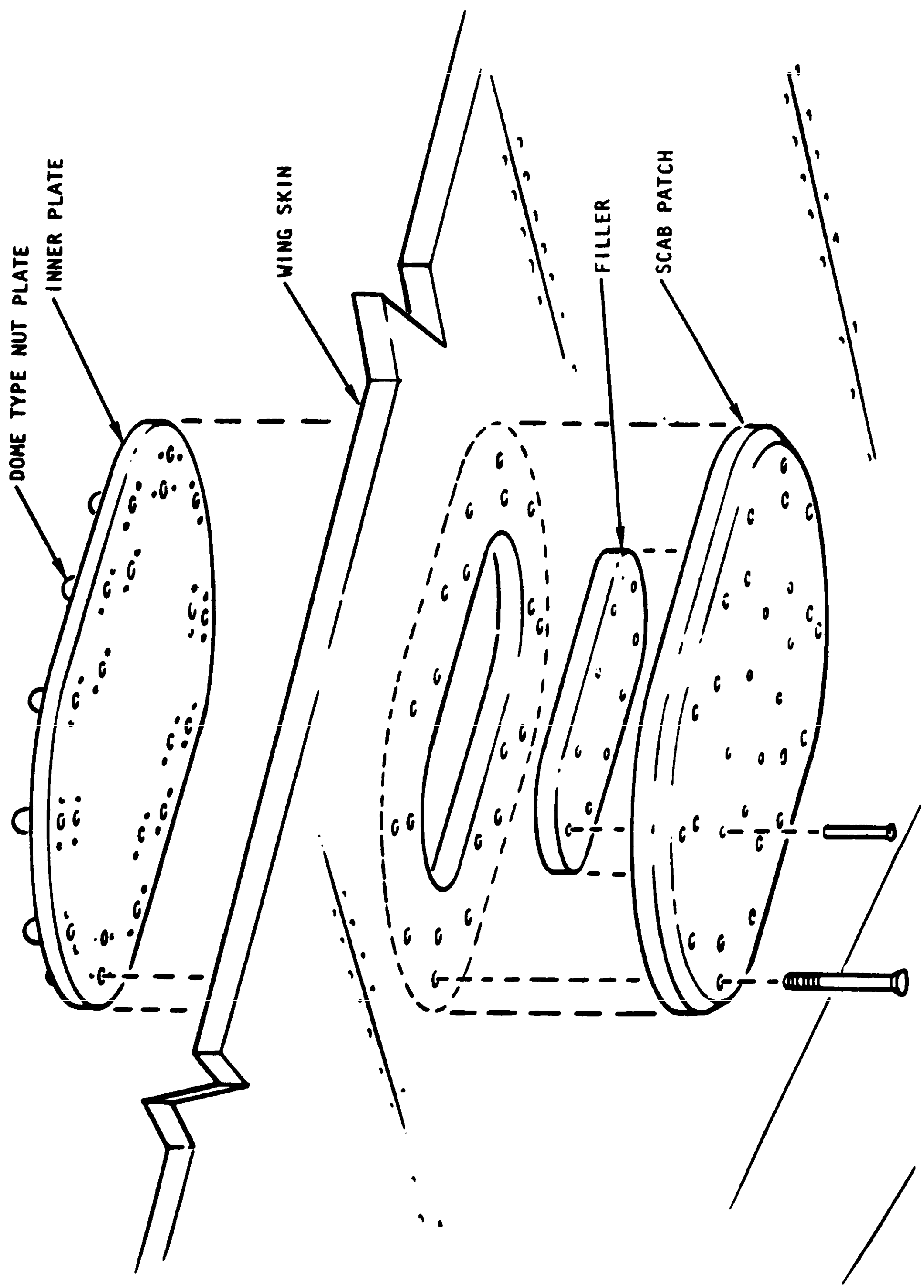

FIGURE 5-9. Scab patch installation for wet wing area.

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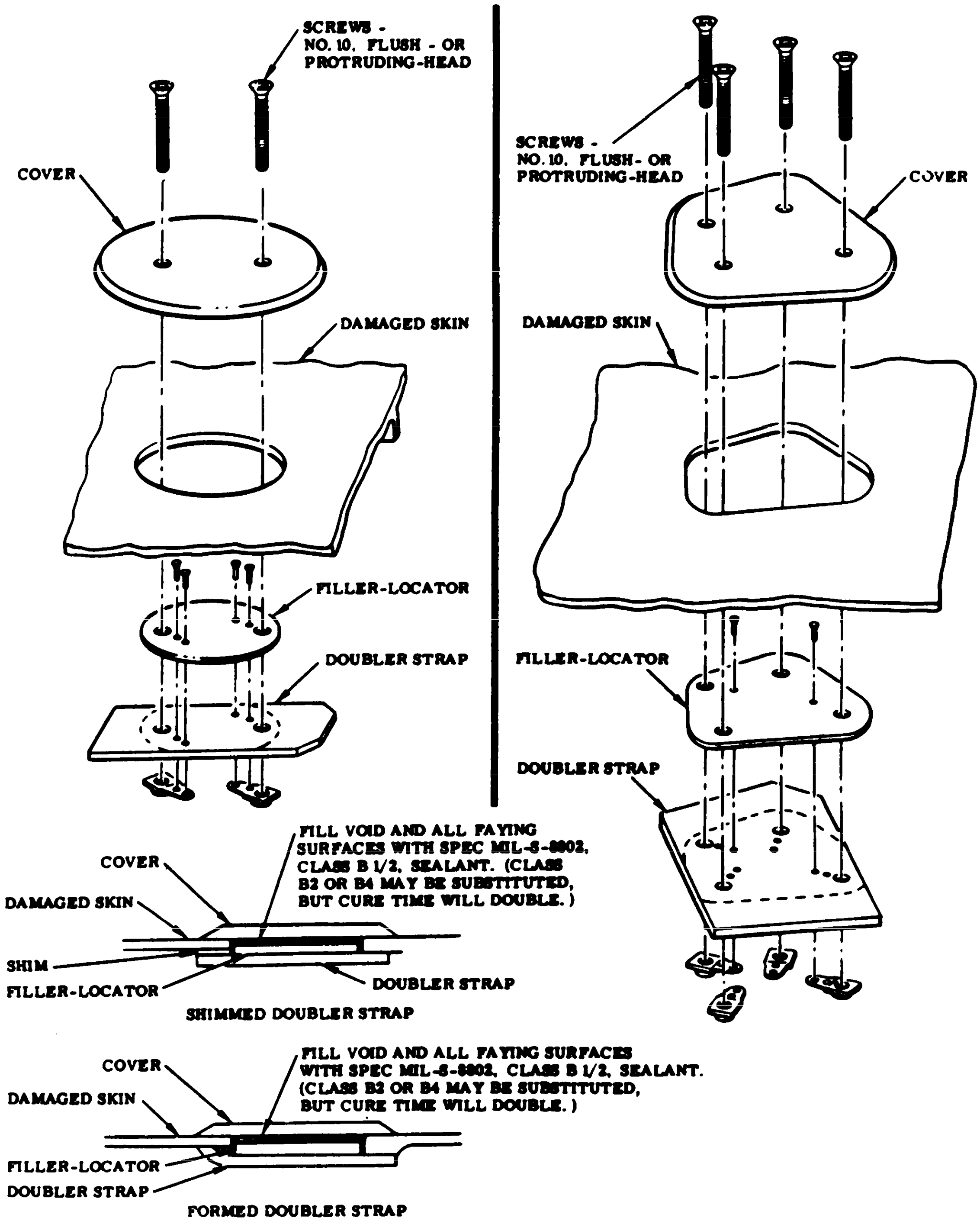

FIGURE 5-10. Nonstructural plug patches - wet wing area.

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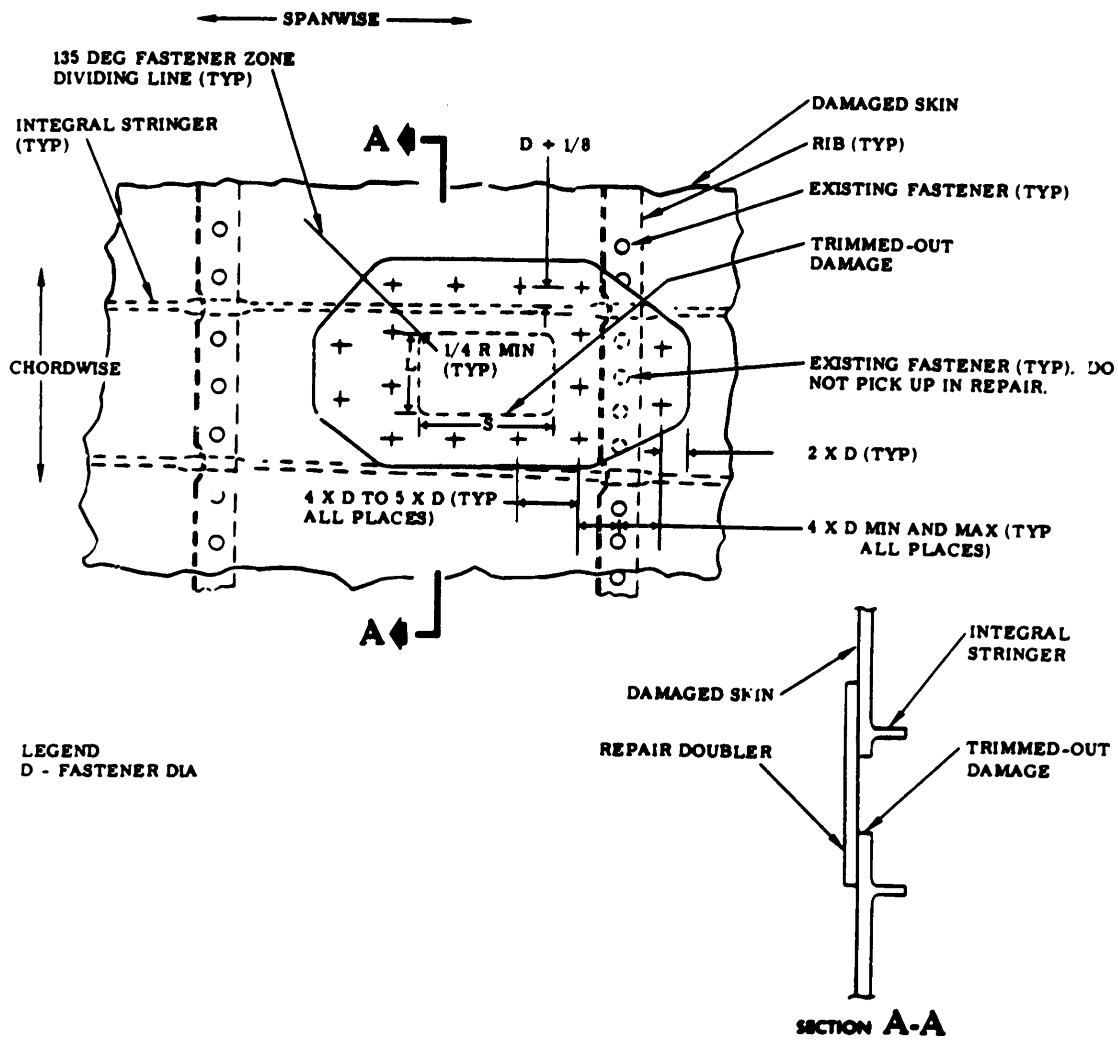

NOTE

In example 1, a 1-1/2 inch trimmed-out chordwise damage (L) is assumed adjacent to, and outboard of, horizontal stabilizer station 88.16.

1. Repair doubler is 0.375 7075-T6 bare (next standard gage above 0.301).
2. NAS1670-3K Fasteners were selected for repair of chordwise damage (L). The requirement for an "L" of 1-1/2 inches is 4.125 or five fasteners each chordwise side of damage.
3. NAS1670-3K or NAS1670-4K Fasteners could be used as spanwise repair fasteners at the referenced station. NAS1670-3K Fasteners were selected and distributed at 3/4- to l-inch spacing.

When trimmed-out damage is such that the required fasteners cannot be Installed between the integral stringers and between ribs. extend the repair doubler across those members as shown. Do not disturb existing rib fasteners but place repair fasteners as close to the rib as possible. See 4 X D MIN AND MAX (TYP ALL PLACES) in sketch. D plus 1/8 inch is minimum fastener spacing from integral stringers because of stringer-to-akin radius.

FIGURE 5-11. Scab patch for damage between integral stringers.

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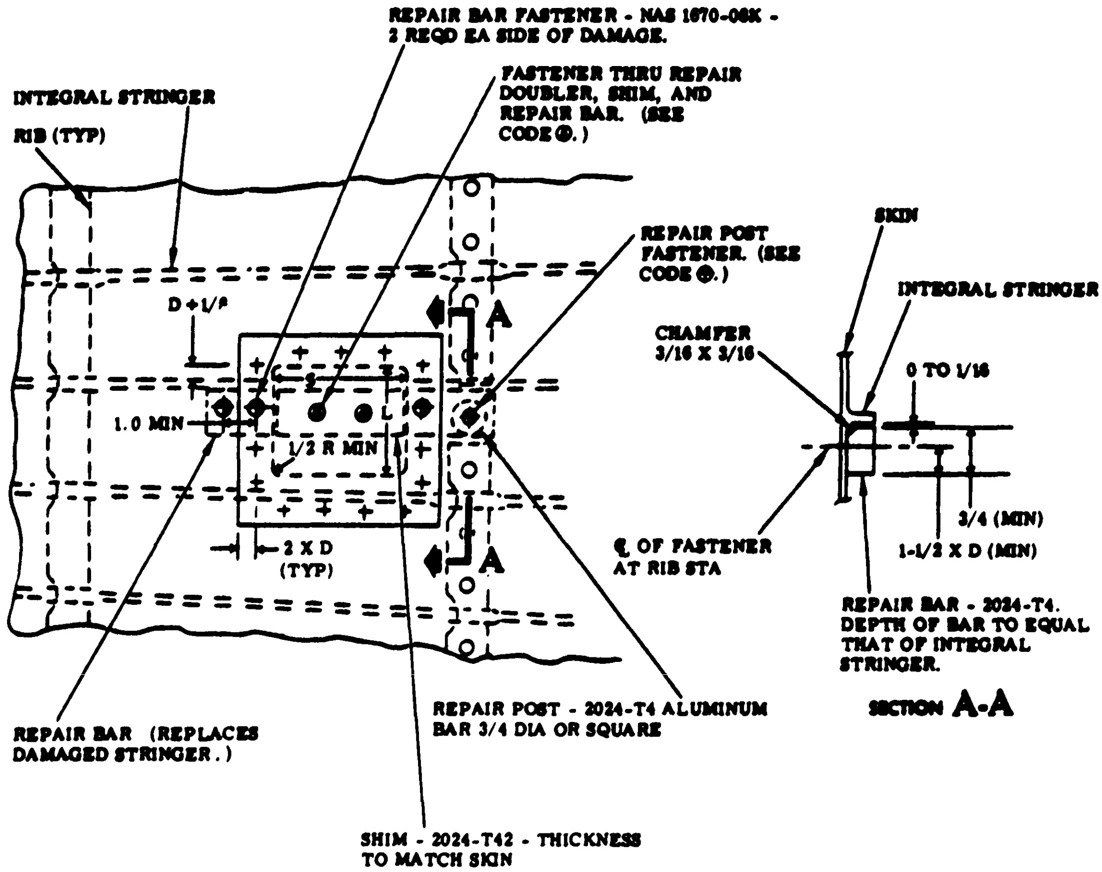

IN EXAMPLE, A REPAIR BAR IS REQUIRED TO REPLACE REMOVED STRINGER. TWO FASTENERS ARE REQUIRED THROUGH SKIN AND REPAIR BAR EACH SIDE OF DAMAGE, WHERE RIB IS TRIMMED OUT TO ACCOMMODATE REPAIR BAR, A REPAIR POST IS REQUIRED. THE FASTENER THROUGH THE REPAIR POST IS COUNTED AS A REPAIR BAR FASTENER.

FASTENER REQUIREMENTS FOR L AND S ARE FOUND AS DESCRIBED IN FIGURE 3-13. FASTENERS THROUGH REPAIR DOUBLER, SKIN, AND REPAIR BAR ARE COUNTED IN REQUIREMENTS FOR L..

LEGEND

D - FASTENER DIAMETER

● - AN509 BOLT WITH MS20365 NUT

+ - REPAIR DOUBLER FASTENERS.

⊕ - FASTENERS TO MATCH THOSE USED IN SPAN-WISE SIDE (L) OF REPAIR. SPACING IS 4 X D MIN, 8 X D Max.

FIGURE 5-12. Scab patch for damage across one integral stringer.

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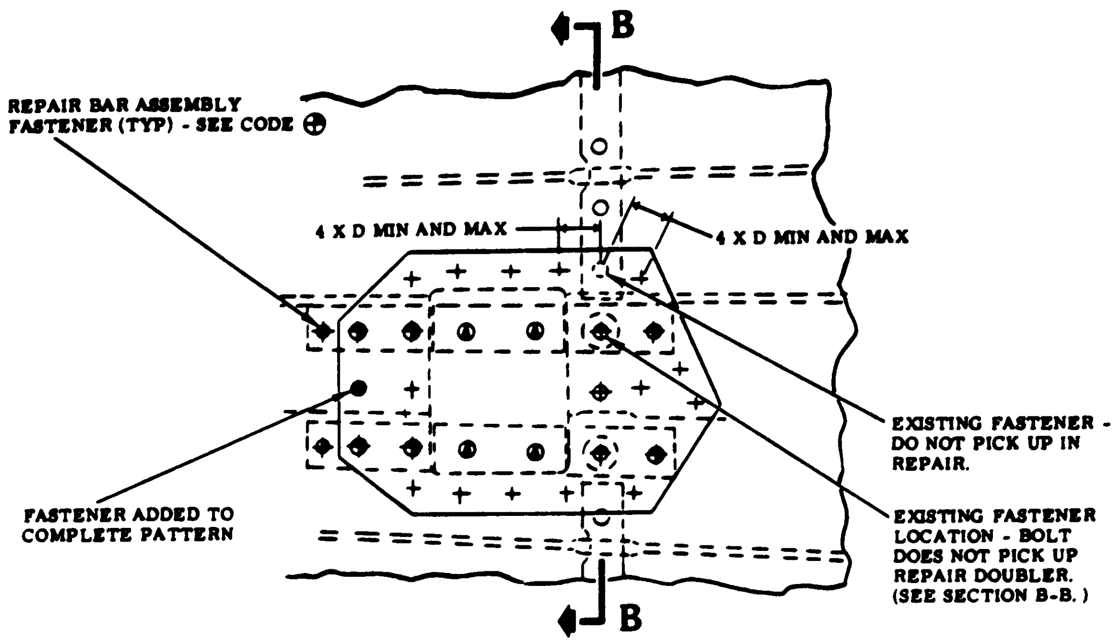

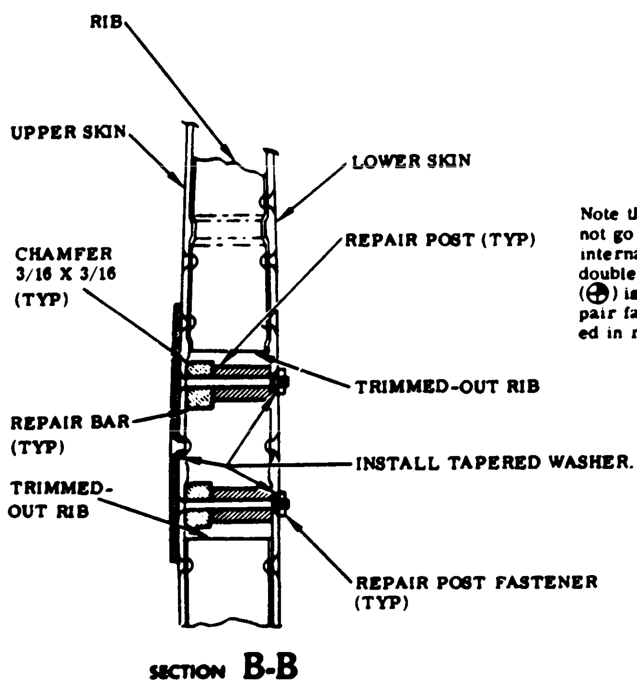

Note that in this repair example repair post fasteners do not go through repair doubler (to facilitate installation of internal repair members) and are not counted in repair doubler fastener requirements. An assembly fastener (⊕) is required at one end of each repair bar for final repair fabrication and assembly. This fastener is not counted in repair requirements.

LEGEND

D - Fastener diameter

⊕ - MS20426AD3 or any small flush-head rivet

⊕ - AN509 Bolt with MS20365 Nut

⊕ - Fasteners to match those used in spanwise side (L_1) of repair. Spacing is 4 x D min, 8 x D max.

FIGURE 5-13. Scab patch across two integral stringers.

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This is particularly important in providing a living space for occupants under crash conditions. The application of parasitic armor on structure must also consider methods to prevent their tearing loose under crash conditions and becoming lethal missiles that could injure the occupants or rupture otherwise crashworthy fuel tanks. Crashworthiness requirements for light fixed- and rotary-wing aircraft are contained in Reference 205.

5.3.1.5 Materials causing secondary hazards. Some materials used for structural applications may, in response to threat effect mechanisms, generate secondary hazards damaging to aircraft equipment and/or aircrew, Their characteristics should be included in the design trade considerations. Some examples of secondary hazards generated by threat effects are listed in Table 5-II.

TABLE 5-II. Examples of secondary hazards.

Material	Secondary hazard
Low ductivity materials Glass Brittle Metallics	 Spallation hazardous to aircrew Spallation hazardous to aircrew
Composites	Freeing of individual fiber filament (hazardous to aircrew)
Beryllium	Generation of toxic substance (hazardous to aircrew)
Magnesium	Spontaneous - burning fire and high-heat areas. Hazardous to structure, equipment, and personnel.

It is good design practice to review all candidate material responses to determine secondary hazard generation and impact on the aircraft, equipment, and crew.

5.3.2 Typical design methods. The majority of aircraft structural design considerations for survivability enhancement against nonnuclear threat effects are applicable to almost all portions of the airframe. These considerations apply to three types of construction: thin skin/stringer, sandwich, and scuptured plate. Each has been used for fuselage, wing, and empennage construction. Helicopter main rotor and tail rotor blades, however, are in a special category that-must be considered individually. Thus, they are addressed separately.

5.3.2.1 Thin skin/stringer construction. The following techniques for minimizing the consequences of threat effects on thin skin/stringer-type structures should be considered:

a. Select materials with high fracture-toughness values to minimize and/or prevent crack propagation following ballistic damage.

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b. Consider the use of bonded "doublers" on high-strength stressed skin panels, such as 7075-T6 aluminum alloy, that may be susceptible to catastrophic failure from a single hit by a projectile. A crack can be arrested by placing a number of fibers across a given zone of stress normal to the line of expected crack direction, thus reducing the stress intensity below the level required to propagate the crack. A thin layer "strap" of fiber glass can be bonded in proximity to the skin to provide such protection. Test programs have shown that a significant improvement in crack arrest can be achieved for very modest penalties. Figure 5-14 illustrates placement of thin fiberglass tape on a typical high-stress panel to provide a crack-arrest feature.

5.3.2.2 Sandwich construction. The following techniques for minimizing damage from projectile impacts on sandwich construction should be considered:

a. Provide high-strength face-sheet-to-inner-core bonding material in areas where fuel or other liquids are carried to prevent or minimize delamination from liquid pressure pulse (hydrodynamic ram) effects caused by ballistic impacts.

b. Consider the use of "planking" construction techniques to limit face sheet delamination from core material as a result of projectile impacts.

c. Use high-temperature-tolerant bonding materials in areas where short-term fires or high-temperature air can be experienced from threat damage, to minimize loss of structural integrity.

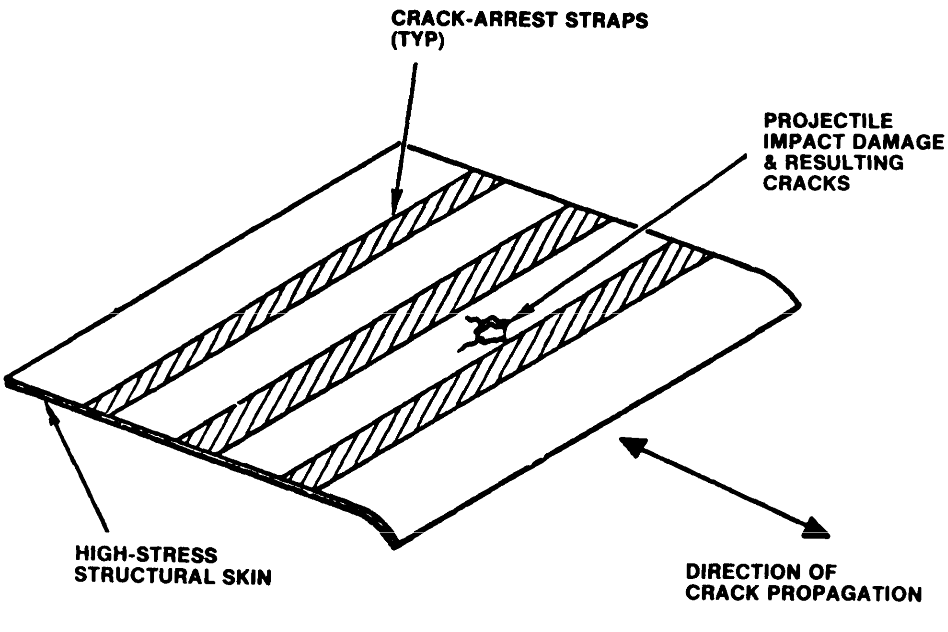

FIGURE 5-14. Crack-arrest straps.

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5.3.2.3 Sculptured plate construction. Where sculptured plate construction is used, the following design techniques should be considered:

a. Use materials with high fracture-toughness characteristics to resist crack propagation from ballistic damage. For example, use 7475 aluminum alloy in place of the higher strength, but more brittle, 7075-T6 aluminum alloy. Select heat-treat condition of material to obtain good fracture-toughness values.

b. Use planking construction for structural areas, primarily under tension-type loads, to limit crack propagation from battle damage.

c. Avoid straight lines of fasteners over large sections subject to high stress loads to limit rapid "zippering" effects due to projectile damage.

d. Design sculptured sections with large radii and avoid abrupt changes in sections where ballistic impact energies can develop high stress concentrations.

5.3.2.4 Composites. The basic concept of filamentary composite structural materials came into being because there never has been a single homogeneous structural material which has been superior in all the desirable attributes which dictate the selection of materials for specific applications. Improved homogeneous material systems are continually being developed, but their ultimate potential will always be limited by the fundamental inability to modify some key physical property, or the fundamental difficulty of improving simultaneously two or more contradictory characteristics. Hence, the concept of combining two or more materials to utilize jointly their desirable characteristics was born. Of particular interest are the composites which consist of fibers imbedded within a matrix of essentially homogeneous material as shown in Figure 5-15. What has recently given composite materials a new impetus toward competitive aerospace applications has been the development of new high-strength, high-modulus, continuous filaments, such as boron and graphite; the development of improved matrix materials; the concept of uniaxial, stabilized columnar filament arrays; and finally, the concept of cross-plied laminates to tailor material strength and/or stiffness to specific envelopes of requirements. The incorporation of high-strength, high-modulus, and low-density filaments into a compatible matrix presents a composite material which offers the potential for major breakthroughs in aerospace vehicle design. These materials are classified as "advanced composites." The following paragraphs describe the basic materials available to the designer, together with a brief explanation of how these materials (filaments and matrix) are produced.

5.3.2.4.1 Filaments. The filaments most commonly being used in advanced composite structures are boron, Borsic (silicone-carbide-coated boron), and graphite. Other fibers, such as sapphire whiskers, ultra-high-modulus graphite fibers, silicon carbide fibers, and a new organic fiber designated PRD-49 have been or are being investigated, but insufficient data are available to warrant their consideration in this volume of the Guide. Some preliminary data on these materials can be found in Volume IV of Reference 155.

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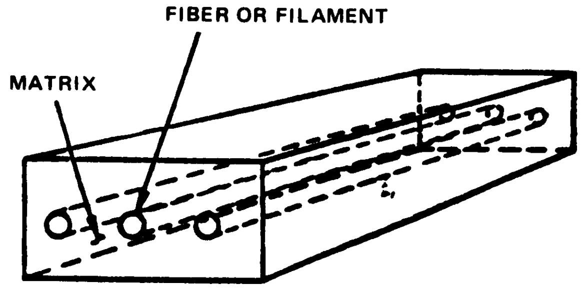

FIGURE 5-150 Filamentary composites

5.3.2.4.2 Lamina and laminate fabrication.

5.3.2.4.2.1 Organic matrix composites. The preimpregnated raw material is manufactured by thoroughly coating or impregnating the properly spaced and collimated boron filaments or graphite fiber tows with the matrix material. The basic sequence involved in the fabrication of prepreg tape and broadgoods, including laminate fabrication, is shown in Figures 5-16 and 5-17,

5.3.2.4.2.2 Metal matrix composites. Aluminum matrix composites, described in Table 5-III are available in sheet and tape forms, with boron and Borsic filaments. Sheet products produced by diffusion bonding are available with either boron or Borsic filaments, and with 6061 or 2024 aluminum alloy matrices. These products are available in a wide range of laminate thicknesses, including monolayer sheet. Plasma-sprayed monolayer tape is available with Borsic filament reinforcement (4 mil or 5.6 mil diameter) only, and with 6061 aluminum alloy or 713 aluminum braze alloy backing. A1-6061 is generally plasma sprayed onto the filaments and backing foil. This tape is used as a starting form and is subsequently fabricated into the desired configuration by diffusion bonding (for tape with 6061 alloy backing) or braze bonding (713 alloy backing). The choice of the alloy backing is based on a tradeoff between ease of fabrication and properties. Continuous tape with nitrided boron filament in 6061 aluminum alloy is also available in widths of 0.6 inch. The tape is normally 0.007 inch thick, with 41 to 44 filaments in the tape. Lengths up to 3,000 feet are available. This tape is generally used as a starting form to fabricate larger and more complex shapes by subsequent diffusion bonding or braze bonding.

5.3.2.4.2.3 Fiber volume fraction. It is possible to fabricate a composite lamina with many different fiber volume fractions. However, virtually all of the existent test data have been generated for one specific fiber volume fraction for each generic system. These volume fractions were selected based on theoretical micromechanical analysis which determined the most efficient configurations. Therefore, all of the boron/epoxy and boron/aluminum data shown in Volume I of Reference 155 are for a 50-percent volume fraction, while all the data on graphite/epoxy reflects a 60-percent volume fraction. It is these fiber volume fractions which are most generally available in the off-the-shelf prepreg materials, although the graphite/epoxy volume fraction may vary between 55 and 60 percent depending on the supplier. Virtually all of the actual hardware

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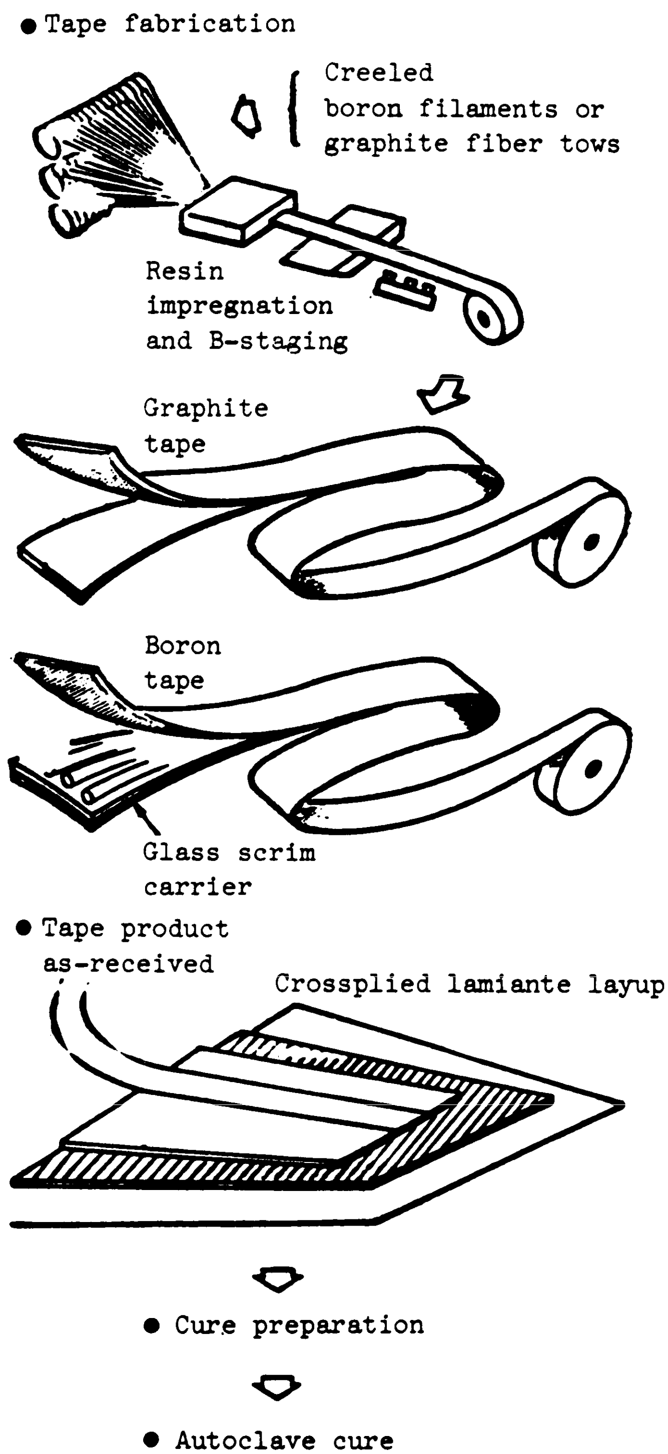

FIGURE 5-16. Graphite or boron/epoxy tape and laminate fabrication process.

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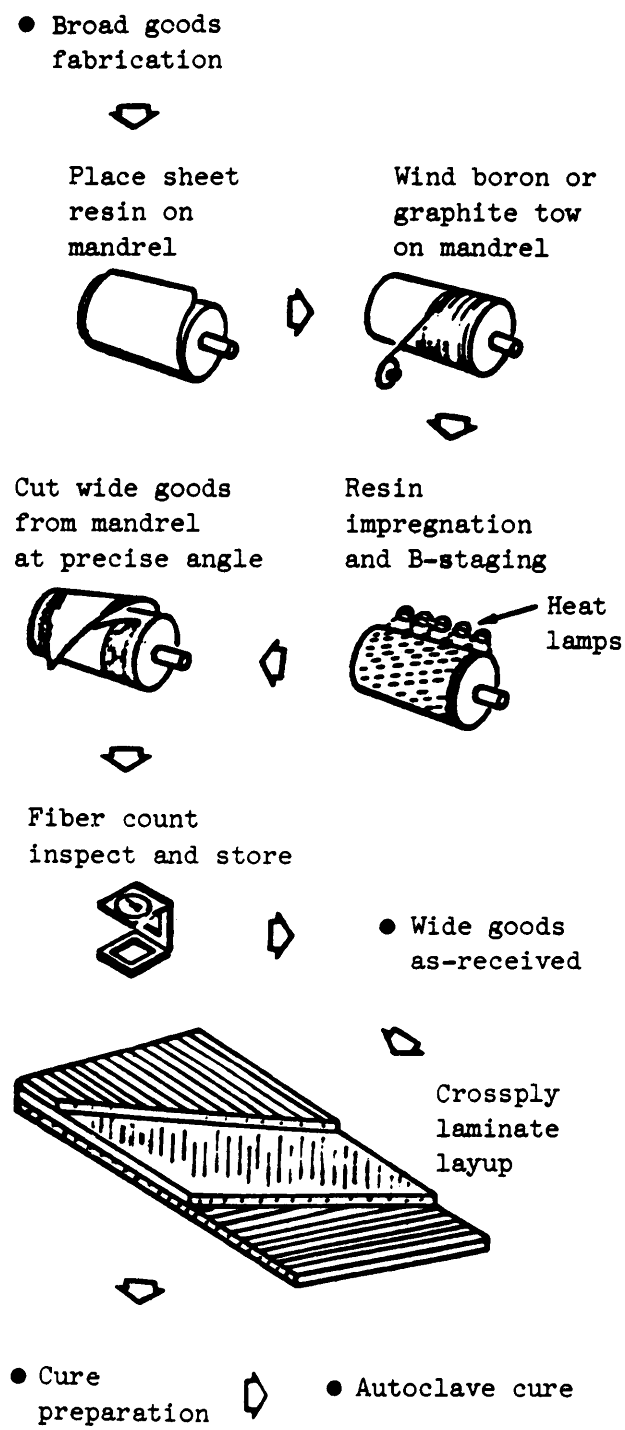

FIGURE 5-17. Graphite or boron/epoxy fiber broadgoods and laminate fabrication process.

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TABLE 5-III. Boron/aluminum composites

Form	Method of Manufacture	Matrix	Filament Type	Filament Dia(in.)	Comments
Sheet	Diffusion bonding	6061 or 2024 aluminum alloy	Boron or Borsic	0.004 0.0056	Available in finished form.
Tape	Plasma spraying	6061 alloy or 713 braze alloy backing: 6061 alloy plasma spray	Borsic	0.004 0.0056	Generally diffusion bonded or braze bonded into desired configuration,

items built to date have been fabricated using these standard volume fractions. A small amount of data is available for other fiber volume fractions on certain specific fiber/matrix systems. These data may be found in Chapter 4.1 of Reference 155 under "Experimental Systems."

5.3.2.4.3 Design concepts and applications. This section presents some typical design concepts which are generally considered to be good design practice when using advanced composite materials, since they were specifically developed to take advantage of the characteristics of advanced composites. In addition to specific concepts, a number of general application areas are discussed which appear to offer advantageous uses for advanced composites. The concepts and applications are discussed with respect to specific systems, such as aircraft, helicopter, etc; however, many of the concepts are interdisciplinary in nature.

5.3.2.4.3.1 Aircraft applications, structural. Much of the advanced composite development work which has been done to date for aircraft applications has been centered on lifting surface types of structure. The most common types of construction currently being used for these structures are full-depth honeycomb, honeycomb sandwich/multispar, and stiffened panel/multirib. These are basically the same types that are often used for metal construction, although the characteristics of advanced composites provide some special advantages. For example, composite material can be cured to the desired shape, greatly simplifying the fitup problem, especially in the case of cocured honeycomb sandwich structure. Also, it is possible to orient the fibers in such a manner as to take maximum advantage of the anisotropic nature of the material. This capability makes it possible to design very efficient stiffeners which are strong and stiff in the axial, or load, direction while avoiding excess weight for unneeded transverse strength. In addition, it is possible to provide sufficient axial load-carrying capability in the spar caps and stiffeners alone to support primary bending loads, while reacting torque loads with skins, either solid or honeycomb, consisting of ± 45° plies. There are, of course, many other methods of carrying the applied loads, ranging from the method just mentioned to one in which there is sufficient strength and stiffness in the skin alone to meet the design requirements. The method selected will depend basically on the size of the component, the load intensities, stiffness requirements, and method of

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attachment. Several other concepts currently under development were conceived specifically with advanced composites in mind. Some are shown in Figure 5-18. The truss web concept is further explored in Figure 5-19. Only a few programs have been devoted to developing fuselage-type structure. The advantages of advanced composites in this area, in addition to their directional properties, include the ability to construct complex shapes in one integral piece, utilizing a mix of materials. An example of this is a typical bulkhead which could be match molded in one piece utilizing chopped fiber as the basic molding material, with unidirectional laminate stiffeners built in to provide the,appropriate strength and stiffness. Flanges and bosses would also be part of the molding. As with lifting surface structures, hat-stiffened and Z-stiffened panels, constructed as a unit, comprise a basic structural element.

5.3.2.4.3.2 Hybrid structure. Another type of design concept that is currently being investigated is the hybrid applications in which more than one type of fiber is used in a laminate. The most common hybrids are those which use some combination of boron, graphite, and glass fibers in a fiber/epoxy laminate. This concept permits even more accurate property tailoring than does a normal one-system laminate and also allows some cost saving in those cases where the specific properties of a lower cost fiber may be used to advantage to fill a particular requirement. The concept also allows more latitude in designing cost-effective structures, since it allows greater variation between cost, weight, and strength.

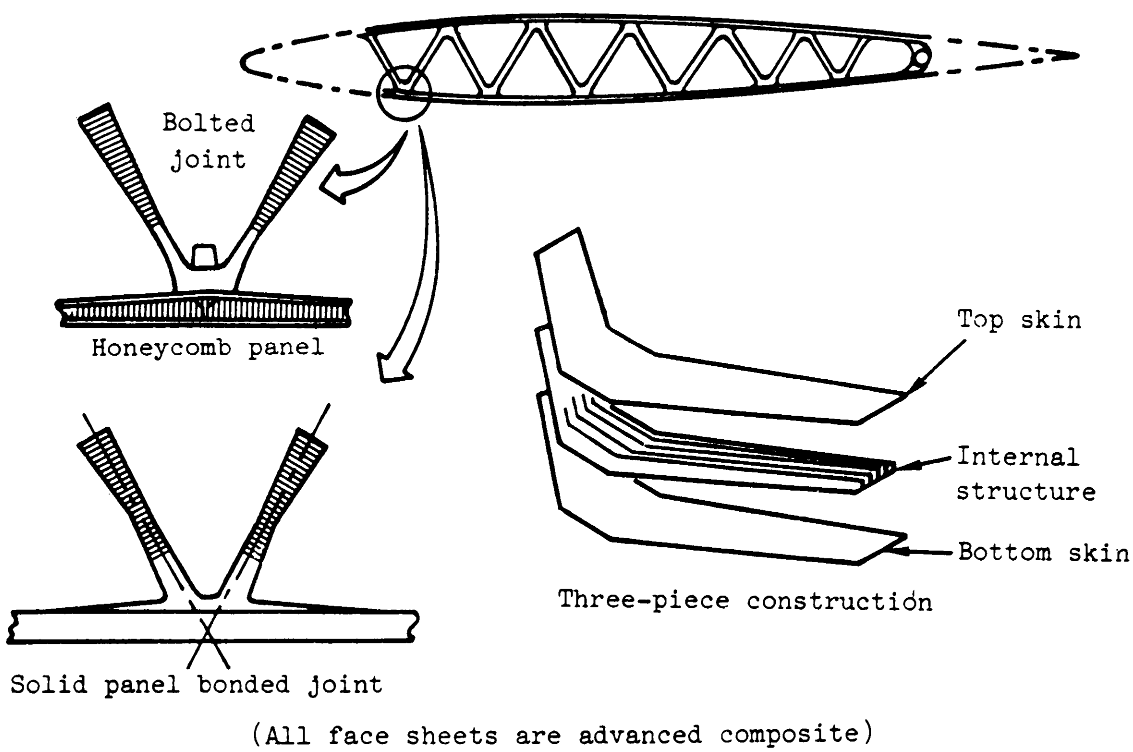

FIGURE 5-18. Truss web design.

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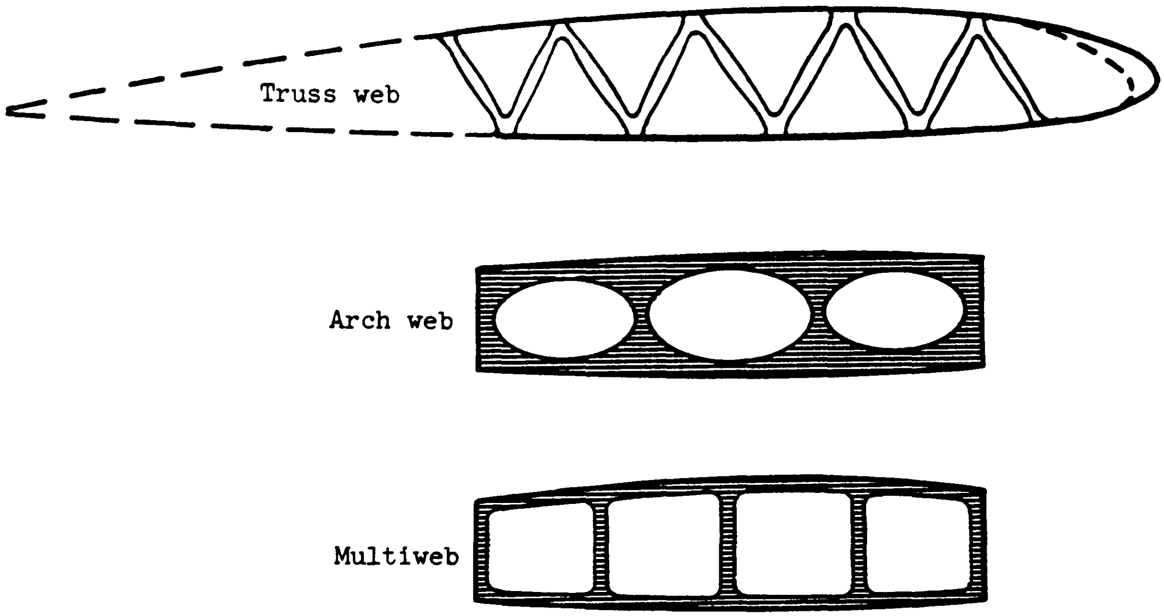

FIGURE 5-19. Design concepts

In addition to the general applications of hybrid composites, studies are also being conducted concerning their use in joint areas. This type of application should be considered especially in tension joints in a basically boron/epoxy material. In this case, the possibility of locally replacing the 0° boron fibers, in a strip through the fastener holes, with low modulus graphite should be considered. Because of the greater strain capability of the graphite, this replacement concept should significantly reduce the stress concentrations at the edge of the hole.

5.3.2.4.3.3 Selective reinforcement. Somewhat related to the hybrid concept is the concept of selective reinforcement, wherein the basic metal part or component is reinforced by the addition of composite material. The most widespread use of this concept is in the area of reinforced stiffeners or beams, wherein the basic metal part is reinforced by unidirection boron/epoxy or graphite/epoxy. This is particularly effective in panel stiffness-critical applications. Several methods of using this concept are shown in Figure 5-20. In these types of applications the designer must take into consideration both the different moduli and the different thermal expansions of the materials being jointly used.

In can be seen from the example that the composite material can be completely protected from the environment as with the tee, hat, and zee concepts. Conversely, the composite material can be directly exposed to the environment as with the honeycomb panel and boron hat stiffeners. In applications where

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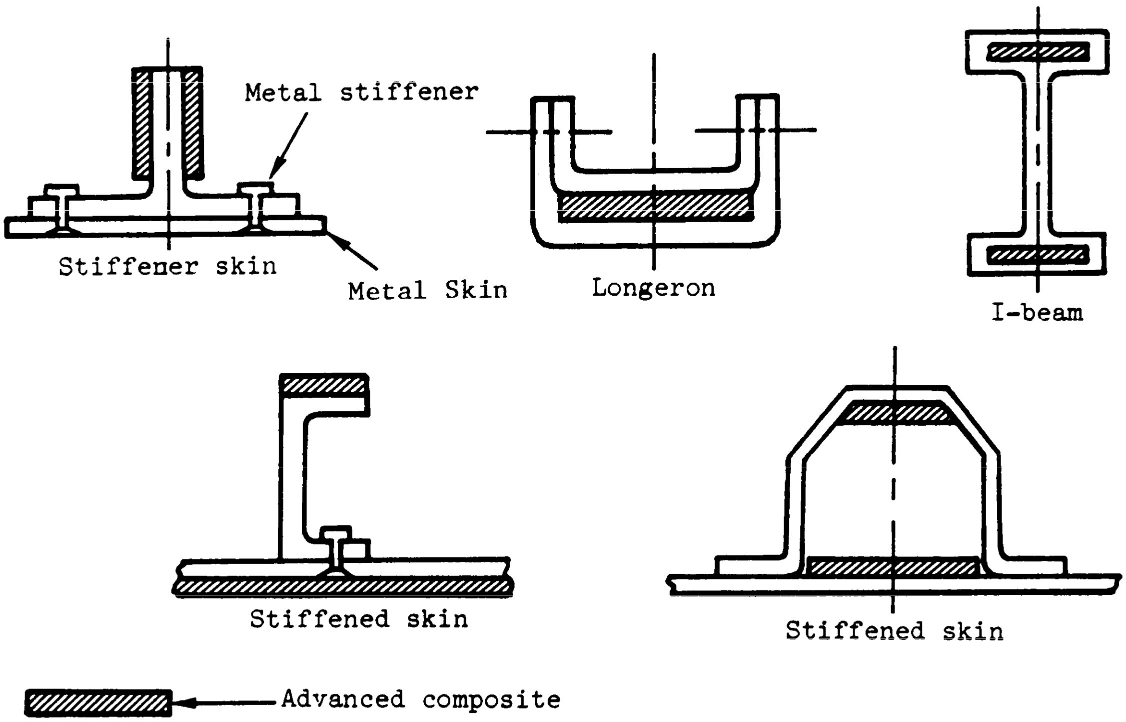

FIGURE 5-20. Reinforcement concepts.

lightning strike or other environmental factors may be present, the protection of the composite material may be very important. Thus, a stiffener design which provides composite material environmental protection from the outset may be greatly utilized. Unidirectional material may also be used to provide all of the load and stiffness requirements of a longeron, while the metal sheathing functions only to protect the composite material and to provide the necessary strength for shear transfer and attachments. This concept is shown in Figure 5-21. The use of unidirectional composites can be extended to such design concepts as beam reinforcements, particularly in the cap areas as shown in Figure 5-22 (a), (b), and (d). However, the truss-type beams may also utilize unidirectional material in the internal bracing areas, since these areas carry essentially axial loads only. This concept is also shown in Figure 5-22.

5.3.2.4.3.4 Helicopter applications. The helicopter operates in a continuous dynamic environment. Variable aerodynamic loads on the rotor blades comprise the principal dynamic load source. The rotor blades are subjected to cyclic pitch change and rotate in a highly variable velocity field. In forward flight the blades rotate and advance simultaneously. From the viewpoint of crew and passenger comfort, the vibration level is of prime importance. From the viewpoint of the structural designer, the component fatigue strength which determines service life is of major concern. The rotor blade is critical for both fatigue strength and deflection. Therefore, materials with high specific fatigue strength and high specific modulus of

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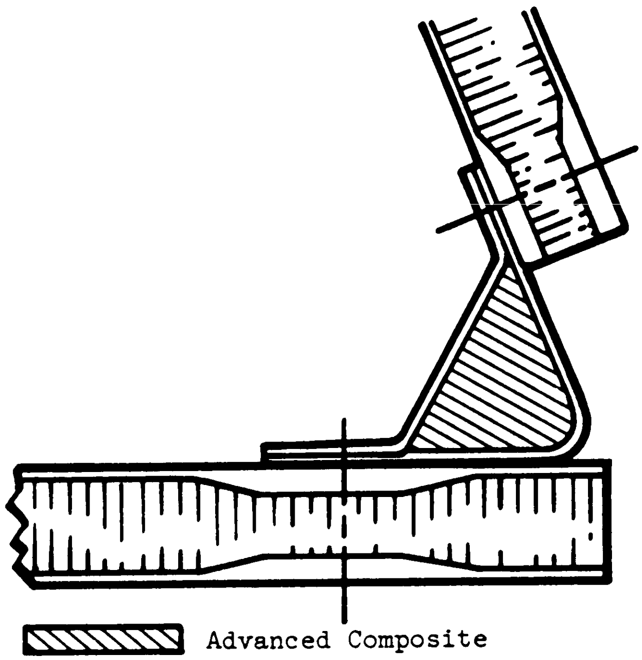

FIGURE 5-21. Constrained unidirectional longeron concept.

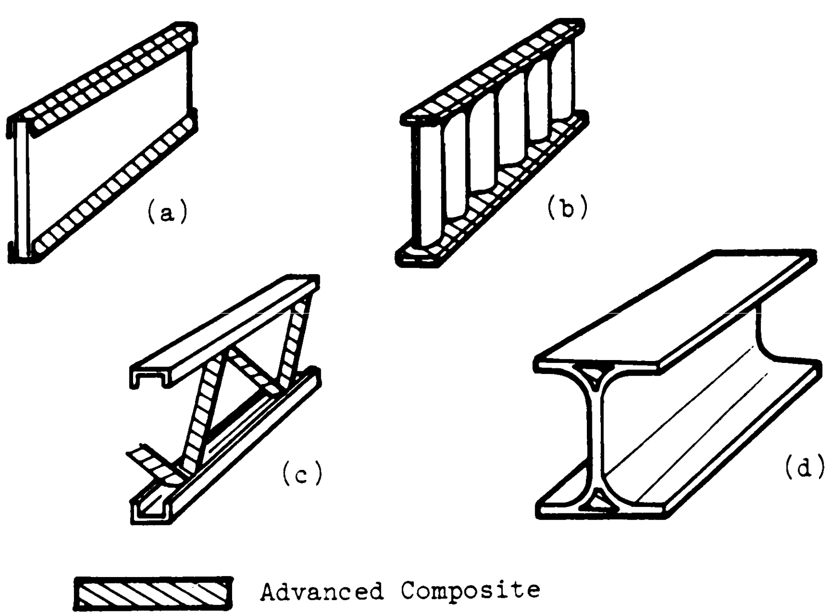

FIGURE 5-22. Beams.

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elasticity offer great advantage. Rotor blade design includes natural frequency tuning. Tuning is necessary to avoid resonant response which occurs if the structural natural frequency is near the system exciting frequencies. Composite materials offer the advantage of permitting blade natural frequency tuning without any penalty in weight. A wide stiffness range, and therefore a wide frequency range, is afforded by composites through variations in fiber orientation.

Typical rotor blades (Figure 5-23) are built-up beams, comprising spars, skins, ribs, a trailing-edge member, and balance or tuning members. The various members are bonded together with structural adhesives. A cross-section of a typical fibrous composite blade is shown in Figure 5-24. The major items shown may be constructed of different materials or could have different fiber orientations. The contribution of each item is determined and combined, using basic mechanics equations, to sum up the total section properties. The actual composite rotor blade design is shown in Figure 5-25, Figure 5-26 shows the boron composite root end of the blade.

5.3.2.4.3.5 Propulsion system applications. The most dominant characteristic of gas turbine engines as related to composite material is the requirement for lightweight rotating parts. In this regard, blade weight is the controlling factor which determines the size or weight of the remaining structure; i.e., wheels, shafts, bearings, and support structure. Therefore, a nominal reduction in the blade weight can result in a substantial decrease in overall engine weight. For this reason, blades offer the largest payoff and have, therefore, received the most attention in terms of applications of composite materials.

5.3.3 HEL protection. The protection of aircraft structural elements against the effects of hostile high-energy laser systems consists of three categories of techniques: (1) multiload structure design to preclude catastrophic failure from damage or weakening of a structural element from burn-through or high-temperature heating, (2) application of barrier and ablative materials to prevent burn-through of critical structural elements, and (3) surface preparation of external structures to obtain high reflectivity of laser energy. Reference 75 contains basic information on passive laser countermeasures that will acquaint the reader with the subject. Considerable research and development of HEL countermeasures techniques is being conducted by many Government agencies. Consult with AFWL/PGV and AFML/LPJ for direction to the agency(ies) for specific areas of information. The bulk of information on HEL damage predictions and countermeasures effectiveness is highly classified and is in a state of continuing change and improvement. When standard methods have been established and adopted, they will be incorporated into the Design Handbook.

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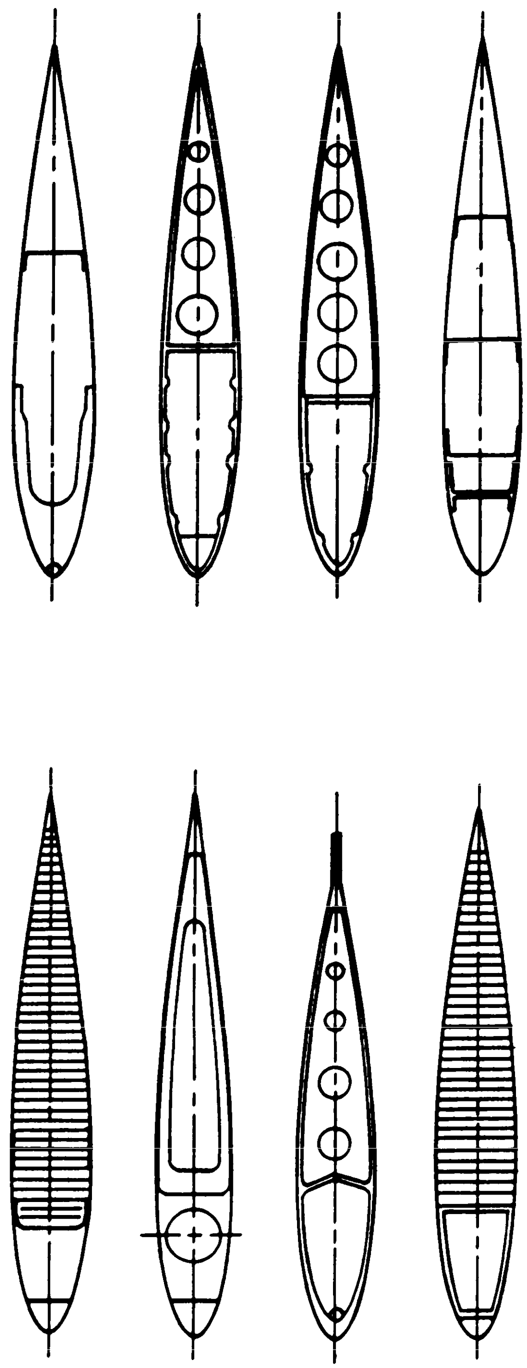

FIGURE 5-23. Typical rotor blade construction.

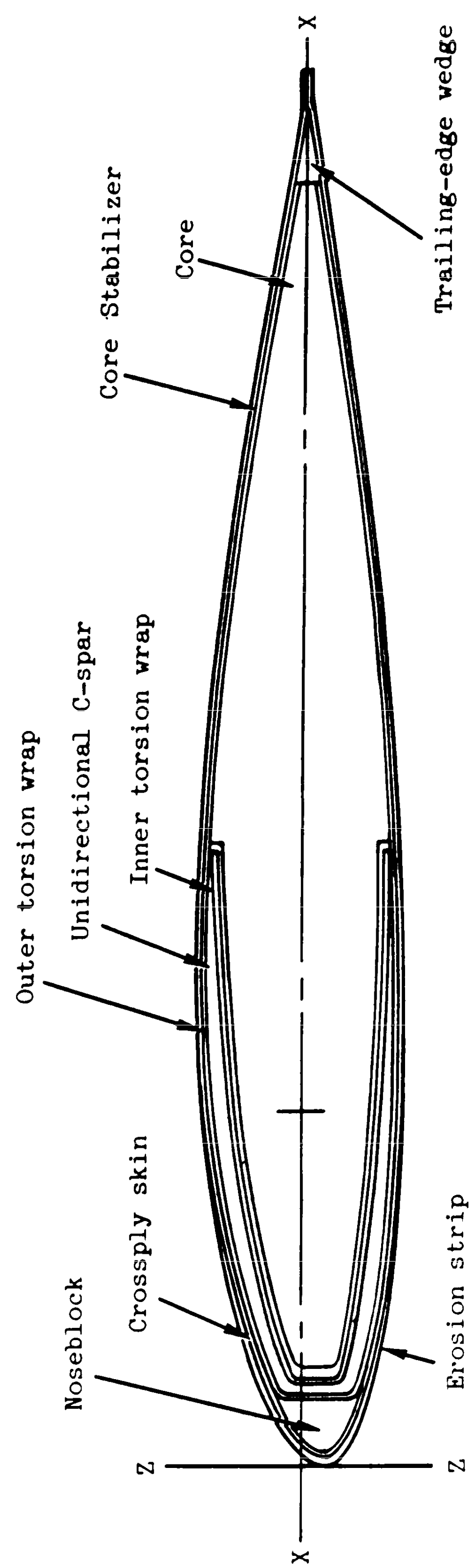

FIGURE 5-24. Typical fibrous composite blade section.

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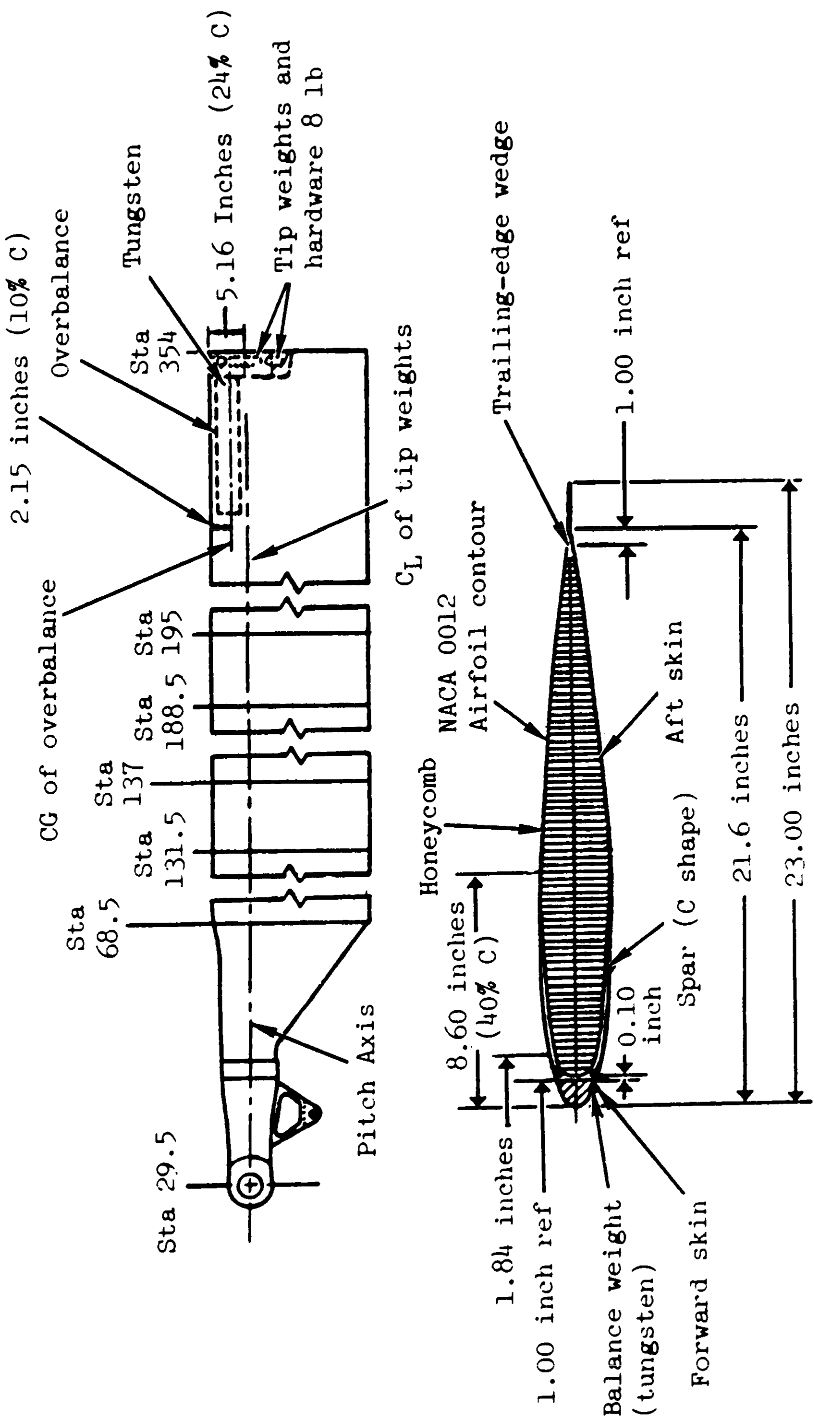

FIGURE 5-25. Composite C-spar of CH-47 blade configuration.

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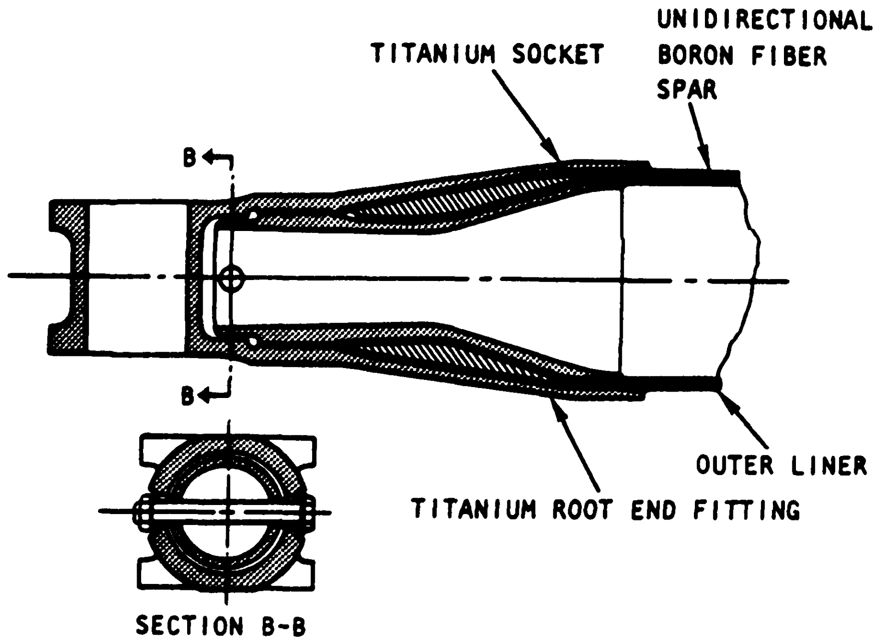

FIGURE 5-26. Sections of full-scale boron composite rotor blade root end for CH-47.

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5.4 Personnel stations. The performance and survivability of personnel in military aircraft exposed to hostile nonnuclear weapon effects is a major design consideration. While the protection of the aircraft operator(s) and other crewmembers is of primary importance, consideration must also be given to protection of passengers as well. Personnel are susceptible to a number of direct and secondary injury mechanisms that may be created by hostile non-nuclear weapon effects, including penetration by projectiles; fragments and secondary spallation; blast overpressure effects; high thermal environment conditions from fires, hot gases, high-energy laser weapon effects, etc; explosive decompression, toxic fumes, smoke, and loss of environmental control functions such as oxygen supply, pressurization, heating and cooling, air conditioning, etc. The dependency of the aircraft system on personnel to perform the designated mission and maintain acceptable controlled flight must be carefully established in the initial design process so that the proper candidate survivability enhancement techniques may be considered and selected. Rapid advances are being achieved in the nonnuclear protection methods for aircraft personnel. Consult the JTCG/AS for the most current information and guidance on this subject.

5.4.1 Personnel ballistic protection techniques protection of personnel in military aircraft against the primary and secondary injury-producing mechanisms of ballistic-type hostile weapon effects has received considerable attention during the past two decades. Significant advancements have been achieved in the development of lighter weight and more effective armor materials and systems. Better understanding of their application and use has resulted in higher protection levels being provided in new aircraft design concepts. As the protection level for ballistic penetrators has risen, the consideration for high-explosive blast protection has become more important. This section contains information on personnel susceptibility to nonnuclear weapon effects (injury factors) , personnel stations locations and arrangements, controls and displays, secondary hazards protections and armor systems.

5.4.1.1 Personnel injury factors. Both operating aircrew members and passengers are vulnerable to projectiles and to span and debris created by the projectiles as they penetrate parts of the aircraft. A man's vulnerable areas are his head, the primary organs within his chest and abdomen, and the larger arteries and veins of his extremities.

Information and data pertaining to weapon effects on crewmembers and passengers are difficult to analyze for several reasons:

a. Data collection to the depth desired is often operationally impractical.

b. In the confusion of combat, it is difficult to identify weapons, ranges, angles of obliquity, etc.

Lethality criteria are developed from experimental investigations with test animals and are correlated with human structure on a medical basis. Systematic, experimental, wound-ballistic programs to supply data for the studies are being

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carried out at various military medical centers. A typical report analyzes combat casualties to U.S. Army personnel aboard combat aircraft. An attempt was made to exclude casualties from (pure) accidents not involving ground-fire hits. The main objective of the study was to identify and define the different types of casualties that occurred, their causes, their frequency, and the attendant encounter circumstances (both qualitatively and quantitatively) as full as possible. The casualty types, locations, and causes identified the areas of concern. The relative frequency of the various casualty occurrences provides the proper perspective for the designer to minimize casualties for similar aircraft. Figure 5-27 provides an effective method for mapping the human body when performing these types of studies.

5.4.1.1.1 Human vulnerability. The human body is composed of soft, pliable tissues surrounding a comparatively soft and brittle skeletal structure. (See Figure 5-28.) This entire mass contains blood vessels that release life-preserving fluids when punctured and nerves that relay paralyzing and fatal shock signals when damaged. Predicting the probability of kill given a hit ($P_{K/H}$) on an aircrewman becomes a rather tenuous engineering guessing game. Some examples of weapon effects are cited that may give the designer, in concert with the medical and life science specialists, a reasonable foundation for performing vulnerability analyses and arriving at tenable conclusions. At present, there is no standard or precise means to equate casualty criteria to projectile types and impact energies. The following is an extract of actual combat wound experiences that provide the designer with an indication of human vulnerability:

a. A 5.56 mm projectile fragmented when it hit a bone.

b. A 5.56 x 0.45 mm projectile pierced the chest cavity near the heart at a range of 100 feet.

c. A 7.62 x 0.39 mm projectile pierced the chest cavity, perforated a lung, and fractured a rib at a range of 150 to 225 feet.

d. Bullet (projectile) wounds of the vital chest structures are more severe than those caused by fragments.

e. In fatalities caused by weapon effects, injuries to the vital structures of the thorax occur in direct proportion to the amount of space occupied by the structures. The lungs are injured more than any other chest structure, followed by the heart and the thoracic blood vessels.

f. Penetrating missile injuries in the area of the heart and the major blood vessels are most likely to be fatal.

g. Ribs are injured in approximately 50 percent of the fatalities.

h. In thorax-abdominal injuries, the liver and spleen are most frequently injured, followed by the stomach and kidneys.

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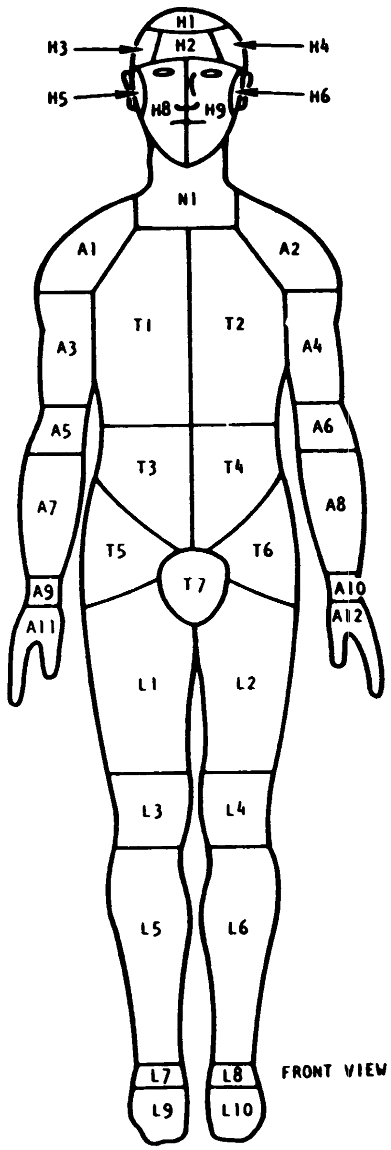

LOCATION	SIDE	SYMBOLS
HEAD & NECK		
TOP	NA	H1
FOREHEAD	NA	H2
SKULL (1)	RIGHT, LEFT, BACK	H3, H4, H7
MASTOID	RIGHT, LEFT	H5, H6
FACE	RIGHT, LEFT	H8, H9
NECK (2)	FRONT, BACK	N1, N2
TORSO (FRONT)		
CHEST	RIGHT, LEFT	T1, T2
ABDOMEN	RIGHT, LEFT	T3, T4
HIP	RIGHT, LEFT	T5, T6
GROIN	NA	T7
TORSO (REAR)		
HIP	RIGHT, LEFT	T5, T6
BACK	RIGHT, LEFT	T8, T9
LUMBAR	RIGHT, LEFT	T10, T11
SPINE (1)	NA	T12
BUTTOCKS	RIGHT, LEFT	B1, B2
ARM		
SHOULDER	RIGHT, LEFT	A1, A2
UPPER	RIGHT, LEFT	A3, A4
ELBOW	RIGHT, LEFT	A5, A6
LOWER	RIGHT, LEFT	A7, A8
WRIST	RIGHT, LEFT	A9, A10
HAND	RIGHT, LEFT	A11, A12
LEG		
UPPER	RIGHT, LEFT	L1, L2
KNEE	RIGHT, LEFT	L3, L4
LOWER	RIGHT, LEFT	L5, L6
ANKLE	RIGHT, LEFT	L7, L8
FOOT (INCL. HEEL)	RIGHT, LEFT	L9, L10

NOTES
1 - NO FRONT SIDE FOR SKULL OR SPINE
2 - NO LEFT OR RIGHT SIDE FOR NECK, SPINE, OR FOREHEAD

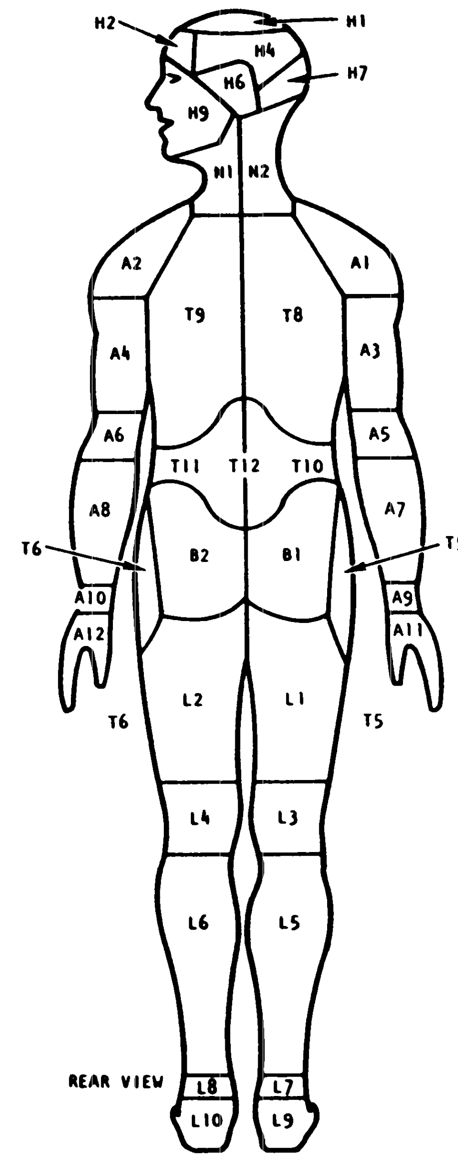

FIGURE 5-27. Human body zones.

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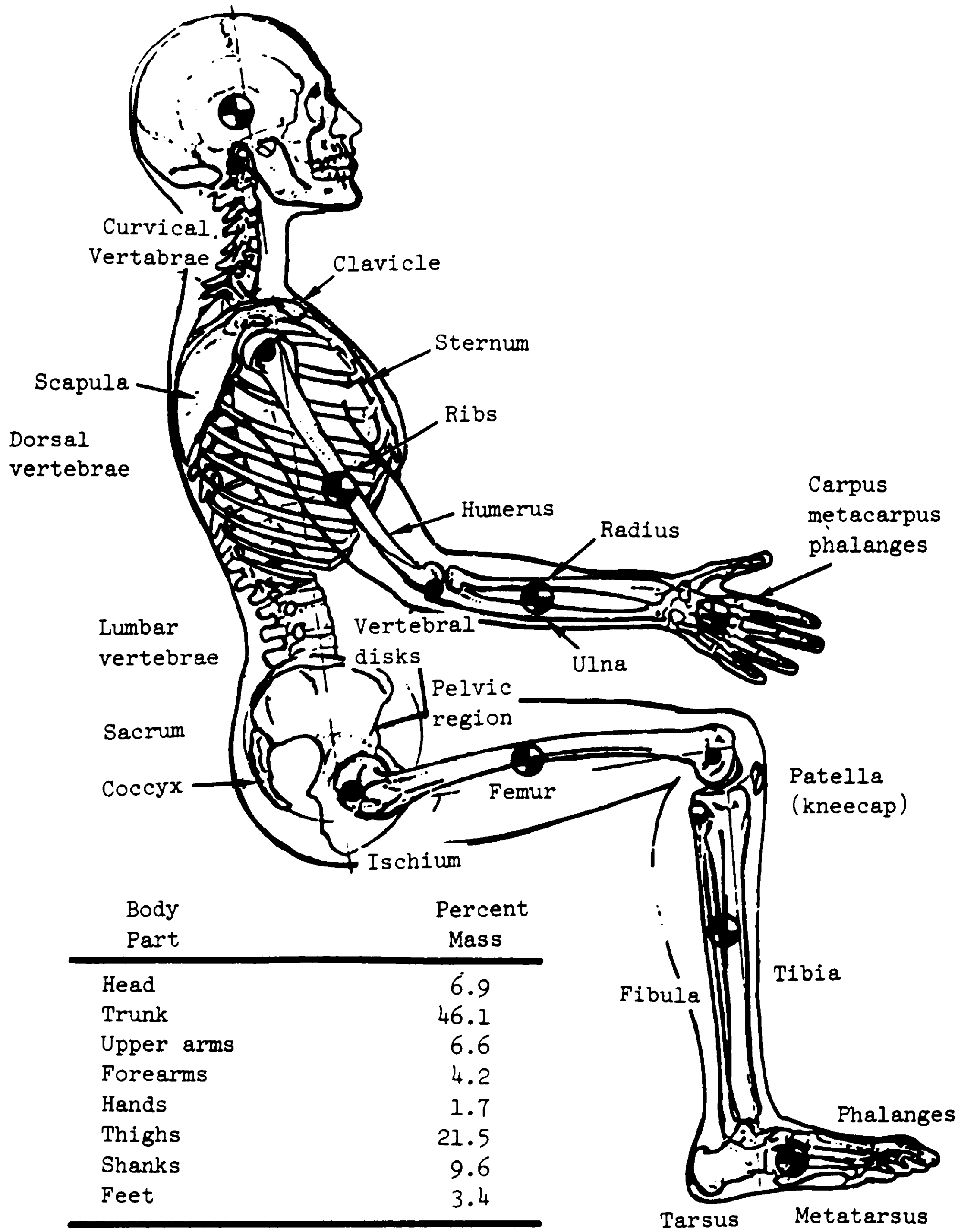

Body Part	Percent Mass
Head	6.9
Trunk	46.1
Upper arms	6.6
Forearms	4.2
Hands	1.7
Thighs	21.5
Shanks	9.6
Feet	3.4
Total	100.0

FIGURE 5-28. Human skeletal structure.

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The penetration of a human body by a penetrator may be estimated by the following equations (Reference 99):

Body penetration threshold:

$$V_{SO} = K \frac{A}{M} + b$$

Where:

A = Penetrator average presented area (cm^2)
M = Penetrator mass (grams)
K = Constant (nondimensional)
b = Constant (meters/second)

Constant	Winter Clothing	Bare Skin
K	73.5	22.0
b	241 m/s	72.2 m/s

Depth of body penetration:

$$P = \frac{MVo}{eA}$$

Where:

M = Penetrator mass (grams)
Vo = Penetrator striking velocity (meters/second)
A = Penetrator average presented area (cm^2)
e = Constant (nondimensional)
P = Depth or penetration (cm)

The criterion probability of kill given a hit ($P_{K/H}$) of a human by a projectile or fragment has utilized a specific minimum kinetic energy level together with a minimum striking velocity. It is used as a rule-of-thumb means for aircraft system vulnerability estimates. The specific values are classified and are contained in Volume 4 of this publication under the same paragraph number as this section. A compilation of projectile types and corresponding impact velocities related to the kill level criterion are provided. The response of the human body to high-explosive blast overpressure is an area of personnel vulnerability where only limited data are available. This is due to the limited empirical data available and the complexity of determining the effective (reflected) pressure imposed upon a subject in an aircraft system. High-explosive projectiles and missile warheads generate fast-rise pressure waves of very short duration. These are generally in the 3- to 5-millisecond range. The injury levels sustained by human subjects from such fast-rise times are shown in Table 5-IV (Reference 99). ,No specific values are available on the susceptibility of human eyes to damage from high-explosive blast waves. This factor should not be ignored in the protection of personnel.

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TABLE 5-IV. Blast Effects on Personnel (No Protection).

Critical Organ Damage	Maximum Effective Overpressure (Pe) (Psi)
Eardrum rupture	
Threshold	5
50 percent	15 - 20
Lung damage	
Threshold	37 - 49
Severe	98
Lethality	
Threshold	112 - 156
50 percent	156 - 217
Near 100 percent	217 - 302

5.4.1.1.2 Personnel secondary weapon effects. Secondary weapon effects also constitute a significant source of potential hazards to aircraft personnel that may be capable of causing permanent or temporary impairment to their capability to perform their assigned tasks.

These hazards include not only those that act directly on the body, but those that impair the capability to perform a required mission-essential function (i.e., vission, communications, etc). The major concerns are those that affect the environment in which personnel are required to operate. One area frequently overlooked is the creation of secondary hazardous conditions that can degrade the aircrew's capability to perform their mission duties. Ignition of combustibles within the cockpit area, either by the direct action of an incendiary projectile or the liberation of hot gases, should be considered. A careful and stringent selection of materials used in the aircrew and passenger compartment will provide a low fire potential that minimizes or eliminates the need for an extensive fire protection or other protection system.

5.4.1.1.2.1 Smoke. Smoke is obviously an irritating substance that is alien to the normal well-being of crewmembers and passengers. Toxins are usually more insidious and can produce an injurious or deadly effect on the human being. Toxic contaminants in an aircraft usually originate from sources such as plastics, lubricating compounds, insulations, paints, cements, and residual solvents from decreasing treatments. Toxins may also be created by the heating of engine and hydraulic fluids. Carbon monoxide is a common contaminant of sealed spaces. High concentrations of carbon dioxide and even oxygen are considered toxic under certain conditions. Table 5-V contains a listing of common materials and the number of milligrams of smoke component produced by the combustion of 1 gram of each material. Table 5-VI shows the smoke produced by combustion of various materials. Table 5-VII shows short-term exposure limits for a number of substances which may be expected to

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TABLE 5-V. Contaminants produced by combustion.

(Milligrams of contaminant produced by the combustion of 1 gram of material)

	Carbon Dioxide CO_2	Carbon Monoxide CO	Hydrochloric Acid HCL	Sulfur Dioxide SO_2	Benzene C_6H_6	Unsat. Hydro-carbons*	Nitrogen Dioxide NO_2	Hydrocyanic Acid HCN	Chlorine CL_2	Arsine AsH_3	Phosgene $COCL_2$
Acrylic	63.82	26.04									
Latex foam	553.50	56.33	0.49	0.006	3.92	0.44					
Leather	247.50	3.53		0.006			0.04	0.005	0.045		
Mineral wool	340.2	46.37					0.10				
Modacrylic	46.62	26.69	1.38	0.001		63.05		2.52			
Polyurethane foam	445.5	15.45				9.59					
Plywood	246.63	42.15				5.92				1.3	
Simulated leather	75.82	33.94				11.29					0.05
Vinyl foam	116.6	29.37			6.46	0.72					
Wool	90.	2.86		0.013							

*Determined as acetylene

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TABLE 5-VI. Critical weights and smoke constituents.

Material	Weight to Produce Critical Limit (grams)	Smoke Constituent Producing Critical Limit
Acrylic	66	Carbon monoxide
Latex Foam	30	Carbon monoxide
Leather	267	Chlorine
Mineral Wool	37	Carbon monoxide
Modacrylic	26	Hydrogen cyanide
Polyurethane Foam	111	Carbon monoxide
Plywood	41	Carbon monoxide
Insulated Leather	51	Carbon monoxide
Vinyl Foam	58	Carbon monoxide
Wool	600	Carbon monoxide
DER* 331 + CA**	0.2	Hydrobromic acid
DER 542 + MDA**	0.3	Hydrobromic acid
DER 542 + MNA**	0.6	Hydrochloric acid
DER X-3448 + MDA**	0.2	Hydrochloric acid
DER X-3448 - MNA**	0.6	Hydrochloric acid

*Dow epoxy resin

**Curing agent

occur in hazardous amounts in smoke. It specifies the highest concentrations which a person may safely inhale for short periods. It must be emphasized that these are not precise figures; but while exposure times of 10 minutes to 1 hour are listed, they should be considered as concentrations which should not be exceeded. Inhalation of greater concentrations is apt to cause a variety of toxic injuries. While some of the figures appear conservative, it must be remembered that carbon dioxide, fear, and activity will increase the respiration rate, thus increasing the dose absorbed by the body in a given time. In addition, it is probable that, when materials are absorbed as particles, they can exert a very much greater effect than when they are inhaled as gas or vapor.

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TABLE 5-VII. Short-term exposure limits for smoke constituents.

Constituent	Parts Per Million (ppm)	mg/m^3	Remarks
Arsine (A_sH_3)	30	96	6 to 30 ppm can be inhaled for 1 hour without serious consequences.
Benzene (C_6H_6)	3,000	9,570	3,000 to 4,700 ppm can be inhaled for 1 hour without serious consequences.
Bromine (Br_2)	4	26	Maximum allowable conc for 30 to 60 min.
Carbon dioxide (CO_2)	50,000	90,000	Navy permits 1-hour emergency exposure to this level. 50,000 ppm provides signs of intoxication on 30 min exposure.
Carbon monoxide (CO)	1,500	1,717	NRC emergency exposure limit for 10 min.
Chlorine (CL_2)	4	12	Maximum allowable concentration for 30 to 60 min.
Fluorine (F_2)	3	5	NRC emergency exposure limit for 10 min.
Hydrobromic acid (BRr)	30	99	By analogy to HCL and CL_2.
Hydrochloric acid (HCL)	30	45	NRC emergency exposure limit for 10 min.
Hydrocyanic acid (HCN)	60	66	50 to 60 ppm for 1 hour has no serious consequences. 45 to 54 ppm for 30 to 60 minutes has no immediate or late effects.
Hydrofluoric acid (HF)	20	16	NRC emergency exposure limit for 10 min.
Nitrogen dioxide (NO_2)	30	56	NRC emergency exposure limit for 10 min.
Phosgene ($COCL_2$)	3.0	12	3.1 ppm is least amount causing immediate throat irritation; 4.0 causes immediate irritation of the eyes; 4.8 causes coughing; 25 ppm is dangerous for even short exposures.
Sulfur dioxide (SO_2)	30	79	NRC emergency exposure limit for 10 min.

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5.4.1.1.2.2 Toxic products. The weight of material which can be burned in a confined area will be limited by various toxic products depending on the material. Table 5-VII lists the type and amount of material that can be safely burned in 1 cubic meter of space, as well as the number of grams required to reach limiting concentrations. As can be seen, the most common smoke constituent to create a toxic hazard is carbon monoxide. Figure 5-29 shows the effect of carbon monoxide concentrations in air at sea level on humans.

5.4.1.1.2.3 Protection methods. Protection against smoke hazards may take various forms. An obvious possibility is selection of materials to minimize the amount of smoke which may be produced. A substantial number of materials produce no visible smoke when heated to 400°F. In this connection, it must be recalled that smoke is not only a product of combustion, but is also a result of pyrolysis or decomposition by heat alone. During actual combustion, some materials burn with very little or no visible smoke, whereas others produce copious amounts of very dense smoke. It is clear then that careful selection of materials can reduce or eliminate visible smoke. Another method for reducing smoke hazard is through the use of nonflammable covers or coatings. While this principle has been in use for some time (seat upholstery, for example), there is an aspect of this practice which requires a word of caution. The products from combustion of certain halogenated epoxy resins, which might be used as fire-resistant materials, can produce a critical amount of halogen acid from very small concentrations. Their extremely irritant quality warns of their presence; however, that may allow corrective action. Other factors to consider when reducing smoke hazards are:

a. A careful and stringent selection of materials used in the crew and passenger compartment can result in a low fire frequency potential that does not require extensive protection provisions.

b. Materials should be selected that will not support combustion and that, when ignited, will not continue to burn when the heat source is removed.

c. Materials should be selected that will not produce toxic products of combustion in quantities greater than can be readily removed by the environmental control systems.

d. Flame-resistant coatings should be considered for combustible items such as Velcro. The success of tetrafluoroethylene coatings has stimulated the development of coatings (e.g., Fairprene) that are capable of resistance to l,OOO°C flame environments with no degration or flame propagation.

e. The use of nitrogen from inflatable equipment sources should be considered for the crew compartment fire extinguishant.

f. Manifolding of stored nitrogen should be considered to provide stream, cone, deluge, or high/low-pressure saturation of crew and passenger compartments and exit areas.

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	Effects
1.28	Immediate effect; Unconsciousness and danger of death in 1 to 3 min
0.64	Headache and dizziness in 1 to 2 rein; Unconsciousness and danger of death in 10 to 15 min
0.32	Headache and dizziness in 5 to 10 min; Unconsciousness and danger of death in 30 min
0.16	Headache, dizziness, and nausea in 20 tin; collapse, unconsciousness, and possibly death in 2 hr
0.08	Headache, dizziness, and nausea in 3/4 hr; collapse and possibly unconsciousness in 2 hr
0.04	Headache (frontal) and nausea after 1 to 2 hr; occipital after 2-1/2 to 3-1/2 hr
0.02	Possibly headache (mild frontal) in 2 to 3 hr

FIGURE 5-29. Effects of CO concentration in air at sea level.

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g. NASA has extensive information on odor, carbon monoxide, total organics, and flashpoint factors of plastic materials. These data can be highly useful for design application.

h. Analyses should be conducted for the following fire safety considerations:
   (1) Sources of ignition hazards
   (2) Determination of equipment capable of explosion or implosion
   (3) Classification of equipment capable of explosion or implosion
   (4) Determination and classification of equipment capable of temperature hazards

i. The handling and use of flammable liquids must be carefully controlled to prevent fires and explosions. The basic measures commonly used are:
   (1) Prevention of evaporation by keeping flammable liquids in closed containers
   (2) Removal of sources of ignition
   (3) Adequate ventilation
   (4) Use of an inerting atmosphere of gas instead of air
   (5) provision of relief vents to minimize structural failure and danger from explosions
   (6) The installation of fixed automatic and manual fire-extinguishing systems

5.4.1.1.2.4 Chemical fire hazards. Chemical fire hazards often are not readily recognized. Apparently harmless chemicals may react vigorously, causing fire or explosion, upon contact with commonplace substances? Some chemicals, when contacted by other materials, will generate heat, give off flammable gasses, or react explosively. Others, through decomposition, may generate heat and ignite spontaneously or support combustion by oxidation. It is important to remember that chemicals may not be flammable in themselves, but can cause fire under certain circumstances. Liquid and gaseous oxygen is not flammable itself, but will support rapid combustion of most other materials. The contamination of any flammable materials by oxygen is extremely dangerous, especially materials such as oil, paint, and grease. The selection of an extinguishing or suppressing system involves a number of considerations. The primary consideration is effectiveness. The designer must select the agent and technique that will accomplish the intent during the worst possible conditions, in the minimum time, and with minimum damage to equipment and systems. Toxicity to personnel can be rated second in importance to effectiveness when exposure to hazardous concentrations is unlikely or when escape from the vapors is possible. Effect of the agent on equipment is important. Extinguishing the fire is of little help if some piece of flight- or mission-essential equipment is damaged beyond use by the extinguishing agent. The most common extinguishing agents are as follows:

Agents	Symbol
Carbon dioxide	(CO_2)
Bromochloromethane	(CH_2BrCl)
Dibromodifluoromethane	(CF_2Br_2)

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Agents	Symbol
Bremotrifluoroumethane	(CF_3Br)
1.2 dibromotetrafluoroethane	(CF_2BrCf_2Br)
Carbon tetrachloride	($CC1_4$)

5.4.1.1.2.5 Explosion-suppression systems. Explosion-suppresstion systems consist of extremely sensitive pressure or flame detectors that sense an impending explosion and discharge an inhibiting agent. The agent suppresses the explosion before the pressure can reach a dangerous level.

5.4.1.1.2.5.1 Pure Air. A limiting factor in use of high-expansion foams and chemicals is the requirement for pure air to complete chemical reactions and foam expansion. Tests have indicated insufficient foam generation where combined with smoke-laden air. Design of any aircraft high-expansion foam system will seriously have to consider this limiting factor.

5.4.1.1.2.5.2 Toxicities. It is to be noted that all fire suppressants identified will require analysis and testing with respect to the extinguishants toxicity levels and toxicities of their pyrolysis products. In the case of HEL, the interaction of the laser beam with the suppressant must be considered. A protective system, for defeating hostile laser energy, should not interact in an unsafe manner with suppressants to produce toxic products.

5.4.1.1.2.5.3 High-thermal conditions. When personnel are exposed to high-thermal (heat) conditions, two main survivability factors must be considered. The first is tolerance to pain, and the second, the thermal level at which exposed skin will experience second-degree burns. The average human experiences "unbearable" pain when the skin has been heated to a minimum temperature between 108° to 113°F. Figure 5-30 provides representative data for exposed skin pain threshold in terms of air temperature. It should be noted that 360°F is considered to be the maximum temperature to which the human respiratory system can be subjected without damage.

5.4.1.1.2.5.4 Loss of pressurization. The loss of personnel station pressurization can have a significant affect upon the capability of a human to survive and/or perform mission-essential functions. This includes both slow and abrupt (explosive) decompression. The values for human debilitation from environment pressure changes is classified. This information is contained in Volume 4 of this publication.

5.4.1.2 Personnel station placement/arrangements. Consider the most advantageous crew and passenger station locations that will provide natural masking against the predominant directions of anticipated hostile weapon attack. Position noncritical or less critical components and elements of the aircraft system so that the most effective amount of natural masking may be obtained for the least weight and cost penalties to the total system. Personnel should also be adequately masked and/or separated from accumulators and other pressure vessels, flammable or toxic materials, and explosive or pyrotechnic devices which, if damaged by nonnuclear weapon effects, would generate

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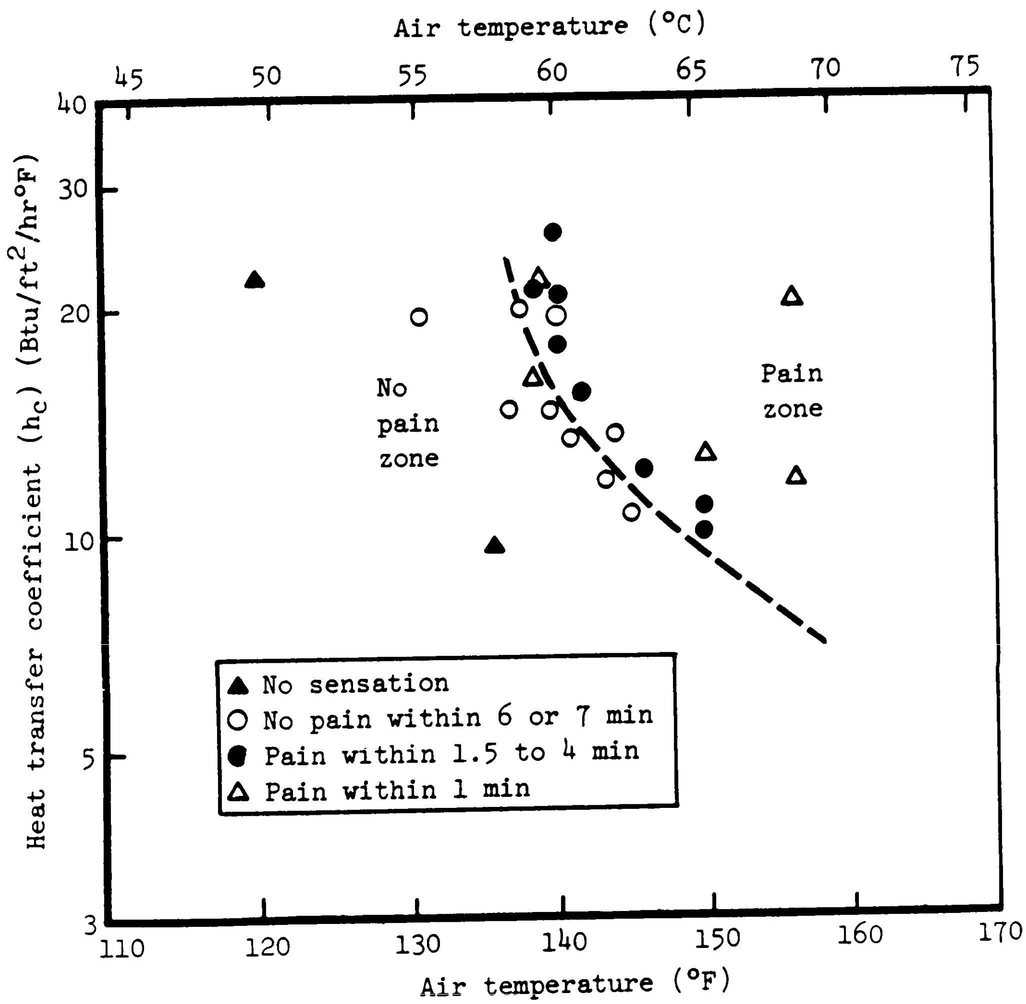

FIGURE 5-30. Exposed skin pain threshold.

hazardous conditions affecting personnel duty performance or health. These data indicate the dividing line between painful and nonpainful heating for air at various temperatures versus the heat transfer coefficient, which depends on air density, air velocity, and surface areas and shape. The data were obtained by exposing a small segment of the cheek to a flowing airstream through a padded hole in the wall of a cylindrical tube. h_c was computed from air velocity and duct geometry.

5.4.1.2.1 Multiple crewmembers. When multiple crewmembers are required, consider crew station design configurations that will permit separation and mutual shielding to prevent or minimize simultaneous injury or fatality of multiple crewmembers from the impact of single explosive and nonexplosive projectiles or missile warheads in a crew station. For example, a pilot and co-pilot, not adequately separated and shielded from each other, may both be

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fatally injured by the detonation of a single high-explosive projectile in the cockpit area. This would cause immediate loss of the aircraft system. A similar loss may also be experienced from the generation of large-spallation material caused by impact of structure or components by nonexplosive projectiles. To preclude this secondary hazard potential, multiload-path thin-section stringers should be used in place of heavy-section longerons for crew and passenger stations in order to minimize the amount of span generated. See Reference 197 for details on Aircrew Protection Requirements.

5.4.1.2.2 Crashworthiness. For light fixed- and rotary-wing aircraft, consideration must also be given to crashworthiness requirements when specified for the aircraft system. The specific requirements and design criteria for crashworthiness are contained in Reference 205. The general crash survivability design factors specify that the probability of occupant survival during crash impacts will be enhanced by incorporation of the following design factors:

a. Airframe protective shell - that portion of the aircraft structure capable of maintaining occupant living space throughout a crash.

b. Occupant acceleration environment - Limiting the direction, rate, and magnitude of impact acceleration forces on the occupant within the specified human tolerance levels.

c. Occupant environment hazard - Avoidance of barriers, projections, and loose objects in the immediate vicinity of the occupant which could cause contact injuries in a crash.

d. Postcrash hazards - Avoidance of design features that could cause fire, smoke, toxic gases, drowning, exposure, etc, hazards following an impact sequence.

5.4.1.3 Controls and displays. Instruments and equipment should be provided that will prevent or minimize the generation of hazardous spallation due to penetration by projectiles or fragments; for example, nonsplintering or nonshattering instrument face glass to prevent or minimize crew injury:

a. The controls and displays should be designed to be free of sharp objects that can cause crew injury. All protrusions should be padded.

b. Electrical systems should be designed to minimize the probability of electrical shock of aircrew due to projectile damage.

c. Displays and malfunction warning systems should be designed to give the aircrew members sufficient information to determine the location of major malfunctions from combat damage and to take corrective action.

d. Delicate components should be located where the probability of a hit will be minimized and where they will be protected from secondary weapon effects.

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e. Controls, such as switches and adjustment screws, should not be located close to dangerous voltages where ballistic damage may cause shorting.

f. Hand-grasp limitations that may be imposed by wounding of the aircrew should be considered.

5.4.1.4 Secondary hazards. Aircraft personnel are susceptible to injury and debilitation from many secondary hazard conditions that may be initiated by hostile nonnuclear weapon effects. Explosive decompression-is a danger for aircrewman at high altitudes where sudden rupture of the cockpit shell occurs. The most sensitive portion of the cockpit enclosure is generally the transparencies (i.e., windscreen, canopy, windows, etc). In aircraft that operate at high altitudes in combat missions, consideration should be given to the selection of materials for the transparencies that will resist large-area damage propagation and failure from projectile or fragment impact. Figure 5-31 shows the result of a projectile impact on a fighter aircraft windscreen where extensive cracking was experienced in the transparent material. Figure 5-32 shows the loss of large sections of the cockpit canopy that was experienced. Had this type of damage occurred at high altitude, explosive decompression would have occurred and subjected the pilot to an extremely hazardous environment.

5.4.1.4.1 External blast wave effect on transparencies. At low altitudes, combat aircraft transparencies can be shattered by high-explosive blast waves and become dangerous hazards to the aircrew. Reference 100 contains the results of tests conducted on the critical shatter overpressure values for flat panes of stretched and unstretched acrylic materials (Plexiglas). Both laminated and unlaminated types of various thicknesses were evaluated. Figure 4-35 shows the results of the tests. As can be seen, the larger the pane, the lower the blast-over-pressure required for failure. It was also found that there was a distinct difference in the cleavage of the stretched and unstretched materials. The unstretched acrylic tended to fail approximately perpendicular to the plane of the transparent surface. The stretched acrylic tended to fail at oblique angles and produce sharper cutting edges. This factor should be considered in the design of aircraft where blast damage could occur and endanger the aircrew and/or passengers. Higher resistance to external blast damage could be obtained by the use of curved transparencies, but this approach must be evaluated against the increased probability of visual detection of the aircraft by hostile forces from glint. Final determination of the type of acrylic material to be used as transparent surfaces should be analyzed with regard to shattering qualities versus threats encountered.

5.4.1.4.2 Internal blast effect on transparencies. The strength and type of transparencies for crew and personnel stations should be considered where internal blast from high-explosive projectiles can be experienced. Personnel will be subjected to the level of overpressure that is the product of the reflected pressure waves produced by the geometry and material properties within the personnel station. Detonation of a high-explosive projectile warhead produces an incident pressure wave. When this incident wave encounters a surface, as shown in Figure 5-34, it produces a reflected wave. This

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FIGURE 5-31. Projectile impact damage in fighter aircraft windscreen.

FIGURE 5-32. Projectile damage of fighter aircraft cockpit canopy.

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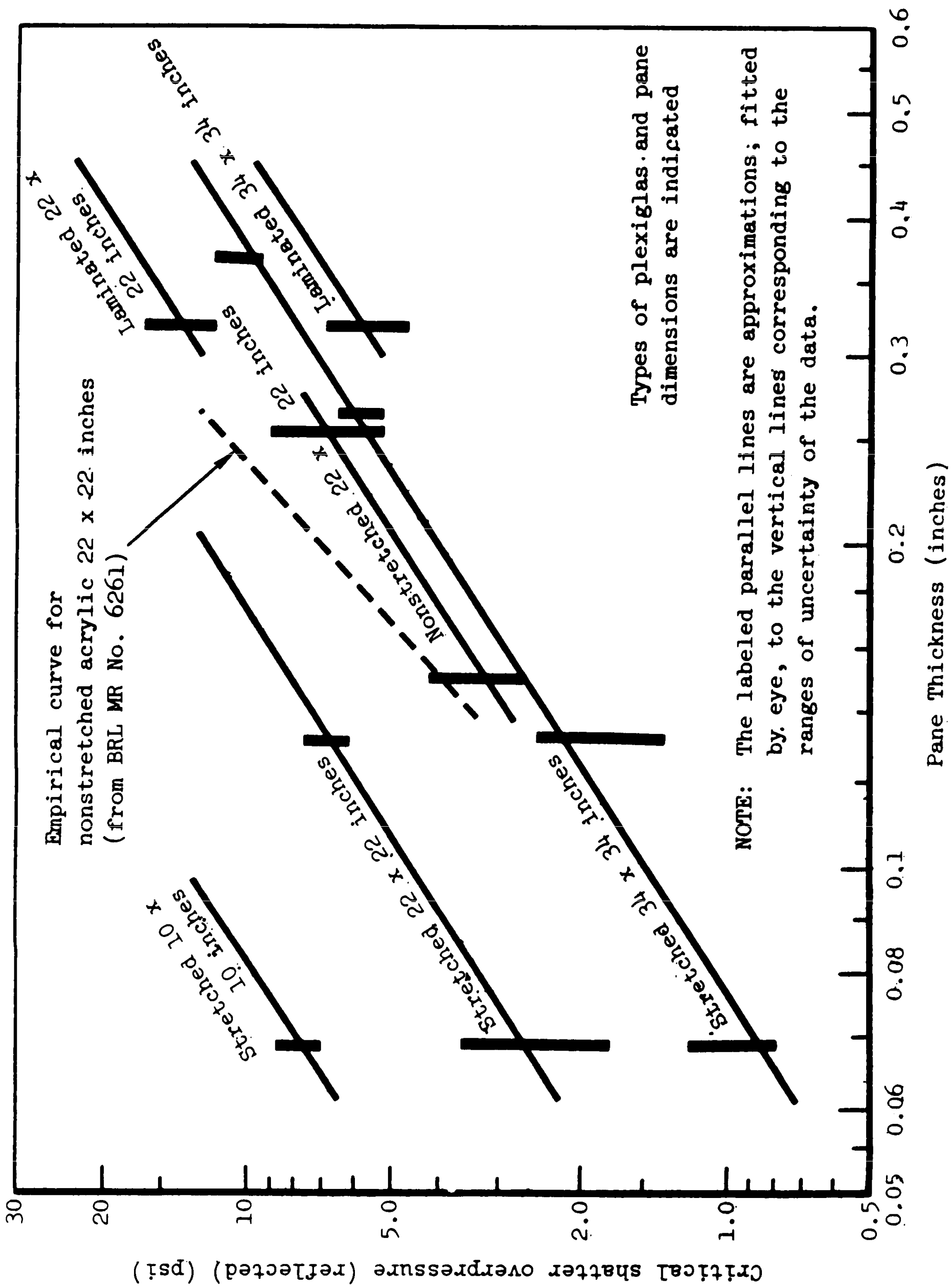

FIGURE 5-33. Critical shatter overpressure (reflected) for panes of Plexiglas.

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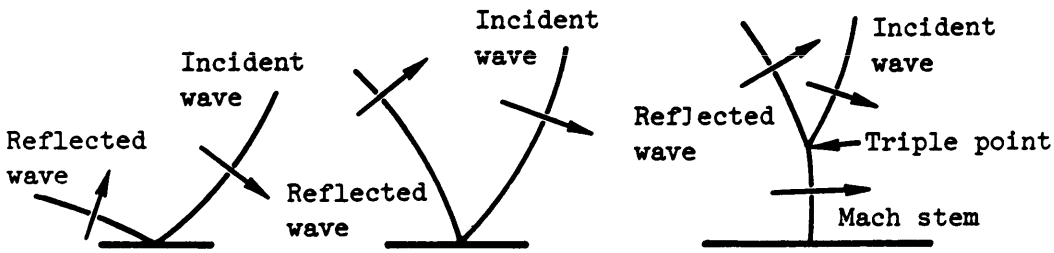

FIGURE 5-34. Fusion of incident and reflected waves and formation of Mach stem.

wave travels through the air that has been heated and compressed by the passage of the incident wave. As a result, the reflected wave attains a higher velocity than the incident wave and overtakes it so that the two fuse to produce a single wave front. This wave interaction point is called the triple point, with the math stem portion below. This interaction produces a higher pressure than the incident wave and is referred to as the reflected pressure. Reduction of the reflected pressures imposed on personnel can be achieved by the geometry and physical characteristics of the structure and equipment close to the subject. Large flat and stiff sections near personnel heads and chest areas should be avoided to reduce the reflected pressures. The transparencies should be designed to allow blowout sections that will also reduce the reflected pressure waves. Figure 5-35 shows an example of transparency failures in a UH-1 helicopter from the detonation of a 23 mm HEI-T projectile within the cockpit area. The preceding design considerations must be incorporated with other protective means, such as body armor protection techniques, to permit personnel survival from the blast and fragmentation effects of the projectile.

5.4.1.4.3 Other secondary hazard considerations.

a. Place breathing oxygen supplies outside of crew compartments where its damage from weapon effects would cause crew injury, inability to complete the mission, or abandonment of the aircraft. Provide a fire- and fragment-resistant barrier between the crew station and oxygen supply compartment to prevent or minimize crew injury from an exploding oxygen bottle or converter.

b. Use separate or redundant oxygen supplies for multiple pilots or crewmembers where loss would result in mission degradation or personnel incapacitation. (Refer to Reference 245 for illustration of multiple oxygen supply system circuits.)

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FIGURE 5-35. 23MM HEI-T Projectile detonation within cockpit.

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c. Provide fire-resistant or suppressant materials in the crew stations to prevent or minimize thermal hazards, toxic fumes, or smoke that would cause crew performance degradation or abandonment of aircraft.

d. Provide automatic warning and necessary corrective actuation of essential subsystems, damaged by nonnuclear weapon effects, where sufficient time would not be available for crew assessment and application of such corrective measures. For example, provide an automatic failure sensing, corrective actuation, and pilot warning system for a hydraulic flight control system where excessive fluid loss in a critical branch would be sensed. Then the branch would be isolated by an automatic shutoff device to prevent complete hydraulic system loss, and pilot warning would be provided to permit damage assessment and subsequent pilot actions.

e. Shield crewmembers, as practically as possible, from accumulators, other pressure vessels, pyrotechnic, or explosive devices which, when damaged from a hostile weapon effect, will cause serious secondary damage or injury. Where applicable, use nonshatterable compressed gas cylinders conforming to Reference 217.

f. Use separated and redundant mission- or survival-essential instrumentation to achieve the mission or survival objective while accepting the least penalty levels.

g. Protection of the aircraft personnel from fires must be considered for Navy aircraft on carrier flight decks and for helicopters after a survivable crash. Considerable research and testing have been accomplished to extend the burn-through time of aircraft structures to provide additional escape and rescue times for the occupants. Contact the JTCG/AS and/or the Naval Weapon Center at China Lake, Calif., for the most current information on this subject.

5.4.1.5 Personnel armor. The protection of personnel against nonnuclear weapon effects requires special consideration in the initial design of an aircraft system and/or in its incorporation into an existing aircraft system. (Refer to Reference 197 for aircrew protection procedures.) The development of the protective system must consider the many design parameters and restrictions in its employment. It requires examination of the various types of armor and natural masking (shielding) that may be employed to select the most beneficial combination of protection features for the individual aircraft system. Table 5-VIII (Reference 101) is an example of the type of evaluation matrix that can be used for the evaluation of all candidate armor concepts. The specific pertinent design parameters must be established for each specific aircraft application to ensure that no significant design factor is overlooked. The installation of armor systems can be cataloged into three basic areas - airframe, crew seats, and body armor.

5.4.1.5.1 Airframe armor. Providing personnel ballistic protection confronts the designer with severe problems of personnel human factors, space and weight limitations, shock attenuation, and armor fabrication limitations.

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TABLE 5-VIII. Candidate armor types and design parameters comparison matrix example.

Pertinent Design Parameters	Body Armor	Adjacent Armor	Integral Armor	Parasitic Armor	Indigenous Armor
Effect on crew performance	Restrictive, especially in aircraft such as fighters where pilot mobility is normally reduced by space limitations.	Restrictive, especially in aircraft where high degree of visibility and mobility are required.	None	None	None
Effect on escape system performance	May be restrictive and require larger energy source for satisfactory ejection. Will also delay arrested descent unless a larger chute is used.	May be severely restrictive due to increase in weight to be ejected and cockpit clearance limitations. Arrested descent delayed.	None	None	None
Effect on aircraft crashworthiness	May degrade restraint system and seat tie down performance due to increased weight.	May be somewhat degrading especially when arranged to protect the frontal zone.	Increase in aircraft weight and structural stiffness will tend to increase magnitude of pulses resulting from impact with the ground.	None if externally mounted. Could be degrading if located internally where panel could tear loose and strike crew or passengers.	None
Effect on bailout operation	Somewhat degrading due to increased weight man must carry. Arrested descent delayed.	May be restrictive depending on cockpit space, especially when arranged to protect frontal zone.	None	None	None
Suitability for protecting against fragmenting projectiles	Very good, except configurations for protecting arms and legs are extremely bulky. Face protection is limited by existing transparent materials.	Very good, except for frontal zone where protection is critical and extremely difficult to achieve without compromising other requirements.	Very good	Excellent	Poor since equipment itself can be a secondary source of fragments when struck by projectiles and other fragments.
Suitability for protecting against threats from the side zones	Fair to poor	Excellent	Very good	Excellent	Generally poor
Suitability for protecting against threats from the forward zone.	Excellent torso protection. Face, leg, thigh, and groin protection is extremely bulky.	Not well suited because visibility and mobility are severely compromised.	Excellent if structural configuration provides convenience of incorporation. Could involve considerable modification to aircraft, particularly those with many forward components such as are characteristic of fighters.	Very good	Depends entirely upon particular aircraft configuration and construction.
Suitability for protecting against threats from the aft zone	Excellent torso protection. Other body areas generally poorly protected.	Excellent	Very good	Very good	Depends entirely upon particular aircraft configuration and construction.
Practical for providing multiple hit capability	No	Multiple hit capability not generally required unless armor is integral with the seat.	Yes, must have multiple hit capability since installation is essentially permanent.	Yes, however the type of armor material used will determine whether multiple hits can be taken or not.	Depends upon nature of equipment and structure.
Conversion from unarmored to armored condition in the field	Excellent	Good to very good.	Not generally practical except for small installations	Fair to good	Not applicable.
Effect on general aircraft maintenance activities	None	Little if any.	None	Could be a hindrance, particularly if externally mounted.	None
Suitability for incorporation into existing aircraft	Excellent where other considerations are not prohibitive.	Very good where other considerations are not prohibitive.	Extremely difficult except for certain isolated locations in the aircraft.	Good	Relocating components is limited. Relocating major structural elements is impossible.
Predictability of ballistic protection afforded	Good	Good	Good	Very good	Very poor because of lack of ballistic data.
Suitability for use in severely space-limited crew stations	Not generally suitable.	Not generally suitable except on seat pan and back.	Excellent	Excellent, if mounted externally.	Very desirable, if possible.

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Considerable research and testing have been conducted on means to provide effective armor protection against nonexplosive projectiles and fragments from externally detonated high-explosive warheads, and for protection against contact fuzed high-explosive projectiles. Detailed information about available armor systems and their application is contained herein. Additional information and guidance may be found in References 23 and 101 through 109. The probability of kinetic energy hits on aircraft in combat is very sensitive to altitude, projectile threat and velocity. High performance aircraft have stringent weight requirements, since weight controls mobility, speed of aircraft and range of operations. The current state of the art on lightweight armor (Reference 123) does not permit complete armor protection of aircraft personnel from all angles of attack for projectile threats above 12.7mm API in size and high velocity large size fragments traveling in excess of 3600 fps from high explosive artillery ammunition or missile warheads. These projectiles vary in mass from 22 to 50 pounds and in muzzle energies from 250,000 to more than 10,000,000 foot pounds. Personnel and aircraft system survivability therefore is dependent upon the combinations of survivability enhancement techniques that can be employed not only to defeat the ballistic penetrators and blast effects of hostile weapons, but those techniques to avoid them as well. For ballistic protection, capability to sustain multiple hits in an area, over 6 inches apart, should be considered. The trunk/torso area of the crew should be protected from the predominant angles of hostile fire to the highest level practical. For fixed- and rotary-wing attack aircraft, the area of coverage desired is usually for positions below a horizontal plane passing over the crewman's shoulder, and in all azimuth directions, with the aircraft in level flight attitude. Although it is difficult to provide full head protection, a limited amount may be possible for the back and portions of the side. The protection of the arms and lower limbs requires additional armor coverage which may be achieved by proper selection and installation of airframe armor together with natural masking features. The basic procedure for the design of protective armor systems is shown in Table 5-IX. It contains the seven steps essential to the development of an adequate armor installation. Consideration should be given to the suppression of spallation within aircraft personnel stations. A number of materials are available for this task and may be incorporated into the aircraft system in order to serve more than one purpose. For example, a fragment-suppression barrier may also serve as crash padding and vibration or sound attenuation devices, in addition to its primary function. Ballistic nylon cloth (Reference 242), fiberglass composites, ballistic felt materials, and Aramid Fiber composites may be employed. The ballistic defeat capabilities of these materials vary with the type of construction and specific material properties. References 123, 112, 111, and 109 contain detailed information on these materials and their ballistic defeat capabilities.

5.4.1.5.1.1 Summary. In summary, airframe ballistic protection shall not restrict or interfere with the movements of the crew that are required for normal operation of the aircraft. In addition, the protection:

a. Shall not restrict the critical portions of the external field of vision of the crew

b. Shall not impair depth perception

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TABLE 5-IX. Seven steps for design of Personnel protective defense against ballistic threats.

Step	Description
1.	Lay out detailed aircraft configuration showing location of personnel and major items of equipment and structure.
2.	Lay out zones of most likely threat aspects on configuration drawing.
3.	Determine natural shielding from equipment and structure. Use this information to select armor material type and ballistic resistance that together will defeat the threat. Modify size and location of panels to minimize penalties.
4.	Position armor panels to cover zones established in step 2. Panel placement will depend upon available space permitted by configuration.
5.	To confirm or reject material selection and panel locations, consider the following design details:
	a. Effects on system weight and center of gravity (CG).
	b. Effect on system operations if armor must be added to escape systems.
	c. Exact space available and limitations or penalties for maintenance actions.
	d. Human factors, such as crew visibility, ability to control the aircraft, mission duties, restriction to movement, fatigue tolerances, and escape capabilities.
	e. Installation penalty factors.
6.	Analyze loads and stresses of panels and their attachments for detail design.
7.	Conduct final weight and CG analysis.

c. Shall not impair color perception

d. Shall not degrade visual acuity

e. Shall include features to permit rapid egress from the aircraft in emergency situations

f. Shall be fire retardant/resistant

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g. Shall present no projections or cutting edges in case of failure due to loads in excess of the crashworthiness design values

h. Shall be interchangeable and not custom fitted for each aircraft. If modular design is used for two threat levels (e.g., caliber .30 and caliber .50), the modules should have common mounting provisions and be interchangeable

i. Shall not be a source of secondary hazards such as span

The use of armor material as basic aircraft structure for the transmission of crash impact loads is considered both feasible and practical. Transparent armor for use in visors, viewports, helicopter bubbles, etc, pose special problems and restrictions. Some glasses have general potential applicability for armor. A suitable shield should be incorporated when armor material is a type that may span on its front face and endanger the protected or adjacent crewmen. Suitable provisions should be made to suppress span and prevent injury to crewmen when armor materials are used that generate span particles from the rear face when defeated. Adding armor to a door can make it heavy enough to permit damage to the aircraft if the aircrew allows it to swing against the structure when entering or exiting. A strong doorstop should be incorporated in the design to hold the door when it is swung open. It is also advisable to include a damper or snubber to prevent the door from being slammed open or closed. The energy absorber, to be efficient, must generate a constant force that is uniform throughout the entire stroke and is independent of velocity. The installed device should not lose its efficiency or require maintenance under typical operating environments.

5.4.1.5.2 Aircrew seat armor. Occupant protection and survival should have primary consideration in the design, development, and testing of aircrew seats. This requirement must be approached from two aspects: the protection capability and the crashworthiness in an aircraft accident. Reference 260 gives detailed information on armored or unarmored crashworthy aircrew seats. Reference 205 states that “adequate occupant protection requires that the seat be retained generally in its original position within the aircraft throughout any survivable accident.” In addition, the seat should in some cases provide an integral means of deceleration attenuation. See reference 113 for detailed information on crashworthy armored seats, including restraint systems. The following paragraphs describe the protection of the seat occupant against ballistic threats.

5.4.1.5.2.1 Design factors. The designer must continually consider functional effectiveness, cost, and ease of maintenance. Protection designed into the seat will defeat its own purpose if it is not used as intended, is discarded by the occupant, is difficult to maintain, or costs too much to produce or to replace. Achievement of acceptable armor confronts the designer with severe problems of comfort, cockpit space limitations, and weight penalties. Thus, the designer must coordinate his seat armor development effort with the requirements and criteria for cockpit/cabin armor. Special problems are created by the configuration and controls of the helicopter and by specialized

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survival and flight equipment. Some of the problems must be worked out empirically with the aid of mockups and experienced aircrew members. The ideal situation of enveloping the pilot/copilot in armor must be compromised in favor of (1) the pilot's controls, (2) the necessary clearance for the operation of the pilot's controls, and (3) the clearance for ingress to and egress from the aircraft.

5.4.1.5.2.2 Operation interference. Armor applied to the seat should supplement other protective devices and techniques and should protect the trunk-torso body area of the occupant when seated in the normal manner. This protection should defeat small-arms fire striking from positions below a horizontal plane passing across a crewmember's shoulders while the aircraft is in level flight altitude. This protective equipment should not restrict or interfere with the normal operation of the aircraft by the crew. The seat protective unit should not interfere with the proper operation of the occupant's safety restraint under either routine or emergency flight conditions. The unit must be well secured to the aircraft structure, must not entangle the crewman with projections, and must permit rapid exit from the aircraft. Sharp corners, edges, and projections must be rounded and padded. Straps, laces, and buckles must be secured to prevent flapping, especially near open doors and hatches. The seat unit must not swivel uncontrollably and must permit the occupant to steer it by means of foot and leg pressure against the floor of the aircraft. The sitting surface and the crotch protector must have sufficient padding to prevent damaging effects from turbulence and vibration. The crotch protection unit must deflect away from the man when it is struck sharply.

5.4.1.5.2.3 Experimental seat. Reference 113 describes an experimental seat assembly. The seat bucket is constructed of ceramic armor and provides ballistic protection for the 95th-percentile crewman from fire from the side, bottom, and back, from midthigh to shoulder height. Armor coverage totals 13 square feet. The restraint system consists of a lap belt, single-point attachment-release buckle, shoulder harness, and center tiedown strap. These are all secured to the seat bucket, to insure occupant restraint during seat bucket movement, e.g., when the seat energy absorber strokes. The seat bucket is attached to the seat support structure in such a manner that the bucket will stroke vertically a minimum of 12 inches while limiting occupant deceleration loading to human-tolerance levels. The vertical movement capability of the seat must not be degraded by the armor weight. This assembly requires adequate strength of the floor to accept crash loads.

5.4.1.5.2.4 Current types. Armored pilot and copilot seats have been designed and produced for many combat aircraft. The most current types are composed of a backup material, fiberglass, aramid fiber composites and aluminum, over which a layer of ceramic armor is bonded. Figure 5-36 shows an example of a helicopter armor seat shell before the application of the ceramic armor. Figure 5-37 is an example of an armored seat complete with cushions and restraint systems. Figure 5-38 shows the seat installed in a rotary-wing aircraft. The armored side panels are fastened to the seat by hinged attachments that permit easy ingress into and egress from the cockpit.

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(Photo courtesy of Russel Plastics)

FIGURE 5-36. Helicopter armor seat shell fabricated from Aramid fiber composite.

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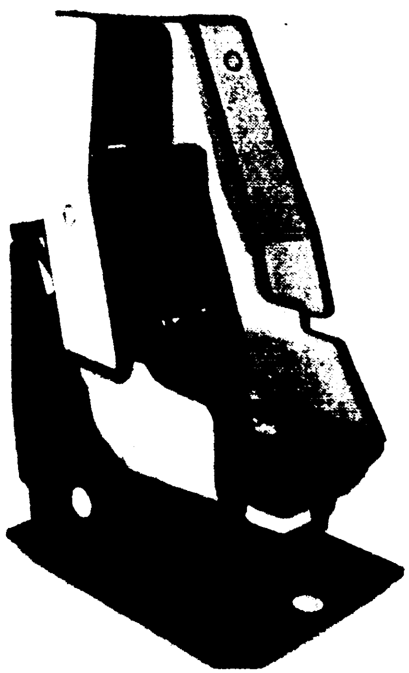

(Photo courtesy of Carborundum Co)

FIGURE 5-37. Ceramic armor seat complete.

(Photo courtesy of Carborundum Co)

FIGURE 5-38. Ceramic armor seat installed.

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Design and operational experience has established the following criteria for armor seats:

a. Where ceramic armor is used, consider small-section design concepts to protect against multiple hits. A ballistic impact in one' section should not destroy or crack another section.

b. An armored torso shield should not interfere with the occupant's capability to operate the controls or equipment.

c. Consider the use of armor panels as structural elements in the seat design.

d. Side, shoulder, and torso shield panels should be easily removed for repair or replacement if damaged and should be completely interchangeable from seat to seat.

e. Side-by-side armor seat concepts most be considered separately from tandem armor seat concepts to take advantage of mutual shielding effects.

f. Armor "convertibility" (designs with two protection levels) should be considered in the seat design for mission flexibility in low- and high-threat areas. The two protection level armor elements should be interchangeable and use the same mounting provisions.

g. Headrest armor should should not interfere with head movements or block the vision for essential viewing angles. Articulated headrest armor should be considered where limited combat viewing angles are acceptable and greater viewing angles are required for takeoff and landing.

h. Seat armor should be designed to prevent interference with the performance of the crewmembers' primary duties. For example, a protective seat for a helicopter door gunner must permit the necessary body movements that will allow firing the weapon straight down, forward, laterally, and aft.

i. In fixed-wing aircraft, armor seat damage should not interfere with its ejection capability and permit proper parachute deployment and seat separation to assure safe crew escape and recovery.

j. Armor seats should accommodate all-size crewmembers (5 to 95 percentiles) while wearing the required combat equipment, including body armor, sidearms, canteens, and survival kits.

k. Armor seats that incorporate a groin (crotch) protector should have a positive stop to prevent the protector from hitting the occupant if impacted by a projectile or fragment. Reference 23 provides detailed evaluation of seat/groin protectors, describing concepts and uses, unit dimensions, operational time limitations, and specific

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feature comments. Reference 23 also provides human factor requirements and recommendations for armor seats, including dimensions, contours, edge finishes, seat cushions, cover materials, seat locations and supporting structures, and clearances with surrounding structures.

l. For rotary-wing aircraft, special space allowances are required for pilot and copilot operation of the collective control lever. Clearance of the operator's hand on the control level is a factor that limits the allowable seat width. Arm clearance must be considered in the design of shoulder armor coverage and seat attachment locations.

m. The design of a torso shield incorporated into the seat should consider the following: (1) chest clearance must accommodate a 95-percentile occupant, (2) underarm height must be nonrestrictive for 25-percentile-size occupant, (3) the shield must be easily articulated for ingress and egress, (4) the shield must be fully supported by the seat, (5) the shield should withstand crash loads without becoming detached and becoming a missile, (6) the shield should have a single-point release mechanism to permit emergency escape in a crash, (7) the occupant should be able to reach forward or overhead instrument/control panels without release of the shield from the locked position, and (8) the shield design should be such that the occupant will not be guillotined or suffer face impact if crash loads would cause abrupt forward head movement.

n. Mockups of armored crew seats should be constructed to check and ensure crew comfort and prevent restriction of crew functions.

Figure 5-39 shows an experimental armor seat with a torso shield incorporated.

5.4.1.5.3 Body armor. Aircrew personnel expected to be exposed to hostile nonnuclear weapon effects are prime candidates for application of body armor. Such protective devices are normally provided as Government-furnished personnel equipment. The aircraft system design manager has the responsibility to consider the use of available candidate body armor systems in the overall survivability of the total system. Where suitable body armor components are not available, consideration should be given to the establishment of design criteria that may be submitted to the responsible military agency for evaluation of new armor systems development. Paragraph 5.3.4.1 of Reference 197 provides the basic guidance for body armor. It specifies that protection capability of the specified body armor shall be considered in the overall aircrew protection system design. For example, body armor designed to protect the front portion of the torso may be considered as a supplemental means, or the only means, to protect a pilot from threats from portions of the frontal attack direction. In addition to considering protection afforded by body armor, integration of

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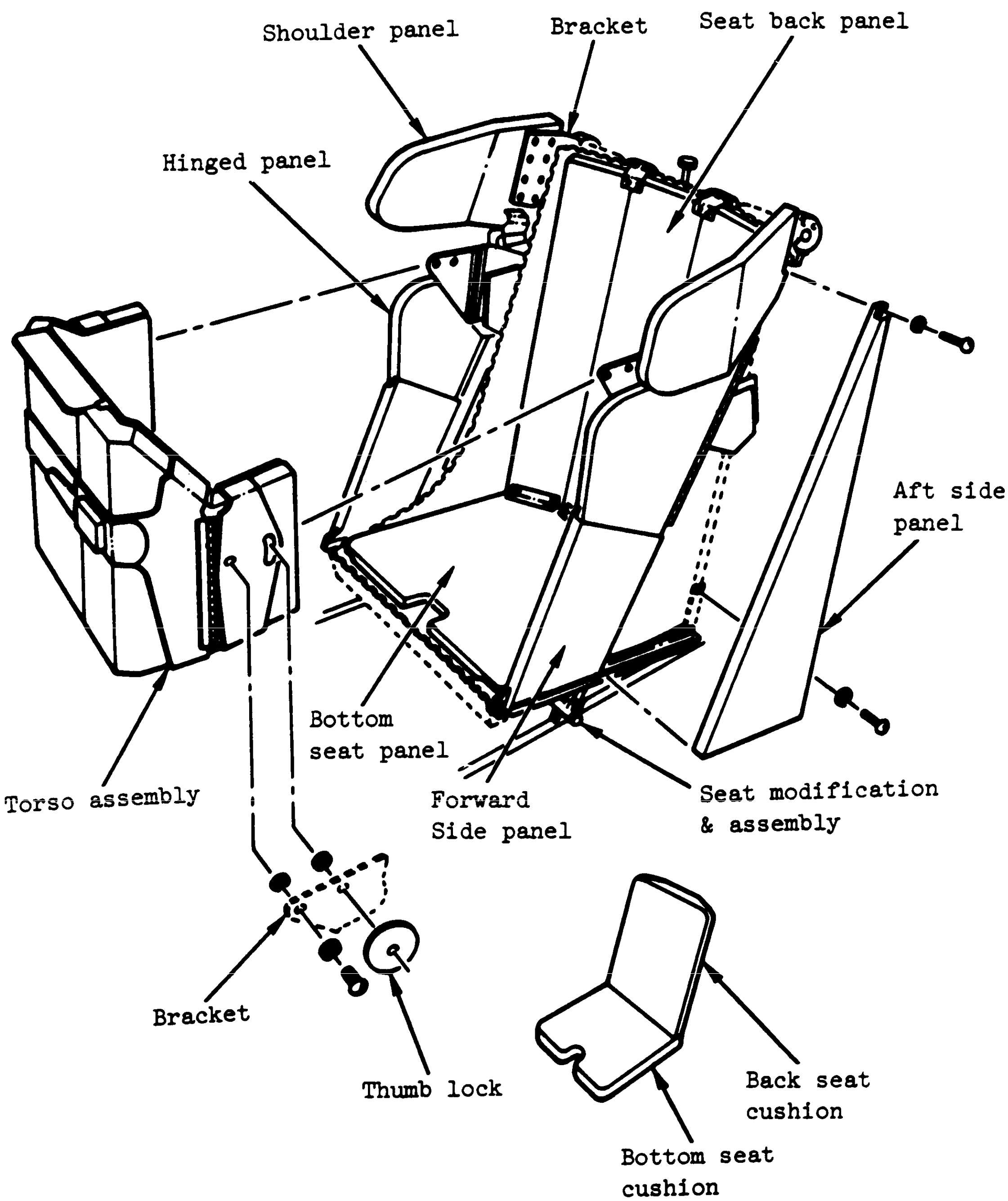

FIGURE 5-39. Armored seat with torso protection.

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body armor with the crew station and associated equipment shall be considered as follows:

a. Effect of the body armor weight and bulk on crew mobility, and consequently crew station arrangement, ensuring crewmembers are not prevented from performing assigned duties nor prevented from accomplishing normal or emergency egress/ingress.

b. Effect of the body armor weight and bulk on crew comfort, ensuring the crew station is designed to minimize fatigue.

c. Compatibility of body armor with the aircrew restraint system, parachute harness, survival gear, and other life support equipment.

d. Effect of body armor weight distribution on the seat plus man center-of-gravity relationship with ejection seat rocket thrust vector.

e. Effect of body armor weight on seat and restraint system crash loads.

Specific design features for individual classes of combat aircraft must be established to be compatible with their mission profiles and expected hostile threat systems. For example, an Air Force requirement, TAC ROC 17-71, contains the following objectives.

5.4.1.5.3.1 Low-performance aircraft. Aircrews operating low-performance aircraft in combat areas require protection from fragmentation and small-arms ground fire. When the aircraft design does not provide an adequate degree of protection, body armor should incorporate the following features:

a. Be lightweight, not to exceed eight pounds. Less than 5 pounds is desirable.

b. Be designed to integrate with life support equipment; i.e., survival vest, life preserver, and other equipment peculiar to the mission/aircraft.

c. Be designed to integrate with cockpit duties and aircraft hardware.

d. Be easily donned or doffed on the ground and in flight and not interfere with ground entry or exit. Zippers/fasteners or other securing devices must not be susceptible to sticking or binding.

e. Be comfortable, nonfatiguing, and possess breathing/ventilating capabilities.

f. Be manufactured from fire-resistant materials.

g. Be designed in various sizes and contain provisions for individual fitting.

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5.4.1.5.3.2 Types of body armor. Current existing body armor is available for pilots, copilots, and gunners in the form of protective vests, helmets, and groin protectors. Table 5-X contains a list of these items (reference 197). Figure 5-40 shows an example of aircrew wraparound body armor, front and back views. Any projectile can be defeated by an adequate thickness of armor material. However, the adequate thickness, in most cases, materially increases the weight that must be carried by the aircrewman, making it harder for him to move about and causing him to tire rapidly. In addition, for threats greater than caliber .30, while the threat can be defeated, the transfer of projectile impact energy through the body armor to the body could be fatal to an aircrewman wearing the armor. Thus, reduction in weight without corresponding loss in protection, as well as effectiveness of body armor to the wearer, is the driving force behind all body armor development programs. First-hand observation is the only way to accurately determine the extremes of movement of the average aircrewman during a normal mission. Therefore, it is important to have the designer as close to the user as possible so that there is a clear understanding of the manner in which the armor will be used. The aircrew member is a human being with psychological and physiological demands, and the designer must be sensitive to his needs. The aircrewman will not tolerate a protection system if it inhibits his ability to do his job. He must be provided an item that is functional; one that will permit him to do his job without unreasonably taxing his endurance; and one that protects him from the danger of projectiles, fragments, shrapnel, and debris or spill from opaque and transparent structures.

5.4.1.5.3.4 Available design information. The design of aircrew body armor is a specialized technology that is normally outside the responsibility of a specific aircraft system development program. It is usually provided as government furnished personnel equipment. For this reason, no detail design information on this subject is contained in this publication. The aircraft designer must consider the impact that any furnished body armor will have on the total system, as noted in this section.

5.4.2 Personnel HEL protection. The human body is highly susceptible to the injury-producing mechanisms from high-energy laser weapon effects. The primary hazards are skin burns and eye damage. A secondary effect is flash blindness that can occur if the person is looking at or near the incident HEL beam. A first-degree skin burn can be experienced with an exposure of 10 joules/cm^2 energy level for a time period of 1 second, A second-degree skin burn may be generated by an exposure to 20 joules/cm^2 for a period of 1 second. The extent of personnel debilitation is dependent upon the location and amount of burn experienced. The amount and type of protective clothing worn by a person greatly affect the amount of HEL energy required to produce body injury. For example, 160 joules/cm^2 for a l-second exposure time is required to achieve burn-through of four layers of temperate-zone military uniform material and produce a 50-percent probability of a second-degree skin burn. Damage to human eyes will occur when exposed to a high-energy laser beam. Experiments on monkeys have shown that a l-second pulse of 20 joules/cm^2 is sufficient to cause severe cornea burns that result in blindness. Nuclear flash blindness tests have shown that temporary loss of

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TABLE 5-X. Existing body armor systems.

Item of Equipment Nomenclature & Specification	Identification Stock Numbers	Level of Protection	Primary Materials	Approximate Weight (lb)
Armor, Body, aircrewman, small arms protective, front plate with carrier LP/P. DES 5-71	8470-935-3183 - short 8470-935-3184 - regular 8470-935-3185 - long	.30 cal AP at 100 yd range and 0° obliquity	Ceramic composite armor (alumina oxide) class 1	Small - 13 lb Regular - 14 lb 3 oz Long - 16 lb 8 oz
Armor, body, aircrewman, small arms protective, front & back plate with carrier LP/P. DES 5-71	8470-935-3192 - short 8470-935-3194 - regular 8470-935-3194 - long	Same as above	Same as above	Small - 24 lb 9 oz Regular - 28 lb 8 oz Long - 34 lb 2 0z
Armor, body, fragmentation protective, vest with 3/4 collar MIL-B-12370(GL)	Without plastic stiffeners 8470-823-7370 - small 8470-823-7371 - medium 8470-823-7372 - large	.22 cal 17 grain fragment simulator V50-1,250 ft/sec	Cloth, ballistic nylon - spec MIL-C-12369	Small - 7 lb 13 oz Medium - 8 lb 11 oz Large - 9 lb 5 oz X-large - 10 lb 3 oz
	With plastic stiffeners 8470-122-1299 - small 8470-122-1300 - medium 8470-122-1301 - large 8470-122-1302 - x-large	.22 cal 17 grain fragment simulator V50 1,250 ft/sec		Small - 8 lb 5 oz Medium - 9 lb 2 oz Large - 9 lb 13 oz X-large - 10 lb 11 oz
Armor, body, fragmentation protective, titanium/ nylon vest - MIL-A-43197(GL)	8470-965-4772 - small 8470-965-4773 - medium 8470-965-4774 - large		Cloth, ballistic nylon - spec MIL-C-12369 & MIL-T-9046C	Small - 8 lb 1 oz Medium - 9 lb 11 oz Large - 9 lb 4 oz

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TABLE 5-X. Existing body armor systems (continued).

Item of Equipment Nomenclature & Specification	Identification Stock Numbers	Level of Protection	Primary Materials	Approximate Weight (lb)
Armor, body, fragmentation protective (for the groin)	8470-753-6110 - size 28 8470-753-6111 - size 30 8470-753-6112 - size 32 8470-753-6113 - size 34 8470-753-6114 - size 36 8470-753-6115 - size 38 8470-753-6116 - size 40 8470-753-6117 - size 42	.22 cal 17 grain fragment simulator V50 - 1,250 ft/sec	Cloth, ballistic nylon - spec MIL-C-12369	Average weight - 4 lb
Helmet flyer: crash type glass outer shell 06-106 (SPH-4) LP/DES 53-70	8415-155-5981 - regular 8415-144-4985 - x-large	None (crash protection only)	Fiberglass & resin polystyrene	3 lb
Body armor, aircrewman, fragmentation - small arms protective for crew chief & gunner, front & back protection LP/P. DES 5-71	8470-450-3698 - short 8470-450-3699 - regular 8470-450-3700 - long	.30 cal AP at 100 yd range & 0° obliquity for ceramic plate & .22 cal 17 grain fragment simulator V50-1,250 ft/sec for vest	Class 1 ceramic composite armor - alumina oxide with cloth, ballistic nylon (nylon 128)	Short - 30 lb 3 oz Regular - 34 lb 3 oz Long - 39 lb 8 oz
Gunner - Crew Chief as above	8470-450-3704 8470-450-3705 8470-450-3706	Same as above	Utilizing boron carbide ceramic	Short - 25 lb 4 oz Regular - 27 lb 9 oz Long - 31 lb 1 oz

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TABLE 5-X. Existing body armor systems (continued).

Item of Equipment Nomenclature & Specification	Identification Stock Numbers	Level of Protection	Primary Materials	Approximate Weight (lb)
Body armor, aircrewman, fragmentation - small arms protective for pilot-copilot, front protection only LP/P. DES 5-71	8470-450-3713 - short 8470-450-3714 - regular 8470-450-3715 - long	.30 cal AP at 100 yd range & 0° obliquity for ceramic plate and .22 cal 17 grain fragment simulator V50-1,250 ft/sec for vest	Class 1 ceramic composite armor - alumina oxide with cloth, ballistic nylon (nylon 128)	Short - 14 lb 5 oz Regular - 15 lb 12 oz Long - 18 lb 8 oz
Pilot - copilot as above	8470-450-3719 8470-450-3720 8470-450-3721	Same as above	Utilizing boron carbide ceramic material, class 3	Short - 11 lb 8 oz Regular - 12 lb 3 oz Long - 14 lb

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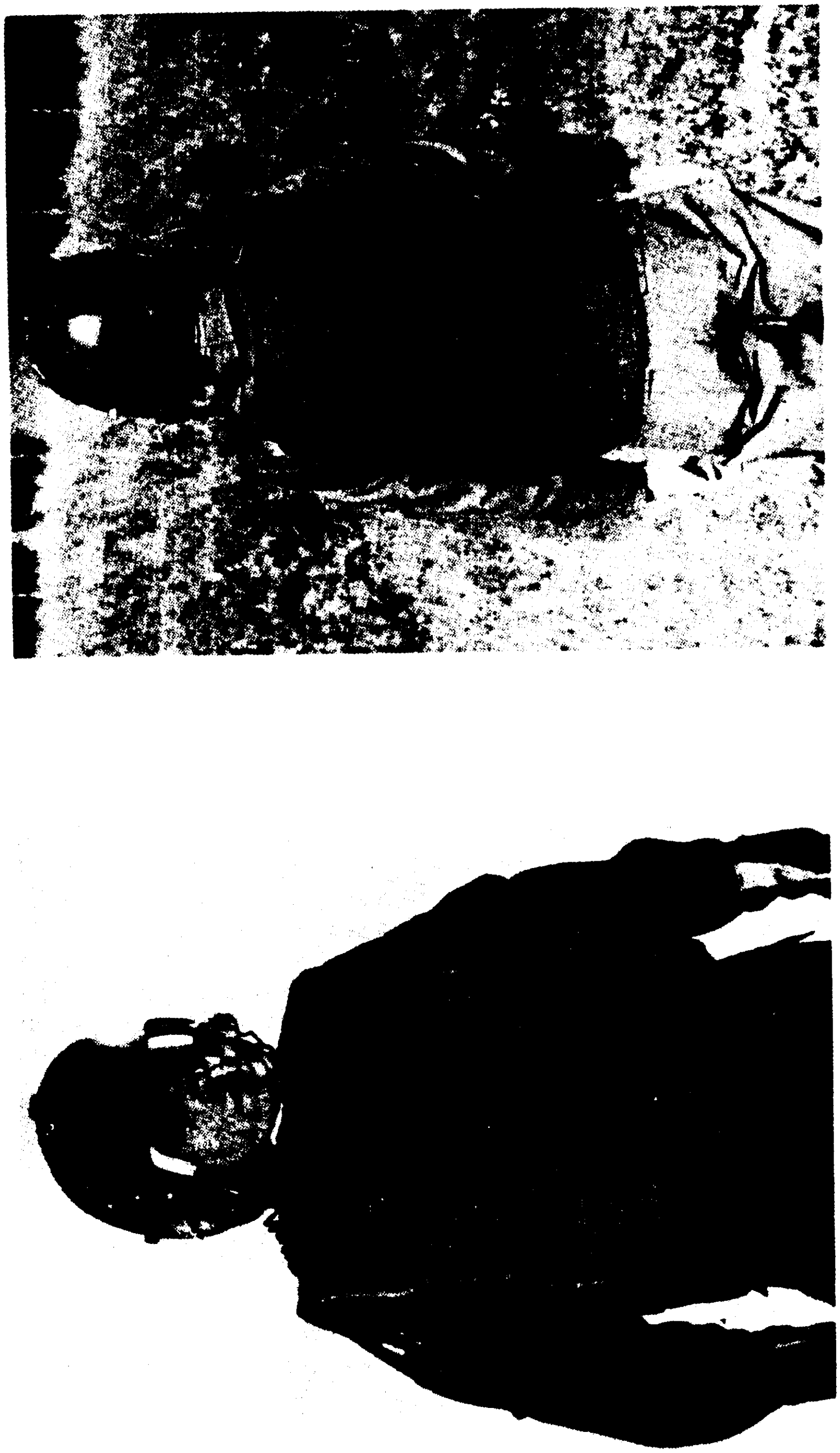

Front View

Back View

FIGURE 5-40. Ceramic composite body armor.

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vision will occur at thermal levels of less than 0.2 joule/cm^2. Protection of the aircrew against HEL weapon effects may be divided into three categories:

a. The first is the opaque portion of the personnel stations that is normally comprised of the structure and equipment surrounding the crew. If this barrier is not sufficient to prevent burn-through by the specified HEL threat, a number of defensive techniques may be used. These include treatment of the fuselage skin to provide a high degree of reflectivity so that less thermal energy is absorbed, incorporation of ablative materials such as "grafoil" or Teflon that absorb the thermal energy while ablating, or use of intumescent materials to react to the initial thermal exposure and form a thick-char material to prevent burn-through. For the latter technique, the char formed is lightweight and fragile. Consideration must be given to the effect of flight airflows that may be capable of sweeping the char away. This would reduce the effectiveness of the protection.

b. The transparent portions of personnel stations require special attention to obtain adequate protection against HEL weapon effects. Acrylics (Plexiglas) rapidly heat to vaporization temperature (950° ± 80°F) and ablate away. Tests have indicated that more crazing of the material occurs from 3-micron-type HEL beams than from 10.6-micron types. Fracture occurs more rapidly at lower powers than at higher powers. Pulsed HEL beams cause rapid vaporization that create hot gases that explosively expand from the parent material and cause high-amplitude stress waves to be transmitted through the transparency that promote failures. The types of glass used in windshields are excellent absorbers of HEL energy at 10.6-micron wavelengths. At high-energy levels, the glass becomes white hot within a few microseconds. The molten glass and gases formed may be swept away by the airflow. In multilayered glass panels, complete burn-through may not occur, but the vision capability will be completely impaired. Considerable effort is being conducted by the Chemical Research Projects Office at NASA-Ames under the sponsorship of the military, including JTCG/AS, for the development of transparent materials with excellent resistance to HEL weapon effects. Improvements are being made to epoxy-boroxine-type materials (EX112 and EX4F9) to enhance their resistance to fire and HEL effects. Contact NASA-Ames for the most current information on this subject.

c. Improvement in personnel clothes and equipment may also be considered to improve their resistance to HEL weapon effects. These improvements may be coordinated with those developed for ballistic protection against fragments and high-explosive blast effects. Aramid (Kevlar) fiber materials are effective for both types of threats and should be evaluated for specific applications.

5.4.3 <u>Personnel stations reliability/maintainability</u>. Personnel stations should be designed to minimize the generation of secondary fragments or span from ballistic penetrators that could cause damage to sensitive instruments,

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components, or transparencies. Provisions should be made to permit rapid removal of instrument panels, equipment, or secondary structures to gain access to electrical cabling, environmental controls, etc., for repairs. Transparencies should be designed to minimize the possibility of explosive shattering when impacted by a ballistic penetrator, The crew stations in an aircraft contain many sensitive items that are easily damaged by primary and secondary weapon effects. These should be identified so that consideration may be given to design methods to remove and replace such items rapidly, either individually or as part of another crew station unit. Transparencies in the crew station are susceptible to damage from ballistic impacts that require direct replacement. They shall be designed to permit such replacement with a minimum of tooling, man-hours, and costs. Materials selected for the transparencies shall produce a minimum of span material that would cause damage to other components and the aircrew in the station.

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5.5 Fuel systems. Past and recent combat experience has demonstrated the vulnerability of unprotected aircraft fuel systems to nonnuclear (ballistic) weapon effects. It has been shown to be one of the primary contributors to aircraft losses in every conflict. Studies and tests have indicated that a similar vulnerability of unprotected fuel systems to hostile high energy laser weapon effects can be expected. Considerable technical advances have been achieved in protection techniques that can provide high levels of survivability for a fuel system. This section contains a compilation of information on aircraft fuel characteristics, combat failure modes, fuel system design, protective techniques, and references to useful data. The designer must consider the type of hostile weapon effects to which the aircraft may be exposed in combat and the primary directions from which it would be experienced. The requirements for fuel system protection features for an individual aircraft will be dependent upon its specified mission, the hostile threat systems it will encounter, and its ability to avoid or degrade the hostile systems detection and tracking capabilities. Fuel system survivability considerations incorporated into an aircraft during its preliminary design phase will produce a greater payoff in terms of total system effectiveness and avoidance of costly and inefficient retrofit modifications after the aircraft has been developed and placed in service.

5.5.1 Hydrocarbon fuel characteristics. With few exceptions, current fixed and rotary wing military aircraft utilize turbine engines for propulsion power. Various fuels have been developed for them over the years. Early jet fuel types, JP-1, JP-2, and JP-3, had operational limiting characteristics that promoted the development of better products. This has resulted in the development of the current jet fuels, JP-4, JP-5, and JP-8, for military use. Commercial Jet A-1 fuel is similar to JP-8. Table 5-XI contains a listing of selected physical properties of these fuels. Table 5-XII contains a listing of jet fuel flammability limits under equilibrium conditions. Volume percent was the measured parameter of the experiments to determine the flammability limits. The Fuel-Air Mass ratio was calculated by assuming a molecular weight for the fuel as follows:

$$\text{FUEL-AIR RATIO (MASS)} = \frac{\text{Volume Percent M.W. (Fuel)}}{\text{(100-Volume Percent) M.W. (Air)}}$$

The Fuel-Air ratios given in Table 5-XII were based on the molecular weights for the liquid fuel. The fuel vapors in the ullage of a tank are a result of evaporation of the "light ends". Therefore, the molecular weights of the ullage fuel vapors is generally 30 to 40 percent less than the molecular weight of the liquid fuel. The reader is also cautioned to be aware that this data is presented as comparative values at equilibrium sea level (pressure/temperature) conditions. The fuel and air concentrations ratio in an aircraft tankage (ullage) is dependent upon a number of variables. They include the temperature of the fuel and air, tank pressures, aircraft altitude and rate of change, tankage geometry, rate of fuel withdrawal, specific fuel properties, sloshing of fuel, and vibration of the installation. Jet fuels are manufactured to the following specifications:

JP-4 and JP-5 MIL-T-5624 (Reference 212)

JP-8 MIL-T-83133 (Reference 262)

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TABLE 5-XI. Selected fuel Properties.

Property	Typical JP-4	Typical JP-5	Typical JP-8	Typical Jet A-1
Distillation				
Initial boiling point, °F	140	360	314	335
End point, °F	455	500	508	510
Gravity, °API	54.4	41.3	43.8	42.3
Freezing point, °F	-80	-56	-65	-58
Flash point, °F	-20	147	118	130
Aromatics, % by weight	11.4	16	16	16
Olefins, % by weight	1	1	2	1
Viscosity centistokes at -30°F	2.4	10.4	8	9.2
Reid vapor pressure PSI at 100°F	2.6	<0.1	<0.1	<0.1
Density, lb/gal	6.41	6.73	6.81	6.78

*Caution: These data are presented as comparative values at equilibrium sea level (pressure/temperature) conditions.

TABLE 5-XII. Jet fuel flammability limits (equilibrium/sea level pressure temperature conditions).*

Fuel Manufacturing Specification Volatility Levels	Flammability Limits			
	Volume Percent		Fuel-Air Ratio (By Weight)	
	Lean	Rich	Lean	Rich
JP-1				
Minimum	0.62	4.66	0.035	0.28
Maximum	0.71	5.15	0.035	0.27
Average	0.67	4.96	0.035	0.27
JP-3				
Minimum	0.76	5.40	0.035	0.26
Maximum	1.70	7.16	0.035	0.25
Average	0.90	6.15	0.035	0.25
JP-4				
Minimum	0.74	5.34	0.035	0.26
Maximum	0.90	6.15	0.035	0.25
Average	0.80	5.63	0.035	0.26
JP-5				
Minimum	0.57	4.38	00035	0.28
Maximum	0.62	4.68	0.035	0.28
Average	0.60	4.53	0.035	0.28

*Caution: These data are presented as comparative values at equilibrium sea level (pressure/temperature) conditions.

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Aviation gasoline, used in piston type engines, is manufactured to specification MIL-G-5572 (Reference 210). Hydrocarbon fuels present a significant fire and explosion hazard to combat vehicles. Low volatility fuels are less susceptible to ignition, sustained combustion, and generation of excessive overpressure, especially if the fuels can be maintained at lower temperatures (typically below 60°F).

5.5.1.1 Flash point and autogenous ignition. ASTM methods are used to determine the flash point and autogenous ignition temperatures of aircraft fuels. The flash point is the approximate minimum fuel temperature necessary to produce a flammable mixture above the liquid fuel surface. An external ignition source is necessary for a reaction. The autogenous ignition temperature is the approximate minimum environmental temperature required for self ignition (no external ignition source) assuming a flammable mixture is at the environmental temperature. The ASTM tests are conducted at sea level conditions. These tests, documented in Reference 172, provide a comparison of the differences in the responses of the different fuel types as shown in Table 5-XIII.

5.5.1.2 Flammability. From a historical point of view it has been common practice to assess the hazards associated with a fuel by comparing the equilibrium flammability range (lean limit to rich limit) with the expected aircraft fuel temperature envelopes. Unfortunately, the determination of equilibrium flammability limits is not an exact science. Flammability is defined as self-propagating combustion. How "self-propagating" is defined is critical to the experimental results. It is well known that upward flame propagation is easier to obtain than downward flame propagation. Also, the term propagation implies some length or time criteria. In addition, the ignition source may affect the apparent measure of self-propagation. The point to be made is that there is no absolute equilibrium flammability range that applies to all conditions.

TABLE 5-XIII. Flashpoint and autogenous ignition temperatures.*

Fuel	Flashpoint [°F]	Autogenous Ignition Temperature [°F]
Jet fuel grade JP-5, MIL-T-5624 (Ref. 212) (least volatile)	140	477
Aviation kerosene JP-8, MIL-T-83133 (Ref. 262)	110	473
Jet fuel grade JP-4, MIL-T-5624	-10	484
Aviation gas MIL-G-5572 (Ref. 210) (most volatile)	-40	844

*Caution: These data are presented as comparative values at equilibrium sea level (pressure/temperature) conditions.

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5.5.1.2.1 Flammability limits. The foregoing discussion may be somewhat academic since the real question is: Is the pressure rise due to combustion sufficient to cause structural damage? Many other factors are involved in this question, therefore, the following flammability limits are based on the historical use of flash point for the lower equilibrium flammability limit. For JP-4 the equilibrium flammability range (sea level) will be somewhere between -20°F and 85°F depending on the particular fuel sample and its aging history whereas for JP-8 the equilibrium flammability range (sea level) will be somewhere between 105°F and 185°F. Although there is no "standard" test procedure for determining flammability limits for hydrocarbon fuels, the type of information presented above is widely used to assess fuel vulnerability. As will be shown in this section, these limits are of little value in assessing fuel vulnerability in the dynamic environment associated with an aircraft. It is well known that the "lean limit" of flammability for jet fuels can be effectively lowered by an addition of fuel spray or mist to the fuel tank ullage. Fuel tank slosh and vibration is one mechanism by which this can occur. Fuel/projectile interaction is another. On the other hand fuel tank venting tends to drive the ullage fuel-air mixture lean thus effectively increasing the "rich limit." It is extremely difficult to quantitatively define the actual environment inside a fuel tank of any operational aircraft at any given time, however, the Air Force Aero Propulsion Laboratory, with JTCG/AS support, has a multi-phase program to more accurately predict the environment in a fuel tank so that more realistic aircraft vulnerability assessments may be conducted. References 173 and 174 provide additional information on this subject.

Fuel mist formation can cause a considerable extension of the lean flammability limit of a fuel as shown in Figure 5-41.

Figures 5-42 and 5-43 illustrate the effects of sloshing and venting on the ullage fuel air mixture.

5.5.1.2.1.1 Lean limit. The Air Force Aero Propulsion Laboratory, using spark ignition, illustrated that fuel sloshing lowered the lean flammable limit. In the program it was shown that with sloshing fuel there was no distinct lean temperature limit at which the ullage gases change from flammable to nonflammable as there is under equilibrium conditions (Reference 175). To illustrate the lowering of the lean limit for JP-8 and JP-5, a slosh frequency near fuel-tank resonance (-17 cycles per minute and 30° double amplitude) was selected and the results are shown in Figure 5-44. The reaction overpressures below the equilibrium lean temperature limit for JP-8 were comparable to the gunfire test results where the projectile generated a fuel spray. As expected, the rich flammable limit for JP-4 was not affected by the sloshing action. The vibration levels (500, 1100, 1200, 2000, 2500 and 3100 cpm and 0.050 inch double amplitude) also used in the test program did not produce sufficient agitation to effect the lean limit. For comparison, Reference 176 gives the typical wing vibration spectrum for the following aircraft.

Aircraft	Frequency (cpm)	Double Amplitude - Inches
F-100	30 to 840	0.1
F-106	30 to 600	0.08
B-58	30 to 42	0.3

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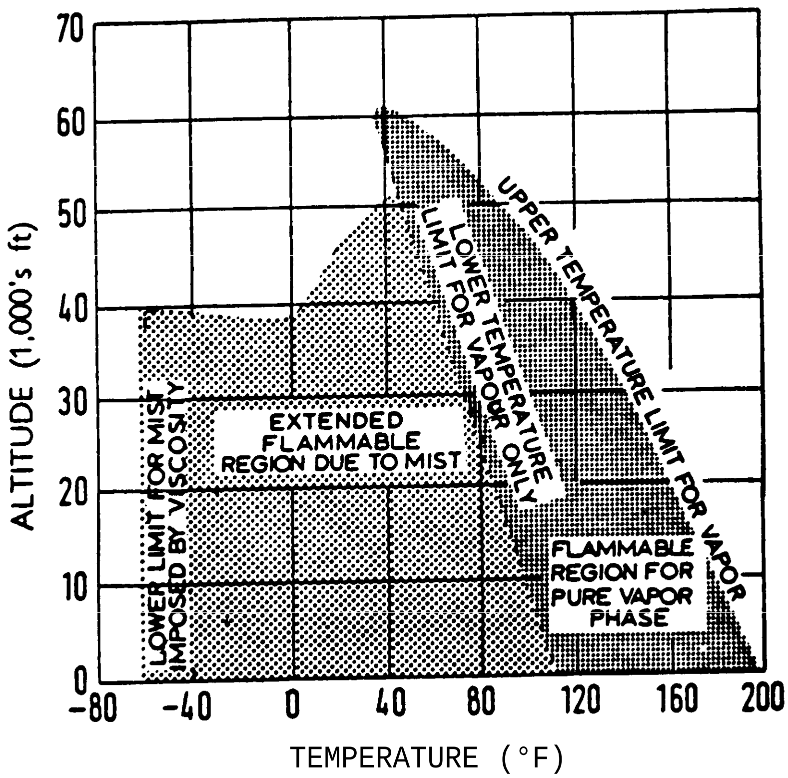

FIGURE 5-41. Flammability limits for kerosene vapor and mist.

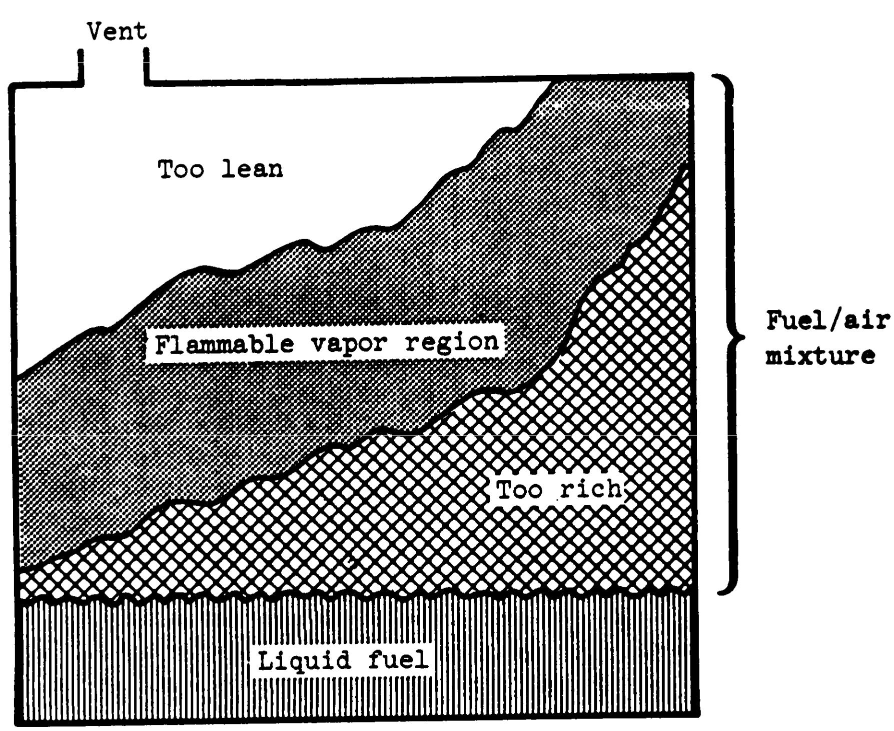

FIGURE 5-42. Flammable vapor stratification distribution layers.

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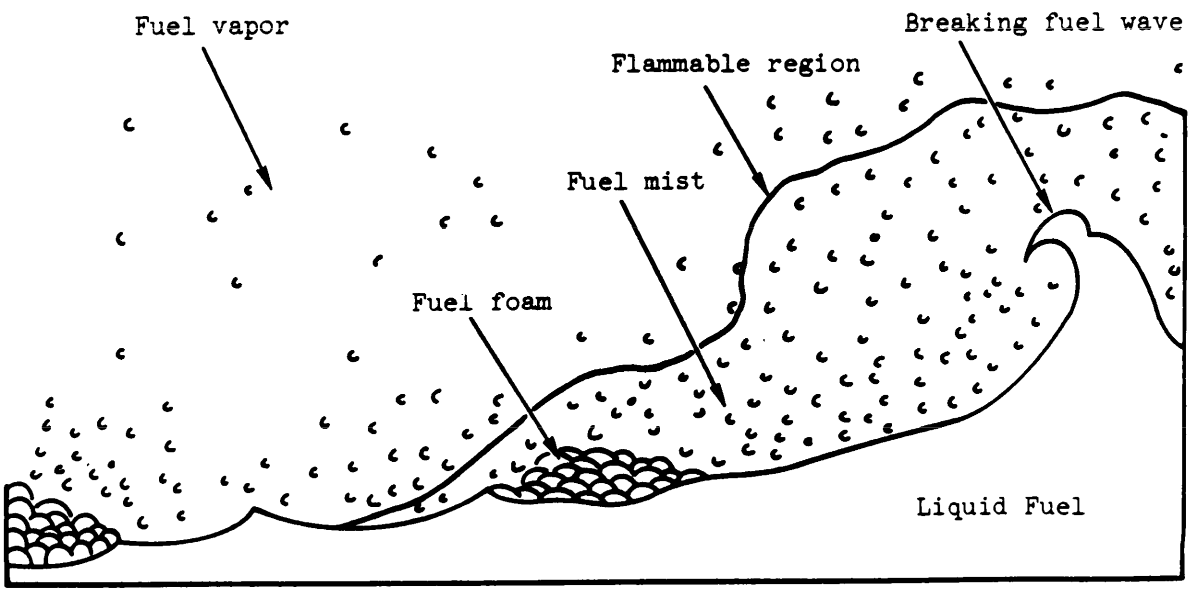

FIGURE 5-43. Flammability regions; sloshing effects.

Although there is insufficient test data and only limited information on the actual amount of fuel agitation experienced in the fuel tanks of operational aircraft, the problem of lowering the lean limit due to fuel agitation may not be as serious as originally expected and may not be a problem at all except during low altitude turbulent flight.

5.5.1.2.1.2 Gunfire. Vertical gunfire (50 CAL. API, 60° pick-up) into a non-equilibrium ullage also gave results (Reference 177) showing an extension of the standard flammability limits. The results are shown in Figure 5-45 and Table 5-XIV.

5.5.1.3 Dynamic factors. Tests have shown that the fuel/air vapor mixtures within a tank are influenced by a number of dynamic factors (Reference 116). These are the temperature of the fuel, the atmospheric temperature, fuel cell vibration, and the outflow rate of fuel from the tank. Figure 5-46 shows an example of the percent of JP-4 fuel by volume in air recorded for the specific test conditions noted. This example was for a tank 30 inches in height. The percent of JP-4 is shown for various levels of fuel in the tank and the distance from the top of the tank. As can be seen, the highest concentration of fuel/air vapor is at the surface of the fuel liquid and decreases as the distance increases. The fuel levels shown in the graph are measured from the top of the tank. The autogenous ignition temperatures vary for JP type aviation fuels in relation to altitude pressures as shown in Figure 5-47. This data is related to the capability of an ignition source to initiate fires

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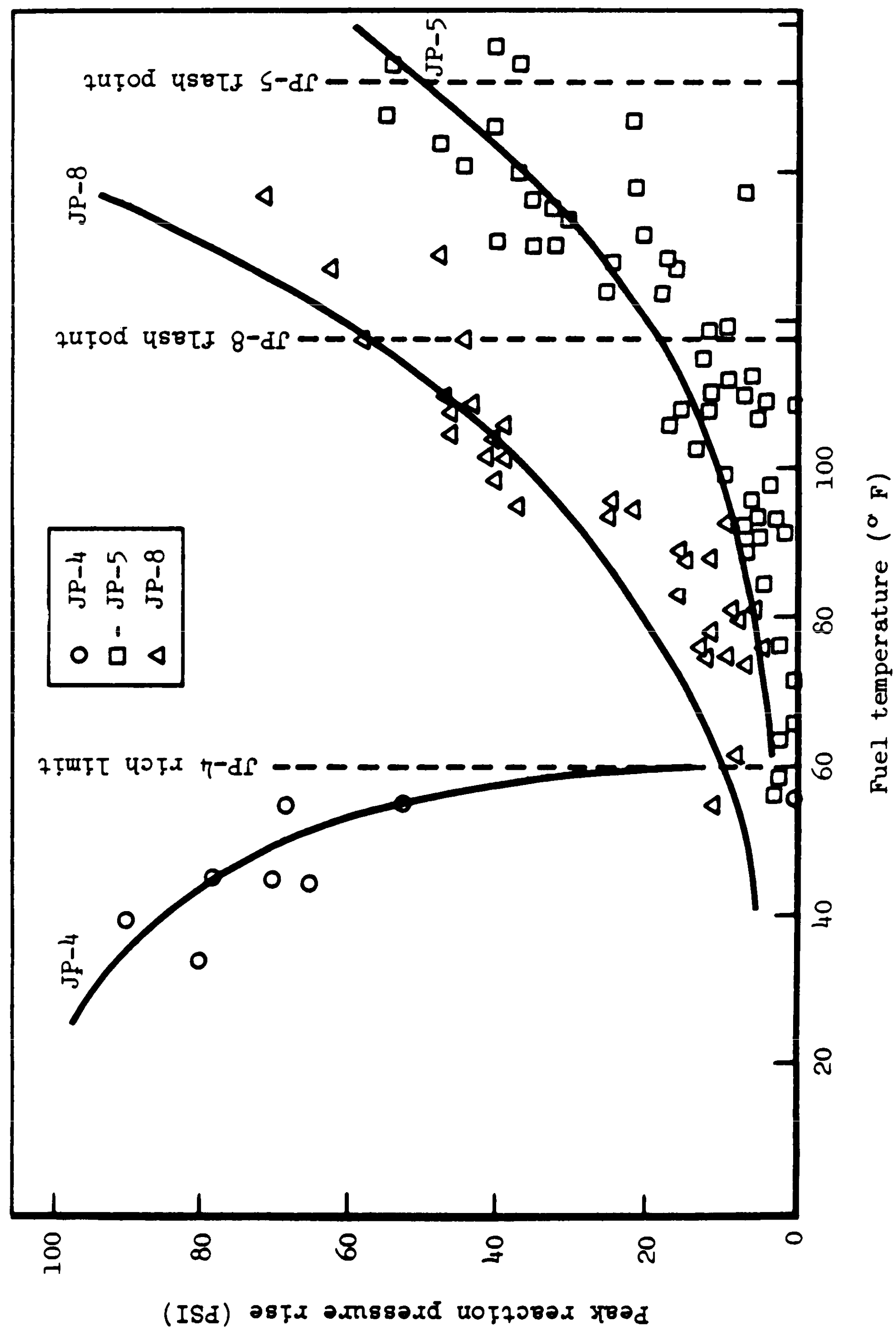

FIGURE 5-44. Extended lean flammability.

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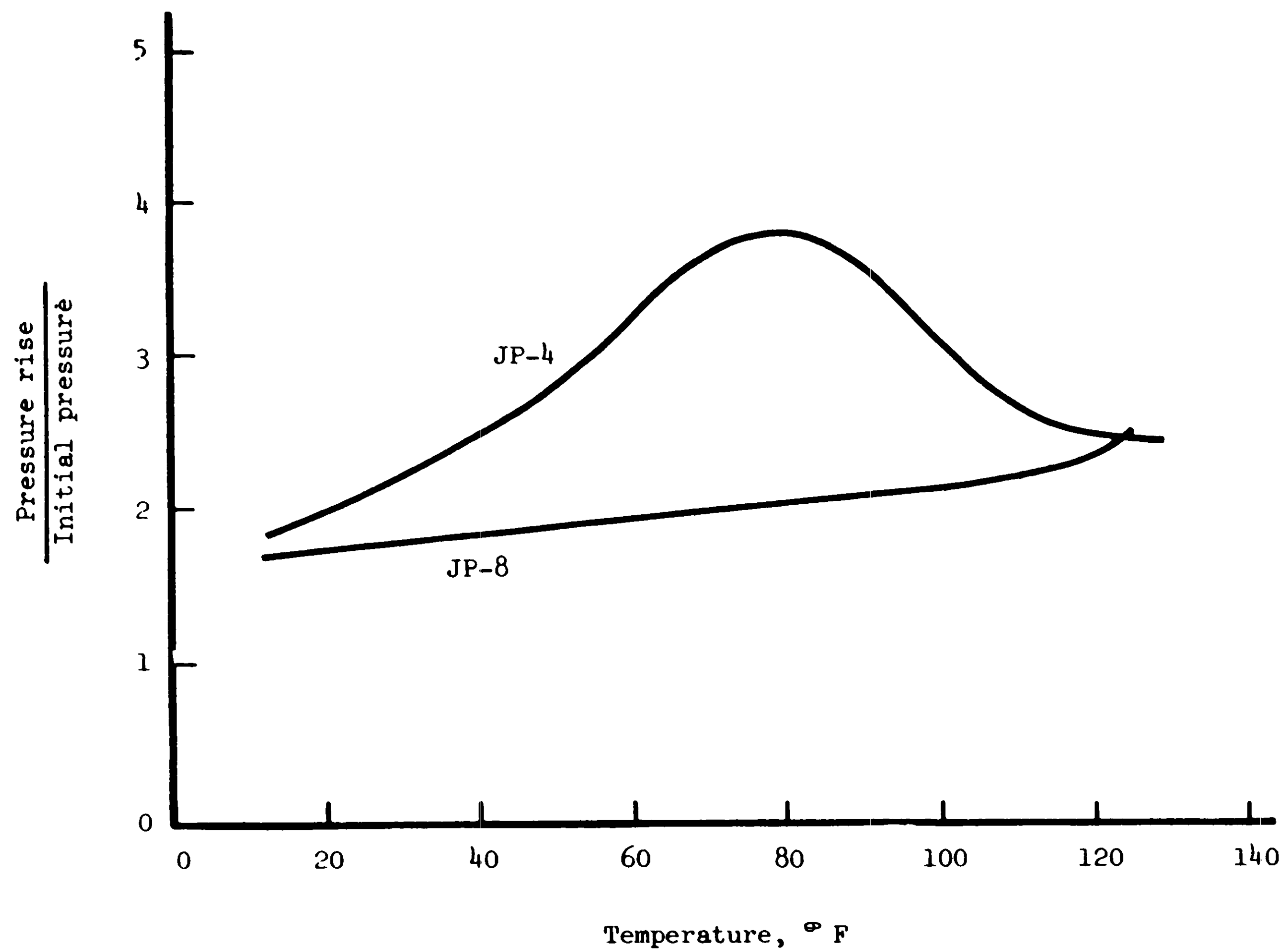

FIGURE 5-45. Effect of fuel temperature on reaction over-pressure in nonequilibrium tests conducted with JP-4 and JP-8, four inch fuel depth, and atmospheric ullage pressure (90 gal. tank)

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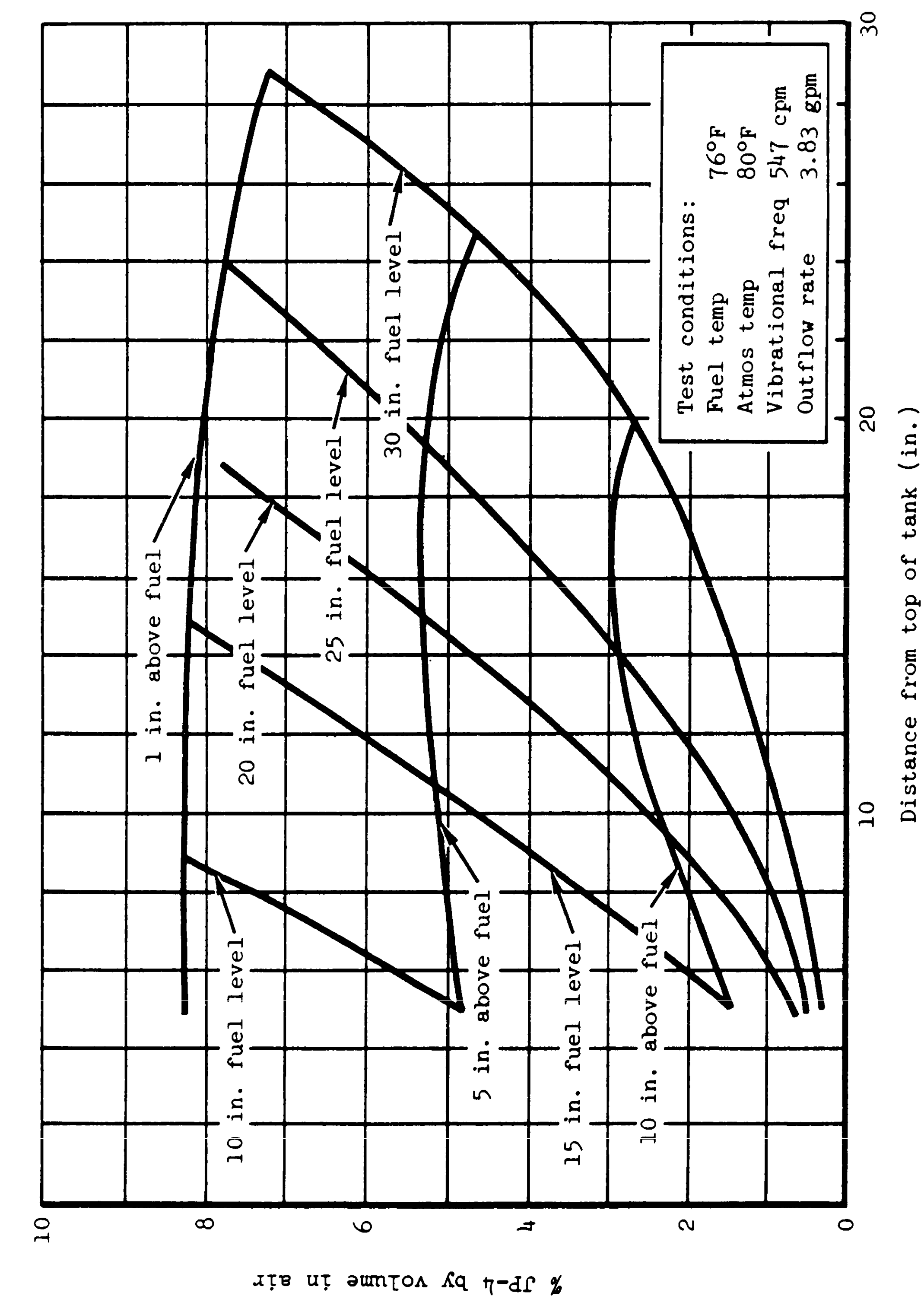

FIGURE 5-46. Fuel tank ullage characteristics under dynamic conditions.

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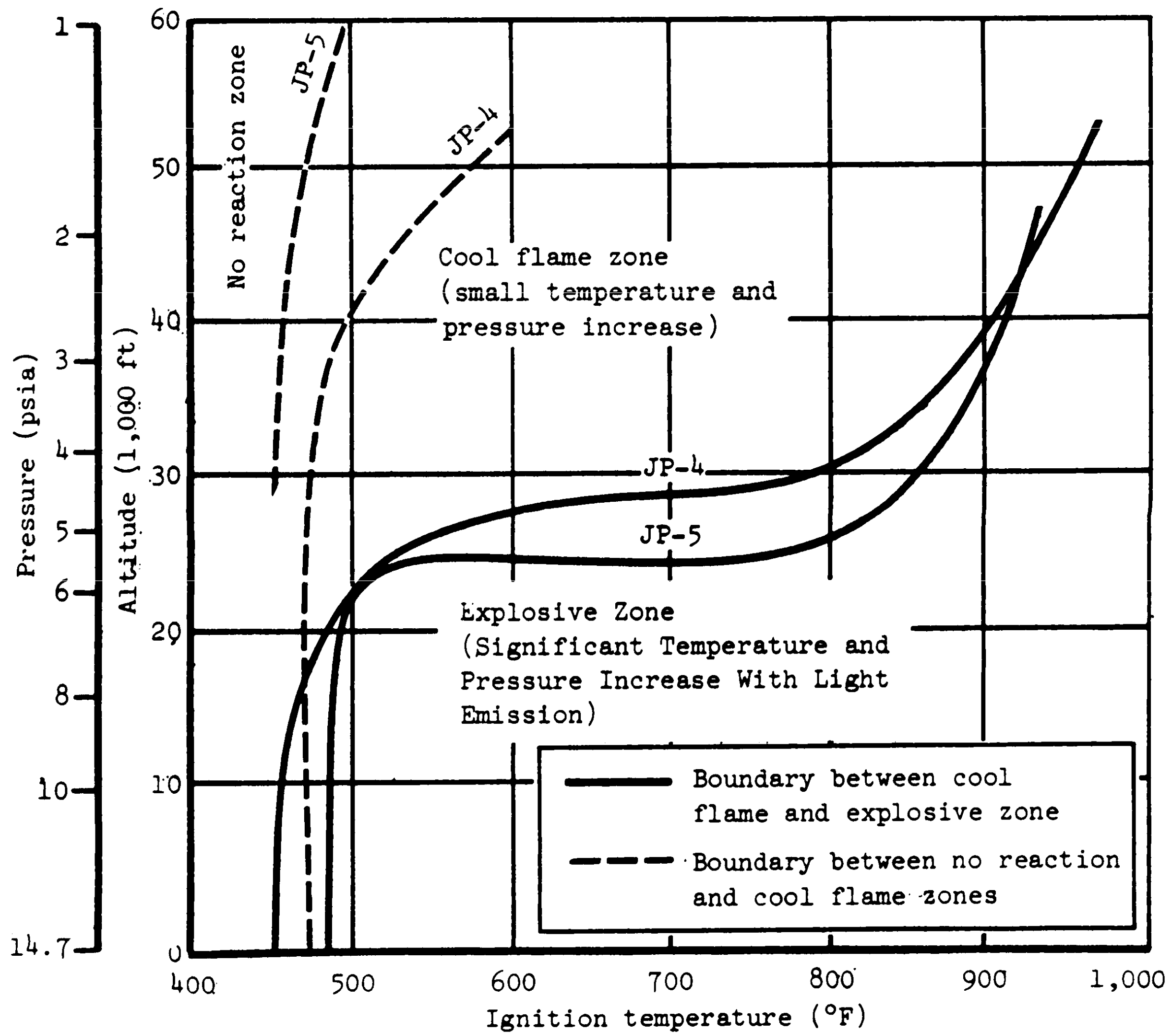

FIGURE 5-47. Autogenous for ignition reaction zones.

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TABLE 5-XIV. Effects of fuel temperature on probability of fire initiation by functioned incendiary projectiles (.50 cal API) in ullage space of JP-4 and JP-8.

Temp. Range (°F)	Number of Tests		Number of Ignitions	Fractional Ignitions
		JP-4		
10-19	5		2	.400
30-39	6		3	.500
50-59	9		9	1,000
60-69	15		14	.933
70-79	5		5	1.000
90-99	6		5	.833
110-119	5		3	.600
120-130	5		1	.200
		JP-8		
10-19	5		2	.400
30-39	9		3	.333
50-59	6		2	.333
70-79	5		3	.600
90-99	17		14	.824
100-109	5		5	1.000
110-119	18		17	.957
120-131	12		11	.917

or explosions in fuel systems. Curves are presented in Figure 5-47 for JP-4 and JP-5 fuels. A similar curve for JP-8 would fall between the curves for JP-4 and JP-5. The designer is cautioned to consider the following:

a. Flammability limits are bands which can vary for individual fuels within their specification limits.

b. Flammability limits shift toward higher temperatures for fuel aged or weathered sufficiently to lose volatile constituents by evaporation.

c. Under operational conditions, tanks normally do not reach equilibrium vapor distribution states; fuel vapor-air ratios may vary from lean through explosive to rich in different portions of a given tank. The variation can exist as explosive pockets or as stratifications, and will depend upon vent design, tank configuration, vibration, and fuel sloshing.

d. High energy ignition sources may shift from the lean flammability limit to a lower temperature (as much as 25°F).

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5.5.1.3.1 Primary responses. The primary responses from nonnuclear weapon effects include the following

a. Penetration, distortion, rupture, and shattering of a component from ballistic impact by a projectile or warhead fragment.

b. Internal or external blast effects in conjunction with multiple fragment impacts from high-explosive projectile or missile warheads. A synergistic effect of the blast overpressure wave loading of the structure and fuel system components, in conjunction with high-velocity fragment impact may be experienced.

c. Ignition of fuel vapors or mists by projectile and missile warhead fragments containing incendiary materials is probable. Sparking from high-velocity fragments also serves as a potential ignition source, depending upon the material penetrated. The high-energy laser weapon effects provide an extremely high-temperature source of ignition of flammable vapors.

d. Burn-through of fuel systems structure and components is a damage producing characteristic of high-energy laser weapons. A complete burn-through may not be necessary to cause a fire or explosion of a flammable material, if sufficient thermal energy is transmitted through the remaining wall material to cause a hot plate effect.

5.5.1.3.2 Fuel system secondary weapons effects. Secondary weapon effects must also be considered in the design of fuel system protection methods. These are the hazardous conditions that are created by the primary weapon effects on other subsystems or components that in turn are capable of causing damage to or undesired response of fuel system elements. The secondary weapon effects include such items as:

a. Spallation from structures/components.

b. Explosive disintegration of high-pressure gas vessels such as accumulators and air bottles that liberate high-velocity fragments, capable of causing damage to fuel system elements.

c. High-temperature conditions from damaged hot gas lines, secondary fires from other flammable fluids, e.g., hydraulic fluids lubricating oils, heat transfer fluids, etc.

5.5.2 Failure modes.

5.5.2.1 Combat failure modes. In a combat environment, five basic failure modes of a fuel system from nonnuclear weapon effects have been experienced. These are:

a. Fuel Depletion - For this mode, the fuel tankage and/or transfer lines or component are damaged to the extent that significant fuel leakage is experienced that would reduce the amount available for aircraft operation. It also includes those conditions in which the capability to transfer fuel to the engine(s) is degraded so that there is a significant amount that becomes unusable.

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b. Fuel Tankage Destruction - This failure mode includes fires, explosions, and hydrodynamic ram effects that initiate inside the fuel tank and can cause substantial damage to the fuel tankage and adjacent structure.

c. External Fire/Explosion - This failure mode is the condition where a destructive fire or explosion can occur outside of the fuel tank. This is caused by the leakage and ignition of fuel from the tankage due to nonnuclear weapon effects. Where the fire or explosion would occur in a closed compartment adjacent to the fuel tankage, this area is commonly described as a "dry bay." The fires/explosions in such locations may cause sufficient damage to nearby subsystem components or structure that would result in their failure or malfunction. The generation of smoke and toxic fumes may also occur and migrate to the crew stations and cause mission abort, forced landings, or aircraft abandonment.

d. Fuel Feed Fire/Explosion - Damage to the fuel feed system that results in the initiation of fire or explosions in areas such as engine installation bays is a basic failure mode. An uncontrolled fire or explosion can cause failure and destruction of all the subsystems and the supporting structure in the area.

e. Engine Fuel Leakage Ingestion - Combat experience and tests have shown that jet engines can be damaged and destroyed from ingestion of fuel into their air inlet system. This failure mode is described in greater detail in Volume 3 of this design handbook. The tolerance of individual jet engine configurations, to the rate and duration of fuel leakage ingestion, determines the probability of its failure or destruction.

5.5.2.2 Weapon effects. The major nonnuclear weapon effects that produce these failure modes include:

a. Direct hit by projectiles or warhead fragments that cause physical damage to fuel system components and the generation of secondary damage effects.

b. A close proximity detonation of an explosive projectile/warhead causing failure of fuel system components through blast or high speed fragment penetration. The evolving hot gases from the blast and the fragment impact flash may act as effective fuel ignition sources.

c. High energy laser weapon effects produce concentrated areas of extremely high thermal conditions that can burn through fuel tanks or components and initiate fires, explosions, and/or system malfunctions or failures.

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5.5.2.3 Secondary damage mechanisms. These mechanisms can operate both independently and in combination. Each primary damage mechanism can initiate several secondary damage mechanisms or responses that can become failure modes For instance, perforation can initiate fuel leakage, hydrodynamic ram, and local structural failure. By interaction with fuel system elements and with elements of other systems in the aircraft, secondary damage mechanisms can cascade into fire and explosion, loss of systems function, fuel starvation of propulsion system, and loss of the aircraft. Table 5-XV contains a tabulation of a number of damage mechanisms and the responses of aircraft fuel systems related to each. Each individual aircraft design must be examined to determine the type of response that may be experienced, and the consequences of the response itself on other subsystems. Fuel fires, for example, have caused rapid failures of other sensitive subsystems that in turn have resulted in loss of aircraft. The hydraulic lines and hoses in flight control systems are particularly susceptible to burn-through and failure. Aluminum push-pull rods in the mechanical portion of a flight control system are also easily damaged and destroyed from the effects of fuel fires. Electrical and avionic equipment and wiring also have displayed low tolerance to heat and fire environments that have caused failures and malfunctions in their systems.

5.5.3 System layout/design. The location and geometry of aircraft fuel systems are established during their initial design process. During this design effort, the basic protection features for the fuel system must be evaluated and incorporated to obtain the most effective design configuration. A significant amount of protection benefits can be obtained for relatively small penalties if they are established at this time. Experience has shown that the add-on of protection features later in the design or production phase of an aircraft imposes high weight, cost, and often performance penalties on the aircraft system. This section contains information and guidance on the existing protective techniques for military aircraft fuel systems against nonnuclear weapon effects. They are arranged in the following order:

a. Tankage
   (1) Ullage Protection
   (2) Self Sealing
   (3) Dry Bay/Void Protection
   (4) Blast Protection

b. Fuel Lines/Hoses

c. Fire Detection/Extinguishment

d. Fire Barriers

e. High Energy Laser Protection

f. Miscellaneous Protection Considerations

g. Current Protection Techniques Development

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TABLE 5-XV. Fuel system damage mechanism and response relationships.

Damage Mechanisms		Responses/Kill Mechanisms				
		Fuel Leakage/Loss	Tankage Overpressure	Fuel Feed Degradation	Fuel Transfer Degradation	Fuel Gaging Degradation
Penetration	Projectiles/ Fragments	Tankage wall, line component damage	Hydrodynamic ran effects, fuel vapor ignition	Component/ line damage	Component/ line damage	Sensor/circuit damage
Blast	Internal	Tankage wall damage	Tankage wall damage	Component/ line damage	Component/ line damage	Sensor/circuit damage
	External	Tankage wall damage	-	Line/connector damage	Line/connector damage	Circuit damage
Ignition	Incendiary material	External fire ignition	Internal explosion ignition	-	-	-
	External fires	Tankage wall burn-through	Tankage wall damage	Line/component damage	Line/connector damage	Circuit damage
	Hot-Gas "torching" high energy laser effects	Tankage wall burn-through	Internal explosion ignition	Line/component damage	Line/connector damage	Circuit damage
	Electrical short circuits	External fire ignition	-	-	-	

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Rapid progress is being made in the field of aircraft fuel system protection techniques through programs sponsored by each of the military services and in conjunction with the JTCG/AS. The reader is cautioned, therefore, to contact the responsible military activities during the initial design development phase to obtain the most current data on the protection techniques of interest for the specific type aircraft being developed.

5.5.3.1 Tankage arrangement. Fuel tank considerations for an aircraft design include internal, external, integral, self sealing designs, crashworthiness, tear resistance, support, access requirements, maintenance features, etc. The type of fuel tank is established in response to the aircraft system requirements. The basic design process must consider the specific nonnuclear weapon effects which the aircraft will encounter, their directions, impact velocities, and the flight conditions during combat. The following information in this section provides the designer with candidate methods for protection. Each must be evaluated for potential use in an individual aircraft design. In the initial design phase, locate fuel tankage to:

a. Minimize presented (and vulnerable) areas in primary threat directions. Locate fuel tanks, fuel system components, and fuel lines, with respect to each other and other aircraft system elements so that combat damage to an element does not cascade into their systems. It should also provide opportunities for substantial survivability enhancement with minimum penalties.

b. Locate all fuel system elements so that leaking fuel or vapors, caused by combat damage will be prevented from blowing or being drawn into areas where fire or explosion can occur. Conversely, locate fuel elements so that perforation of fuel containers and heat sources, (bleed air lines, APU'S etc) will not result in ignition.

c. Critical fuel system plumbing should be inside fuel tanks to obtain some shielding by the fuel inside the tanks. Locate self-sealing components so there is a minimum of shielding between the self-sealing material and the threat. Impact with shielding often tumbles and distorts the penetrator projectile, tearing the jacket of projectiles and creating sharp projections. The distorted, torn, or tumbled projectile causes much more serious damage, sealant coring, and leakage than if it were in the "as fired" condition.

d. Fuel quantities should be proportioned between wing and fuselage tanks to take advantage of the more favorable surface-to-volume ratios of fuselage tanks. The larger surface-to-volume ratio of wing tanks results in a heavier self-sealing material weight penalty per gallon of fuel and an increased susceptibility to excessive impact damage due to hydraulic pressure surges which may peril structural integrity of the wing if hit when full of fuel. Empty fuel tanks, however, are more susceptible to explosion. Tradeoff studies should be conducted of fuel management between wing and fuselage fuel. The favorable surface-to-volume ratio of fuselage over wing tanks can be used to minimize vulnerable area. Consider airframe designs which maximize the proportion of fuel in the fuselage to minimize vulnerable area.

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e. Locate tanks to minimize critical fuel line runs and exposures.

f. Obtain maximum practical tankage and component masking by heavy structure, less critical fuel masses, and less critical components.

g. Position less critical fuel below and/or ahead of “get home” fuel.

h. Minimize fire and explosion hazards from ballistic damage leakage and flow of liquid fuel or vapor to existing or potential ignition sources, and contact with crew or fuel-sensitive components.

i. Minimize potential ignition hazards from sources such as engine burner torching, high-temperature bleed air, and electrical or electronic equipment.

j. Provide fuel management options.

k. Take advantage of locations, external to the airframe, to reduce fire and explosion hazards to the aircraft.

1. Install self-sealing fuel tanks to permit easy removal and reinstallation for damaged tank repair or tank replacement and structural/ airframe repair accessibility.

m. Avoid fuel tank locations that will place fuel in direct contact or in close proximity to engine inlet ducts.

n. Minimize the number of dry bays (void areas) adjacent to fuel cells that would normally contain fuel during a combat encounter. These areas require special protection techniques to prevent catastrophic fires/explosions and to provide adequate survivability against ballistic and high-energy laser weapon effects.

o. Fuel system components. Locate all fuel system components, fuel feed manifolds, fuel feedlines, and valves inside of fuel tanks where possible. This provides shielding for components and confines battle damage leakage, from them, within the fuel tank. Minimize the length of exposed fuel lines.

Figure 5-48 (Reference 79) shows the fuel tank installation in a rotary wing aircraft. They are close to the engine, which permits minimal length fuel feedlines. This installation is readily adaptable for use of self-sealing fuel cells and use of internal and external reticulated foam. The fuel system components include the pumps, filters, fuel control and fuel pressure powered actuators, fuel/oil collers, sequence valves, flowmeters, etc, on the engine. Suction fuel systems which affect transfer of aircraft tank fuel to the engine inlet through suction pressure from an engine-mounted boost pump are coming into use. Typically, the fuel is routed through a centrifugal pump element, then a main filter and, for nonafterburner fuel, next through a positive displacement pump, into a fuel control where some is metered for combustion and the remainder is returned to the pump inlet. Finally, the

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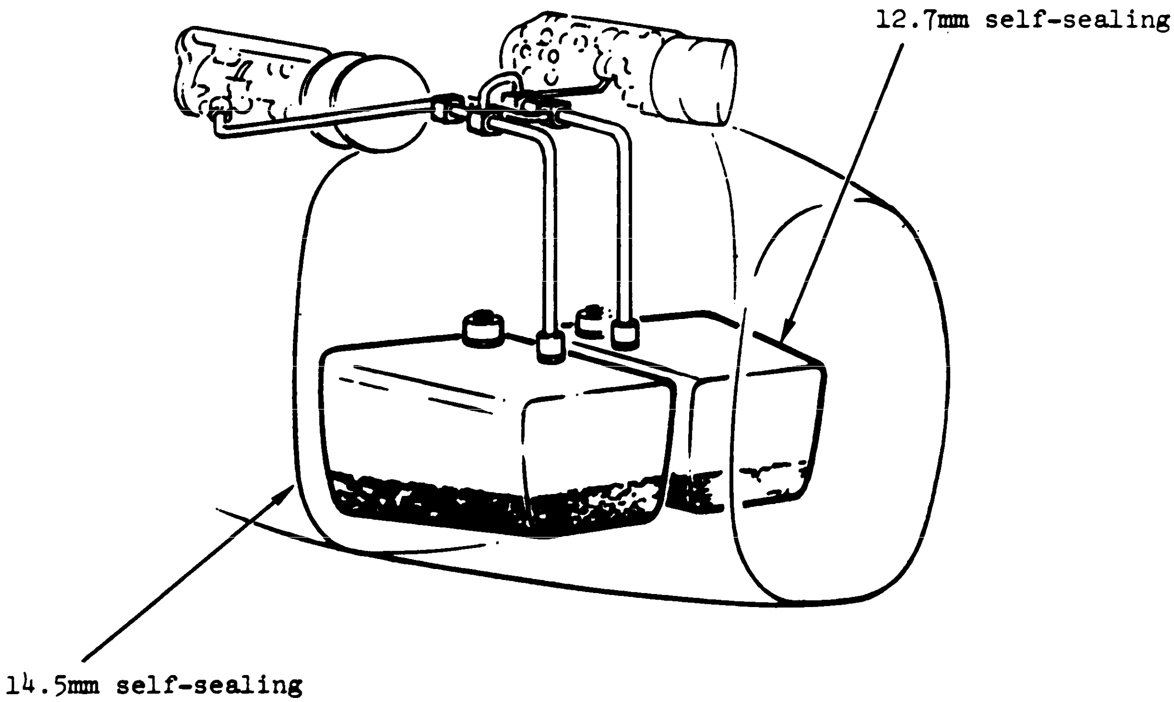

- Two self-sealing fuel tanks
  - Increased threat tolerance
  - Increased mission tolerance
  - Reduced replacement cost
  - Short self-sealing feed lines
  - Cross feed system
  - Engine mounted boost pumps

FIGURE 5-48. Rotary-wing aircraft redundant fuel system.

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metered fuel is routed through a fuel/oil cooler into the combustor fuel manifold. Upstream of the positive displacement pump and in parts of the fuel control, pressures are 100 psi or less (low pressure); downstream, pressures are greater than 400 psi and possibly as high as 1,200 psi (high pressure). Figure 5-49 shows a fuel tank arrangement for a fixed wing attack aircraft that employs self-sealing tanks with voided internal foam and rigid external foam for ballistic protection. The fuel flow distribution and management sequence should be designed so that the maximum amount of fuel is available to the propulsion system by gravity feed.

5.5.3.1.1 Fuel management systems. Fuel management systems should be designed to:

a. Provide fuel management, considering the effects on individual tank vulnerability.

b. Proportion fuel use so that no tank is completely full or completely empty during the portion of combat missions where projectile impacts can be expected.

c. Minimize aircraft center-of-gravity displacement problems if fuel transfer capability is lost.

5.5.3.1.2 Fuel gaging systems. Fuel gaging systems should be designed to:

a. Minimize total system failures from single hits.

b. Provide quantity difference indications sufficiently sensitive to permit detection of fuel loss from specific tanks.

5.5.3.1.3 Fuel flow management. Fuel flow management should be designed to:

a. Provide fuel transfer control that will permit bypassing of damaged fuel tanks to conserve fuel supply.

b. Detect line leakage with manual or automatic means to isolate damaged line from fuel supply. For example, with two redundant engine fuel feed lines, the damaged line would be isolated by a shutoff valve to prevent loss of vital fuel and minimize fire/explosion hazards.

5.5.3.1.4 Tank geometry/closure. Design tank geometry/closures to:

a. Minimize vulnerable area of individual tanks in principal threat directions. Avoid complex shapes and attachments which provide stress concentrations and which tend to be ruptured by pressure pulse surges.

b. Avoid common walls between mission-essential tanks.

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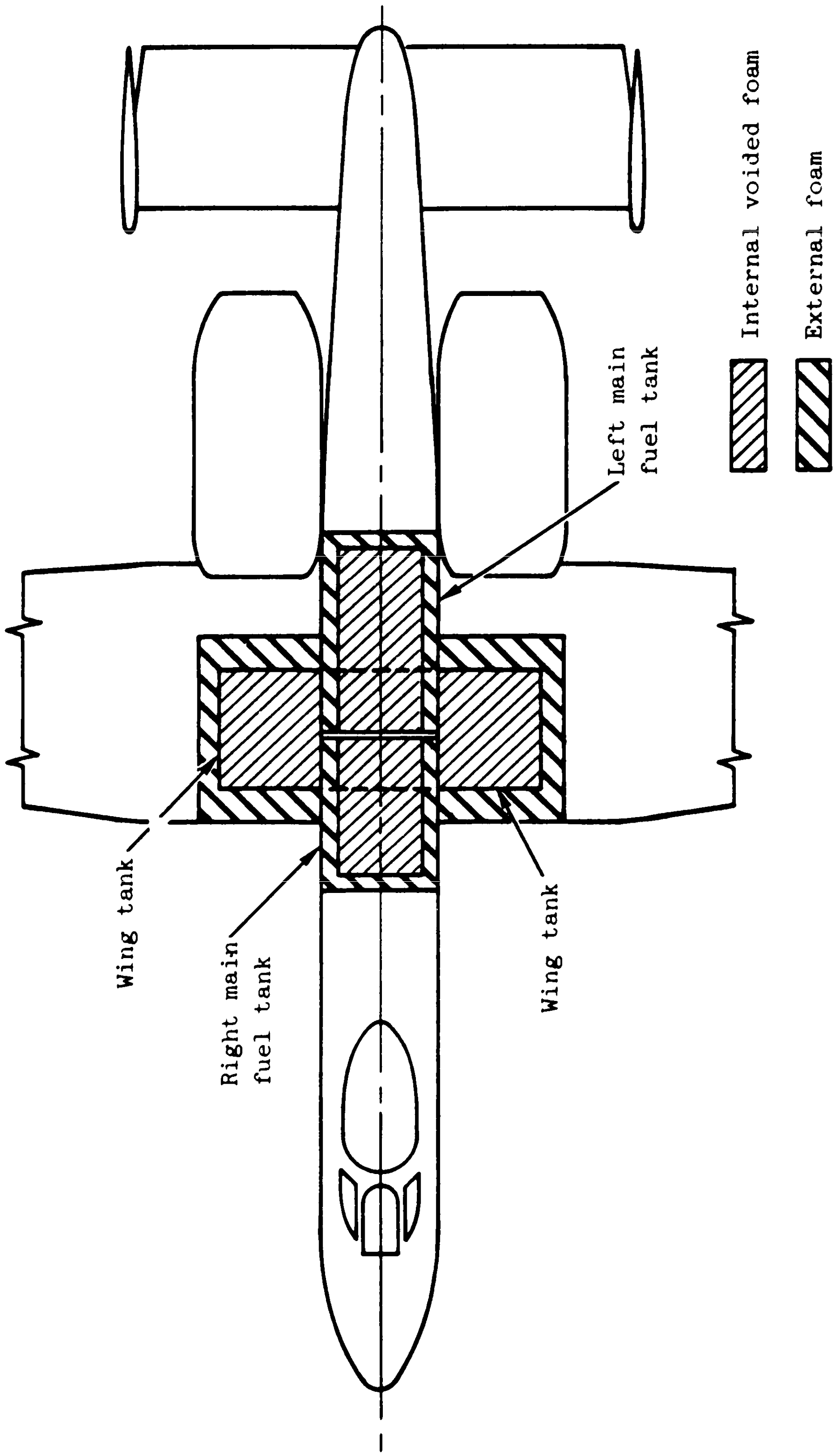

FIGURE 5-49. **Fixed wing aircraft protected fuel design.**

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c. Avoid spaces over l-inch between fuel cells and supporting structural walls to minimize fire propagation through intervening space.

d. Locate lines, connectors, and closures to enter and exit in upper, nonfuel, wet tank area.

e. Design all closures of high-fracture-toughness materials with configurations which provide adequate strength to resist liquid pressure pulse and crash landing forces in aircraft to meet crash-worthiness requirements.

f. Design all tank closure fittings in accordance with MIL-T-27422B, (Reference 196), to prevent fuel leakage when separated from fuel system and/or structure by severe threat effects or crash landings.

g. Consult Reference 205 and Reference 198 for crashworthy fuel system design techniques.

5.5.3.1.5 Critical element protection. Consider the following techniques to maximize critical element protection from primary threat directions by:

a. Interposing heavy structure

b. Interposing less critical components

c. Concentration of critical components, if armor protection provided

d. Interposing ballistically significant fuel quantities

5.5.3.1.6 Ballistic mask. Fuel may serve as a ballistic mask for fuel system components, other systems, systems, or aircrews. Consider opportunities for masking critical components above, behind, and between redundant or less critical tanks. The value or capability of fuel to slow down a projectile can be approximated by use of a general formula and nomograph, contained in paragraph 4.2 of this design handbook. Apply armor for ballistic protection only after all other protection techniques have been thoroughly exploited, and then only to essential areas such as fuel pumps, critical fuel system interconnect lines, etc. Consult References 74, 114, 115, 125 and 127 for additional information and guidance on this subject.

5.5.3.2 Hydrodynamic ram protection. Hydrodynamic ram is a series of pressure waves developed in a fuel tank from the impact of large high-velocity projectiles or fragments. These mechanisms include the effects of the shock wave system generated by the impact, and the sudden transfer of kinetic energy and nomentum to the liquid fuel as the penetrator decelerates. The major structural loads are due to (1) a pressure pulse in the fuel caused by penetrator drag, and (2) restraint of the violent fuel motion produced by the travel of the penetrator through the liquid. Certain structural designs are more susceptible to hydrodynamic ram damage. These include walls of honeycomb, integrally stiffened walls, and materials with poor fracture toughness.

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The ram effect can be divided into three phases: the early shock phase, the later drag phase, and the cavity phase. The shock phase is initiated when a projectile penetrates the wall and impacts the fluid. As energy is transferred to the fluid, a strong hemispherical shock wave centered at the point of impact is formed. This creates an impulsive load on the inside of the entry wall in the vicinity of the entry hole which may cause the entry wall to crack and petal. As the projectile travels through the fluid, its energy is transformed into kinetic energy of fluid motion as the projectile is slowed by viscous drag. A pressure field is generated as fluid is displaced from the projectile path. In contrast to the pressures developed in the shock phase, the fluid is accelerated gradually rather than impulsively, so that the peak pressure is much lower; however, the duration of the pressure pulse is considerably longer. A cavity develops behind the projectile as it passes through the fluid which is filled with fuel vapor evaporated from the cavity surface and air which can enter the cavity through the entry hole. As the fluid seeks to regain its undisturbed condition, the cavity will oscillate. The concomitant pressures will pump fluid from any holes in the tank and they may be sufficient to damage fuel cell components. This cavity oscillation is called the cavity phase.

5.5.3.2.1 Structural response. The structural response of the fuel tank walls to the hydraulic ram pressure is a complicated process. The pressure in the fuel caused by the penetrating projectile acts on the tank walls, causing them to displace. This displacement in turn affects the pressure in the fuel, thus leading to a complex interaction between the fuel and the tank walls. Any cracking and petaling of the walls will also change the pressure in the fluid, and hence the subsequent loading on the walls. This interaction phenomenon is referred to as fluid-structure interaction. Figure 5-50 shows an example of hydrodynamic ram damage experienced in the bottom side of an integrally stiffened wing fuel tank structure impacted by a 0.50 caliber projectile. It illustrates the large damage area that can be produced through the hydrodynamic ram phenomenon. A number of design techniques have been developed to provide varying degrees of protection to hydrodynamic ram. These are:

a. Maximize volume of fuel in each tank to avoid small tanks. Liquid pressure pulse attenuation is dependent upon the fuel mass available to absorb it. Small (low-volume) tanks, if unavoidable, can be made survivable, provided they are shallow and are not totally filled during exposure to ballistic impact.

b. Use concentric walled tanks with fuel scheduling priority to deplete interstitial fuel before primary fuel.

c. Use smooth, simple tank contours with shapes and structures designed to resist internal pressure.

d. Avoid narrow, complex tank shapes and abrupt section cutouts.

e. Maximize flexibility of tank structure and fuel cell. Liquid pressure drops rapidly with relatively small displacement of fuel.

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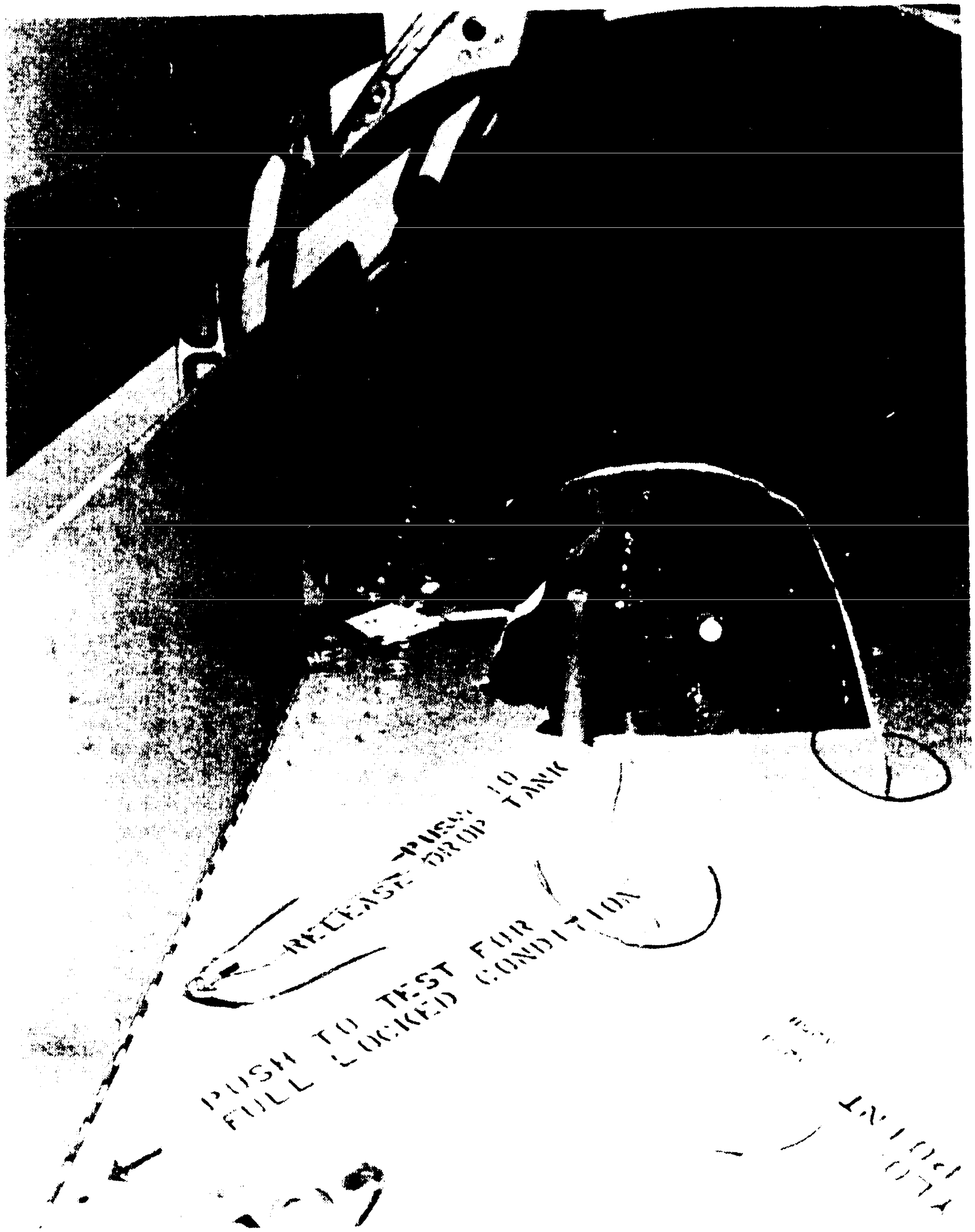

FIGURE 5-50. Hydrodynamic ram damage.

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f. Integrate self-sealing cells and backboard concepts to enhance flexibility.

g. Apply crash-resistant tank (Reference 196) and structural concepts.

h. Consider use of reticulated foam (Reference 261) to attenuate liquid pressure pulse. However, for most designs, minimum pressure reductions, measured, are due to reticulated foam.

i. Use self-sealing tank materials.

j. Use sealed reticulated foam as a tank internal liner to decouple liquid pressure from tank walls.

5.5.3.2.2 Honeycomb construction. Aluminum honeycomb sandwich construction with aluminum face sheet may be used between an engine inlet duct wall and fuel tank (Refer to Reference 182). The honeycomb duct is designed to replace the commonly used frame/skin construction and carry equivalent structural loads. The energy absorption qualities of honeycomb allow it to crush when subjected to blast and hydrodynamic ram pressures. Thus, the honeycomb minimizes damage to the air inlet duct skin and prevents massive fuel ingestion, This concept may be used with integral, bladder, and self-sealing tanks. The aluminum honeycomb duct concept is shown in Figure 5-51.

5.5.3.2.3 Peak pressure. Tests have shown that for fuel tanks of moderate size, the most catastrophic damage occurs on the exit side of the tank. This is praticularly true when a projectile is tumbling as it passes through the tank. As it approaches the exit wall, the liquid pressure increases rapidly. This is illustrated in Figure 5-52 which shows the peak pressure (psi) for distances from the entrance and exit holes for a test case. As can be seen, the exit pressures are much higher. This prestressing of the wall material leads to zippering effects when the wall is penetrated by the projectile. The rapid decrease in peak pressure with radius causes a corresponding decay in the impulse ($I = \int Pdt$ on the exit wall. Figure 5-53 shows the impulse versus radius on the exit wall. The peak impulse is about 800 psi-msec at the hole. At 2 inches from the hole, the impulse has dropped to below 80 psi-msec. Figure 5-54 shows the hoop tension versus time history in the aluminum exit wall where the bullet will exit the tank. Note that large hoop tensions, corresponding to the yield strength of the aluminum (60,000 psi), develop before the bullet begins to penetrate the exit plate. Thus the bullet penetrates an exit plate which is yielding in hoop tension. Propagation of cracks radiating from the exit hole will therefore be enhanced (Reference 131).

5.5.3.3 Self-sealing. Consider self-sealing for all tanks, except externally-carried tanks. Design in accordance with Reference 196, 198, and 213. Design so that the fuel container rests within and is supported by structure, but not carry airframe loads. The fuel container may be either metal or nonmetallic structure, but usually consists of an elastomer bladder cell or an elastomer self-sealing cell. The tanks and cells carry only local loads imposed during installation, and such loads as vent pressure, fuel head pressure, liquid pressure pulse surges, and fuel slosh and acceleration loads.

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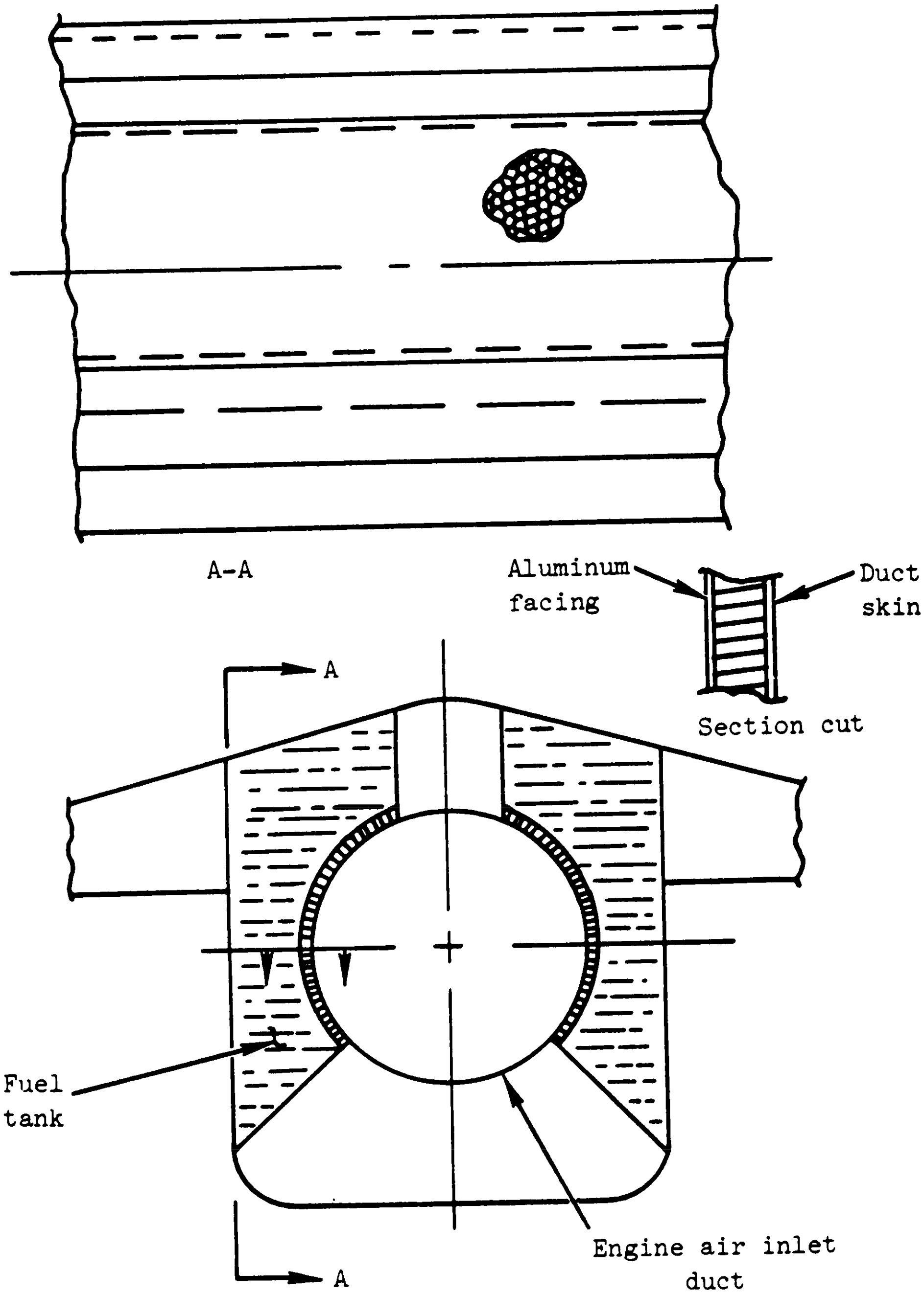

FIGURE 5-51. Honeycomb duct concept air inlet.

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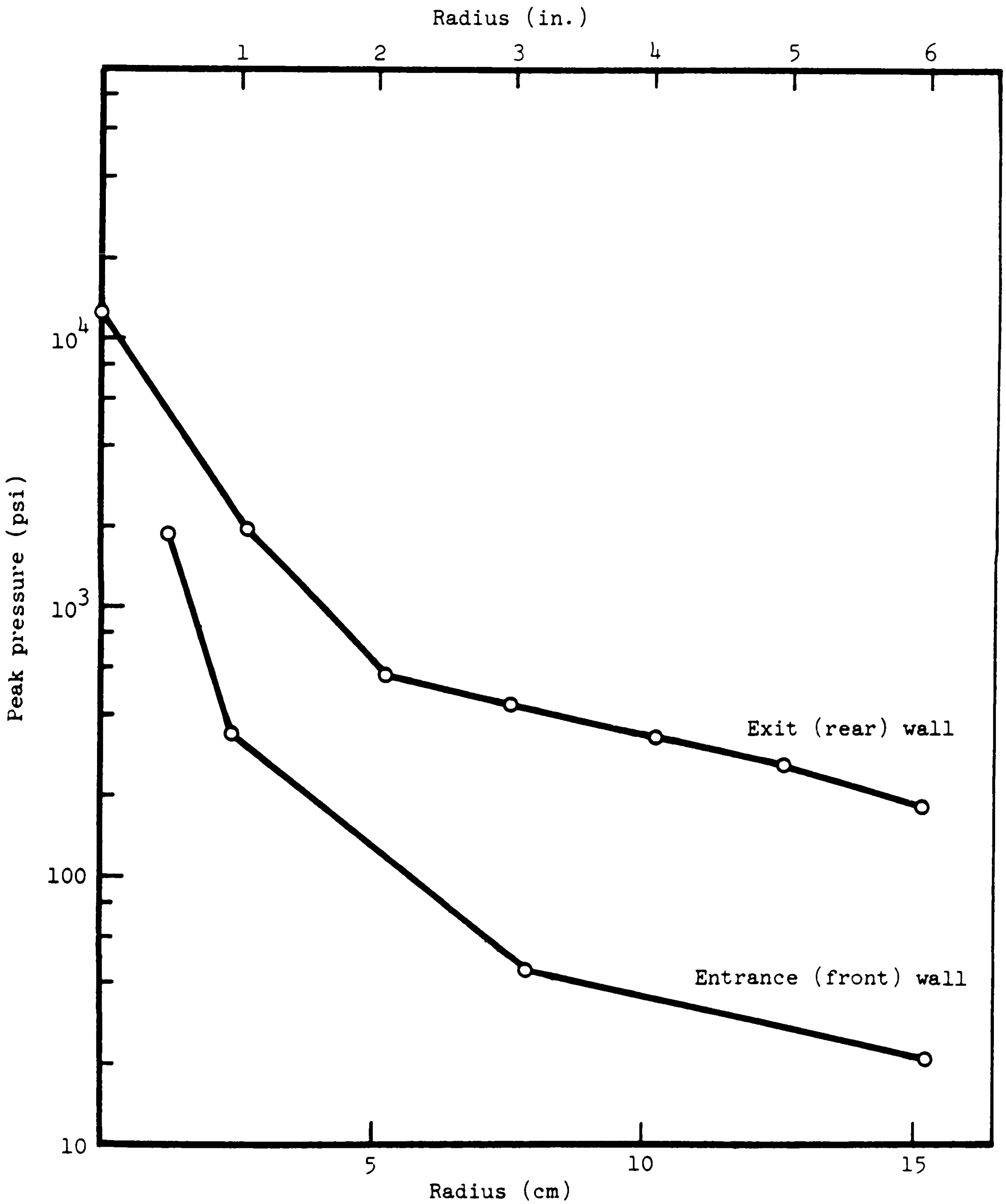

FIGURE 5-52. Peak pressure versus radius (distance from entrance or exit hole) on tank walls.

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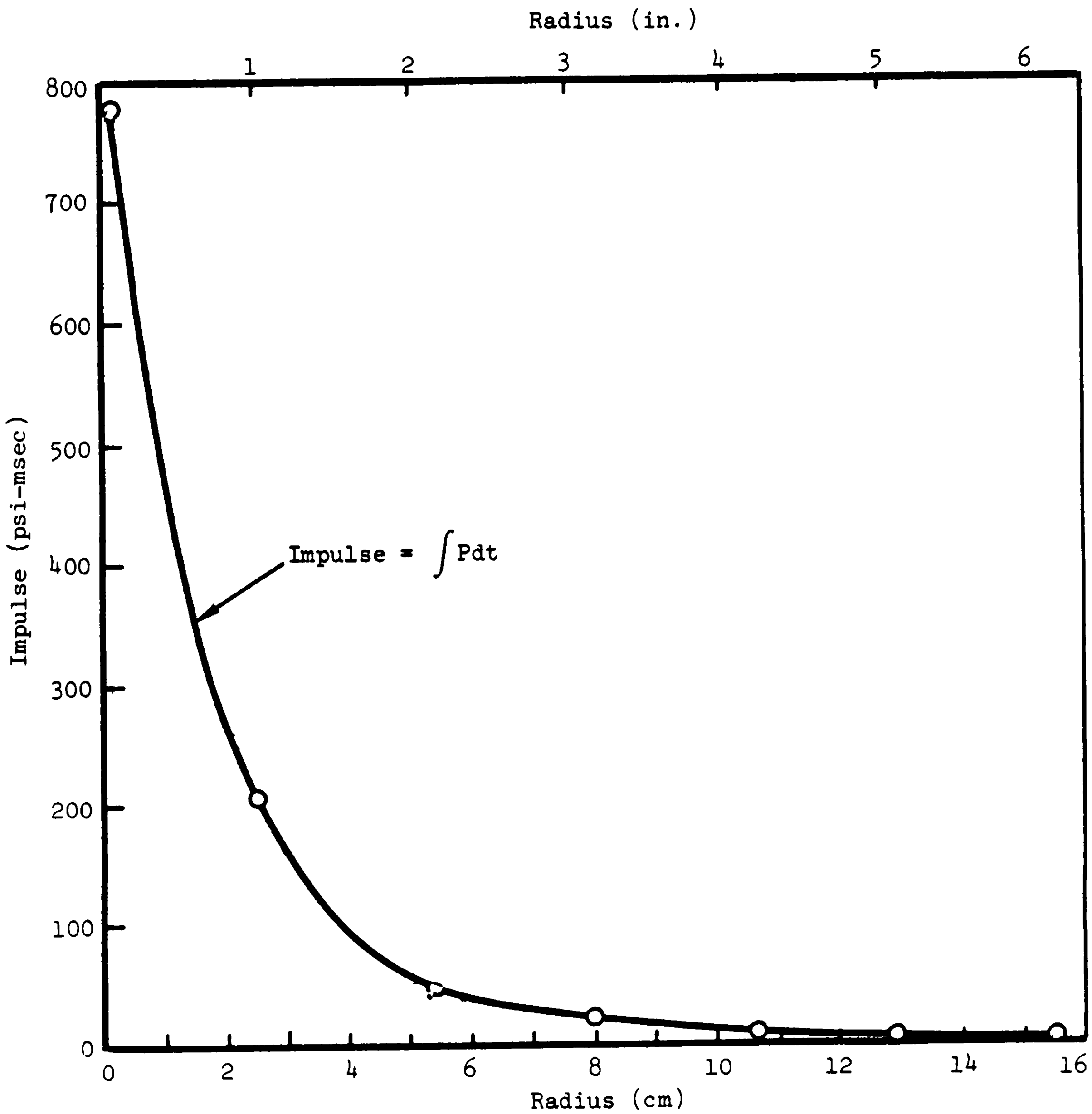

FIGURE 5-53. Impulse on exit wall as a function of radius (distance from exit hole).

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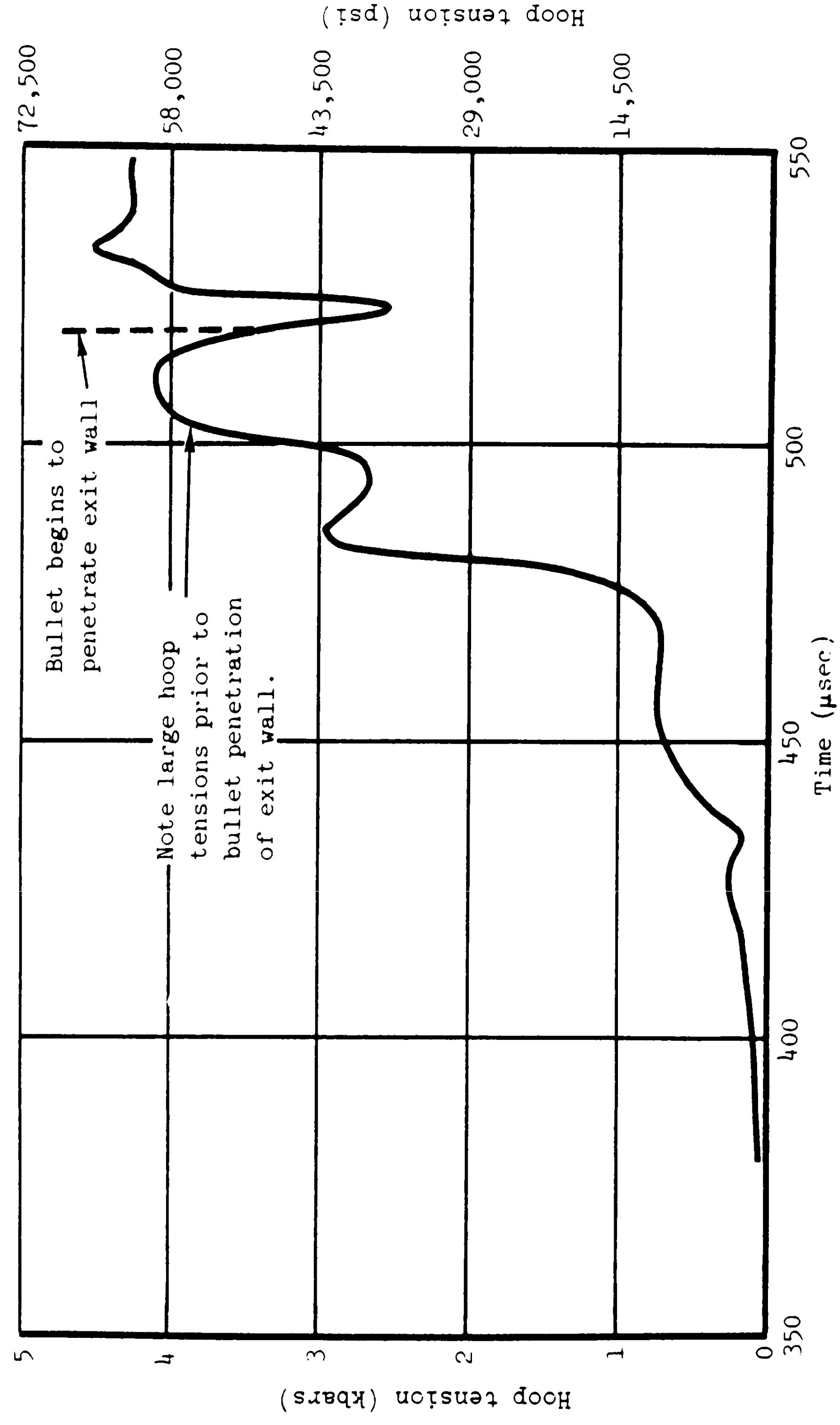

FIGURE 5-54. **Hook tension in aluminum exit wall (near bullet exit hole) as a function of time.**

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These loads are transferred through the self-sealing and backboard materials into the aircraft structure surrounding the tanks. Consider use of crash-resistant self-sealing tanks (Reference 196), where installation and related factors permit. Effective self-sealing is accomplished by conventional self-sealing cells installed inside the airframe. These cells are of multilayer elastomeric construction, made from the inside out, of a fuel-resistant inner ply, a fuel vapor barrier layer, alternate layers of fuel-sensitive elastomer sealant, and plies of elastomer-coated fabric plus a fuel-resistant outer coating. Fabric plies are usually concentrated on the exterior of the sealing material construction to support the sealing layers against fuel head pressure during the sealing action and to transmit fuel loads to backing material and supporting structure. These outer plies resist bursting and tearing from the liquid pressure surges, and also serve as bonding areas for installation straps, if required, to support the weight of upper portions of an empty fuel cell. The other ends of the installation straps are drawn up and attached to the airframe. Other factors to be considered are:

a. Minimize fuel tank internal pressure to 2 psig or less (zero gage pressure preferred), when in combat area, to enhance sealing and to reduce weight of self-sealing material.

b. Minimize self-sealing weight by minimizing thickness of or eliminating self-sealing material in upper portions of fuel cells. If fuel is not in contact with the upper portions of the cell during combat, weight may be saved in this area by using the tear-resistant bladder cell construction without sealant. Reduced sealant. thickness may be used where fuel pressure and fuel head are low. The cost of fuel cell fabrication may be only slightly increased by modular variations in sealant thickness. The lighter weight cells can be used in good installation, with adequate thickness of backboard.

c. Design cell installation openings in airframe with adequate size to avoid installation damage to fuel cells and backboards. Conventional flexible self-sealing cells can be folded, and even rolled, into relatively small bundles for placement in the fuel cell compartment.

d. If the installation opening is too small, the flexible cell must be folded so tightly that damage is likely. This cell damage may not be detectable for some time until fuel swells the sealant and progressive disintegration of the cell has started.

e. Select minimum self-sealing cell thickness providing acceptable sealing probabilities. Table 5-XVI gives sealing material construction parameters for various threats at near-muzzle velocity. This information was compiled from supplier’s data. Consider light construction for installation substantially in accordance with protective criteria of this design guide. Apply construction where protective criteria must be compromised by other design considerations. Classified data for larger threats is contained in Volume 4.

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TABLE 5-XVI. Fuel tank self-sealing/external fire protection.

Threat Level		Fuel Tank Material		Backing Board		Void Filler	
		Material Thickness (in.)	Areal Density (lb/ft^2)	Material Thickness (in.)	Areal Density (lb/ft^2)	Material Thickness (in.)	Areal Density (lb/ft^2)
0.30 cal API	Light Medium Heavy	0.076 to 0.102 0.10 to 0.122 0.147	0.43 to 0.49 0.54 to 0.64 0.77	0.102 to 0.122	0.49 to 0.64	1.5	1.60
0.50 cal API	Light Medium Heavy	0.158 to 0.173 0.214 to 0.217 0.247	0.824 to 0.86 1.06 to 1.15 1.2	0.170 0.178 0.247	0.855 0.909 1.200	1.50	1.60
14.5 mm API/ 105 grain frag	Noncrash resistant Crash resistant	0.346 0.40	1.7 1.9	0.070	0.360	1.50	1.60
23 mm API-T	Noncrash resistant Crash resistant	Classified data, contained in volume 4.					
23 mm	HEI-T	Classified data, contained in volume 4.					

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5.5.3.3.1 Cell construction. Typical cell constructions from various suppliers are shown in Table 5-XVII. Consult with suppliers for latest improved designs.

5.5.3.3.2 Cell design criteria. Refer to Table 5-XVIII and Reference 196 for general design criteria for self sealing tanks. Selecting of the self-sealing cell depends primarily upon definition of the threat effects. Both the kinetic energy and the characteristics of the projectile or fragment must be considered. Large tanks may seal better than smaller tanks. Tanks with more pressure-resistant shapes tend to seal better.

TABLE 5-XVII. Self-sealing tank materials.

Manufacturer and Designation	Protection Level Caliber	Gage (in.)	Weight (lb/sq ft)	Qualified MIL-T-5578 Level	Installed in
Firestone					
1316.3	.30	0.210	1.01	B	Army air boats
1451	.30	0.118	0.57		
Goodyear					
FTL-13	.30	0.100	0.543	B	S-64, S-61, HH-3C
Uniroyal					
us 179	.30	0.122	0.64	B	
US 180	.30	0.102	0.49	B	AH-lG, OV-10, FH-1100, LOH
Firestone					
1146	.50	0.240	1.310	A[a]	A-4E, TA-4E
*1550-1	.50	0.184	0.938	A	
Goodyear					
FTL-11-13	.50	0.247	1,200	A	B-47, F-84F, F3H, F-101, UH-1
FTL-17	.50	0.170	0.855	A	
*ARM-061A	.50	0.178	0.909	A[a]	
Uniroyal					
us 173	.50	0.217	1.15	A	A-7A
US 182	.50	0.173	0.86	A[b]	
*US 750	.50	0.216	1.07	A[a]	

[a]Also meets MIL-T-27422B (Reference 196).

[b]With Conolite B33FG1W backing board.

*These are the only ones acceptable to the Army.

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TABLE 5-XVIII. General design criteria for self-sealing tanks.

Given threat: .50-caliber AP M2, at 2,900 fps (13,000 ft-lb)	
Sealing Effectiveness Parameters	Satisfactory Criteria
Fuel volume (gal)	≥ 80 (10.7 cu ft)
Surface-to-volume ratio (Sq ft/cu ft)	≤ 3.3
Pressure surge attenuation, reticulated foam, MIL-B-83054	Filled with foam[a]
Fuel level in tank	≤ Full[b]
Tank pressure (psi)	≤ 2 [c]
Structural rigidity	≤ Conventional center fuselage
Self-sealing cells (lb/sq ft)	≥ 0.86
Fuel cell backboard	
Goodyear BBC-8 (lb/sq ft)	≥ 0.038
Air logistics 700 SIEBNN (lb/sq ft)	≥ 0.040

[a]Installation did not meet MIL-T-55780 (Reference 198) self-sealing requirements without foam.

[b]Full fuel tanks are not recommended for survivability enhancement. This table entry illustrates that tanks of fuel can be self-sealing against .50-caliber AP M2 at 13,000 ft-lb if other listed requirements are met. The total installation would undoubtedly be lighter for the same sealing performance if the tank were not full of fuel.

[c]Sealing was about 80-percent effective at 6 psi.

5.5.3.3.2.1 Fuel cell backboard. Select fuel cell backboard for compatibility with tank configuration and design. Use low-modulus backboard if tank support spacing does not permit excessive cell sagging under fuel loads. Backboard used effectively with self-sealing fuel cells provides satisfactory sealing with a minimum combined weight of cell and backing board. The backboard is distorted and torn less than the airframe structure and skin in the vicinity of the perforation. Thus, it can provide support for the self-sealing material and align the perforation edges to allow effective sealing, even if external structure is locally torn away. Sealing capabilities are enhanced if self-sealing materials do not sag under fuel head loads. Also, penetrator impact may cause flowering and petaling of skin and structure. The backboard prevents these metal projections from entering the perforation and holding it open, preventing sealing. The types of backboard presently being used include high modulus (Reference 218), low modulus (BBC-8 and ARM-62), honeycomb panels, and semi-rigid plastic foam.

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5.5.3.3.2.1.1 High-modulus backboards. High-modulus backboards are constructed of fiber glass epoxy laminations with different fiber directions in adjacent plies. Facing materials include DuPont Nomex, polyurethane, or the matrix material itself. Backboard thickness usually ranges from 0.023 to 0.070-inch, depending on installation, load, and threat requirements. Table 5-XIX summarizes the backboard area. Backboards may be obtained as flat sheets which may be bent to simple contours. If compound contours or sharp bends are required, the backboard may be premolded to fit the particular application. Backboards may be attached to aircraft structure with flattop fasteners such as blind and cherry rivets, or with fuel-resistant adhesives. Installations should be designed with a minimum number of attachments, to allow the backboard to deform with impact in order to absorb ballistic energy. Low-modulus, energy-absorption materials have been developed which perform well as backboards. They have performed well in gunfire tests, ant their higher impact strength (135 feet per pound compared to 41 feet per pound for typical MIL-P-8045, (Reference 218) fiber glass epoxy material of about equal weight) may offer advantages for high-level threat applications. The lower modulus, higher elongation characteristics of the BBC-8 may afford opportunities for dissipation of liquid pressure pulse forces. BBC-8 is not as stiff as fiber glass and therefore presents some cell support problems.

TABLE 5-XIX. Backboard materials.

Manufacturer and Designation	Protection Level Caliber	Gage (in.)	Weight (lb/sq ft)	Spec
Air Logistics				
700S1-ESNN-23	l 30	0.023	0.22	MIL-P-8045
700S1-EB00-37	l 50	0.037	0.37	MIL-P-8045
700S1-EBNO-39	l 50	00039	0.39	MIL-P-8045
700S1-EBNN-41	l 50	0.041	0.41	MIL-P-8045
Conolite	l 30	0.026		MIL-P-8045
	l 30	0.033		MIL-P-8045
	.50	0.060		MIL-P-8045
Firestone				
F1-41	.50	0.800	0.41	MIL-P-8045
B-2	.50	0.800	0.41	MIL-P-8045
Goodyear, Arizona				
BBC-8		0.070	0.35	MIL-P-8045
ARM-62		0.070	0.601	MIL-P-8045

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5.5.3.3.2. 1.2 Additional concepts. Two additional backboard concepts have been successful in specific applications. Honeycomb panels with aluminum core and glass reinforced plastic face next to the fuel cell have been successful in installations where liquid pressure pulse from projectile impacts has not been severe. Liquid pressure pulse tends to delaminate honeycomb panels. Semirigid plastic foam has functioned well as a combined backboard and void filler. However, this foam tends to transmit fuel loads to the skins, and is likely to damage skins and skin attachments. Newer, low density variations (1.5 pounds per cubic foot or less) are currently available which do not exhibit the skin damage tendency.

5.5.3.4 Blast Protection. Fuel tanks can be protected against nearby detonations of explosive projectiles by "cocooning" the fuel tanks with energy absorbing materials and fragment stoppers. Certain metal honeycombs exhibit excellent energy absorption characteristics. Ballistic nylon or the recently developed "Kevlar" synthetic cloth (now being used to make flexible bullet resistant vests and ceramic armor backing material) show superior fragment stopping capability. An optimally designed, protected fuel tank can combine many of the above described concepts. For example, a self-sealing tank could be filled with reticulated foam, then surrounded with a combination of ballistic resistant cloth, metallic honeycomb filled with rigid, fire resistant foam, an outer layer of ballistic cloth, and decoupled from any critical surrounding structure for ram attenuation.

5.5.3.5 Ullage protection. Fuel tank explosions are a result of ullage deflagrations where the combustion over-pressure generated exceeds the structural strength of the tank. Explosion protection techniques, therefore, fall into several categories including inerting, extinguishing, fire suppression and over-pressure attenuating. These systems are further classified as passive and active. Passive systems are those which require no activation, mechanical or logistic support to maintain their operating capability, making them effective on an around-the-clock basis. Foam or other void filler-type materials are included in this category. Nitrogen inerting, halon extinguishant, and fuel fogging systems are included in the active system category. State-of-the-art explosion protection systems and the required materials and equipment are described in the following paragraphs. The primary source of this information is Reference 178.

5.5.3.5.1 Reticulated polyurethane foam (Reference 261). Foam explosion protection system design varies with the physical properties of the material, the degree of protection required, and the installation access. The material is a polyester-based urethane linked compound, reticulated to an open-celled configuration, and is approximately 98 percent void. The fibers forming the cells in the foam occupy about 2 percent of the volume of the bulk material. The size of the pores or openings in the foam varies inversely with the number of pores per linear inch (ppi) which ranges from 10 to 25 ppi, and may be held to a tolerance of +3 ppi and -2 ppi. Foams with different pore sizes are used for explosion suppression, but the thickness required to eliminate flame propagation, and therefore the amount needed to protect any particular tank volume, varies according to the pore size. The smaller pore size (25 ppi) material may be cored or voided to larger degrees than the larger pore size (10 to 15 ppi) foams, while offering the same. degree of protection. Materials

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densities and fuel-retention values also vary for the materials with different pore sizes. Materials with smaller pores generally have a greater fuel-retention because of their greater fiber surface area, but as previously mentioned they can be voided, which offsets the weight and fuel volume penalties associated with their use. Physical property descriptions of these materials are given in Table 5-XX.

TABLE 5-XX. Foam physical properties and characteristics.

Property	Yellow (15 PPI)	Red (25 PPI)
Density Range (lb/ft^3)	1.35 ±0.1	1.2 to 1.45
Porosity (pores per inch)	8 to 17	19 to 30
Air pressure drop (in. of water per in. of mat'1)	0.014 to 0.220	0.240 to 0.330
Tensile strength (psi)	15 (min)	15 (min)
Tensile stress at 200 percent elongation (psi)	10 (min)	10 (min)
Ultimate elongation (percent)	220 (min)	220 (min)
Tear resistance (lb/in.)	5 (min)	5 (min)
Constant deflection compression (percent)	35 (max)	35 (max)
Compression load deflection at:		
25 percent deflection (psi)	0.30 (min)	0.30 (min)
65 percent deflection (psi)	0.50 (min)	0.50 (min)
Load deflection curve from 0 to 80 percent deflection	ASTM D1564-1 (Suffix D) 25 and 65 percent deflection level	ASTM D1564-71 (Suffix D) 25 and 65 percent deflection level
Fuel displacement (volume-percent)	2.5 (max)	2.5 (max)
Fluid retention (volume-percent)		
Fuel	2.0 (max)	3.0 (max)
Water	7.0 (max)	10.0 (max)
Flammability (inches per minute)	15 (max) Report	15 (max) Report

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TABLE 5-XX. Foam physical properties and characteristics (Continued).

Property	Yellow (15 PPI)	Red (25 PPI)
Extractable materials (weight)		
Volume increase after fluid age		
Type I fluid (volume-percent)	0-5	0-5
Type III fluid (volume-percent)	0-12	0-12
Grade JP-4 turbine fuel (volume-percent)	0-10	0-10
Low Temperature flexibility (-40°C)	No cracking or breaking of strands	No cracking or breaking of strands
Entrained sol d contamination (milligram/ft^3)	110 (max)	110 (max)
Steam autoclave exposure (tensile loss in percent) (1 hr @ 140°C)	40 (max)	40 (max)

5.5.3.5.1.1 Fully packed foam explosion protection concept. A fully packed system is defined as one where all potential combat tank ullage is filled with foam with cutouts for equipment only. This system is desirable where little or no tank overpressure can be tolerated, for example, aircraft fuselage fuel tanks. The yellow 15 ppi or red 25 ppi foam can be used for this application. However, the yellow foam is recommended because of its lower fuel retention penalty since the same degree of protection is provided by both materials in a fully packed installation. This material is presently specified by Reference 261. A description of its physical properties is given in Table 5-XX. The following is a narrative description of the operational principles, constraints, performance, benefits, and disadvantages of using a fully packed foam system.

Principle of Operation — The fully packed foam system suppresses explosions and flame fronts by absorbing radiant and sensible heat on its large complex surface created by the foam cell webs. It reduces the normal turbulence and mixing action, that is characteristic of an unrestrained flame front, to a point where the reactive collisions between the fuel and oxygen molecules occur at too slow a rate to allow flame propagation. The heat of combustion, of the few reactions that do occur, has sufficient time to be absorbed by the air-fuel foam environment. Some pyrolysis of the foam does occur in this process, but little, if any, damage to the foam is evidenced.

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Application Constraints	Install under 3 to 5 percent compression. Design and cut foam to fit the contour of the tank with cutouts for equipment and plumbing. Cutout areas should allow a minimum of one inch of space around components such as pumps, and valves for ease of flow and venting in these areas. The use of hot wire cutting is suggested for major sculpturing since this method reduces particulate contamination (caution: fume are toxic); however, for smaller cuts and voids, the use of an electric carving knife is permitted. A final cleaning is suggested which involves rubbing each foam piece over a frame-mounted mesh screen or hardware cloth to dislodge any frayed or loosened foam particles on the surface. Strict handling and storage procedures are required to minimize contamination and degradation of the foam. During installation, detailed inspection procedures are required to assure a proper fit, especially in component and void areas. This is required in order to eliminate any interference with working components and system performance. As a final check on the installation, each aircraft is tested to assure proper fuel system operation. This acceptance testing normally involves such items as fuel quantity gauge recalibration, booster pump performance, vent testing, and contamination checks. In addition to these acceptance tests on each aircraft, the first prototype aircraft that is modified should be tested in detail to demonstrate the adequacy of the basic foam design for that particular aircraft fuel system. This testing involves the acceptance test mentioned, and other tests, including the establishment of new tank capacities, usable fuel quantities, and gross weight changes.
System Performance	Excellent explosion suppression. Provides complete explosion protection at all times, regardless of ignition source, temperature, altitude, and fuel condition. Significant protection against projectile initiated, sustained fires has also been shown for several designs. The system requires minimum logistic and maintenance support.
Configuration	The present foam material, designated “Scott Safety Foam” because of its application, is basically low-density, reticulated, polyester-polyurethane that is produced by a special process in which all the membranes are eliminated by thermal reticulation from the conventional strand and membrane structure. The resulting structure is an open pore, three-dimensional, skeletal network of strands having a nominal pore size of 15 pores per linear inch (ppi) and a density of about 1.4 pounds per cubic foot l It is produced by the Scott Foam Division of Chester, Pa., and is distributed by Firestone, Goodyear, and U.S. Rubber (Uniroyal) tire and rubber companies.

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Configuration (Continued)	Procurement by the Air Force is based on the requirements of Reference 261.
Availability	The foam can be supplied in "bun" form, 80 x 40 x 8 inches in size, or cut by the supplier to specified shapes and sizes as required.
Additional Benefits	Other benefits derived from the use of fully packed foam systems include surge and slosh mitigation, as well as aiding the alignment of wounds in self-sealing fuel tank walls; thus increasing the margin of effectiveness in sealing ability. Cursory testing also indicates that the effects of hydrodynamic ram from projectiles may be reduced. This system also provides for multiple hit capabilities of both a simultaneous and a separate nature.
Disadvantages	Data to data indicates that the life of this material is approximately 5 years in an environment of high temperature (95°F) and high humidity (95 percent) if the foam is used inside fuel tanks and is wetted. Under a tropical environment as experienced in Southeast Asia however, the life is reduced to 3 to 3-1/2 years. Newer blended ether/ester based polyurethane foams show promise of greater life expectancy.

5.5.3.5.1.2 Voided foam explosion suppression concept. Voided foam concepts are used where overpressures can be tolerated in the fuel tanks. The higher the allowable tank overpressures, the greater the possible foam voiding. There are two basic ways to apply this technique, which can result in up to 95 percent decrease in the quantity of foam required to protect the tanks. The first approach provides integral isolation (compartments or voids within the foam), while the other takes advantage of natural structural compartmentalization. The integral isolation concept lends itself to large fuselage or wing type fuel tanks, where subdividing the tank into intercommunicating compartments is accomplished with the foam itself forming the walls of the individual cells. Foam is used to isolate the fire and/or explosion to the combustion cell (cell where ignition occurs) by acting as a flame arrestor and preventing the flame from propagating to the adjacent cells. This allows the remaining voids as well as the foam itself to serve as relief volumes; thus reducing the combustion overpressure. This mechanism permits system design based on allowable tank pressures where combustion volumes, relief volumes, and required foam thicknesses govern the allowable percentage voiding. Figure 5-55 shows a variety of possible integral isolation foam concepts. The concepts shown represent designs where the particular fuel tank is empty of liquid fuel. Where fuel tanks are partially full, only the ullage space at any design angle of attack need be protected with foam. This ullage foam in turn may be voided for additional weight saving.

5.5.3.5.1.2.1 Fifty percent void. Fifty percent void foam systems have been successfully proven and qualified for use in fighter-type aircraft fuselage fuel tanks, where tear-resistant bladder material is used for the tank

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itself, and skin/stringer-type construction is used for the airframe. Higher percentage void systems are possible, but the design requires additional test data, based on the geometry of the tank and the pressure limitations on the structure.

5.5.3.5.1.2.2 Model assumption. The simplest model of a relieved explosion depicting the integral-type design is shown in Figure 5-56. In this model, V_c is the combustion volume, and V_f is the arrestor volume. The relief volume (V_r) is supplied by the arrestor material only. If, however, the depth of the arrestor material is greater than that needed to stop flame propagation, voiding behind the arrestor material is possible as shown in Figure 5-56(B). The total relief volume (V_r) now is V_r plus V_f with basically no change in the model parameters.

5.5.3.5. 1.2.3 Hydrocarbons combustion. Since, in the combustion of hydrocarbons with air, little or no change occurs in the average molecular weight or total moles of gas present, the following relationship can be assumed to be true:

$$\frac{P_1 V_1}{T_1} = \frac{P_C V_C}{T_C} = NR = CONST. \qquad (1)$$

where subscript "l" refers to initial conditions and subscript "C" refers to final conditions.

Further, since the maximum ratio of T_c/T_1 is eight for most hydrocarbon, air stoichiometric mixtures of interest and is independent of all other model parameters, it isconsidered a constant (K) in the analysis. Thus the combustion processcan be written as:

$$KP_1V_1 = P_CV_C \text{ or } \frac{P_C}{P_1} = K \text{ where } V_1 = V_c \qquad (2)$$

The above equation is satisfactory for unrelieved explosions; however, when free adiabatic expansion is allowed and flame propagation is limited to the available combustion volume, as assumed in this model, two possible solutions to the attenuated model exist. The first assumes that all of the combustible gases in V_c burn and expand to equilibrium in the total volume. This solution results in the maximum predicted pressure rise for the attenuated model. Experimental work has shown this solution to be invalid.

5.5.3.5.1.2.4 Dynamic model. Divergence of the predicted overpressure values of the model occur as the mass transfer resistance to the relief volume increases. The resistance is a function of the mass transfer rate which in turn is influenced by the size and type of ignition source, the initial pressure, the combustion volume and the relief area and volume. To accommodate the mass transfer rate and resistance, a dynamic model has been formulated and is included in Reference 162. For single cell protection, the static model

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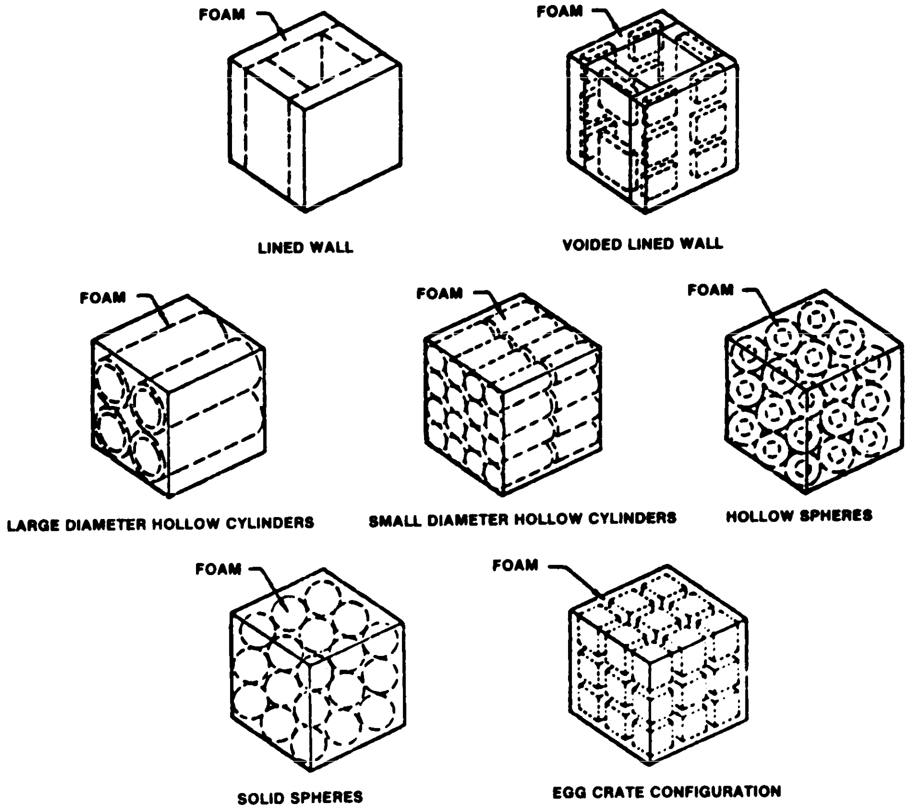

FIGURE 5-55. Integral isolation concepts.

FIGURE 5-56. Single tank model.

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satisfactorily predicts the results for up to 60 percent voiding. Where structural compartmentalization is used as described below, the relief area to combustion volume must be considered and dynamic effects may alter the results. In any case, the maximum overpressure can be predicted by considering each cell individually.

5.5.3.5.1.2.5 Integral wing fuel tank design. The structural isolation concept is readily acceptable to integral wing fuel tanks where the structure offers natural compartmentalization, with intercommunicating openings between cells. Foam is placed over these openings, and is used to isolate the reaction in the combustion cell by acting as a flame arrestor, stopping the flame propagation to the adjacent cells.

a. First solution. Pressure generated by the combustion process in the ignited cell is relieved through the foam and intercommunicating holes. The parameters of combustion volume, relief volume, and foam thickness; ignition energy; and intercommunicating hole size, as they relate to allowable tank pressures; govern the design of this type system.

b. Second solution. The second solution assumes that only a portion of the combustible volume (V) burns, venting part of the original unreacted volume through the foam into the protected relief volume (V_r). Introducing (V_x) into the model and using the nomenclature shown in Figure 5-57, yields the following relationships:

$$KP_1(V_x)^N \quad + \quad P_2(V_C)^N \qquad (3)$$

P_2 = final pressure

$V_x \rightarrow V_C$ = Adiabatically

N = specific heat ratio

$$P_1V_r \; + \; (V_C \; - \; V_x)^N \; = \; P_2(V_r)^N \qquad (4)$$

Using relationships (3) and (4), solving for P_2/P_1 yields:

(5)

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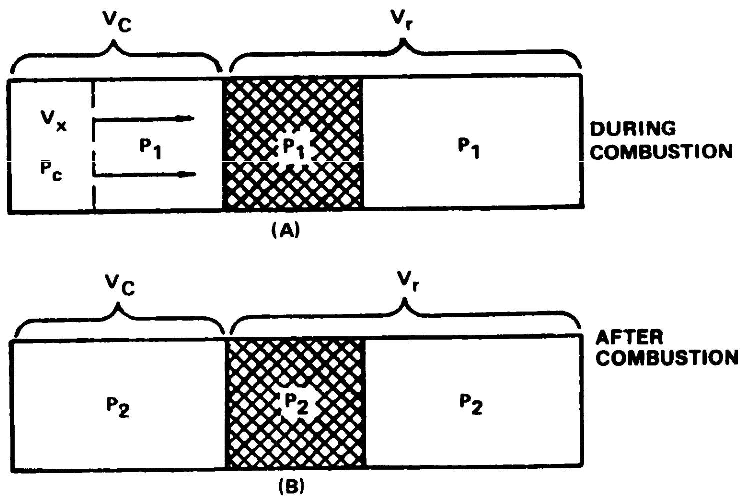

FIGURE 5-57. Theoretical model.

When (V_r) equals zero - i. e., an unrelieved explosion, equation (5) reduces to:

$$\frac{P_2}{P_1} = K$$

which is identical to equation (2) and therefore P_2 for this case equals P_c.

Although equation (5) is for ideal gases and does not account for heat loss or flow restriction, correlation with experimental data (shown in Figure 5-58) is quite good. Where systems, as shown in Figure 5-59 are applied to wing-type tanks, considerable voiding (up to 95 percent) is possible.

5.5.3.5.1.2.6 Small intercommunicating holes. Overpressures are increased, but are acceptable because of the higher allowable structural limits for most wing primary structure areas. If the intercommunicating holes are small (less than the 5 to 10 percent of wall area), as is normally the case; relief is restricted, and the pressure in the combustion cell exceeds the case; relief is restricted and the pressure in the combustion cell exceeds predictions, as previously discussed. This has been shown to be the case, where full-scale gunfire tests on a simulated wing structure produced data indicating that each cell, protected as shown in Figure 5-59(A) or 5-59(B), acts as a separate unit divorced from the adjacent cells, from a relief standpoint.

5.5.3.5. 1.2.7 Large intercommunicating holes. Smaller ignition (spark) sources cause fire propagation at a slower rate; thus allowing flow and relief

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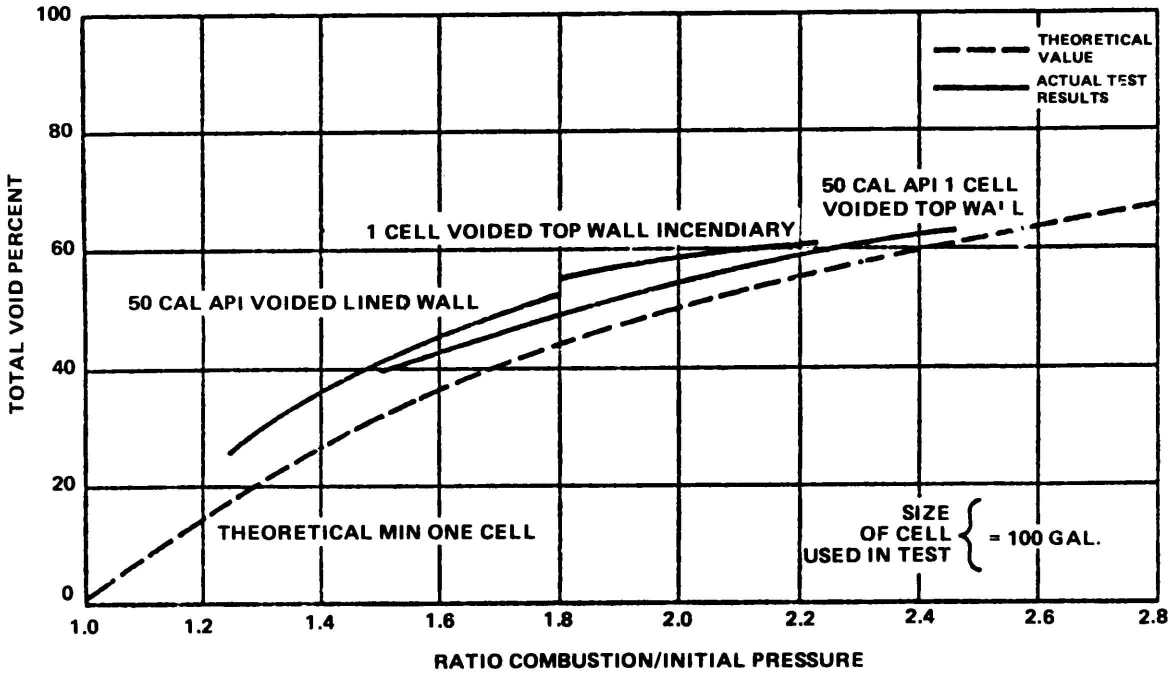

FIGURE 5-58. Fuel tank gross voided foam gunfire and incendiary data (single cell).

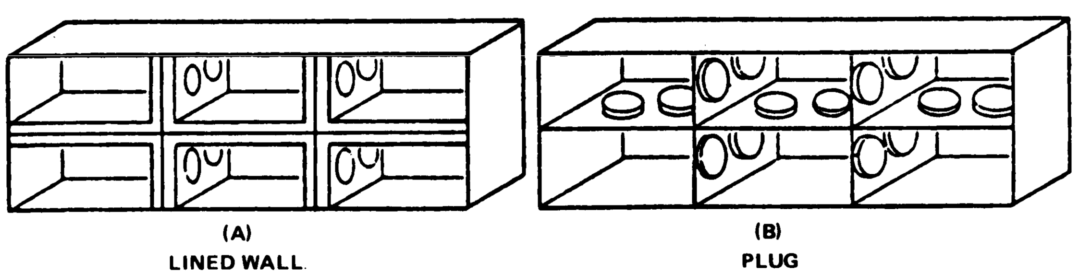

FIGURE 5-59. Structural isolation concepts.

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through the intercommunicating holes. Increasing the hole size will also allow more flow, but alters structural design, and can result in increased weight by requiring heavier skins or internal reinforcing members to maintain the aerodynamic-structural requirements. The result is usually a compromise where additional foam is added to reduce the combustion overpressure. This reduces the allowable combustion volume for any given cell and adds assurance that burn-through of the foam to the adjacent cells does not occur. In the case of no burn through for this multicelled type system, the theoretical minimum pressures agree very closely with actual test results, as illustrated in Figure 5-60. The divergence of the test data from the theoretical values in most cases is due to the slight amount of burning that takes place in the foam itself raising the predicted pressure slightly.

5.5.3.5.1.2.8 Current design. Current design techniques for wing tank type explosion protection systems use up to 80 percent voiding (20 percent foam by volume) and have been qualified through 0.50 caliber API gunfire tests.

5.5.3.5.1.2.9 Theoretical model. The theoretical model, relating over-pressure to volume of relief and volume of combustion, assumes that the polyurethane foam successfully prevents flame penetration into adjacent voids. Unfortunately, there is no model to predict the thickness of foam required to prevent flame penetration. Experimental results must be relied upon to determine the thickness, required for any voiding configuration consisting of multiple voids and/or large voiding percentages.

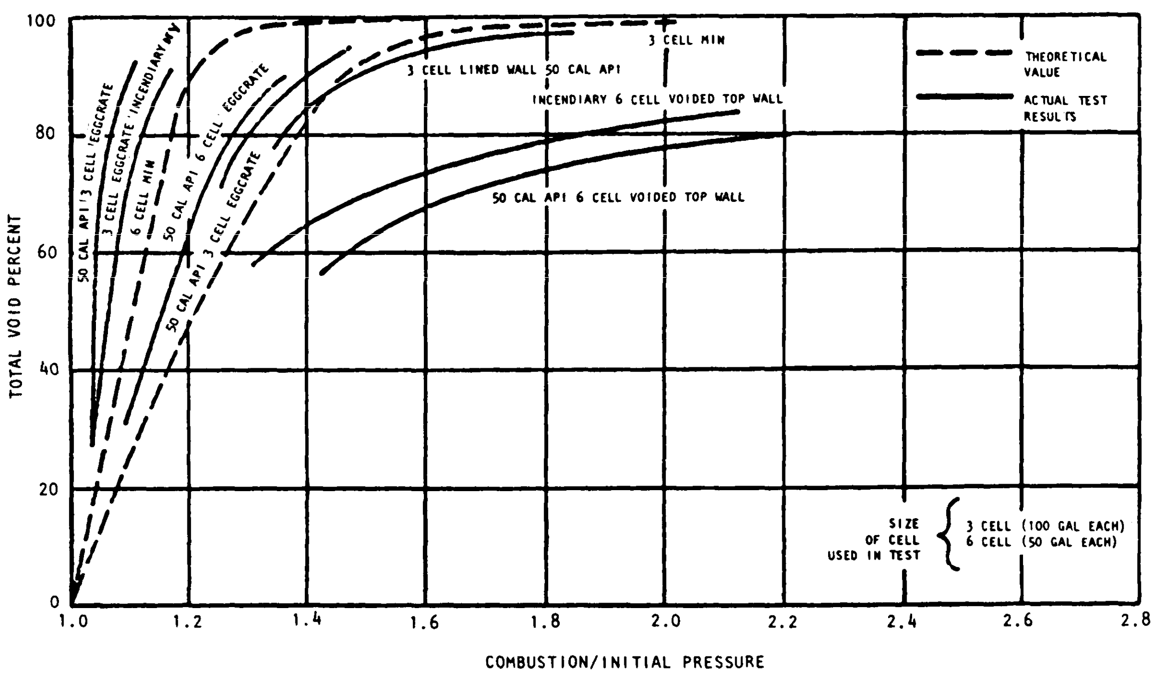

FIGURE 5-60. Fuel tank gross voided foam gunfire and incendiary data.

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5.5.3.5.1.2.10 Best overall performance. Both incendiary pellet and gunfire test data indicates that 25 ppi (Red) reticulated polyurethane foam, as specified in Reference 261, provides the best overall performance. The following is a system description narrative that outlines the basic design parameters for the integral and structural type foam protection systems.

5.5.3.5.1.2.11 Integral type.

Principle of Operation	The integral foam system allows an explosion to occur, but limits it to small internal void volumes, relieving the generated combustion pressure into adjacent cells, thus reducing total system overpressures to a level within the structural limits of the airframe. Isolation of the combustion cells is accomplished by geometric design of closed foam containers with walls of sufficient thickness to stop flame propagation. Fifty percent void systems have been qualified against 0.50 caliber API and high velocity fragment threats for this type design on fuselage-type tanks. Where this foam weight and volume is prohibitive to the particular aircraft design, greater voiding may be accomplished by reducing foam wall thickness and increasing the void volume. In so doing, increased overpressures result as burn-through occurs and adjacent void volumes are ignited. The resulting increased overpressures are not linear with respect to the combustion and relief volume relationships, because the delay of the flame front, caused by foam walls, allows previously burned voids to act as relief volumes for the adjacent cells.
Installation Constraints	Install under 3 to 5 percent compression. Design and cut foam pieces to fit the contour of the individual tank with cutouts for equipment and plumbing. Voiding design must consider structural integrity of the foam after the installation process to ensure that the void volumes are not collapsed due to the compression fit. No adhesive is required for proper installation. Cutting techniques and acceptance tests and procedures are identical to those defined previously in the open cell flexible foam fire protection narrative. The system must be designed and installed to prevent cascading of foam into void areas from violent aircraft maneuvers.
system Performance	The integral foam system is an excellent explosion suppression and overpressure control device. It provides protection at all times, but voiding may be limited if the HEI ignition source is considered. This type of system can be tailored to the tank and structure to provide considerable weight savings by the voiding technique. Verification testing of the system's performance is necessary for a large voiding percentage.

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Configuration	The present foam material, designated "Scott Safety Foam" because of its application, is basically low-density, reticulated-polyester polyurethane that is produced by a special process in which all the membranes are eliminated by thermal reticulation from the conventional strand and membrane structure. The resulting structure is an open-pore, three-dimensional, skeletal network of strands having a nominal pore size of 25 pores per lineal inch (ppi) and a density of about 1.4 pounds per cubic foot. It is produced by the Scott Foam Division of Chester, Pa., and is distributed by Firestone, Goodyear, and U.S. Rubber (UniRoyal) tire and rubber. Procurement by the Air Force is in accordance with Reference 261.
Availability	The foam can be supplied in "bun" form, 80 x 40 x 8 inches in size, or cut by the supplier to specified shapes and sizes as required.
Additional Benefits	Some fuel surge and slosh mitigation occurs, and alignment of wounds in self-sealing fuel tank walls are other benefits derived from the use of this system. It also provides for multiple hit capability, both simultaneously and at spaced intervals, as well as logistic-free operation. Simultaneous hits may result in slightly higher overpressures for reasons described in section 6.1.1.2. Some blast attenuation and protection against sustained fires is also obtained.
Disadvantages	The urethane polyester base material is hydrolytically unstable and has a problem of fuel absorption. High temperature and humidity greatly reduces its life; for example, Southeast Asia conditions resulted in a 3 to 3-1/2 year life. Newer foam material using a blended ether/ester linkage promises to increase the life of the material by 2 to 5 times the current figures.

5.5.3.5.1.2.12 Structural type.

Principle of Operation	The structural foam system allows an explosion to occur, but limits it to the combustion cell, and attenuates the overpressures to a level below the structural limit of the tank. Isolation is accomplished by either the geometric design of closed foam containers and their placement in the individual cells, or by utilizing the natural structural compartmentalization in wing-tank-type design in which the intercommunicating holes are covered, as well as to stop flame propagation. Combustion overpressures are controlled by the amount of foam and the size of combustion volumes, all somewhat regulated by the design of the structure. Cutting techniques and acceptance tests and procedures are identical to those defined previously in the 15 ppi foam narrative chart.

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Installation Constraints	Installation of the lined-wall and plug-type configuration required the use of an adhesive to bond the foam to the structure and seal any possible flame path, created by improperly cut foam material or interfering structure. Several types are available, but care must be taken in their selection for compatibility and weight of the adhesive. The design and installation must be such that any cell to cell communication must go through the foam barrier. (See description narrative, integral isolation concept.)
Configuration Availability	See description narrative, integral isolation concept.
Additional Benefits	Fuel surge and slosh mitigation, multiple-hit capability, logistic-free, and multiple-mission capability are benefits of this type system.
Disadvantages	See description narrative, integral isolation concept.

5.5.3.5.2 Nitrogen inerting (liquid nitrogen source). There are basically three state-of-the-art systems capable of providing nitrogen to the ullage. These are:

a. Closed vent - Where nitrogen is fed into the tank ullage as the fuel is used.

b. Open vent - Where a sweeping action is utilized to reduce the oxygen concentration of the ullage.

c. Scrubbing - Where fine bubbles of nitrogen are formed in the bottom of the fuel tank to remove the dissolved oxygen.

Two storage and supply systems for nitrogen exist, cryogenic liquid and high pressure gas. For the purpose of this report, only the liquid nitrogen storage system will be considered, because it is considerably lighter in weight. In nitrogen inerting systems for aircraft-type fuel tanks, the parameters of mission profile and tank ullage in the combat environment play an important role in sizing the system. The mission profile dictates the number of excursions to altitude, and thus the quantity of nitrogen lost through the pressure and vent sequences. The tank ullage at combat, defined by the mission profile, determines the required volume to be maintained in an inert condition. Two factors must be considered in rendering a fuel tank system inert by nitrogen dilution. The first is the tank ullage volume which must be purged with nitrogen, and the second is the fuel itself, which must be scrubbed with nitrogen to remove the dissolved oxygen. Oxygen is introduced into the tank ullage through the pressure and vent system during aircraft flight. The fuel absorbs an amount of air, dependent upon the total pressure, and as the aircraft gains altitude, some of the dissolved gases will be expelled. The volubility coefficients are such that the dissolved gases in the JP-4 fuel contain 35 percent oxygen, and when these gases are expelled, oxygen

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enrichment of the ullage occurs. When this occurs without nitrogen dilution of the evolving gases, the oxygen concentration will exceed the safe level. In order to prevent supersaturation and subsequent oxygen release, the fuel is scrubbed by injecting very small bubbles of nitrogen into it. The large surface area of the bubbles and the long contact time allows equilibrium diffusion to occur in each bubble; thus scrubbing out and diluting the dissolved oxygen. The oxygen concentration is the governing parameter in the successful operation of a nitrogen inerting system. It has been shown that if the oxygen concentration in the vapor space can be reduce below 12 percent by volume, flame propagation does not occur. At a 12 percent oxygen concentration, and using 0.50 caliber API projectiles as the ignition source, combustion occurs within the incendiary plume, but does not propagate throughout the ullage. Associated with this combustion is an overpressure that may rupture the tank, depending on the size of the tank and its allowable structural limits. In these cases, the volume of gas ignited by the ignition source compared with the volume of the tank must also be considered, in addition to the oxygen concentration. The data in Figure 3-64 was obtained using a 100 gallon test tank. As the volume of this tank is increased, the total overpressure from combustion will decrease. Further relief of the overpressure is accomplished as venting occurs through the projectile entrance and exit holes and will vary according to the size of these holes. These overpressures are reduced as the oxygen concentration is reduced, but are never negated completely (Figure 5-61). Design of a nitrogen inerting system is based simply on filling the ullage with nitrogen as the aircraft uses fuel and changes altitudes, and scrubbing the fuel with nitrogen bubbles during initial climb to altitude. A simple PVT relationship is used to determine the required quantity of nitrogen for any given tank and its ullage volume. For example, consider the following:

Wing tank ullage at time of combat:

50 ft^3 volume

Wing temperature = + 10°F

Wing pressure = 1.5 psig

Altitude = 25,000 ft (pressure = 5.5 psig)

N_2 lost at post-combat refueling or N_2 required to fill the tank

$$PV = \frac{WRT}{M}$$

$$W = \frac{PV(M)}{RT}$$

$$W = \frac{(5.5 + 1.5)\ (144)\ (50)\ (28)}{1544\ (460 + 10)}$$

$$W = 1.36 \text{ lb}$$

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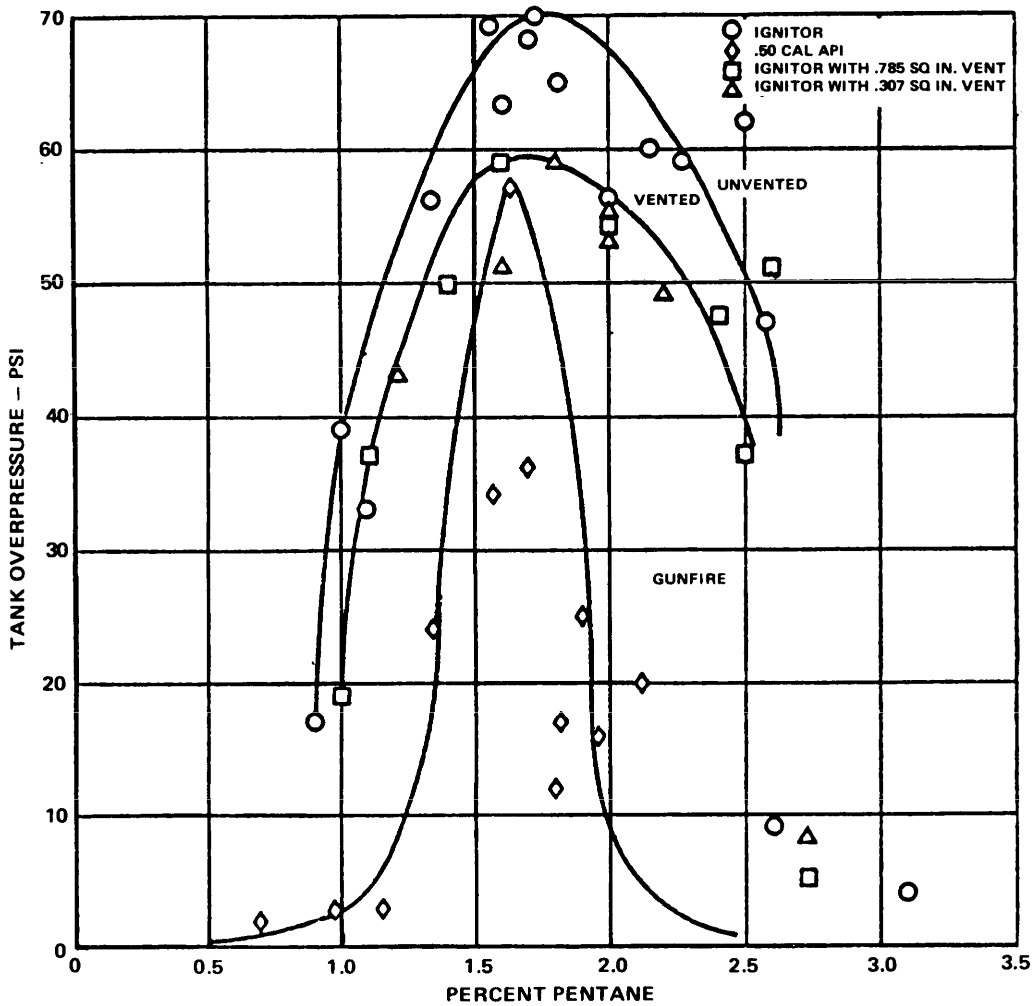

FIGURE 5-61. Tank overpressure vs. percent pentane at 12 = 0.2% oxygen.

This procedure is followed for the total ullage volume in the aircraft after each combat excursion and totaled to determine nitrogen requirements. Several options are available to size the system. These include inerting all ullage throughout the entire flight, inerting only during combat and return flight, and inerting during combat only. It should be pointed out that a constraint on part-time inerting, unless using a Halon, is the need to purge in order to make the tanks inert. The last, of course, is the lightest in weight for the aircraft in question. Scrubbing rates are calculated, using Stokes law relationships for bubble rise rate. The bubble size and composition are affected by:

(1) The diffusion of nitrogen and oxygen into and out of the fuel.

(2) The diffusion of the fuel vapor into the bubble.

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(3) Change of pressure with depth and tank total pressure.

(4) Rise time.

By combining the nitrogen inerting and scrubbing volumes, the total inerting system may be developed and designed as shown in Figure 5-62.

The inflight scrubbing process may be discarded if the fuel transferred to the aircraft has been scrubbed and maintained under a nitrogen blanket, and if the aircraft fuel system vent is closed and pressurized by nitrogen during modes of the flight profile which would add air to the fuel. A non-venting closed-type system is also possible where the aircraft tanks are structurally capable of withstanding the pressure differentials with changes in altitude.

The following is a narrative description of nitrogen inerting system operational principles, applications, constraints, benefits, and disadvantages:

Principle of Operation — The nitrogen inerting system is a moderate weight, active explosion-proofing mechanism that operates on the principle of oxygen dilution of the ullage and the fuel to a level below the concentration required to propagate a fire. It can be operated by using either a gaseous or a liquid nitrogen supply. The system requires a supply reservoir, pressure regulators, relief valves, a pressure demand feed control, and the necessary plumbing required for distribution to the fuel tank areas.

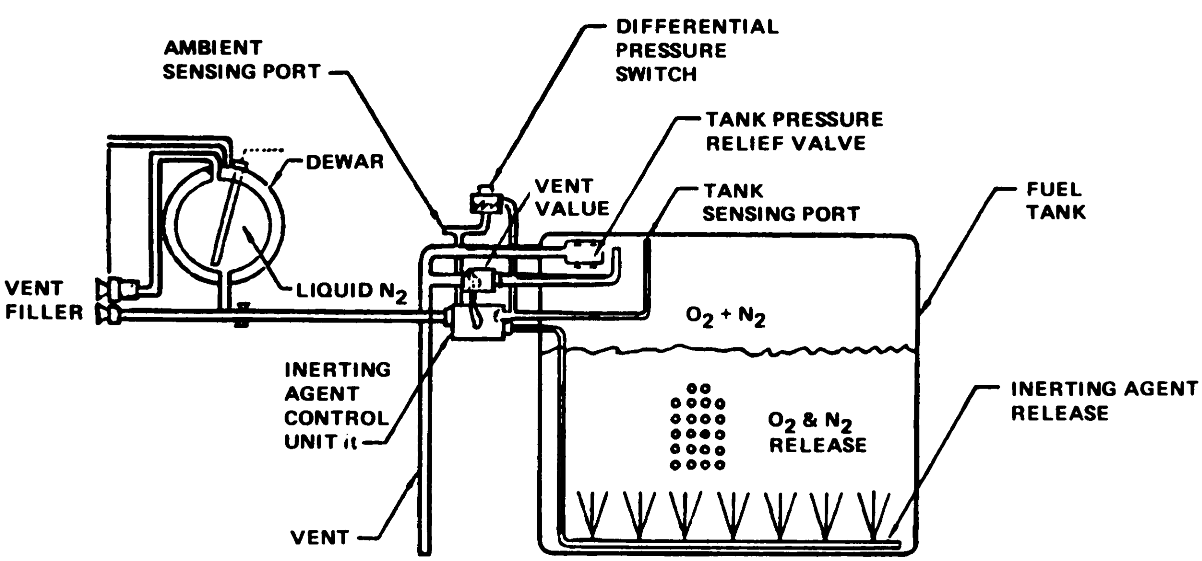

FIGURE 5-62. Typical Ln_2 distribution and inerting system.

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Application Constraints	The system must be designed to: (1) keep a slight positive pressure in the fuel tanks during the inerting cycle, (2) provide sufficient quantities of nitrogen for damage induced losses, (3) maintain the oxygen concentration level in the fuel tank ullage below that required to propagate a fire, and (4) be able to function in existing vent line and fuel tank arrangement and designs. Oxygen concentrations normally are not allowed to exceed 9 percent.
System Performance	The nitrogen inerting system provides excellent fire and explosion protection as long as the fuel tank ullage oxygen concentration can be maintained at low levels. With large ignition sources, combustion will occur and overpressures will vary according to threat level, tank volume, and oxygen concentration (Reference 22). Multi-hit capabilities are limited by leakage of nitrogen through battle damage.
Configuration	A generalized array of equipment required for the system is shown in the schematic, Figure 5-62. Automatic valving and sensing is required to compensate for changes in altitude.
Availability	All equipment required for this system is within the state-of-the-art and is readily available.
Additional Benefits	It can be used as a fire extinguisher in areas adjacent to the fuel tanks, such as dry bays and engine bays, but is not very efficient and would require additional plumbing and more nitrogen. The scrubbing action in the fuel by injecting small bubbles of nitrogen has, through limited testing, given indications of a reduction in hydrodynamic ran pressures.
Disadvantages	Logistics and maintenance requirements are high because facilities for supplying liquid nitrogen are required at each air base, and regular periodic check of equipment is necessary to insure operation capability. It cannot be used in habitable compartments.

5.5.3.5.3 Fuel Fogging. The fuel-fog inerting system is based on two principles: first, that all aircraft fuels have a rich concentration limit of flammability; and secondly, that finely divided suspended liquid fuel (fog) acts, with respect to ignition and flame propagation, as if it were in the vapor state. Since the rich limit is defined as the concentration of fuel vapor to air above which flame propagation cannot occur and fog acts as vapor, the addition of fuel fog to the tank ullage, in sufficient quantity, will theoretically cause the tank to be inert. The vapor concentration is dictated by the ambient total pressure and the fuel vapor pressure which is dependent on fuel temperature only. This being the case, the equilibrium flammability

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concentration of fuels is commonly expressed as temperature at any given altitude. The fog acts as a vapor, adds to the vapor concentration, and lowers the fuel temperature required for the normal JP-4 rich flammability limit (Figure 5-63). It can be seen that a change in the rich limit of flammability occurs and is referred to as the degree of inerting. The inerting is measured by the depression down the temperature scale of this rich limit. These tests were performed using a spark ignition source of the capacitance-discharge type. With a change in ignition energy, the rich limit shift for JP-4 (Figures 5-64 and 5-65) indicates that the basic flammability boundaries are highly dependent on ignition energy. That is, the higher the ignition energy, the higher the temperature at which ignition will occur. The degree of inerting from the fogging technique being used is approximately the same (34°F) regardless of the ignition energy. However, the total region is displaced. This indicates that there is a limit to the usefulness of a fogging system of this type with low volatility fuels where spray nozzles are used to produce simulated fog.

The following is a narrative description of the operating principles, constraints, performance, benefits, and advantages of fuel fogging systems:

Principle of Operation	The fuel fog system is based on the principle that finely divided liquid fuel (fog) acts as if it were in the vapor state, adding to the natural vapor concentration; thereby driving the tank ullage to the overrich condition.
Installation Constraints	A fuel fogging system lends itself well to either retrofit or production installation. Plumbing requirements consist of tubing and nozzles to each tank, routed to provide the best ullage coverage with the fog spray, Fuel is used as the inerting medium, and the pressure required for the fuel nozzle flow may be provided by onboard pumps.
System Performance	System performance is dependent on equipment capable of creating and distributing very small (5 to 50 microns) fuel particles throughout the ullage of the tank. This is best done by spraying fuel at high (500 psig) pressure through nozzles designed to produce uniform fog dispersion. With state-of-the-art equipment, system performance is limited since only partial inerting with jet fuels is possible. This partial inerting is best described by reviewing Figure 3-66 and noting the depression in the rich flammability limit when a fuel fog is sprayed into the existing ullage of the tank. There is no known way to insure that the system is always operating to required performance.
Configuration	The system configuration consists of nozzles, filters, and the necessary plumbing to flow high pressure fuel to these nozzles. The fuel fog distribution manifold with fog nozzles must be located to produce uniform fog distribution through the fuel cells under all degrees of ullage and dynamic flight conditions.

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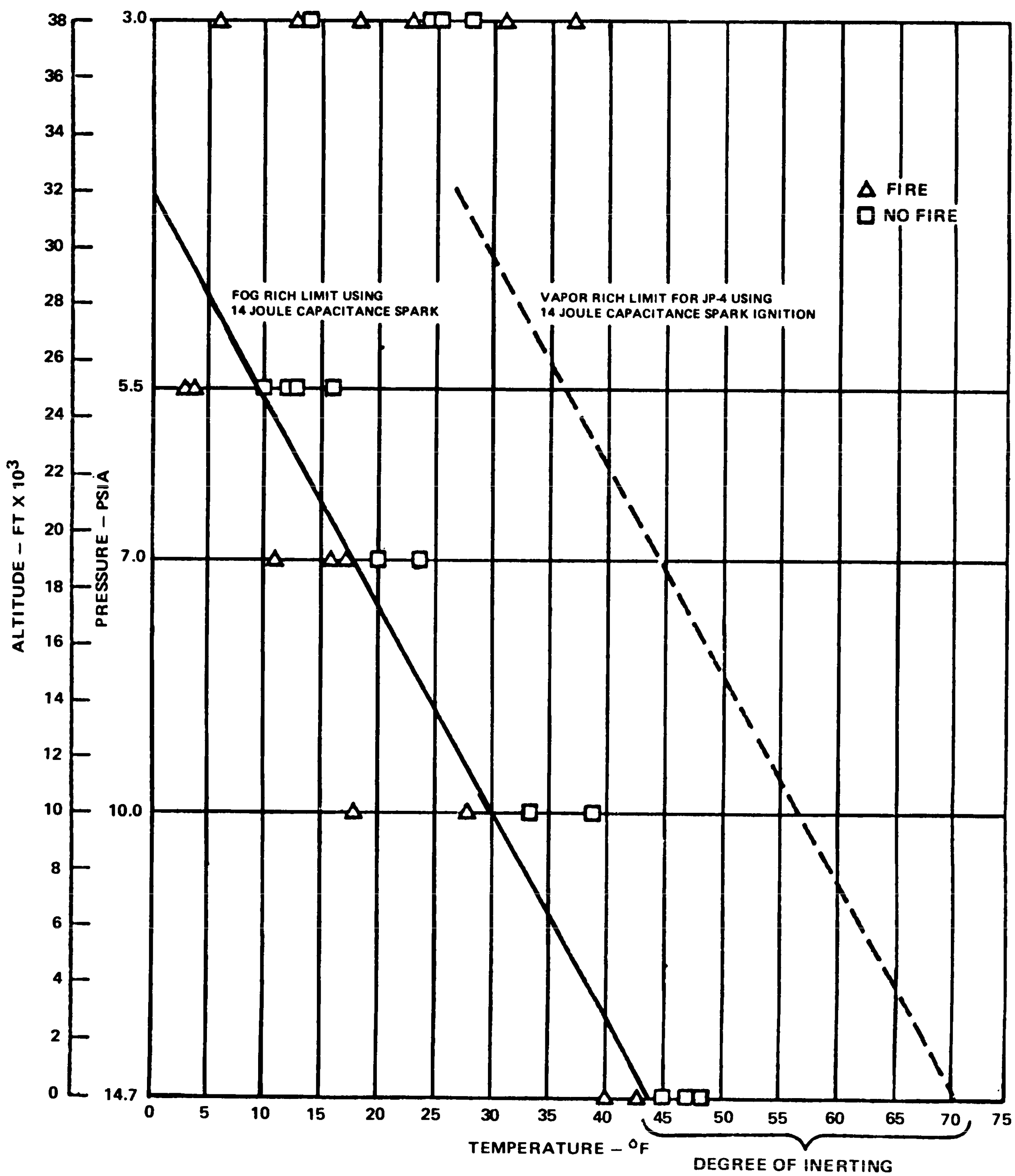

FIGURE 5-63. Rich limit for JP-4 under dynamic fog condition.

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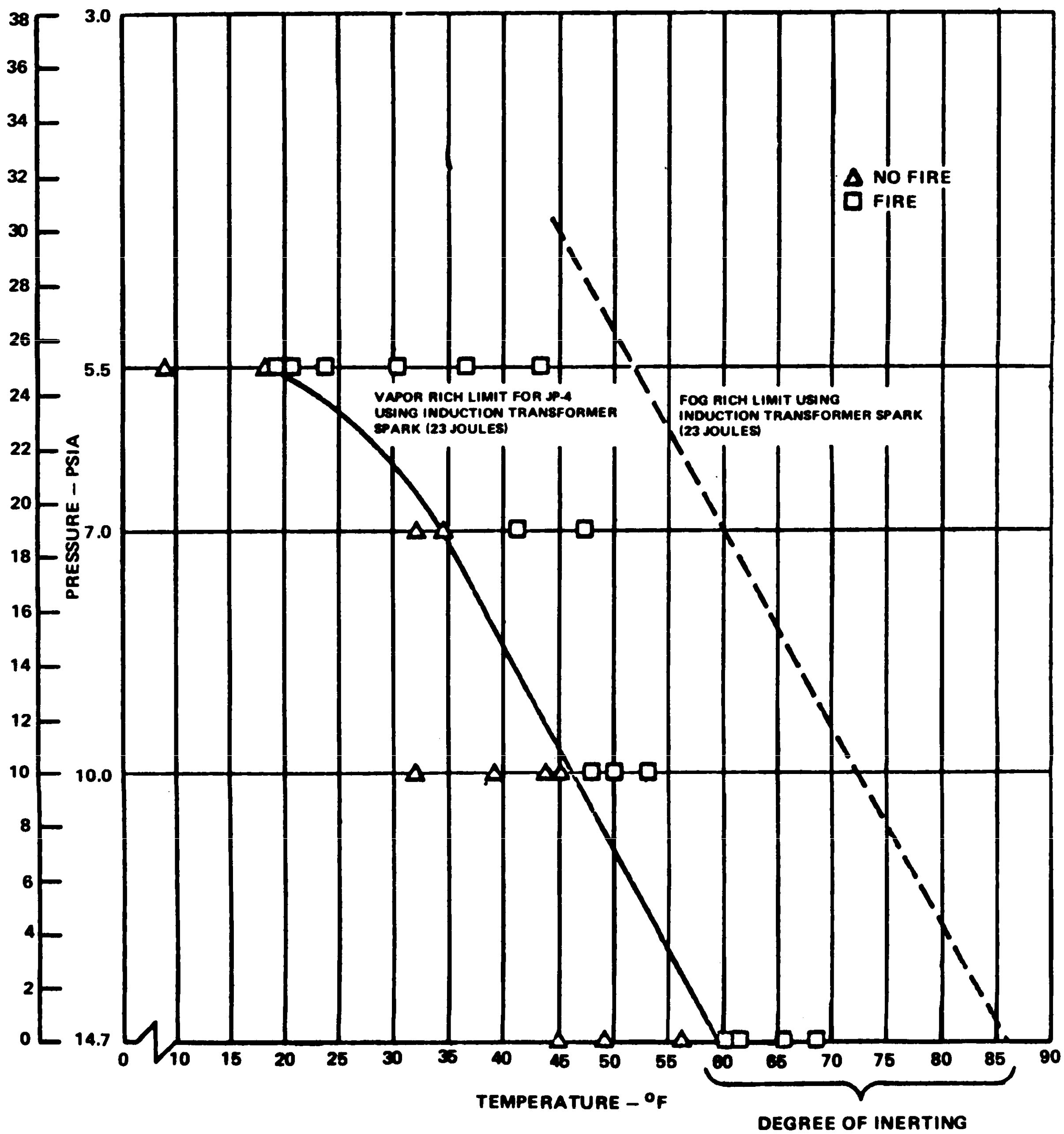

FIGURE 5-64. Rich limit for JP-4 under dynamic fog condition using 23 Joule transformer spark ignition source.

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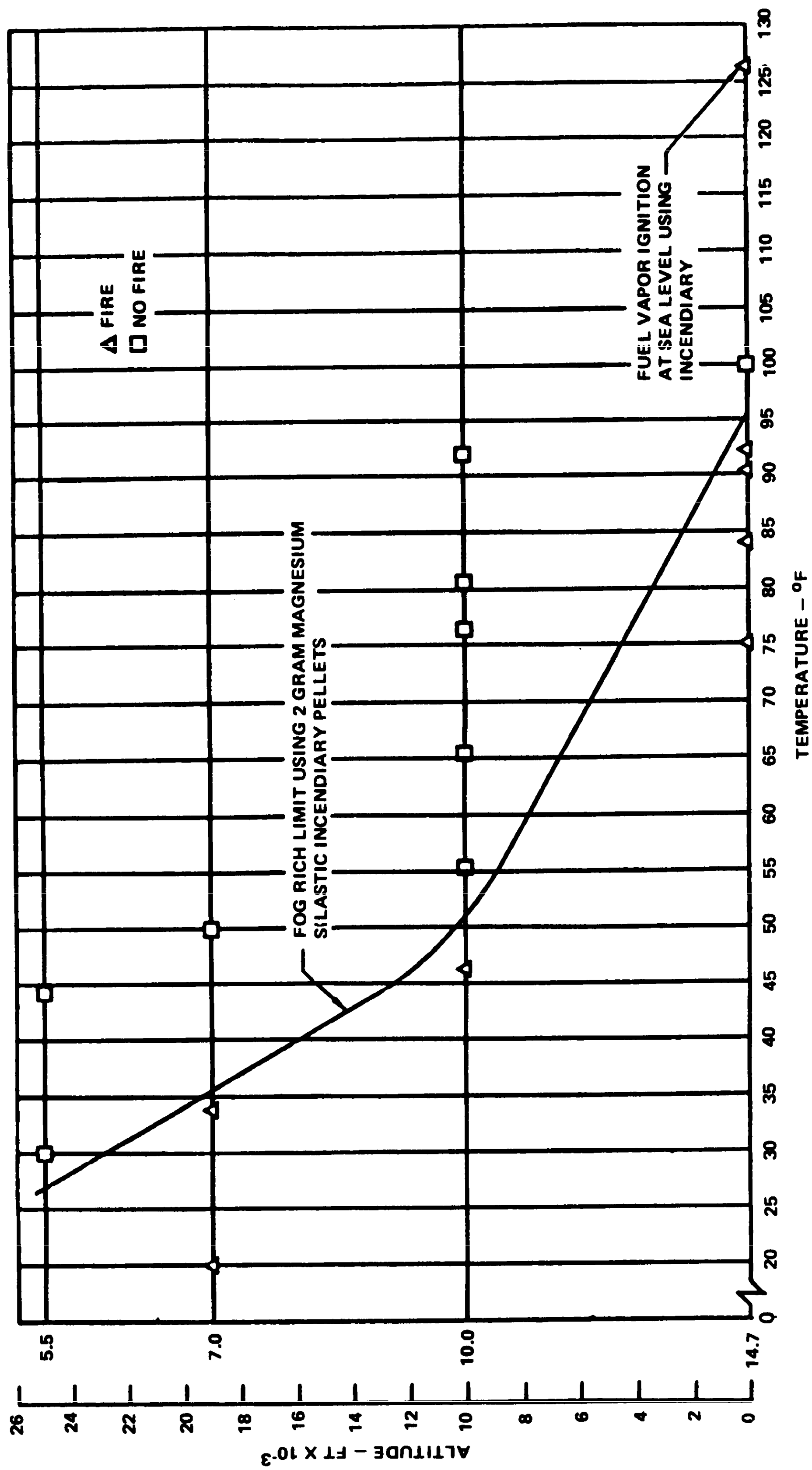

FIGURE 5-65. Rich limit for JP-4 under dynamic fog condition incendiary ignition source.

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Availability	Equipment as described herein is within the state-of-the-art, and is readily available.
Additional Benefits	This system offers the advantage of requiring minimum logistics support, no special handling techniques are required, and little if any maintenance is necessary.
Disadvantages	With present state-of-the-art hardware, fuel tank inerting over the entire flammability range of JP-4 is not realized. The system usage is thus limited to applications where the fuel temperature never gets more than 35°F below its rich limit. Work is continuing to improve the rich limit depression.

5.5.3.5.3.1 Hydraulic-type nozzles. Hydraulic-type nozzles proved far superior to the pneumatic type nozzle, although both showed an ability to partially inert. Hydraulic-type nozzles, operating at a pressure of 500 psig, were able to suppress the rich flammable temperature limit of JP-4 a total of 35°F, while the pneumatic nozzles were able to suppress this limit by only 15°F. With very limited test data, the degree of inerting, using the hydraulic nozzle, was substantially improved (44°F depression) when the fuel supply was pressurized to 500 psig with nitrogen, and then fed into the nozzles. The inerting improvement established in these tests showed the system to be time-dependent, with time being the period that the fuel is fogged into the chamber. This same degree of improvement could possibly be realized with a pneumatic nozzle if the driving pneumatic supply were nitrogen. A hydraulic nozzle that showed the best performance, from a fog inerting standpoint, operated by flowing high pressure fluid through a small hole (0.005 inch) in the exit face of the nozzle onto an impingement pin located directly in front of the exit hole. This impingement pin breaks up the fluid stream into small particles having an average diameter of 30 microns, which is well within the droplet size limitation of 10 to 100 microns required for droplet suspension (fog). Fog concentrations on the order of 0.14 pounds of fuel per pound of air is needed to theoretically make the fuel ullage inert over the full operating range of temperature l

Additional evaluation of the fuel fog inerting concept was conducted in which the fuel was heated prior to fogging. This flashing of the fuel through the nozzle aperture provides further droplet break-up, resulting in a denser fog. Analysis of this test data indicated that a potential inerting capability existed when, in a two nozzle system, one nozzle was fed warmer than ambient temperature fuel. Differences in fuel temperature as small as 5°F were tested. All the results of these tests pointed to inerting success when a match type ignition source was used. Subsequent work with fuel-burner-type nozzles showed that, where 0.30 caliber incendiary projectiles were used for the ignition source, fire resulted in the ullage space each time. Two possible explanations are given for this: (1) the incendiary impact itself alters the ullage atmosphere, and (2) incendiary ignition does not depend on flame front propagation. Although only marginal inerting capabilities are possible at the present state of development of nozzles, limited usage of this system is possible where the aircraft environment will permit this partial capability.

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5.5.3.5.4 Extinguisher type explosion suppression system. This type of explosion suppression system operates on the principle of detecting the initiation of a flame front and reacting to it by explosively dispersing a chemical extinguishing agent. The detector system generally utilizes an infrared sensitive lead sulfide photoelectric cell, or an ultraviolet sensitive tube, to trigger the release of extinguishing agent. Since radiation sensors are line-of-sight type detectors complex or multicell fuel tanks may require more than one detector, and sometimes multiple dispensers. The detectors must also be shielded from all stray light to insure that the system is not inadvertently triggered. The chemical extinguishants used are highly efficient, requiring only 25 cc's per cubic foot of ullage protected. Tests with this type of system, using spark ignition, have shown it to be very effective. However, gunfire ignitions using 0.50 caliber incendiary projectiles, have failed the system. The difference between the two ignition sources is the time to peak pressure. With incendiary ignition this time ranges from 2 to 40 milliseconds, while for spark ignition it can be 100 milliseconds or greater, depending upon tank volume and other parameters.

Decreasing the response time of the seeking and expelling system may overcome these combustion rates but the greater sensitivity would increase inadvertent functioning. Overpressures would still occur in spite of the reaction time because combustion will occur in the incendiary plume. This overpressure will be a function of the plume to ullage volume ratio and the available oxygen in the system. The primary advantage of the system is its small volume. The disadvantages are that it is a single-shot system (although it lingers for a time dependent on vent rate), stray light from battle damage can deplete the extinguishant before it is needed, the complexity of the system degrades its reliability and maintainability, and finally, the dispenser containers are destroyed when the extinguishant is deployed increasing the logistics requirements. The operating principles, constraints, benefits, and disadvantages of extinguisher type explosion suppression systems are contained in the following narrative:

Principle of Operation	The extinguisher type explosion suppression system is a light weight active technique, operating by releasing an extinguishant into the fire zone once a fire is detected through its sensors. Halons 1301, 1211, 1011, 2402, and 1202 are the most commonly used extinguishants. Detectors are normally light sensitive devices, installed in sufficient quantity to allow light detection at any location in the tank.
Application Constraints	This system must be installed so that complete coverage of the entire tank volume by the extinguishant is accomplished. In many aircraft tank designs, more than one agent container per tank is required. This same requirement is necessary in the case of the detector installation.
Configuration	The suppression system consists of a self-contained unit, consisting of the high pressure containers which contain the extinguishing chemical, and a detection device, usually a light seeking cell designed to trigger an explosive charge to disperse the agent from its container.

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Availability	Equipment for this type system is readily available.
Additional Benefits	The required container installation is easily adaptable to any size and type of fuel tank, although more than one container per tank may be required.
Disadvantages	The fire extinguishing type system is not applicable where internal fuel tank peak combustion pressure is reached before the detector can activate the extinguishant, as is the case for projectile induced ignitions. Logistics support for this type system is high, because the bottles must be replaced after each activation. Periodic inspection of the bottles is also required to insure that inadvertent activation has not occurred. A deactivation circuit is required for routine tank maintenance.

5.5.3.5.5 On-board nitrogen generating/inerting systems. Many schemes for generating inerting quality nitrogen on-board aircraft have been investigated. However, the primary disadvantage of nitrogen inerting systems has been identified as the logistics requirements. Three candidate systems have emerged; absorption, diffusion, and catalytic combustion systems. A description of each system follows along with a comparison summary.

5.5.3.5.5.1 Sorbent-bed inert gas generator. The sorbent-bed fuel tank inerting concept is derived from the principle of oxygen absorption from air by a metal chelate, fluomine. The basic sorbent system consists of two beds; one absorbs oxygen from the air stream directed into the fuel tank ullage while the other simultaneously desorbs oxygen overboard. When the sorbent beds become fully loaded with (or depleted of) oxygen, the air streams are reversed. Since absorption is carried out at higher pressures and lower temperatures than resorption and the heat of reaction must be removed or added during absorption/desorption respectively, these bed conditions must be cycled for system operation. A schematic of the system is shown in Figure 5-66. The system consists of a bootstrap compressor for air pressurization, heat exchangers for temperature conditioning, a freon heat-of-reaction transfer circuit, and sundry switching valves for reversing flows and component functions. The valving complexity, the number of rotating turbines, and the complex functional controls result in a low reliability system compared with a liquid nitrogen storage system. The life of the chelate sorbent material is an unknown in this system, in that it degrades during oxygen resorption. The degradation rate is a function of resorption temperature. The cyclic operation of the system makes the heat transfer complicated and has a questionable impact on its life, size, and weight. Reduced temperature oxygen stripping can be accomplished with low pressure air purging. Physical sorption beds, such as molecular sieves, are less temperature sensitive and could be used in lieu of chemical absorbants in a similar inert gas generator system. Unfortunately, because of their coabsorption characteristics, little or no separation occurs at equilibrium. However, dynamic separation does occur. Thus, since their specific rates of absorption for oxygen versus nitrogen are significantly different, a dynamic sorption system can be designed. A more complex system design results because the oxygen concentration would be a function of flow rate pressure, temperature, and time.

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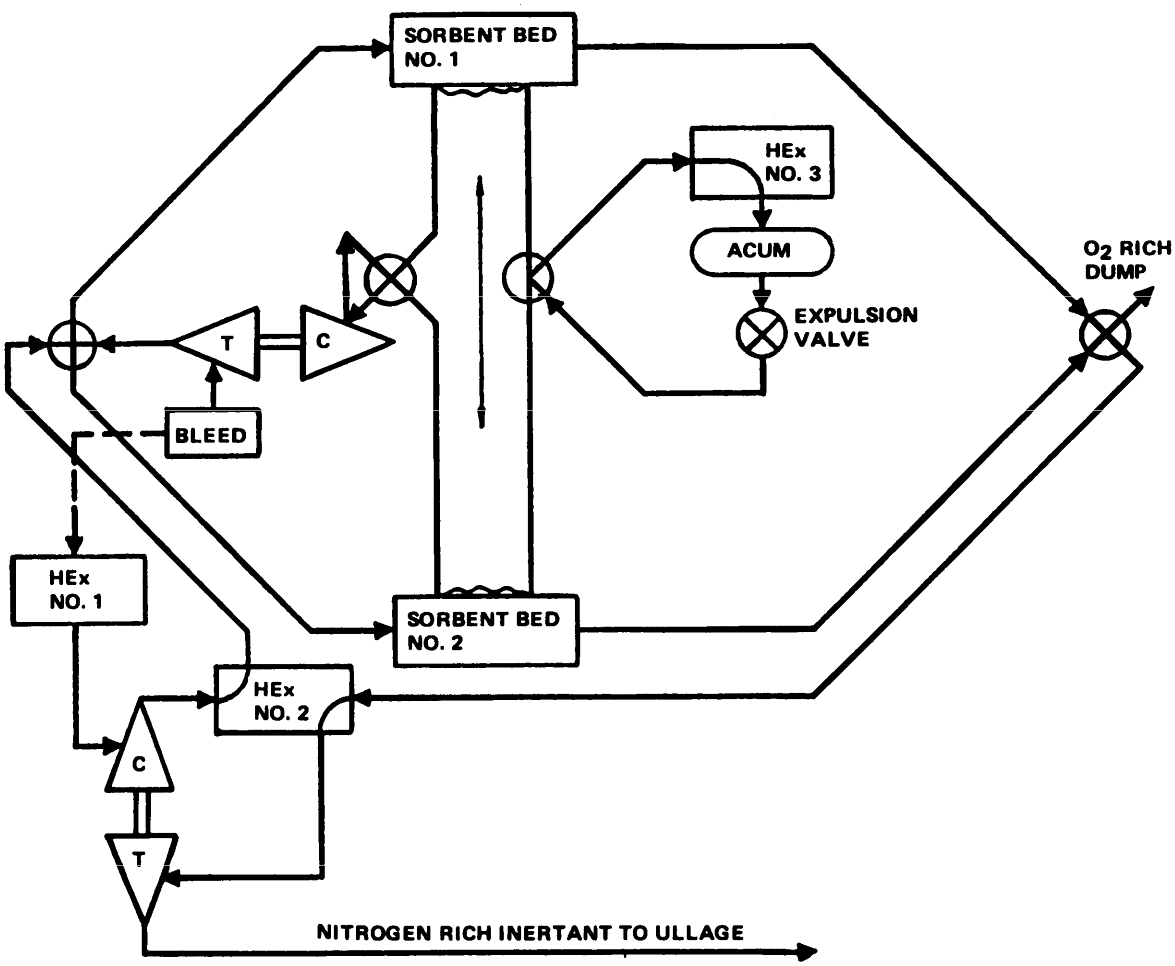

FIGURE 5-66. Sorbent-based inertent generator.

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5.5.3.5.5.2 Catalytic reactor inert gas generator. This system generates inert gas by reducing the oxygen concentration of bleed air through catalytic oxidation of jet fuel at low temperature. A constant mass flow bleed air conditioned to 45 psig and 450°F, along with fuel at stoichiometric mix, feeds a reactor which is held at 1300°F. Excess inert gas flow is dumped overboard. Since constant mass flow is a requirement for the reactor and the range of flows necessary for aircraft fuel tanks varies widely, the need emerges for two reactors to minimize power waste. A small cruise reactor is included. This small unit is used to simplify start-up and warm-up operations of the larger generator. The reactor and existing inert gases are cooled with additional bleed air. Final cooling is accomplished with ram air cooling, followed by turbine expansion. When ram air temperatures are too high, fuel cooling is substituted. Contaminant removal from the inert gases consists of manganese dioxide pellet removal of sulphur dioxide at the exit of the reactor, water removal by condensation and centrifugal separation, and particulate removal by final filtration. A schematic of the system is shown in Figure 5-67.

5.5.3.5.5.3 Permeable membrane - inert gas generator. The permeable membrane inert gas generator system works on the principle off selective gas diffusion where oxygen is preferentially removed from the primary gas stream. The membranes are made of organic polymeric materials that transfer oxygen more readily than nitrogen, with mass transfer ratios on the order of 4:1. Organic, ceramic, and metallic materials are available, but the selection of membrane material is a compromise based on physical properties and mass transfer rates as well as separation efficiency. The mass transfer rate relationship of each gas species through the membrane is given by the following equation.

$$Q = \frac{SD\ (\Delta P)\ A}{t}$$

Q = mass transfer rate
S = volubility coefficient
D = diffusion coefficient
P = species partial pressure differential
A = transfer area
t = membrane thickness

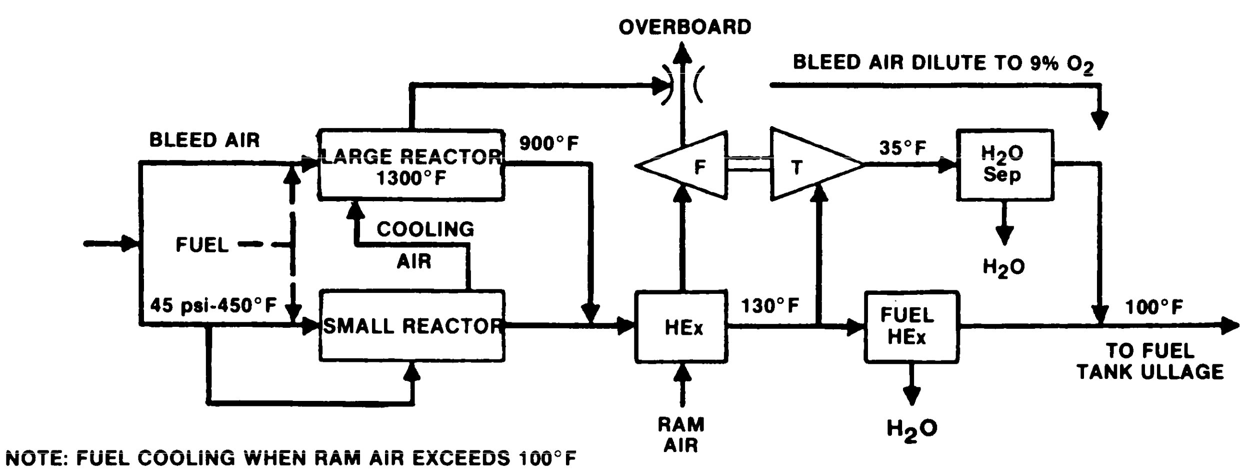

FIGURE 5-67. Catalytic reactor inert gas generator.

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From the equation, it is quite apparent that both solution and diffusion are combined in the process, and the product of their coefficients is the permeation coefficient. Thus the mass transfer mechanism starts by the solution of the gas species into the membrane, setting up a concentration gradient across the membrane which drives the diffusion. Dissolution of the gas species, on the opposite surfaces, maintains the concentration gradient and mass flow. Although gas diffusion is only part of the transfer mechanism, it is usually rate controlling, allowing the surface concentrations to reach near equilibrium with the gas streams partial pressures in accordance with Henry's law. In order to limit the weight and volume of the permeation unit, the area must be minimized, which means partial pressure differential to thickness must be optimized to the maximum. The ultra thin hollow micro fiber technology approach makes the permeable inert gas generator system practical. Figure 5-68 is a schematic of such a system. This system uses bleed air as the primary stream. A turbine/compressor, a heat exchanger, water, and dust separators precondition the air prior to processing. Ram air is used for cooling and sweeping the oxygen rich fraction overboard. During ground operation, fan air replaces ram air requiring auxiliary power.

5.5.3.5.6 Combination systems. The capability of foam, fuel fog, and nitrogen inerting methods to protect aircraft fuel tanks from damaging projectile-induced explosions has been demonstrated. However, these systems have limiting characteristics which restrict their overall usage. For instance, foam explosion-suppression systems, while passive and logistics-free, exhibit higher weight and displacement penalties for single-cell, low-structural-strength fuel tanks. Fuel fog is an active logistics-free system, but has limited inerting effectiveness, particularly for low-volatility fuels and cold ambient temperatures. Nitrogen inerting requires increased logistics, and, because it is an active system, has decreased reliability. Its weight penalties, however, are quite low and it is insensitive to scaling. Preliminary test data obtained to date indicates that improved system performance and a reduction in weight and logistics penalties could be achieved by combining the best characteristics of each system. The candidate systems considered include:

5.5.3.5.6.1 Gross voided foam diluent systems. A gross voided foam system trades off weight for combustion pressure rise, from ignition, for protection to an extent that can be withstood structurally by the tank. The combination of this system with partial nitrogen inerting appears to have merit because the maximum overpressure can be significantly reduced, with the addition of small amounts of nitrogen. Thus, the attenuating effects of the voided foam will result in much lower tank overpressures, or at the same overpressure, greatly reduced foam requirements. The reduced nitrogen requirement could make on-board nitrogen generator systems viable, and the combined system could be attractive from the standpoint of weight, displacement, and logistics over a pure nitrogen inerting system. Other inert gases or halogenated hydrocarbons may be even more effective.

5.5.3.5.6.2 Fuel fog diluent systems. Fuel fogging operates on the principle of producing an over-rich non-flammable ullage, The fog and the fuel vapor are additive, thus making the fuel-to-air ratio higher at low temperatures, which in turn depresses the temperature at which inert conditions exist.

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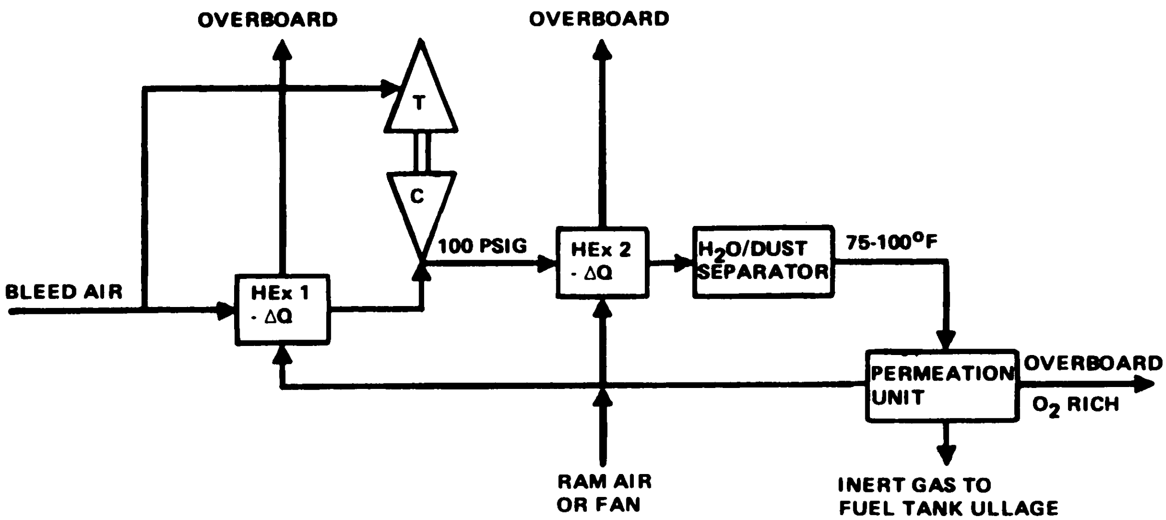

FIGURE 5-68. Permeable membrane inert gas generator.

Past work with fuel fogging has shown that the fog concentration is limited, and, without the contribution of sufficient fuel vapor, the ullage is explosive. The addition of inertants, such as nitrogen and Halons, severly depresses the rich limit, and thus may reduce the fog concentration required at any given temperature to establish over-rich inert conditions, as shown in Figure 5-69. One complicating factor, revealed in previous fuel-fog-inerting investigations, is that the rich limit is a function of ignition energy. Higher ignition energies extend the rich flammability limit. The addition of an inert gas, however, can eliminate or attenuate flame propagation, and thus reduce the maximum combustion overpressure generated.

5.5.3.5.6.3 Anti-mist additive systems. The conclusions from recent tests involving the addition of anti-misting compounds to commercial grade aviation fuel, indicated a significant potential reduction in crash type fuel fires (Reference 30). Subsequent work, involving 0.50 caliber API gunfire ignition tests, also reached similar conclusions. The results of these tests, showing potential additives and their respective combustion overpressures, are presented in Table 5-XXI. It can be seen that the anti-misting additives were effective only with low volatility fuels (for example, JP-8), and their effectiveness was essentially negated with higher volatility fuels such as JP-4. Caution must be exercised, however, in making this observation, because of the fuel temperature conditioning. The ambient temperature (60 to 70°F) test conditions placed JP-4 well within its flammability range, whereas JP-8, the lower volatility fuel, was in the very lean condition. Since fuel droplet number and size has considerably less effect on the vapor in the flammability range, the anti-misting compound will therefore have a negligible effect on the flammability of JP-4 using these temperature ranges. Further investigation of the various additives and the mechanism involved in their operation is warranted where the fuels tested are temperature conditioned to their respective flammability ranges. Once the mechanism of how the additive actually operates is learned, additional materials might then be developed that would greatly extend their effective range.

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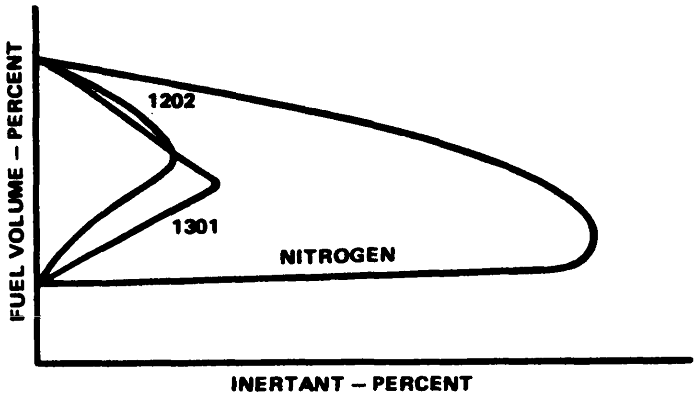

FIGURE 5-69. JP-4 Vapor inerting.

TABLE 5-XXI. Summary of anti-mist fuel additive evaluation.

Fuel/Additive*	Total Shots	No. of Reactions	Average Pressure Rise (psi)	Highest Pressure (psi)	No. of Reactions Over 10 psi**
Base Line Neat JP-4	16	14	54.8	72.0	14
Neat JP-8 (Flash Point 114°)	15	13	38.0	55.0	13
JP-4 + FM-4	15	12	67.5	79.0	12
JP-8 + ESSO A	16	16	31.7	62.0	14
JP-8 + FM-4	16	14	8.6	40.0	2
JP-8 + AM-1	15	12	9.8	33.0	3
JP-8 + XD 8132	15	15	13.1	30.0	6

*All fuel additives at a concentration of 0.3% by weight with exception of XD8132. Concentration was 0.7%.

**10 psi is considered within the structural limits of most aircraft fuel tanks and is acceptable from s system success standpoint.

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5.5.3.5.7 Advanced explosion protection techniques - combination system test program. The capability of foam, fuel fog, and nitrogen inerting systems to protect aircraft fuel tanks from damaging projectile-induced explosions has been demonstrated. All these systems, however, have some limiting characteristics which restrict their usage. Foam explosion-suppression systems, while passive and having low maintenance and logistics, exhibit higher weight and displacement penalties for single-cell low-structural-strength fuel tanks. Fuel fog, which is an active, relatively low logistic support and maintenance system, has limited inerting effectiveness, particularly for low-volatility fuels and under cold conditions. Nitrogen inerting, which is also an active system, required increased logistics. The nitrogen system, on the other hand, has a relatively low weight penalty and is insensitive to scaling. However, altitude excursions increase the nitrogen demand, and the fuel tank vent system must be closed. A review of these inerting systems indicated that combining the best characteristics of each could lead to an improved performance system, with reduced weight and logistic support penalties. Exploration of this possibility, therefore, formed the objective of this portion of the program. The investigation consisted primarily of exploring the effects of adding nitrogen in combination with varying void percentages of reticulated foam and fuel (JP-4)/air fogs. In both cases, baselines were first established using propane/air mixture with varying percentages of nitrogen and fuel/air fog at varying temperatures. Additional background information, such as the energy required to ignite various percentages of nitrogen diluted fuel/air fog mixtures at various temperatures, was also determined. All testing was performed in a 12.5-inch diameter by 21.5-inch long cylindrical test chamber. This 1.5 cubic foot chamber was equipped with a 1-inch thick lucite lid used in the nitrogen/foam tests and an aluminum lid for the fuel/air fog tests.

5.5.3.5.7.1 Nitrogen dilution of propane/air and propane/air/foam. The test schematic for the nitrogen dilution of the propane/air and propane/air/foam combinations is shown in Figure 5-70. Two different types of reticulated foam were used in the tests, the majority of which were run using the 25 pores/inch red foam. Some baseline and 70 percent void tests were also run with 20 pores/inch blue foam. For expediency, the baseline tests (without foam) were performed concurrently with the foam tests through the use of the in-line sampling bomb. The latter could be isolated from the test chamber after each had been filled with the selected gas mixture and then independently ignited to obtain the baseline data. Foam was initially applied to the vertical wall of the test chamber, however, because of the small chamber volume, the foam thickness for an 80 percent void was of marginal effectiveness, and the testing of a 90 percent void configuration was prohibited. This test setup was subsequently modified by relocating the foam immediately below the lid, therby permitting increased foam thickness for each void percentage. An initial test procedure adopted by the test laboratory was later changed after it was discovered that the propane concentration was constant. As a result, the equation was corrected as follows:

$$\frac{\text{Propane (Commercial Grade)}}{\text{Total Gases - (Nitrogen + Propane)}} = 0.06$$

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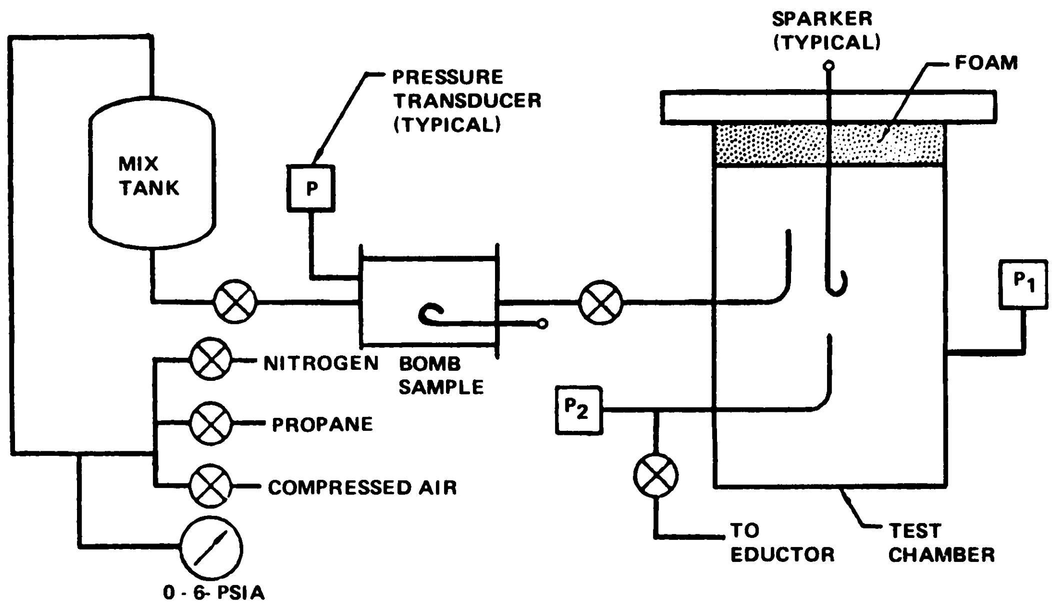

FIGURE 5-70. Test schematic for nitrogen dilution of propane/air and propane/air/foam combinations.

Combustion overpressure data was obtained for a stoichiometric propane/air mixture at 26, 50, 70, 80, and 90 void percents for red foam (25 ppi), and nitrogen dilutions of 0, 5, 9.1, 16.67, 23.08, 28.57, 32.89, and 35 percent respectively. These data are plotted in Figure 5-71. In addition, overpressures were also measured for nitrogen dilutions of 0, 5, 10, 15, 20, 25, 30, 35, and 40 percent with blue foam (20 ppi) at 70 void percent. From the data, two conclusions can be drawn; first, the foam/nitrogen explosion suppression is more effective at foam voids greater than 50 percent for single-cell configurations, and second, greater reductions in combustion overpressure are derived from the initial 20 percent of nitrogen.

Analysis of the data reveals that the combustion overpressure is reduced by a factor of approximately two. This would indicate that by the addition of only small amounts of nitrogen to a voided foam system, the amount of foam required to maintain an equal combustion overpressure could be effectively reduced.

5.5.3.5.7.2 Nitrogen dilution of fuel/air fog. The test schematic for the fuel/air fog and the nitrogen dilution of the fuel/air fog is shown in Figure 5-72. A sonic type pneumatic nozzle was used to produce the fogs, which consisted of droplets of approximately 5 to 50 microns in diameter. The basic test procedure used consisted of spraying the JP-4 fuel through the nozzle for a five minute period prior to ignition, in order to stabilize the temperature conditions. The test chamber was vented to the atmosphere during this period to maintain the ambient pressure conditions. The lid of the test

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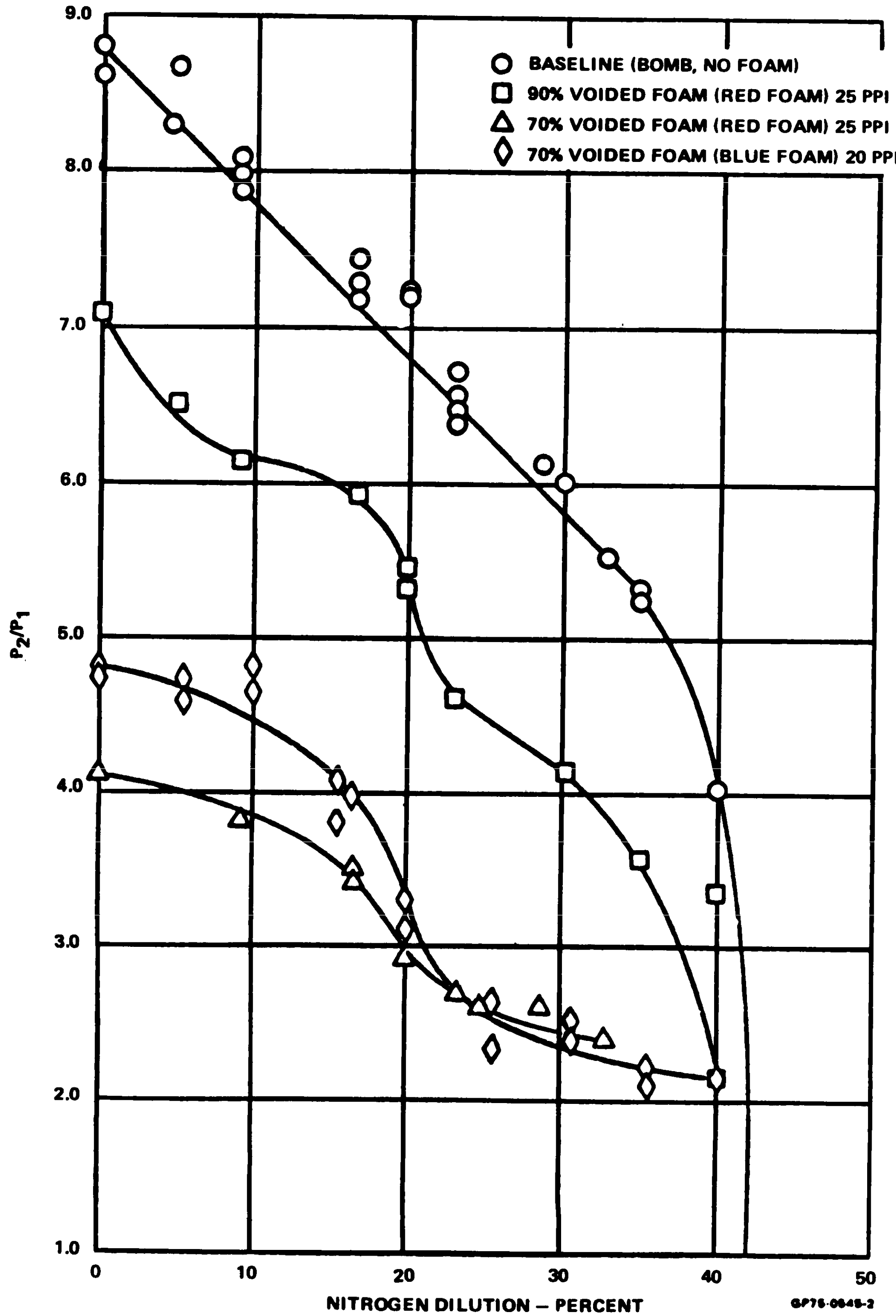

FIGURE 5-71. Nitrogen dilution with and without foam.

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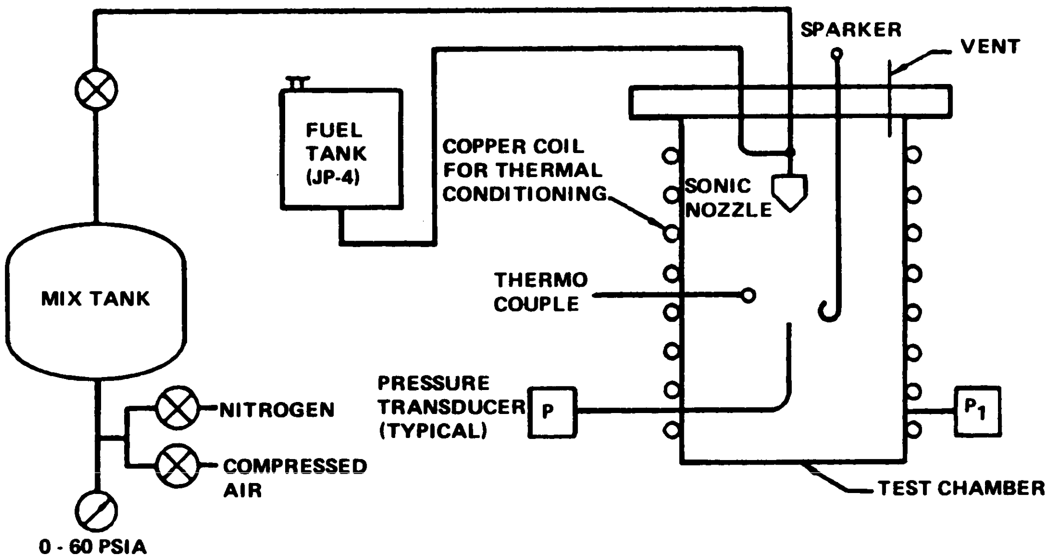

FIGURE 5-72. Test schematic for fuel/air fog and nitrogen diluted fuel/air fogs.

chamber was permanently raised off the sealing face of the chamber body by spacers, for the majority of the tests. This vent area was then closed off with masking tape prior to each test. This technique was performed after one of the first fuel/air tests shattered the original lucite lid. The lid was fully seated, however, during the last series of tests in which peak pressures had to be measured. Ignition energy levels for the nitrogen diluted fuel/air fogs was initially determined using a 25 millijoules capacitance discharge sparker. This was later replaced by a rheostat controlled 110 volt spark ignition system when the former proved to be inadequate.

Ignition energy values were obtained for neat fuel/air fog over the temperature range of 30° to 70°F. Values for 20 and 30 percent nitrogen dilutions were also obtained over a temperature range of 15° to 100°F. These data are reported in Table 5-XXII and plotted in Figure 5-73. In addition, overpressures were measured for fuel/air fogs with 10, 20, and 30 percent nitrogen respectively, over a temperature range of 20° to 60°F. These data, plotted as pressure (peak, psia/ambient) versus temperature, are shown in Figure 5-74. While the addition of increasing amounts of nitrogen to the fuel/air fog reduces the ignitability of the resulting fog, the ignition energy values appear to approach one another at about the stoichiometric temperature of the JP-4 vapor. A review of the data generated further shows that addition of nitrogen to pneumatically generated fuel/air fogs provide some reduction in overpressure. This reduction, however, is not proportional to that obtained in a nitrogen inerting system without fog. The fog, therefore, appears to defeat the effect of nitrogen inerting, at least for pneumatically generated fogs. As an example, the baseline curve (no foam), shown in Figure 5-71 indicates a pressure ratio (P_2/P_1) of 5.75 at 30 percent nitrogen, whereas an equal amount of nitrogen to the fuel/air fog (Figure 5-74) shows a pressure ratio of 7.3.

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TABLE 5-XXII. Fuel fogging.

Test No.	Fog Temp. (°F)	Powerstat Setting	Ambient Temp. (°F)	Flow Time (min.)	Fire No Fire	Energy (Joules)
0% N_2 Added						
1	72	25	66	5.0	No Fire	1.05
2	72	40	66	7.0	Fire	1.65
3	74	25	66	10.0	Fire	1.05
4	75	25	66	5.0	Fire	1.05
5	67	15	73	5.0	Fire	0.63
6	78	15	71	5.0	No Fire	0.63
7	78	20	71	7.0	Fire	0.84
20% N_2 Added						
1	74	15	75	5.0	No Fire	0.63
2	74	18	75	6.0	No Fire	0.75
3	74	20	75	6.5	Fire	0.84
4	87	25	78	6.0	No Fire	1.05
5	87	28	78	8.0	Fire	1.17
6	70	18		5.0	No Fire	0.75
7	70	20		5.0	Fire	0.84
8	55	25		5.0	No Fire	1.05
9	55	28		5.0	Fire	1.17
10	72	20	70	5.0	No Fire	0.84
11	72	23	70	5.0	Fire	0.96
12	84	25	70	5.0	No Fire	1.05
13	84	28	70	5.0	Fire	1.17
14	90	28	70	5.0	No Fire	1.17
15	90	30	70	5.0	Fire	1.26
16	60	15	70	5.0	No Fire	0.63
17	60	18	70	5.0	Fire	0.75
18	45				No Fire	
19	54	20	70	5.0	Fire	0.84
20	56	15	70	5.0	No Fire	0.63
21	56	16	70	5.0	Fire	0.675
22	55	15	55	8.0	No Fire	0.63
23	55	18	55	8.0	Fire	0.75
24*	66	18	55	5.0	No Fire	0.75
25	66	20	55	5.0	Fire	0.84
26	45	15		5.0	No Fire	0.63
27	45	18		5.0	Fire	0.75
28	42	17		5.0	No Fire	0.72
29	42	18		5.0	Fire	0.75
20% N_2 Added (Continued)						
30	45	15		5.0	No Fire	0.63
31	45	16		5.0	Fire	0.675
32	57	15		5.0	Fire	0.63
33	65	15		5.0	No Fire	0.63
34	65	16		5.0	Fire	0.675
35	25	100		5.0	No Fire	3.6
36	36	100		5.0	No Fire	3.6
37	45	35		5.0	No Fire	1.47
38	45	40		5.0	Fire	1.65
39	50	15		5.0	No Fire	0.63
40	50	18		5.0	Fire	0.75
41	53	18		5.0	No Fire	0.75
42	53	19		5.0	Fire	
30% N_2 Added						
1	87	25	78	6.0	No Fire	1.05
2	87	28	78	8.0	Fire	1.17
3	70	20	78	6.0	No Fire	0.84
4	70	23	78	6.5	Fire	0.96
5	50	25	72	5.0	No Fire	1.05
6	50	28	72	5.0	Fire	1.17
7	62	23	72	5.0	No Fire	0.96
8	62	25	72	5.0	Fire	1.05
9	74	100	72	5.0	No Fire	3.6
10	84	100	72	5.0	No Fire	3.6
11**	70	35	73	5.0	No Fire	1.47
12	70	40	73	5.0	Fire	1.65
13	75	50	73	5.0	No Fire	
14	56	15	73	5.0	Fire	0.63
15	58	23	73	5.0	No Fire	0.96
16	58	25	73	5.0	Fire	1.05
17	65	18	73	5.0	No Fire	0.75
18	65	20	13	5.0	Fire	0.84
19	70	40	73	5.0	No Fire	1.65
20	70	43	73	5.0	Fire	1.80
21	46	18	73	5.0	No Fire	0.75
22	46	20	73	5.0	Fire	0.84
23	36	20	73	5.0	No Fire	0.84
24	36	23	73	5.0	Fire	0.96

NOTES: *Plotpoints 24 thru 36
**Same bottle of mixed air/N_2 used for tests 11 thru 24

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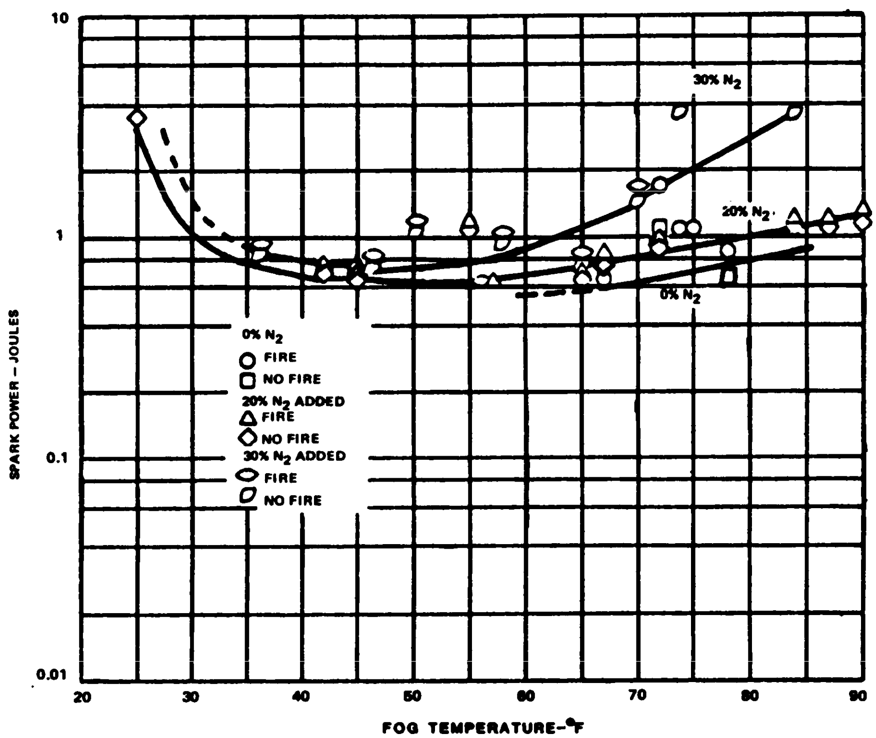

FIGURE 5-73. Fuel fog ignition tests.

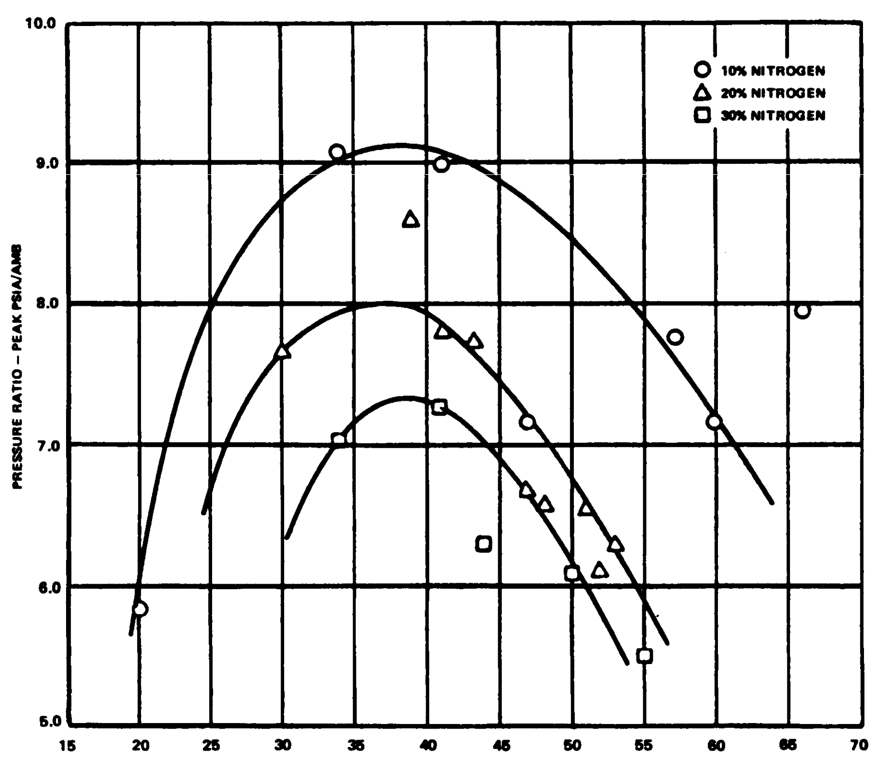

FIGURE 5-74. Fuel fog tests with nitrogen dilution.

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5.5.3.6 Dry bay/void protection. One of the most critical considerations associated with fuel tankage protection is the prevention of fires in the void areas between a fuel cell and adjacent structure and in equipment compartments (dry bays) sharing a common wall with fuel tankage. Severe and catastrophic fires have been experienced in such areas as a result of hostile non-nuclear weapon effects. Figure 5-75 illustrates the mechanism by which a fire can be initiated from the impact of an incendiary projectile. When the projectile strikes the outer skin of an aircraft, the thin metallic jacket on the front end of the projectile is ruptured. This exposes the incendiary material to the air which, in conjunction with the impact event, causes it to ignite and be released into the void area as shown. The projectile continues on its flight and penetrates the fuel tank wall. If the impact is in an area where fuel is present, it causes a spray of fuel to be injected into the void area where the incendiary material is burning. Then interaction will cause a fire to be initiated. If there is continued fuel leakage into the area, a sustained fire can occur. The duration and seriousness of the fire will be a function of the void space, fuel leakage, and air flow into the area. A similar fire condition can be caused by the impact of a high velocity fragment from an externally detonated high explosive projectile or missile warhead. Figure 5-76 shows the sequence of a fire initiation process. When a high velocity steel fragment, or non-incendiary steel core projectile impacts a metallic structure, part of the metallic skin is vaporized and is ignited by the high temperature generated by the penetration. This causes a flash of burning metallic particles to be formed. As the fragment or projectile continues in its trajectory, it penetrates the fuel tank wall and, if there is fuel present, causes a spray of fuel to be released. If the spray and the vaporific flash, from the fragment impact come in contact with each other, a fire can be started. It is generally accepted that a minimum impact velocity is required to generate sufficient vaporific flash for ignition of a fuel spray. Tests show fragments capable of starting fires at 2000 to 2200 feet per second. An effective means of preventing airframe fires is the filling of the voids between fuel tanks and walls with a baffling material which eliminates one of the essential fire-sustaining constituents (airflow, flame propagation, or fuel vapor/mist). The state-of-the-art systems include low-density, open and closed-cell, and/or flexible and rigid foams, in addition to fire extinguishers and inert gas filled purge mats. Material properties and system descriptions are as follows.

5.5.3.6.1 Open-cell flexible type foam. Low-density, ether type, reticulated-polyurethane foam used for fire protection systems is similar to the reticulated ester-type polyurethane foam, presently used for explosion protection systems in aircraft fuel tanks. The ether-base material is a more hydrolytically stable compound than the ester-type and lends itself well to the environment of dry bay areas, where high temperatures and high humidity are common. This material will swell to some degree when immersed in hydrocarbon-type fuels. The material is presently not covered by military specifications; however, its physical properties are presented in Table 5-XXIII. The highest cell count (smallest cell size) available to date for this material is 37 pores per inch (ppi), which is more than adequate for drainage. The following is a narrative description of the principles of operation, constraints, performances availability, benefits and disadvantages of the open, all flexible-type foam.

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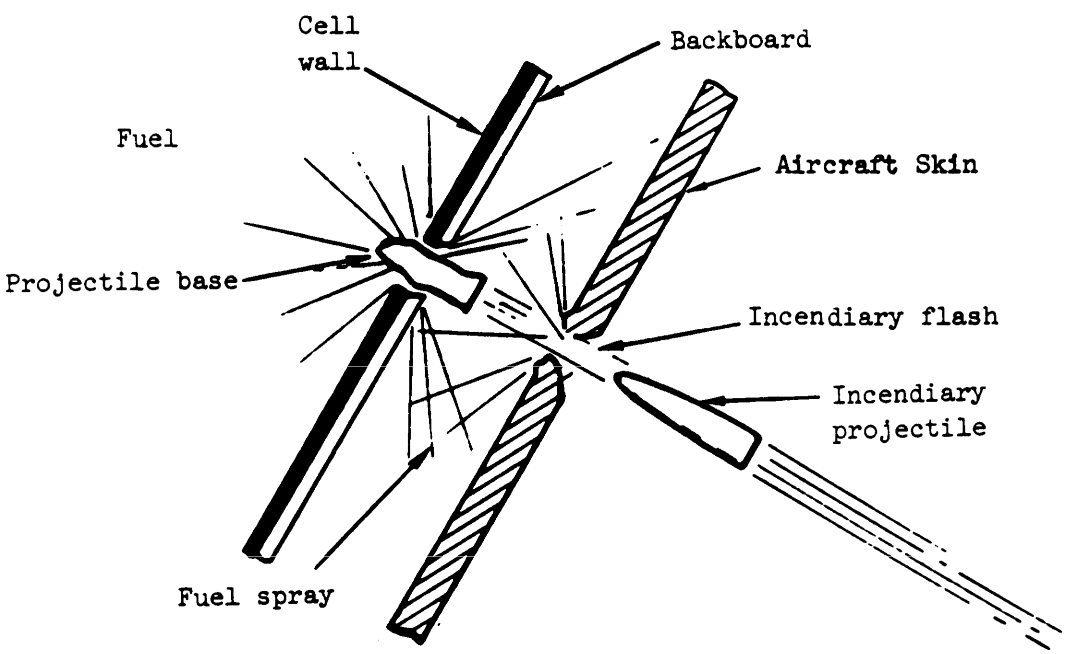

FIGURE 5-75. Ignition mechanism, activated incendiary.

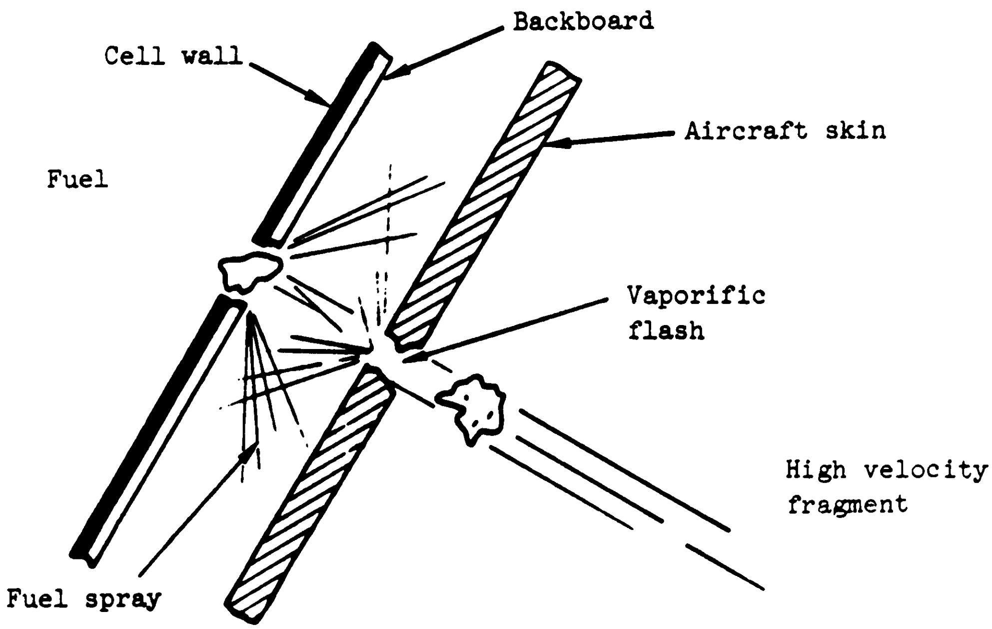

FIGURE 5-76. Ignition mechanism, vaporific flash.

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TABLE 5-XXIII. Physical properties and characteristics of polyether reticulated urethane foam.

Density (lb/ft^3) 1.35 to 1.45
Pore Size - 30 to 50 (37 nominal) ppi

Properties	Fresh	Aged(1)	Autoclave 5 Hrs(2)	Autoclave 10 Hrs(3)
Tensile (PSI)	24.0	18.0	19.0	18.0
Elongation (%)	275	260	300	300
Tear (lb/in)	5.0	500	4.5	
Compression load deflection at 25 percent deflection (PSI)	0.30	0.25	0.25	
65 percent deflection (PSI)	0.53	0.37	0.37	
Compression Set				
50%	10%			
90%	15%			
Fluid Retention (per Mil-B-83054)	Sunoco 190		8.5%	
	Diesel Fuel		14.0%	
Fuel Swell Data - % Volume Swell - 7 Day Immersion				
Sun Gas - 190	30-35%			
Sun Gas - 260	40-45%			
JP-5	19-22%			

(1) 22 hrs. @ 140°C
(2) 5 hrs. @ 15 psi steam
(3) 10 hrs. @ 15 psi steam

Data Supplied by Scott Paper Co.

Principles of Operation — This method reduces spray of fuel from leaking tanks and lines and physically inhibits mixing of fuel and air needed for sustained fires. The foam is open-cell, permitting free drainage of leaking fuel to drain holes located at low points in the aircraft.

Application Constraints — The foam should be installed under 3 to 5 percent compression. Design and cut foam to fit the contour of the bay. Cut-outs are not required for small equipment and plumbing. The material is simply draped over lines and equipment located in the dry bay areas and compressed to fit into the required area. Cutting techniques, acceptance tests, and procedures are identical to those for the polyester type explosion protection foam described in Section 4.

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System Performance	In most installations, this material provides excellent fire protection against projectile sizes up through 23mm HEI regardless of temperature, altitude, and fuel conditions (Reference 2). The system requires minimum logistic support as well as multi-hit capability.
Configuration	This low-density ether-type reticulated-polyurethane foam is manufactured by the Scott Foam Division of Scott Paper coo, Chester, Pa. The pore size currently available ranges from 25 to 50 ppi and is not covered by a military specification.
Availability	The foam can be supplied in bun form, 80 x 40 x 8 inches, or cut by the supplier to specified shapes and sizes, as required.
Additional Benefits	In addition to allowing free drainage, reticulated polyurethane foams also are non-wicking. They further permit free passage of air through the foam, which may be required for ventilation and heat rejection around the fuel cell. Recent tests conducted by the Air Force (Reference 2) have indicated that this material, installed in a 2-inch deep void adjacent to the side of the fuselage fuel tank and under 5 percent compression, may provide a reduction in hydrodynamic ram damage and subsequently aid in sealing self sealing tanks.
Disadvantages	The material will swell and lose some of its physical strength when subjected to long soak periods in hydrocarbon-type fuels. The continuous upper temperature limit is 375°F. The material is flammable and may support combustion especially when large skin damage occurs, as with HEI projectiles.

5.5.3.6.2 Closed-cell rigid foam. Low-densitv, closed-cell rigid tvpe foam consists of an expanded polyurethane and is designated by its manufacturer, AVCO, as 51 polyurethane foam. Table 5-XXIV describes the physical properties of this material. The basic operating principle, for fire protection of a dry-bay adjacent to fuel tanks, with rigid foam is simply to fill up the void so that fuel from a leaking or ruptured tank, if ignited by either a projectile-induced or electrical source, is prevented from propagating into a destructive-type fire. When this space is filled, the oxygen supply to the spilling fuel is limited or eliminated in the internal segments of the aircraft, and fire in these areas will not readily propagate. In this respect, the designer is charged with the task of assuring that the rigid-foam material remains in place and does not break up too severly when impacted. This can be accomplished by reinforcing the material itself or containing the foam between layers of ballistic nylon cloth or other type binder. When rigid foam is used for application in dry-bay areas of four inches or less in thickness, the volume is filled with the material for best results. A generic fuel tank, protected with this type foam is shown in Figure 5-77. It was designed for survival against the 23mm HEI threat, where the explosive warhead is detonated

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TABLE 5-XXIV. Summary of physical properties 51 Polyurethane foam.

Property[1]	Units	Method	Parallel to Rise Typical	Parallel to Rise Specification	Perpendicular to Rise Typical[2]	Perpendicular to Rise Specification
Density[4]	Lb/Ft^3	ASTM D1622	2.3	2.2±0.5		
Compression		ASTM D1621				
Stress at:						
1.5% Offset	psi		24		15	
10% Strain	psi		21	16 min.	14	10 min.
50% Strain	psi		24		18	
Modulus	psi x 10^6		0.00063	0.00047 min.	0.00031	0.00023 min.
Thermal Conductivity (at 250°F)	$\frac{BTU}{Hr\ Ft\ °F}$	ASTM C177	00022			
Porosity (4)		Kerr Smith Pycnom-eter		5 max.		
Size 1 x 1 x 1 inches			9			
1.25 X 1.25 X 3.0 inches			2.5			

(1) Room Temperature values except as noted

(2) Typical - Arithmetic mean value

(3) Specification - Minimum (maximum) values or nominal values with tolerance limits

(4) Density and porosity are independent of direction

(5) Higher and lower densities are available.

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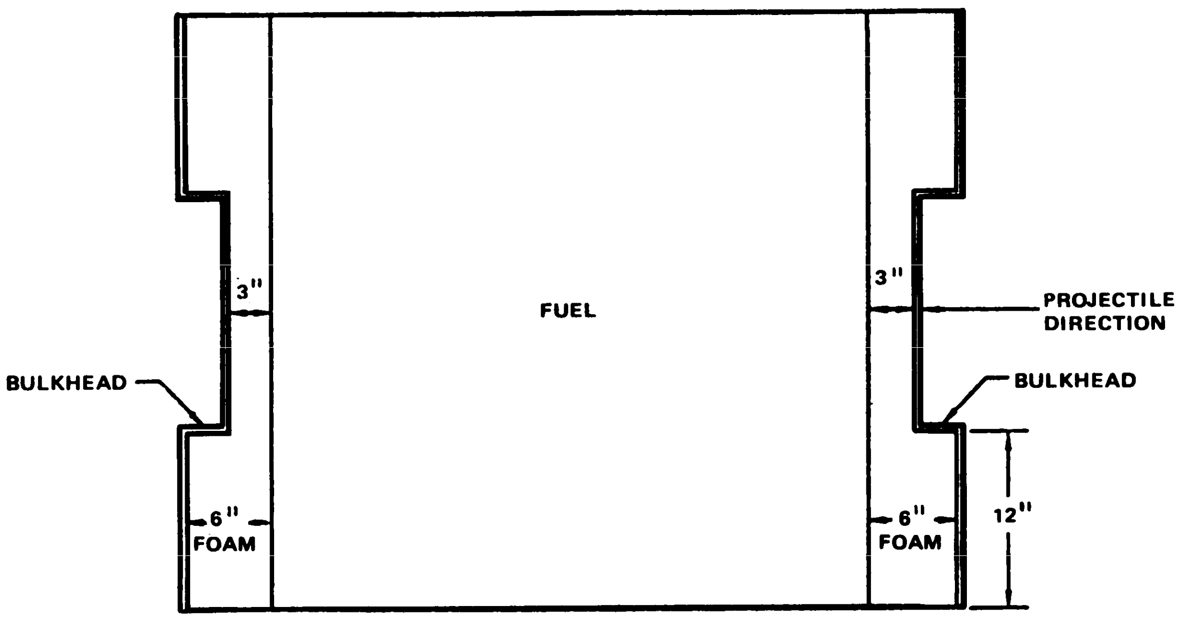

FIGURE 5-77. Top view of generic fuel tank.

within the tank. This particular model represents minimum rigid external foam application for the threat, with the projectile attack direction through the foam. The tank is large and representative of a typical fighter fuselage or helicopter fuel tank. According to current test data, in no case should there be less than three inches of material outside the tank, and the foam should be contained within a bulkhead as shown. Where other types of projectiles are used, or points of detonation from these projectiles occur at different locations, other considerations must be given. It has been found that if a high explosive round (23mm HEI) goes off in the foam itself, approximately 10 inches are required, as a radius dimension from the point of detonations to offer fuel tank or dry bay protection. Armor-piercing incendiary (API) projectiles tend to core holes in the rigid foam materials. This has been shown to be true in limited testing conducted by the AFFDL, where the installation of rigid foam in the dry bay areas around fuel tanks successfully defeated the external fire potential for the 23mm HEI threat, but failed when subjected to the 23mm API, due to coring of the material. An attempt to stop the coring and breaking up of this rigid material was made by applying a ballistic nylon cloth to both sides of the foam. This technique proved to be successful in limiting the breakup of the foam, but did not stop the coring. A layer of flexible foam or backing board next to the tank wall has been tested, and preliminary results indicate that dry-bay fire potential from API projectiles can be greatly reduced or eliminated. Limited testing of combinations of rigid and flexible foam has shown significant improvement in fire suppressing performance in combinations over each of the foam types used individually.

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The following is a narrative description of the design considerations for this closed cell rigid foam:

Principles of Operation	This foam suppresses fire by occupying the void adjacent to the fuel tank, thus eliminating the free air necessary to propagate and sustain fires.
Application Constraints	The foam must be cut or molded to fit the bay where it is to be applied. If lines, wires, or any other equipment are located in these areas, cut-outs must be provided. It cannot be applied in areas where cooling and ventilating air flow is required. It is recommended that the material either be reinforced by or sandwiched between layers of ballistic nylon cloth to eliminate the effects of coring and breakup of the foam. It is recommended that the dry bay volume be filled completely with the foam up to three inches in depth, and that a minimum of three inches be used in larger voids to make the system effective.
System Performance	This foam provides excellent fire protection at all times, regardless of temperature, altitude, and fuel conditions, and will require a minimum of logistics support requirements. The design of the system is dependent upon the level of threat expected. Damaged sections should be replaced before they are subjected to a renewed hostile environment.
Configuration	The 51 foam is a closed-cell rigid polyester type polyurethane, exhibiting a low friability but good mechanical strength, currently available at 1.5 pounds per cubic foot l It is a castable foam and can be supplied in a variety of shapes and sizes depending on its final use and requirements. It is provided with additives to give char stabilization and improved char yield upon exposure to large-scale fuel fires to block convective heat transfer. Evolution of reactive fire suppressant agents also occurs, which scavenge the free ions necessary in the hydrocarbon combustion process. The material may be cut to size and shape by the hot wire technique (caution: fumes are toxic) or by an electric knife. It is readily cut and easily adaptable to any size or shape cut-out.
Availability	The foam is available in various sizes and shapes, since it is a castable material that will form to the shape of its mold or container. Normally the designer would specify the required size and shape and require the supplier to provide the foam accordingly.
Additional Benefits	When this material is used outside the fuel tanks, it may substitute as a tank backing board material, depending on the threat environment specified for the aircraft. It

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Additional Benefits (Continued)	provides some hydrodynamic ram structural protection, acts as a firewall, and aids, in self-sealing by providing realignment of the wound through support of the tank.
Disadvantages	Closed cell rigid foam acts as a wick and does not drain freely. It requires the use of ballistic nylon or other equal property type materials to be bonded to the faces for ballistic tolerance. This adds considerable weight to this type of system. Closed-cell foam cannot be applied to an area where air flow for ventilation or cooling is required.

In summary, each rigid foam design for dry-bay application must be qualified according to the test data available at this time. In all cases, the successful use of rigid foam type 51 for dry-bay application, requires the use of ballistic nylon cloth or other similar material bonded to each face of the foam. This serves to hold the rigid material together when subjected to ballistic impact. It is also important that, for assurance of best results in dry-bay application, the bay should be completely filled.

5.5.3.6.3 Purge mats. Purge mats are flexible bags that occupy the entire void to be protected and are filled and pressurized with an inerting media. These mats consist of two layers of fabric impregnated with fuel-resistant rubber. Nylon drop stitches are woven into both sheets of fabric and retain the desired shape and thickness when the mat is inflated. Tests have shown that this concept is effective only at high pressures. Therefore the mat is constructed for operation in the 50 to 60 psi range. Figure 5-78 shows a cross-section of a typical purge mat construction. The purge mat concept is based on the release of the inert gas contained in the bag upon projectile penetration. The released gas inerts the immediate surrounding atmosphere where the fuel and ignition source are present. Fires associated with the leaking fuel and the incendiary ignition sources are thereby temporarily eliminated. This technique has been proven to be effective for small (0.30 and 0.50 caliber) API projectile ignition sources, but for larger threats of the HEI type, the purge mat system is unsatisfactory. The reason for the failure of this technique against larger threats is because of the projectile blast, which in combination with the purge mat's internal pressure, disperses the inerting gas rapidly over a larger area, thus negating the inerting effect. This theory is supported by tests where the explosive in the larger projectile was initiated at some distance from the purge mat. The system in this case was successful in preventing fires. Table 5-XXV contains the results of firing tests conducted on a three-inch thick purge mat filled with nitrogen gas. More recent data indicates that, if a fire extinguishing powder is substituted for the nitrogen gas in the purge mats, a higher degree of effectiveness against larger caliber threats is possible. In this case, the powder does not automatically escape through the wound, but is in fact evenly distributed throughout the protected area by the subsequent hydraulic shock, providing better fire suppressing capability.

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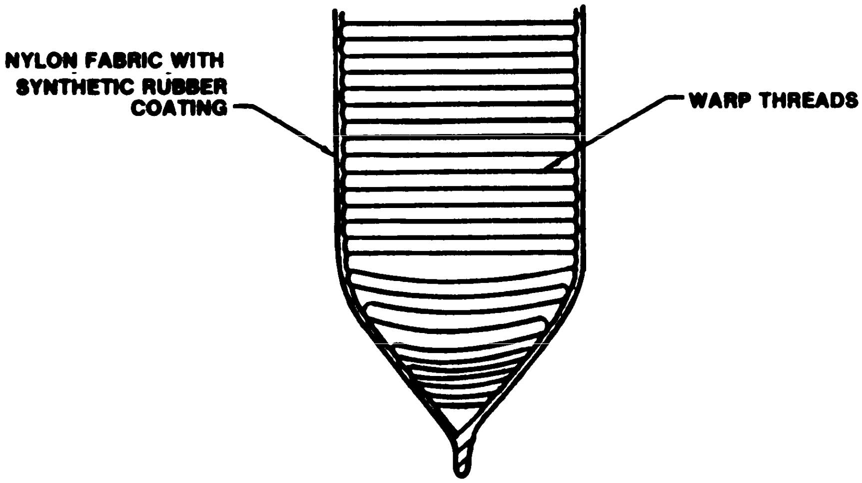

FIGURE 5-78. Purge mat (inflated).

TABLE 5-XXV. Fire test of inerting mats.

Projectile	Function Distance, Inches	Mat Pressure psi	Fires/Fair Hits W Mat	Fires/Fair Hits W/O Mat
Cal. 0.50 Inc.	3	60	0/1	---
Cal. 0.50 Inc.	3	30	0/3	4/4
Cal. 0.50 Inc.	3	15	1/1	---
20mm HEI	3	60	3/3	---
20mm HEI	3	60	2/2	---
20mm HEI	3	50	l/1*	---
20mm HEI	3	30	1/1	2/2
Cal. 0.50 Inc.	28	60	0/2	2/2
Cal. 0.50 Inc.	33	--	---	1/1
20mm HEI	30	60	0/2	2/2
20mm HEI	30	--	0/1	---
Cal. 0.50 Inc.	14	--	---	1/1
20mm HEI	14	--	---	0/1**
20mm HEI	14	60	1/2	0/1
20mm HEI	38	60	0/1	---

*Cell had plexiglass front which broke
**Flash fire for 1 or 2 seconds

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The following is a narrative description of the design considerations for purge mat use:

Principle of Operation	The purge or inerting mats consist of inflated bags, located outside the fuel cell and filling the void volume. Projectile penetration through the bag or mat into the fuel cell releases and provides an inert atmosphere, thus preventing sustained fires. In tests of the system, nitrogen has been used most frequently as the inerting agent, although suitable halogenated hydrocarbons, such as dibromodifluoromethane (Halon 1202), could also be used. Fire extinguishing powders may be substituted in place of the gas.
Application Constraints	Design mat or mats to fit contours of the bay. cut-outs are not required for equipment and plumbing except where distortion or mechanical interference affect operational safety.
System Performance	Provides fire protection on a limited basis only, depending upon the size of the threat and the respective location of threat initiation. It is also a single-hit system, as presently designed. Powdered filled mats appear to work better than the gas filled mats.
Configuration	Typical construction consists of an envelope of fabric impregnated with a fuel-resistant rubber reinforced with nylon drop stitches between the fabric walls to retain the desired shape and thickness when the mat is inflated. The gas filled mats have an approximate specific weight of 0.25 pounds per square foot and are designed for an operating pressure of 50 to 60 psi with a burst pressure in excess of 100 psi. Powder filled mats need not be pressurized.
Availability	Must be fabricated by the supplier to specified shapes and sizes as required.
Disadvantages	The gas filled bag system to date does not perform with contact fused high-explosive threats, such as 20mm HEI, and must be limited in application where air flow in the dry bay is not required. It is difficult to install where dry bay is not required. It is difficult to install where tank walls are not flat and where wire bundles, control cables, and tubing are routed through these dry-bay areas.

5.5.3.6.4 Fire extinguishing systems. Dry bay fire extinguishers are used in compartments which contain combustible fluids or are adjacent to fuel tanks. The design of these systems is dependent on a number of parameters including: toxicity, thermal stability, corrosion, storage, quantity requirements, stay time, and effectiveness. Toxicity is a factor where the

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extinguishant can penetrate habital areas or when release of the agent occurs in an enclosure, such as a maintenance hangar. The toxicity of the most commonly used agents have been evaluated by several agencies and the data is published in Reference 171. Halons 1301, 1211, 1011, 1202, and 2402, are most commonly used and are listed here in increasing order of toxicity. The agent quantity required to extinguish a dry bay fire depends upon the particular agents effectiveness (i.e., volume percent required to extinguish a fire and the air change per unit time in the compartment, along with the specified (Reference 247) stay time of one-half second). A generalized formula for agent quantity has been devised which accounts for the properties of the specific agent to be used. The basic properties of the agent, such as vapor pressure and freeze point viscosity, affect the design of the storage and dispensing equipment. Environmental conditions of -65°F to maximum compartment temperature effect fill ratio and material compatibility, maximum design pressure, and weight of the system. Under cold conditions, if the agent's vapor pressure is insufficient to propel its nitrogen pressurization is used. Nitrogen pressurized systems generally use 600 psi nitrogen at ambient temperature. This pressure increases with temperature, imposing a considerable weight penalty on the system. Another approach is to use a pyrotechnic generated gas to pressurize the system. Such systems are lighter and use less volatile extinguishing agents. The primary disadvantages of extinguishing systems are: reliability in detecting a fire, providing protection against rekindling fires (single shot versus multiple shot systems) and maintenance of the storage vessel. The latter requires routine inspection to see that it is fully pressurized, has not leaked, or has been expended. In the case of dry bay compartments with high air flows, extinguisher systems may weigh more than passive baffling systems. The following is a narrative description of the design considerations for fire extinguishing equipment:

Principle of Operation	The extinguisher type fire suppression system is a lightweight active technique, in which an extinguishant is released into the fire zone upon detection of the fire by its sensors. Halons 1301, 1211, 1011, 1202, and 2402 are the most commonly used extinguishants. Detectors are normally optical sensing devices, installed in sufficient quantity to allow light detection at any location in the tank.
Application Constraints	This system must be installed so that complete coverage of the entire void volume by the extinguishant is accomplished. Application of this system should be limited to large dry bays rather than the small void volumes adjacent to the tanks, because individual containers are required for each segmented area.
Configuration	The extinguishing system consists of a self-contained unit made up of a high pressure container of the extinguishing agent and a detection device, usually an optical sensing device designed to trigger an explosive charge that releases the agent from the container. In most cases the extinguishant is manually released.

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Availability — Equipment for this type system is readily available.

Disadvantages — Logistics for this type system is high since the container must be replaced following activation. Periodic inspection of the containers is also required, to insure that inadvertent activation has not occurred.

5.5.3.7 Fuel lines. Protection of fuel lines in an aircraft must be considered for those that are essential for engine feed, mission essential fuel transfer, and for those that present a potential hazard when damaged by hostile weapon effects. The following design techniques can be used to enhance the survivability of the fuel lines and hoses:

5.5.3.7.1 Routings and installation.

a. Minimize potential leakage by:
   (1) Minimizing number and length of lines and hoses which are external to fuel tanks.
   (2) Using self-sealing covers on critical lines which are external to tanks.
   (3) Using self-sealing hoses for exposed hose applications.
   (4) Applying damage-tolerance concepts to all lines not protected by self-sealing material.
   (5) Routing lines to avoid areas of span from hits on adjacent structure and components.

b. Minimize potential fire and explosion hazards by:
   (1) Routing lines to avoid potential fire or ignition source areas.
   (2) Routing lines in areas which have fire and explosion protection.
   (3) Applying void filler foam (Reference 257) to surround lines with layers at least 3 lines thick.
   (4) Applying self-inerting shrouds or quench packs with scuppers and overboard drains to all lines and hoses, not otherwise protected from fire hazards.
   (5) Employ pilot selectable, suction feed for use during actual combat.

5.5.3.7.2 Material/construction selection. Minimize ballistic impact damage, suppress leakage, and increase damaged tolerance by selecting:

a. Materials with high-impact strength and high-fracture toughness.

b. Designs avoiding work-hardening embrittlement during fabrication, installation, and service.

c. Couplings, connectors, and related elements designed to avoid stress concentrations and thin sections likely to fail catastrophically.

d. Lines of filamentary composite materials, parallel laid and filament wound.

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5.5.3.7.3 Self-sealing fuel lines/hoses. Liquid pressure pulse from interaction of ballistic penetrator with liquid fuel in the line can cause cracking, tearing, shattering, or petaling of the line walls. Liquid pressure pulse effects:

a. Increase size of perforations and leakage.

b. Interfere with sealing function of the self-sealing material.

Minimize leakage and maximize self-sealing effectiveness by:

(1) Line material/construction selection.

(2) Application of self-sealing hoses (Reference 214) and self-sealing line covers as shown in Figure 5-79.

Table 5-XXVI contains a summary of self-sealing line cover materials.

5.5.3.7.4 Damage tolerance. Maximize damage tolerance by:

a. Considering application of damage-limiting line wraps or filament windings of nylon, glass, and other filamentary composites with polyurethane, rubber, or epoxy matrices.

b. Reducing leakage rates of critical lines inside fuel tanks by application of polyurethane elastomer (Vithane-type) covers, formulated to resist fuel immersion.

5.5.3.8 Fire detection/extinguishment. In areas where liquid fuel or vapors, liberated by hostile weapon effects, may migrate, consideration should be given to the use of fire detection and extinguishing systems. Such an approach should be integrated into any safety requirements for fire extinguishing systems in the aircraft system. Dual purposes may be satisfied for little or no appreciable additional penalties to the total system. Most fire extinguishment systems require some type of fire detection, efficient agent delivery, and storage for the agent selected to meet the protection requirements of the given vehicle. Two general classes of detectors are available: thermal sensors and radiation sensors.

5.5.3.8.1 Thermal sensors. One type has normally open electrical contacts, which close when the surrounding air temperature reaches a pre-set temperature. The other type sensor responds to changes in electrical resistance or expansion of gas, caused by increasing temperature.

5.5.3.8.2 Broadband radiation detectors. Broadband radiation detectors usually incorporate a large angle cone of vision photovoltaic type sensor, an amplifier, and a test circuit. The important performance characteristics of these types of detectors are speed of response and volume coverage.

5.5.3.8.3 Ultraviolet radiation detectors. Ultraviolet radiation detectors incorporate a sensing device which operates in the ultraviolet spectral

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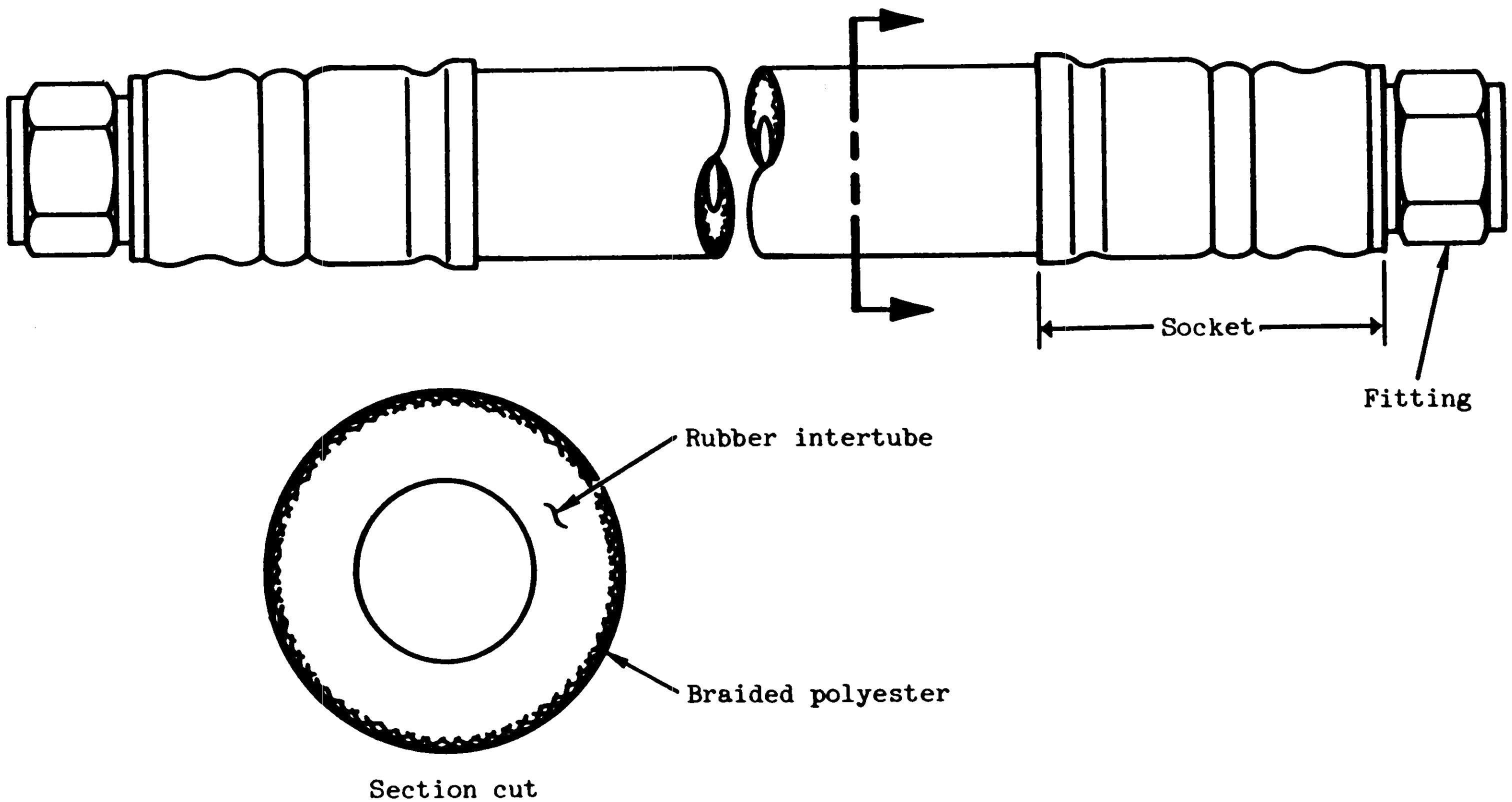

FIGURE 5-79. Self-sealing line concept.

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TABLE 5-XXVI. Self-sealing fuel lines/hoses.

Type	Thickness	Density	Performance	Description
Flexible Self-Sealing Cover	0.399 in.	2.02 lb/ft^2	MIL-C-83291 (Reference 265) .50 caliber 50 psi	Linear, sealant plies and tire cord reinforcing plies. Applied to fuel lines and bases in uncured state then vulcanized.
Rigid Self-Sealing Metallic Line	0.25 in.	1.5 lb/ft^2	MIL-C-83291 .50 caliber 30 psi	Chem-milled metal line, woven fiberglass/epoxy reinforced, sealant, six plies of open braided nylon in polyurethane resin.
Flexible Self-Sealing Fabric Hose	Not determined	3.2 lb/ft^3	MIL-C-83291 14.5 caliber 15 psi	Braid, rubber, nylon, sealant hose with woven wire rein-forcing.

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region only. They have the advantage over broad band detectors of being blind to solar radiation and will, therefore, not give false alarms if exposed to direct sunlight.

5.5.3.8.4 Pilot energized system. Fire extinguishing systems are installed in areas where this method of fire protection is advantageous. Pressurized inert gas usually supplies agent expulsion power. Lines and nozzles must be sized to achieve desired flow rates and spray patterns of extinguishment agent. Multiple shot extinguishers may be required to protect against the possibility of fire reignition. Most systems provide a flashing indicator light to the pilot, who makes the determination to select and energize the agent.

5.5.3.8.5 Automatic systems. As an alternative, fire suppression systems with automatic agent discharge by the detection system may be considered for some applications. Freon 1301 is capable of suppressing fuel fires in precharged closed compartments in concentrations as low as 10 percent. Multiple hit protection using this concept is questionable. However, the concept imposes minimum weight and cost penalties, is simple to incorporate even on a retrofit basis, and eliminates all complicated hardware requirements. Adequate sealing, corrosion resistance, toxicity to crew members, and frequent concentration determinations and recharging factors must be accounted for when considering use of this concept.

5.5.3.8.6 Halogenated hydrocarbon compounds. A large number of halogenated hydrocarbon compounds, possessing fire extinguishing properties, have been formulated. Specific compounds which have received, or are currently receiving, predominant consideration for aircraft fire protection applications are listed in Table 5-XXVII along with their pertinent physical and chemical properties. The relative fire extinguishing effectiveness of these agents is not included in this table, since effectivity of an agent will be dependent, from a practical standpoint, upon the type(s) of fire situations it is expected to cope with. Accordingly, the relative effectiveness of the Halon compounds of current interest need to be analyzed separately for each major fire problem area.

5.5.3.8.6.1 Threshold emergency exposure limits. Table 5-XXVIII provides comparative threshold limit values (TLV) and emergency exposure limits (EEL) for these Halon fire extinguishants. It should be noted that for several of the Halons the TLV and EEL values are estimates which are used by the Air Force as temporary guidelines only until such time as documented values become available.

5.5.3.8.6.2 Properties of Halon extinguishers. Table 5-XXIX lists the fire properties of selected Halon extinguishants (Reference 179). It should be recognized that certain Halon compounds can pose a fire and explosion hazard in themselves depending on the specific environmental conditions under which they are used. The hazard is of particular concern when certain agents such as Halon 1011 are utilized under high temperature of in oxygen atmosphere environments.

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TABLE 5-XXVII. Properties of halogenated hydrocarbon fire extinguishants.

Chemical Name	Halon No.	Molecular Wt.	Freezing Point, °F	Boiling Point, °F	Critical Temp., °F	Density (Liq) @ 70°F, lbs/gal	Storage Thermal Stability, °F
Carbon Tetrachloride	1040	154	-9	170	341	13.2	400
Methyl Bromide	1001	95	-135	38	381	14.4	---
Bromochloromethane	1011	129	-125	153	567	16.1	250
Dibromodifluoromethane	1202	210	-223	73	390	19.0	350
Bromotrifluoromethane	1301	149	-282	-72	154	13.1	>500
1, 2 Dibromotetrafluoroethane	2402	260	-167	117	418	18.0	>500
Bromochlorodifloromethane	1211	165	-257	25	309	15.3	400
Foamed Halon*	61 wt% - Halon 1211 30 wt% - Halon 1301 Balance Additives	---	<-65	---	---	---	---

*Typical Composition

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TABLE 5-XXVIII. Halogenated hydrocarbon fire extinguishant exposure limits (parts per million).

Compound	Threshold Limit Value (TLV)	Emergency Exposure Limit (EEL)
Carbon Tetrachloride (Halon 1040)	10**	---------
Methyl Bromide (Halon 1001)	15**	---------
Bromochloromethane (Halon 1011)	200**	(10,000)
Dibromodifluoromethane (Halon 1202)	100**	(3,000)
Bromotrifluoromethane (Halon 1301)	1000**	60,000***
1,2 Dibromotetrafluoroethane (Halon 2402)	(100)	(1,000)
Bromochlorodifluoromethane (Halon 1211)	(1000)	50,000***
Foamed Halon (61% Halon 1211, 30% Halon 1301)	(No greater than Halon 1211)	---------

*Typical Candidate Composition

( ) Number in parentheses are unpublished values which represent estimates for use as temporary guidelines only until such time as documented values become available.

** American Conference of Governmental Industrial Hygienists (ACGIH)

*** National Academy of Science, National Research Council (NAS/NRC)

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TABLE 5-XXIX. Fire properties of halogenated hydrocarbon fire extinguishants in air and oxygen atmospheres.

Compound	Min. A.I.T.(1) °F		Flammability Limits (Volume Percent)			
	Air	Oxygen	Air L.E.L.	Air U.E.L.	Oxygen L.E.L.	Oxygen U.E.L.
Halon 1011	842	694	Nonflammable @ 2-95(3)		10(4)	85(4)
Halon 1202	930	847	Nonflammable @ 5-95(3)		29(5)	80(5)
Halon 1301	>1,100(2)	1,100(2)	Nonflammable @ 10-95(3)		Nonflammable 12-98(3)	
Halon 2402	1,054	860	Nonflammable @ 6-95(3)		21(6)	52(6)
Halon 1211	>1,100(2)	1,098	Nonflammable @ 14-95(3)		Nonflammable 14-95(3)	

(1) Atmospheric pressure in a 250 cu cm glass vessel.

(2) If autoignition occurs, the AIT value is assumed to be greater than 1,100°F.

(3) Mixture temperature 450°F; Double numbers (2-95) indicate halogenated hydrocarbon percentage range over which experiments were conducted.

(4) At 212°F.

(5) At 122°F.

(6) At 212° and 450°F.

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5.5.3.8.7 Design goals. The design of an effective fuel fire extinguishing system should consider the following points (Reference 179):

a. The selection of an effective extinguishing agent.

b. Determination of an adequate quantity of this agent.

c. Suitable equipment to store the agent until it is required.

d. Means to control the flow of the agent to the affected compartment, and distribution of the agent within the affected compartment.

e. Adequate duration of agent concentration within the compartment.

5.5.3.9 Fire barriers. In areas where leakage and migration of fuel liquid and vapor leakage from hostile weapon effects cannot be prevented, the use of fire barriers in specific locations may be considered. They need to be located in those areas where an unimpeded fire would cause failure or malfunction of flight or mission essential equipment, such as flight controls and armament systems. Priority should be given to those critical items that would fail after short time exposure to an inflight fire. Limited research has been accomplished on military aircraft applications. Some organic and inorganic materials have been investigated and tested (Reference 169). Organic materials investigated consisted of various formulations of polyurethane, closed cell, rigid foams. Inorganic materials tested were flexible silicon and alumina silica rigidized materials. Additionally, metallics combined with both organic and inorganic insulators were tested. A detailed listing of all materials and combinations of materials tested is presented in Table 5-XXX. The basic performance acceptance criteria for the barrier system was that it should neither burn through nor let the air space in the protected area, measured 15 cm (6 inches) normal to the barrier face, exceed 205°C (400°F) for ten minutes, when subjected to fire barrier simulator tests. The test conditions consisted of the following:

a. A heat rate of approximately 11.35 W/cm^2/see (10 BTU/ft^2/see) uniformly across the test specimen face.

b. An airflow velocity of approximately 5 m/see (10 knots) across the test specimen face.

c. A nominally fuel-rich fire typical of that postulated to exist in a typical aircraft accidental on-board fire.

5.5.3.10 Miscellaneous protection considerations. Protection of other fuel system components must also be considered for total system survivability. This includes such items as fuel pumps, valves, filters, and level control sensors. The following are the basic protective methods that may be employed.

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TABLE 5-XXX. Materials evaluated in aircraft fire simulator tests.

Test specimen description				Source	Remarks
Designation	Thickness, cm (in.)	Density, kg/m^3 (lb/ft^3)	Characteristics		
Organic Materials					
5A43	5.1 (2)	40 (2.50)	Glass reinforced, semirigid (no outer skin)	NWC Mixed	Ingredients supplied by AVCO, mixed to NASA specifications
5A43	2.5, 5.1, 7.6 (1, 2, 3)	50 to 65 (3 to 4)	Spray molded (without skin) (also closed-mold type)	AVCO	...
BX352-P	7.6 (3)	50 to 60 (3 to 3.75)	Glass reinforced, semirigid	Grumman	Spray-molded
5F14RS	5.1 (2)	50 to 65 (3 to 4)	Silica fiber reinforced, semirigid	NASA-Ames	Molded
Inorganic Materials					
WRP-X-AQ	2.5 (1)	320 (dry) (20)	Ceramic felt	Grumman	Density up to 1120 kg/m^3 (wet)
...	5.1 (2)	320	Silicone foam, flexible	Grumman	...
Metallics					
301 CRES + TBS-758	0.64 (0.27)	...	Silicon ablative on stainless	Grumman	...
Fiber glass + TBS-758	0.68 (0.29)	...	Silicon ablative on fiber glass/epoxy	Grumman	Fiber glass on both sides of silicon
321 CRES + 5F14RF	2.5, 5.1 (1, 2)	...	Polyurethane foam on stainless	NASA-Ames	Fireside of foam covered with aluminum sheet
Intumescent Coating					
1000 & 1000 modified; 1010, 1200 (flexible sheet); 1600B; 313				AVCO	...
477 GF				Grumman	...
M-30; Lacquer type, semiflexible sheet				NASA-Ames	Lacquer type is P-nasa salt in nitrocellulose lacquer

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5.5.3.10.1 Fuel system ballistic protection. Minimize weight for ballistic defeat protection of components by:

a. Maximizing effectiveness of masking.

b. Applying armor protection techniques.

C. Considering use of dual-hardness/electroslag remelt steel or 6A1-4V titanium annealed for component cases.

5.5.3.10.2 Damage tolerance. Maximize damage tolerance by

a. Designing for dual, redundant functional elements with minimum but adequate separation.

b. Applying damage-tolerance techniques to component cases to minimize failures.

5.5.3.10.3 Material/construction selection. Maximize component protective effectiveness by:

a. Selecting materials with high fracture toughness values.

b. Using malleable, ductile materials and wrought, forged or formed (instead of cast) component housings. Figure 5-80 shows more severe ballistic damage to cast than to wrought aluminum fuel component housings.

5.5.3.10.4 Self-sealing coverings. Minimize leakage, fire, and explosion by applying self-sealing covers to all critical fuel system components such as fuel lines, filters, and pumps. Many of the self-sealing line cover designations currently in use can be applied to component cases. Current self-sealing materials have the following nominal characteristics:

a. Weight - 2 pounds per square foot

b. Thickness - 0.375 inch

Self-sealing covers can be applied to component cases most effectively by high-temperature bonding, molding, and vulcanization processes, conducted at the self-sealing equipment supplier’s facility. Consult with self-sealing material and equipment suppliers for latest developmental and qualified self-sealing protection. Consider leakage rate reduction for critical components inside tanks by application of polyurethane elastomer (Vithane-type) covers formulated to resist fuel immersion.

5.5.4 Fuel systems HEL protection. Many of the protective techniques for the defeat of high-energy laser (HEL) weapon effects are under continuous change and improvement. The basic principles of protection involve the use of materials that either reflect the HEL energy or convert it into other forms through ablation, sublimation, or charring. Table 5-XXXI contains a listing of candidate methods to provide high-energy laser protection in aircraft fuel systems.

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Entrance

Exit

Cast aluminum

Entrance

Exit

Wrought aluminum

FIGURE 5-80. Ballistic damage to aluminum fuel components.

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TABLE 5-XXXI. Representative HEL/gunfire hardening candidates for fuel tankage.

Ballistic Protection Techniques	Primary Purpose	Application	HEL Hardening Approaches
Reticulated foam (internal)	Ullage explosion protection	Integral fuselage cells & wing tanks	Moldline skin reflective coating systems; natural laser protection
Ballistic baffles	Hydrodynamic ram	Fuselage cells	None required
Gaseous inerting	Ullage explosion protection	All cells & tanks	Natural laser protection
Bladder assembly	Self-sealing of puncture wound	Fuselage cells & fuel lines	Carbon fibers, fabrics, microballoons; improved resin; fire-retardant agents
Backing board	Bladder lift-off from puncture wound	Fuselage cells	Carbon fabric; improved resin; intumescent coating; fire-retardant agents
Dry bay area	Skin blow-off & petalling free space	Fuselage cells & integral wing tank areas	Hardened rigid & rigidized ballistic foams; honeycomb construction
Reticulated foam (external)	Fire protection	Dry bay area	Unknown compatible approach; apply areal barrier to external tank wall
Rigid ballistic foam	Fire protection	Dry bay area	Carbon & Kevlar fabric/composite faceplates; carbon fibers
Rigidized foam (external)	Hydrodynamic ram	Dry bay area	Carbon fibers, microballoons; improved resin; fire-retardant agents
Honeycomb construction	Hydrodynamic ram	Dry bay areas & engine inlet tank walls	Natural reflection; Kevlar honeycomb; ablative fillers

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5.5.5 Fuel systems repairability/maintainability. The fuel tankage and distribution system of an aircraft forms one of its largest subsystems and, therefore, is susceptible to a significant portion of hostile weapon effects. Properly protected, it can sustain a considerable amount of ballistic damage and still permit recovery of the aircraft. A high priority should be assigned in the design of the fuel system to provide for its rapid repair and/or replacement during combat operations. The internal fuel tankage shall be designed to permit rapid access for inspection, repair, or replacement. The selection of materials and type of construction shall fully consider the level of damage that can be experienced from hydrodynamic ram effects, caused by ballistic impact of a penetrator in liquid-fuel sections. The amount of damage and resulting repair shall be minimized. For integral tanks, the construction material and design shall be selected to avoid shattering and large-area damage that would result in extensive repair efforts or destruction that would be beyond repair. For example, high-strength sculptural skin with inadequate fracture toughness has shown a tendency to experience large-area holes, accompanied by extensive cracking, when subjected to ballistic impact. Fuel distribution line installations should be designed to be readily accessible and replaceable. Consideration should be given to the design of interchangeable fuel line sections that would minimize the number of spare fuel lines required for replacement of damaged components. Fuel feed, vent, and transfer lines should be designed in sections so that removal and replacement of each section can be accomplished without disturbing the other sections.

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5.6 Propulsion systems. The selection and incorporation of the propulsion system in military aircraft requires special attention to survivability enhancement methods. This section is concerned with the installation of the engine in an aircraft and those ancillary interfaces with the airframe. The survivability enhancement of the engine itself is described in volume 3 of this publication. This arrangement has been made to provide the engine manufacturers with the information and guidance related to their product that is generally procured directly by the military and has the responsibility for establishing the engine survivability requirements. The propulsion installation designer is required to interface with the engine manufacturer in order to develop the most effective installation in a new aircraft system, or as replacement in an existing system. This task must consider the effect of engine selection and type of installation on the minimized detection criteria established for specific aircraft system design concepts and to the selection of the most effective combination of engine protection methods against designated nonnuclear weapon effects. These effects include both ballistic and high energy laser weapons.

5.6.1 Minimized detection. Consider design concepts to minimize the propulsion system contribution to the various types of detection signatures relevant to the hostile threat systems specified for the total aircraft system. Consider methods to reduce (1) Radar Cross Section Signatures, (2) Infrared Radiation Signatures, (3) Aural Signatures, and (4) Other Signatures as described in section 4.2.5 of this volume. These methods must be coordinated with the characteristics and capabilities of the engine selected for use.

5.6.2 Protection methods. Military aircraft propulsion systems are comprised of two basic categories: piston and turbine, with the latter being the type that is currently utilized in most aircraft, and is expected to be used in the future. Propulsion systems are major critical elements in an aircraft that are exposed to nonnuclear weapon effects and require careful design consideration or selection to enhance survivability. The vulnerability of turbine engines is highly sensitive to the response of the specific design to the range of threat kill mechanisms. These threat kill mechanisms must be closely examined in the initial design phase. Location and orientation of engines, as well as their vulnerable components with regard to the critical aspects and range of hostile weapon effects, must be considered for the total aircraft configuration and missions. Reduction of vulnerable areas by design innovation, shielding, or redundancy are basic methods to be considered. Secondary hazard effects due to damaged engines and/or damaged blades, such as liberation of high-temperature gases into areas where other essential or critical engine subsystems may fail or malfunction, must be considered. With the exception of single-engine aircraft, consideration should be given to the inclusion of a fixed fire extinguishing system for enhanced aircraft survivability.

Design multiple engine installations to provide:

a. Single engine capability during portions of the flight envelope which are combat significant

b. Separation and shielding to prevent fire, explosion, or catastrophic mechanical failure of one engine causing failure of another

c. Redundant and damage-tolerant power transmission systems

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5.6.2.1 Inlets. The design of engine inlets can have a significant effect upon the survivability of an engine and its continued performance after exposure to nonnuclear weapon effects. Consider the following methods to prevent or minimize the probability of propulsion system failure or malfunction:

a. Construct inlets with materials and structural features that will minimize the generation of secondary fragmentation or debris capable of causing foreign object damage (FOD) if ingested by the engine. Low density sandwich construction should be considered to avoid the use of metallic fasteners that could be dislodged by ballistic impact, blast effects, or high energy laser burn through. With metallic structures, avoid use of rivets in the area of inlet airflows where distortion of the structure from hostile weapon effects would allow these to become dislodged and ingested.

b. On aircraft requiring air induction control systems, consider design arrangements that will permit fail safe response of the system in the event of nonnuclear weapon effects damage. Where loss of power or control is experienced, provide means to cause or permit the inlet geometry to be positioned so that it will provide the aircrew with an optimum setting for safe flight and recovery of the aircraft.

5.6.2.2. Engine compartment. Design engine supports to prevent or minimize the probability of adverse engine reaction or position due to damage of any of the supports from hostile weapon effects. Consider use of high fracture toughness materials, multiple load paths, fail safe and damage tolerant design features, etc.

Apply fire and explosion techniques in engine compartment designs, with due consideration of the following environmental conditions for specific applications:

a. High thermal conditions

b. Fire resistance/fire proofing requirements

c. Engine compartment ventilation flow paths and rates

d. Collection and absorption of flammable fluids in porous materials

Emphasize fire/explosion suppression techniques that are particularly useful for the engine compartment. These include:

(1) High-velocity ventilation and forced, high-rate drainage of potential hazardous leakage areas.

(2) Low-velocity ventilation and fire/explosion detector/suppressors and/or fire extinguishers. A “second shot” of fire extinguisher action should be available to the crew.

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(3) Automatic and crew override controlled fuel, lube, and hydraulic fluid shutoff valves to stop flow of flammables until fire extinguishers can put out the fire

(4) Shielded and sealed electrical and other ignition sources

(5) Quench packs (foam in enclosure) around ignition sources

(6) Quench packs with scupper drains shrouding potential leakage sources

(7) Reference 257 plastic foam space filler in plastic film envelopes installed in areas where flammable liquids or vapors could collect but which are not practical to drain and ventilate

5.6.2.3 Lubrication systems. One of the more important items for the reduction of overall engine vulnerability is a fail-safe lubrication system. vulnerability of this system is caused by:

a. The relatively large presented areas of:
   (1) The lube oil tank, pump, filter, and oil cooler
   (2) The engine oil and accessory gearbox sump
   (3) Oil lines, hoses, and valves

b. The ease of perforation of lube oil system components and elements by relatively small projectiles, fragments, and span

c. The very short time the pilot has to act after loss of oil pressure, and the serious hazards that result

Protective design techniques for lubricating oil systems follow. Examples of related damage and failure modes are also presented. Figure 5-81 shows the damage to an engine oil tank from a projectile impact. Note the extent of damage caused by hydrodynamic ram effect.

(1) Providing for manual override by pilot to prevent automatic shutdown of engine after loss of oil pressure and to permit escape from immediate combat area.

(2) Consideration of bypass systems to isolate engine oil circulation from damaged and leaking portions of oil circulation systems, such as system developed for a helicopter (Reference 55), shown in Figure 5-82.

5.6.2.4 Propulsion systems ballistic protection. Consider the use of integral and/or parasitic armor only after:

a. All other protective design techniques to reduce vulnerability have been fully exploited.

b. The design configuration of the armor has been carefully adapted to miniaturization and concentration of the items being protected.

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FIGURE 5-81. Engine oil tank damaged by projectile impact.

c. A cost/weight design trade-off study has been made for selection of the basic armor material and the armor installation.

d. The advantages of maximizing the proportion of the armor installation which can be installed and replaced in the field has been determined. These include:
(1) Removal of armor from aircraft for maximum aircraft performance and payload during long-ranges training, and low-threat operations.
(2) Field replacement of damaged armor without repairing ballistic damage.
(3) Installation of higher threat-resistant armor for special missions.

Conduct armor installation design trade-off studies to maximize installation merit rating from optimum combinations of the following:

(a) A separate shell of armor around the vulnerable components. Figure 5-83 shows an example (extracted from Reference 23) of this concept.

(b) strategically placed armor pieces in areas of greatest sensitivity. Figure 5-84 shows an example of this technique on an existing aircraft.

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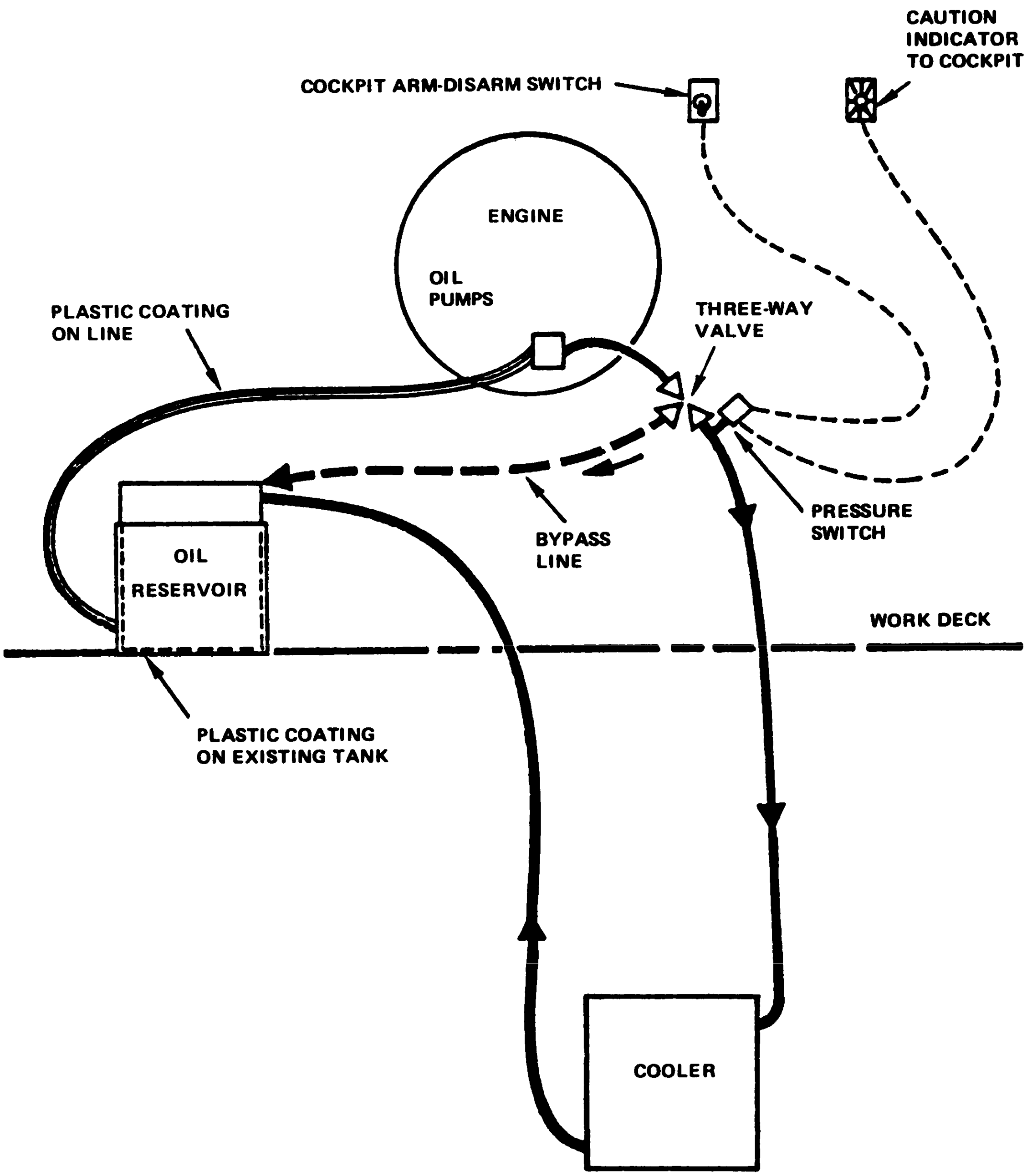

FIGURE 5-82. Engine oil system oil cooler bypass modification

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5.6.2.5 Propeller systems. For propeller blades, gearbox housing, and pitch controls:

a. Select material to provide maximum toughness and fracture resistance.

b. Design component configurations to minimize crack propagation.

c. Design all elements for high damage tolerance capability.

d. Design for maximum resistance to dynamic forces from out-of-balance operation.

5.6.2.5.1 Propellers.

a. Design the propeller with a strong structural box core to minimize blade throwing after impact.

b. Consider steel spar-fiber glass structural composite blade propeller.

5.6.2.5.2 Gearbox. Apply protective design techniques presented for gearboxes, accessory cases, and power transmission systems in Volume 3.

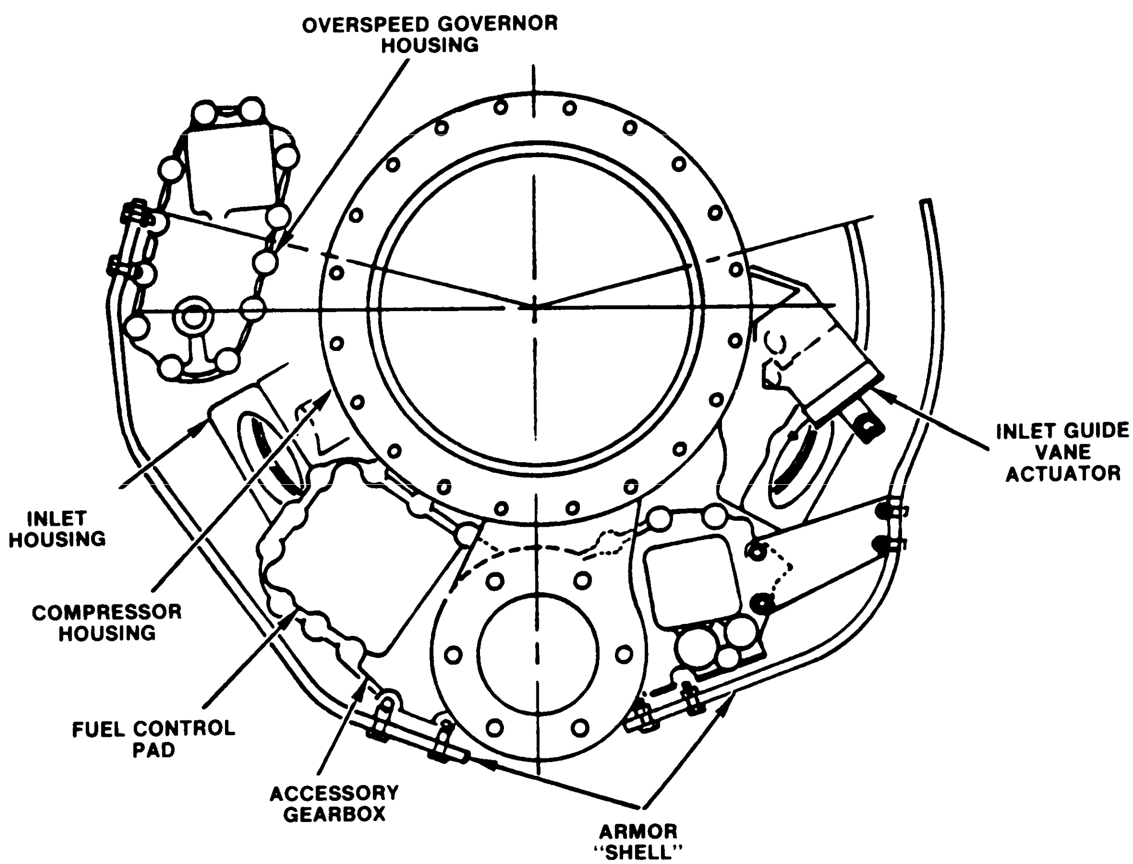

FIGURE 5-83. Engine "Shell" armor.

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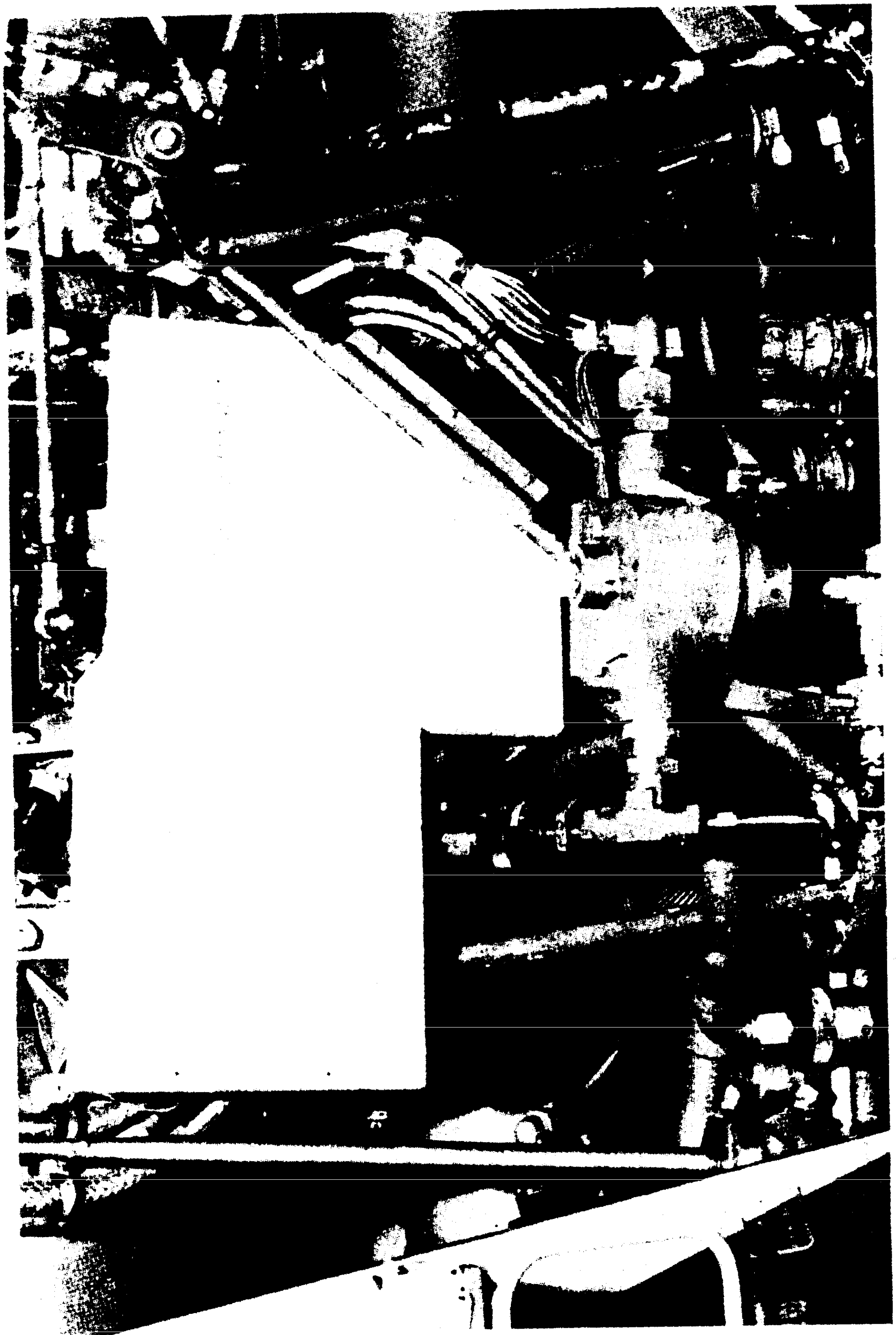

FIGURE 5-84. Armor in areas of greatest sensitivity.

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5.6.2.5.3 Pitch control.

a. Apply protective design techniques for accessory and gearbox cases to the pitch control.

b. Design pitch control for fail-safe blade angle positioning.

c. Integrate the propeller control with the gearbox in a position to obtain the most beneficial natural "masking" of the sensitive components.

5.6.2.6 Propulsion systems HEL protection. Protection of propulsion system components against high energy laser weapon effects may be accomplished by a number of candidate methods. They may be grouped into two separate defense concepts.

a. The first is the "hardening" of a component itself to resist the HEL weapon effects by proper material selection and thickness, by damage tolerant design concepts, or by incorporation of design features to delay failure of the component beyond the length of time the HEL beam is expected to be focused on the component. For components containing flammable fluids, such as fuel, lubrication, or hydraulic media, consider the use of metallic seals in place of commonly used elastomer seals that quickly fail at relatively short HEL exposure times and generate a serious fire and/or explosion hazard.

b. The second defense concept is the shielding of mission or flight essential components of the engines, or propulsion system units, with thermal barriers or reflector surfaces. Consideration should be made to integrate any ballistic protection concept together with any for HEL protection to obtain the most effective combination of each. Ablation insulation, and intumescent materials should be considered for barriers. Consult with the JTCG/AS for the most current information on the subject.

5.6.3 Propulsion systems repairability/maintainability. Repair of battle-damaged propulsion installations in aircraft has constituted a significant portion of the total aircraft system repair activities. The contractor should design the installations so that rapid access, inspection, removal, and replacement of engines may be accomplished. Since the probability of fire from hostile weapon effects exists for propulsion installations, consideration should be given to the incorporation of fire detection and extinguishing systems. Provisions should also be considered to limit the amount of fire damage that can be propagated to other portions of the aircraft so that the amount of repairs may be minimized. Where fire damage can occur, provisions should be provided to permit removal and replacement of the installation structure as an interchangeable unit on all aircraft of the same model. Criteria should also be established by the engine manufacturer for modular construction of major sections to permit cannibalization of other damaged engines to permit assembly of one complete engine with undamaged sections. Aircraft propulsion installations should be designed to limit the amount of damage that

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may be sustained from the direct and secondary effects of hostile weapons. Fire is the predominant secondary weapon effect that has been experienced in combat. It can be fed by either leaking fuel, lubrication, or hydraulic oil. Consideration should be given to means to limit the propagation of fire damage so that survivable damage may be repaired for the least expenditure of time and effort. In areas where high probability of fire (given a hit by weapon effects) exists, heat barriers should be considered. These should be coordinated with fire detection and extinguishing systems where possible. Battle damage repairs should be simplified to the maximum extent possible, and a wide range of material and fastener substitutions considered. Material requirements should be to the lowest strength possible, thus providing a wide range of stronger substitute materials. Repair fasteners selected should be those in common use and, generally, the lowest-strength fastener (within practical limits) to provide the widest possible range of fastener substitution.

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5.7 Power train systems. Power train systems carry primary responsibility for flight capability in all rotary-wing aircraft, and for those propeller-driven fixed-wing aircraft dependent upon speed reduction gearboxes. A variety of main rotor drive system configurations have evolved over the past 20 years of helicopter development. Each system consists of a series of transmission or gearboxes and connecting drive shafts to transmit power for engine(s) to rotor blades. The need for antitorque thrust capability in single-rotor helicopters creates a requirement for an additional drive system. Figure 5-85 shows a schematic diagram of the drive system of the UH-1 helicopter, which is reasonably typical of turboshaft-powered, single-engine, single-main rotor helicopters. The high output speed ($\approx$ 20,000 rpm) from the power turbine is first reduced within the engine to about 6,000 rpm. It is then transmitted to the main transmission, where the speed is further reduced through a set of spiral bevel gears and two stages of planetary gears, finally providing a main rotor speed of 324 rpm. The trend in helicopter drive systems is toward incorporation of all speed reduction in one transmission to reduce overall weight and complexity. Most twin-engine (turboshaft) driven helicopters have direct drive from a high-speed power turbine to intermediate transmissions or to a main rotor transmission. Figure 5-86 shows a schematic of the CH-47 medium transport helicopter, with the major power train system components identified. The engine power turbine output speed ($\approx$ 15,400 rpm) to the engine transmission is reduced to 12,200 rpm through a set of bevel gears, and further reduced in the combined transmission bevel gears to 7,050 rpm and directed through interconnecting shafts to the forward and aft transmissions. A third set of bevel gears in each main rotor transmission reduces speed to 4,000 rpm; finally, reduction through two stages of planetary gears provides a main rotor speed of 230 rpm. The main transmission performs many other functions in addition to speed reduction and transmission of primary power; e.g., output drives for tail rotors, hydraulic pumps, and generators often originate from the main transmission. The following paragraphs discuss the ballistic damage effects and the detailed design considerations that may be used to achieve the best combinations of survivability features for application to drive systems. Additional information may be found in Reference 135.

5.7.1 Power train systems ballistic damage effects. Power train systems exposed to threat impacts have two general failure mechanisms: (1) direct projectile damage to critical dynamic components such as bearings, gears, and shafts; and (2) loss of lubrication, usually caused by perforation of oil containing components. Loss of lubrication is the predominant failure mode for existing transmissions and gearboxes in a threat environment.

5.7.2 Loss of lubrication. The lubrication system for most present-day helicopter transmissions is not self-contained and usually consists of externally mounted components such as filters, coolers, and interconnecting lines or hoses. Most lubrication systems consist of a wet sump that recirculates oil to lubricate and cool the bearings and gears. The cooling requirements are usually much greater than the lubrication requirements. The number and size of lubrication system components vary from one aircraft to another, but, in general, they amount to a significantly large exposed area. Probability of an oil leak developing increases significantly with increasing lubrication system components and complexity. Even low-velocity bullets and

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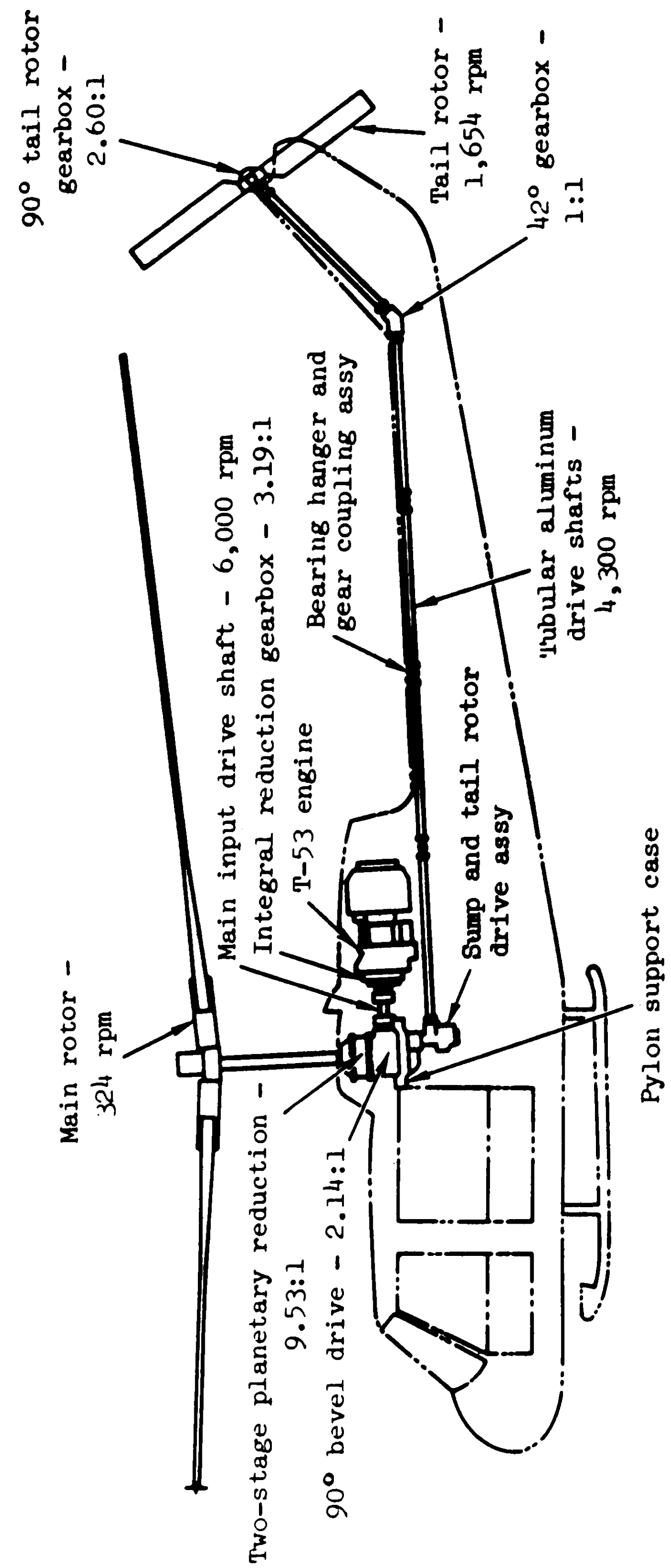

FIGURE 5-85. UH-1 power transmission system.

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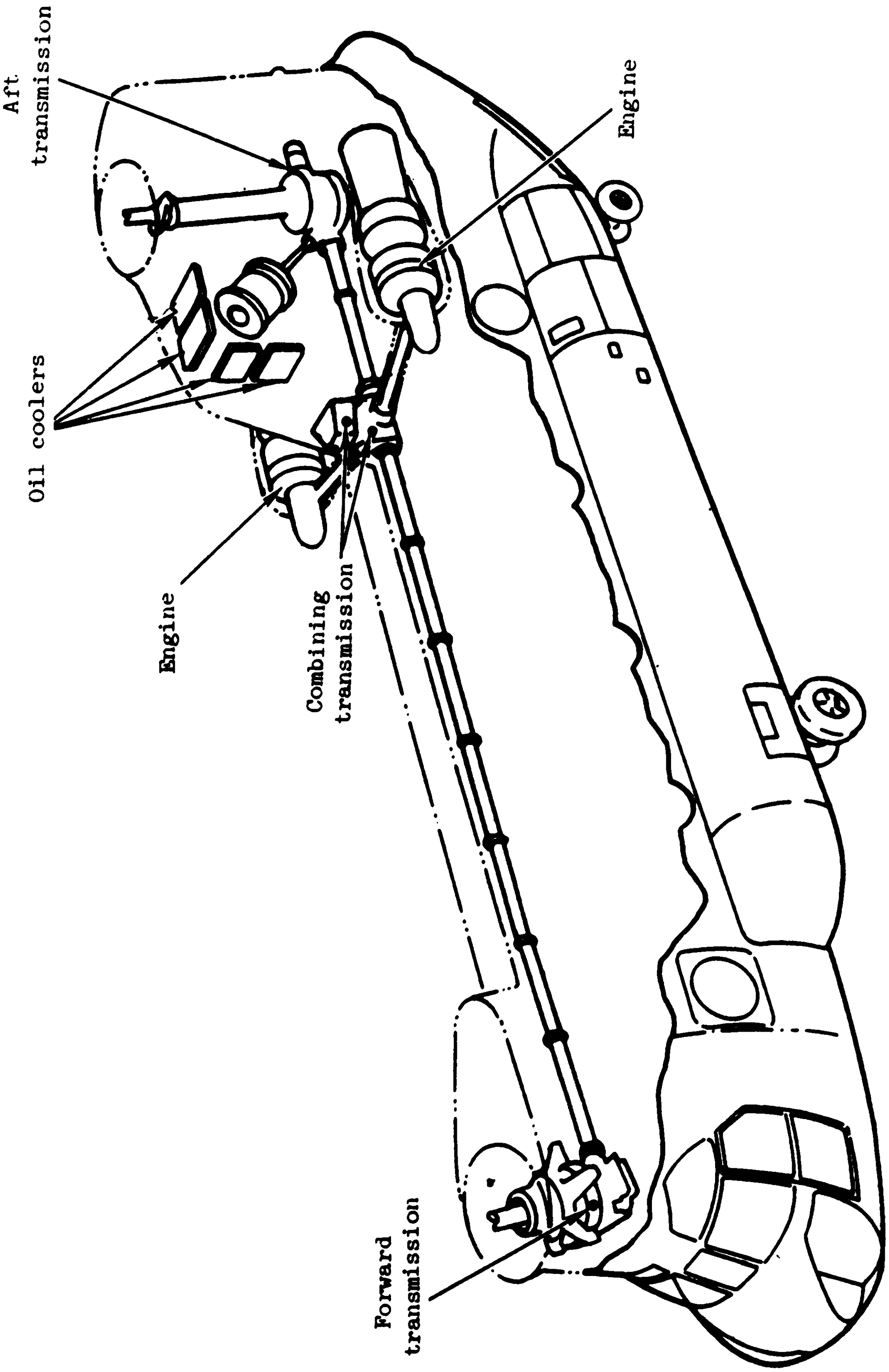

FIGURE 5-86. CH-47 power transmission system.

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fragments find little difficulty in perforating the "soft" aircraft skin, structure, and, most important, the exposed lubrication system components. Figure 5-87 shows a few typical examples of projectile damaged components which illustrates the "soft," easy to perforate, characteristics that result in oil leakage. Loss of lubrication failures are most often related to the bearings, where loss of heat removal and thermal imbalance result in bearing seizure. Bearing failures, in some cases, cause misalignment of gear meshes, resulting in heavy scoring, extreme temperatures, and eventually gear teeth melting as shown in Figure 5-88. Failures are often catastrophic, causing transmission case rupture and fire after input pinion failures, and main rotor seizure after planetary assembly failures. In some applications, loss of lubrication causes loss of clearance and backlash in gear meshes which, in turn, leads to complete loss of the gear teeth. Projectile impacts on many areas of the transmission/gearbox housings and supports cause significant damage, especially against less ductile materials such as castings; however, loss of their function occurs only when large quantities of oil can leak out. Figure 5-89 and 5-90 illustrate typical projectile entrance and exit hole damage to a main transmission housing.

5.7.3 Direct projectile damage. Power train components, mainly bearings, gears, and shafts, are susceptible to primary projectile damage mechanisms, which usually result in either immediate loss of the\units function of extended operation is possible before failure occurs. Projectile impacts directly on high-speed bearings usually cause significant damage to them and, in some cases, are aggravated by the loss of oil. The gears, in general, tend to resist damage from projectile impacts much better than bearings. However, chips and debris from either the projectile or gear can jam the oil pump, causing loss of lubrication. Projectile impacts on drive shafts can cause immediate severence of the shaft, especially if the hit is near the bottom or top surface, or the projectile impacts in a tumbled or yawed condition. Figure 5-91 illustrates the critical impact areas for a typical drive shaft. This area varies with shaft material properties, diameter, and thickness, as well as projectile size and orientation at impact. Figure 5-92 shows the results of a typical projectile impact on a drive shaft in the critical impact area where operating loads caused complete failure.

5.7.4 Design considerations. The operational requirements for a rotary- or fixed-wing aircraft dictate the basic load requirements of power transmission or propeller gearboxes. These power requirements must be translated into design concepts that incorporate the most beneficial combination of survivability, reliability, safety, and maintenance features. For rotary-wing aircraft, power transmissions, shafting, and gearboxes are used. The following are survivability enhancement techniques that should be considered for initial and retrofit design efforts.

5.7.4.1 Transmission/gearbox lubrication. Damage tolerance techniques to minimize or prevent failure due to lubrication system damage can provide significant benefits for little or no penalties if incorporated into the initial design. Minimizing the probability of lubrication system failures has been researched and studied extensively during the past decade. Figure 5-93 illustrates some of the alternative solutions that may be considered for helicopter

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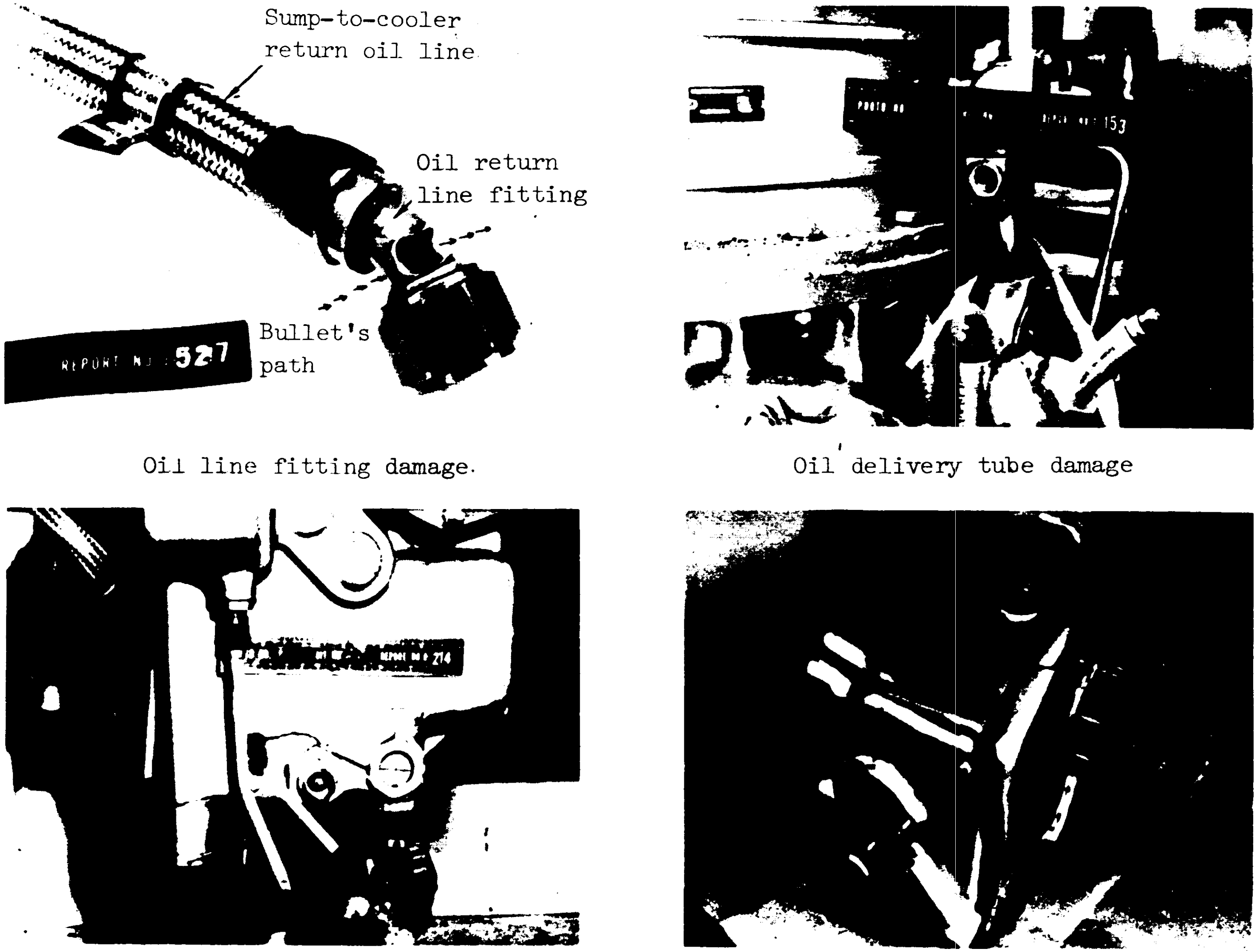

Oil line fitting damage.

Oil delivery tube damage

Tumbled bullet damage to sump (entrance)

Tumbled bullet damage to sump (exit side)

FIGURE 5-87. Damaged oil lubrication components.

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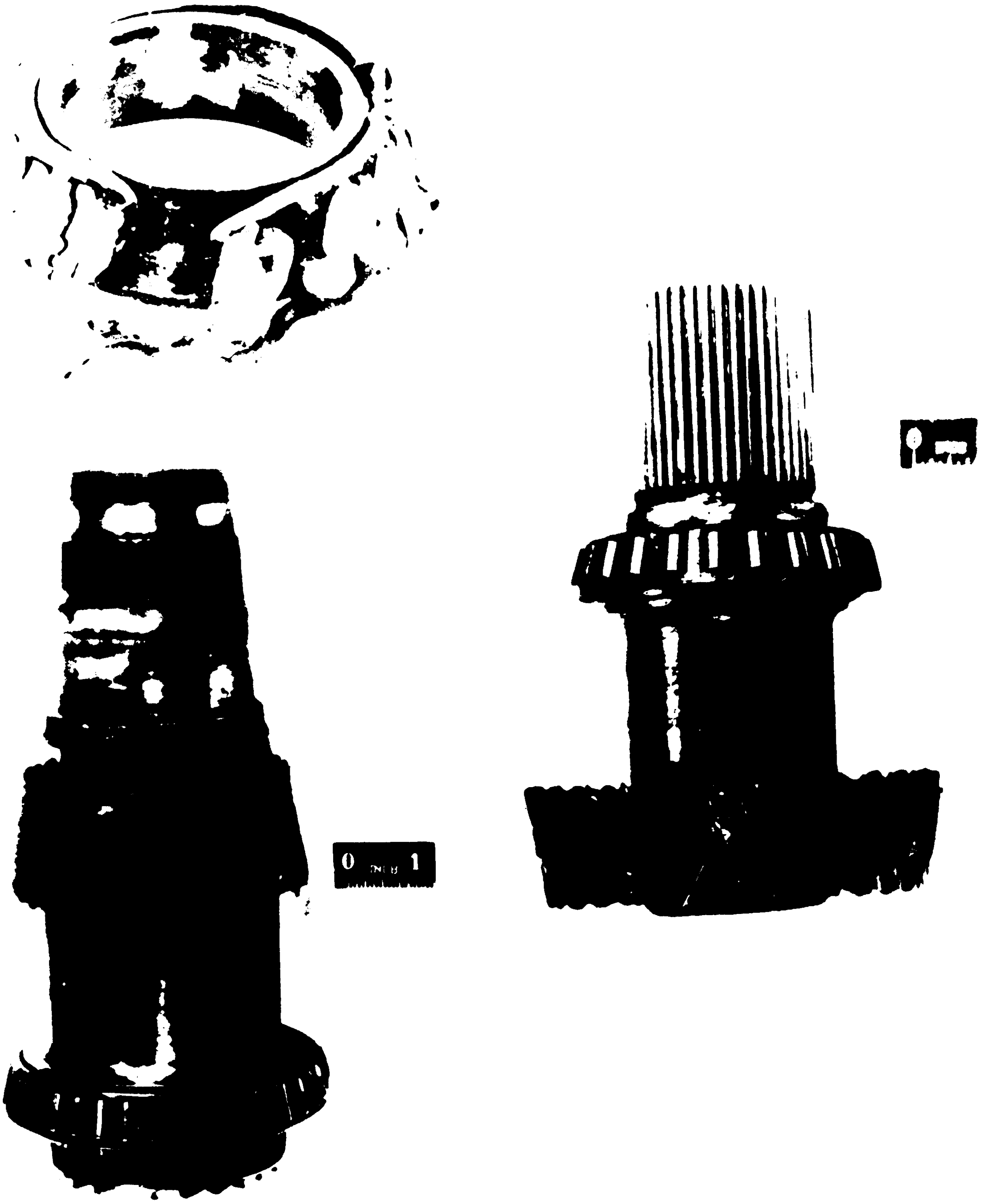

FIGURE 5-88. Gear teeth damage due to misalignment caused by bearing failure.

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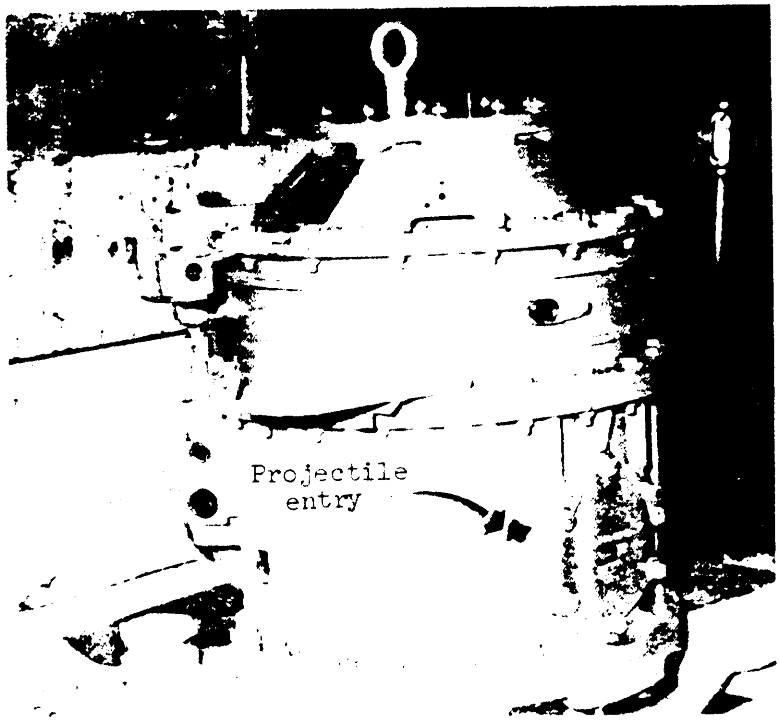

FIGURE 5-89. Main transmission housing damage.

FIGURE 5-90. Main transmission housing projectile exit damage.

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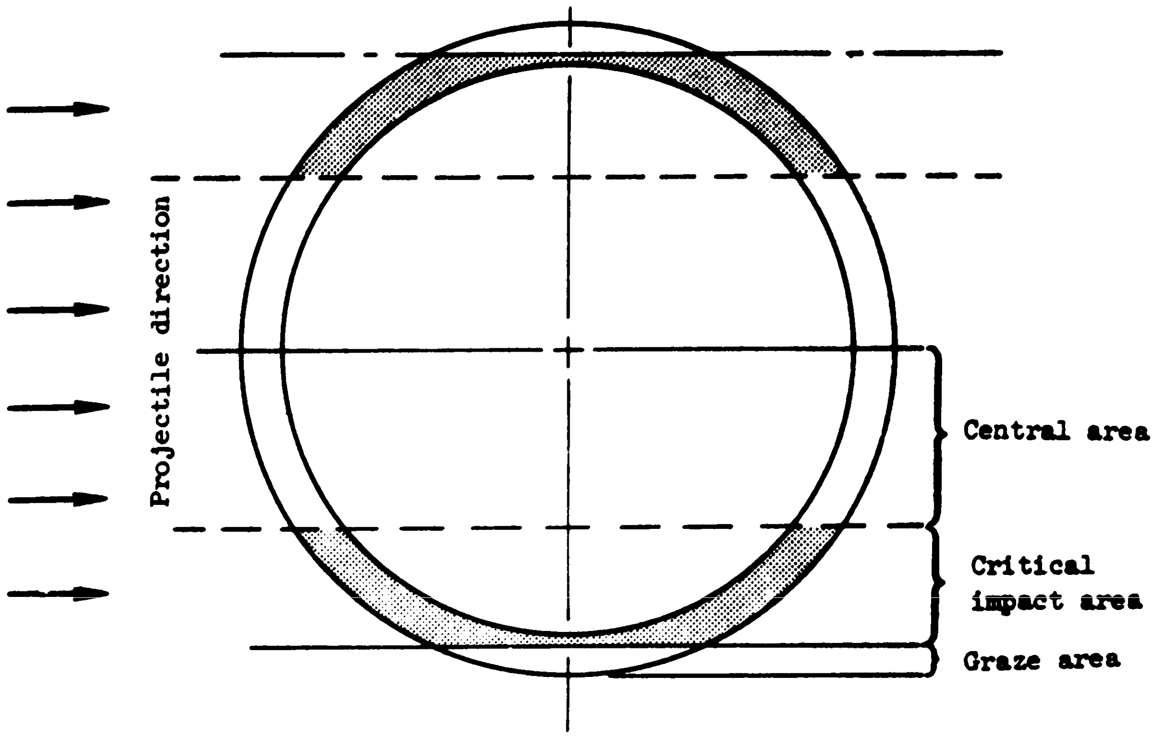

FIGURE 5-91. Critical impact area of driver shafts.

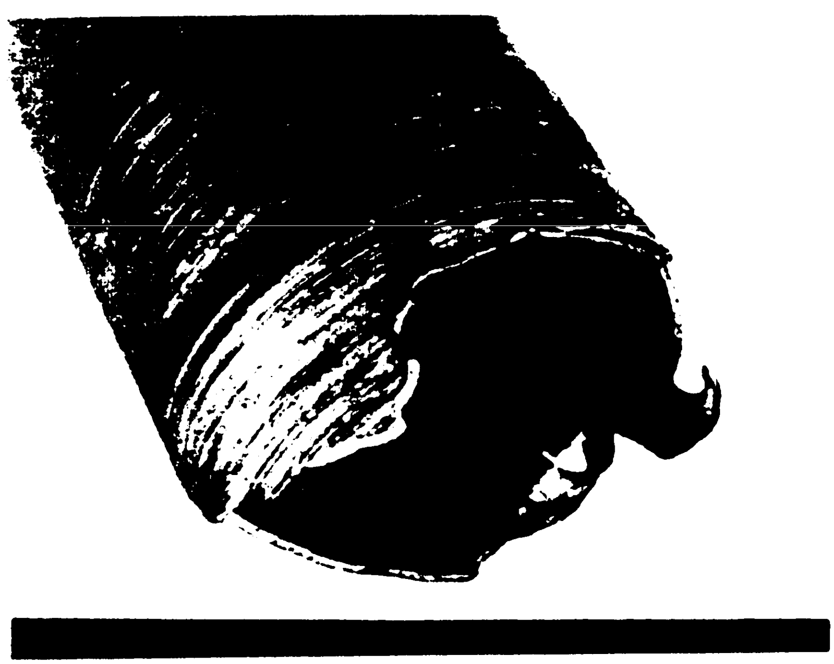

FIGURE 5-92. Drive shaft ballistic damage and failure.

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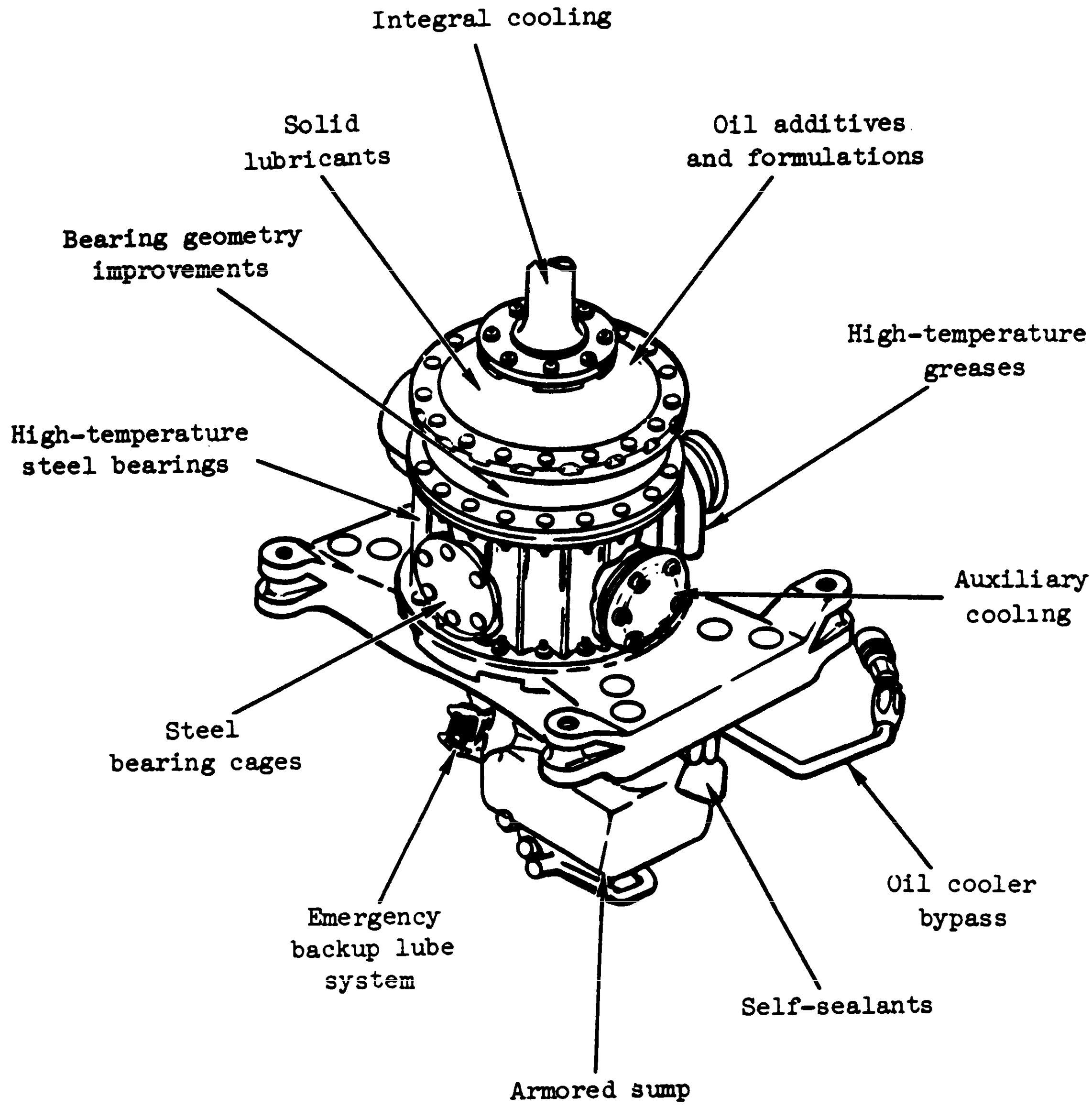

FIGURE 5-93. Alternate solutions to reduce vulnerability of main transmissions.

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main transmission systems. The following paragraphs briefly describe some of the various transmission oil cooling systems.

5.7.4.2 Rotor shaft system. The rotor shaft cooler (Figure 5-94) uses the main transmission rotor shaft as effective natural masking of the oil cooling system heat exchanger (Reference 23).

5.7.4.3 Annular system. The annular oil cooler uses a radially directed airflow coupled with a circumferential oil flow, which does not result in a true 90-degree crossflow heat exchanger. Figure 5-95 illustrates its basic design features. Heated oil is introduced into a divided manifold, which directs it in a counterclockwise direction through stacked core sections. cooling air is directed radially inward or outward to achieve forced convection heat transfer. The cooled oil is then returned to the transmission system through the outlet port (Reference 23).

5.7.4.4 Integral oil-air system. The integral oil-air system (Figure 5-96 is composed of an annular, two-pass, crossflow heat exchanger mounted directly on the bottom of the forward transmission. Cooling air is directed through the outside diameter of the cooler core and is discharged into the inside diameter, where a blower forces the hot air overboard through a duct. The hot oil from the filter enters the oil cooler, is cooled, and returns to the transmission oil jets (Reference 117).

5.7.4.5 Close-coupled oil-air system. This system (Figure 5-97) employs a three-pass, crossflow oil cooler mounted within the forward pylon, immediately aft of the forward transmission, Air enters the inlet air screen in the forward pylon, flow around the forward transmission, and into a blower, which is belt-driven from the synchronizing shaft. After discharge from the blower, the air travels into a transition duct where it is directed through the oil cooler core and ducted overboard. Hot oil from the filter travels through an oil line to the cooler, where it is cooled; the oil then returns through a second line to the transmission oil jets (Reference 117).

5.7.4.6 Oil-water/glycol-air system. The oil-water/glycol-air system (Figure 5-98) employs a liquid-to-liquid heat exchanger, completely enclosed by the oil sump, which transfers the heat from the oil to a water/glycol solution; this solution is then piped through lines to an air-water/glycol cooler located in approximately the same position as the oil-air cooler in the close-coupled oil-air system. In this system, the oil does not leave the transmission (Reference 117).

5.7.4.7 Oil-boiling refrigerant-air system. This system (Figure 5-99) operates on the same principle as the oil-water/glycol-air system except that refrigerant is used as the secondary cooling medium. The refrigerant passes through the oil cooler, where it is vaporized; it then flows to the condenser where the waste heat is rejected to the atmosphere. The condensed liquid then returns to the oil cooler. The flow around the loop is maintained by a combination of natural convection and a gerotor pump (Reference 117).

5.7.4.8 Air cycle-heat pump system. The air cycle-heat pump system (Figure 5-100) is similar in its basic arrangement to the integral oil-air

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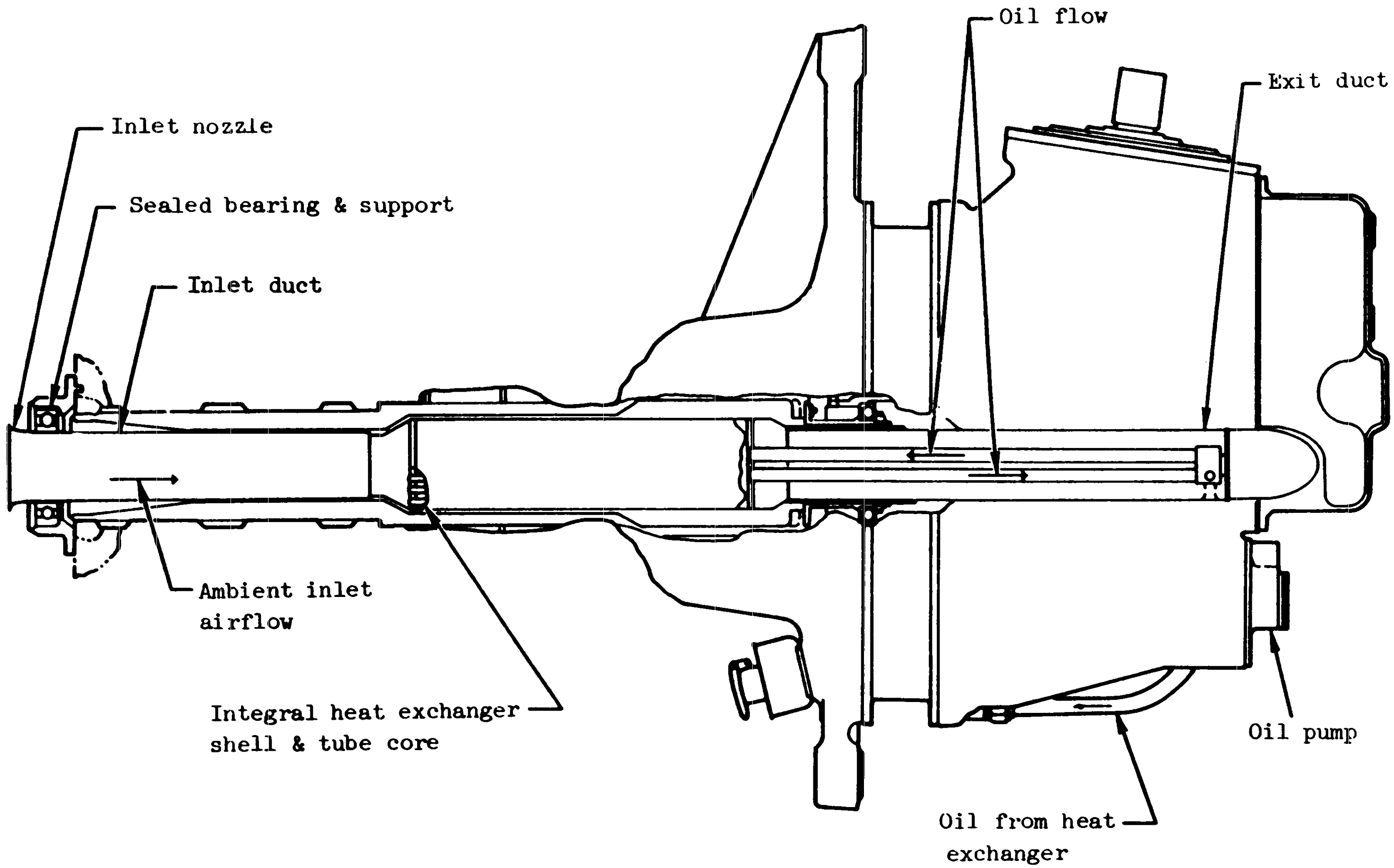

FIGURE 5-94. Rotor shaft oil cooling system concept.

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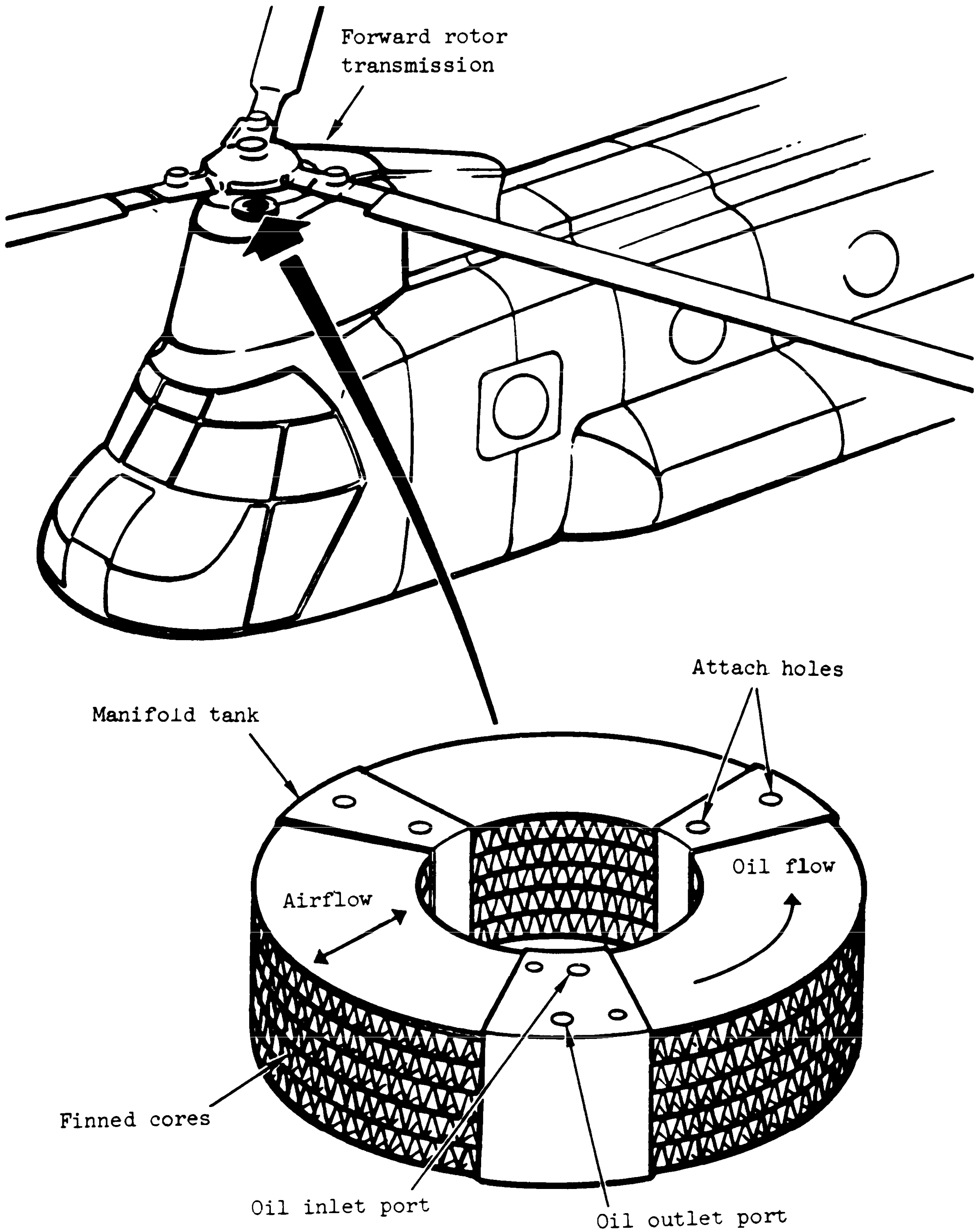

FIGURE 5-95. Annular oil cooler concept.

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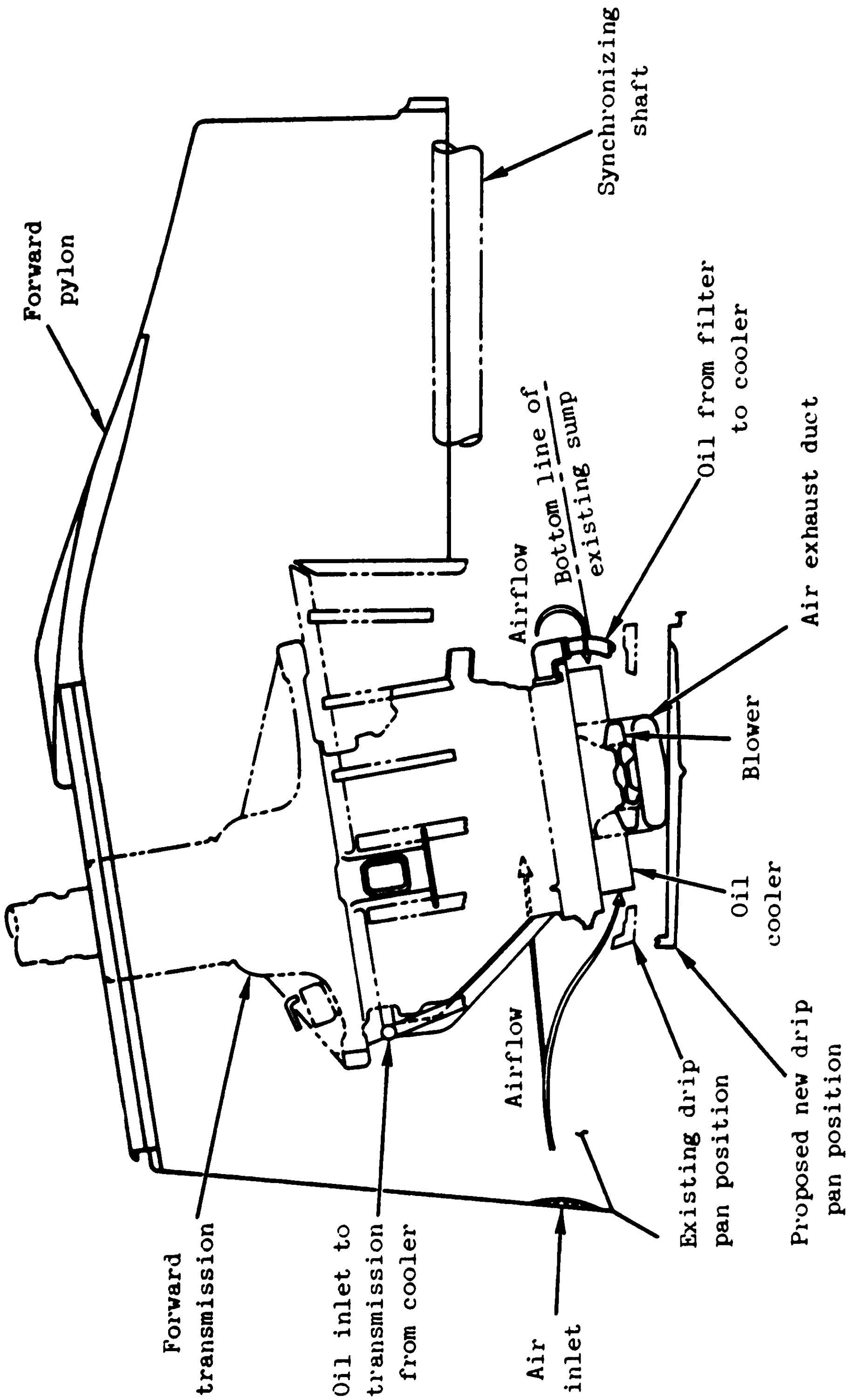

FIGURE 5-96. Integral oil-air system.

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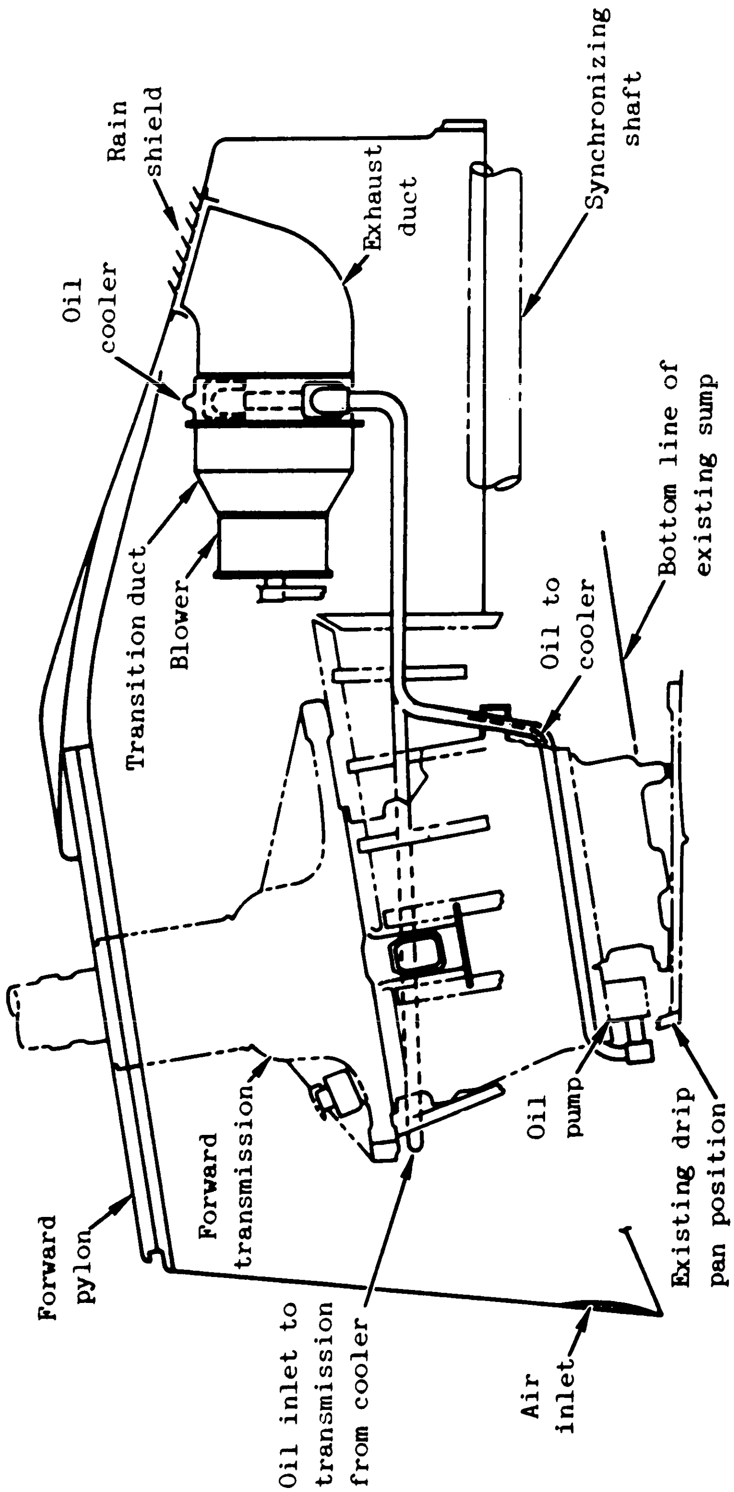

FIGURE 5-97. Close-coupled oil-air system.

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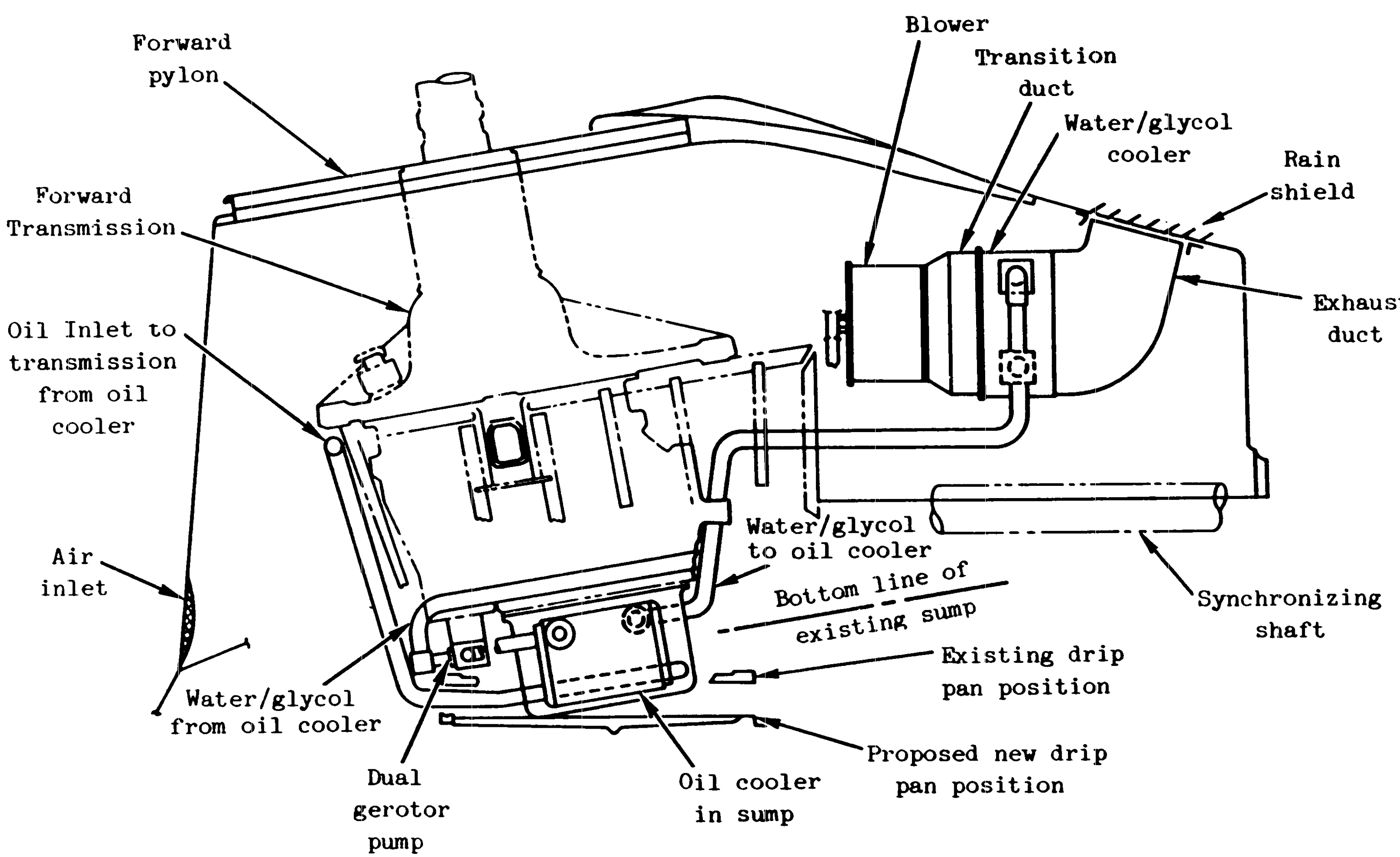

FIGURE 5-98. Oil-water/glycol-air system.

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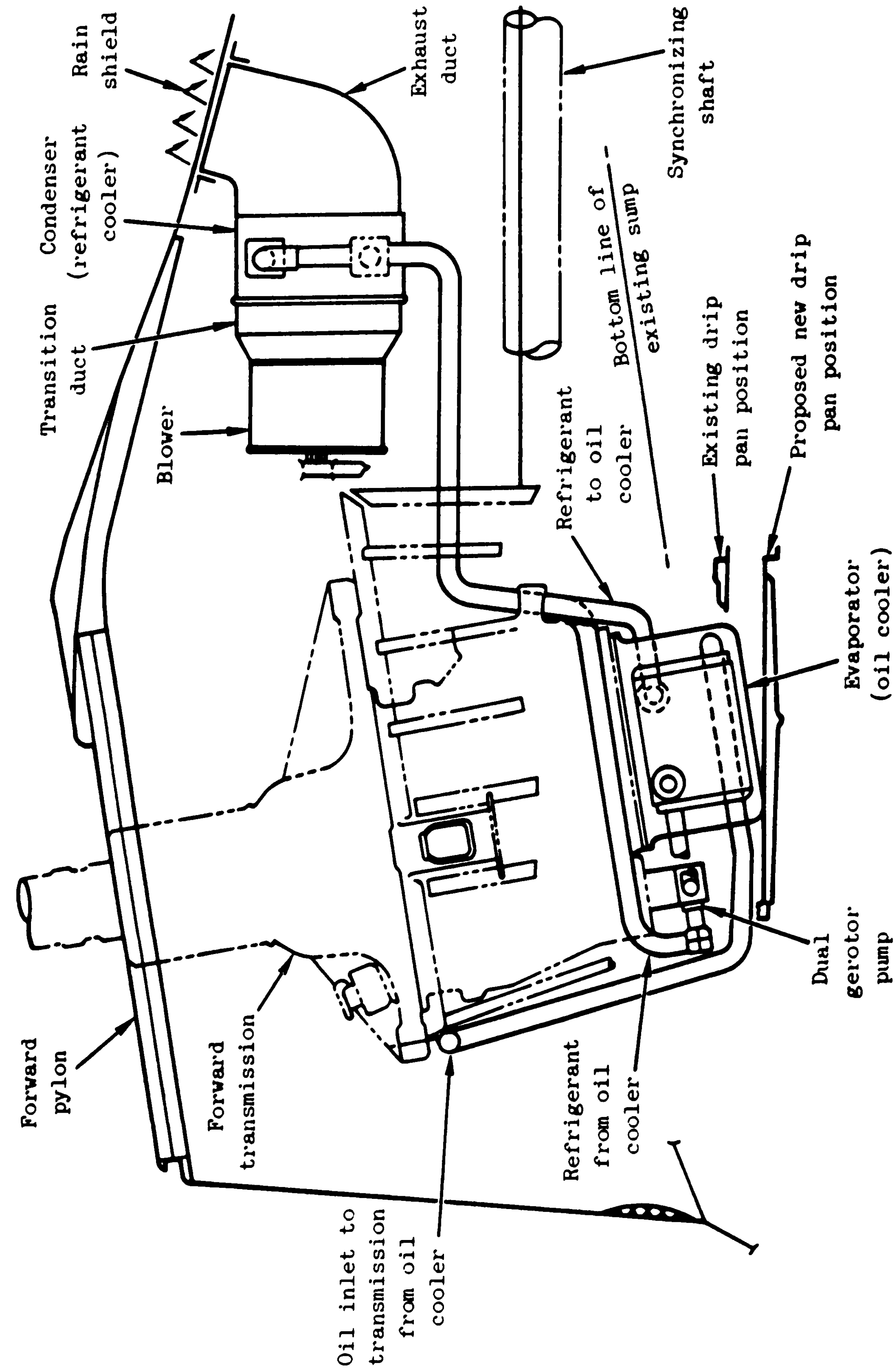

FIGURE 5-99. Oil boiling refrigerant-air system.

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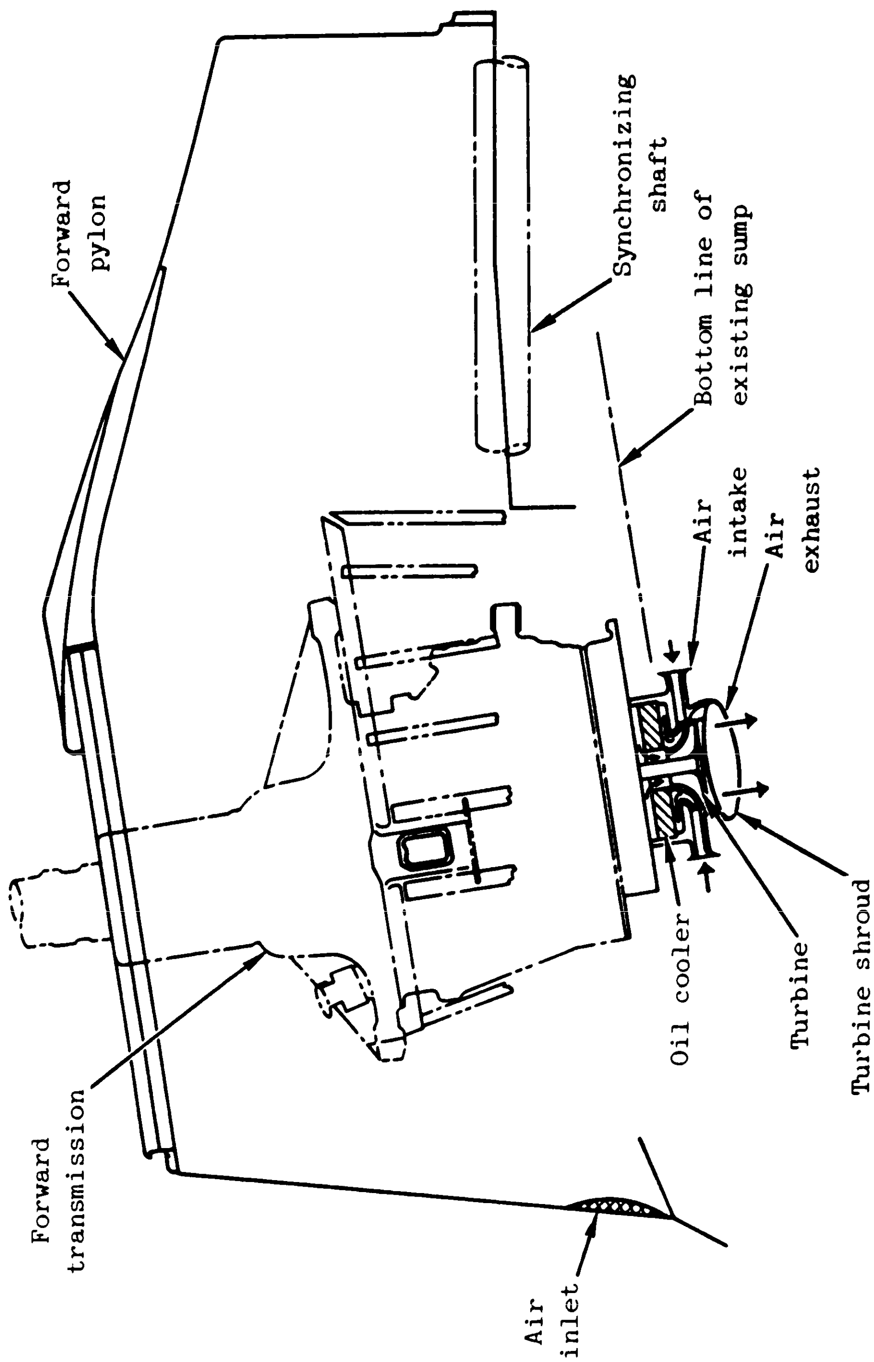

FIGURE 5-100. Air cycle-heat pump system.

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system; however, the heat pump system employs a turbine rather than a blower to circulate the air. The turbine expands the incoming air to reduce its temperature and to afford a larger allowable air temperature drop. The cool air is then directed through an oil-air cooler which removes the heat from the oil. The air is then compressed to atmospheric pressure by the compressor section of the turbine and is dumped overboard through an exhaust duct. The entire assembly is contained completely within the oil sump by shrouds which direct the airflow (Reference 117).

5.7.4.9 Heat pipe system. In the heat pipe system (Figure 5-101), refrigerant is vaporized in the evaporator end of each of the tubes mounted in a boiler within the oil sump. The refrigerant provides cooling for the transmission oil. A slight vapor pressure gradient drives the vapor up into the core of the plate tube condenser, where it is condensed by the rejection of heat to the air forced through the condenser by a belt-driven blower. Condensed liquid refrigerant returns to the oil cooler by gravity reflux down the tube walls. A dynamic circulation system is thus set up within each tube. Because each tube is independent of its neighbor, a puncture of one or more of the 260 tubes by a projectile, would not greatly affect the overall oil cooling capacity of the system (Reference 117).

5.7.4.10 Vapor cycle system. The vapor cycle system (Figure 5-102), which is a true refrigeration cycle, combines an evaporator in the oil sump with a condenser and blower in the same location as in the close-coupled oil-air system. The vapor cycle system employs Refrigerant-11, which undergoes a constant-pressure change of phase from liquid to vapor as it absorbs heat from the transmission oil in the evaporator. The slightly superheated refrigerant vapor leaving the evaporator is compressed by a pump (stack-mounted on the present oil pump) to a higher pressure and temperature. The vapor leaving the compressor is cooled and condensed at constant pressure by rejecting its acquired heat to the air which is forced through the condenser by the blower. The high-pressure, slightly subcooled liquid refrigerant leaving the condenser is expanded across a throttling valve, and the resulting two-phase mixture is fed to the evaporator to complete the cycle (Reference 117).

5.7.4.11 Air cycle-air cooling system. This system (Figure 5-103) is mounted in the space immediately aft of the forward transmission within the confines of the forward pylon. Air at atmospheric temperature and pressure passes through a compressor which raises the pressure and temperature. The compressor output is then passed through an air-to-air heat exchanger, where 90 percent of the compression heat is removed by atmospheric cooling air which is forced through the heat exchanger by a blower. The air is then expanded through a cooling turbine to a pressure slightly less than atmospheric, which reduces the temperature by removing energy in the expansion process. The cooled air then travels through a duct to an oil-air heat exchanger, located within the forward transmission oil sump, which reduces the oil temperature to the required level. The air is then exhausted from the heat exchanger and ducted overboard (Reference 117).

5.7.4.12 Absorption system. The absorption cycle refrigeration system is shown in Figure 5-104. The refrigerant used for this analysis was ammonia

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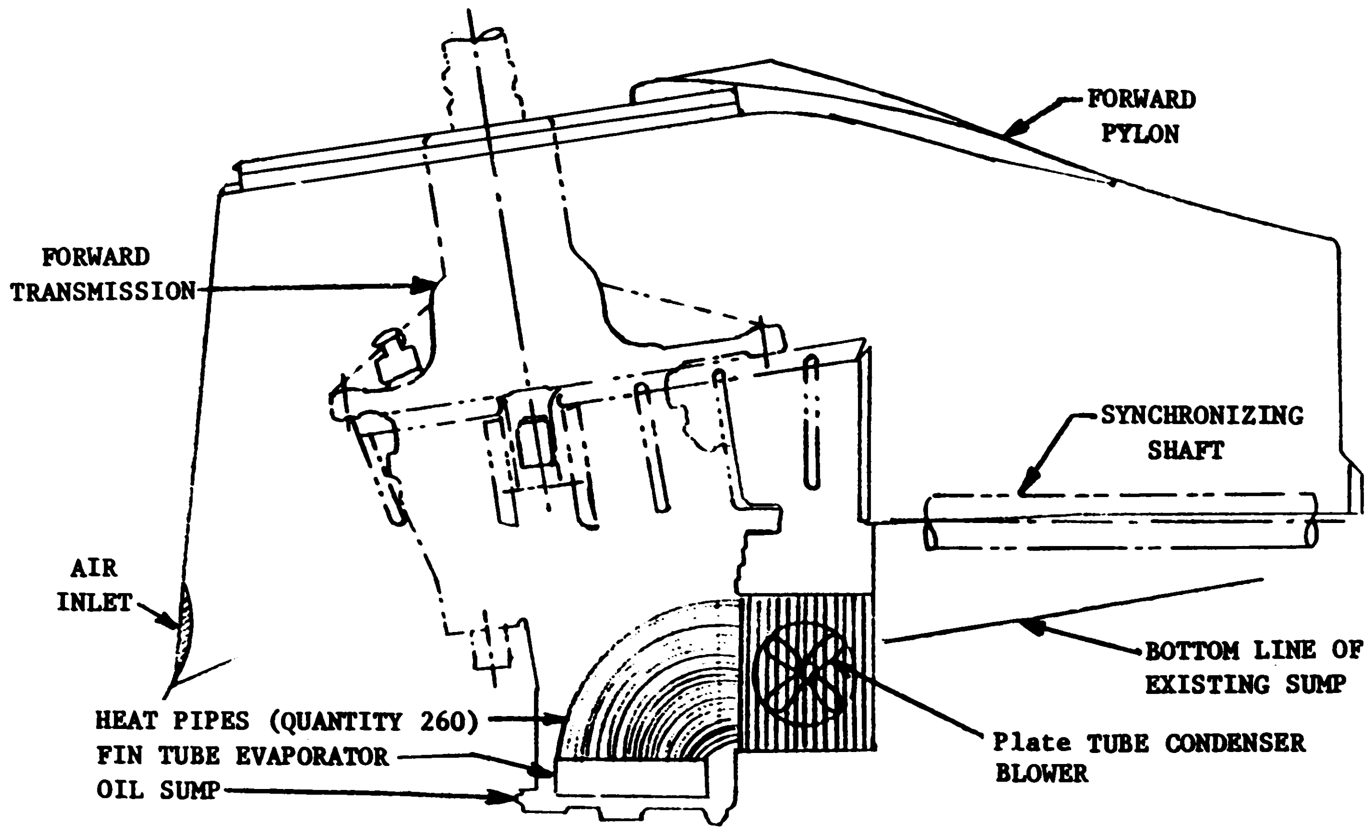

FIGURE 5-101. Heat pipe system.

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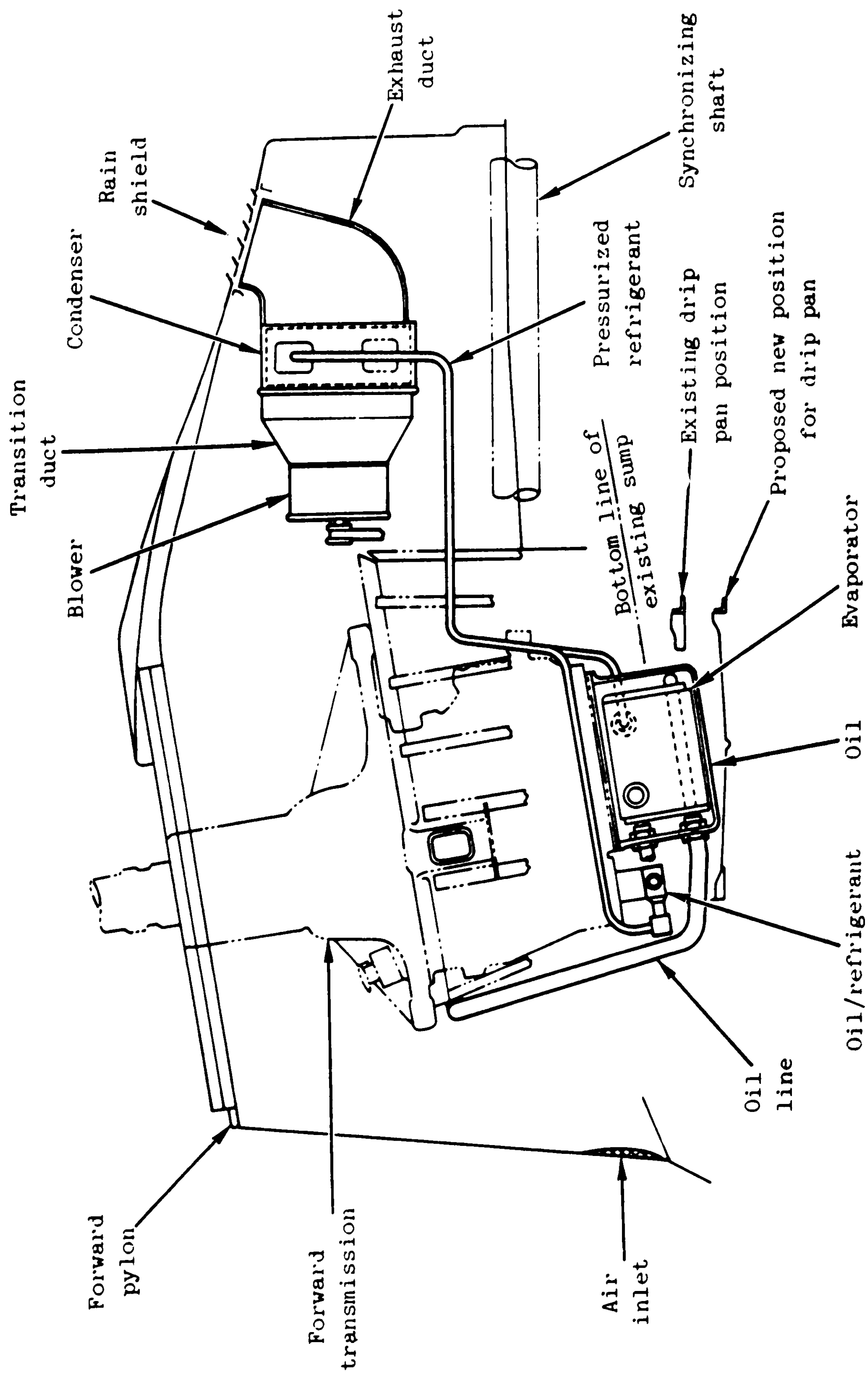

FIGURE 5-102. **Vapor cycle system.**

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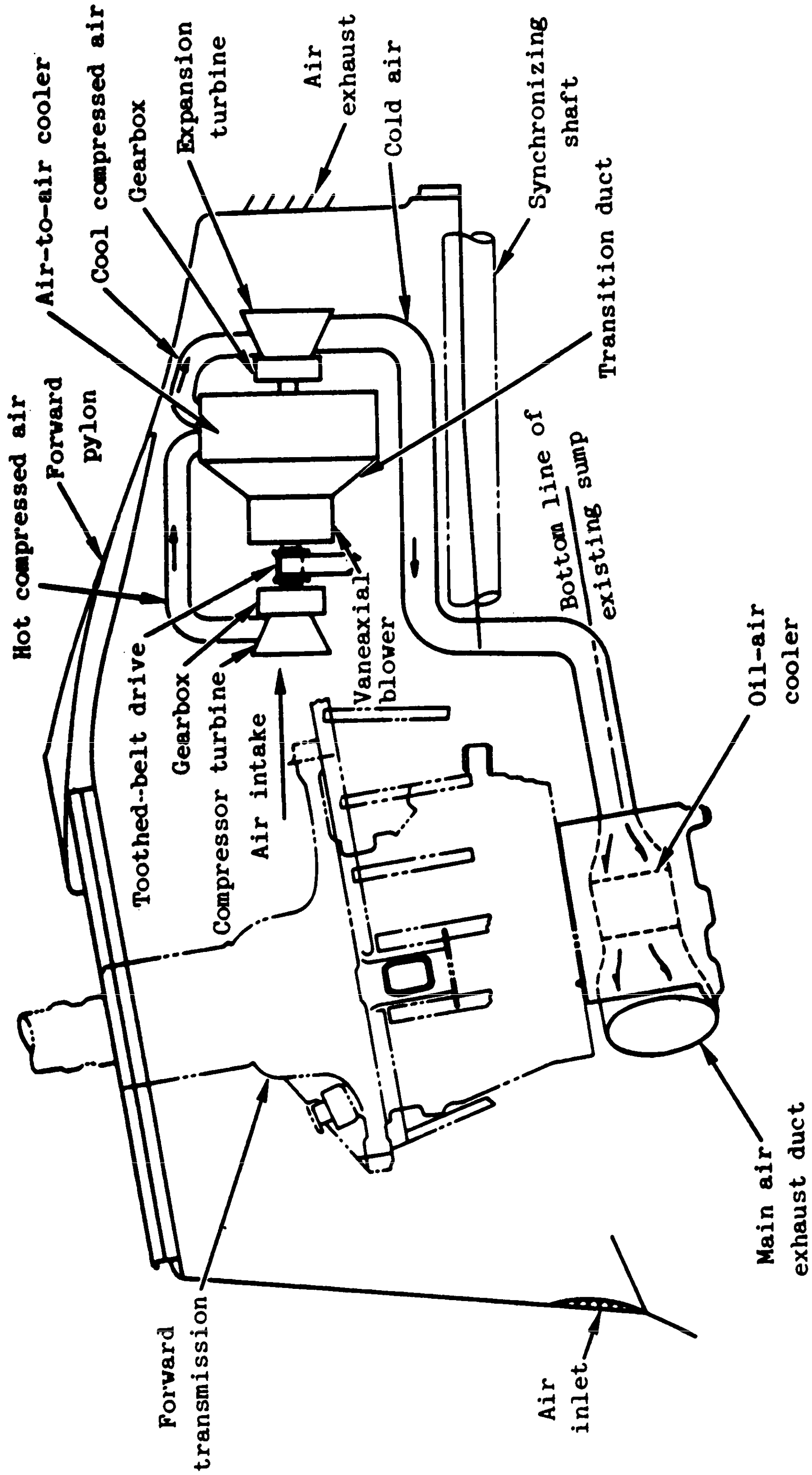

FIGURE 5-103. Air cycle-air cooling system.

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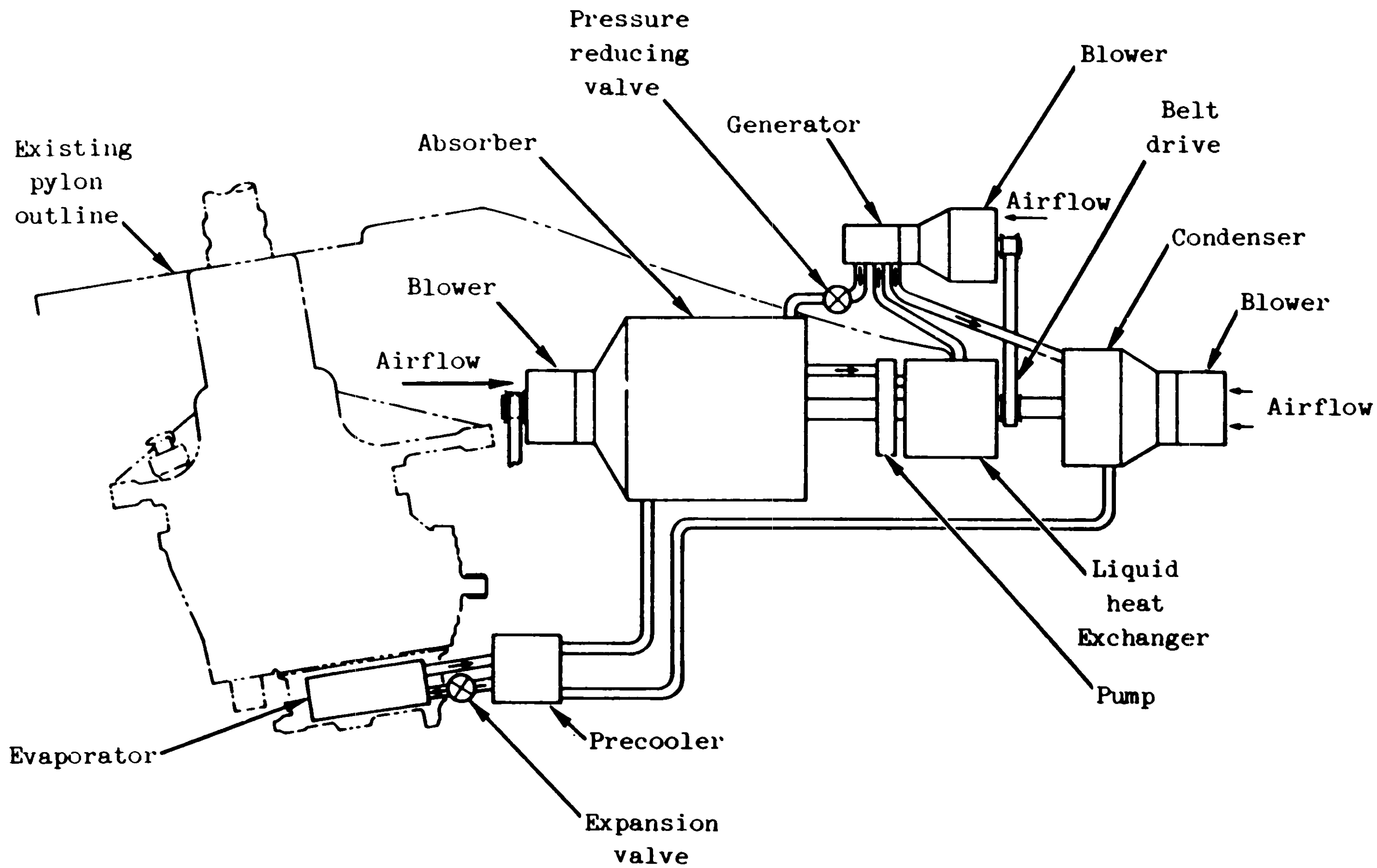

FIGURE 5-104. Absorption system.

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with water as the absorbant. If ammonia is an objectionable refrigerant for use in an aircraft, a lithium bromide/water combination could be used; however, the results of this study show that this system is not competitive. Therefore, the change of refrigerant would have little effect on the rating of this system in the study. Figure 5-105 shows that the liquid ammonia leaves the condenser in a saturated condition and enters the precooler, where it is subcooled by refrigerant vapor from the evaporator. The subcooled liquid is then reduced in pressure by the expansion valve and enters the evaporator, where it vaporizes by absorbing the heat from the transmission oil. The ammonia vapor from the evaporator within the oil sump passes through the precooler and enters the absorber. The ammonia is assumed to be dry from the condenser to the absorber in this analysis. In the actual system, however, there would be a small amount of water mixed with the ammonia (i.e., less than 1 percent). A temperature control may be necessary to prevent the water from freezing. In the absorber, the ammonia vapor is absorbed in a weak solution of ammonia and water. Absorption of the ammonia lowers the pressure in the absorber, which in turn draws more ammonia vapor from the evaporator. Cooling is required in the absorber to remove the heat of condensation and the heat of solution evolved there. For this system, an air-to-liquid heat exchanger is used where atmospheric air is drawn through the exchanger by a blower. The resulting strong solution of ammonia and water is then pressurized by a liquid pump and passes through a liquid-liquid heat exchanger, where its temperature is raised by the weak solution coming from the generator. The strong solution enters the generator where heat is added. The heat vaporizes the ammonia, driving it out of solution and into the condenser where the heat of vaporization is removed by the atmosphere. The weak solution left in the generator after the ammonia has been driven off flows through the liquid-liquid heat exchanger, through a pressure-reducing valve, and back to the absorber to be recycled (Reference 117).

5.7.4.13 Bypass systems. Bypass lubrication should be considered for applications where oil coolers external to the transmission are in use or cannot be-avoided in a new design concept. This technique isolates the transmission oil sump from the oil cooler circuit when a leak is detected or the oil level declines to a predetermined level. Figure 5-106 illustrates the basic system technique. The bypass valve is actuated by an automatic system or by the crew when a leak is detected. This diverts the pump output flow through a bypass circuit line directly back to oil sump area in the transmission mix box (Reference 23). A. check valve is used to prevent flow of oil back into the oil cooler and associated lines where the ballistic damage has most probably occurred. Without the heat rejection capability of the oil cooler, the temperature of the unit's bearings will rise. Tests indicate that the temperature rise will be gradual and will stabilize long enough to enable the aircraft to return to its home base or to an area where a safe forced landing could be made. Figure 5-107 shows the temperature rise from normal to over 400°F for the nine major bearings took approximately 30 minutes. The temperature stabilized at this point for a total of 70 minutes, at which time the test was terminated. Analysis of the test results indicated that bearing velocities are the dominating factor in temperature rise rates (Reference 23).

5.7.4.14 Auxiliary system. The auxiliary lubrication system, shown schematically in Figure 5-108, incorporates a small backup sump and pump to provide

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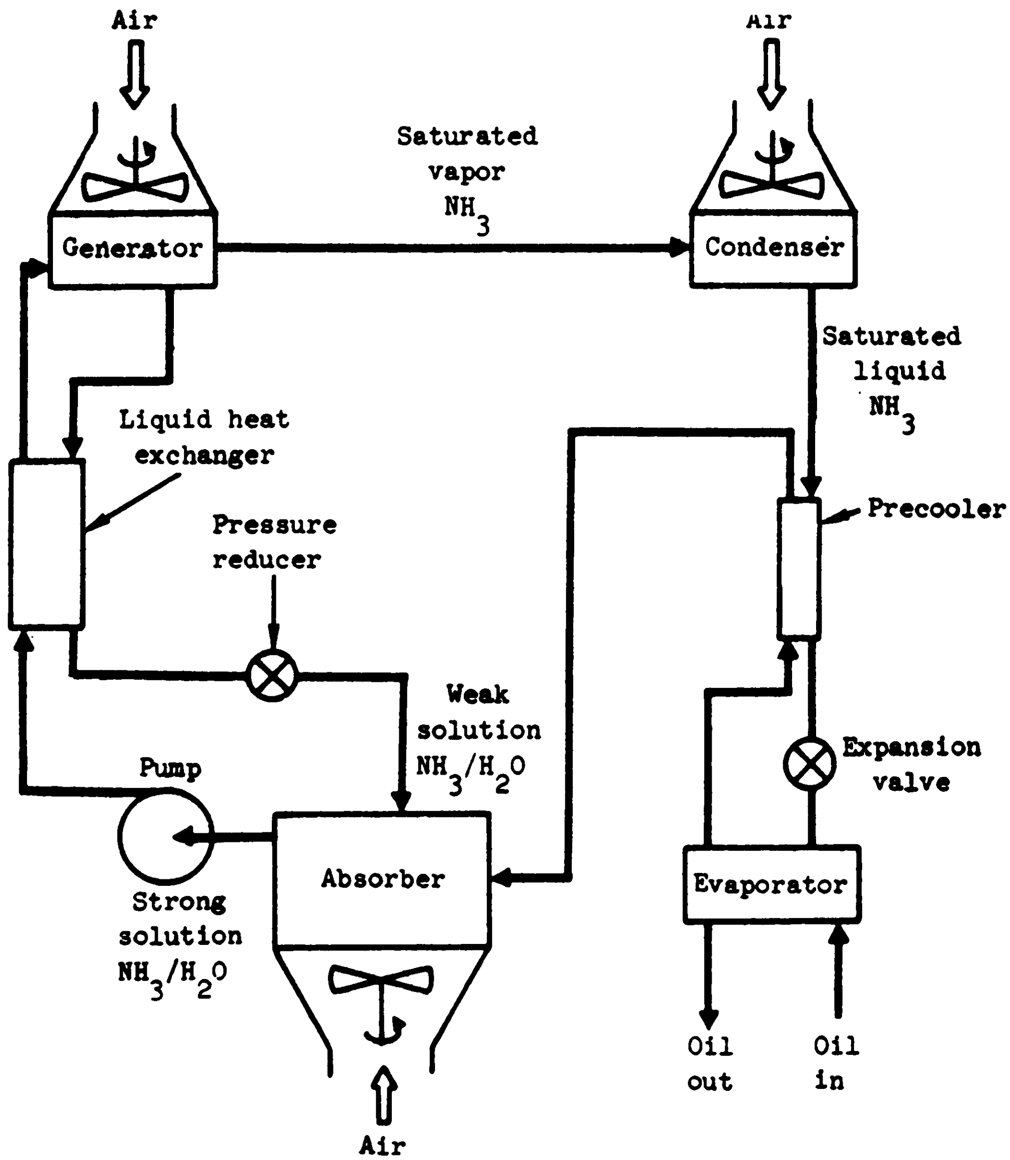

Notes: 1. NH_3 = ammonia

2. H_2O = water

Figure 5-105. Absorption system operational cycle.

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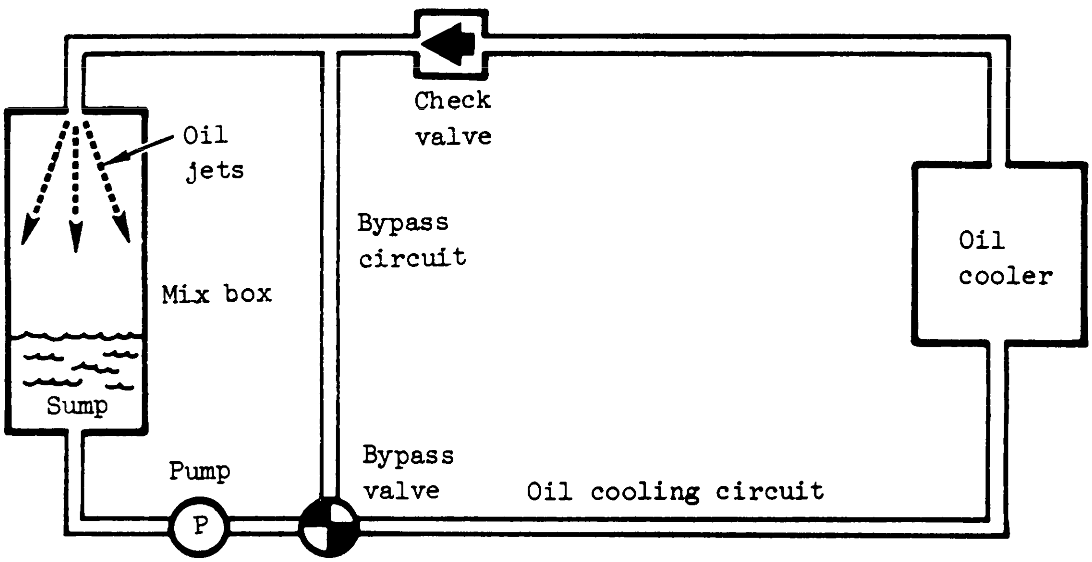

FIGURE 5-106. Mix box - bypass lubricating system.

minimal oil flow to critical areas of the transmission. Ideally, all auxiliary oil lines should be located within the gearbox, and the sump and pump should be protected (Reference 23).

5.7.5 Solid lubricants. Research has also been directed towards the use of solid lubricants in transmissions to extend their useful operational life if the lubricating fluid is lost. Results of research efforts have shown that bearings with solid-lubricant retainers, and gears using solid lubricant idlers will perform satisfactorily during normal operation with oil lubrication, and will provide significant operational life after lubrication oil loss in certain helicopter transmission applications. Teflon solid-lubricant-filled silver alloy matrix was found to provide the best long-term operation at a speed of 1,000 rpm. Reliable long-term operation at 2,000 rpm achieved by use of tungsten diselenide/gallium-indium composites (Reference 23).

5.7.6 Transmission/gearbox lubrication - retrofit. Minimizing the amount and rate of helicopter transmission lubrication fluid loss should receive design consideration for retrofit, and also in the initial design for special severe environments. A number of self-sealing materials can be used to perform this function, with Vithane being one of the more promising materials. It can be applied directly to the outer surfaces of reservoirs and large lines. Its effectiveness is dependent upon the size, type, and impact conditions of the enemy projectiles (Reference 23).

5.7.7 Transmission/gearbox housings. Material selection is a primary consideration for transmission and gearbox housings. The selection process should evaluate both ballistic-tolerant and ballistic-resistant material candidates.

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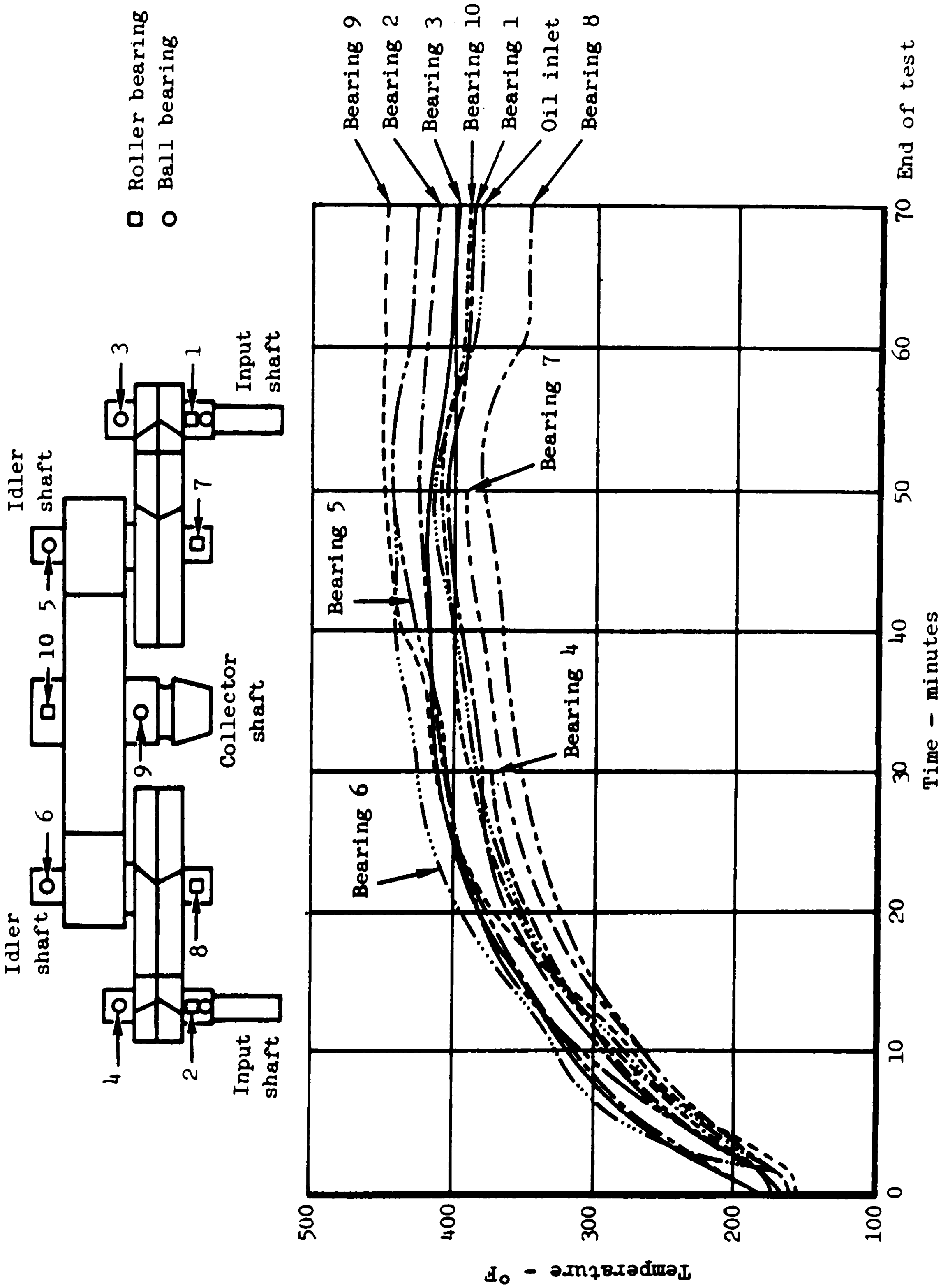

FIGURE 5-107. Mix box - bypass lubrication test temperature history.

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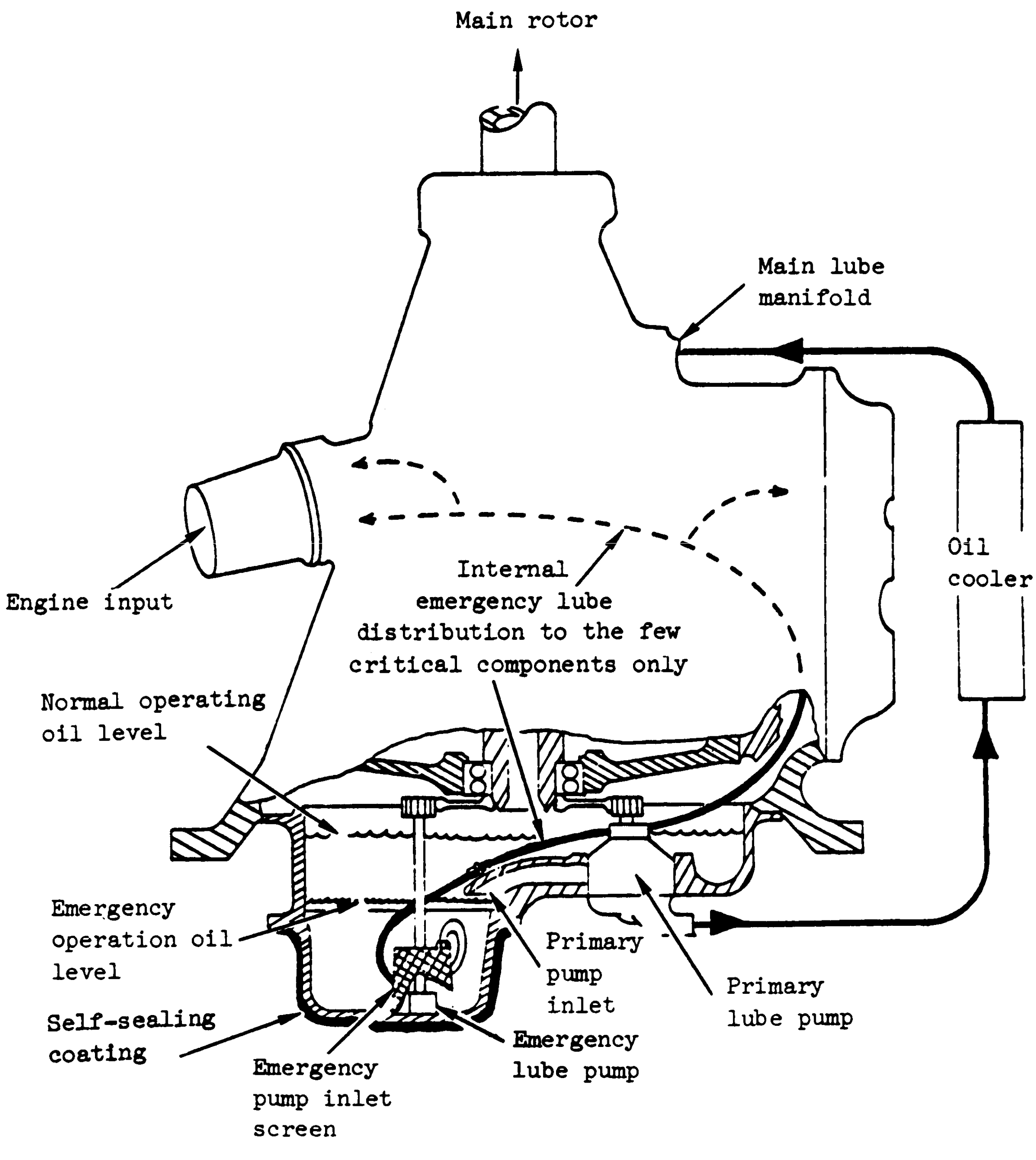

FIGURE 5-108. Backup or emergency lubrication system for helicopter transmissions.

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For those portions of the housing where a degree of penetration can be tolerated or is effectively masked or otherwise protected, material with high fracture toughness and ductility should be used. Where penetration of a transmission or gearbox housing by a projectile cannot be tolerated, ballistic protection should be considered. Parasitic armor can be used for protection of existing equipment, as illustrated in Figure 5-109 and 5-110. The first figure shows a transmission shield fabricated from dual hardness steel armor designed to defeat a .30-caliber armor-piercing (AP) projectile for a CH-47 engine transmission. As can be seen, the armor is directionally oriented to the aspect angles of hostile gunfire. Figure 5-110 shows a shield fabricated from dual hardness steel armor for a CH-47 main rotor transmission forward oil sump. The oil sump itself could also be fabricated directly from dual-hardness steel armor.

5.7.7.1 Special consideration. Special consideration should be given to major or critical high-load, high-speed bearing supports. Catastrophic failure of a transmission or gearbox can occur if the main load-bearing support fails or the bearing itself is fractured from the impact of a projectile. Bearing support structure should be designed for ruggedness and toughness with redundant load paths. Where protection of large-size major bearings is essential, consider the use of ballistic-resistant bearing sleeves that will provide the degree of protection required. Figure 5-111 shows a bearing sleeve, for the CH-47 high-speed transmission, that has been fabricated from DPSA material (Reference 23).

FIGURE 5-109. CH-47 experimental high-speed transmission shield.

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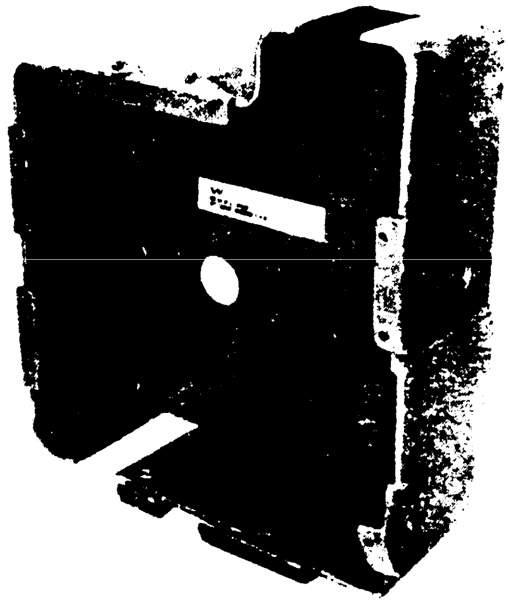

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5.7.8 Drive shaft design. Helicopter drive-shafting is required to transmit power under conditions of angular, axial, and lateral misalignment of the driving and driven equipment. As improvements in gas turbine engine power and speed are made, corresponding increases in shafting rotational speeds will be required. The typical speed range for drive shafts to the transmission has been between 6,000 and 8,000 rpm, and 4,000 rpm for tail rotor systems. Shafting is being developed to operate in the 15,000 to 30,000 rpm range for drive shafts, and 4,000 tc 6,000 rpm for tail rotor systems. Design of such high-speed shafting systems dictates careful consideration of design techniques and features to prevent or minimize failures due to small-arms projectile damage. Particular attention must be paid to systems that are designed to operate at or near critical speeds that occur when the centrifugal force due to initial unbalance exceeds the internal elastic restoring force, or shaft stiffness, and the "whirl" deflection theoretically increases to infinity. The "whirl," caused by ballistic damage, may cause bending stresses in the shaft which would exceed the strength capability. Shaft design, therefore, must provide for safe operation after being hit by single or multiple projectiles. Shaft diameters and wall thickness ratios must be evaluated to determine the amount of material that will be lost and the remaining strength for the size and type of projectiles that may be encountered. Large, thin-wall shafts are less susceptible to failure from ballistic damage than small, thick-wall shafts. Shaft couplings and intermediate shaft supports or hangers must also be designed for ballistic damage tolerance to minimize failure or malfunction from ballistic impacts. Materials with high fracture toughness must be considered for maximum protection.

5.7.8.1 Tail rotor drive shaft ballistic tests. The following is an example of ballistic tests and test results conducted on a 5-foot length of 4.5-inch outside diameter by 0.065-inch wall, 6061-T6 aluminum tail rotor driveshaft. Fully tumbled 12.7 mm API B32 projectiles were used for the tests.

5.7.8. 1.1 Ballistic test summary. Threat: 12.7 mm API (B32) fully tumbled

a. Shot 1 Obliquity: 45 degrees Nominal velocity: 1,611 fps See Figure 5-112. One end of the tumbled projectile impacted at the central plane of the tube, cutting an oblique (45-degree) path approximately 0.6-inch wide across the tube. The exit damage was substantially greater, extending approximately 4 inches perpendicular to the projectile path. During the torque loading test to failure, the tube wall tore at each end of the projectile path. The subsequently measured total indicator runout (TIR) was 0.34-inch. The measured imbalance was 20 inch-grams, with the periphery of the tube rotated on V-rollers spaced 18 inches apart.

b. Shot 2 Obliquity: 70 degrees Nominal velocity: 1,611 fps See Figure 5-113. One end of the tumbled projectile impacted approximately 1.1 inches above the central plane of the tube. The projectile produced a jagged slot approximately 6 inches in length along the 70-degree oblique path whose width was 0.7-inch minimum, 2.0 inches maximum. It also produced a second slot approximately 4.5 inches long by 0.7-inch wide. Between these two slots there was a bridge of metal approximately 1.2 inches long displaced inward approximately 1.4 inches from its original

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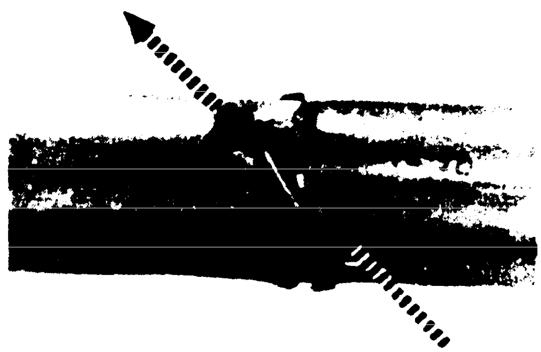
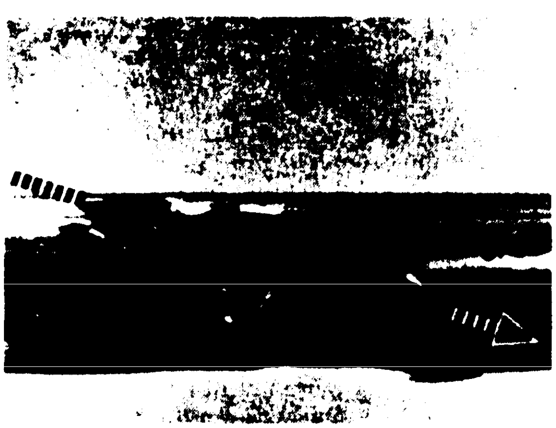
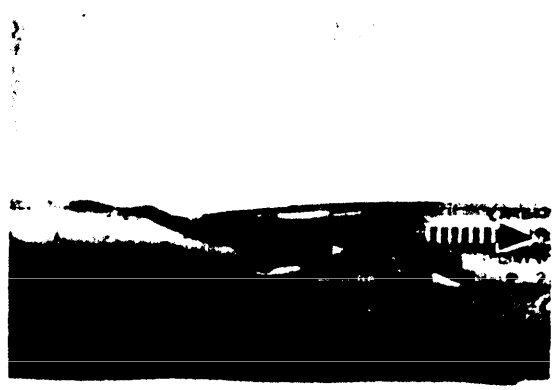


Path of tumbled
12.7mm API projectile
(plan view)

FIGURE 5-112. Tube, 4.50 inches OD by 0.065-inch wall; 6061-T6; shot 1; obliquity 45 degrees.



3(a) Path of tumbled
12.7mm API projectile
(plan view)



3(b) Path of tumbled
12.7mm API projectile
(front view)

FIGURE 5-1130 Tube, 4.50 inches OD by 0.065-inch wall; 6061-T6 shot 2; obliquity 70 degrees.

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position. It is estimated that 40 percent of the area of these slots resulted from removal of the tube wall and the other 60 percent by petalling of the wall inward on entry and outward on exit. During the torque loading test to failure, the tube wall tore at the entry end of the projectile path. The subsequently measured TIR was 0.12-inch. The measured imbalance was 60 inch-grams, with the periphery of the tube rotated on V-rollers spaced 18 inches apart. The incendiary functioned on impact of the projectile with the specimen.

c. Shot 3 Obliquity: 0 degree Nominal velocity: 1,611 fps See Figure 5-114. The tip of the tumbled projectile impacted at the central plane of the tube, cutting a slot transverse to the tube axis, approximately 0.55-inch wide in the entry side and 0.70-inch wide in the exit side. The entry hole was produced by shearing action or the projectile removing the tube wall. The exit hole was primarily a result of petalling of the tube wall, with very little actual removal of material. During the torque loading test, the tube wall tore at the entry and exit ends of the projectile path.

d. Shot 4 Obliquity: 45 degrees Nominal velocity: 1,611 fps See Figure 5-115. The base of the tumbled projectile impacted at the central plane of the tube, cutting an entrance slot 3.5 inches long by 0.70-inch wide and an exit hole of irregular shape 3.5 inches long with a width varying from 0.60 to 3.1 inches. In addition, there was a separate exit hole with maximum lateral damage of 1.5 inches. The entrance slot was almost entirely due to shearing and removal of the tube wall. Approximately 60 percent of the area of the exit hole was a result of petalling of the tube wall. Between the two holes there was a bridge of tube wall approximately 1.5 inches long. This bridge contributed substantially to the residual torque strength of the tube. During the torque loading test, tube wall failure was initiated at both ends of the projectile entry slot.

e. Shot 5 Obliquity: 45 degrees Nominal velocity: 1,220 fps See Figure 5-116. One end of the tumbled projectile impacted at the central plane of the tube, cutting an entrance slot 4.0 inches long by 0.7-inch wide and an exit hole in the shape of an equilateral triangle, 2.8 inches on a side. The entrance hole was almost entirely due to shearing and removal of the tube wall. Approximately 40 percent of the triangular exit hole area was due to petalling. Between the entry and exit holes there was a bridge of tube wall approximately 2.4 inches long. This bridge contributed substantially to the residual torque strength of the tube. During the torque loading test, tube wall failure was initiated at both ends of the projectile entry slot and also to a lesser extent at the exit edge of the bridge.

f. Residual tube strength after simulated ballistic damage - the ballistic tests established the general pattern of damage produced by tumbled projectiles and generated five specific residual strength data points. In order to provide the structures and vulnerability analysts with data in a parametric format, nine additional tube specimens were prepared and

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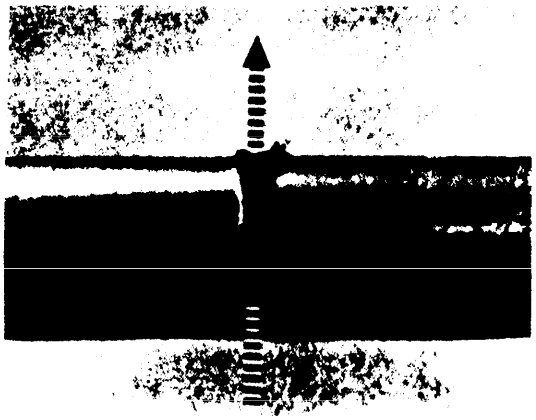
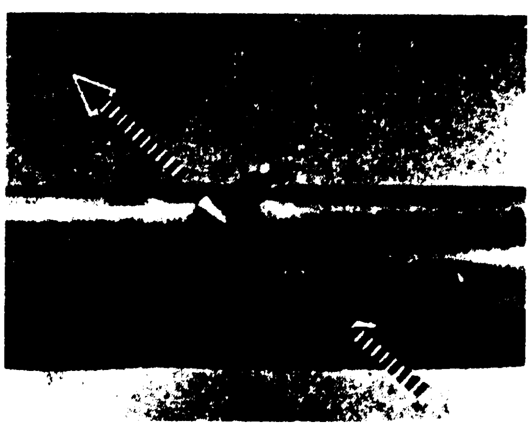


4(a) Path of tumbled 12.7mm API projectile (plan view)

4(b) (Front view)

FIGURE 5-114. Tube, 4.50 inches OD by 0.065-inch wall; 6061-T6; shot 3; obliquity 0 degrees.



5(b) (Front view)

FIGURE 5-115. Tube, 4.50 inches OD by 0.065-inch wall: 6061-T6; shot 4; obliquity 45 degrees.

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6(a) Path of tumbled 12.7mm API projectile (plan view)

6(b) (Front view)

FIGURE 5-116. Tube, 4.50 inches OD by 0.065-inch wall; 6061-T6; shot 5; obliquity 45 degrees.

tested under torsion to failure. For this series of tests, the ballistic damage was simulated by rectangular, sharp-cornered, sawed single-slot and double-aperture cutouts. This approach offered the advantage of providing a more specific correlation between residual strength and the readily measurable geometric damage. Figure 5-117 presents detailed sketches of the simulated damage to the test specimens.

Plots of the test results, torque versus twist angle, to values past the ultimate load are presented in Figure 5-118 for specimens 1-3, which simulated zero-obliquity ballistic damage; Figure 5-119 for specimens 4-6, which simulated 45-degree obliquity ballistic damage; Figure 5-120 for specimens 7-8, which simulated double-aperture, zero-obliquity damage; and Figure 5-121 for an undamaged specimen. The ultimate load values for each specimen have been plotted in Figure 5-122 as a function of depth of cut. Inspection of this figure shows that, for the single-slot simulated damage, the OIC and 45 degree obliquity cases gave mixed results. Consequently, an average curve has been faired through the single-slot data points and extrapolated to zero at the full diameter of 4.5 inches. For the specific double-aperture case, which had a bridge 0.25-inch high between apertures, the curve was extrapolated to intersect the single-slot damage curve at 4.25 inches. The configuration is no longer “double-aperture” once the depth of cut reaches this value. As expected, the presence of a bridge between apertures substantially increased the residual strength of the tube for a given depth of cut simulation of ballistic damage. This is a special problem associated with HEL vulnerability of this type of component.

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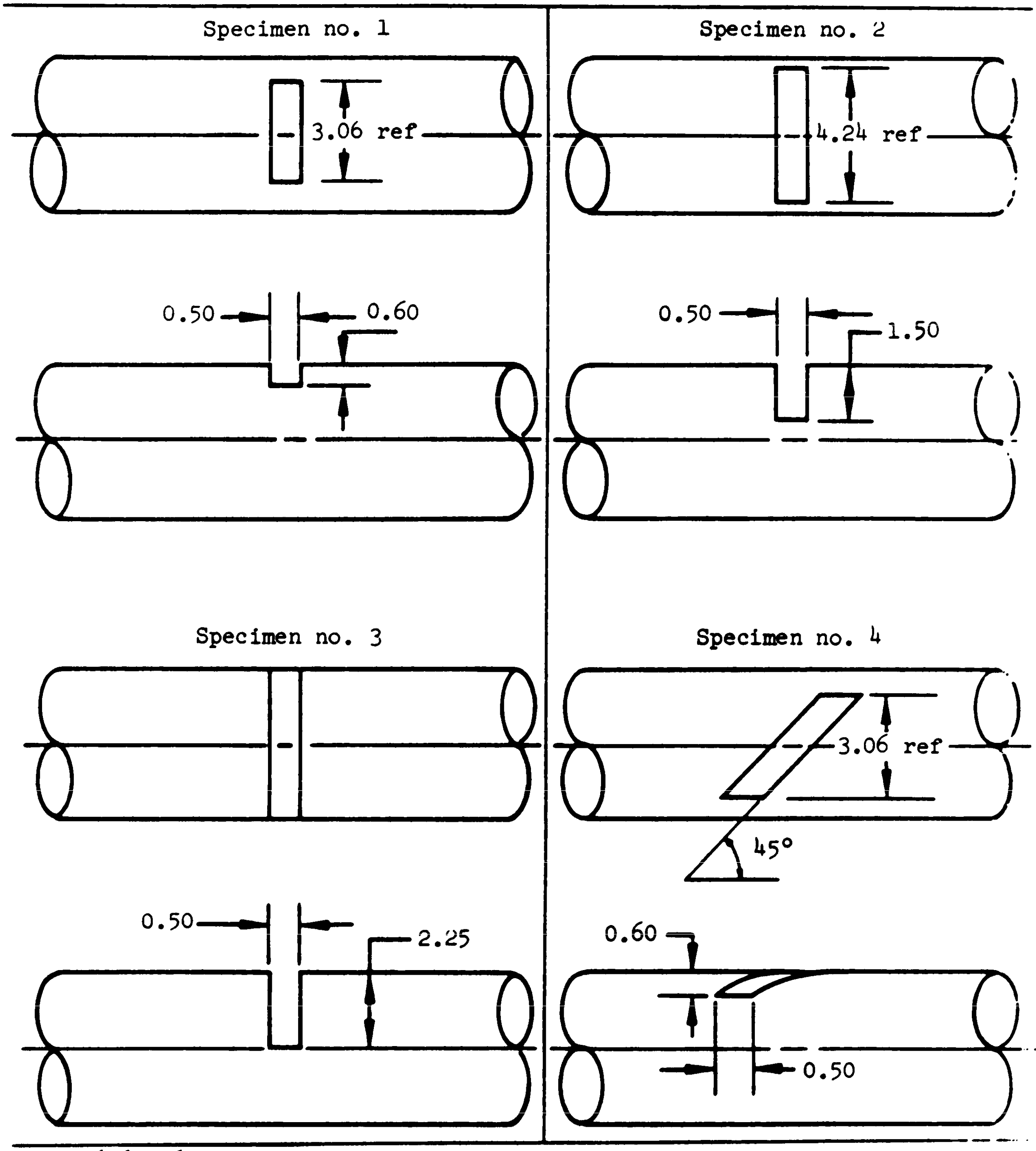

6061-T6 aluminum tubes,
48 inches long, 4.50-inch OD,
0.065-inch wall thickness

FIGURE 5-117. Specimen configurations: tail rotor shaft section with simulated ballistic damage (sheet 1 of 2).

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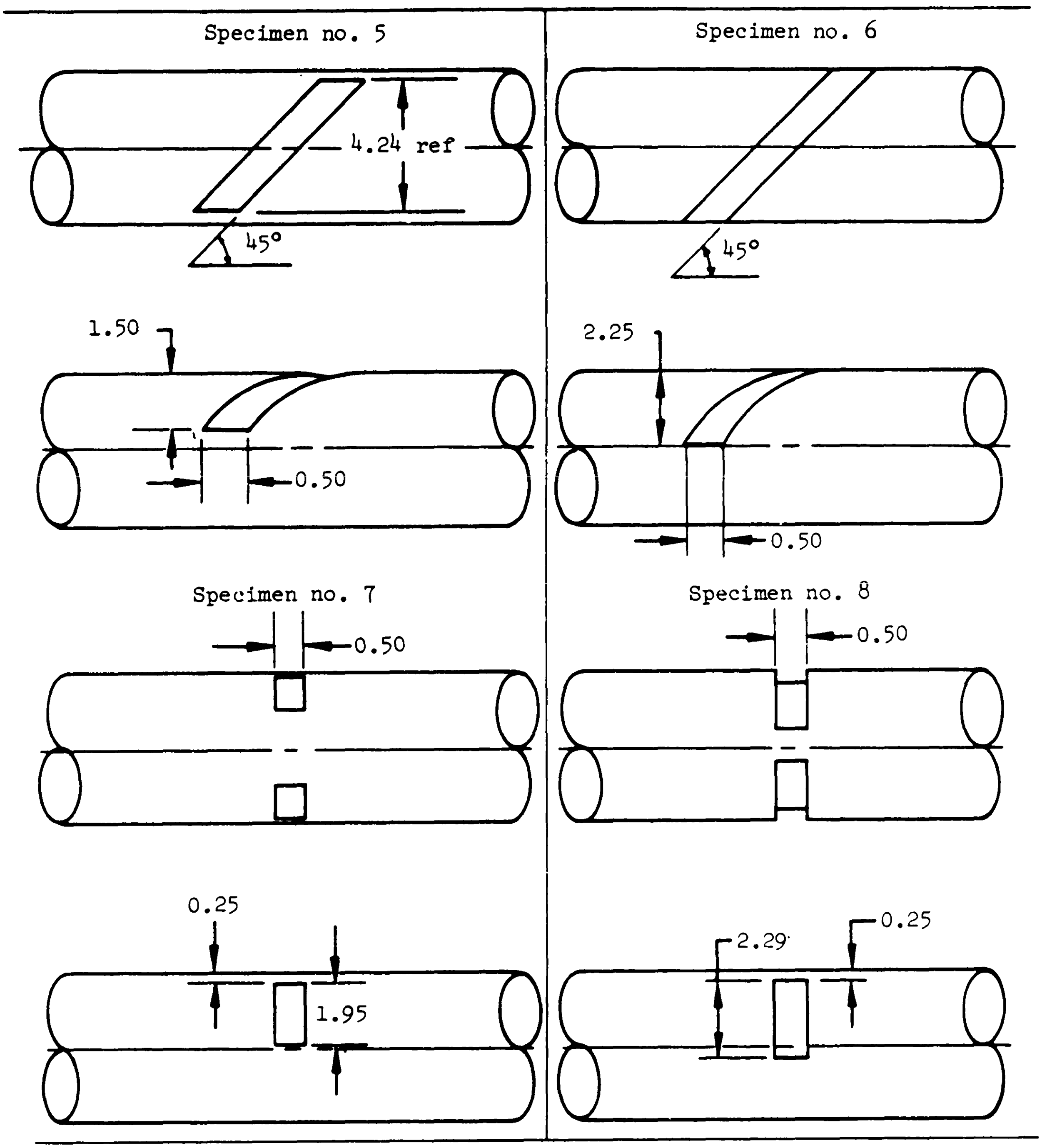

FIGURE 5-117. Specimen configurations: tail rotor shaft section with simulated ballistic damage (sheet 2 of 2).

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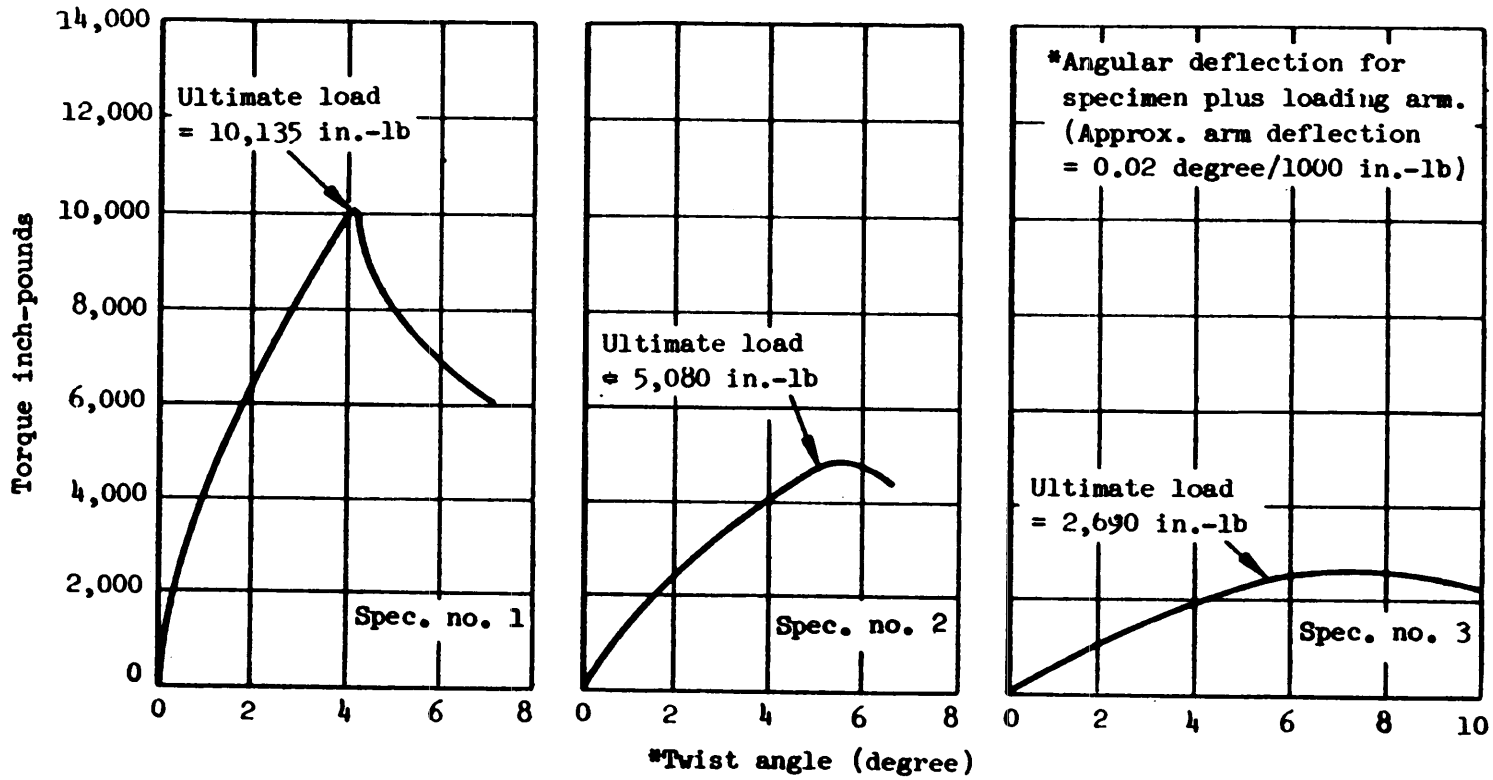

FIGURE 5-118. Tail rotor shaft section strength with simulated ballistic damage at zero obliquity.

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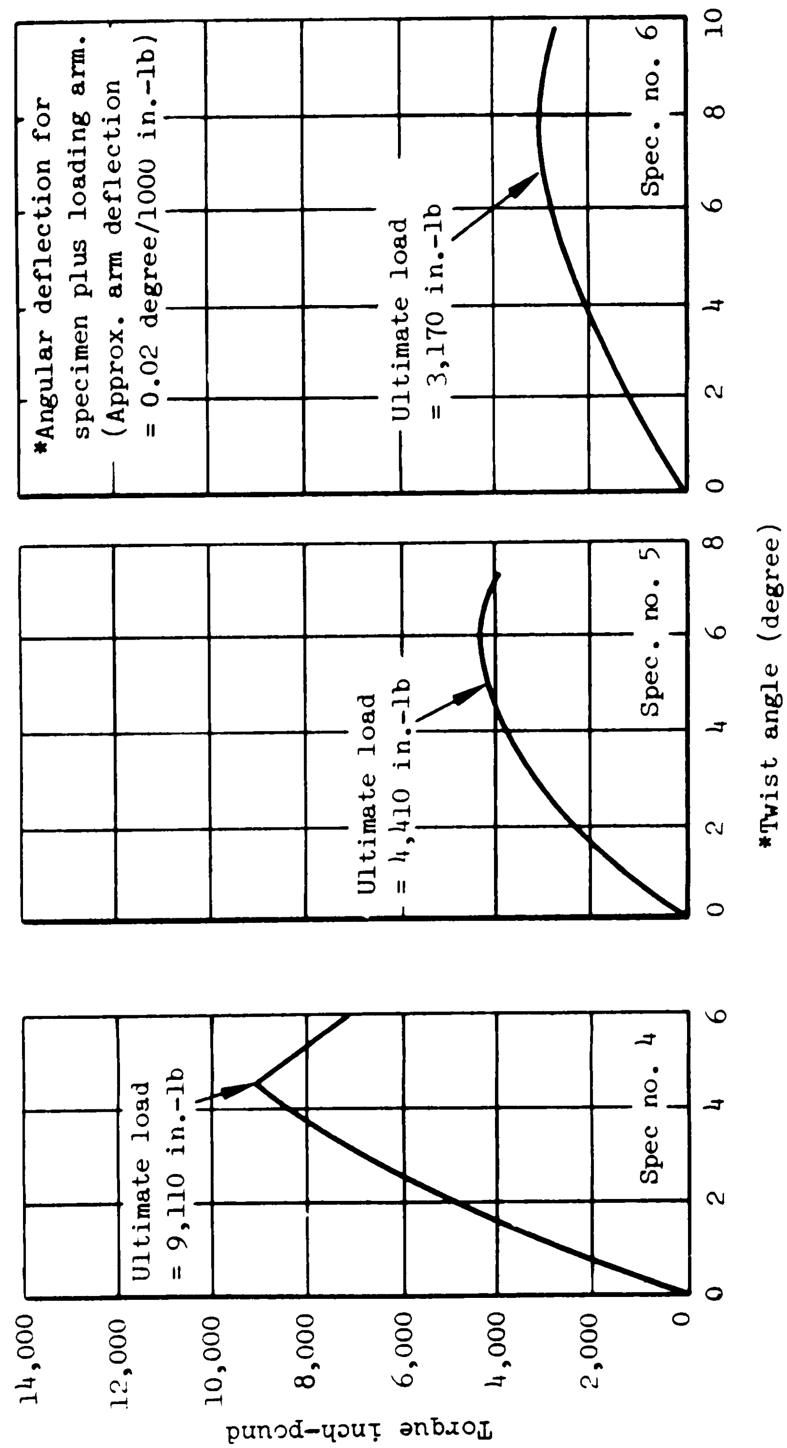

FIGURE 5-119. Tail rotor shaft section strength with simulated ballistic damage at 45-degree obliquity.

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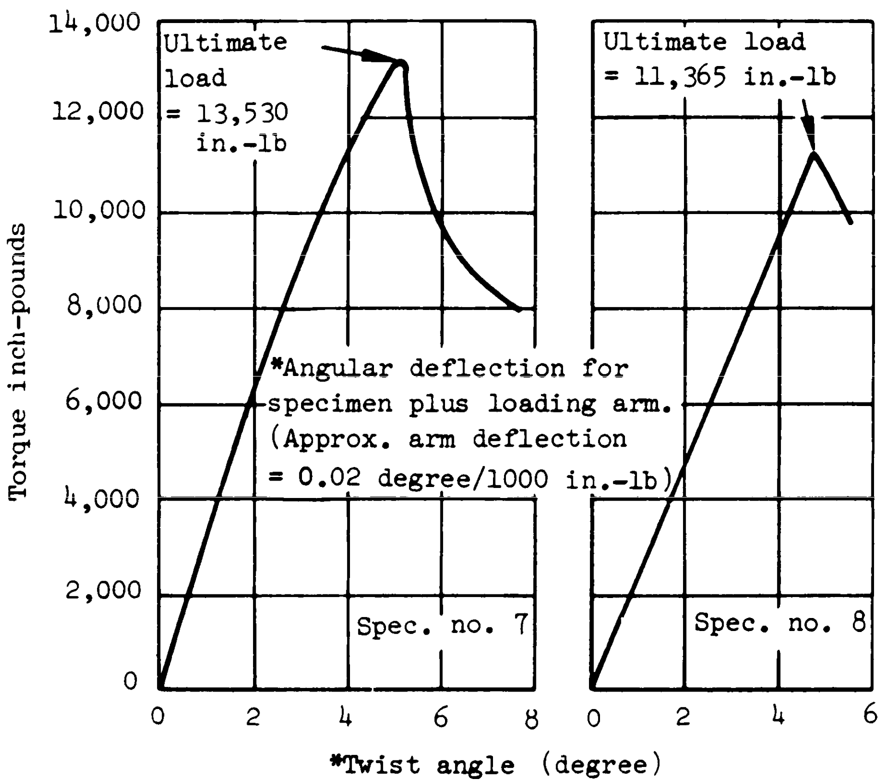

FIGURE 5-120. Tail rotor shaft section strength with simulated ballistic damage at zero obliquity, with double aperture.

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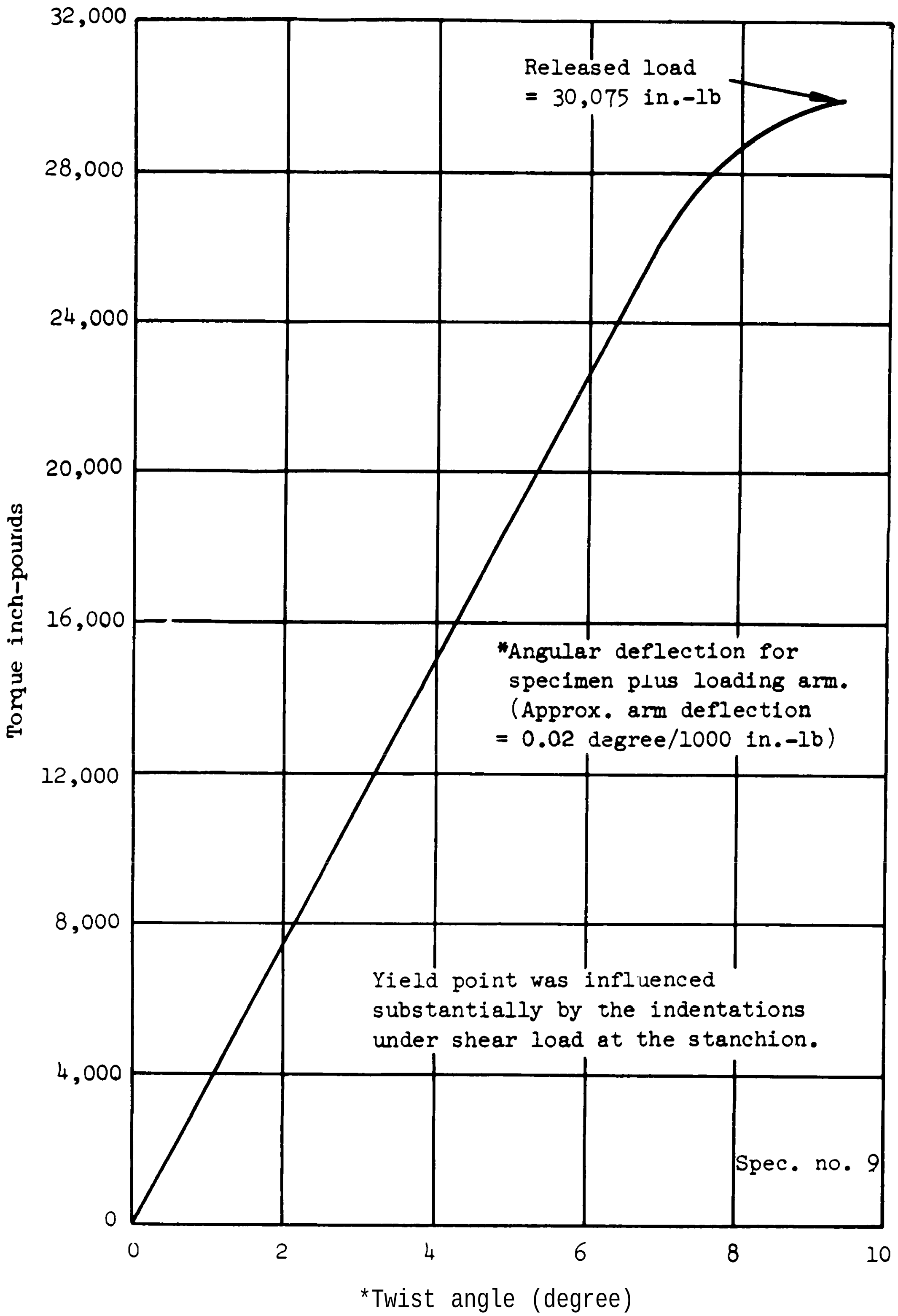

FIGURE 5-121. Tail rotor shaft section strength, undamaged.

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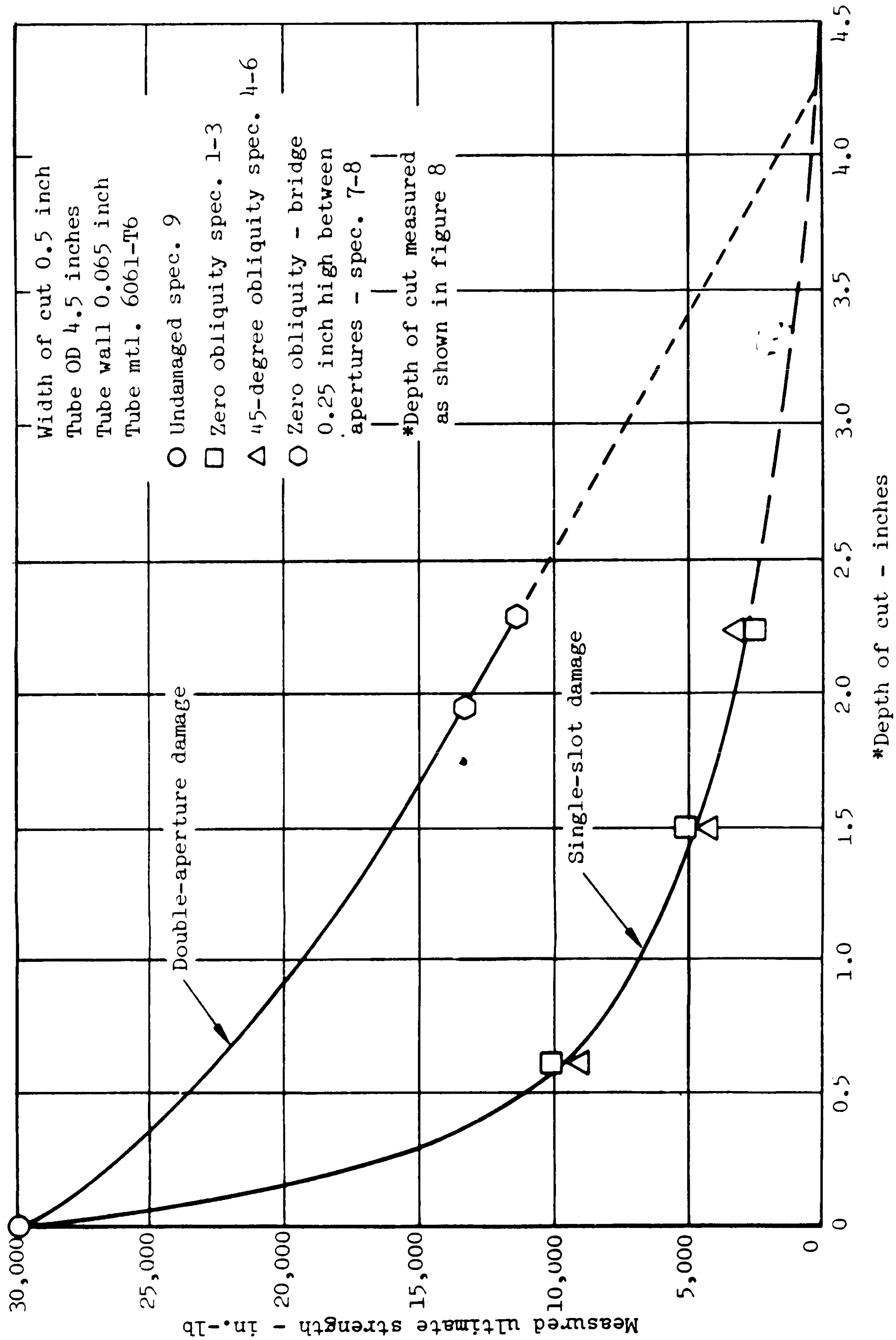

FIGURE 5-122. Static residual ultimate strength of tail rotor drive shaft with simulated ballistic damage.

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5.7.9 Gearing design. Transmission and gearbox design requirements determine the loads that must be transmitted by the individual gears in each unit. Destruction or jamming of any one of these can destroy or degrade its capability to perform its function. Where protection of the units internal gears is marginal or cannot be provided, consideration should be given to incorporating ballistic-damage-tolerance features in the gear trains. Wide section gears should be used in preference to narrow-width section types. This will permit a portion of the gear to be broken out or removed by a projectile impact and still retain a degree of operation. Figure 5-123 shows a wide section ring gear that sustained a projectile hit and was able to continue to operate. Tough, rather than brittle, gear material should be used to minimize the effects of ballistic impacts.

5.7.10 Bearing selection. Bearings with inherent capability to operate after loss of normal lubrication or cooling should be considered and selected for major critical bearing applications in transmissions and/or gearboxes. The state-of-the-art in this field is changing rapidly, and the designer should consult with bearing manufacturers to obtain the latest information and candidate bearings available. Careful consideration should be given to the number of and size of bearings selected. A larger bearing may be more advantageous than several smaller bearings, depending upon rotational speeds and heat transfer or distribution characteristics of the specific installation. The amount of heat generation and bearing high-temperature operating capabilities must be also considered in the material selection of the bearing. For additional suggested vulnerability reduction methods, refer to Volume 4 of this handbook.

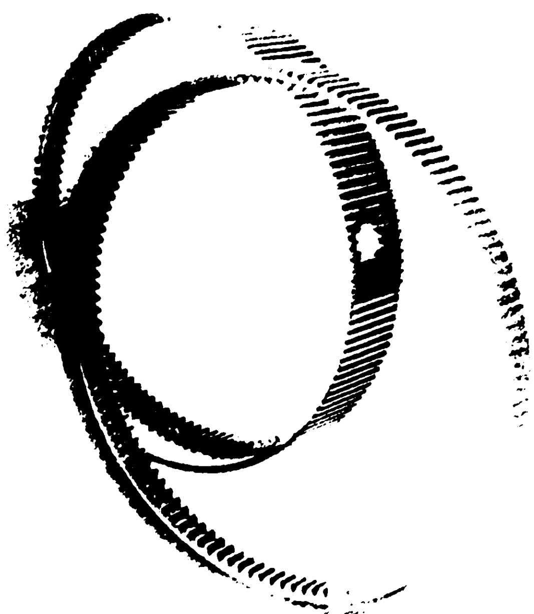

FIGURE 5-123. Damaged ring gear.

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5.7.11 Power train systems HEL protection. Power train systems should be designed in a manner that exhibits hardness to HEL threats. Internal parts should be located to make maximum use of inherent shielding. External parts should be made out of carefully selected materials. Care must be taken to minimize secondary effects such as lubrication leaks, fires, etc.

5.7.12 Power train systems reliability/maintainability. Power train systems carry primary responsibility for flight capability in all rotary wing aircraft and for those propeller-driven fixed-wing aircraft dependent upon speed-reduction gearboxes. Power train systems exposed to ballistic impact have two general failure mechanisms: (1) direct projectile damage to critical dynamic components such as bearings, gears, and shafts, and (2) loss of lubrication, usually caused by perforation of oil-containing components. Loss of lubrication is the predominant failure mode for existing transmissions and gearboxes in a ballistic threat environment. Damage-tolerant techniques to minimize or prevent failure due to lubrication system damage can provide significant benefits for little or no penalties if incorporated into the initial design. Drive shaft design must provide for safe operation after being hit by a single, or multiple projectiles. Shaft diameters and wall thickness ratios must be evaluated to determine the amount of material that will be lost and the remaining strength for the size and type of projectiles that may be encountered.

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5.8 Rotor blades. The design of helicopter main and tail rotor blades requires the application of the aerodynamic principles, imposed for fixed wing lifting surfaces, as well as the structural dynamic principles required for rotating elements. All of the aerodynamic and load stress factors for rotor blades can be affected by nonnuclear weapon effects that in turn affect their degree of vulnerability and effectiveness of operation. Rotor blades are subjected to a combination of dynamic stress forces and frequencies not normally imposed on fixed wing structures. These include tension, compression, torsion, and bending forces that rapidly change as the blade rotates around its hub . Main rotor blade sets (single or multiple) are configured into a main lifting section(s) together with a lateral stability group (tail rotor system) unless a pair of counter rotating main rotor blade system is utilized. Each rotor blade set may consist of two or more blades. The selection of the aerodynamic and structural properties, within the limits of the specific aircraft system design requirements, can have a significant effect upon its effectiveness and survivability. Figure 5-124 shows the cascading effects of rotor blade improvements in the areas of weight savings, decreased droop, improved aerodynamic efficiency, structural damping and dynamic properties, improved fatigue strength and decreased notch sensitivity, and decreased tooling costs. The effects of nonnuclear weapon effects damage upon each of the above design factors must be carefully considered in the early design activities to ensure adequate system survivability is realized. The following paragraphs describe the major design considerations for rotor blade systems. See Reference 82.

5.8.1 Rotor blade detectability. The tactical combat role of military helicopters has rapidly expanded in the past several decades. They are being used primarily as low level flying systems to provide close support for surface combat units. As such, they are exposed to hostile threat systems that utilize visual, radar, infrared (IR), and aural detection and/or tracking systems. Consider methods to minimize radar cross section signatures, aural signatures, and visual cues by which they can be located and tracked by the defined threat systems. Research has shown that the radar cross section of main rotor and tail rotor blades can be minimized by incorporation of certain design principles. For main rotor blades, the shaping of the main spar provides reduced RCS signatures for certain radar wave bands. The specifics of this technique are described in Reference 76. Tail rotor blades have been developed with reduced radar cross section and improved repairability. These were fabricated from Kevlar 49 aramid fibers and epoxy using the wet filament winding process. It consisted of an inner Kevlar 49 core, a layer of microwave absorbent material, an outer Kevlar 49 spar, and a Kevlar 49 skin. Details on this type of construction are contained in Reference 77. The noise generation by a rotor blade system may be minimized through reduction of blade loading factors and by selection of multiple blades with appropriate spacings. Such reductions have been accomplished to produce “Quiet Helicopters” as described in references 78, 79, 80, 81 and 110. Reduction of visual signatures for main and tail rotor systems is described in Section 4.2.3 of this volume.

5.8.2 Rotor blades ballistic protection. Satisfactory operation of a rotor blade system requires that its structural integrity be maintained following

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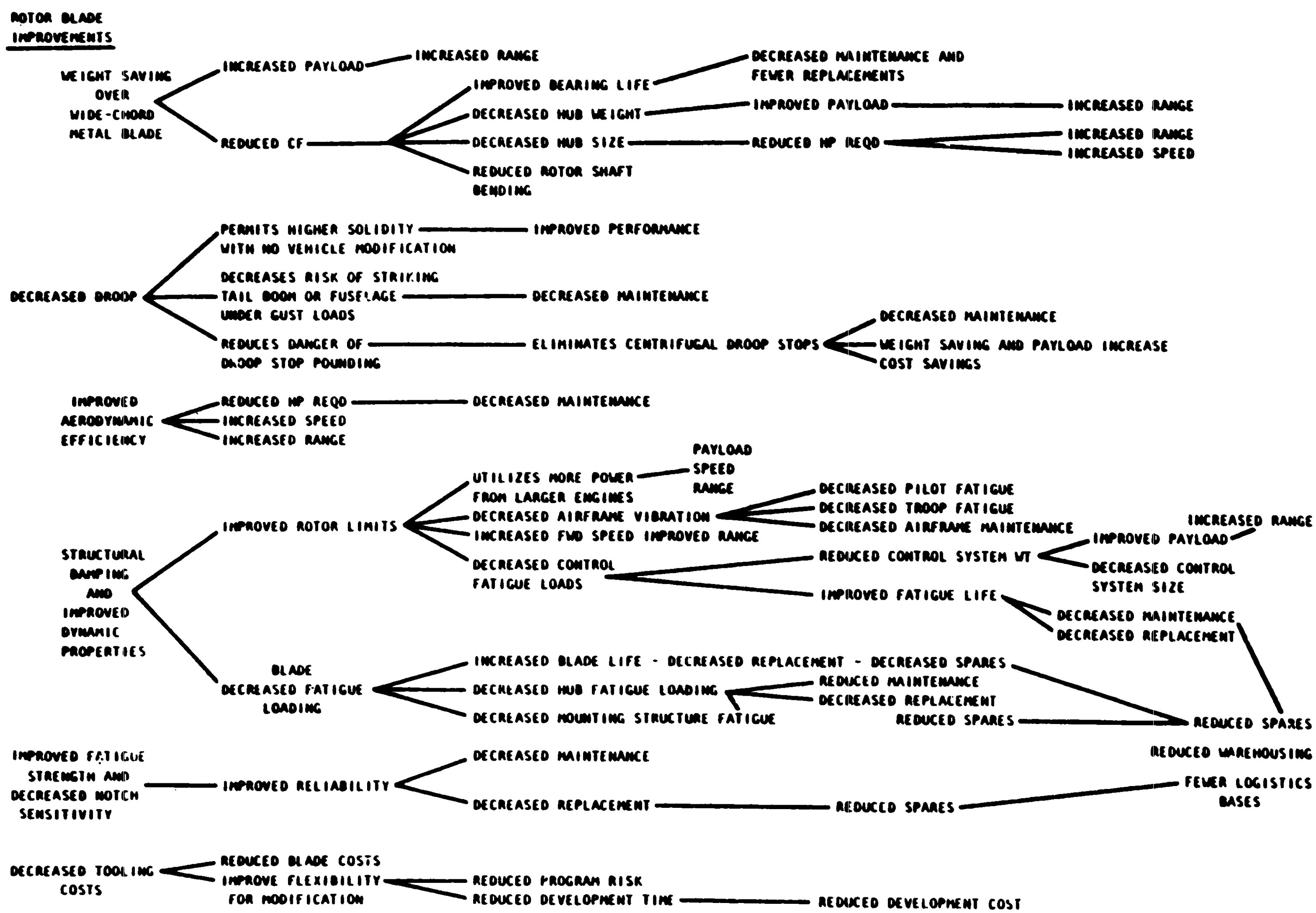

FIGURE 5-124. Cascading effects of rotor blade improvement.

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ballistic impact, and/or exposure to high explosive blast effects. Balance of the rotor blade must also remain between within specific limits to avoid catastrophic failure or unacceptable vibration levels. Combat experience has shown most conventional main rotor blade design concepts, such as those shown in Figure 5-125, are relatively tolerant to small-arms ballistic impact up through 12.7 mm projectile size. Special attention must be paid to the capability of a rotor blade to operate a minimum length of time under realistic operational loads so that escape from the combat area can be affected and a forced landing or safe recovery realized. Apply fracture mechanics technology together with the specific operational mission parameters to develop an S/N curve such as the example shown in Figure 5-126. This may be used to evaluate the survivability of the rotor blade design against the defined threat systems. Rotor blades operate at a delicate balance of weight, strength and stiffness to permit safe flight of the aircraft. When a blade is ballistically damaged, a number of factors may change which degrade the blade's operation:

a. Rotor unbalance - Probably the most critical consequence of ballistic damage is rotor unbalance due to the separation of a section of blade outboard of the hit point. This loss of mass in one blade generates high alternating l/rev in-plane hub forces. These forces could cause cockpit and control vibrations of sufficient magnitude that the pilot could lose control of the aircraft. In addition, large hub forces could do critical structural damage such as tearing the rotor transmission out of the fuselage.

b. Blade instability - Blade instability can be a flight-critical factor even if the blade does not separate. A local reduction in blade stiffness due to a hit could result in either classical flutter or a divergent pitch oscillation. Either of these conditions could prove to be catastrophic.

c. Blade out-of-track - Blade out-of-track due to a local reduction in blade stiffness can also be critical if it becomes excessive. Blade out-of-track is probable when the reduction in stiffness is in the range caused by 23mm HEI hits on the spar. Excessive blade out-of-track produces high levels of 1/rev vibration. In the extreme, excessive blade out-of-track could also cause blade contact with the fuselage. This could occur either in flight or on the ground and is particularly likely after shutdown.

d. Loss of lift - Loss of blade lift could be caused either by separation of part of the blade or by a locally reduced blade stiffness which could result in its operating at a lower angle of attack. Analysis and flight experience with failing blades confirm that loss of lift is not generally as critical a consequence of blade damage as other factors. Since the loss is generally small, except when operating under extreme conditions of over-weight altitude, or temperature, the lift loss sustained by one blade can be readily compensated for by increased pitch on all blades.

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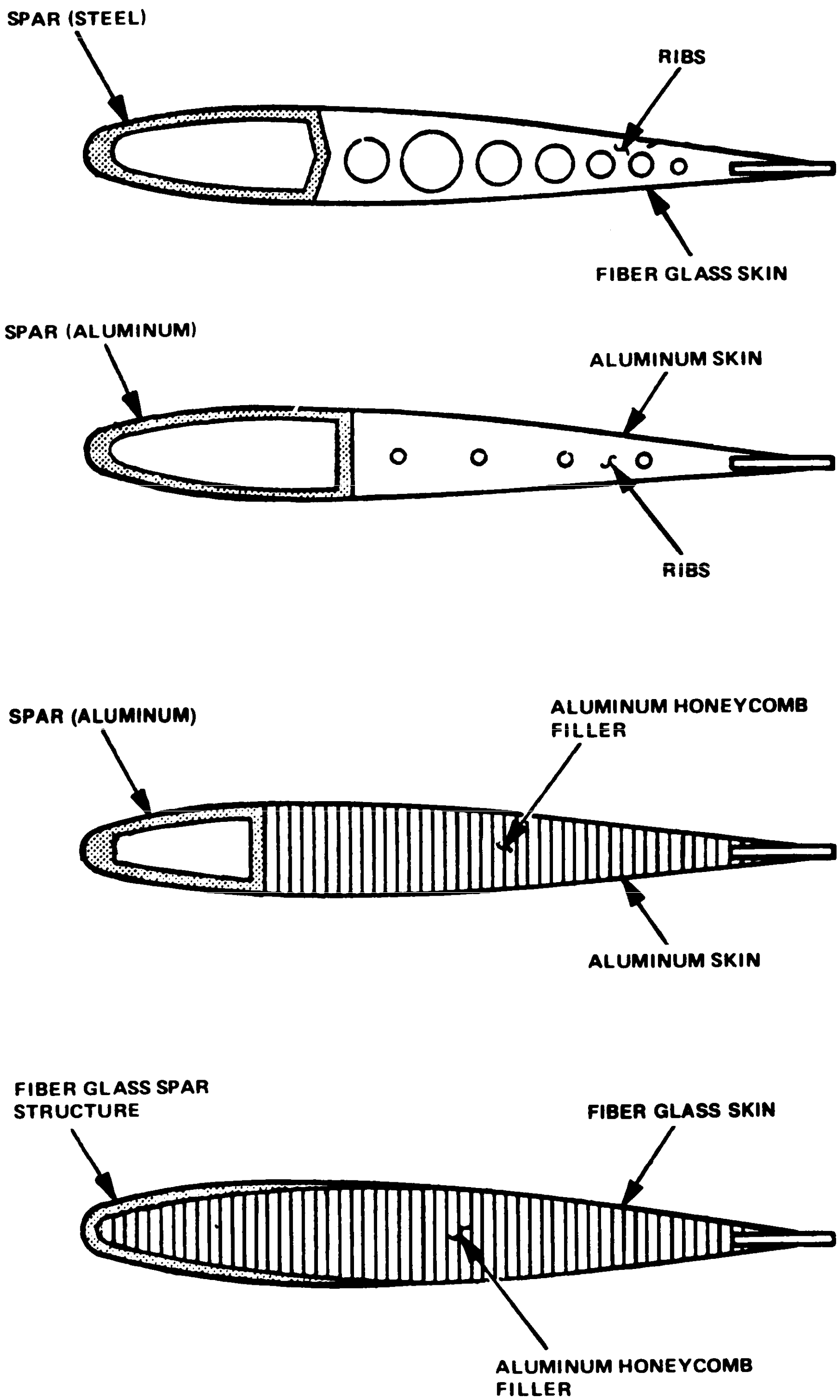

FIGURE 5-125. Major types of blade design.

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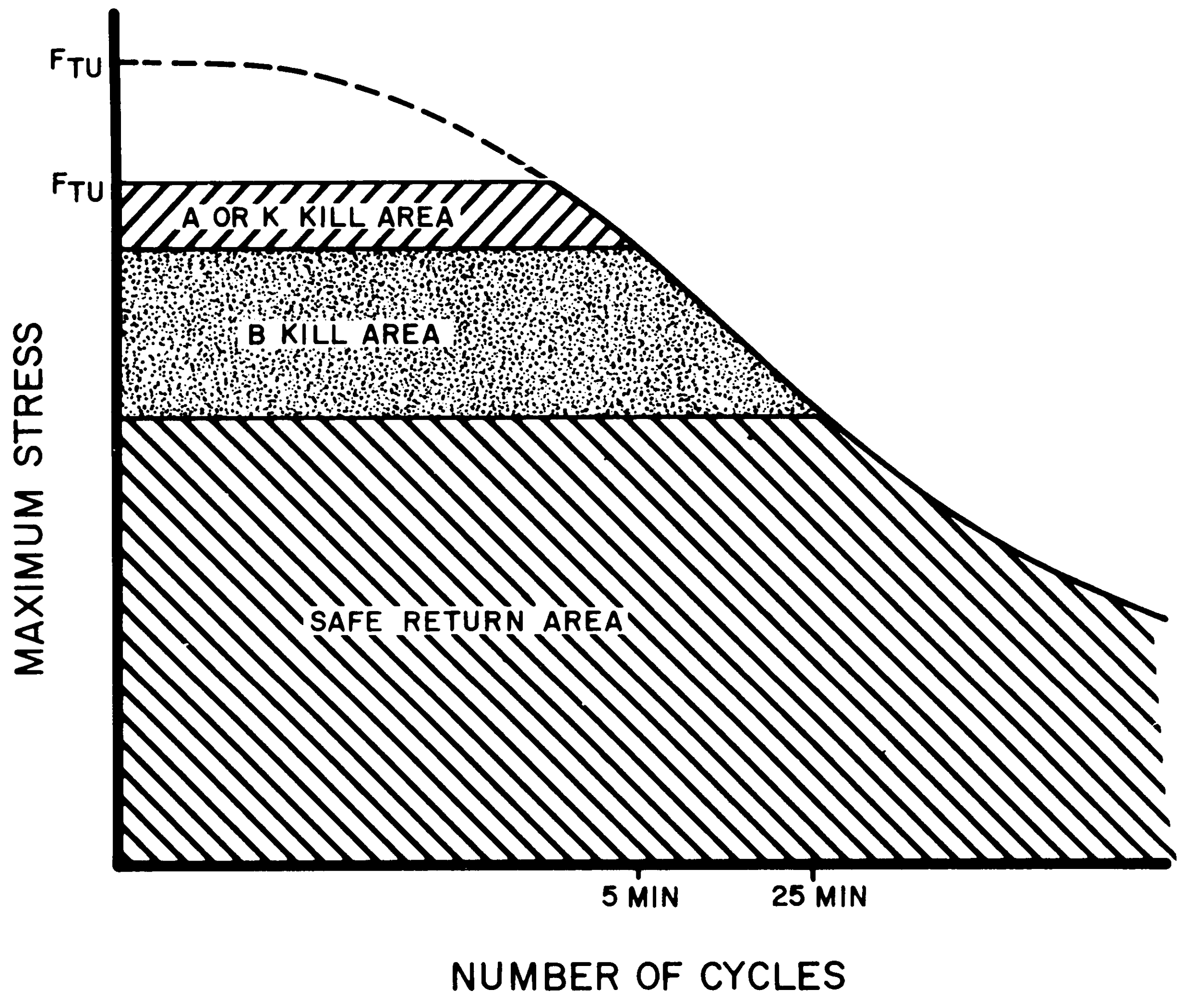

FIGURE 5-126. Typical rotor blade S/N curve.

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5.8.2.1 Load paths. The prime consideration in blade survivability is to keep the blade intact, that is, to prevent it from separating so that an outboard section is lost. As previously described, the unbalance effect due to the separation of a spanwise blade section could be catastrophic. The secondary aim is to maintain sufficient stiffness about the flap, chord, and pitch axes to prevent instability or excessive out-of-track. In order to achieve these two results, it is helpful to provide the blade with separated, survivable load paths as shown in figures 5-127 through 5-130. These load paths should run spanwise to carry the major centrifugal force, bending and torsional loads. They should be spaced chordwise so that a given hit will not eliminate enough of the load paths that blade separation will occur or that insufficient stiffness will remain. Also, their cross sections should be large enough to provide a good probability of surviving hits by fragments.

Analysis of rotor blades has shown that interlaminar shear forces developed at the blade root-hub interfaces may be critical in a survivable design. To compensate for these effects, the attachments should be highly redundant so that damage levels generated as a result of threat environments will be minimized. The development of adequately separated survivable load paths may be restricted because of the limited areas involved. Smaller site rotor configurations or restricted areas where bearings and control linkages attach are examples of this restriction. Where possible, these small area regions should be protected (i.e., shielding, armor, etc.) or an alternative method used. An example of a design concept is one that uses a “torsion pitch control” technique to minimize the vulnerability of a tail rotor system. Figure 5-131 illustrates its basic principles. A “torque tube” is bonded at its end to the interior of the rotor blade. A flexible collar is used to permit angular pitch adjustments by control linkage input that “twists” the torque tube. Considerable ballistic damage can be sustained by this type of construction without loss of operational capability. Complete loss of the rotor blade is virtually impossible because of the large areas of tube attachment to the blade and the inherent stability that would be present if the control linkage attachment were severed.

5.8.2.2 Withstanding direct hits from 23mm HEI-T projectiles. Considerable progress has been made to construct main helicopter blades with capability to withstand direct hits from 23mm HEI-T projectiles. Each have incorporated multiple load paths, and crack and rip stoppers to limit the extent of damage and amount of material removed. Examples of the type of damage experienced in conventional rotor blades from 23mm HEI-T projectiles are shown in Figures 5-132 and 5-133.

5.8.2.3 New design concept. Research into new design concepts have shown that all composite type material rotor blades can be constructed with excellent damage tolerance to nonexplosive and explosive threats. The basic design concept is the use of a geodesic truss structure box spar composed of many elements forming redundant gridwork covered with an aerodynamic skin. The principal advantages of this structure derive from its crack-insensitve nature and the fact that the structurally expendable skin tears out locally, allowing venting of the pressure wave generated by the detonation of the projectile. Figure 5-134 shows the structural concept basic elements. Figure 5-135 and 5-136 show the level of damage, sustained under test conditions, of the main rotor blade design concept

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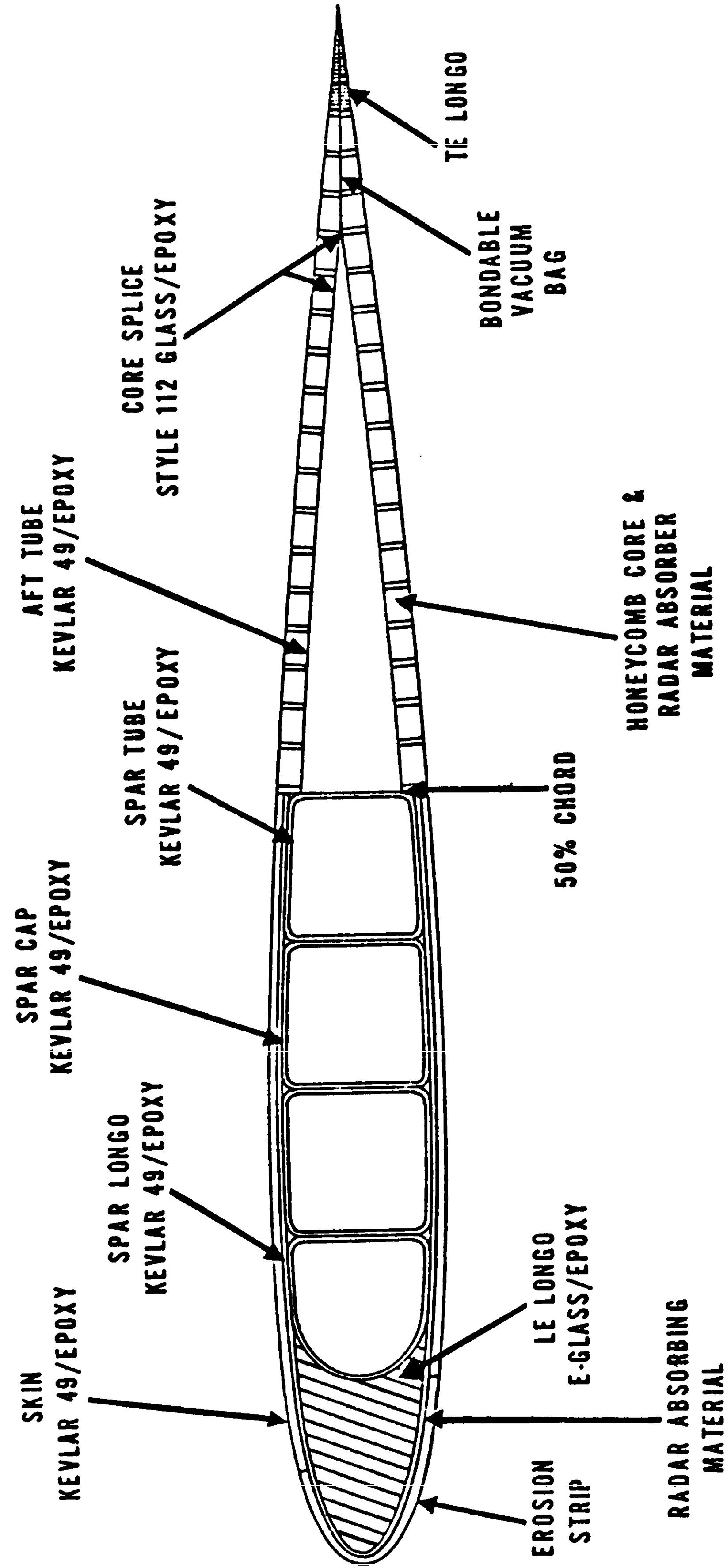

FIGURE 5-127. Helicopter 23mm HEI-T survivable multi-tubular spar(MTS) main rotor blade.

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FIGURE 5-128. Multi-tubular spar helicopter main rotor blade.

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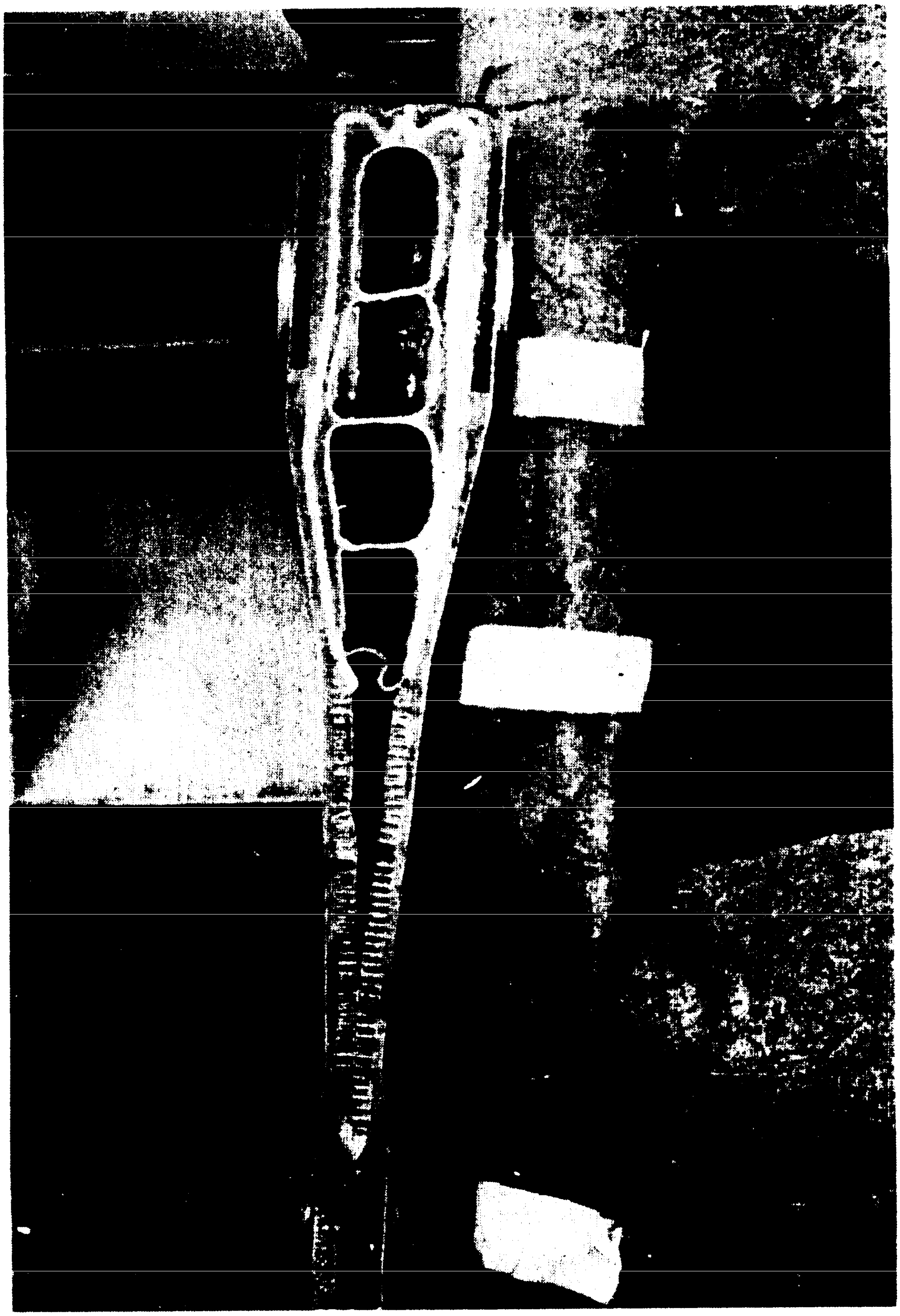

FIGURE 5-129. Multi-tubular spar helicopter main rotor blade.

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FIGURE 5-130. 23mm HEI-T survivable multi-tubular spar main rotor blade.

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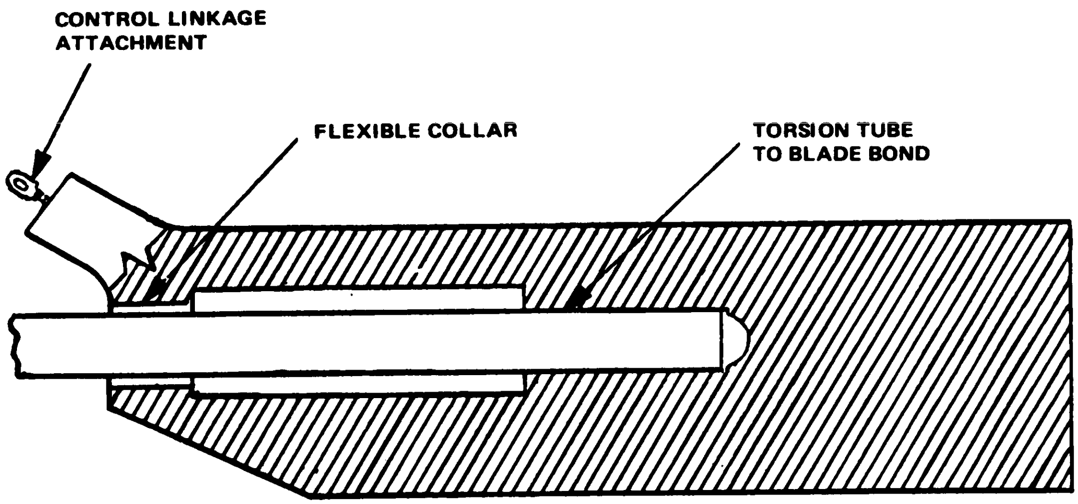

FIGURE 5-131. Torsion pitch control tail rotor concept.

impact by a 23mm HEI-T projectile. Figure 5-137 shows the maximum extent of damage sustained with a cross sectional view of the rotor blade and the detonation point of the projectile.

5.8.3 Rotor blade HEL protection. Main rotor blades have been found to be relatively tolerant to the levels and sizes of high energy laser weapon effects currently tested. Consideration should be made for the protection of rotor blade systems to the degree defined for each individual aircraft system. Protection may be incorporated into the basic blade design by selection of materials that will act as ablators, insulators, or reflective materials.

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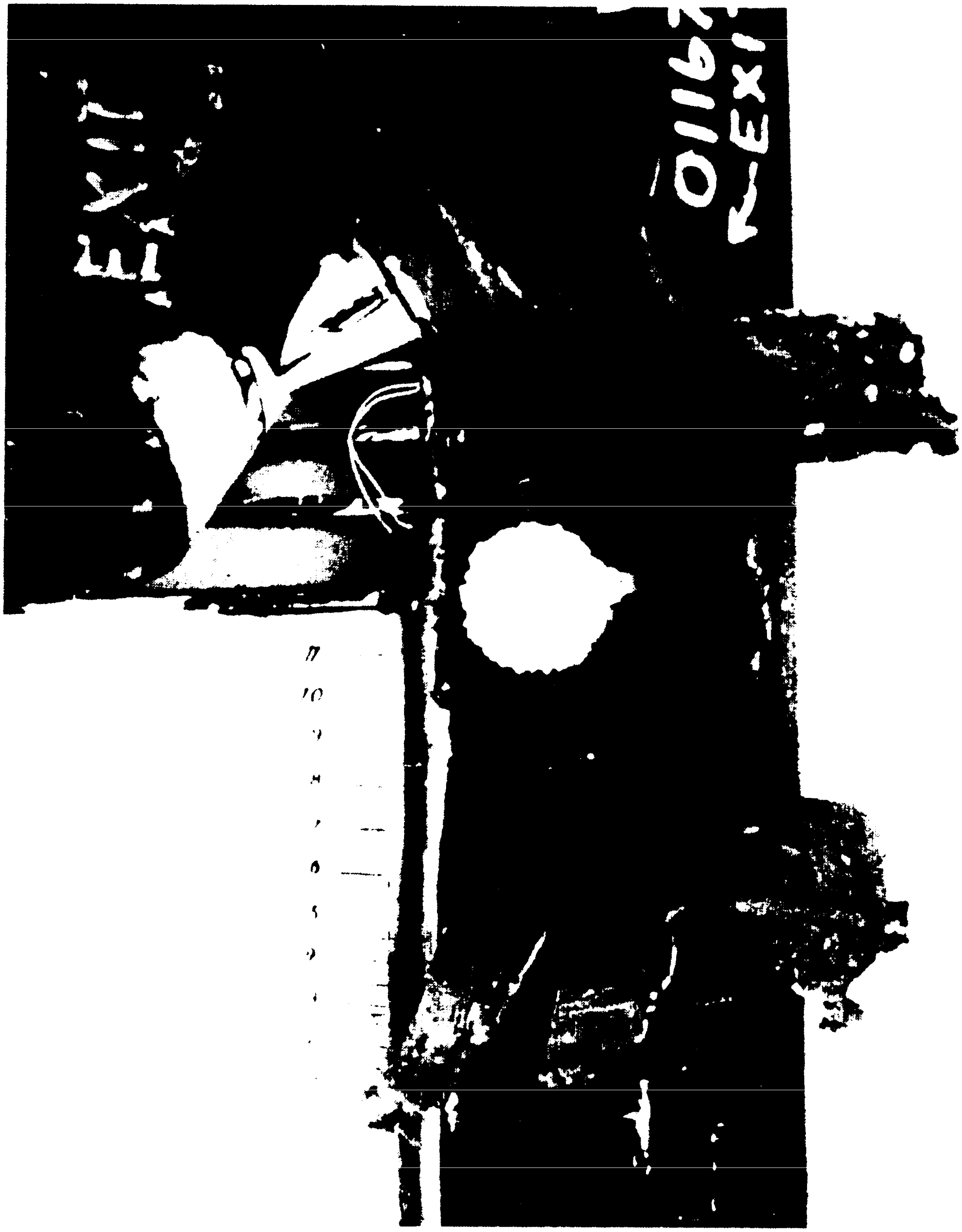

FIGURE 5-132. 23mm leading edge damage to helicopter main rotor blade.

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FIGURE 5-133. Attack helicopter main rotor blade damage from 23mm HEI-T projectile.

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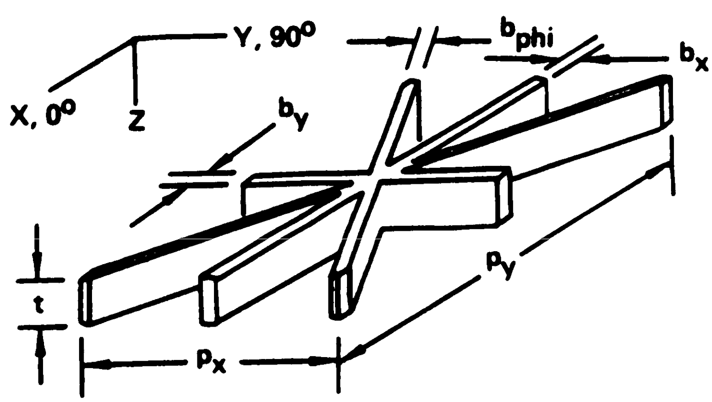
a) TYPICAL GRID PATTERN (SHORT DASHED LINES ENCLOSE TYPICAL CELL)



b) THREE-DIMENSIONAL VIEW OF TYPICAL CELL

FIGURE 5-134. Geodesic structural concept.

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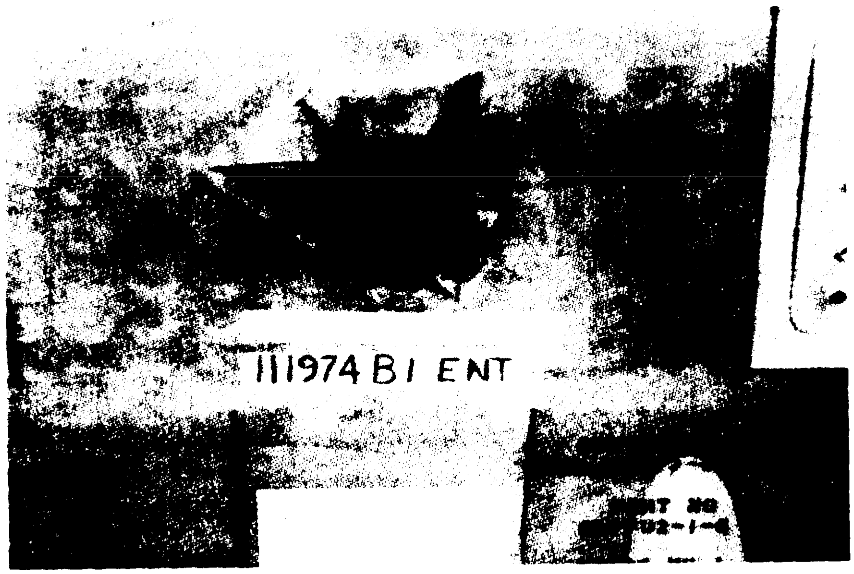

FIGURE 5-135. Rotor blade damaged at entry.

FIGURE 5-136. Rotor blade damaged at exit.

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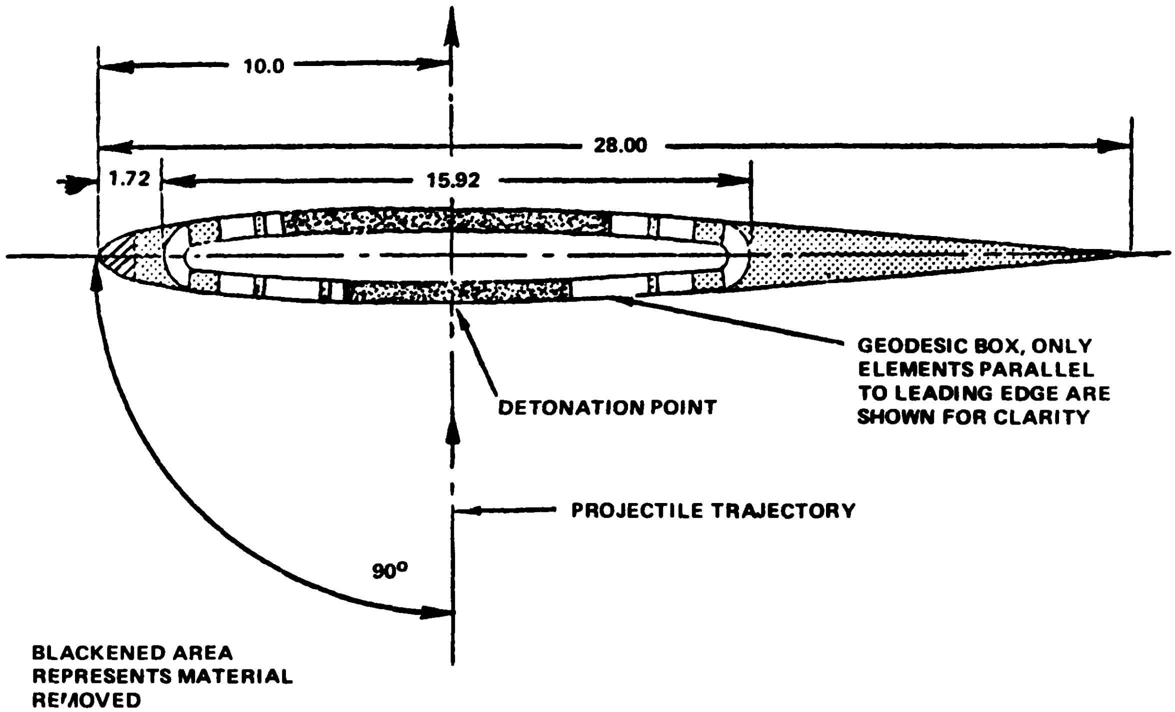

FIGURE 5-137. Ballistic damage to rotor blades.

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5.9 Flight controls.

5.9.1 Survivability enhancement guidelines. In this section, guidelines are presented for increasing the survivability of flight control systems to nonnuclear threats. The objective is presenting this material is to provide general suggestions for consideration during the aircraft design phase. Hence, the concepts are discussed in a general manner. The specific measures which can be successfully applied will depend, of course, on the particular aircraft and its combat mission. Many of the ideas presented are not original, but were obtained from existing reports; i.e, References 62, 73, 156, and 157, which were formulated from "common sense" considerations. The interested reader is referred to the aforementioned documents for further information. In general, there are three basic methods for improving survivability:

a. Reduce vulnerable area

b. Redundancy

c. Isolate damage effects

In the first method, a reduction of the vulnerable area of the system results in a reduction in the probability that the system will be damaged. The second method involves the practice of adding extra components to the system to provide alternate functional continuity for critical components. The basic concept of the third method is to contain damage effects, so that damage to one component will not propagate to disable the system.

5.9.1.1 Vulnerable area reduction. One of the most important methods for increasing survivability is to reduce the vulnerable area of the FCS. This method is effected on the component level in two ways: (1) the presented area can be reduced (miniaturization), or (2) the probability of damage given a hit (pal/h) can be reduced. Simplifying the system may reduce the system area. Component miniaturization increases survivability by reducing the physical size of the target presented to the enemy threat; i.e., a small target is more difficult to hit than a large target. An example of this method is the use of a fly-by-wire system to replace a mechanical signal transmission system. In addition to increased survivability, miniaturization usually also provides a side benefit of reduced weight. Thus, it is a good design practice to reduce the size of all FCS components as much as possible. Obviously, there are some limitations which need be observed in applying this method; for example, performance, maintainability, reliability, and manufacturability producibility should not be sacrificed solely for reduced size.

5.9.1.1.1 Reducing component $P_{d/h}$. There are several ways in which survivability can be enhanced through reducing component $P_{d/h}$. The simplest way is to add external armor plating to vulnerable components. However, this technique should be reserved for those components which cannot be improved by any other method because of the large weight and performance penalties incurred. A better way to armor components is to redesign them to use armor materials in the construction of the components themselves. This technique, referred to as integral armor, minimizes the extra weight added to the component. Reference

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103 discusses this method in more detail. In some cases, it is possible to reduce the $P_{d/h}$ of highly vulnerable components by positioning them within the aircraft to take advantage of the shielding offered by other components and aircraft structural members. This technique is often used to protect electronic components such as flight control computers and electrical system equipment. Damage probabilities can also be reduced by using ballistic damage tolerant components in the FCS. These components are specially designed to allow small threat projectiles to pass through them without causing critical damage. Some examples of this type of component are ballistic damage tolerant bellcranks and pushrods.

5.9.1.1.2 Combining Techniques. Applications utilizing combinations of these various techniques for reducing vulnerable area are also possible. One especially important example is the integrated actuator package (Reference 69). In this design, the flight control actuator and hydraulic power supply are combined into a single, compact unit. Survivability benefits are obtained from two sources. First, the maze of hydraulic lines connecting the actuator to the hydraulic power supply are eliminated, thereby reducing presented area. Second, because the hydraulic power supply is packaged with the actuator, it receives the benefit of shielding from the actuator, and the whole assembly can be protected with integral armor, significantly lowering the Pal/h for the entire unit. Integrated actuator packages (IAP) have also been developed, including two or more piston assemblies for redundancy purposes.

5.9.1.2 Redundancy. The major benefit of redundancy in a flight control system is that no one failure resulting from the effects of battle damage will cause loss of control system performance below the flying qualities needed to recover the aircraft and/or complete the mission objective. This technique is in concert with existing design requirements for safety and reliability of flight control systems as defined in Reference 220. The advantages of employing redundancy in a system, to replace a singly vulnerable component or subsystem with a multiply vulnerable arrangement, must be weighed against the increased complexity, weight, and costs. The most important consideration in using redundancy methods is the means employed to ensure that the redundant components and/or subsystems are sufficiently separated and mutually protected/ or shielded from each other so that the probability of simultaneous damage and failure from a single hostile weapon effect is kept below an acceptable value. The penalties for providing any integral or parasitic "masking" or armor must be included in the evaluation.

5.9.1.2.1 Complex Systems. For highly complex portions of a flight control system, such as "fly-by-wire" concept, the design implementation of providing redundancy can be difficult. A thorough analysis of the multiple combinations of combat damage effects must be evaluated in order to select the most effective system arrangement. The decision to use parallel, independent, or mixed signal circuits, failure detection, decision logic and shutdown logic must be carefully analyzed to identify the most acceptable arrangement for a specific air vehicle application.

5.9.1.2.2 Single to two component design. A simple example of the redundancy concept is the one already illustrated; namely, replacing a single

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component with a configuration consisting of two components of the same kind connected in parallel (i.e. , connected such that a malfunction of one component will not disable the other component). Examples of this type of application include using two sets of cables to transmit control signals from the stick to the actuators, or providing multiple sets of sensors for input to the augmentation systems. Another type of redundancy application, known as functional redundancy, consists of providing backup capability to a system, using a second functionally equivalent but physically different system. All backup flight control systems (BUFCS's) fall into this category. A specific example is the use of a fly-by-wire system to back up a mechanical control signal transmission system.

5.9.1.2.3 Analytic. Recently the concept of functional redundancy has been extended to two new areas - analytic redundancy and surface management. Both of these techniques were developed to maximize the redundancy benefits of systems already existing on aircraft; thus, weight penalties are not incurred. The first technique, analytic redundancy (Reference 160), utilizes a digital filter to increase the redundancy of the aircraft sensor complement, thereby increasing the survivability and reliability of the system. Alternatively, this concept can also be used to reduce the number of sensors required to meet survivability and reliability specifications, offering a savings in cost and weight. In addition, some indirect improvements in survivability may be possible through the use of analytic redundancy to automatically detect failures of other electronic equipment, a job presently delegated to the pilot.

5.9.1.2.4 Surface Management. Surface management is a functional redundancy technique in which the surviving control surfaces on an aircraft are reorganized to fly the aircraft following incapacitation of the primary FCS. That is, the aircraft FSC contains a hierachy of control laws consisting of a primary control mode, which utilizes all aerodynamic surfaces, and various reversion control modes, which utilize “flyable” subsets of the aerodynamic surfaces. The FCS is structured such that if any one aerodynamic surface on the aircraft is disabled thereby defeating the primary control mode, the aircraft can remain controllable by reverting to one of the remaining reversion modes. The principal advantage of this technique is that it provides additional redundancy to the FCS using aerodynamic surfaces which already exist on the aircraft. In all fairness, it should be pointed out that some weight penalties may be incurred with this technique due to the logic elements and extra control laws which must be added. Volume I of Reference 161 contains additional information on the mechanization of surface management concepts and a design example illustrating the application of surface management to the F-14.

5.9.1.3 Damage isolation. The third basic method for improving survivability is the use of mechanisms which contain damage. Although this method is generally not as effective as the other two methods, in some cases moderate improvements can be obtained.

5.9.1.3.1 Logic Element. Logic elements can be added to hydraulic systems to detect hydraulic fluid leaks and to isolate the damaged portion before sizable loss of fluid occurs. Fluid in other branches of the system is preserved, permitting the operation of actuators outside the damaged portion of the system. The two most common types of hydraulic logic elements are hydraulic fuses and reservoir level sensors.

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a. Hydraulic fuses, also known as flow difference sensors, operate on the principle that return flow varies in direct proportion to supply flow in a correctly functioning hydraulic system. A difference from the normal ratio between return flow and supply flow is detected as a leak, and that part of the system is disconnected from the rest of the system. Reference 168 contains the results of flight test evaluation of a flow difference sensor in an F-4E aircraft.

b. The reservoir level sensor is not really a leak detector, but, rather a monitor of fluid level in the reservoir. If a low fluid level is detected, the sensor can shut off nonessential hydraulic components, thereby conserving the remaining hydraulic fluid for flight essential actuators, or alternatively, it can activate a backup hydraulic system. A more complex arrangement might include return line pressure sensors in conjunction with the reservoir level sensor to determine which branch of the system contains the leak. This branch could then be disconnected from the rest of the system.

5.9.1.3.2 Rip Stop. Another technique that is used to isolate damage in flight control actuators is called rip-stop design. This concept is used to prevent failures in one chamber of a multiple-chambered actuator from spreading to the other chamber. To accomplish this objective, the individual chambers are machined from different pieces of metal, such that a crack starting in one chamber cannot propagate to the other chambers.

5.9.1.3.3 Physical separation. In some applications, increased survivability can also be obtained from physical separation of components. This method applies primarily to redundant components. In fact, lack of adequate separation between components can completely eliminate the benefits of redundancy. For example, an FCS containing two redundant hydraulic systems may have the same survivability as a configuration with only one hydraulic system if the redundant hydraulic lines are installed side by side. In this arrangement, a single projectile could disable both systems. Thus, in general whenever redundancy is used to improve survivability, care should be exercised to ensure that the redundant components are installed far enough apart that a single projectile cannot damage both components.

5.9.2 Flight control system concepts. Aircraft stability and control is one of the most critical factors affecting mission effectiveness and completion, and survival or recovery of the aircraft and/or crew. The faster the aircraft, the more critical and complex the FCS becomes. Consideration must be given to the specific hostile weapon effects (kill mechanisms) to which the aircraft will be exposed over the full range of its missions and threat deployment, to ensure that no control system survival weakness is ignored or overlooked. FCS's are divided into two major classifications - manual and automatic (Reference 240). Manual Flight Control Systems consist of electrical, mechanical and hydraulic components which transmit pilot control commands or generate and convey commands which augment pilot control commands, and thereby accomplish flight control functions. This classification includes the longitudinal, lateral-directional, lift, drag and variable geometry control systems. In addition, their associated augmentation, performance limiting and control devices

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are included. This classification includes the longitudinal, lateral-directional, lift, drag, and, variable geometry control systems. In addition, their associated augmentation and performance limiting and control devices are included. Automatic flight control systems (AFCS) are those combinations of electrical, mechanical, and hydraulic components which generate and transmit automatic control commands which provide pilot assistance through automatic or semi-automatic flight path control, or which automatically control airframe response to disturbances. This classification includes automatic pilots, stick or wheel steering, autothrottles, and structural mode control. Rapid advancements are being made in this field by various Government and industrial activities. Consult the JTCG/AS Directory of Aircraft Survivability Specialists and Their Affiliations for referral to specific authorities or individual flight control survivability enhancement techniques for fixed-or rotary-wing aircraft. Considerable advancement in protection of control systems against ballistic damage has been made in recent years. The basic principles of current techniques are presented in this section to give the designer the greatest possible selection of options that can be applied to his specific configuration. One of the most sensitive factors is the weight penalties that may be imposed for improved survivability for both initial design and operational aircraft retrofits. For existing designs, such weight increases degrade the performance and capability of the system. For new designs, increased system weight and costs are experienced. These factors must receive primary consideration in the selection of flight control survivability features. Figure 5-138 illustrates the relationship of relative weight to vulnerability for an existing rotary-wing FCS, with regard to fly-by-wire (FBW) concepts, ballistic tolerance concepts, and

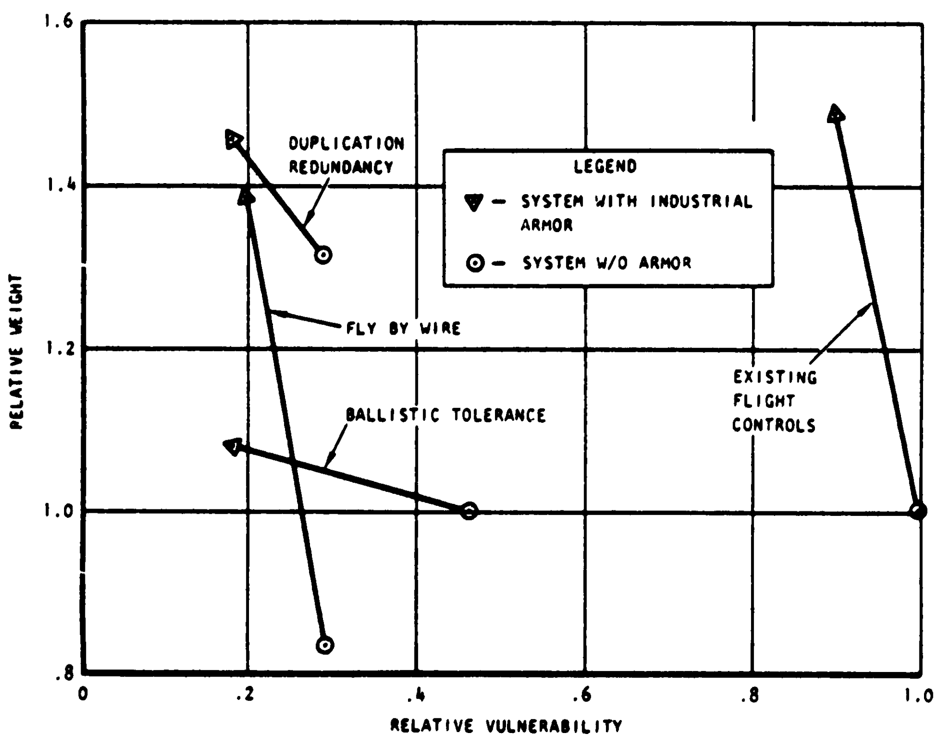

FIGURE 5-138. Relative weight versus relative vulnerability of an existing helicopter flight control system.

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duplication/redundancy concepts, with and without armor protection. Such factors for new designs must be considered early in the design concept process in order to avoid unnecessary penalties and/or redesign efforts. Continuing advancements are being made in this discipline to develop even more effective survivability techniques.

5.9.2.1 Hostile damage effects. Consideration of the potential hostile weapon damage mechanisms must be made during the initial design of an aircraft system. This will assist the configuration and FCS designers in their selection of the FCS type and location of the components within the airframe. For nonnuclear ballistic weapons, the primary damage mechanisms are impact and penetration by nonexplosive projectiles or fragments, internal and external high-explosive blast effects, and incendiary material activation. The primary damage effects from hostile high-energy laser weapons are burn-through and/or high-temperature heating of control system components or elements. Secondary damage mechanisms may also be generated by ballistic" or HEL primary weapon effects. These include spallation, fires and explosions, airframe structure distortion or damage, liberation of corrosive materials or hot gases, etc. These primary and secondary damage mechanisms may have the capability to cause failure or degradation of FCS functions by severing, shattering, or jamming of mechanical linkages or components such as those shown in figures 5-139 through 5-141. Material damage to electrical and/or hydraulic power connections to FCS components which are required for system operation may occur. High thermal conditions may cause material loss of strength, leading to failure or malfunction of the system element.

5.9.2.2 System design. Control systems are designed to activate aerodynamic surfaces by using a combination of basic system concepts. The power and response requirements for the flying qualities of the aircraft dictate to a great degree the complexity needed. While complying with the requirements for designing the total system, consideration must be given to the options available to minimize vulnerability to hostile weapon effects. The basic system elements are; (1) technical linkage, (2) boosted power system, and (3) full-power system. A mechanical linkage (non-powered) system may be used by itself or in combination with a powered system, and is the arrangement conventionally used. Newer concepts may use FBW techniques to replace the mechanical linkages. The advantages and disadvantages of each must be carefully examined in regard to system survivability and operational use of the aircraft to insure that most effective system design is obtained.

5.9.3 Emergency backup flight control systems. In the preliminary design process, consideration should be given to the incorporation of emergency backup control concepts, in the nonpowered section, that would permit safe escape from the combat area and possible recovery of the aircraft, after experiencing primary control failure or malfunction. The basic criteria for such backup systems must be based on minimum control flying qualities for the specific aircraft system. The design of minimum authority controls requires retention of the fundamental flying characteristics which allow a pilot to perform the necessary survival maneuvers without excessive workload.

5.9.3.1 Concepts. The requirement that the aircraft be statically stable in all flight modes is mandatory for an emergency backup system. A physical

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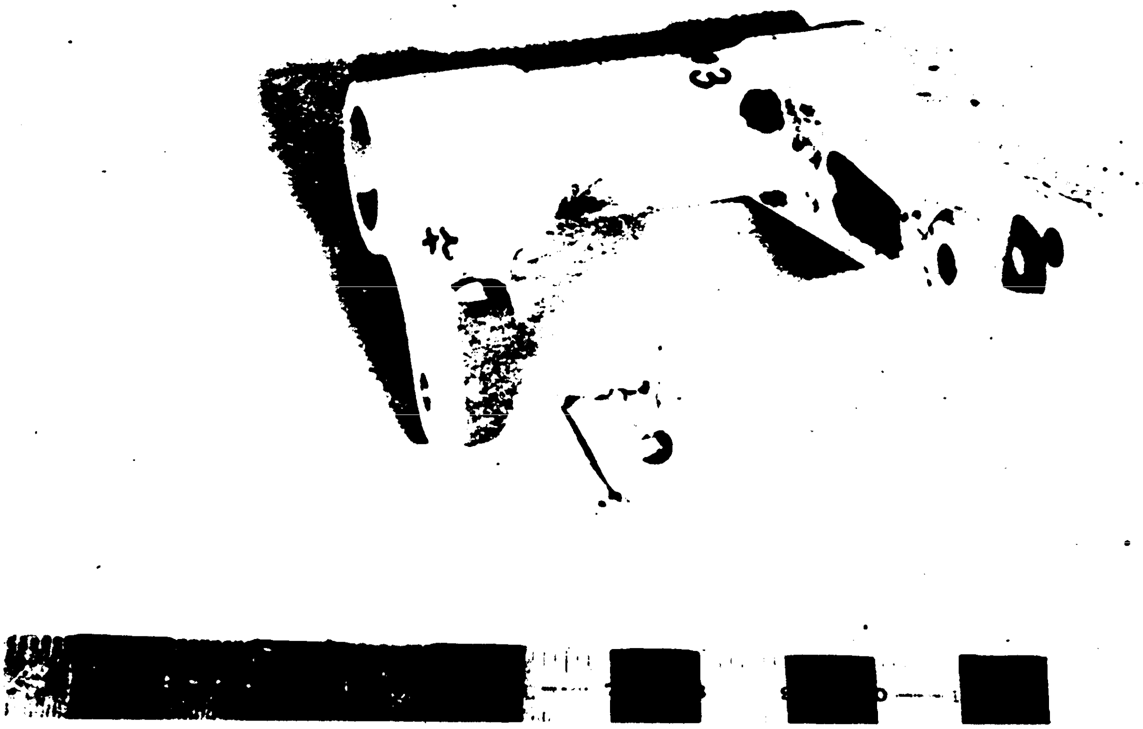

FIGURE 5-139. Damaged bellcrank.

FIGURE 5-140. Flight control linkage.

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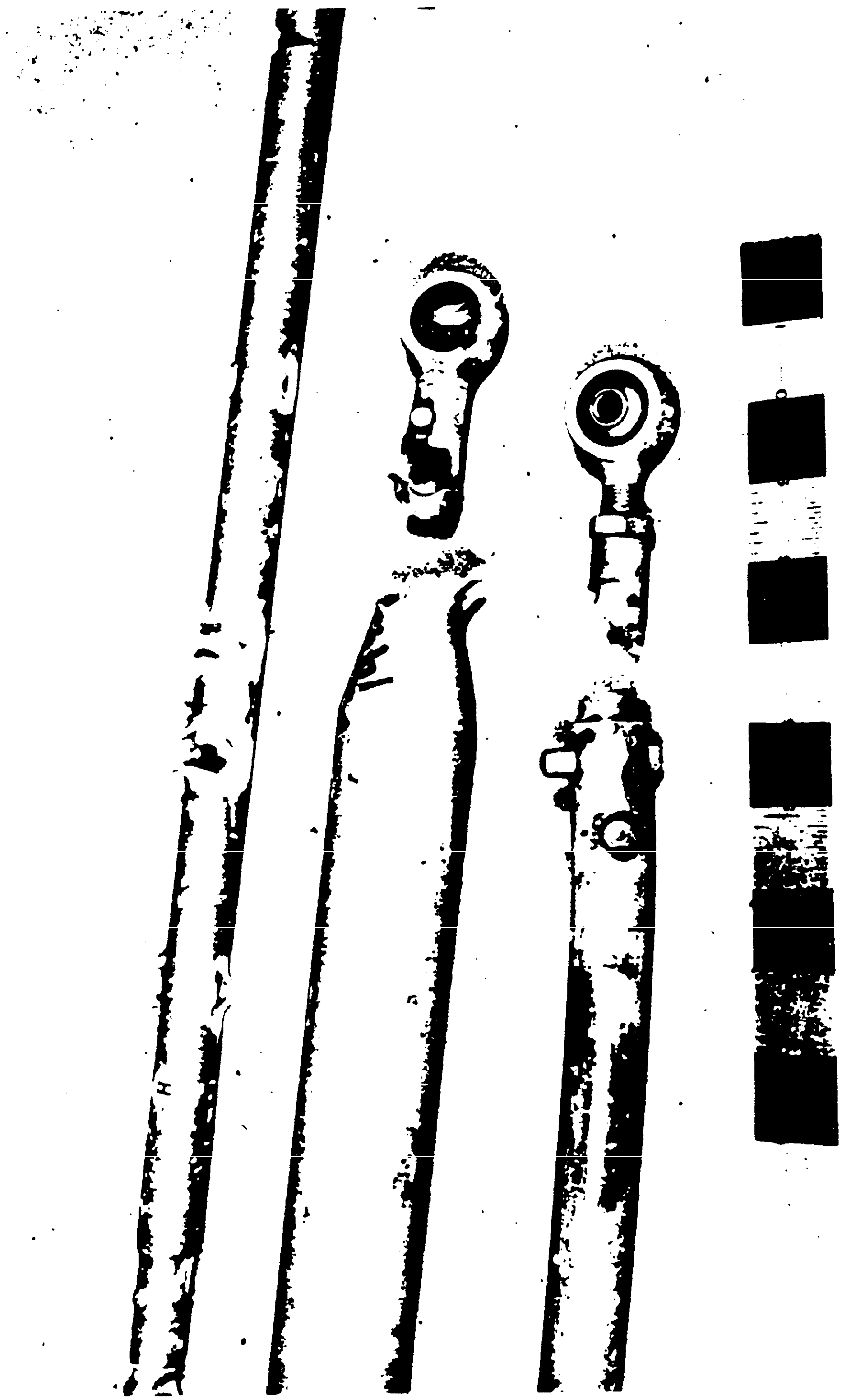

FIGURE 5-141. Control rods.

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interpretation of static stability concerns the relative location of the aircraft center of gravity with the lift neutral points. Static stability is assured if the center of gravity remains forward of the neutral point. Aircraft may be designed statically unstable, with control augmentation restoring stability. This implies that the backup system must provide stability augmentation in addition to basic control power necessary for survivability. There must be no pilot-induced oscillation (PIO) tendencies. Limited authority control systems are more prone to this problem. Major influencing factors causing PIO are reduced authority and rate, particularly rate, causing system lags to pilot inputs (Reference 62). The MIL-F-8785 (Reference 220) handling quality classifications for backup flight controls of a class IV aircraft are shown in Table 5-XXXII. A number of backup systems have been studied, developed, and tested in fixed-wing aircraft. These have varied, from a simple stabilator lock that positions the longitudinal control surface in a fixed position, to FBW that retains full control authority. Power for backup systems may be obtained through use of electrical energy, engine bleed air, mechanical energy, propellants, and pilot effort. Some of the future backup systems may utilize:

a. Exhaust vanes - System employing engine exhaust deflector vanes actuated by separate control signals.

b. Canard control - System employing canard control surfaces actuated by emergency power sources and control signals.

TABLE 5-XXXII. <u>Handling quality classification for backup flight controls</u>.

Specification	Description
Aircraft, class IV	High-maneuverability aircraft such as: Fighter-interceptor Attack Tactical reconnaissance Observation Trainer
Flight phase Category B	Nonterminal flight phases normally accomplished using gradual maneuvers, without precision tracking, although accurate flight path control may be required.
Category C	Terminal flight phases normally accomplished using gradual maneuvers, and usually requiring accurate flight path control.
Flying quality, level 3	Aircraft can be controlled safely, but pilot workload is excessive, mission effectiveness is inadequate, or both. Categories B and C can be completed.

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C. Variable deflector thrust - System that uses a variable-angle bidirectional jet flap that produces lift and thrust when located at the trailing edge of an airfoil. The jet thrust and deflection angles may be controlled by varying the pressure levels in the plenums preceding and jet exit slots.

5.9.3.2 Backup flight control specifications. The basic specifications for these flying qualities are contained in Reference 220.

5.9.4 Examples of suvivable control components.

5.9.4.1 Mechanical systems components. Mechanical components and linkage have been used in flight control systems since the beginning of manned flight. Their function is to transmit a signal or force in a system that is required to position a control surface or other related mechanisms in response to commands from the aircrew or automatic control system units. A "pure" mechanical control system is one that consists entirely of mechanical components from the pilot control input to the control surface. Mechanical linkages can be and are used as part of boosted or full power control systems. Even in "fly-by-wire" systems, the powered output of the actuation system may use mechanical linkages or components to position control surfaces. This section, therefore, is concerned with the survivability enhancement methods that should be considered for the mechanical elements of any type flight control system. System elements may consist of pilot control sticks, cables, pulleys, sectors, bellcranks, push-pull rods, torque tubes, lever arms, gears, etc. For the general arrangement of mechanical linkages, the following survivability techniques shall be considered:

Duality of mechanical linkage systems is required by Reference 240 for aircraft that may be exposed to conventional weapons. Separation of such redundant linkages should be accomplished to a practical degree that will provide mutual masking by intervening structure and equipment. The separation and masking shall consider the ballistic damage potential for the size type, and directions of fire of enemy weapon systems that may be encountered.

Consider methods to permit full FCS operation through one redundant path of such systems where the other path has been severed or jammed due to nonuclear weapon effects. A design concept to provide protection against dual mechanical linkage opening or jamming in one of the redundant paths of a powered control system is described in Reference 72. While the example is for a fixed wing aircraft, the basic principles are applicable to rotary-wing control systems as well. It utilizes two design features. One is a dual hydraulic control valve arrangement on an actuator that permits operation of either control valve independently of the other and bypasses the jammed system to permit free operation of its piston. In the event of a severed control linkage, normal operation of both valves may be obtained to the extent of the available travel in the severed linkage. When restricted travel is encountered, the override of the restricted valve would be realized. One technique for protection of a jam in one side of a redundant mechanical linkage is the use of spring preloaded antijam capsules that will disengage under moderate pilot effort. The minimum and maximum allowable control forces for successful pilot control of an aircraft under emergency conditions must be established for the individual system. Other factors to be considered are:

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a. Where a pilot and copilot have dual mechanical control systems, consider the use of a design concept to permit simple disengagement of the control interconnect in the event one may become jammed from hostile weapon effects. Consider the use of hybrid mechanical control and FBW system that may be operated independent of the other if one system is damaged and jammed (Reference 136).

b. Push-pull control rod concepts with damage-tolerant design features are considered to be more survivable to nonnuclear weapon effects than conventional cable systems. Either system should be routed as closely as practical to heavy primary structure elements, within the limitations of Reference 240, to obtain inherent masking protection and to minimize the probability of failure or malfunction of attachments and fairleads from structural distortion or damage.

c. For push-pull rod systems, consider the effect of ballistic threats on short- and long-rod concepts. Long push-pull rods can be susceptible to jamming if structure deformation or adjacent component damage is encountered. In such areas, consider the use of short-length push-pull rods with swing-arm bellcranks (idler links) as shown in Figure 5-142.

d. Provide frangible or pull-away fairleads to prevent system jamming due to a nicked cable or damaged push-pull rod. (See Figure 5-143 for an example of each fairlead type.) Exercise care in design to ensure that failure or displacement of such fairleads, because of damaged and jamming control cables or rods, improper maintenance methods, or material failures, will not cause other control system malfunctions or flight safety hazards.

e. Use self-aligning bearings for torque tubes to prevent, or minimize, the possibility of jamming due to deformation of torque tube or supporting structure from weapon effects.

5.9.4.1.1 Ballistic damage-tolerant control system linkages. The detail design of mechanical control system elements is vitally important for survivability. One of the most recent and important techniques developed is that of ballistic damage-tolerant control system linkages. This concept is somewhat contrary to established methods of degrading the effect of weapon effects damage. It is an approach to design components with multiple loadpaths to accept multiple hits, yet remain functional so that control system will permit continued safe flight. Low-density nonmetallic composite materials that allow projectiles to core out material with minimum structural damage can be used for construction. This concept minimizes the amount of kinetic energy that the projectile can impart to the component, and localizes the damage. A number of experimental control system components such as bellcranks, idler links, pulleys, and tension-compression links have been developed to reduce the vulnerability. Descriptions of these and recently developed concepts are presented to acquaint the designer with the techniques that may be applied or modified to suit his particular design efforts. Consult Reference 62 through 67 for additional ballistic damage-tolerance flight control component designs.

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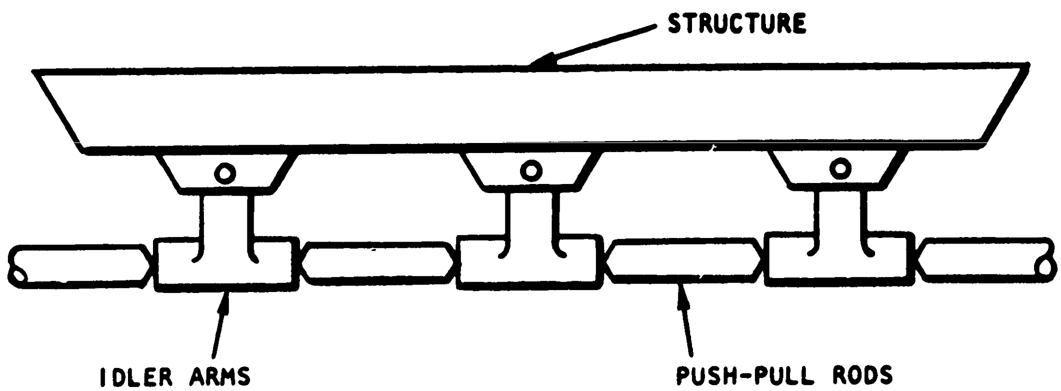

FIGURE 5-142. Short length push-pull rod installation.

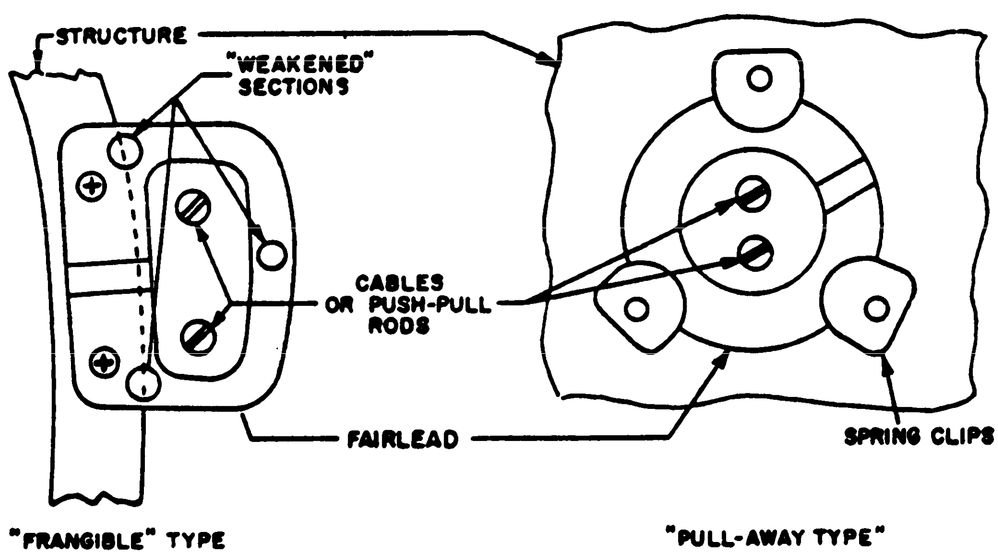

FIGURE 5-143. Frangible and pull-away fairheads.

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5.9.4.1.2 Tri-pivot concept. Redundancy can be incorporated in the normally critical bellcranks and rod end attachments by development of a unique tri-pivot concept, shown schematically in Figure 5-144 (refer to Reference 79). This concept permits a larger diameter rod at the rod end attachment, providing increased ballistic tolerance. Any single pivot and, for some cases, two pivots may be damaged without suffering functional loss of the bellcrank.

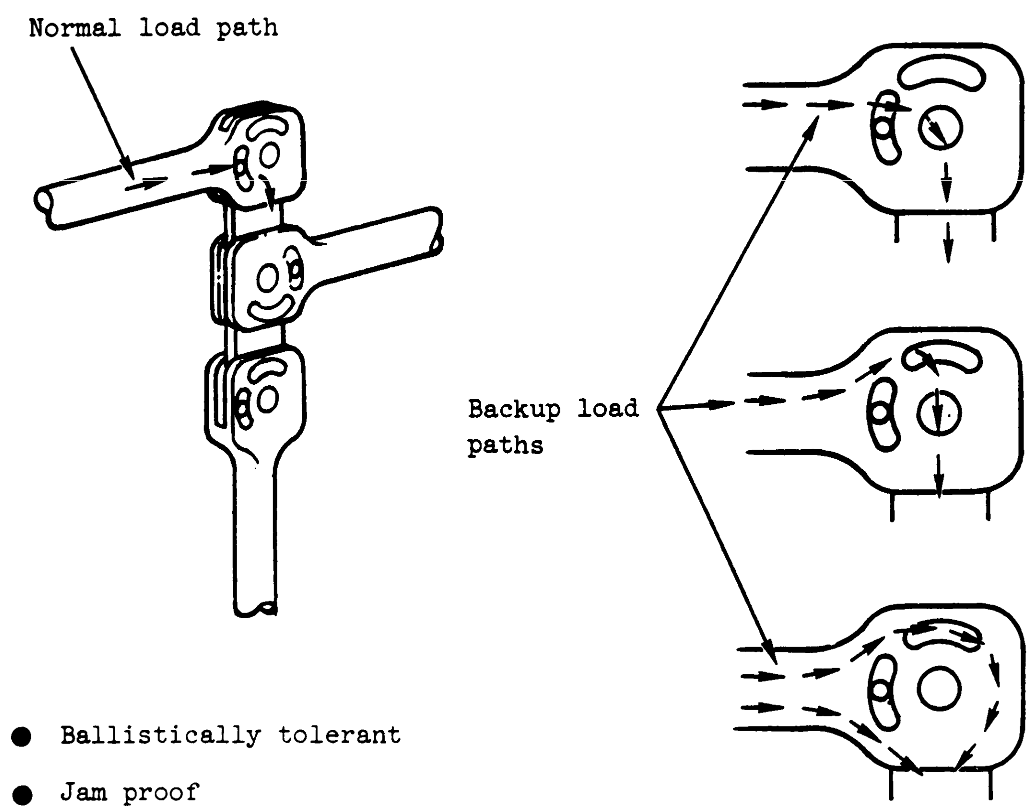

FIGURE 5-144. Redundant tri-pivot control rod end attachment.

5.9.4.1.3 Additional concept.

a. Figure 5-145 illustrates the basic construction of a fiber glass-foam core ball, socket, and support design that was developed for ballistic tolerance. It is fabricated from epoxy resin, chopped glass fibers bearing support, and surface layers of fiber glass. Figure 5-146 is a photograph of a test component that has been damaged by two projectiles. The component was able to sustain damage that would have destroyed conventional types of bellcranks, and it was still capable of performing its function.

b. Figure 5-147 shows the original rotor head pitch link for a helicopter and illustrates its vulnerability to small-arms fire. A ballistic damage-tolerant experimental replacement pitch link was designed and

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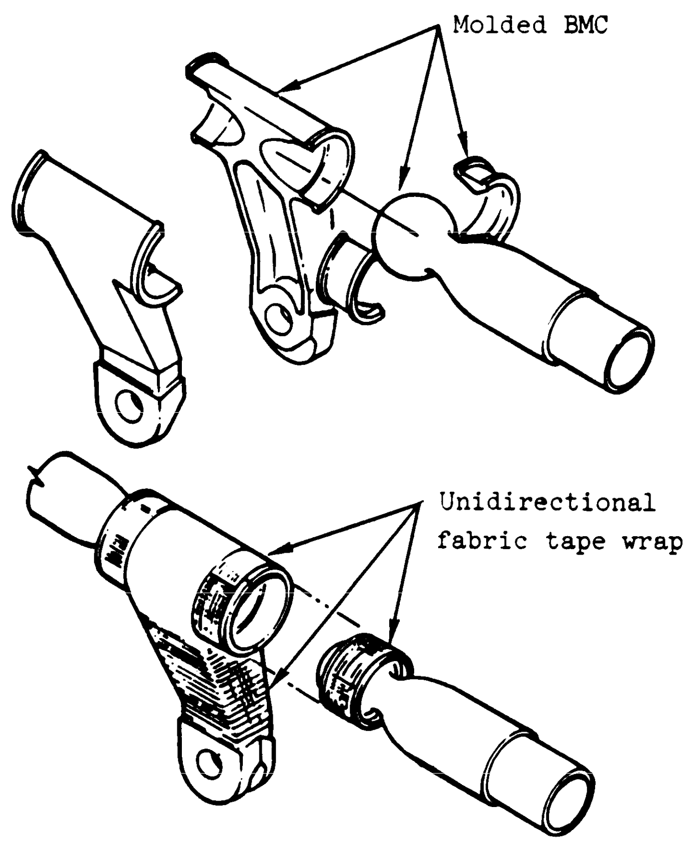

FIGURE 5-145. Development idler link construction (Fiber glass bulk-molded ball, socket, and support fiberglass wrapped).

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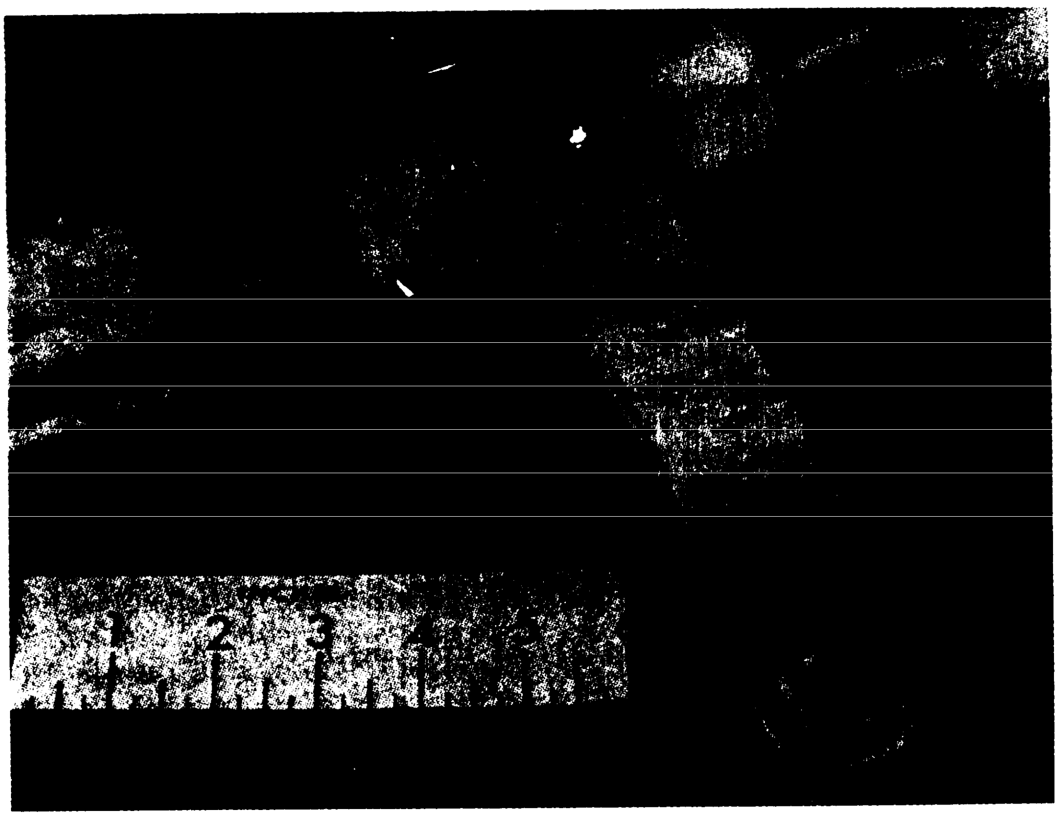

FIGURE 5-146. Idler link test component damaged by two projectiles.

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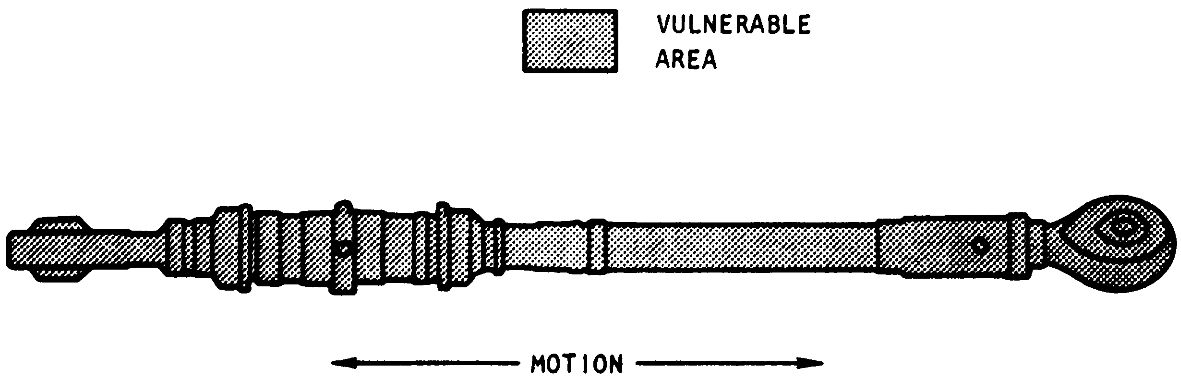

FIGURE 5-147. Vulnerability of existing pitch link

fabricated from glass cloth and epoxy resins. This link is about 25 percent as vulnerable as the original rotor head pitch link, and that only around the bearing areas. It was subject to multiple projectile hits as shown in Figure 5-148. The link was still capable of performing its design function with a limited reduction in total strength (Reference 137).

c. Extensive research and development effort has been expended to develop ballistic-tolerant components for the applications shown in Figure 5-149 and 5-150. Many different approaches and configurations have been fabricated and tested, including sheet metal buildup and several glass/epoxy concepts. The latter have been found to provide the most beneficial design concepts to limit damage.

d. Figure 5-151 shows a three-dimensional experimental space structure bellcrank concept using woven-glass fibers with an epoxy covering known as Tetra-Core. This type of construction is shown in Figure 5-152. Subsequent efforts have developed design concepts using hollow fiber glass tubing and face sheets for bellcrank designs. Figure 5-153 illustrates the basic principles of this construction. Ballistic tests have indicated that it is most tolerant to ballistic impacts, since there is no low-density filler material, as in honeycomb or foam designs, that tend to force delamination of the face sheets on the exit side of the penetrators path.

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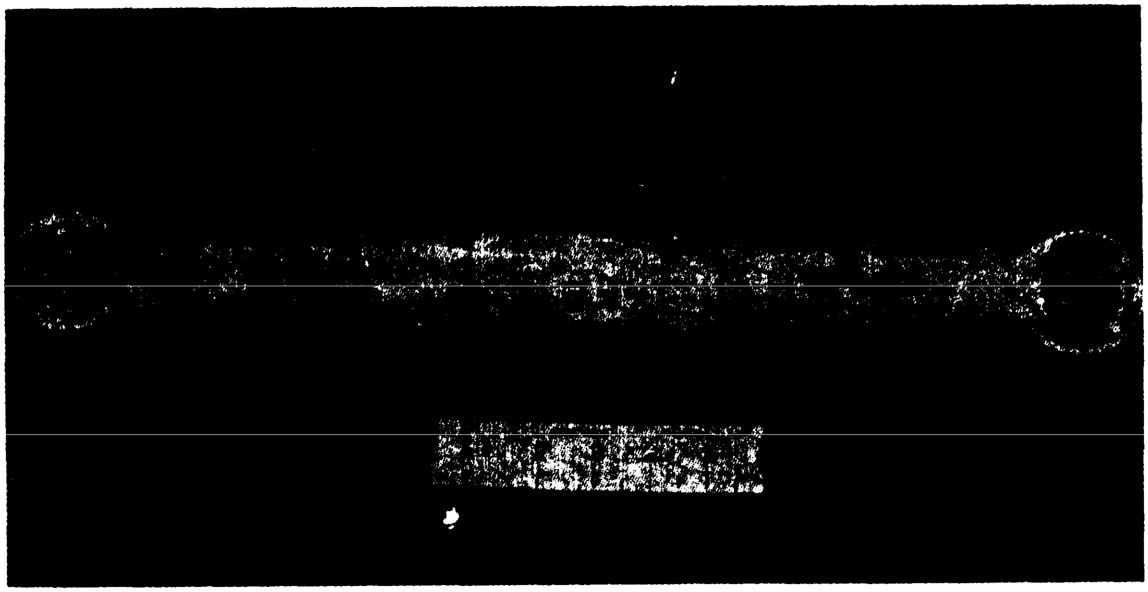

FIGURE 5-148. Ballistic damage-tolerant experimental pitch link.

e. Ballistic-tolerant control bellcranks, push-pull rods-sectors, and ball rod ends have been fabricated from epoxy, resin filled with chopped glass fibers. References 63 and 64 are design guides for these types of components. References 65, 137 and 167 contain design and manufacturing guidelines for their fabrication, such as those components shown in Figures 5-154 and 5-155.

f. Use heat resistant materials and designs for mechanical control elements where fires or hot-gas torching could occur due to hostile weapon effects. This will prevent, or delay, loss of FCS function when high-temperature conditions exist in the area of the control element. For example, steel should be used for brackets, torque tubes, bellcranks, etc, instead of slightly lighter, but more vulnerable, aluminum or magnesium construction.

g. Where duplicate cable or push rod systems are provided, separate these systems as far as possible to obtain the maximum advantage of the duplicate system with regard to nonnuclear weapon effects. Where possible, parallel systems should be on opposite sides of the fuselage, opposite sides of the wing spar, or similarly separated.

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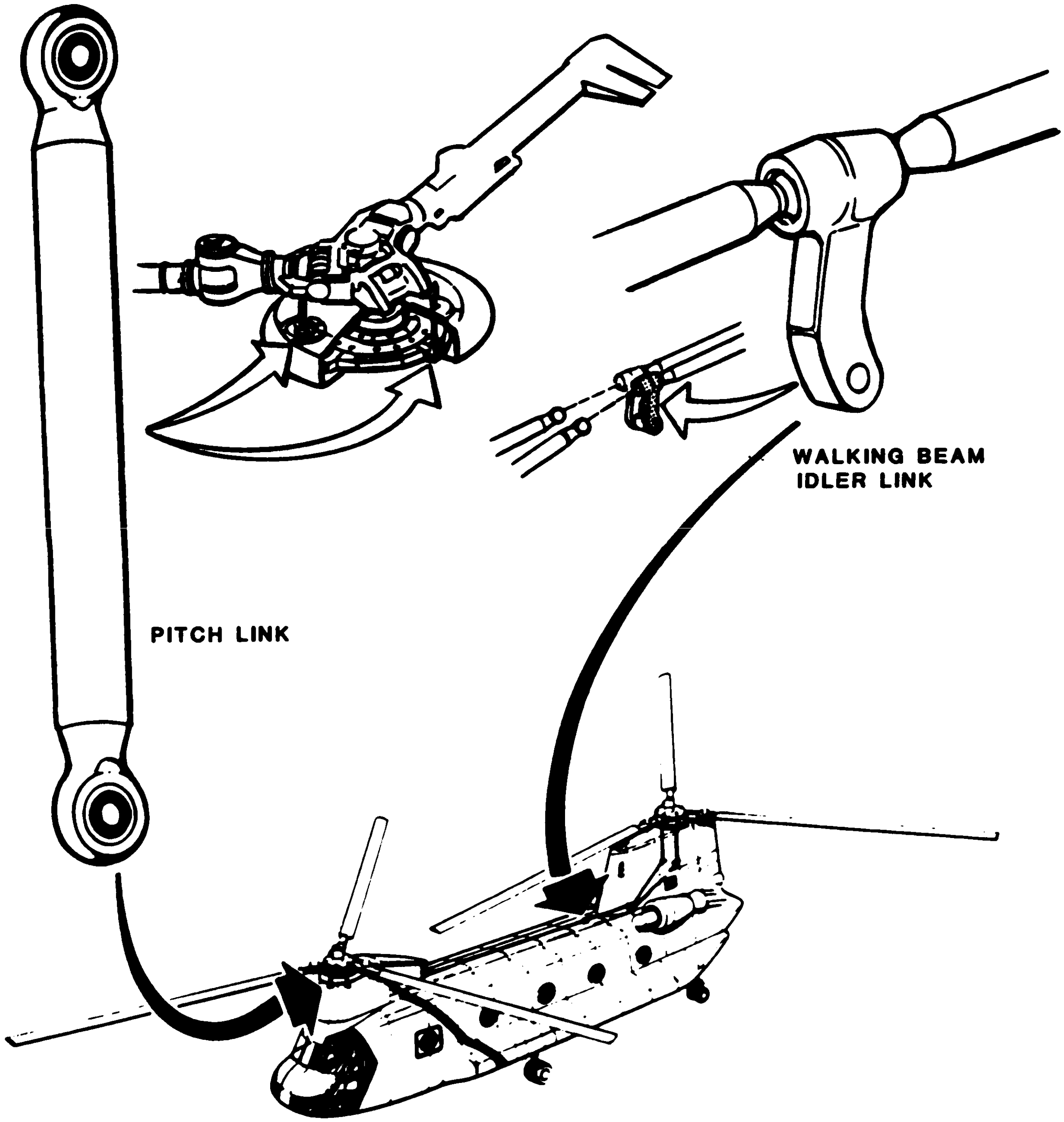

FIGURE 5-149. Ballistic damage-tolerant experimental replacement flight control components.

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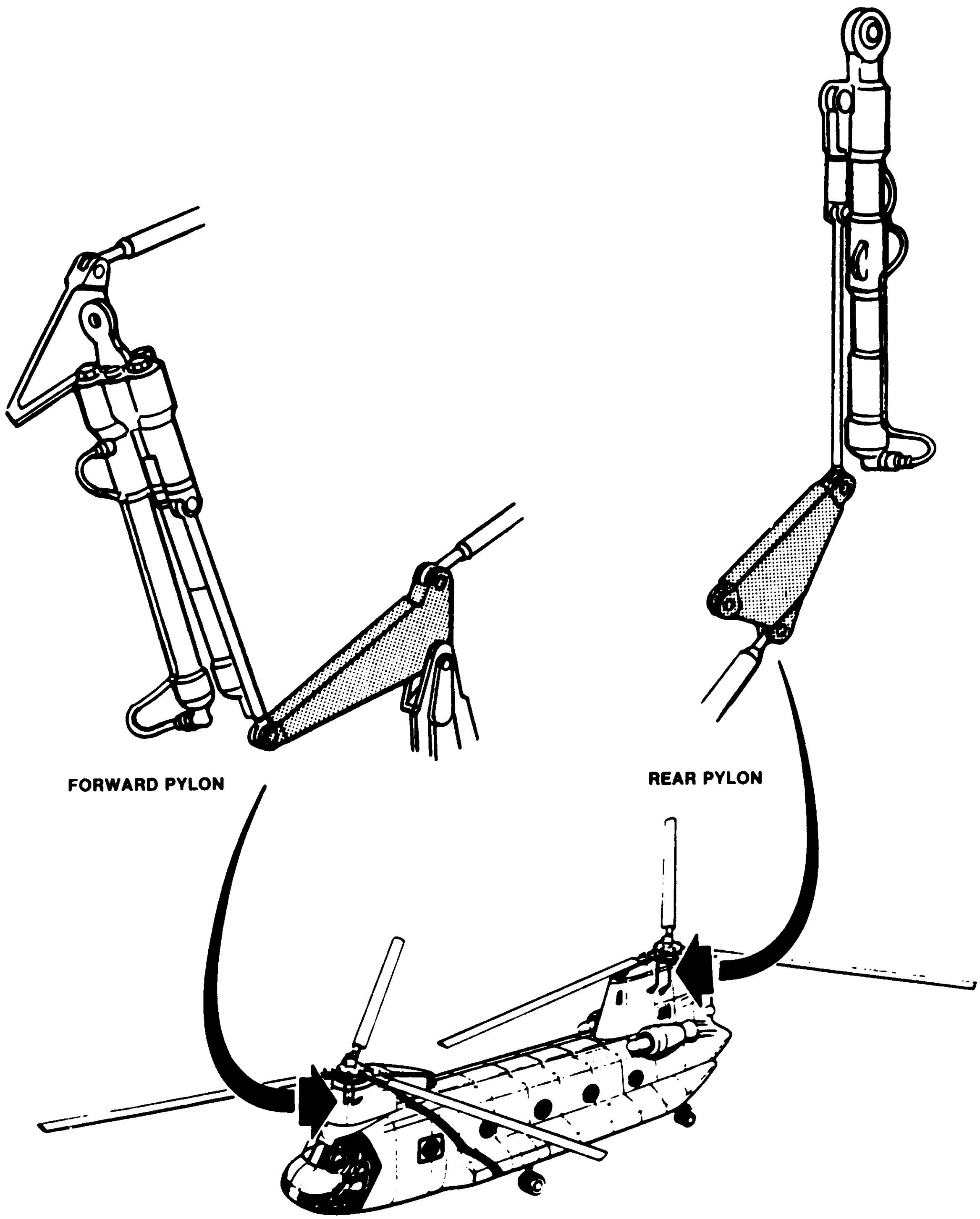

FIGURE 5-150. Ballistic damage-tolerant bellcranks.

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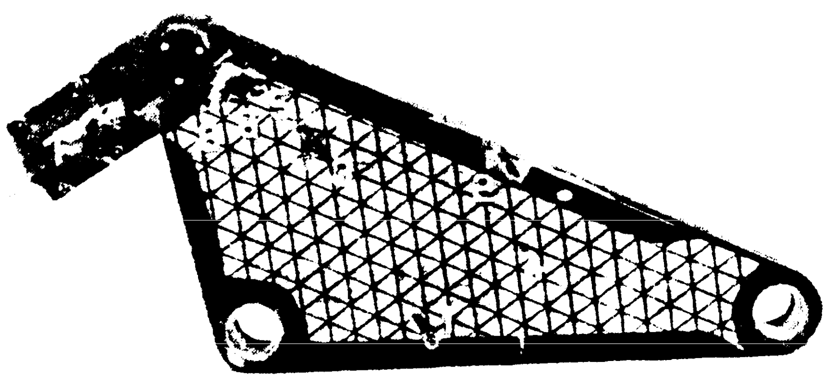

FIGURE 5-151. Tetra-core space structure bellcrank.

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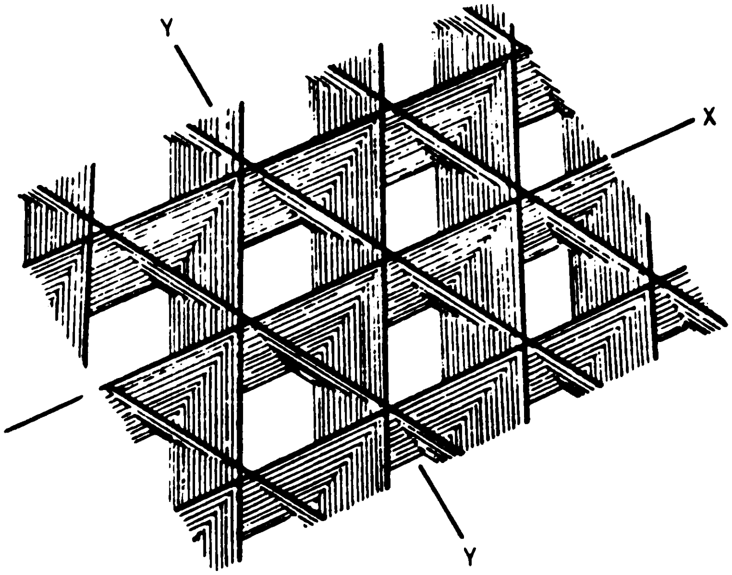

FIGURE 5-152. Basic "Tetra-core" element.

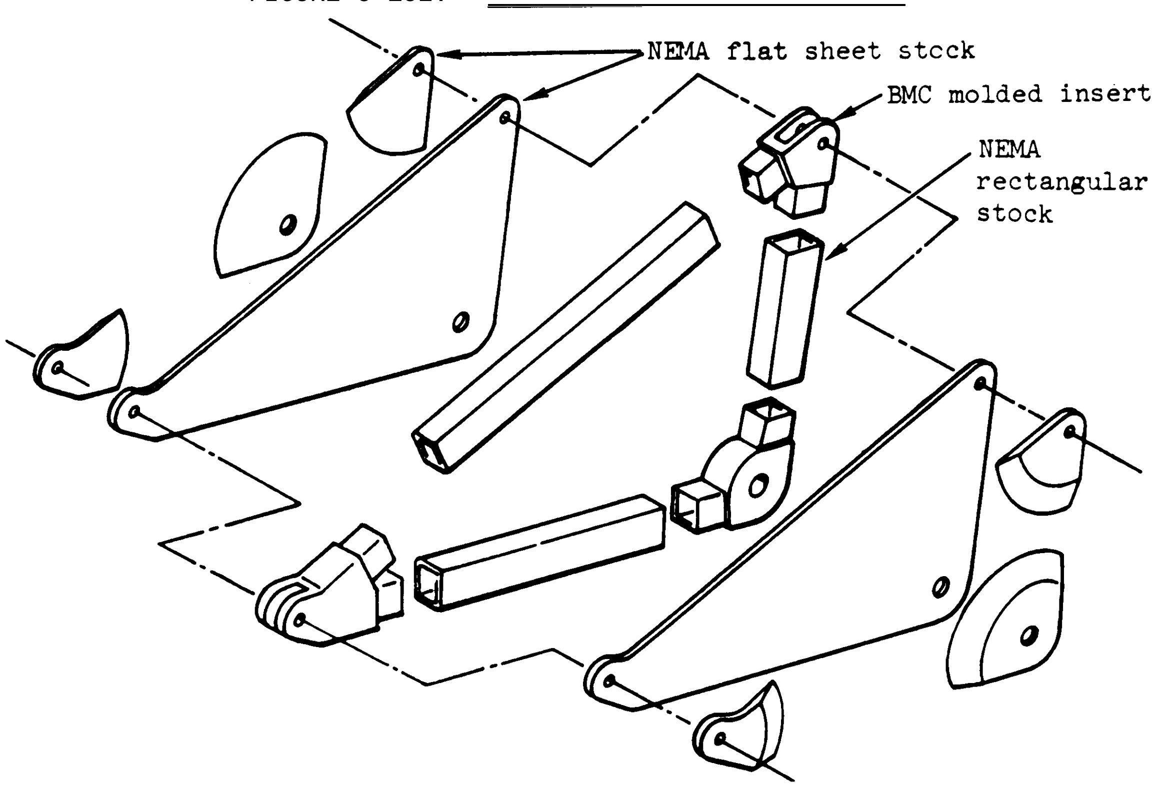

FIGURE 5-153. Ballistic damage-tolerant bellcrank design.

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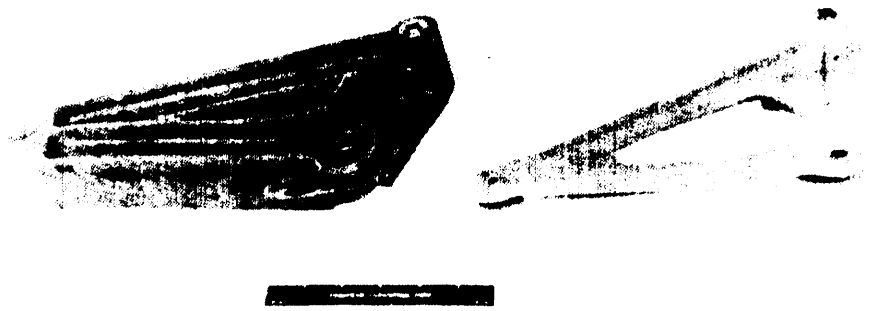
Bell UH-1/D Quadrant Assembly



Boeing CH-47C Aft Pylon Upper Bellcrank

Boeing CH-47C Aft Controls Bellcrank (Idler)

FIGURE 5-154. Chopped fiber composite compression molded ballistic - damage-tolerant helicopter flight control components, compared with conventional components.

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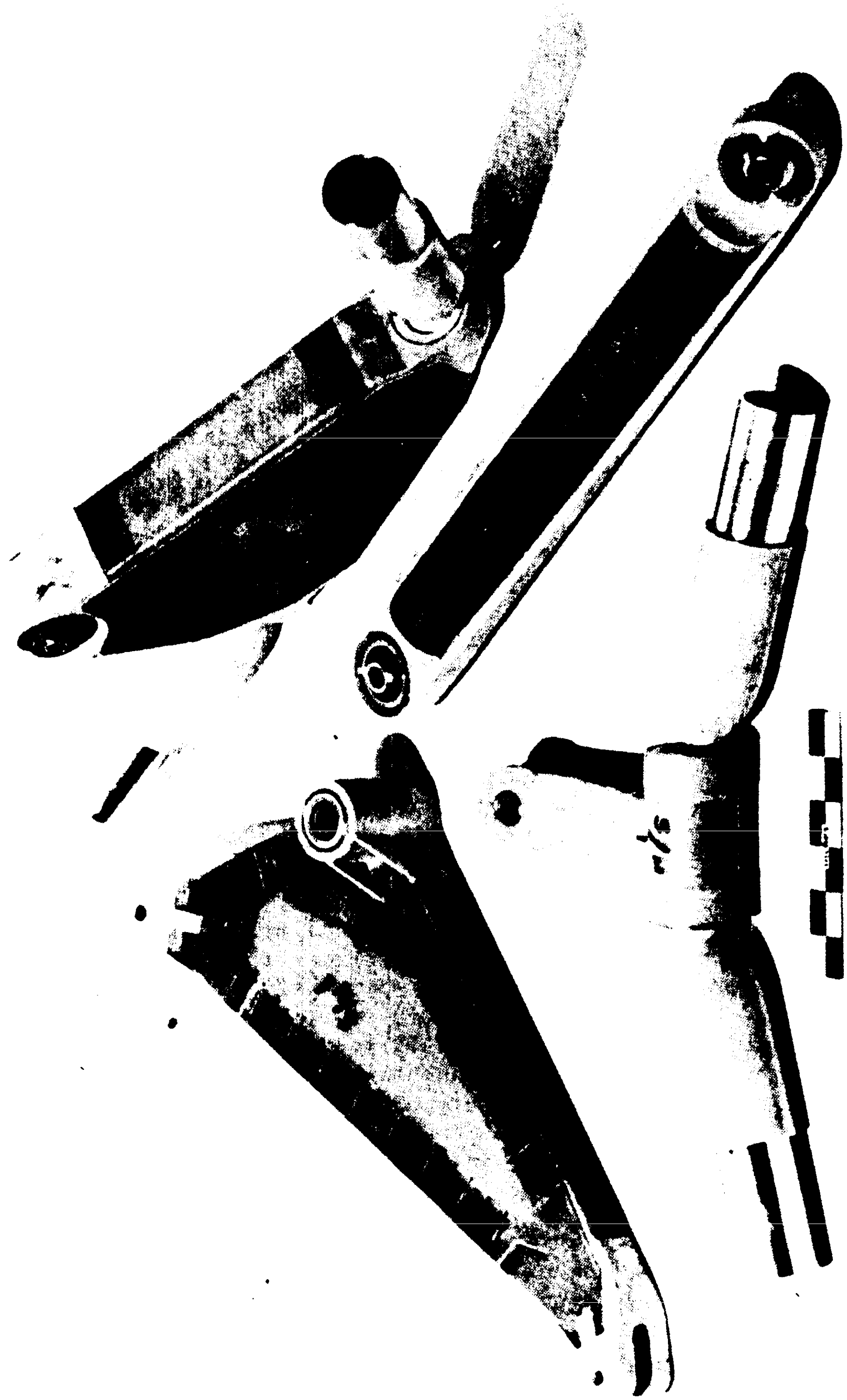

FIGURE 5-155. MM&T ballistic-damage-tolerant helicopter flight control components.

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5.9.4.2 Powered components. Powered FCS's are used where pilot strength capability is insufficient to adequately control the aircraft throughout its flight envelope. Two types of powered systems may be used: boosted or full-power. In the boosted power system, pilot actuation forces, transmitted through mechanical linkage to move the control surfaces, are amplified or assisted (boosted) by a special booster power source. It is a reversible load system wherein a portion of the surface forces are transmitted back to the pivot. In the event of power failure, only pilot forces are available to move the control surfaces. This type of system should be evaluated in comparison with full-power control systems. The boosted system would provide a means to permit recovery of the aircraft that would not be available with a full powered system. In the full-powered control system, the pilot activates power control servo-mechanisms, through mechanical linkages that position the control surfaces in response to pilot position commands. These servo-mechanisms are totally dependent upon hydraulic system or other power sources to maintain any control over the aircraft. Hydraulic systems are the mean of providing power for military aircraft control systems. However, they are sensitive and vulnerable to ballistic and secondary hazard damage and require careful study and consideration for new systems designs. The following are considerations that should be evaluated eary in the design effort.

a. Boosted or full-power hydraulic system redundancy is usually necessary to comply with system safety requirements. Separation and inherent masking or armor should be used to minimize the probability of simultaneous failures from single- or multiple-projectile impacts that may be experienced from one attack direction. Separated or dual-control actuators should be considered in favor of single-tandem types to provide effective separation and mutual masking. Figure 5-156 illustrates the basic principle for a boosted-power system. The sensitive actuators and power sources are arranged to provide two completely separated and redundant power sources and actuators that will provide the needed control actuation. Such boost systems should be designed to be fail-safe so that a degree of control is available to the pilot through manual effort, in the event of complete power failure, that would permit escape from the combat area and safe recovery. For full-power systems, the separation and mutual protection of hydraulic power systems is even more essential, since loss of both will deny the pilot means of controlling the aircraft flight path and result in almost certain loss of the aircraft and injury or death for personnel aboard.

b. Consideration should be given to packaged hydraulic power system concepts. Hydraulic power is generated in an independent package, located close to the control surfaces, by use of electrical power inputs.

c. All mechanical power sources should be considered for secondary FCS operation (i.e., slots, flaps, etc). This technique uses mechanical power, from the engine or power transmission, through

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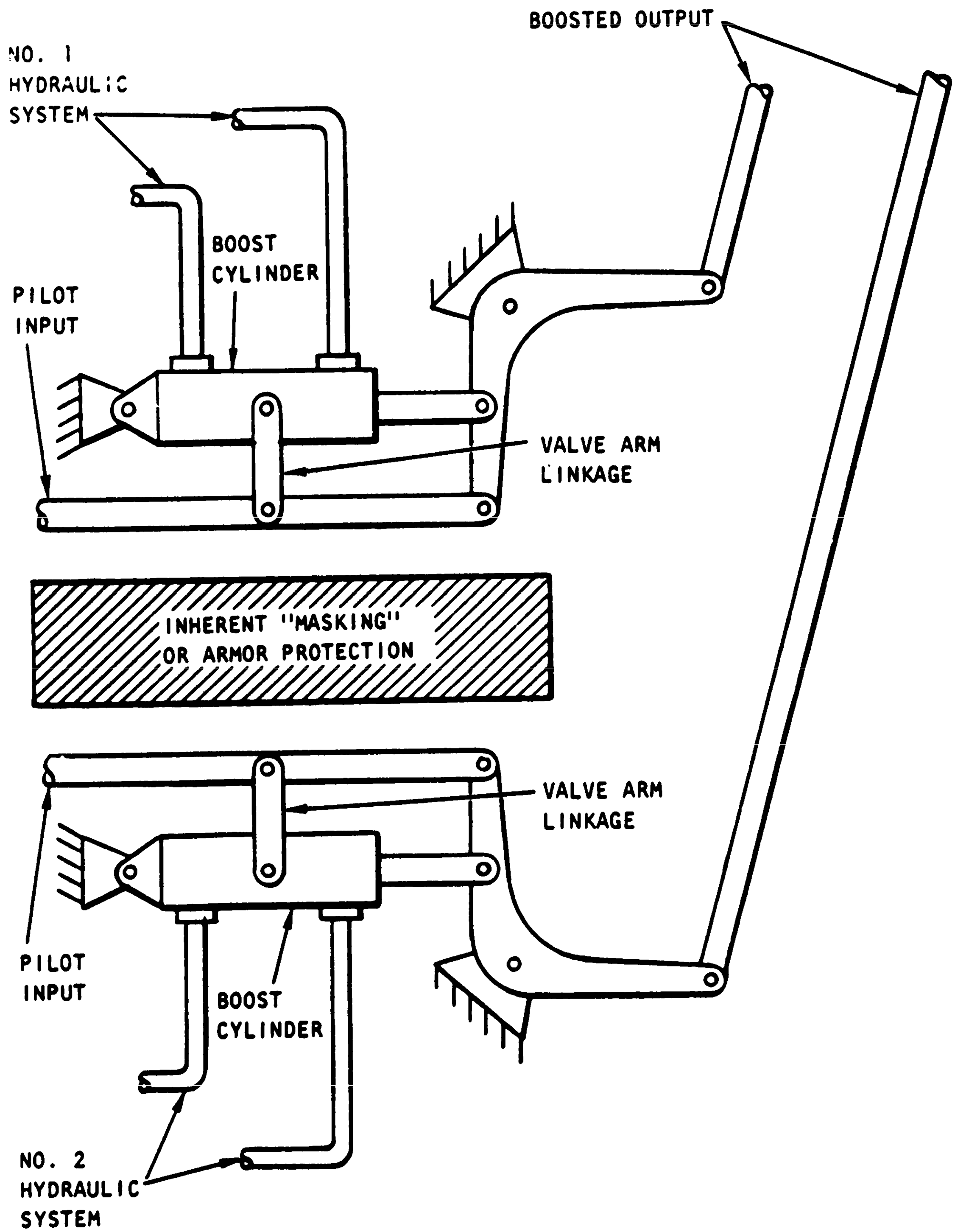

FIGURE 5-156. Redundant boosted control system.

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rotating shafting, and a mechanical servomechanism that positions the control surface in response to pilot command. A simple schematic of this concept is shown in Figure 5-157. This type of system can minimize secondary weapon effects hazards, in that it can be relatively insensitive to spallation effects, fire, and hot-gas torching, and it does not contribute flammable byproducts when struck by projectiles.

d. Fly-by-wire (FBW) flight control systems are the outgrowth of technology evolution that has been influenced by the increased performance required in military aircraft. Figure 5-158 illustrates this evolution from the point in time where powered flight control systems were found to be necessary. Early aircraft used manual control exclusively. Then when the pilot could no longer move the control surface, a hydraulically boosted system much like automotive power steering, was added.

e. The next major step was to fully powered controls; the mechanical linkage moves only the valves on the hydraulic actuators. The pilot is no longer mechanically connected directly to the control surface and must rely entirely on hydraulic power. In this case, he has to be artificially provided with stick "feel" through such devices as springs, bob weights and "q" bellows, which generate the desired handling qualities for the particular type of aircraft. Virtually all modern, high-performance military have fully powered flight control systems, as do several commercial aircraft.

f. From power augmentation, the next step was to stability augmentation systems (SAS), where feedback of aircraft motion damps out unwanted motion or oscillations of the aircraft. A control augmentation system (CAS) combines the damping function with an electrical feed-forward control signal, allowing the use of high feedback gain (or a more sensitive damper).

g. Adding a clutch or other means of disconnecting the mechanical system provides pseudo-fly-by-wire (FBW); removal of the mechanical linkage transforms the system into FBW.

h. Dampers or SAS are in common use in all modern commercial and military aircraft to provide better handling qualities and a smoother ride. CAS is being used successfully in several modern military fighters and the Concorde SST is an example of the successful application of pseudo FBW.

i. An example of an aircraft with a FBW flight control system is the F-16. In a FBW system, control stick motions or forces are sensed by the position or force transducer, which, in turn, provides an electrical signal to the electronic control box. This signal is processed in conjunction with needed airframe dynamic sensors to provide an electrical signal to the command actuator. The actuator responds to the

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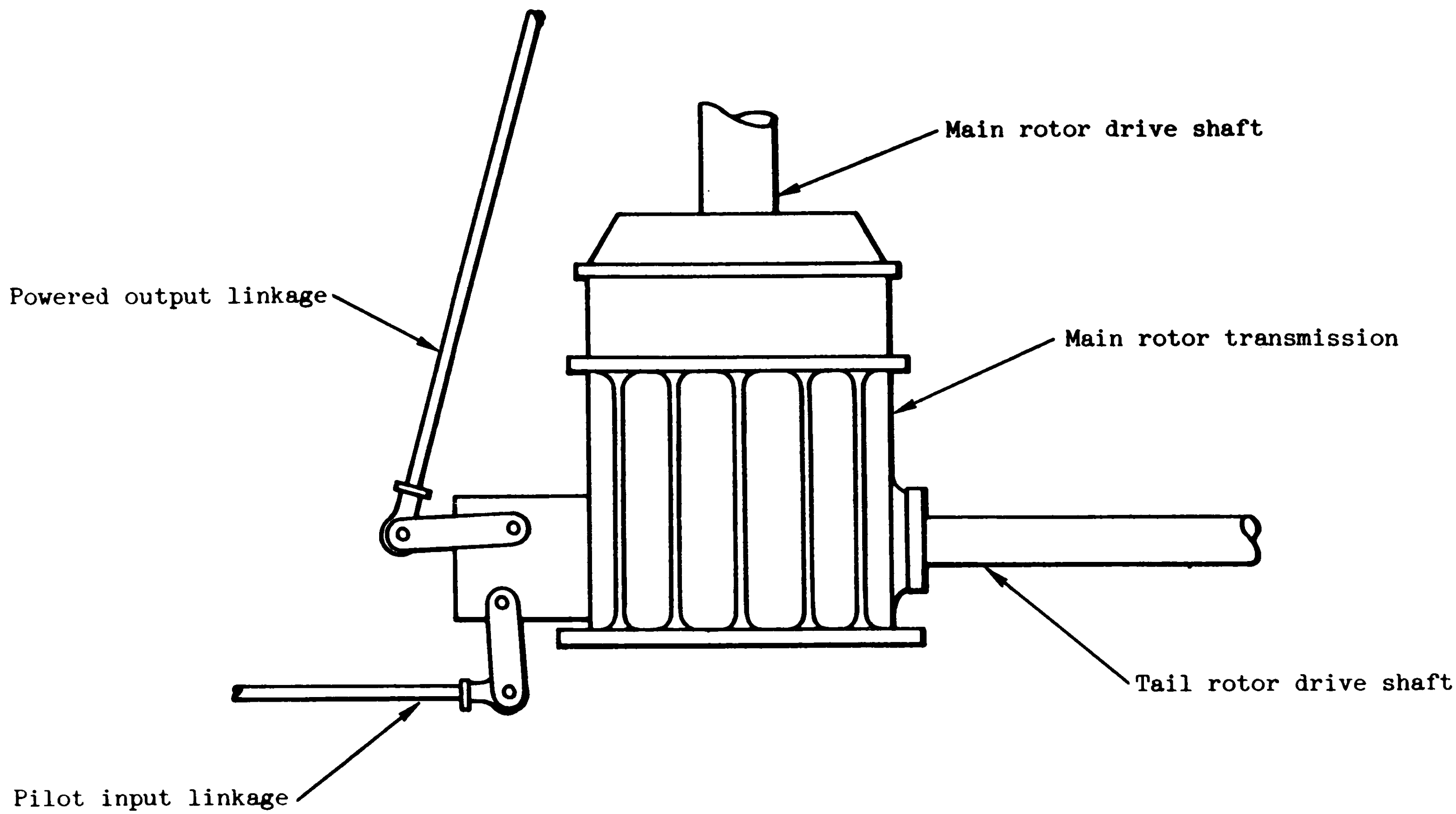

FIGURE 5-157. Example of all mechanical power control for rotary wing aircraft.

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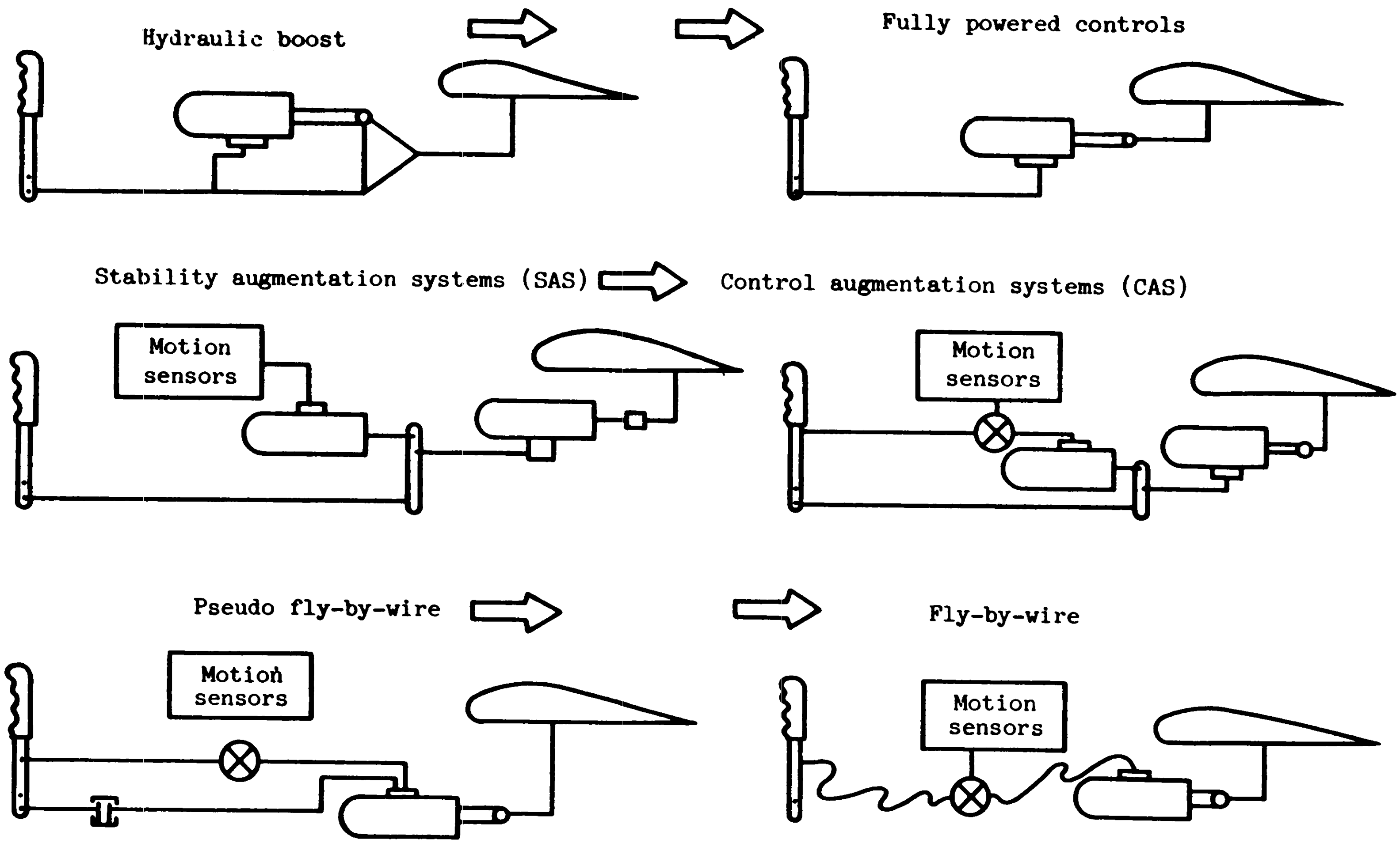

FIGURE 5-158. Fly-by-wire system concept evolution.

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command and positions the control surface or element. A feedback system provides the electronic control box with the position or load information required. Multiple-channel redundancy is an essential ingredient of FBW systems. This factor lends itself to potential survivability enhancement if adequate separation and mutual masking and/or armor protection of those areas considered vulnerable can be provided. Figure 5-159 shows a quadruply redundant FBW control system. Of primary importance is using an FBW system is the provision for multiple redundant electrical power sources that in themselves are insensitive or protected from the small-arms primary and secondary weapon effects.

j. Considerable advancements have been made in the development and testing of FBW systems in high-performance, fixed-wing aircraft. Both fighter and bomber class aircraft are represented. The FBW concept has other potential survivability enhancement benefits other than reduced vulnerability. They may be used to improve the handling and maneuverability characteristics of an aircraft system that will enable it to better avoid or attack a hostile weapon system or defended target. Research is currently being conducted on control configuration vehicles (CCV), using FBW systems with active feedback systems to provide stability and control of an otherwise statically unstable aircraft. Reference 66 through 72 contain more detailed information on FBW system and component design.

k. Longitudinal control is considered the most critical axis to be protected and should receive first priority. Limited lateral or directional control is also considered essential. For example, use of differentially operated wing flaps, operated by a separate power source, may be utilized to provide the minimum control needed.

l. Use separate redundant control surfaces, each operated by its own power system; i.e., three aileron panels, each operated by its own separate power source.

m. Fluidic systems have also been developed, during the past decade, to make use of fluid characteristics for control functions. According to the National Fluid Power Association, "A fluidic system is one in which sensing, control, information processing, and/or actuation functions are performed primarily through utilizing fluid-dynamic phenomena." This does not rule out the use of spool valves, ball valves, or other miniature control elements in which the moving mass is so small that it does not significantly affect response of the device. Use of this technology should be considered for those applications where their small size, volume, and independence of power sources, other than the operating media, can reduce the complexity and vulnerable area of the system. Fluidic servoactuators have been designed and tested for helicopter flight control applications. Figure 5-160 shows the basic schematic of the system. It was designed for installation as an extensible link in each of the three control axes. The function of the servoactuators is to drive the surface control boost actuator pilot

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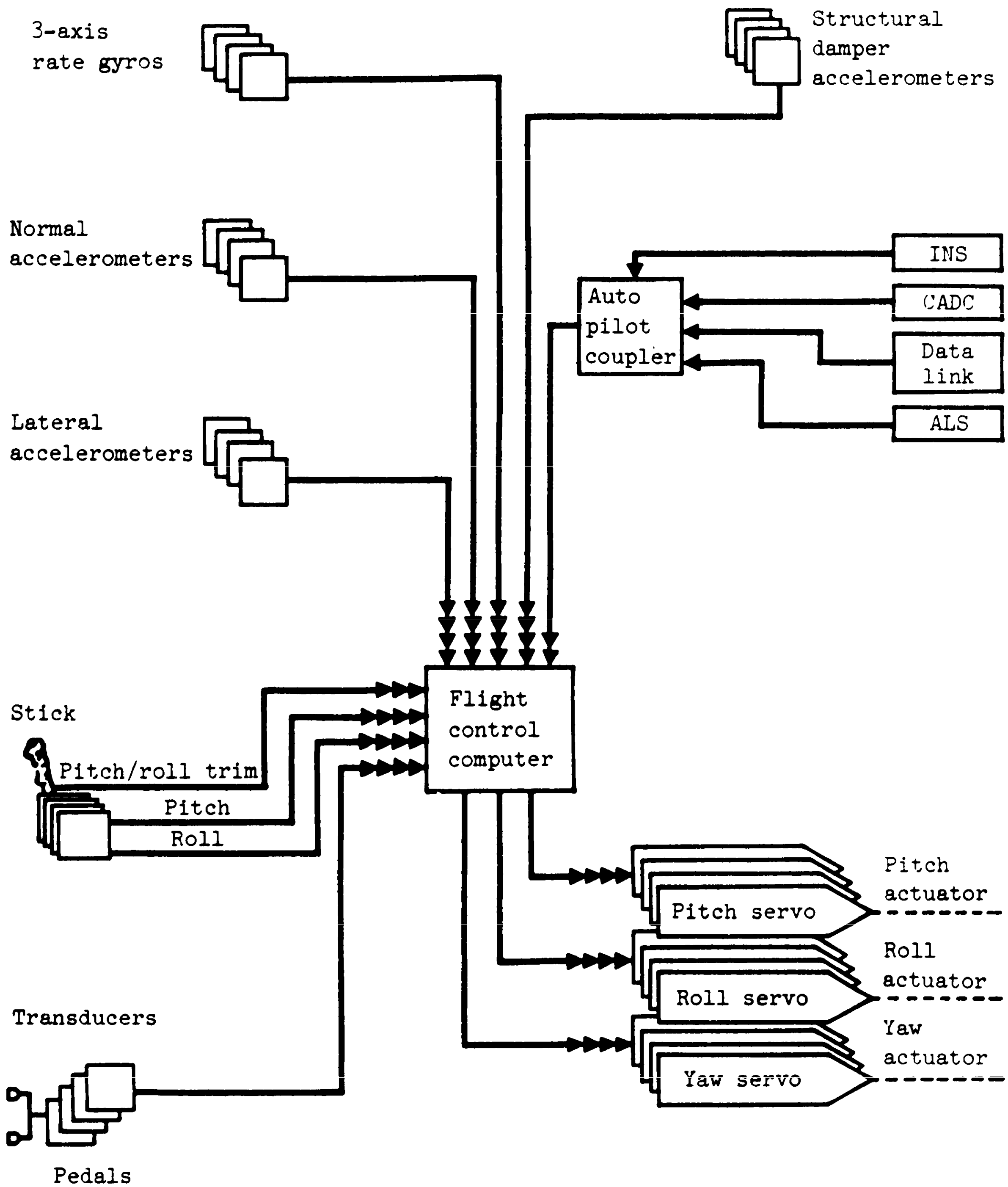

FIGURE 5-159. Quadruply redundant fly-by-wire flight control system.

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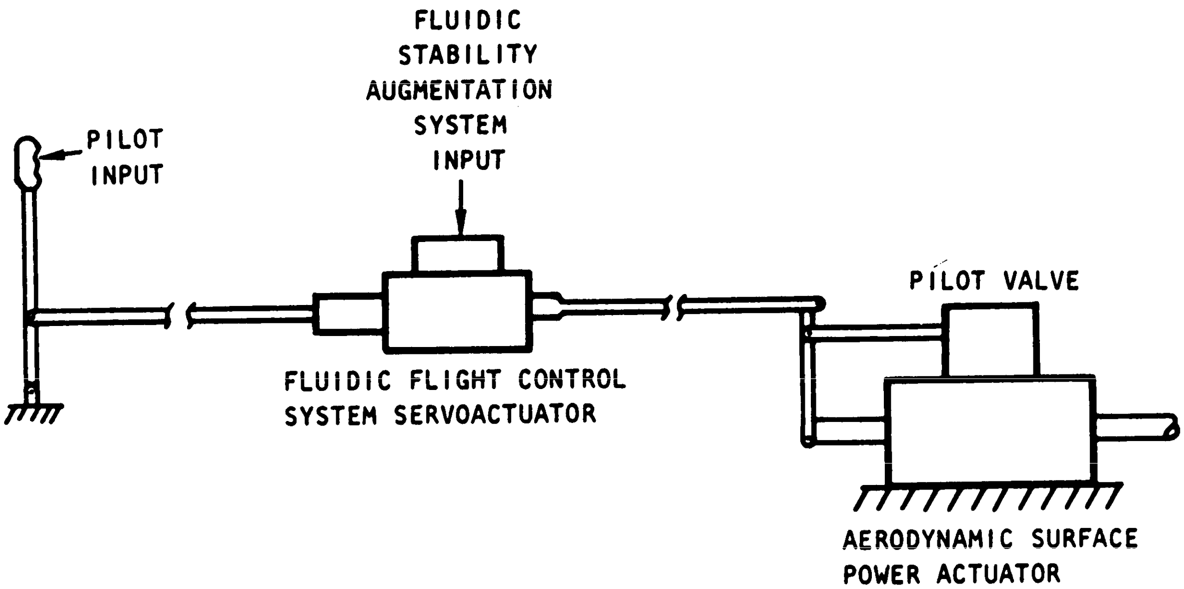

FIGURE 5-160. Primary flight control system schematic

valves and damp out gust disturbances imposed on the aircraft. In the absence of hydraulic system pressure, the servoactuator ram is centered and locked to provide a fixed link in the system. Recent advance in fluidic technology have resulted in significant miniaturization of the sensing and control elements. This can provide a greatly reduced vulnerable area for stabilization systems. Electronically controlled augmentation systems are dependent upon electrical power sources and sensor elements that can present larger and more sensitive vulnerable areas.

Figure 5-161 is a schematic of a backup FCS system block diagram using both FBW and mechanical portions.

5.9.5 Interface between the flight control system and the hydraulic system. Hydraulic power is commonly used as the prime mover for actuating primary and secondary flight control surfaces. In this role, hydraulic pressure may be controlled and ported to:

a. Linear hydraulic actuators which are directly coupled to the control surfaces or

b. Hydraulic motors which are indirectly coupled to control surfaces. In the instance, gearing is used to amplify hydraulic motor bidirectional rotational output. Drive shafts interconnect motor output with mechanical screw actuators.

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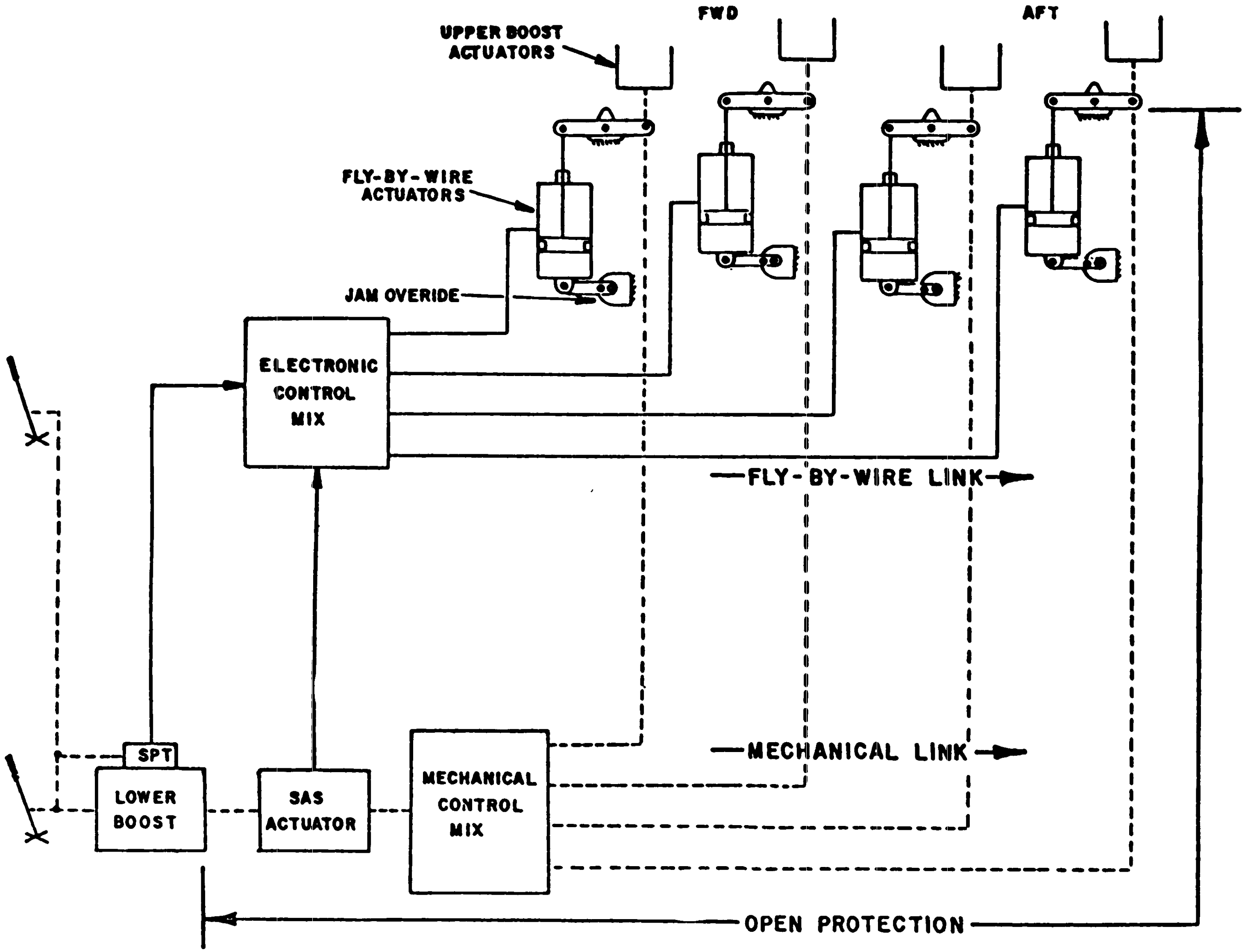

FIGURE 5-161. CH-47C backup flight control system - block diagram.

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In both instances, if redundancy is a requirement, it can be provided by using redundant, independent hydraulic power sources which power redundant actuators or motors. Dependent upon design constraints, redundant actuators may be installed in series or in parallel. In the series configuration, the redundant actuator will have a common piston rod and attach point. The output of the hydraulic motors may be force or differentially summed. A more detailed discussion on hydraulics systems, which includes the topics: (1) hydraulic system response to damage, (2) system considerations and (3) detailed design considerations, is presented in section 5.10 of this handbook.

5.9.6 Actuator component detail design. Minimizing vulnerability of hydraulic-powered flight control system components may require the use of ballistic protection in order to prevent loss of the operating fluid, although redundancy, flow difference sensors, reservoir level sensors, and return (line) pressure sensors are also helpful. The following are techniques that should be considered:

a. Ballistic-resistant hydraulic actuators may be fabricated from metallic armor materials. Dual-hardness steel armor (DHSA) has been used in an actuator cylinder to defeat small-arms projectiles. Figure 5-162 shows experimental servoactuator bodies fabricated from such material. Electroslag remelt (ESR) steel is a new armor material that should be considered for this application also, since its fabrication costs should be less than DHSA.

b. Arrangement and geometry must be considered in minimizing the actuator vulnerability to ballistic threats. Significant benefits can be gained by locating the control valve and sensitive linkages on the side of the actuator away from the most probable direction of hostile gunfire. Figure 5-163 shows a representative configuration of a control system actuator with sensitive areas in a favor able position. This provides natural masking protection for the elements shown, and presents the most favorable geometry of the cylinder to minimize projectile penetration. Remaining critical areas which are still vulnerable should be protected by armor shields. The cylindrical shape is the most efficient for obtaining obliquity angles to the threat projectile for even distribution over the total presented area of the actuator. As shown in Figure 5-164, the angle of obliquity increases as the line of impact moves away from the cylinder centerline and the line normal to its major axis.

5.9.6.1 Rip-stop actuators. In the design of multipower system hydraulic servoactuators, consider the use of “rip-stop” actuator body construction This technique employs separate sections of the actuator body that are fastened together at the junction between each power system to prevent the propagation of a crack penetrated by a hostile weapon effect, from one portion of the actuator body, to a point where hydraulic fluid would be liberated from both sides of the unit and cause total loss of its function.

5.9.7 Control system analysis. Aircraft flight control systems can be very complex, especially for high-performance aircraft systems. To develop

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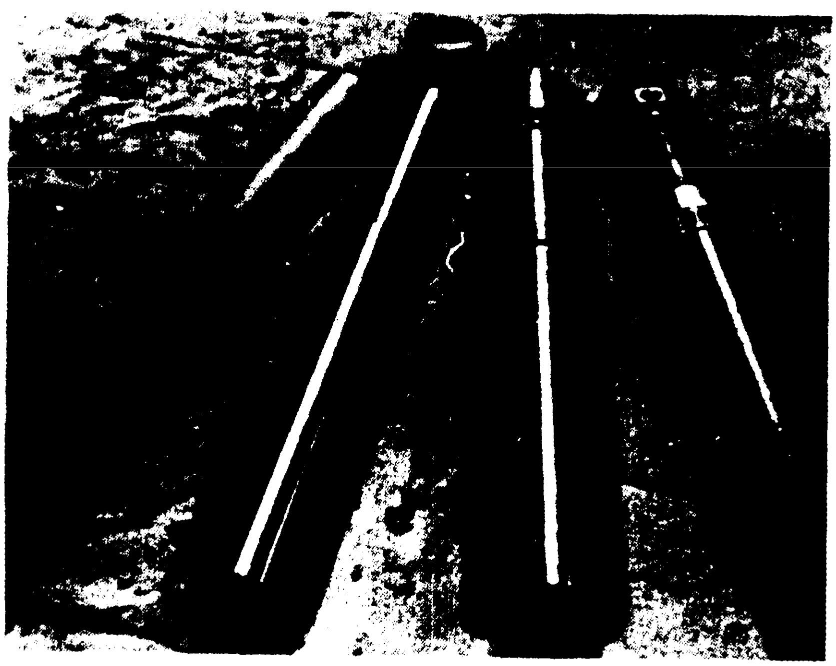

FIGURE 5-162. Servo actuator body fabricated from dual property steel armor.

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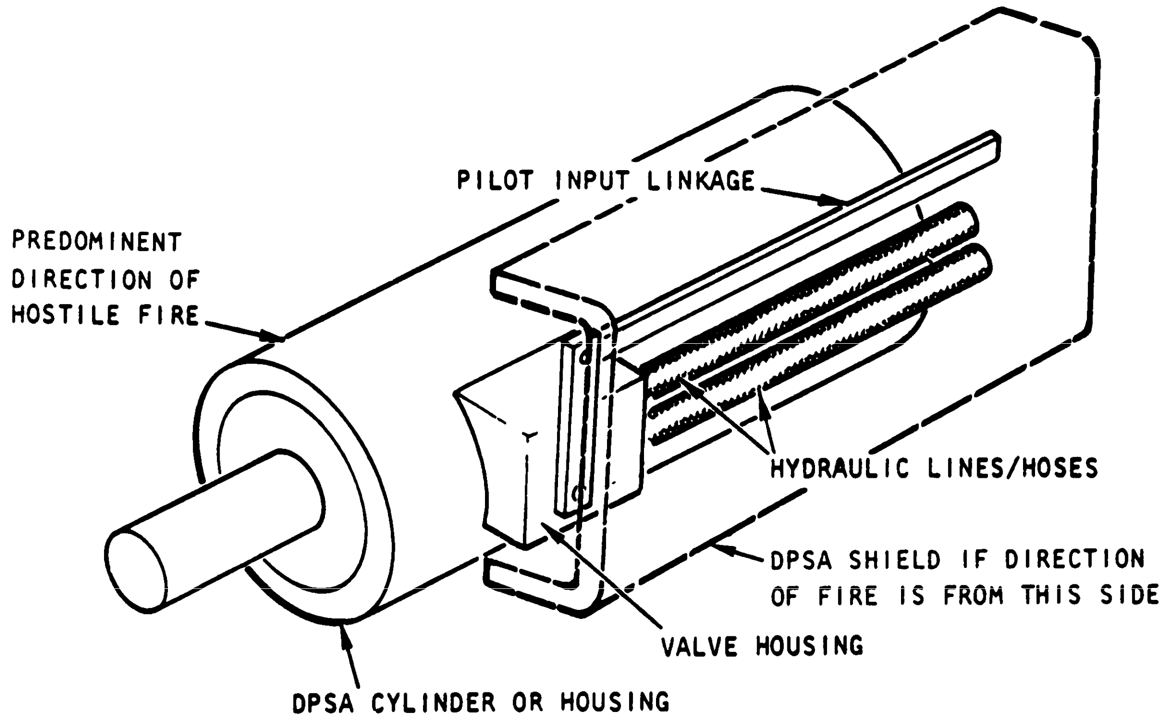

FIGURE 5-163. Favorable actuator arrangement.

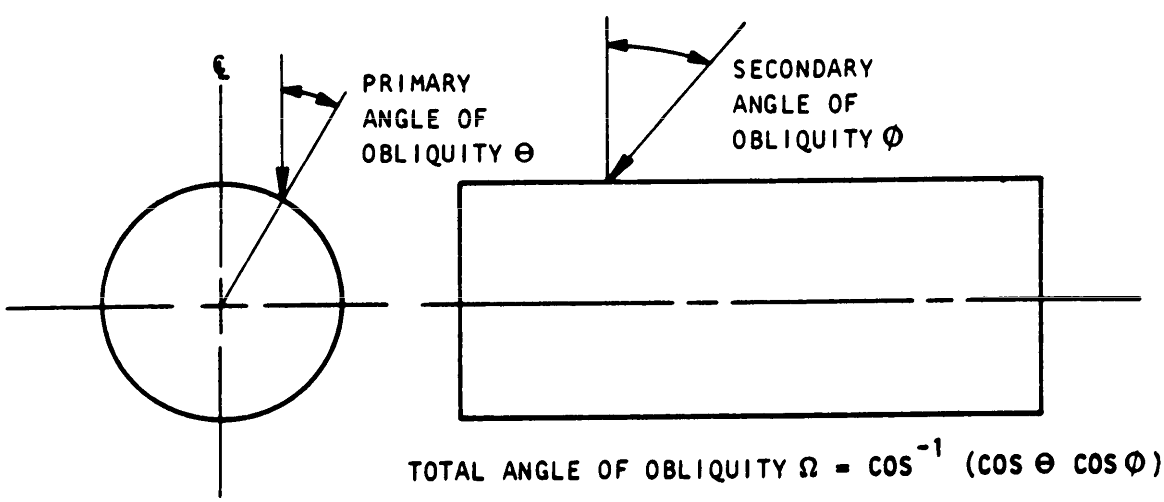

FIGURE 5-164. Angle of obliquity.

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a system that will have the desired survivability characteristics requires a thorough analysis of the failure modes that can occur from hostile weapon effects damage. Each portion of an FCS must be examined to determine its failure modes in the range of weapon effects to which it may be exposed, and the effects of this damage upon system operation must be evaluated. By considering such damage effects, a systematic evaluation of means to prevent or minimize system vulnerability can be made to find the most effective combination of techniques that may be used. Damage/failure mode and effect analyses can be used to systematically Identify vulnerable components and sensitive areas with a control system design. A representative control system for a helicopter is shown in Figure 5-165. As can be seen, system redundancy is provided by two servo cylinders, each powered by separate hydraulic systems. This is a conditional redundancy, however, in that the failure mode of either system must exclude jamming that cannot be overcome by the undamaged unit. For jamming failure modes, the resultant effect on the overall system is locking of the system in the position it was in when the damage occurred. Each component or element in the system must be examined to consider the types of failures that may be induced by weapon effects and the consequences of such damage on total system operation and survivability. This type of analysis may be conducted manually as described previously for relatively simple control systems. Highly complex and sophisticated control systems may be more readily analyzed using methods developed by the Air Force Flight Dynamics Laboratory, as reported in Reference 73. This system also uses AND/OR gate logic to describe a flight control system so that singly and multiply vulnerable components may be identified and evaluated. A computer program has been developed to evaluate survivability probabilities of components, subsystems, systems, and total aircraft, and is also contained therein.

5.9.8 Flight controls HEL protection. The primary protection techniques for flight control systems against high-energy laser weapon effects is the use of thermal barriers and ablative materials on components and linkages, marking of critical elements behind heavy structures and less essential components, and hardening of the structural shell in critical areas to prevent laser beam burn-through. In the detail design of flight control system components, consider the means to make them more resistant to high-thermal conditions that may be created by HEL weapon effects. Elastomer seals are generally the first element to fail under high-thermal environments. Consider the use of metal seals to delay leakage and/or failure of hydraulic servoactuators and fittings. In critical areas, consider the use of continuous hydraulic system flow to act as a heat sink to conduct thermal energy away and enhance the capability of the system to maintain its integrity or delay the failure so that its effects are minimized. In areas where liberated hydraulic fluid would constitute a fire hazard, suppression techniques, such as intumescent materials, void fillers, and fire detection and suppression systems, should be considered. As part of the total aircraft protection system, consider the methods to prevent burn-through of the structural shell covering the critical or sensitive flight control system elements. Other nonnuclear ballistic protection techniques should also be considered to perform as HEL protection methods. This includes items such as redundancy and separation of critical components and connecting electrical wire bundles, and fail safe/fail operational design concepts.

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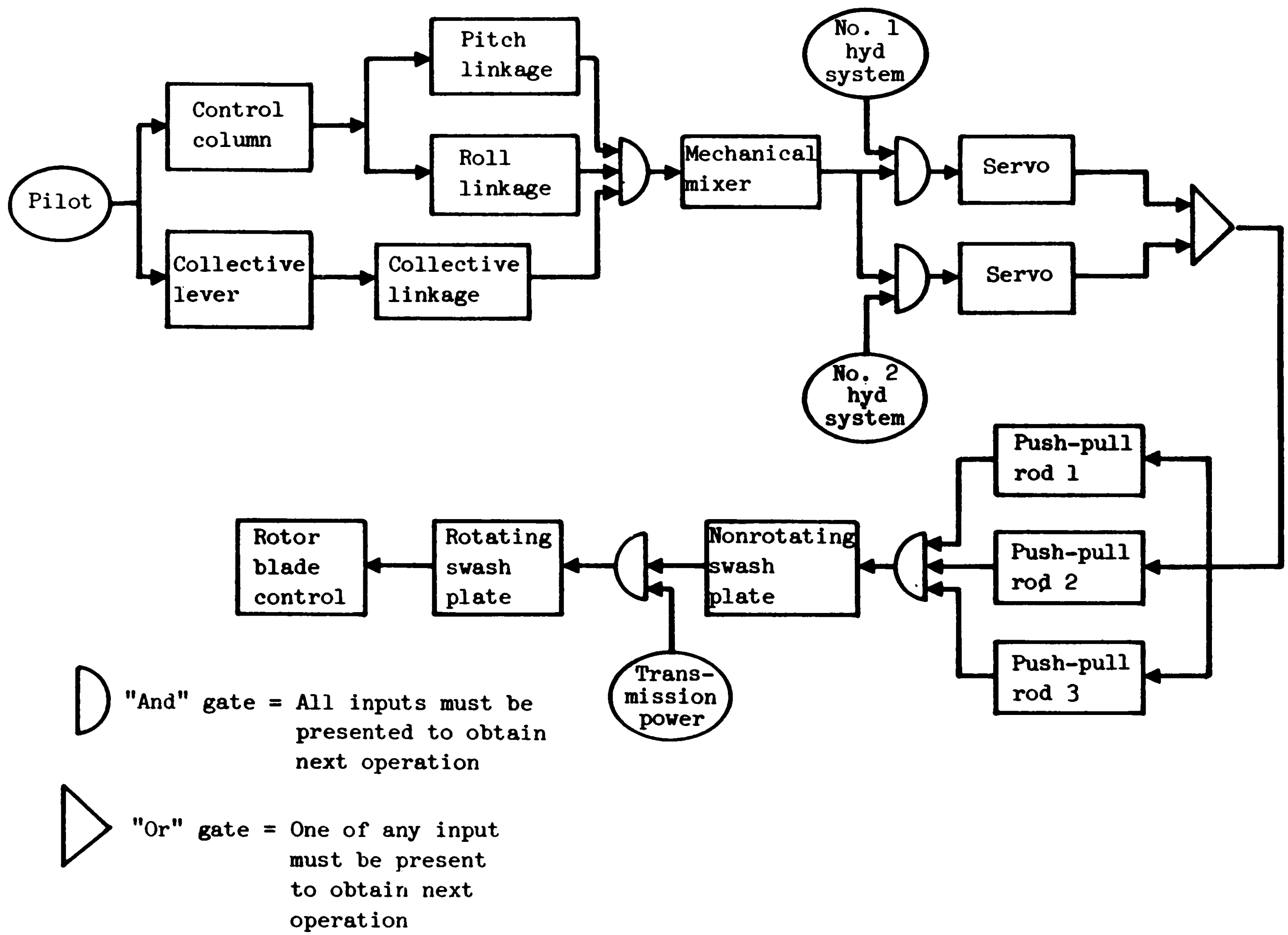

FIGURE 5-165. Redundant flight control system example for helicopter main rotor blades.

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5.9.9 Flight controls repairability/maintainability. The mechanical linkages of an aircraft FCS should be designed to permit rapid access for inspection and repair of battle damage. FCS components should be made removable for repair or replacement without dismantling of primary structural elements. Electronic portions of the control system should be designed for replacement of damaged components and a minimum of recalibration or readjustment to match other components in the system. The components should be designed to permit the removal and replacement of a damaged item with a minimum of disassembly of the overall system. Particular attention shall be given to development of the system so that rigging and/or adjustments may be accomplished in sections with a minimum of readjustments or rerigging after battle damage repair. Support brackets for the mechanical systems should be designed to be damage tolerant and be repairable for a reasonable degree of battle damage. Easily shattered materials should be avoided for supports. Avionics components in FCS's are usually complex, expensive to replace, and normally beyond the operational unit capability to repair. Components in this category should receive priority in locations that would minimize their probability of being damaged. Those that are required for mission accomplishment should be ranked ahead of those that are in the pilot-assist category.

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5.10 Fluid power. The use of fluid power for aircraft-essential subsystem operation increases as the size and/or performance of the system grows. Flight control systems, for example, require more power than the pilot can produce when aerodynamic loads exceed certain values. Other subsystems (i.e., landing gear, armament, secondary controls, etc) also become dependent upon power sources to perform their required functions. Fluid power consists of hydraulic and pneumatic systems. Hydraulic systems have been used almost exclusively for such functions in military aircraft since the inception of required force augmentation. Pneumatic power, on the other hand, has not been used to any significant extent. Its use has been generally limited to secondary subsystems where "two-position" actuation (extend-retract) was required. Because of aircraft losses in combat resulting from hydraulic system failures, considerable attention has been directed, during the past decade, toward improving the survivability of hydraulic systems against ballistic threats. Little effort has been directed toward similar improvements in pneumatic systems, since their damage and/or failure has not contributed significantly to aircraft losses. Most of the survivability enhancement techniques contained in this section, therefore, are for hydraulic systems. As for all design techniques, the penalties and benefits for each must be carefully considered for both initial design and operational aircraft modification efforts.

5.10.1 Nonnuclear weapon effects. Nonnuclear ballistic impacts, blast effects, and high-energy laser effects can create a variety of damage mechanisms that can destroy or degrade the capabilities of fluid power systems. These possibilities must be evaluated in the design process in order to insure that the most practical and effective combination of survivability features is incorporated into the system. Hydraulic and pneumatic subsystems have different responses to weapon effects as described in the following paragraphs.

5.10.1.1 Hydraulic system response. The major hydraulic system damage mode from projectile impact, blast damage, or HEL burn-through, is leakage of the operating fluid from components or lines. The major effect of the leakage is depletion of the system fluid supply and pressure available for component operation. A secondary effect is liberation of a fluid which, depending upon its characteristics, may be ignited by a projectile's incendiary characteristics, HEL effects, or other ignition sources, thus resulting in a hazardous fire condition. Other damage modes can include deformation of hydraulic components or lines that does not result in leakage but causes restriction or blockage of the return line, which may cause a "hydraulic lock" condition. This would "freeze" the actuator in its position at the time of the damage occurrence and destroy its ability to perform its designated function. High-thermal conditions may be generated by weapon effects (i.e., fuel, lubrication oil, other flammable materials fires, or damaged hot air-bleed systems) that may be capable of causing failures of hydraulic system components or lines. These failures, in turn, may cause loss of essential subsystem capabilities. Smoke or toxic fumes may also be generated by ignition or heating of hydraulic fluids, which, in turn, could affect the capabilities of the aircrew to perform their assigned duties. Penetration of high-pressure vessels, containing compressed gases, such as accumulators and shock struts, by projectile impacts or HEL effects may cause explosive disintegration of the unit, which, in turn, may cause secondary fragments to be generated that could be capable of inflicting personnel injury or damage to other vulnerable systems. Damage modes and

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effects for each essential and nonessential hydraulic system should be analyzed to insure that primary and secondary vulnerabilities are not overlooked. Figure 5-166 shows a simplified schematic of a hydraulic circuit. The basic elements of a hydraulic system serving flight- or mission-essential and non-essential subsystems are shown The primary and secondary weapon effects must be evaluated for each hydraulic system component and element to determine its response and effect upon the aircraft's survivability. This analysis serves to identify system vulnerabilities to which survivability enhancement techniques may be applied. Internal and external blast effects from high-explosive projectiles, rockets, and missile warheads can create damage to fluid power systems that, in turn, may cause failures or malfunctions. Prominent among these is the distortion and crushing of aircraft structural elements to which the fluid power components and distribution system lines and hoses are attached. Separation, twisting, bending, tearing, etc, can be experienced that can cause leakage of the power fluid, restriction of pressure flows, or restrictions of return flows to reservoirs and/or pumps. In liquid systems, the pressure flow restriction reduces the rate at which a component, such as an actuating cylinder or servoactuator may operate. Restriction of a return line will also cause reduced operation rates if there is no other return path available. Complete closure of a return line can cause hydraulic lock.

5.10.1.2 Pneumatic system response. Pneumatic systems are susceptible to the same basic damage mechanisms as the hydraulic systems, but the responses are somewhat different. Leakage from pneumatic-operated systems can be tolerated to some degree, since the operating medium (gas or air) is continuously being supplied by an air compressor and is not dependent upon a fixed stored volume. The compressed gas energy in pneumatic system components provides a potential explosive-type hazard if the container disintegrates or shatters when damaged. The temperature of the pneumatic operating medium can also pose a secondary hazard to other nearby essential subsystems by "hot torching" effects or generation of high-pressure conditions in other equipment such as hydraulic system accumulators. Hot gases may also provide an ignition source for flammable materials liberated by prior, concurrent, or subsequent small-arms fire. The hot gases may also create a direct hazard to the aircrew or passengers by impinging upon their occupied space, or by generation of smoke or toxic fumes.

5.10.2 Hydraulic systems.

5.10.2.1 System considerations. Survivability must be considered during the development of the system circuitry and its general arrangement in the aircraft, including the selection of power sources, isolation of essential circuits, masking or armor-shielding sensitive areas, and selection of the operating hydraulic fluid. All of these considerations must be evaluated against the rest of the aircraft design requirements as well, to select the most appropriate combination of survivability features. The following techniques should be considered.

5.10.2.1.1 Fluid medium selection. MIL-H-5606 (Reference 211) is the most commonly used hydraulic oil by existing military aircraft. It can be readily ignited by incendiary projectiles or by other ignition sources when liberated.

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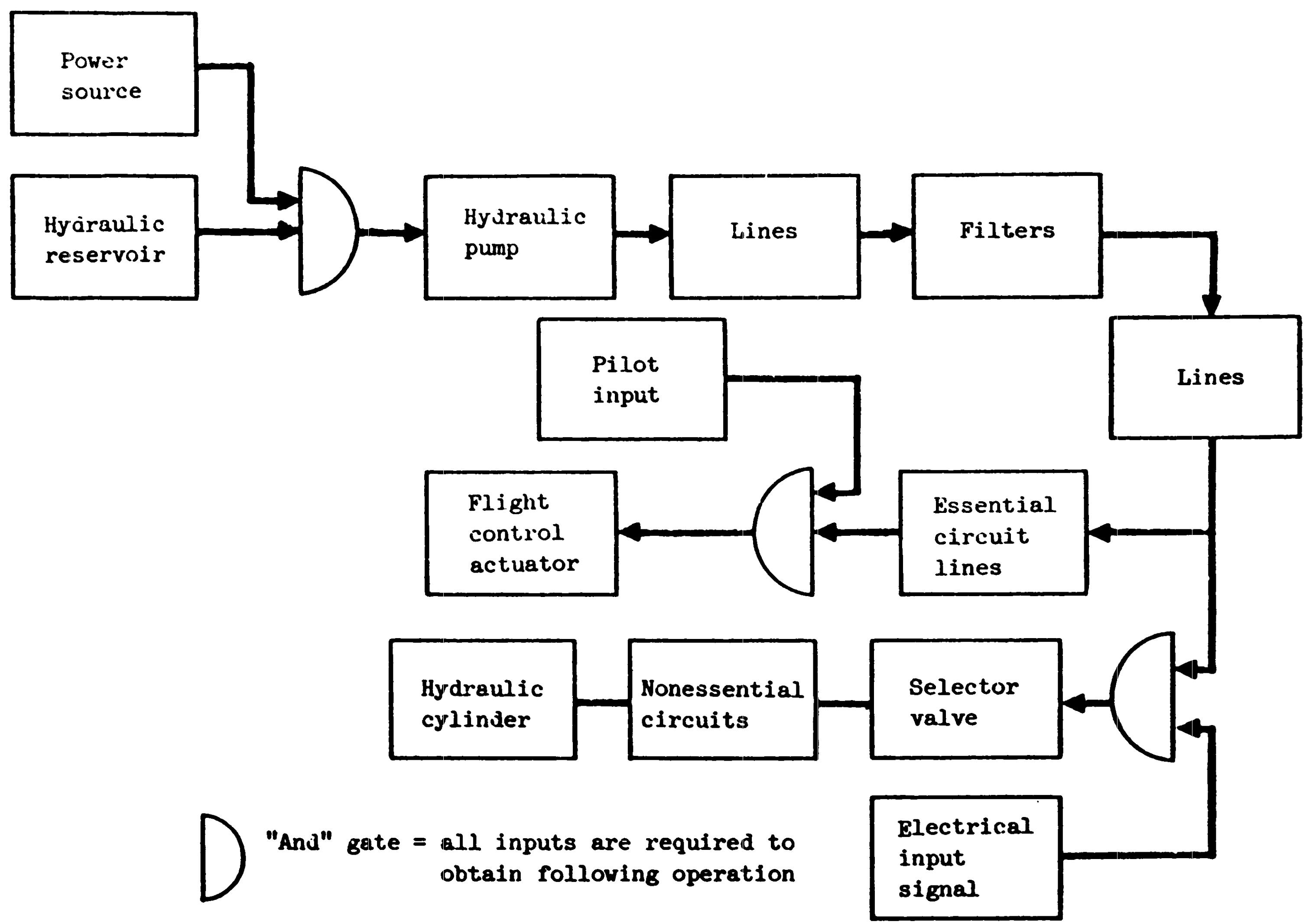

FIGURE 5-166. Representative hydraulic circuit.

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More sophisticated hydraulic fluids have been developed in recent years that exhibit reduced flammability characteristics. They have varying penalties associated with them in terms of cost, availability, special seal elastomer requirements, and impact upon operational logistics if introduced into military aircraft inventories. Table 5-XXXIII contains a listing of candidate hydraulic fluids together with data on flash points, auto ignition temperatures, and ranking for comparative safety. The most successful of the new fluids has been MIL-H-83282 (Reference 264). It is being used in certain military aircraft (e.g., Navy carrier-based aircraft) to minimize fire hazards due to hostile weapon effects and accidents. Selection of a fluid must be made on evaluation of all factors involved, particularly the configuration of the aircraft and other techniques to prevent and/or suppress hydraulic system fires. Currently, research is being conducted to develop a nonflammable hydraulic fluid system for use in military aircraft. A number of candidate fluids are being considered for this program in the following classes:

a. Fluorinated fluids

b. Perfluoroakyl ether

c. Perfluoroakyl ether friazine

d. Fluorakyl ether

e. Halofluorocarbon

Use of these type fluids will require appreciable changes in the fluid power system components, such as pumps, servo cylinders, valves, accumulators, filters, etc. Changes in seal materials and design may also be necessary. Contact the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio, for the latest information on this subject.

5.10.2.1.2 Circuit design factors. Redundancy of flight control hydraulic systems is required by Reference 208 and Reference 239. where other mission-essential functions are dependent upon hydraulic system powers redundant and physically separated systems should be considered to minimize the probability of aircraft loss or mission abort. Critical circuits should be arranged to minimize the size and complexity of the systems that can be exposed to small-arms fire. Noncritical segments of the hydraulic systems should be isolated from the essential systems by pressure-line shutoff valves and appropriate location of return-line check valves to minimize vulnerable areas and the volume of fluid that could be liberated and become a potential fire hazard. Figure 5-167 illustrates the basic principle of this technique. Ranking of the priority of each set of components powered by a specific hydraulic system should also be considered. The system reservoir, pump, and necessary accessories (i.e., filters, accumulators, pressure transducers, etc) should be located as close as practical to critical components to minimize vulnerable areas exposed to hostile gunfire. The location of the system should consider material masking features to the greatest extent practical, and armor applications for sensitive areas that cannot be protected in any other manner. The isolation valve should be fail-safe to the closed position, in the event of

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TABLE 5-XXXIII. Hydraulic fluid flammability comparison.

Fluid Type	Min Flash Point (°F)	Min Auto Ignition Temperature (°F)	Increased Safety
Hydrocarbon MIL-H-5606 MIL-H-27601 MIL-H-83282	 200 360 400	 475 700 650	↓
Silicate ester	420	760	↓
Phosphate ester Low-density High-density	 340 550	 1,000 925	↓
Polyphenyl ester Five-ring	 550	 1,135	↓
Silicon Fluoropropylmethyl Methylchlorophenyl	 430 550	 850 900	↓

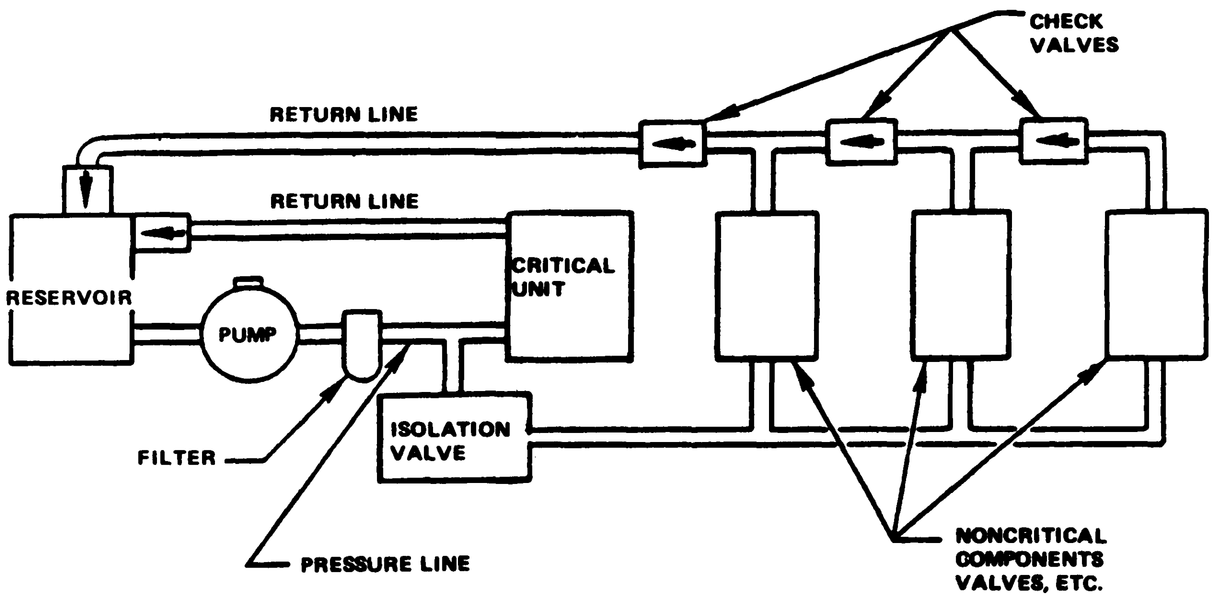

FIGURE 5-167. Hydraulic circuit considerations.

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electrical power disruption, but it should also be evaluated for emergency operation in noncombat or recovery portions of the mission where actuation of the noncritical components (i.e., landing gear extension) may be required for system safety requirements.

5.10.2.1.3 Pulsating hydraulic systems. Research and testing feasibility studies have indicated that a "pulsating" or at-type of hydraulic system can provide a less vulnerable power source for critical or mission-essential components. The basic principle of such a system is shown in Figure 5-168. This arrangement shows a three-line pulsating system, A variable-delivery hydraulic pump provides continuous pressure and flow to an alternator valve driven by a separate motor. The alternator delivers a pulse of hydraulic pressure to each of the three transmission lines through individual diaphragms that separate the pump system from the lines. The pressure pulses pass through a transformer unit designed to magnify the system pressure. They then pass through a rectifying valve to provide positive pressure to the actuator. The system is designed so that it can sustain ballistic damage to a transmission line without loss of the essential component operation, but this fact has yet to be verified. As long as one transmission line remains intact, a degree of operation, at reduced rate, is retained. In contrast, with a conventional continuous-flow system, damage to either the pressure line or the return line will result in loss of component operation and, depending upon the circuitry, in loss of the entire hydraulic power system. As can be seen, a weight penalty is associated with this type of system that must be carefully evaluated against other means of protecting a conventional hydraulic power system (Reference 23).

5.10.2.1.4 Integrated actuator packages. An integrated actuator package (IAP) is essentially a self-contained hydraulic system that operates at the point of control surface actuation. It consists of an electrically driven motor, hydraulic pump, reservoir, valving, and accessory equipment. Electrical power is supplied by the aircraft's electrical power generating sources to the electrical drive motor. This technique is also referred to as a hydraulic packaged power concept, as shown in Figure 5-169. Redundant power supply lines should be considered for such applications. The system concept can be considered both for normal operation of an actuator or as a separate emergency power system designed to recover the aircraft, with limited operating capability if the primary power source is lost. The electrical power source vulnerability and the possible weight penalties associated with the concept must be carefully assessed (References 67 and 69).

5.10.2.1.5 Fire/heat tolerance. Hydraulic systems are susceptible to failure from fires or high-heat conditions that may be initiated by nonnuclear weapon effects. A significant increase in system survivability, or extended operational capability to permit controlled recovery or forced landing, can be realized by techniques that prevent or delay hydraulic system failures. Steel hydraulic lines should be used for both pressure and return lines in areas where fires or high-heat condition can occur. Coiled tubing should be used in place of hoses where line flexure is required in the hazardous areas. Conventional hydraulic line connectors are prone to loosening and leaking when exposed to high temperatures. They should be located away from the potential hazard areas. Most important is providing a degree of flow through the lines to essential system components. This acts as a heat sink that prevents or significantly delays line failure that could otherwise occur if no flow is present.

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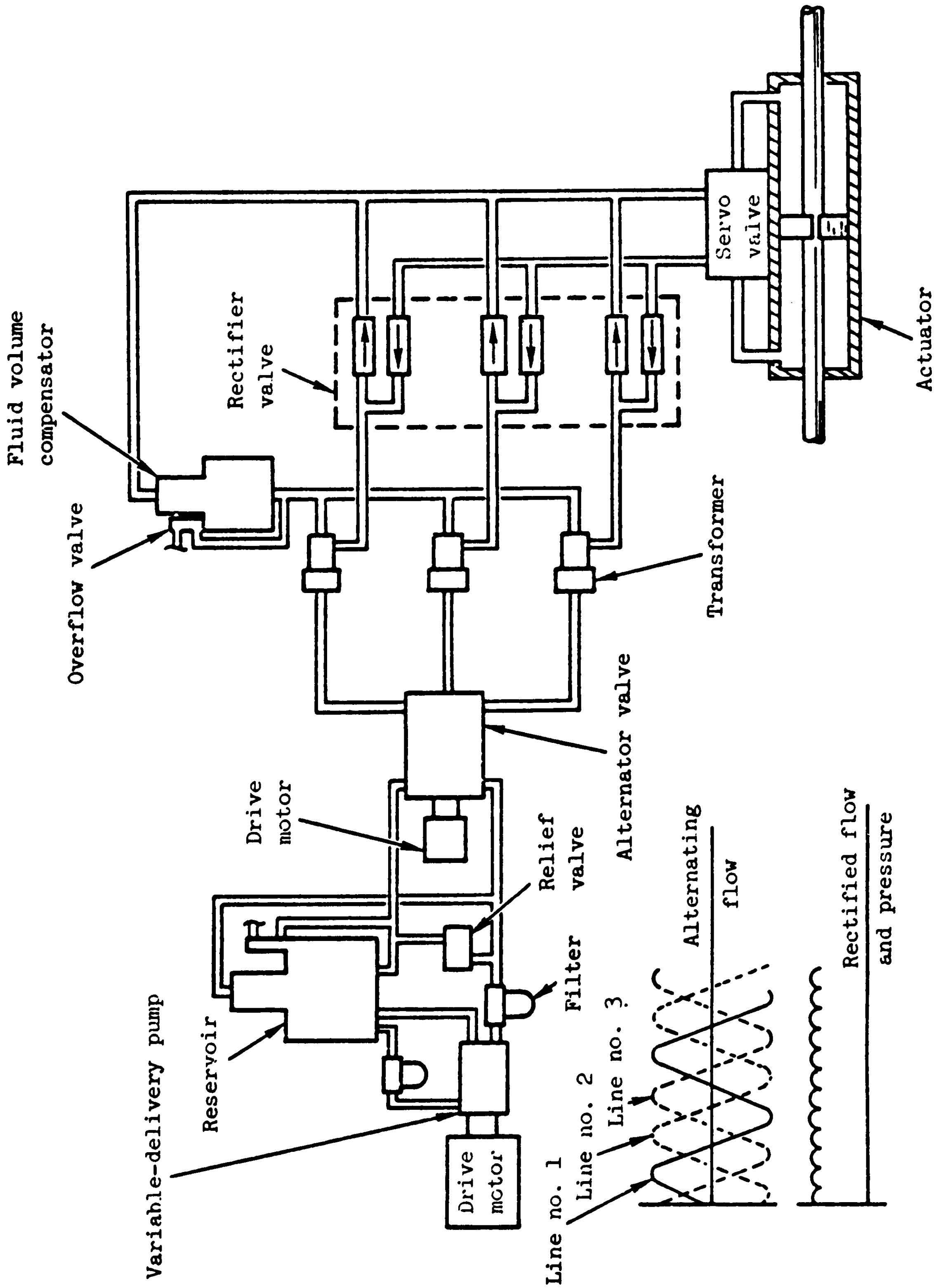

FIGURE 5-168. Three-line pulsating system.

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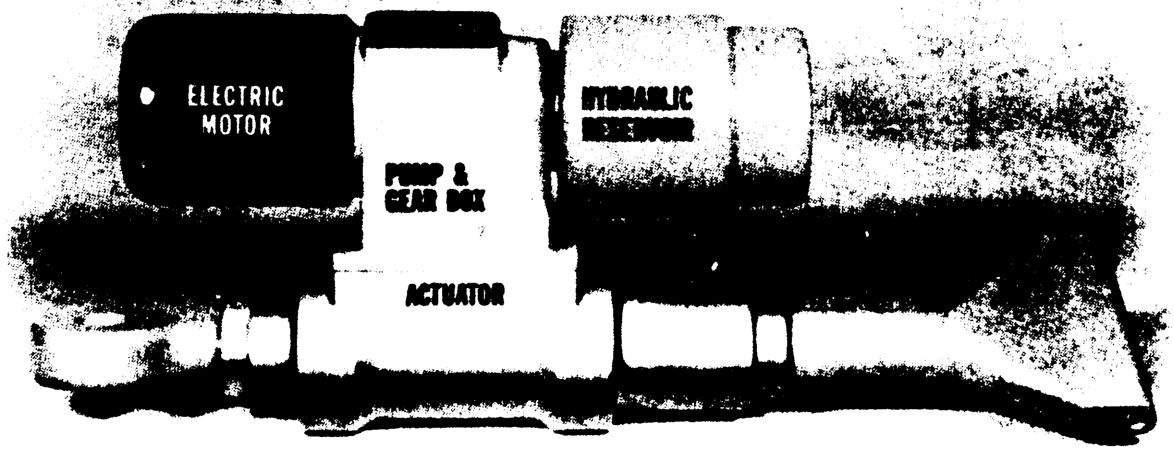

FIGURE 5-169. Hydraulic package power concept.

5.10.2.1.6 Leakage isolation. Recent research has resulted in the development of devices to sense leakage or pressure loss of hydraulic fluid in a circuit and automatically isolate the hydraulic pressure line in that portion of the system. One such unit is known as a flow difference sensor. Figure 5-170 illustrates the application of the device in a critical flight control hydraulic system circuit. The flow difference sensors are located in areas removed from potential damage areas. In the event of damage to the lines or the actuator that results in a given leakage rate, the flow difference sensor automatically shuts off the hydraulic pressure flow to the actuator. This prevents failure of the hydraulic system itself so that it is still able to operate other or more critical units it is designed to service. The operational principle of the unit, as shown in Figure 5-171, uses two sets of orifices to create pressure drops across two areas, giving two forces proportional to flow. These forces are applied to a summing lever assembly so that equal forces (correct flows) balance each other out. An unbalance of the forces causes the lever assembly to move. This allows the shutdown spool to move to the right, cutting off the pressure-line flow to the actuator. Once the shutdown spool has cut off the press re-line flow to the actuator, the pump pressure at the left end of the shutdown spool keeps it in the shutoff

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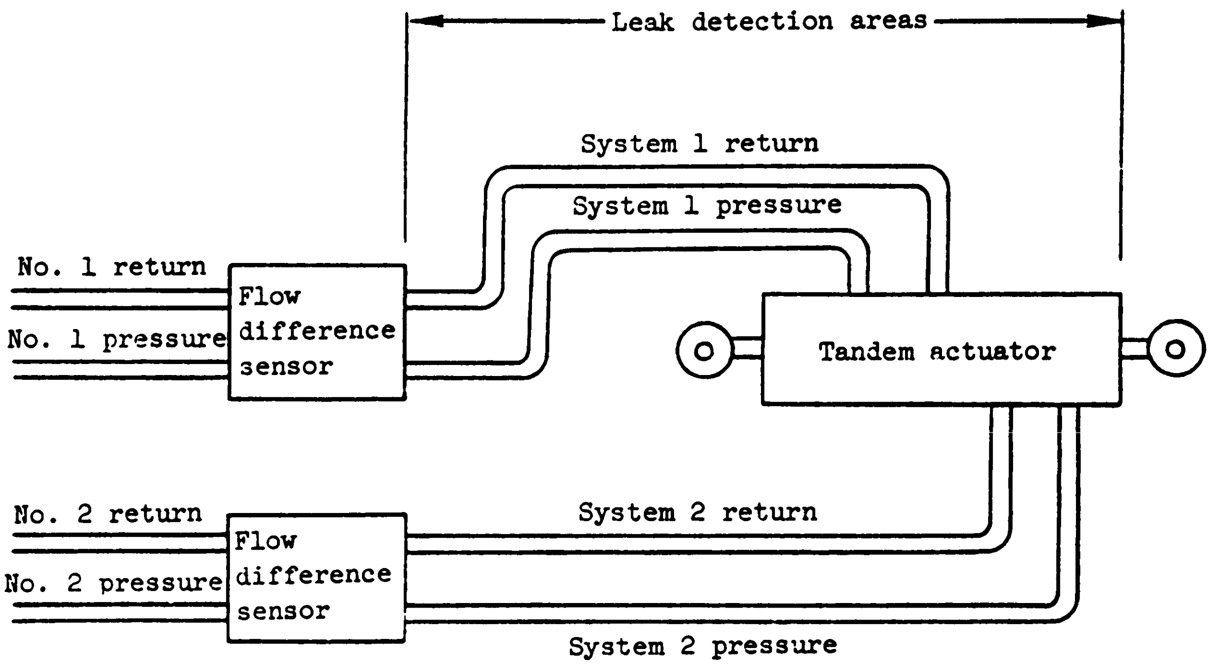

FIGURE 5-170. Flow difference sensor application.

position. A check valve is used to prevent reverse flow when supply flow is shut off. A preload spring, loading the summing lever in one direction, is used to establish a leakage flow detection threshold. To obtain a reasonably linear pressure-to-flow relationship with minimum temperature sensitivity, it is necessary to use sharp-edged orifices in a staging configuration. For low flows, a small orifice is used. As the flow increases, a second, larger orifice is opened up. A monodirectional damper is incorporated in the right end of the shutdown spool. This damper delays the shutdown long enough so that the normal transmission line delay characteristic between pressure and return line transient flow does not cause shutdown. A reset button is incorporated to allow resetting of the unit manually after it is tripped.

5.10.2.1.6.1 Reservoir level sensor systems. Reservoir level sensor (RLS) systems have 'been developed to detect the loss of hydraulic fluid quantity in a system reservoir and shut off the pressure to a damaged circuit. This circuit isolation technique is used to retain integrity of the hydraulic power system for essential functions in other portions of the system's circuits. The basic principle of the technique is shown in Figure 5-172. The hydraulic reservoir has a shaft with an integral cam that extends when the fluid level is depleted. The cam mechanically actuates pilot valves as it travels past them. When the No. 1 pilot valve is actuated, it directs system pressure to shutoff valve No. 1, causing it to go to a closed position. This isolates circuit No. 1 from the hydraulic system pressure supply. The pilot valve remains in the actuated position after the shaft cam has traveled beyond the

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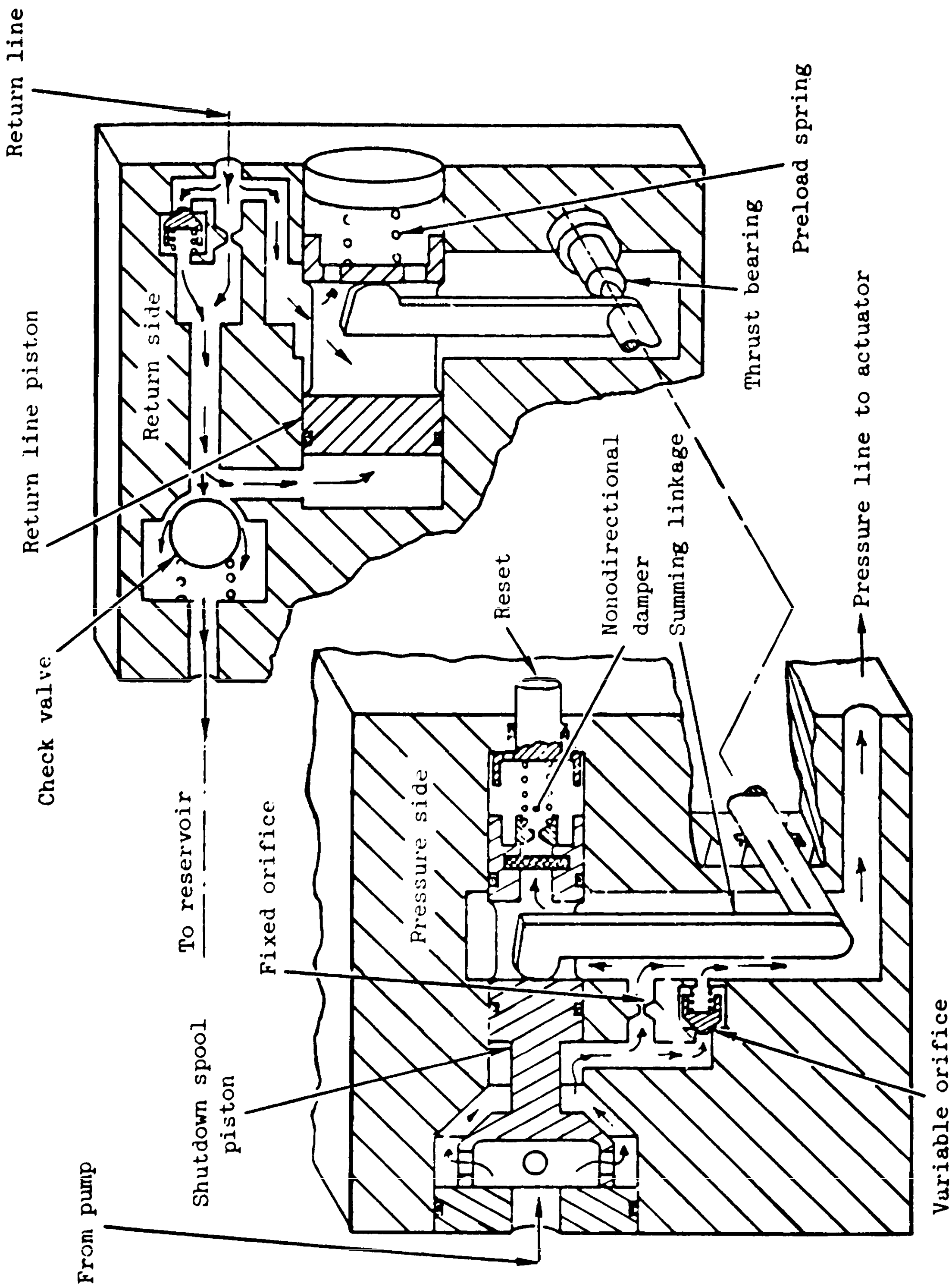

FIGURE 5-171. Flow difference sensor.

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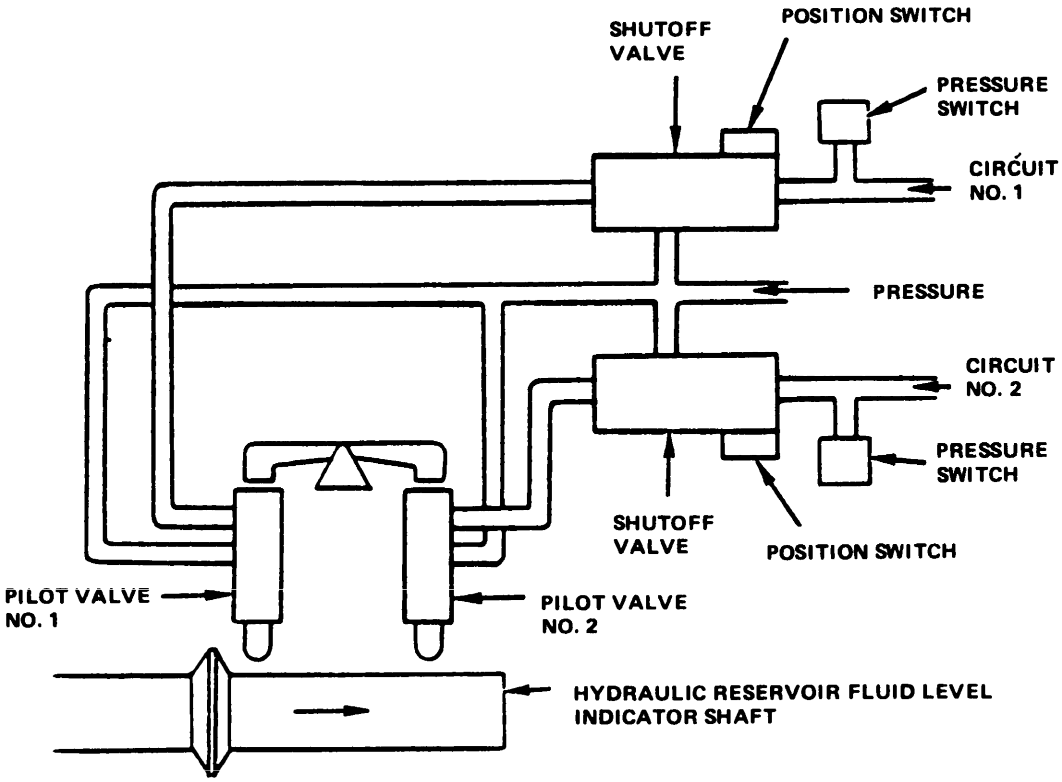

FIGURE 5-172. Reservoir fluid level sensing.

initial actuation point. If circuit No. 1 had sustained battle damage, then by isolating it from the pressure supply system, the loss of hydraulic fluid would be stopped, and the reservoir fluid level shaft would not continue to extend. If the damage is in circuit No. 2, then shaft extension would continue until pilot valve No. 2 would be actuated. This would direct system pressure to the shutoff valve that would isolate circuit No. 2. At the same time, a mechanical interconnect between the two pilot valves would position pilot valve No. 1 back to its initial position and allow the shutoff valve for circuit No. 1 to reopen. Each of the shutoff valves contain a position and pressure tranducer switch that is used to provide the pilot with hydraulic circuit condition information.

5.10.2.1.6.2 Return pressure sensor. In conjunction with reservoir level sensor (RLS) systems, return pressure sensor (RPS) devices are being used. This type of system monitors the pressure of the return side of an essential circuit. If the return side pressure falls below a minimum value, it provides a signal to an RLS system, which prevents switching of system pressure into that specific circuit that would result in additional loss of hydraulic system fluid . The RPS may be used independent of the RLS.

5.10.2.1.6.3 Hydraulic lock. To prevent hazardous actuation rate degradation or "hydraulic lock" of critical hydraulic components, such as flight control actuators, due to restriction or blockage of hydraulic return line or components, runaround check valves as shown in Figure 5-173 may be used. This

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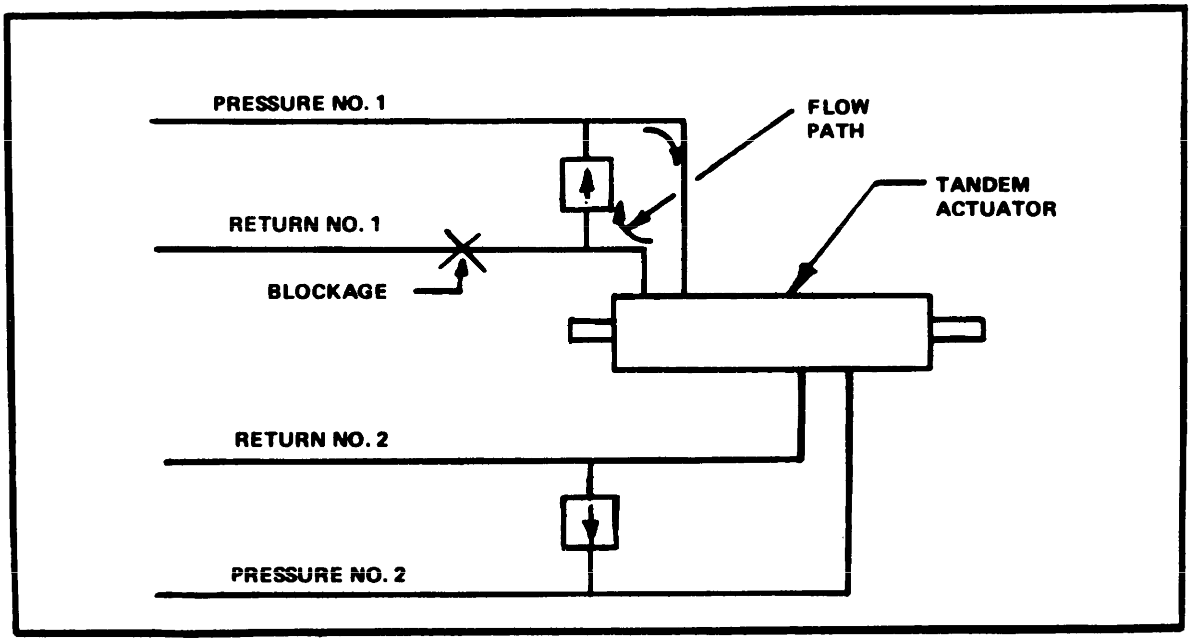

FIGURE 5-173. "Runaround" check valve system.

type of protection is applicable only to tandem balanced arm actuation systems. Its principle of operation is to permit the blocked return-line fluid, which will be at a higher than normal system pressure to flow through the check valve and enter the pressure side of the actuator.

5.10.2.2 Detail design considerations. Hydraulic systems are composed of many difference types of components. They include pumps, actuating cylinders, filter assemblies, accumulators, valves, pressure switches, gauges, servo valves, etc. The following techniques should be considered in the initial design process to select the most beneficial one for the specific application.

5.10.2.2.1 Material selection. Construct components from materials that will resist failure from cracking or shattering when struck by a projectile or span. This technique is particularly applicable to low or unpressurized components such as reservoirs, where a degree of system capability would be retained if the damage is contained within those limits that still permit the unit to hold the minimum amount of hydraulic fluid for system operation. Figure 5-174 illustrates the basic principles of the concept. The selection of nonbrittle material also serves to limit the amount and rate of flammable fluid that would be liberated and minimize secondary spallation hazards to nearby sensitive components.

5.10.2.2.2 Ballistic resistance. Consideration should be given to the integral construction of units from ballistic-resistant materials such as dual-hardness or electro slag remelt steel armor. The material serves two purposes: (1) to defeat the ballistic threat, and (2) to perform its operational function. Figure 5-175 shows an experimental servoactuator unit for a

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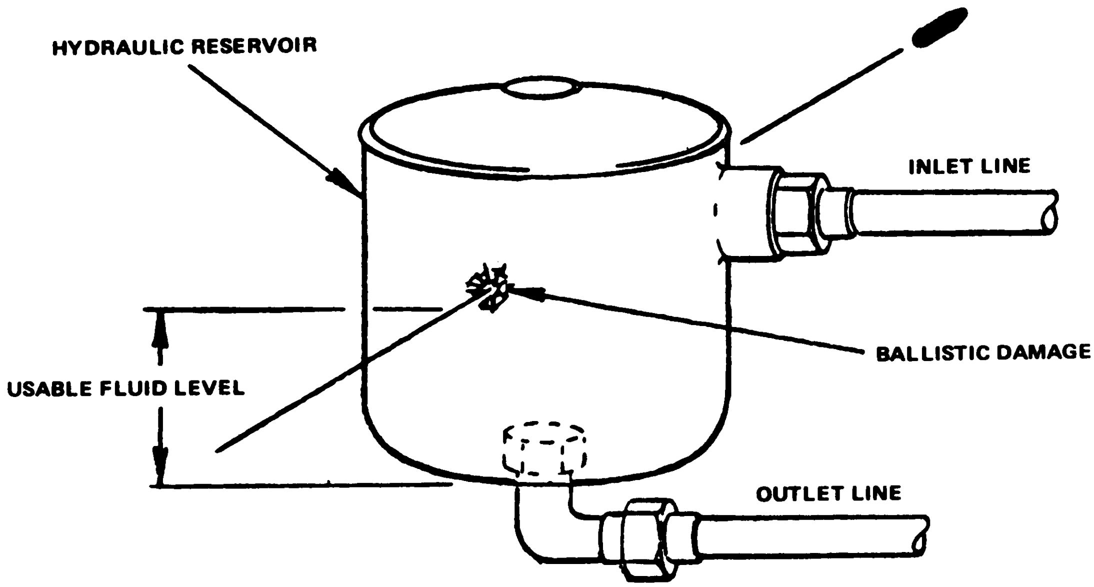

FIGURE 5-174. Ballistic damage-tolerance application.

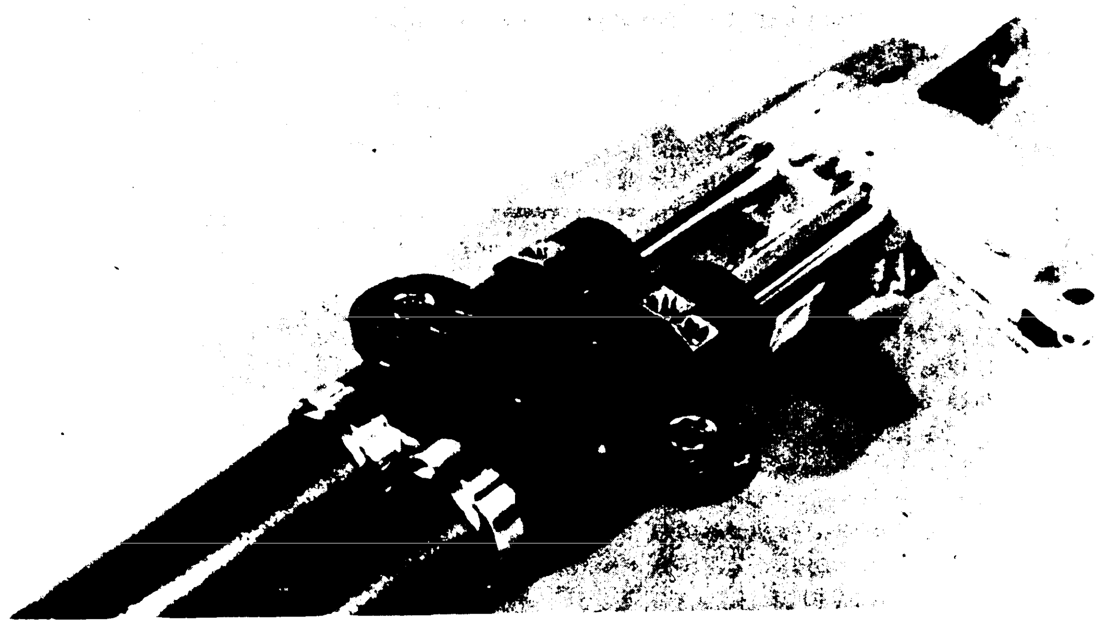

FIGURE 5-175. Helicopter servoactuator fabricated from DPSA.

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helicopter, with the cylinders fabricated from dual property steel armor (DPSA). Care must be taken in this design to select the proper thickness of electro slag remelt (ESR) or DPSA, not only to defeat the projectile threat but to pre-elude any internal dents of the cylinder wall resulting from projectile impact. Where such construction is not feasible and ballistic protection must be provided, parasitic armor, shaped to provide the most effective coverage, should be considered and can also be used in conjunction with integral armored components to protect remaining critical vulnerable areas. Figure 5-176 shows a helicopter servoactuator unit protected by a parasitic armor shield fabricated from dual-hardness steel. In conjunction with the aforementioned technique, the incorporation of flow passages within the main body of the unit should also be considered, rather than the use of external hydraulic lines that are highly sensitive to projectile and secondary fragment damage (Reference 23). Another technique for providing a level of ballistic resistance is to incorporate a steel cylinder sleeve within an aluminum cylinder body to act as a deformable barrier to preserve the integrity of the hydraulic power system. Figure 5-177 illustrates the concept. Ballistic tests have shown that some steel sleeve deformation from projectile (.30 caliber) impact could be sustained and still retain system operation (Reference 23).

5.10.2.2.3 Miniaturization/integration. Vulnerable areas of hydraulic systems are the sum of vulnerable sections of each component and the hydraulic lines connecting them. Significant reduction of such areas is possible by miniaturization of the units and/or integration of the units into packages that can more easily and effectively be protected. The use of higher pressure hydraulic systems (4,000 versus 3,000 psi) would enhance miniaturization of actuator sizes. However, care should be taken to assure that surface stiffness and flutter conditions are met. Integrated actuator packages would also enhance use of higher system pressure and eliminate some hydraulic lines. Combinations of filters, selector valves, pressure transducers, etc, have been designed for improved maintenance and accessibility benefits that can complement survivability enhancement features as well.

5.10.2.2.4 Thermal tolerance. Where essential hydraulic components are located in areas where short-term fires or high-temperature conditions may be generated by small-arms fire, metallic static and dynamic fluid seals should be used to prevent or extend time to failure. A degree of internal fluid flow should also be provided to prevent or prolong burn-through and failure. The flow passages should be located on the side of the unit away from the most probable line of hostile weapon fire.

5.10.2.2.5 Installation. Consider primary and secondary damage mechanisms because of weapons effect upon hydraulic power equipment and distribution systems. Use the following techniques to minimize system malfunction or to prevent failure when subjected to weapon effects:

a. Route critical hydraulic system lines along the heaviest portion of the structure that will provide the best shielding from the critical aspects of anticipated hostile threats.

b. Install dual or multiple flight control hydraulic generation and distribution systems as far apart as practical.

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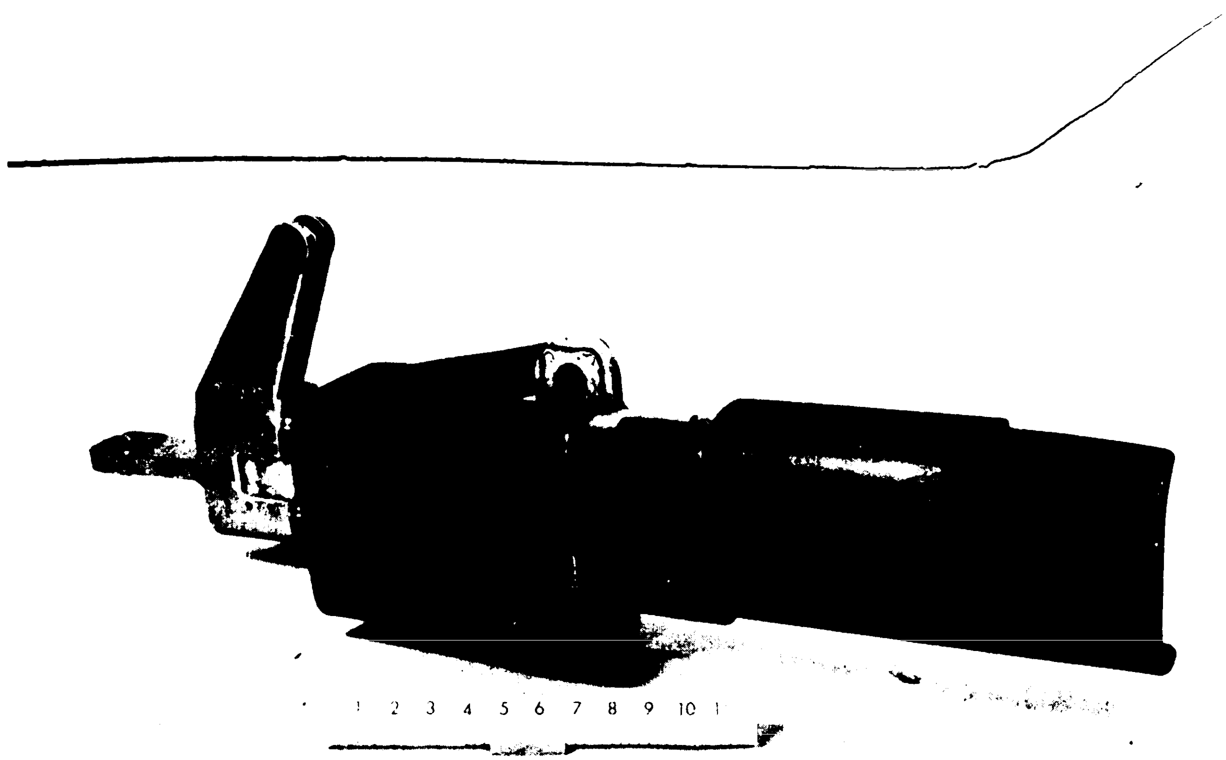

FIGURE 5-176. Helicopter servoactuator protected by parasitic armor shield.

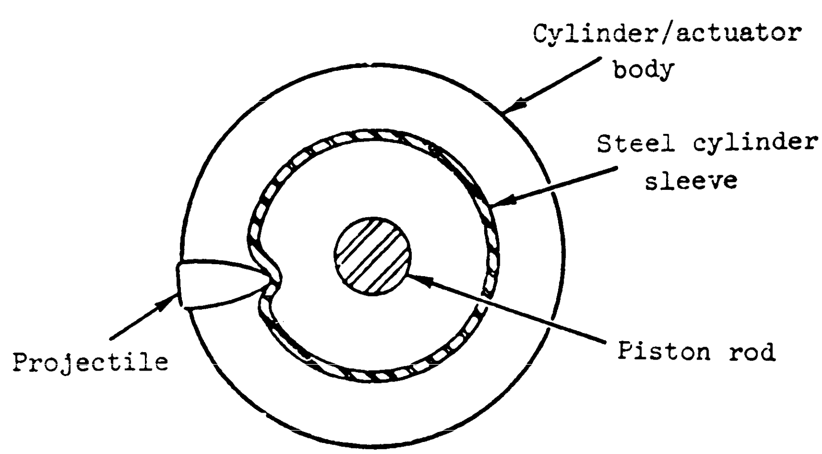

FIGURE 5-1770 Cylinder steel sleeve barrier.

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c. Separate dual or multiple flight control hydraulic generation and distribution systems with sufficient natural or armor shielding to prevent or minimize simultaneous failure of such systems from penetration by multiple fragments from high-explosive warheads or structural damage from weapon blast effects.

d. Keep critical system line lengths to a minimum, consistent with good shielding and separation practices.

e. Use clips or frangible clamps to allow hydraulic lines to pull free and remain intact if structure is damaged or distorted by hostile weapon blast effects.

f. Use frangible sections of structure, where bulkhead fittings are employed, to allow the hydraulic lines and fittings to remain intact if structure is damaged or deformed by hostile weapon effects.

g. In fire and high thermal hazard area, use high-temperature resistant lines, such as stainless steel, to prevent or prolong time to failure. Consider using coiled tubing in such areas where hydraulic hoses would fail when exposed to fires or high-temperature torching of hot engine gases.

5.10.2.2.6 Hydraulic systems HEL protection. The primary protection techniques for hydraulic power systems against HEL weapon effects are the use of thermal barriers and ablative materials on components and distribution lines/hoses, masking of critical elements behind heavy structures and less essential components, and hardening of the structural shell in critical areas to prevent burn through. In the detail design of hydraulic components, consider means to make them more resistant to high-thermal conditions that may be created by HEL weapon effects. Elastomer seals are generally the first element to fail under high-thermal environments. Consider the use of metal seals to delay leakage and/or failure of hydraulic components and fittings. In critical areas, consider the use of continuous hydraulic system flow to act as a heat sink to conduct thermal energy away and enhance the capability of the system to maintain its integrity or delay the failure so that its effects are minimized. In areas where liberated hydraulic fluid would constitute a fire hazard, suppression techniques, such as intumescent materials, void fillers, and fire detection and suppression systems should be considered.

5.10.3 Pneumatic systems.

5.10.3.1 Pneumatic systems function. Pneumatic systems are generally utilized for secondary subsystem operation or as emergency backup systems to secondary hydraulically powered subsystems, such as landing gear and wheel brake systems. The potential secondary hazard effects of high-pressure pneumatic systems when damaged by weapon effects must be considered. Penetration by projectiles or spallation is the major kill or damage mechanism for such systems, and extremely high energy may be released and cause major aircrew, airframe, or subsystem damage (Reference 23).

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5.10.3.2 System considerations.

5.10.3.2.1 Fluid medium selection. Selection of the pneumatic medium is chiefly limited to compressed atmospheric air, nitrogen, or turbine engine bleed air. Basic aircraft considerations usually dictate this choice, unless the high temperature of engine bleed air is found to be more hazardous than mechanically compressed air, and this factor may out-weigh other penalties.

5.10.3.2.2 Circuit design. Consider survival enhancement during the initial or modification design phase by applying the following techniques that are suitable for the specific circuit:

a. Design basic pneumatic circuits to minimize size and complexity of the system area vulnerable to nonnuclear weapon effects. Provide pressure-line shutoff valves or devices (circuit breakers) to isolate nonessential circuits during exposure of the aircraft to hostile weapons.

b. Use automatic failure and shutoff systems to prevent or limit secondary failures that could occur from weapon effect damage.

5.10.3.3 Detail design considerations

5.10.3.3.1 Components. These include compressors, reservoirs, actuators, cylinders, filters, moisture removal elements, gauges, valves, pressure regulators, etc. Consider using the following techniques to minimize malfunction or prevent failure from weapon effects:

a. Construct high-pressure components to resist explosive disintegration when struck by projectiles or fragments to prevent or minimize structural or other subsystem damage from the released gases or fragments from the component.

b. Design component attachment lugs to fail, instead of component critical sections, when the component or structure is subjected to blast or other deformation loads because of hostile weapon effects.

5.10.3.3.2 Lines/hoses. Select pneumatic lines and hose to resist damage or failure when subjected to deformation, fire, or high-temperature torching effects. Consider repair and replacement penalties for various types of pneumatic line configurations such as standard flared or flareless tube connectors, and brazed or welded line fittings. Quicker and easier repair of combat damage with standard connectors may be preferred over lower weight penalties of brazed or welded systems.

5.10.3.3.3 Installation. Consider primary and secondary damage mechanisms because of weapon effects upon pneumatic power equipment and distribution systems. Use the following techniques to minimize system malfunction or to prevent failure when subjected to weapon effects.

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a. Route essential or critical pneumatic lines close to heavy structures to obtain the most natural shielding from projectiles or fragments as practical, as well as the least structural deformation-induced damage from weapon effects.

b. Separate redundant pneumatic lines as far as practical, while providing natural or armor shielding to prevent or minimize simultaneous damage and or failure from multiple fragment or spallation weapon effects.

c. Provide pull-away clips or frangible clamps to allow pneumatic lines to remain intact if attaching structure is deformed by weapon blast effects.

d. Keep critical pneumatic line lengths as short as practical to minimize their vulnerable area.

e. Use frangible sections of structure where pneumatic bulkhead fittings are attached, to minimize line failure due to structural deformation from weapon effects.

5.10.3.4 Pneumatic systems HEL protection. Protection of pneumatic fluid power equipment against HEL weapon effects can be achieved with the same techniques specified for the hydraulic system elements. Consideration should be given to use of lower pressure, larger size lines or ducting to minimize the probability of failure, or malfunction from a burn through by a laser weapon and the potential for creation of secondary hazards from high-pressure pneumatic system element disintegration.

5.10.4 Fluid power repairability/maintainability. Fluid power includes both hydraulic and pneumatic power systems. Hydraulic system design shall consider the routing of the hydraulic lines to avoid areas where ignition of flammable fluids from damaged lines may cause increased damage to the aircraft system. Means to detect and isolate damaged hydraulic circuits shall be considered to limit loss of hydraulic fluid and minimize the need to repair or replace other hydraulic system components.

5.10.4.1 Detail design of system. Careful consideration must be given to the detail design of hydraulic and pneumatic power systems in aircraft. The distribution lines and/or hoses shall be designed so that ease of access, inspection, removal, and replacement of damaged lines/hoses is achieved. Special evaluation shall be made of the line connector features to ensure that minimum disassembly of other components is required to disconnect and reconnect the lines/hoses. Where brazed or welded line connections are contemplated, consideration for operational unit skill, equipment, and available facilities shall be made. Provisions shall be considered in hydraulic systems to prevent the total loss of a system through use of circuit failure detection and isolation techniques to minimize possible damage to the hydraulic pumps from cavitation. Such provisions also may be employed to limit the amount of hydraulic fluid liberated by battle damage and thereby minimize potential fires and other secondary damage. Components such as pumps, valves, filter assemblies,

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etc, in hydraulic or pneumatic systems should be as interchangeable as possible so that the spare parts required for repair may be minimized and effective cannibalization from one aircraft to another permitted. Pressurized vessels, such as hydraulic or pneumatic accumulators, shall be designed to be nonshatterable when struck by ballistic threats. This is to minimize the probability of secondary damage fragments being created that would cause additional repair efforts. Consideration shall also be made for the incorporation of high-temperature blowout plugs in the high-pressure gas sections of such vessels that may be exposed to fires or hot gasses created by hostile weapon effects. These would be similar to those used in landing gear wheels to prevent tire blowouts due to excessive heat buildup. Where hydraulic lines are installed in areas of potential high-temperature hazards due to hostile weapon effects, consideration of thermal protection techniques shall be made.

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5.11 Environmental control system. Environmental control systems (ECS) are comprised of pressurizing, cooling, heating, ventilating, moisture control, and environmental protection subsystems and components. Portions of these subsystems can be essential for mission completion and/or aircrew survival.

5.11.1 Environmental control system damage effects. The environmental control system includes the pressurizing, cooling/heating, ventilating, contamination control, and moisture control subsystems. The general specification for these systems is MIL-E-38453 (Reference 249). The ECS is rarely listed as the cause of a mission abort because of the complexity of the interface between the ECS and all other subsystems in the aircraft. The secondary effects following an ECS failure are normally entered on the accident and damage reports under the heading of primary cause. Table 5-XXIV is an abbreviated listing of aborted missions that are representative of this situation. The designer can see how easily the original cause can be overshadowed by the secondary effect. It is also easily recognized that weapons effects are capable of causing the failures that are listed. This listing was compiled for a wide range of low- and high-performance aircraft to provide the designer with a comprehensive understanding of secondary hazard considerations. It indicates the importance of evaluating the effect of the aircraft's operational environment along with the primary failure that may be caused by hostile weapons. The altitude, speed, maneuvers, weather, mission objectives, and terrain can be contributing factors to a condition that could cause loss of mission or loss of the aircraft. Such hazards must be considered by the designer early in the design process in order to prevent or minimize them in his individual design configuration. The designer should, therefore, identify the portion of the ECS that is essential for mission completion and for aircrew survival. The ECS should be designed to service the mission-essential elements of the other aircraft subsystems in a suitable order of priority to enhance total system survivability and capability if subjected to ballistic impacts.

5.11.2 Design criteria.

5.11.2.1 Cooling/heating. Environmental cooling and heating systems are used to maintain the temperature of crew stations or subsystems within the limits required for comfort and proper operating conditions. Design systems to service mission-critical aircrew stations and equipment in order of priority for mission completion and aircrew/aircraft survival. Consider the following techniques to obtain acceptable survival values when aircraft is subjected to ballistic weapon effects (Reference 180):

a. provide redundant or emergency cooling and heating system that will provide necessary temperature control for time necessary for mission completion or crew/aircraft recovery.

b. Provide emergency, automatic, or aircrew-operated shutoff or isolation of high-temperature heating systems, the failure or malfunction of which, caused by weapon effects, would result in unacceptable crew comfort or performance, other subsystem malfunction or failure, or secondary hazard conditions, such as internal fires, smoke, and toxic fumes.

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TABLE 5-XXXIV. Representative mission aborts due to ECS problems.

Reason for Mission Abort	Component/Assembly Failed or Damaged	Secondary Problems
Loss of aircraft subsystems functions	Bleed-air duct	Hot gas torching
	Air-conditioning system	Fogging of windshield
	Rain removal air duct	Fire
Loss of cabin pressure	Anti-icing duct	Electronics overheat
	Hot-air duct	
	Air-conditioner duct	
	Duct coupler	
Engine(s) shutdown	Rain removal attachment	Smoke in cockpit
	Cracked heat exchanger	Oil pressure to zero
	Hot-air duct	Smoke and fog in cockpit
	Seventh-stage air line	
	Bleed-air duct	
	Nose refrigeration duct	
	Generator cooling duct	
	Anti-icing duct	Engine fire

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TABLE 5-XXXIV. Representative mission aborts due to ECS problems (continued).

Reason for Mission Abort	Component/Assembly Failed or Damaged	Secondary Problems
Human incapacitation	Mixer valve	Frostbite - copilot
	Cockpit heater	Smoke and burns - pilot
	Canopy seal	Hypoxia - crew
	Primary heat exchanger	Nausea - pilot
	Window heater terminal	Nauseous fumes - cockpit
	Isobaric control	Bends - navigator
	Shutoff valve	Hypoxia - navigator
	Door seal	Bends - crew
	Water separator	Hypoxia - crew
	Pressure controller	Electrical fumes - eye irritation - aircrew
	Temperature control	
	Magnetic amplifier	Dehydration - pilot
	Temperature control box	
	Safety valve seal	Hypoxia - pilot
	Pressure regulator	Bends - gunner
		Bends - pilot and EWO
	Catalytic filter	Bronchial, throat, and chest irritation

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TABLE 5-XXXIV. Representative mission aborts due to ECS problems (continued).

Reason for Mission Abort	Component/Assembly Failed or Damaged	Secondary Problems
Miscellaneous	Auxiliary cooling tap-off line	Radar and Doppler failure
	Bleed-air manifold	Hydraulic failure, flight control failure, smoke in cockpit
	Camera heat duct	Short-circuited wires in servo's (elevator, rubber) yaw damper
	Ram-air duct	Interference with elevator control cable caused aircraft to porpoise on low-level run

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c. Locate refrigeration unit components (heat exchangers, air cycle machine, etc) so as to provide natural or armor shielding from weapon effects.

d. Construct-components to resist shattering or explosive disintegration that could cause damage or failure of other subsystems, or injury to personnel from fragmentation.

e. Keep high-temperature gas/air line pressures as low as possible to minimize secondary hazards from penetration of such lines by projectiles or fragments

f. Route high-pressure and high-temperature gas/air lines to avoid potential fire hazard areas. Route such lines in channels or other heavy structure to isolate them from other subsystems as illustrated in Figure 5-178.

g. Position hot gas/air line connections in areas where their failure from weapon effects will cause the least secondary hazard from release of high-temperature air/gas.

h. Design high-speed rotating equipment of refrigeration unit so that its containment capability following exposure to weapon effects is not lost.

i. Provide a pre-cooler heat exchanger near the source of high temperature air to reduce the temperature of the air ducted throughout the aircraft to a level that minimizes the hazards resulting from penetration of ducting by projectiles or fragments.

j. Provide a leak detector along high temperature ducting to warn the crew of a hazardous high temperature leak resulting from penetration of ducting by projectiles or fragments.

5.11.2.2 Pressurization systems. Mission requirements for aircraft pressurization systems are, with few exceptions, altitude dependent. The crew station (cockpit) pressurization system, canopy/hatch inflatable seals, crew pressure suits, avionics, fuel, and hydraulic systems are the major subsystems that may require pressurization. Malfunction or degradation may influence survival or mission completion. The crew anti-G suit is not altitude dependent. Its operation is required for any altitude where high-maneuvering "G" forces are required. Loss of this function could significantly affect mission completion and survival of the aircraft and/or crew. Consider the following techniques which may be applied to specific systems that would enhance mission completion and crew/aircraft survival:

a. Provide redundant and separate pressurization sources for essential crew or subsystem operation. Design sensing and control systems to provide pressurization on a priority basis if aircraft pressurization system capabilities may be degraded by nonnuclear weapon effects.

b. Design and construct pressurization system elements of materials to resist explosive shattering and/or complete failure if struck by projectiles, fragments, or secondary spallation.

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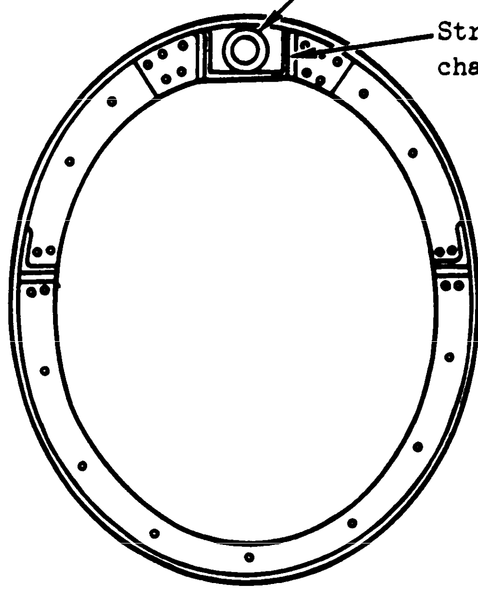

FIGURE 5-178. Hot-air line isolation

c. Design crew station pressurization systems to resist explosive decompression due to sudden loss of pressure source by means of crew station inlet check valves (see Figure 5-179).

d. Use emergency ram-air pressurization for critical subsystems where only single pressurization sources are available or other trade considerations (i.e., vulnerability, complexity, safety, reliability, or weight) or modification factors are involved.

5.11.2.3 Ventilation/contamination. Proper ventilation and contamination control may be essential for specific subsystem performance needed to achieve mission completion and/or aircrew/aircraft survival. These subsystems may include aircrew stations, engine bays, armament functions, and other critical compartment so Provide priorities for subsystem operation, and incorporate these into the basic design phase to direct ventilation to those subsystems whose failure or malfunction would degrade the aircraft/aircrew survivability or mission completion. Consider the following techniques to obtain optimum survival of the aircraft/aircrew:

a. Provide positive ventilation to those compartments and areas where flammable vapors or liquids may migrate if their containers have been damaged by ballistic weapon effects.

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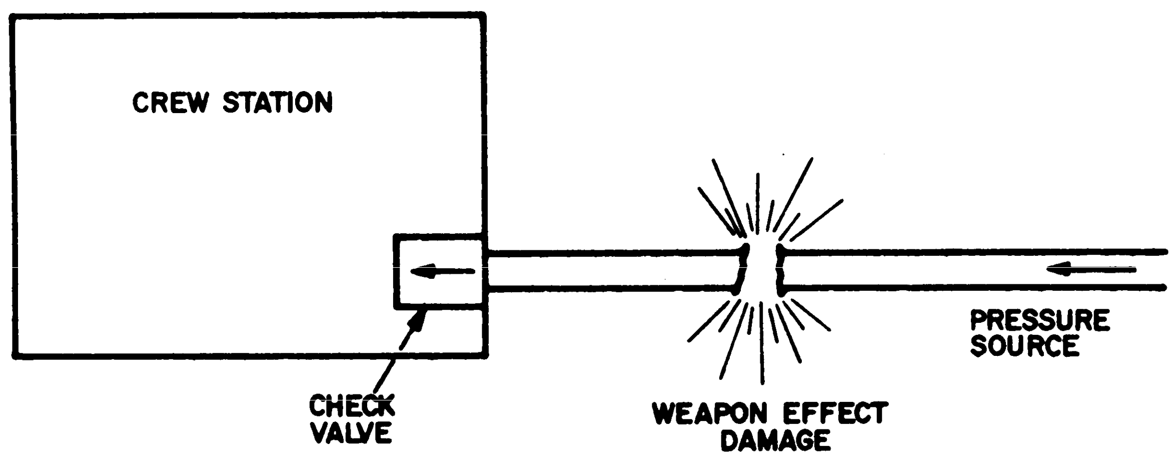

FIGURE 5-179. Crew station pressurization check valve.

b. Design and/or construct system components to resist cracking and shattering when struck by a projectile.

c. Route ventilation lines to avoid secondary hazard areas where fire explosions, smoke, or toxic fumes may be ingested into aircrew stations.

d. Use ram-air emergency ventilation for aircrew stations and critical subsystems when the normal system has failed or malfunctioned.

5.11.2.4 Moisture control. Moisture control is required for the aircrew compartment and electronic equipment. Introduction of moisture into the aircrew compartment because of control failure from weapon effects could result in poor visibility for the aircrew, and the moisture could cause failure or malfunction of essential electronic equipment. In applications where moisture control and electronic equipment is accomplished through the use of a liquid coolant fluid, secondary hazards may be caused by the release of coolant liquid or vapor into the aircrew compartment area that would be detrimental to the crew's performance or health and lead to loss of the aircraft or to mission failure. In addition, a leak in the liquid coolant circuit due to combat damage will result in loss of cooling for the electronic equipment and subsequent failure of the electronic equipment. Consider the following techniques to enhance aircrew survival:

a. Use an air coolant system In preference to a liquid coolant system where vulnerability of the latter is greater or would create an unacceptable secondary hazard.

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b. If a liquid coolant is used, select one that will prevent or minimize toxic or fire hazards.

c. Avoid locating liquid coolant lines in aircrew stations.

d. Locate moisture controls where they will be provided natural masking from weapon effects.

e. Adequate means for windshield defogging should exist even with the air conditioning shut-off valve closed.

5.11.2.5 ECS installations.

a. Insure that air flows from cockpit to cabin or afterstation. This is to prevent the movement of fire, smoke, or toxic gases from other parts of the aircraft into the cockpit area.

b. Materials used in the ECS should not emit toxic or explosive gases when exposed to elevated temperatures that are caused by weapon effects.

c. Materials used in the ECS should resist explosive shattering if struck by projectiles, fragments, or spallation.

d. Fire hazard due to high-temperature air may be minimized by isolation, precooking, and the use of noncombustible material in areas of potential hot-air impingement. Line routing shall prevent or minimize the hazards associated with weapon effects.

e. Mission-essential components shall be In areas where they receive natural shielding or armor protection from weapon effects.

5.11.3 Environmental control system HEL protection. ECS design techniques should include methods to prevent secondary effects, such as toxic fumes, smoke, etc. from causing injury or damage to the crew or other equipment. Utilization of inherent masking, materials that do not emit toxic fumes when burned, special coating, etc. should be considered.

5.11.4 Environmental control system repairability/maintainability. Environmental control includes the pressurization, cooling/heating, ventilation, moisture control, rain removal, and contamination control systems. Each of these systems employs various types of equipment, ducting, and lines. Battle damage repair is predominantly concerned with removal and replacement; therefore the main consideration shall be for ready access to inspect and replace. The ducting in some systems may be of a size and type of construction that it may lend itself to repair. For this possibility, the capability to repair in place as well as to remove, repair, and replace shall be considered. In the installation of lines, care shall be exercised to position connectors so that removal and replacement of damaged sections may be accomplished with a minimum of disturbance to other components or structures.

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5.11.4.1 Design limitations. The use of hot-gas systems in an aircraft should be minimized to prevent damage to structure and/or other sensitive subsystem components from punctured hot-gas ducts or equipment. Where such systems cannot be avoided, provisions should be made to permit shutoff of the hot gas as close to the source as possible. The ducting for these systems should be designed to permit rapid removal and/or repair for battle damage.

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5.12 Oxygen systems. Oxygen breathing systems are required for human flight at altitudes where without such assistance degraded functions and/or physiological damage can occur. The only oxygen stored in the human body is that being transported by the blood stream. Although muscles can function temporarily without oxygen, when doing so they build up toxic fatigue products that limit the muscle activity. The tissues most sensitive to oxygen, i.e., the central nervous system (brain and eyes), cannot tolerate a lack of oxygen. A human brain represents approximately 2 percent of total body weight, but demands about 20 percent of the total body oxygen consumption. Table XXXV provides information on the altitude limits for human tolerance (Reference 171). Conventional oxygen supply systems utilize either low-pressure gaseous supply systems or liquid oxygen high pressure systems. If low-pressure gaseous systems are used, consideration must be given to methods of providing redundant supplies to crew members in the event one supply cylinder is damaged. Figure 5-180 shows such arrangements for single and multiple place aircraft (Reference 171). Liquid oxygen supply systems are generally of two types - a single container with a single distribution line, or two or more containers with two distribution lines. Schematics of these type systems are contained in Reference 245. Considerable hazards can be created from rapid escape of oxygen from a container damaged by nonnuclear weapon effects. Intense fires can be experienced if combustible material is in the area of such leakage.

5.12.1 Oxygen systems ballistic protection. Consider the following methods to minimize the effects of combat damage (Reference 5):

a. Place breathing oxygen supplies outside of crew compartments where its damage from weapon effects would cause crew injury, inability to complete the mission, or abandonment of the aircraft. Provide a fire and fragment resistant barrier between the crew station and oxygen supply compartment to prevent or minimize crew injury from an exploding oxygen bottle or converter.

b. Provide fire resistant or suppressant materials in the crew stations to prevent or minimize thermal hazards, toxic fumes, or smoke that would cause crew performance degradation or abandonment of aircraft.

c. Design oxygen container supports to withstand the same inertial loads as the seats of the occupants. Ensure maximum container support, and design to prevent the container from tearing loose when hit by gunfire. Liquid oxygen support brackets are an integral part of the container, therefore, securely fasten them to the airframe to meet the same combat requirements. Locate portable oxygen containers in areas where the likelihood of fire is remote,.

Considerable research is being conducted to develop oxygen supply systems that do not depend upon pressure storage methods. These systems extract oxygen from water and other substances at the rate demanded by the crew usage. Substantial reduction in potential fire hazards and explosive fragmentation from damaged pressurized containers can be achieved. Consult with the responsible activity for current information on the status of such systems.

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TABLE 5-XXXV. Human altitude limits.

Altitude (Ft)	Limits
5,000	Maximum for normal night vision without supplemental oxygen
8,000	Altitude at which supplemental oxygen should be used
10,000	Maximum without continuous use of oxygen
15,000	Maximum for emergency without use of oxygen
20,000	Altitude at which consideration should be given to use of pressurized cabins
23,000	Altitude at which there is evidence of repressurization sickness
25,000	Approximate time of consciousness without oxygen is 115 sec
28,000	Maximum to avoid decompression sickness. Approximate time of consciousness without oxygen is 70 sec
30,000	Altitude above which slight positive pressure breathing should supplement demand oxygen to avoid air leaks into oxygen mask. Approximate time of consciousness without oxygen is 55 sec
35,000	Maximum for continuous use of demand oxygen system. Approximate time of consciousness without oxygen is 30 sec
40,000	Approximate time of consciousness without oxygen is 23 sec
42,000	Maximum for continuous use of pressure breathing. Bombardment and fighter aircraft not having escape capsules but having a requirement to remain above this altitude for periods in excess of five minutes after loss of cabin pressurization require provisions for use of pressure suits
43,000	Maximum for emergency use of demand oxygen - (time of useful consciousness without oxygen is 15 see)
50,000	Maximum for emergency use of pressure breathing demand oxygen. Bombardment and fighter aircraft not having escape capsules but having combat ceilings above this altitude require provisions for the use of pressure suits.

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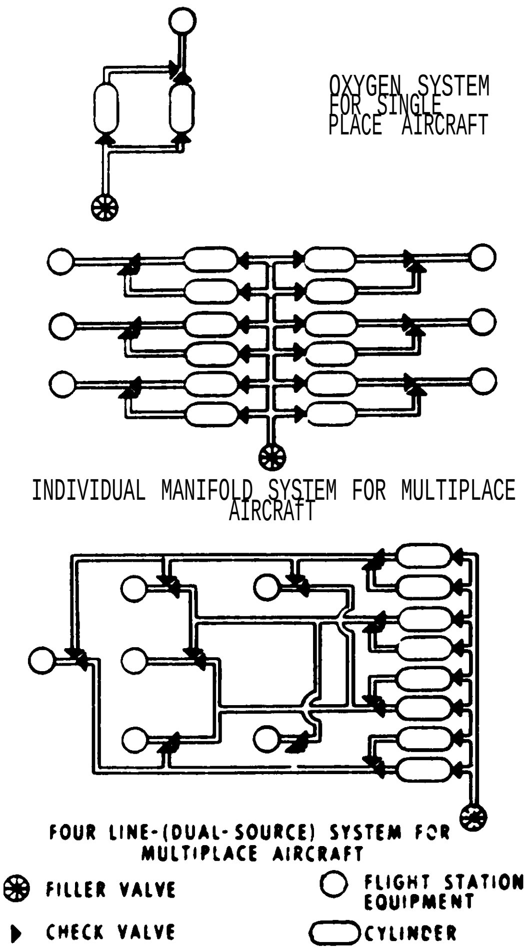

SINGLE-PLACE AIRCRAFT REQUIRE TWO OR MORE STORAGE CYLINDERS. FOR PROTECTION AGAINST OXYGEN LOSS FROM GUNFIRE, SUBSYSTEM SAFETY DESIGN REQUIRES CHECK VALVES ON THE FILLER AND DISTRIBUTION MANIFOLDS. A FILLER VALVE AND THE FLIGHT STATION EQUIPMENT COMPLETE THE INSTALLATION.

A MULTIPLACE AIRCRAFT USING AN INDIVIDUAL MANIFOLD OXYGEN SUBSYSTEM PROVIDES A SINGLE INDEPENDENT MANIFOLD FOR EACH INDIVIDUAL STATION OUTLET. THE SAFETY DESIGN ADVANTAGE IS THAT NO SINGLE PUNCTURE OR RUPTURE WILL DEPRIVE MORE THAN ONE CREW MEMBER OF HIS OXYGEN SUPPLY. THE LENGTH OF CRITICALLY VULNERABLE TUBING IS REDUCED TO A MINIMUM. ALL OXYGEN CONTAINERS ARE CONNECTED TO A COMMON FILLER LINE, SO THAT UNTIL THE CHECK VALVES ARE CLOSED BY PUNCTURE OR SUDDEN LOSS OF PRESSURE IN SOME PART OF THE SUBSYSTEMS, PRESSURES IN SOME, OR ALL, OF THE CONTAINERS (OXYGEN CYLINDERS) CAN BE KEPT EQUALIZED AT ALL TIMES.

IN MULTIPLACE AIRCRAFT USING A FOUR-LINE (DUAL-SOURCE SUBSYSTEM, SEVERAL OUTLETS ARE CONNECTED TO A SINGLE MANIFOLD, BUT THE VARIOUS MANIFOLDS ARE SO INTERCONNECTED THAT EACH OUTLET IS ACTUALLY SUPPLIED FROM TWO MANIFOLDS. EITHER MANIFOLD MAY BE PUNCTURED WITHOUT DRAINING THE OTHER. THE ADVANTAGE OF THIS SUBSYSTEM IS THAT MANY OUTLETS CAN BE SUPPLIED BY RELATIVELY FEW CYLINDERS AND DISTRIBUTION LINES WITH MAXIMUM SAFETY . THIS TYPE OF SUBSYSTEM CAN BE MAINTAINED WITH LITTLE DIFFICULTY.

FIGURE 5-180. Gaseous oxygen supply systems.

5.12.2 Oxygen systems HEL protection. The basic protection techniques currently applicable to oxygen systems involve the use of materials to reflect the HEL energy or convert it into other forms through ablation, sublimation, or charring. Careful consideration must be given to the protection of pressurized oxygen containers or lines vulnerable to laser energy exposure where fire hazards and/or explosive rupture would result.

5.12.3 Oxygen systems repairability/maintainability. Placement and design of oxygen systems should permit rapid removal and replacement of combat damaged components, lines, and fittings. In areas where a survivable oxygen fed fire can be sustained, consideration should be given to use of insulating or intumescent materials that would minimize structural damage that would otherwise require extensive repair or replacement efforts and material costs.

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5.13 Armament systems. An armament system provides for the carriage, aiming/sighting, arming, launching, and terminal guidance of weapons. The major classifications of weapons are bombs, missiles, rockets, guns, and chemical/biological dispenser systems. The system may also include active defense systems to enhance mission completion and aircraft survival by suppressing or destroying the hostile force weapon effectiveness.

5.13.1 Armament systems damage effects. Successful ordnance delivery requires the proper operation of the armament system while exposed to hostile weapon effects. The design criteria and suggestions are directed at general and specific requirements for enhancing the survivability of the armament/weapon delivery systems of aircraft when exposed to weapons effects. The information presented on ammunition and larger stores can also be applied to ordnance being shipped via transport aircraft. When impacted by bullets or fragments, a wide range of reactions of ammunition stored onboard an aircraft can be expected, including sustained fires that are capable of causing secondary cookoff-type reactions. There are several related questions to be answered when assessing the vulnerability of targets containing large amounts of high-explosive (HE) ammunition to fragment or bullet impact:

a. How does one round react when subjected to fragment or bullet impact?

b. When one round reacts explosively to fragment or bullet impact, what effect does it have on adjacent rounds?

c* What types of reactions are required to achieve an unacceptable level of damage to various types of containers for the ammunition?

Once the threat has been defined, the first two questions can be answered independent of a given container or storage configuration. Testing may indicate that single rounds or groups of rounds are not vulnerable to bullet or fragment impact and do not increase the vulnerability of the ammunition containers. Conversely, testing may indicate that one round will react explosively to bullet or fragment impact and that this explosive reaction will cause all remaining rounds in the container to react similarly. This will usually result in a catastrophic kill of the container. If and when the test results fall between these two extremes, testing full-scale mockups or actual production items may be required.

5.13.1.1 Gun magazines. Aircraft gun magazines containing HE projectiles present a potential vulnerability problem. The problem is complicated by the density of the packaged rounds, the reaction characteristics peculiar to each projectile configuration for each threat, and the physical location of the ammunition magazines with respect to critical aircraft structure or components.

5.13.1.2 Nonvented ammunition. Nonvented ammunition containers are vulnerable to the blast effects of contained ammunition reacting to small-arms bullet impact. The smaller the container, the more likely it is to be structurally damaged. This is primarily caused by the difference in internal volume. For an equivalent explosive reaction in each of two containers, it is apparent that the container with the smaller internal volume will generate the highest internal pressures, given the same explosion.

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5.13.1.3 Test programs. In various test programs, vented containers have maintained their structural integrity to a higher degree than nonvented containers of similar construction when tested under similar conditions. Reference 118 describes firings that were conducted to investigate the vulnerability of modern-armed helicopter systems using 30 and 40 mm ammunition in large containers. Individual rounds, groups of rounds, and a variety of HE-loaded ammunition containers were used as targets. The rounds were struck on their fuzes, projectile walls, propellant cases, and primers by caliber .30 and .50 bullets. Also examined were the effects on a helicopter containing a simulated ammunition system with 30 and 40 mm HE rounds contained in the system. The conclusions presented in volume II of Reference 118 include information on the vulnerability of ammunition and of the aircraft, and techniques that can be used for vulnerability reduction.

a. Reference 119 presents the results of a series of test firings of various small-arms projectiles into a mockup of the AH-56A Cheyenne helicopter ammunition bay containing 30 and 40 mm ammunition magazines. The severity of structural damage for various types of ammunition reactions, potential fire hazards, magazine ventings and other resultant effects that concern overall aircraft vulnerability are discussed.

b. Tests to determine the vulnerability of bombs to bullet impacts are described in Reference 120. The results of the tests indicate that small caliber armor-piercing bullets are superior to other small-arms types in their destructive effect upon 100- and 500-pound TNT-loaded general-purpose bombs.

c. Reference 121 describes tests that were conducted to determine the vulnerability of JATO units to single cylindrical steel fragments and bullets fired at normal or nearly normal angle of impact. Because JATO units have changed considerably since these tests, the results can give only a general idea of their vulnerability- The conclusions presented in the referenced document provide information on vulnerability of more than one type of JATO unit.

5.13.2 Design criteria.

5.13.2.1 Aiming/sighting systems. Mission success and effectiveness of an assault aircraft are greatly influenced by the accuracy of ordnance delivery. This can be highly dependent upon the usefulness of the aiming/sighting system. Consider the following means for reducing its vulnerability:

a. Use methods to prevent or minimize complete failure of the system as a result of damage or failure of one of its elements caused by ballistic weapon effects. Provide redundant circuits or elements to insure full or acceptable degraded performance when subjected to hostile weapon damage.

b. Use a “fixed” sight capability, either automatic or selected, that is not dependent upon operation of the normal sighting/aiming system to permit delivery of the ordnance in a degraded mode.

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c. Locate critical system components to use natural shielding protection. Avoid those locations where secondary hazard effects, such as short-term fires, high-temperature environments, or structural deformation caused by hostile weapon effects, could degrade or destroy the component functions.

5.13.2.2 Arming/release systems. Proper arming and release of weapons is required for effective ordnance delivery. Consider the following techniques to enhance survival and operation of arming and release systems when exposed to nonnuclear weapon effects:

a. Isolate arming and release electrical circuits from other electrical or electronic circuits, and give them priority of protection to prevent failures or malfunctions.

b. Use redundant or backup arming and/or release systems where basic survival of the normal system is unacceptable. For example, provide a mechanically operated or emergency electrical weapon arming and/or release system that will permit delivery of ordnance when the normal electrical system is inoperative due to weapon effect damage.

c. Provide emergency or redundant power sources for essential operation of ordnance arming/launching system.

d. Where multiple ordnance launchers or stations are used, provide separated and protected arming and/or launching circuits to avoid complete loss of weapon delivery capability due to a single hit.

e. Air launched missile and rocket propulsion systems must satisfy AS 4449 (Reference 203) Safety Requirements for air launched Guided Missiles, target drones, aircrew escape and Rocket Propulsion Systems.

5.13.2.3 Internal gun systems. Operation of internal gun systems is dependent upon ammunition stowage and feed systems, power supply (if not self-powered), firing signals, case and/or link disposal, charging (if self-powered), gun gas purging, and gun/ammunition compartment venting/cooling performance. Consider the following techniques to enhance resistance of internal gun systems to failure or malfunction due to nonnuclear weapon effects:

a. Provide gun gas purging, gun/ammunition compartment venting/cooling, and gun charging (if required) systems that are not dependent upon operation of a highly vulnerable electrical or fluid power system. If this cannot be accomplished, provide emergency backup capability for such operation. For example, provide an emergency accumulator for a hydraulically operated gun charging or purge door operation. Automatic operation of the emergency system is preferred along with pilot warning of primary system failure.

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b. Design ammunition feed systems as compact, and transfer chutes as short, as practical to minimize the vulnerable area and probability of malfunction or jamming due to hostile weapon effects. Avoid rigid attachment of feed and return chutes to structure where deformation from weapon effects could cause jamming of gun or feed operation.

c. Provide case ejection chute installations that will resist failure or malfunction due to hostile weapon effects. Consider using metallic or nonmetallic materials that will accept minor penetration and/or blast effects and still allow case retention and/or disposal that will prevent or minimize loss of gun operation.

d. Design ammunition stowage area to preclude or minimize destructive buildup of pressures within aircraft structure. Where hostile projectile impact and ignition of stowed ammunition can occur. Provide vented ammunition containers/compartments and provisions for relieving pressure from ammunition stowage area to avoid explosive damage from rapid burning of propellant or cookoff of high-explosive warheads. See Figure 5-181 for an example of a vented ammunition stowage container configured to allow rapid escape of burning propellant gas and prevent a hazardous explosion from occurring within aircraft structure.

5.13.2.4 Carriage systems. Weapons may be carried either internally or externally, depending upon the specific weapon and aircraft. Each of these carriage mechanisms may carry arming, releases force ejection, jettison, and sequencing systems that weapon effects may damage and cause to become inoperative.

5.13.2.4.1 Internal carriage. Bombs, rockets, missiles, etc, may be carried internally in weapon bays, for aerodynamic concealment or special environmental reasons. Consider the following survivability design enhancement techniques to achieve required level of mission completion when aircraft is exposed to hostile nonnuclear weapon effects:

a. Design weapon bay door hinges and actuating mechanisms to prevent or minimize jamming from blast or weapon penetration effects.

b. Provide redundant or emergency power sources for weapon bay door and articulated weapon positioning devices such as missile or rocket launchers. Hydraulic, pneumatic, and electrical systems are primary types that should be compared to determine which one, or combination, will provide the most survivability for the specific application. The emergency backup system may be hydraulic accumulators, pneumatic pressure bottles, batteries, cartridges, or other stored energy devices.

c. For installations where weapon bay doors may be jammed or become inoperative from weapon effects, provide a means to jettison doors. Frangible or explosive hinge pins or explosive primer cords are examples of such means. However; this is not recommended, as the hazards are high. The damaged doors may not separate properly and cause additional damage to the aircraft.

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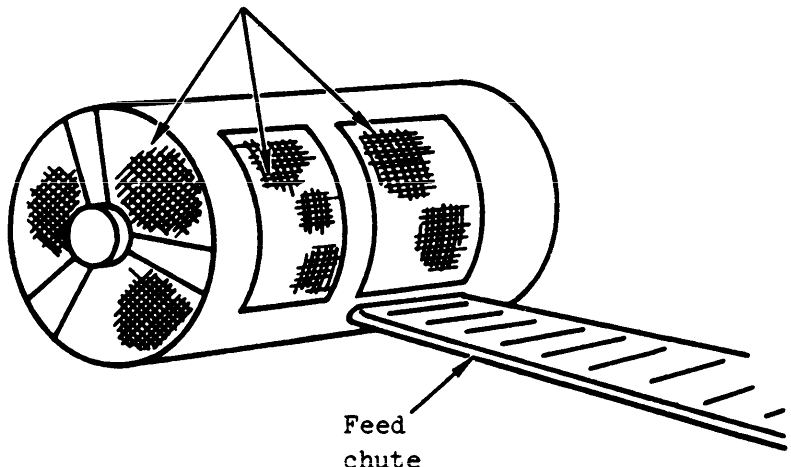

FIGURE 5-181. Vented ammunition storage.

5.13.2.4.2 External carriage. Provisions for the external carriage of weapons are generally flush-mounted to or semisubmerged in structure or mounted on pylons. Consider the following enhancement techniques to achieve required level of mission accomplishment:

a. Concentrate operating linkages and equipment to minimize their vulnerable area and possibility of jamming or malfunctioning from weapon effects.

b. Provide single-motion jettison capability for external weapons that are capable of producing a hazardous condition such as ignition of incendiary bomblets and flares.

c. Mask weapon arming and actuation of electrical circuitry in external pylons to present the least vulnerable aspect or area to weapon effects. Where this cannot be avoided, use redundant circuits.

5.13.2.5 General. Consider the following design techniques to achieve a required level of survival:

a. Mission-essential elements, components, and hardware should be located to make use of natural masking protection.

b. Locate ballistic-impact and incendiary-sensitive ammunition and/or other ordnance so as to minimize personnel injury/fatality and damage to essential subsystems from explosion or burning initiated

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by hostile weapon effects. Consider the relative merits of external and internal carriage.

c. Provide adequate venting of internal ammunition containers to avoid destructive buildup of gases generated by burning explosives.

d. Consider venting aircraft fuselage in area of ammunition storage.

e. Consider the use of heat barriers and/or fire-suppression systems for sensitive ordnance compartments to limit damage.

5.13.3 Armament systems HEL protection. The armament system poses a serious fire/explosion hazard when exposed to an HEL threat, due to the inherent characteristics of weaponry. Maximum utilization of inherent shielding, coatings, paints, etc. provide some protection by. delaying burn through. Internal bays should be designed to tolerate a certain amount of fire/explosion without critical structural damage. Secondary effects must be considered.

5.13.4 Armament systems repairability/maintainability. Consideration should be given to the location and configuration of ordnance carriage on an aircraft system to minimize the secondary damage that may be generated from the response of ammunition, missiles, rockets, bombs, flares, etc, to direct ballistic impact. Provisions to rapidly jettison burning ordnance should be considered where continued carriage would cause additional aircraft damage. Ordnance carried by aircraft are inherently hazardous when damaged by hostile weapons. Low- and high-order detonations can occur with explosive devices as well as burning of propellants, flares, etc. Those carried internally are generally those whose reaction to battle damage will have the capability of producing additional damage that would increase the repair problem. In such installations, considerations should be given to means of limiting the spread of damage by shielding, insulation, or rapid emergency jettison means. The avionics and wiring for armament weapon control, fuze function control, and special weapons should be designed for rapid-access inspection, repair, and/or replacement.

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5.14 Electrical power system. The techniques and practices of electrical design include several elements that enhance the capability to survive ballistic threats from small-arms projectiles. For example, the redundancies built in for reliability purposes can be installed so that survivability is also enhanced. The power-limiting functions built into all electrical distribution systems protect the system if a projectile causes a short circuit, and the design objective of minimum volume also minimizes the equipment presented area. The following paragraphs are intended to provide survivability enhancement methods that can be integrated with general design practice.

5.14.1 Electrical power system ballistic damage effects. Electrical power systems are particularly sensitive to the primary and secondary damage mechanisms associated with nonnuclear weapon effects. Primary effects are those that are the result of projectile penetration and impact. These effects can cause severance of electrical wires, penetration, and shorting of electrical circuits. Secondary weapon effects are those hazardous effects created by projectile impacts that, in turn, can adversely affect electrical elements. These include fires, explosions, high-temperature conditions, and liberation of hazardous materials. Failure modes of electrical elements are disruption and shorting of circuits and malfunctioning of equipment.

5.14.2 Circuit design. The following design techniques should be considered to prevent or minimize loss or degradation of electrical generation, storage, conversion, and distribution for systems essential to mission accomplishment and crew/aircraft survival:

a. Provide multiple redundant circuits so that failure of a circuit or component due to nonnuclear weapon effects will not result in serious degradation or loss of essential electrically powered equipment. Redundancy should also encompass drive mechanisms for single-engine aircraft electrical generators so that redundant power sources are not dependent on a common drive mechanism such as the engine accessory drive or aircraft hydraulic system.

b. Use multiple-wire feeder lines to minimize or eliminate possibility of complete system loss due to nonnuclear weapon effects.

c. Provide an emergency power source that provides power to power bus or that bypasses normal feeder circuits providing power directly to essential equipment. Employ sensing devices to provide rapid and automatic actuation of emergency systems whenever primary system loss occurs for a specified time duration, see Figures 5-182 and 5-183.

d. Provide parallel or redundant power conversion units or systems for operation of critical subsystems where adequate protection cannot be provided for a single electrical power conversion system.

e. Avoid controls which use ground circuit switching to preclude inadvertent operation of systems or components (due to grounding by weapon effects) that would reduce aircraft survivability or cause mission failure/degradation, see Figure 5-184.

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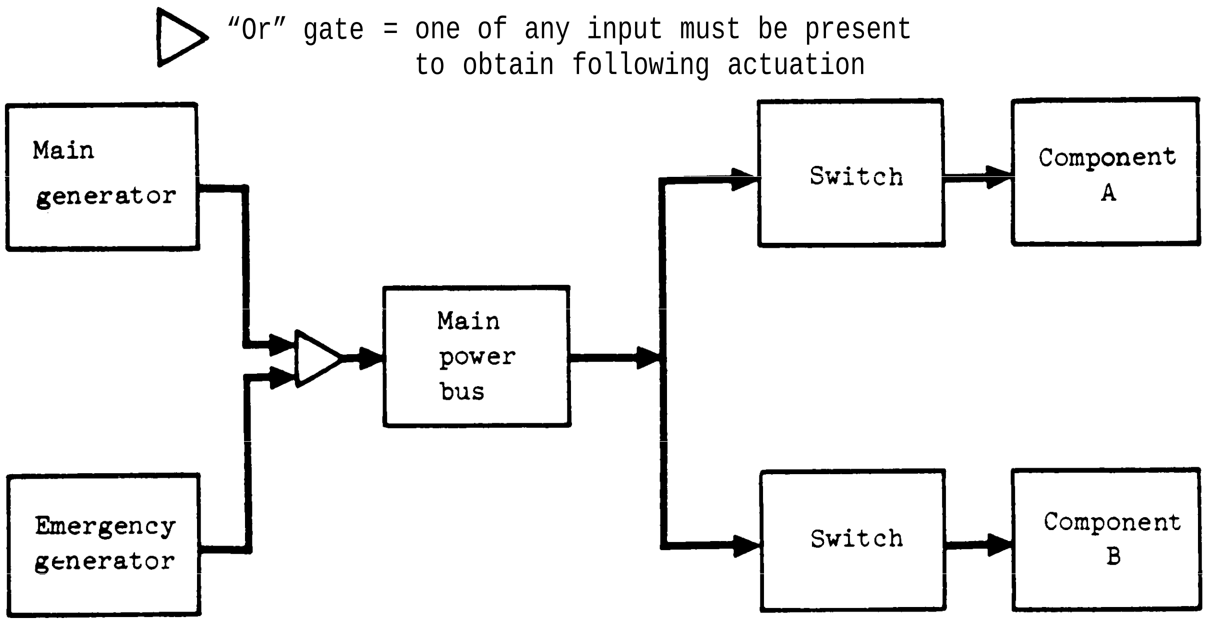

FIGURE 5-182. Single power bus system.

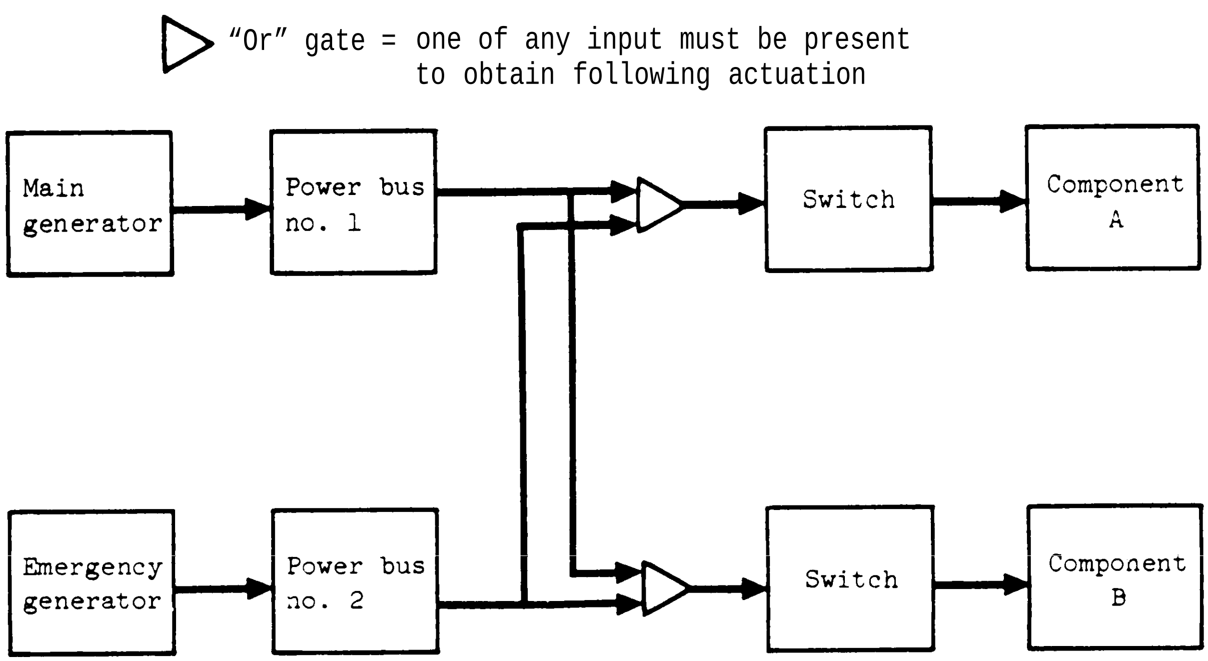

FIGURE 5-183. Separate power bus system.

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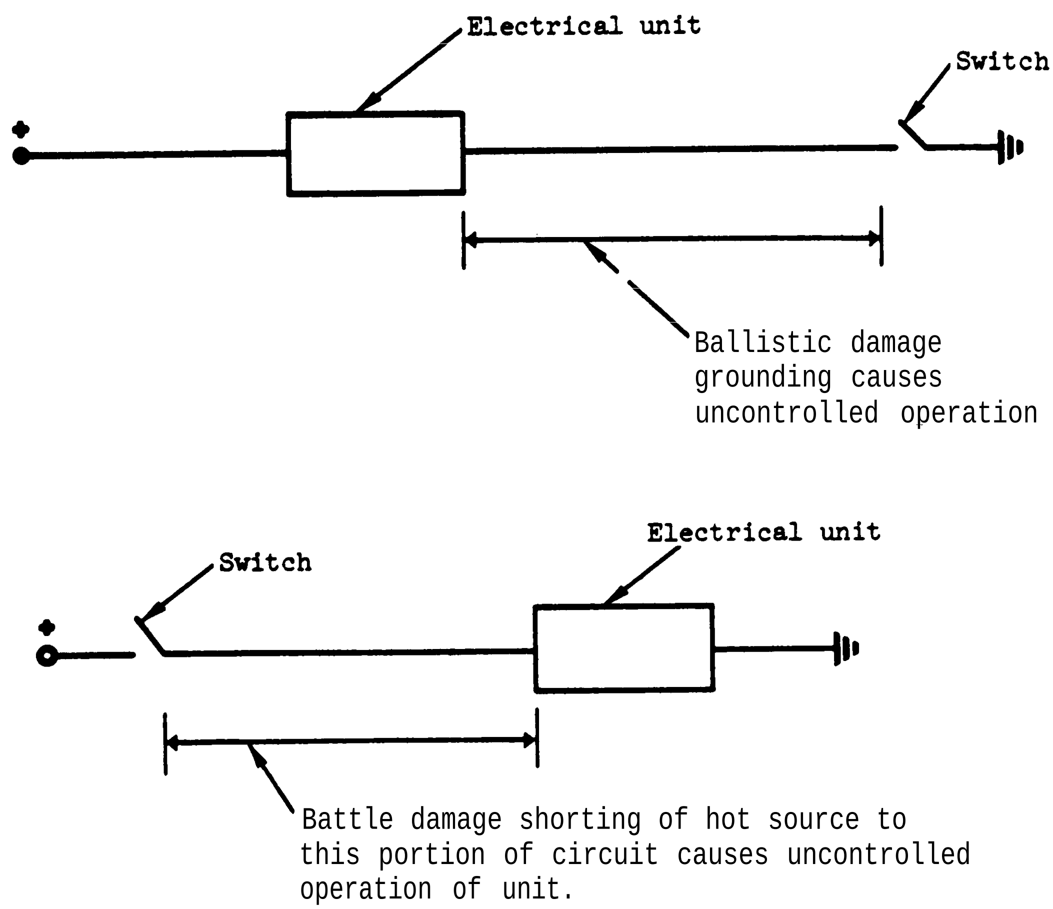

FIGURE 5-184. Ground circuit switching.

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f. Use circuits that will provide electrical grounding of both sides of activation circuits for critical components or systems. This will prevent inadvertent operation, due to a short of electrical energy from combat damage, see Figure 5-185.

5.14.3 System installation. If an electrical system is critical to the mission and no redundancy exists, then the installation must consider suitable masking from the ballistic threats, or armor provisions. The location of components is critical from a secondary hazard standpoint, if it provides an ignition sourve when damaged. The installation of some electrical equipment includes a grounding connection to the structure. If this connection is broken, the potential difference can be a highly efficient ignition source. Ignition can occur from voltages of as little as 0.5 volt, from a point contact between the two potential levels. Capacitance-type fuel quantity measurement systems commonly use a potential difference of up to 75 volts. Any possibility that debris or other material from ballistic damage could cause a short circuit in such a system should be carefully scrutinized. Batteries should be designed or procured with ballistic impact tolerance and should provide a degree of power, even when damaged. Battery bays should be sealed to prevent migration of corrosive battery acids to nearby sensitive equipment or components. Provisions should be made to drain or vent corrosive fluids and/or vapors overboard to locations that are not sensitive to corrosive fluids. The following design techniques should be considered for electrical power installations:

a. Route electrical wiring away from hazardous or hazard-producing areas such as fuel bays and oxygen cylinders. Where hazardous areas cannot be avoided, provide shielding for protection of cabling and for protection of surrounding potentially hazardous equipment from possible electrical arcing caused by damaged wiring.

b. Consider pull-away bulkhead fittings to minimize possibility of wire damage due to displacement of, or damage to, supporting structure.

c. Use shortest possible wire runs to provide minimum exposure of circuits to nonnuclear weapon effects.

d. Locate bus bars and essential terminal strips in those areas of the aircraft which are least vulnerable considering design mission requirements of the aircraft.

e. Design circuits to minimize crew compartment electrical system wiring. Use shielding where crew compartment wiring is unavoidable, and use wire, insulation materials, and system elements which, when subjected to fire or intense heat, will not produce smoke and noxious or toxic vapors.

f. Use cooling system duct materials which will accept nonnuclear weapon or secondary projectile penetrations without disintegration.

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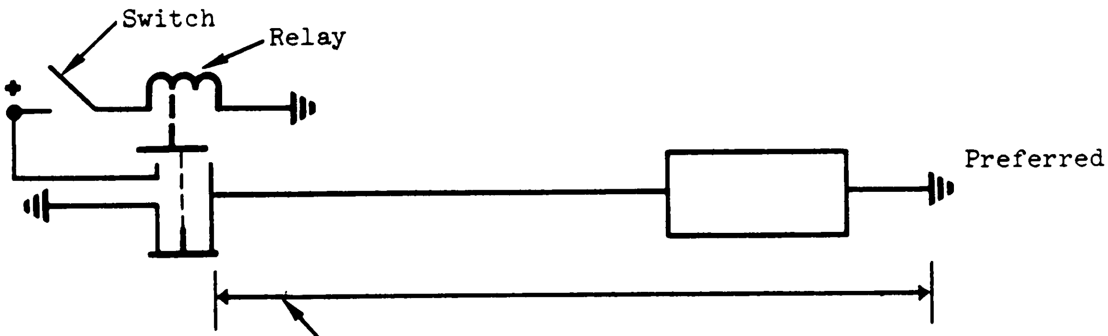

FIGURE 5-185. Grounding both sides of activation circuit.

g. Separate as far as practical all redundant wire runs and system elements to avoid total system loss from a single nonnuclear weapon effect. Route essential wiring deep within wire bundles, thereby utilizing shielding effect of nonessential wiring.

h. Provide insulated rigid ducts, installed along strong structural sections, to prevent short circuits due to fragment damage. Ducts should be fireproof, smokeproof, and nonabrasive. Provide adequate access through one side of the duct or allow complete removal for maintenance or repair.

i. Provide continuous wire runs as far as practical to avoid or minimize terminal strips, splices, connectors, etc. , which are more susceptible to damage or failure from weapon effects.

j. Avoid using common connectors or terminal strips for routing control circuits of multiple power sources to prevent total power failure from a single weapon effect.

k. Locate essential components to take advantage of natural shielding offered by other nonessential components.

5.14.4 Electrical power system HEL protection. Electrical power systems are directly and indirectly susceptible to HEL damage. Components should be carefully placed to take advantage of inherent shielding. Materials should be chosen that exhibit high tolerance to HEL burn through. Special coatings should be considered. Secondary effects are also a major concern, as fires and explosions initiated by HEL threats can cause serious damage to otherwise undamaged electrical components.

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5.14.5 Electrical power system repairability/maintainability. Electrical power generation and distribution systems in military aircraft are generally complex and extend throughout the airframe. The wiring cables, connectors, terminal strips, etc, are sensitive to ballistic impacts, fires, explosions, and hot-gas impingement. Their locations and routings shall be designed to avoid areas of highest secondary damage effects potential. Provisions shall also be incorporated to permit rapid access for inspection and repair. In the detail design of electrical power and distribution systems, considerations should be made to permit standard repairs to be developed for wiring cabling and connector points. There should be sufficient room to permit damaged connector replacement without excessive removal of other components or structure. Where electrical power system wiring enters or exists in a modular section of the aircraft, connectors should be provided that permit removal and replacement of a damaged module with an interchangeable section. This applies particularly to fuselage, wing, and empennage sections. The installation of electrical power equipment should permit rapid access, removal, and replacement. The allocation of spare parts, with the higher probability of damage, should be increased for combat operations. Past experience has shown that the man-hours for repair of electrical power systems are reasonable, but that the calendar time for replacement parts has been significant.

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5.15 Avionics systems. Avionics systems are made up of components interconnected by cabling. These elements are highly susceptible to damage by nonnuclear weapon effects. These include penetration, overpressure, shock, mechanical distortion, and high-temperature hazards. Aircraft/crew survival and/or mission completion can be highly dependent upon avionics system performance in hostile nonnuclear environments. Some of the most influential factors in aircraft survival are the capability to prevent or minimize its detection by hostile forces, detection of hostile weapon search and homing systems, and confusing or misdirecting the hostile weapon systems. Mission completion and/or aircraft/crew recovery may also be highly dependent upon fire control, communications, flight control augmentation, data processing, or navigation systems.

5.15.1 Avionics systems ballistic damage effects. The basic nonnuclear threats and kill mechanisms that may be experienced by avionics systems are penetration or impact shock by projectiles, fragments, secondary spallation; high-explosive blast effects; or secondary thermal hazards such as fires or hot air/gas torching effects. Vacuum tube and solid state are the two basic avionics equipment configurations. Each type has characteristics that must be considered for the specific aircraft configuration, mission, and threat environments. From Table 5-XXXVI, it can be seen that the solid-state electronic systems exhibit higher survivability advantages in most areas and should receive first consideration in the initial design.

TABLE S-XXXVI. Avionic construction types and relative comparisons.

System Type	Relative Vulnerable Areas	Shock resistance	Penetration Resistance	Thermal Resistance	Cooling Required	Weight	cost
Vacuum tube	Large	Low	Low	Low	High	High	Low
Solid state	Small	High	Low	Low	Low	Low	Low to high

5.15.2 Circuit design. The following design enhancement techniques should be considered to provide the optimum survivability for the specific critical equipment or system:

a. Design critical system circuitry to avoid complete loss of functions if one element or group of elements is damaged or destroyed. For highly critical systems, consider separated redundant systems or portions of systems that would be exposed to weapon effects. Provide self-sustained systems that are not dependent on, or interrelated with, other avionics equipment.

b. Design circuits to provide long-time-to-die features from high-temperature hazards that may occur in specific aircraft design due to nonnuclear weapon effects. This includes hot gas torching from a damaged turbine engine, survivable internal fires, loss of environmental cooling, etc.

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c. Provide safety monitoring systems with a "valid" signal parity check-type circuitry to prevent hazardous, erroneous, or "hard over" signals to critical systems due to damage, malfunction, or destruction of one of the system elements caused by weapon effects. Provide fail-safe system disengagement or positioning of system along with pilot warning.

5.15.3 Avionics elements.

5.15.3.1 Components. This category includes all functional units, such as sensors, black boxes, antennas, and instruments. Consider the following enhancement techniques to minimize component failure or malfunction due to weapon effects:

a. Construct components to withstand high shock loads caused by projectile or fragment impact on component or adjacent units or structure. Stabilize potential failure areas with adequate mechanical shock mountings to withstand weapon effects in addition to normal vibration conditions.

b. Separate redundant circuits within components as far as practical to minimize possibility of simultaneous failures from projectiles or fragments, structural distortion, or blast effects.

c. Provide support, potting, or lightweight fillers within electronic equipment to prevent or minimize shock failures. Select type of shock protection that will provide level of protection needed with least penalty for access, maintenance, and/or repair.

d. Provide breakaway mounting features on equipment where distortion of case would cause malfunction or failure of item due to its deformation by weapon effects.

e. Use insulating material for exterior wrapping of critical equipment to provide extended operational time where exposure to high-thermal conditions may occur due to weapon effects.

5.15.3.2 Cabling. Electronic equipment connecting cabling is highly vulnerable to direct and secondary nonnuclear weapon effects. Observe the following techniques to prevent or minimize system malfunction or failure:

a. Provide heat-resistant wiring, connectors, potting, terminal strips, etc, in high-thermal hazard areas for critical avionics circuits.

b. Provide smokeless cabling in crew stations or locations where smoke or toxic fumes would be introduced into crew stations due to fire or high-thermal conditions caused by weapon effects.

c. Provide ballistic-resistant cable bundle covers for isolation and protection of critical equipment cabling from small fragments or spallation due to weapon effects.

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5.15.4 System installation. Consider passive survival techniques such as separation, concentration, and shielding to minimize malfunction or failure of critical avionics equipment and connecting cabling. In addition, consider the following techniques applicable to critical systems in specific aircraft design:

a. Locate equipment to obtain best balance between shielding of equipment and routing of connecting cabling to minimize vulnerability of total system. Where adequate cabling survival cannot be obtained, consider using redundant cabling with suitable automatic failure sensing and switch over capability.

b. Provide equipment shock mounting to provide maximum practical protection from blast shock effects.

c. Isolate and route critical equipment cabling apart from nonessential cabling to minimize hazardous short circuits from weapon damage. Avoid using common connectors where such short circuits may also occur.

d. Provide frangible pull-away attachments (such as those shown in Figure 5-186) for structural attachments of cabling connectors to prevent or minimize wire breakage, separation, or shorting due to structural deflections resulting from weapon effects.

e. Route critical cabling as close as practical to heavy primary structure to obtain natural shielding from weapon effects and minimize probability of structural deflection induced damage. Avoid areas where secondary fires, high-thermal effects, or hazardous spallation may occur.

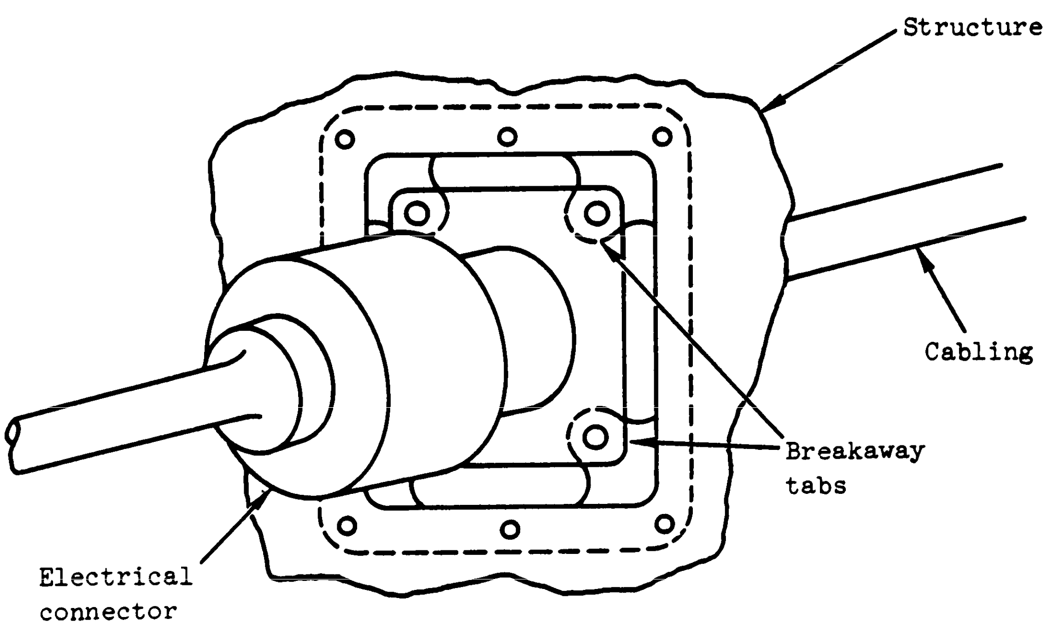

FIGURE 5-186. Cabling bulkhead connector breakaway fitting.

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5.15.5 Avionics systems HEL protection. Avionic systems are directly and indirectly susceptible to HEL damage. Components should be carefully located to make maximum use of inherent shielding. Component casings, shelving, etc. should be constructed of materials that exhibit high tolerance to HEL burn through. Special coatings should be considered. Problems associated with secondary effects, such as fires and explosions must be considered and minimized.

5.15.6 Avionics systems repairability/maintainability. The military avionics in aircraft are those associated with specific mission functions. The design of avionics equipment installation shall consider means to permit rapid removal of single components and/or modular sections of an assembly to permit inspection and repair of the bay. Connecting electrical cabling shall be designed to be accessible for repair or replacement without need of major structural disassembling. Avionics components have been found to require the longest average calendar time for replacement parts. The spare parts requirements for those pieces of equipment most susceptible to battle damage should be increased for combat operations over the normal stocking requirements for training missions. Military avionics equipment is highly susceptible to ballistic damage. It also generally exhibits the longest delay in obtaining replacement parts in combat operations. Consideration shall be given to placement of the more complex and expensive avionics equipment in areas that are less likely to be exposed to hostile weapon effects. Experience has also shown that significant inspection and failure diagnostic time has been required to isolate malfunctioning avionic units and/or wiring. Consideration shall be given to the overall design of the avionics systems to minimize the time and effort required to identify the damaged unit(s).

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5.16 Launch and recovery system. Landing systems on rotary- and fixed-wing aircraft have not shown any significant vulnerability to nonnuclear ballistic threats. Landing systems are designed to accept large dynamic loads for safety and crashworthiness factors which provide them with an inherent tolerance to ballistic impacts. Vulnerability, however, cannot be overlooked for future, more sophisticated and higher performance aircraft. Landing systems are divided into two major classifications: fixed gear and retractable gear. A simple fixed-gear landing system for rotary-wing aircraft usually consists of two strut-mounted, shock-dampened skids aligned longitudinally along the aircraft fuselage. The right and left skids are usually connected to the aircraft fuselage through removable struts and side braces that pivot as a unit when the shock damper assemblies are extended or retracted through their actuation stroke. Another type of fixed landing gear system consists of three to four strut-mounted, shock-dampened wheel assemblies using either a conventional (tailwheel) , tricycle, or quadricycle gear configuration. The wheel assemblies are attached to shock struts (or oleo units) which are connected to the aircraft fuselage structure. A retractable landing gear system usually consists of strut-mounted, shock-dampened wheel assemblies using either a conventional or tricycle gear configuration with the capability to retract the wheel and strut assemblies into the aircraft fuselage wing, or sponsor-type structures to improve aerodynamic smoothness.

5.16.1 Launch and recovery system ballistic damage effects. Consideration must be given to the ballistic damage effects to which the landing system will be exposed over the full range of the aircraft mission to insure that no system weakness is overlooked. Damage effects may be caused by penetration of ballistic projectiles (small arms) and secondary spallation fragments piercing, shattering, or severing critical elements or components and the ignition of incendiary effect of flammable hydraulic fluids. The landing system must be designed to accept some ballistic damage without losing its capability to perform its full function or jeopardizing safety. A systematic method should be followed to identify vulnerable elements, their failure modes, and their effects upon mission-essential or recovery functions. Figure 5-187 shows a simplified functional flow diagram for a retractable landing system. This representation of the system can be used to assess the damage mode and effects from ballistic threats. By accomplishing this analysis, all vulnerable portions of the system can be identified for application of survivability enhancement techniques. Redundancies in the system are shown by use of “OR” gates, while “AND” gates are used where more than one element is needed to perform a given action.

5.16.2 Basic design, landing gear.

5.16.2.1 Fixed gear. The following are those survivability enhancement techniques to be used as a guide in the initial design or modification of fixed landing gear systems:

a. Design landing system and components with multiload path capability and damage tolerance to avoid landing hazards from single-element damage or failure.

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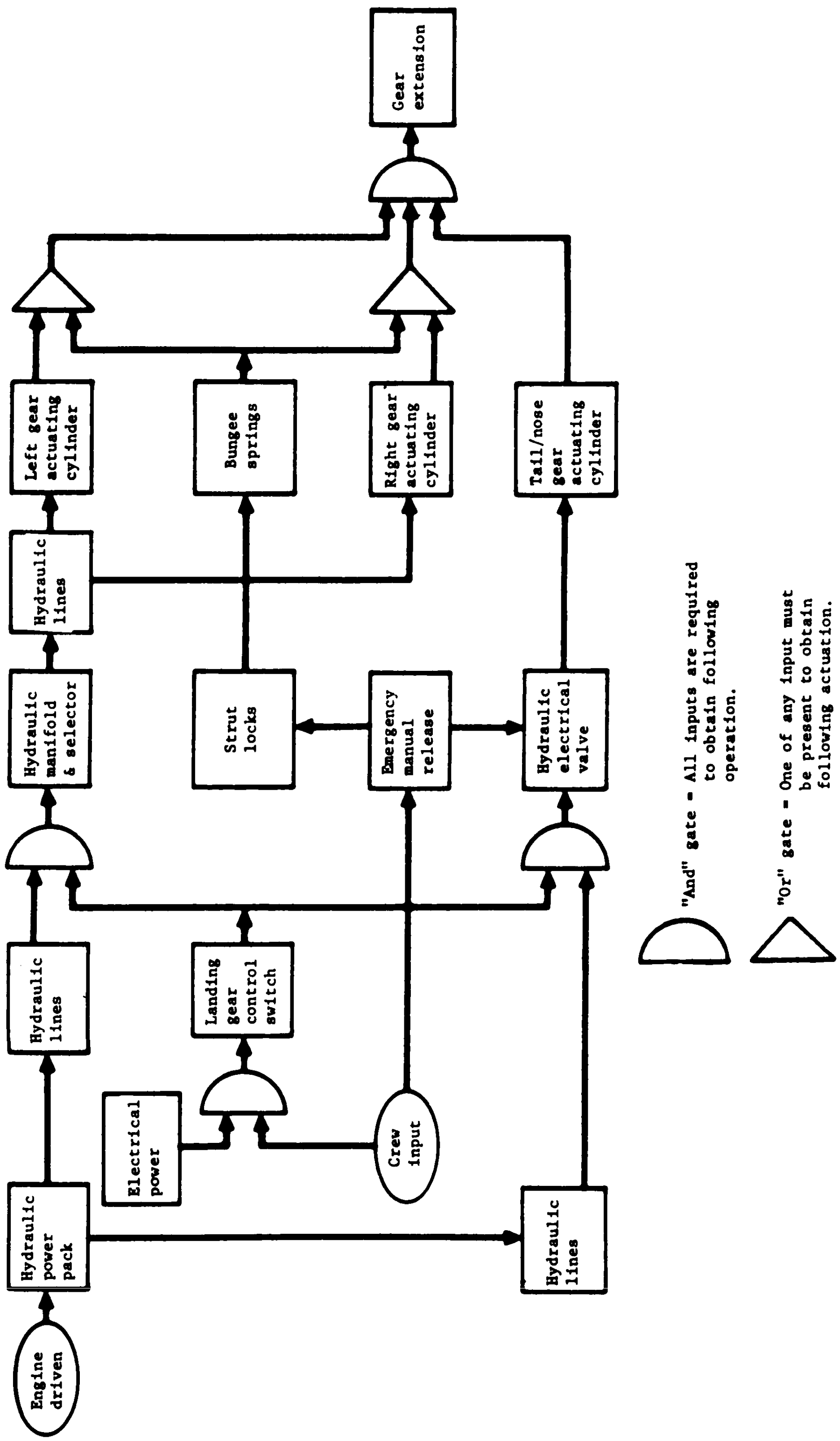

FIGURE 5-187. Representative retractable landing gear system (functional flow).

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b. Provide for use of large-diameter, thin-wall tube construction for critical landing system linkages, struts, or supports.

c. Avoid landing-gear-to-fuselage attachment designs using brittle materials, such as castings, which could otherwise fail when struck by a projectile. Provide for use of large-area ductile material which will accept projectile or fragment penetration with minimum probability of element failure.

d. Avoid major attachment points using only one primary securing element that would be susceptible to ballistic damage failure. Provide for multiple securing elements at critical attachment points.

e. Design for lowest practical shock strut or damper internal pressures to minimize disintegration from ballistic impacts.

f. Design for lowest practical tire pressures to minimize tire and wheel destructive disintegration from ballistic impacts.

5.16.2.2 Retractable gear. The following are those survivability enhancement techniques to be used as a guide in the initial design or modification of retractable landing gear systems:

a. Provide for manual free-fall release and extension of retractable landing systems.

b. Provide for adequate separation of electrical power sources and hydraulic/pneumatic lines to avoid simultaneous failures from ballistic impacts or spallation.

c. Route manual release control cable as close as practical to heavy primary structure to provide masking against ballistic threats.

d. Avoid landing gear attachment designs using brittle materials such as castings for basic support structure.

e. Compare relative benefits and penalties for use of electrical versus hydraulic/pneumatic power sources in basic design concept. Electrical power sources are generally less vulnerable than hydraulic or pneumatic sources and are more easily adaptable for redundancy. Electrical sources, however, usually require greater space and are heavier than comparable fluid sources. Survivability design techniques for fluid power sources are provided in section 5.10.

f. Design for easy replacement and/or repairability of landing struts that can easily be damaged from ballistic effects or forced/crash landing.

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5.16.3 Detail design.

5.16.3.1 Components. Components include shock struts, wheels, brakes, actuating cylinders, valves, accumulators, and drag braces. Consider using the following detail design criteria to minimize failure or other system degradation due to ballistic effect damage:

a. Provide for construction of components from materials that resist failure from cracking or shattering when struck by projectile threats or secondary spallation.

b. Consider lowest possible tire pressure for wheel assemblies to minimize destructive disintegration from ballistic impacts. Consider use of foam-filled tire assemblies in lieu of pneumatic type.

c. For detail design criteria for hydraulic or pneumatic components, refer to section 5.10.

d. For detail design criteria for control rods and control linkages, refer to section 5.9.

5.16.3.2 Attachments. The following design techniques should be considered to incorporate effective survival enhancement features in the landing system attachment design development:

a. Avoid landing system attachment designs using brittle materials such as castings, which could shatter/crack and fail when struck by projectiles or fragmentation. Consider structural attachments using ballistic-resistant or high-fracture-toughness materials.

b. Avoid landing system major attachment points using one primary securing element. Provide for multiple securing elements at critical attachment points.

c. Design attachments and supports for essential subsystem mechanisms to resist failure or jamming from ballistic damage (i.e., gear retraction and extension system).

5.16.4 Basic design, arresting hook. Design hook assembly so that bounding tendencies are at a minimum on initial ground contact. Specify no allowable bounce so that no possibility can exist to miss barrier engagement. Specify hook length sufficient to engage arresting cable under most extreme angles which can be expected during emergency landings or aborted takeoffs. Hook length is influenced by the following factors: (1) the number, spacing, and height of arresting cables, (2) aircraft weight, (3) control characteristics in the stall attitude, (4) location of the hook in relation to the aircraft wheels, and (5) effectiveness of the holddown devices.

5.16.4.1 Arresting hook extension controls. If the arresting hook extension is designed to be used only under emergency conditions, no retracting mechanism is required; however, ensure that there is a positive latching

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device which prevents inadvertent extension in flight or on the ground. If system is electrically actuated, ensure that controls from cockpit to uplock release mechanism are totally redundant. Extension may be by either mechanical or manual means, but it must extend in 2 seconds or less. It is required that a hookdown indication be provided to the pilot. Specify that this indication also warns when actuating handle position is different from hook position. Specify that this indication operates directly from hook. If release mechanism is electrically actuated, ensure that ground safety pin, when installed, interrupts electrical power to release mechanism. This will prevent release mechanism damage if the cockpit switch is actuated with the ground safety pin installed. In the interest of personnel safety, it is imperative to design the release mechanism to prevent installation or removal of the ground safety pin with the arresting hook in any position other than fully up and locked. Provide a shock-absorbing device designed to eliminate bounce tendencies as much as possible. The arresting hook system shall fail safe in operation so that (1) the arresting hook will lower in the event of failure of the release installation, and (2) the arresting hook will remain lowered in the event of failure or damage of any part of the release or actuating system.

5.16.4.2 Arresting hook installation. Design arresting hook so that all portions of aircraft, including all external stores, will clear runway by no less than 6 inches when subjected to arresting forces. Locate hook so that engagement is ensured after arresting cable has been depressed by aircraft wheels passing over it. Specify a location which will apply minimum possible loads on nosewheel and strut. (For further design information, refer to References 223, 244, 263 and 200 (Sec. 4B).) Ensure that protection is provided to prevent engagement during normal high angle-of-attack landings when hook is in stowed configuration. If dynamic load analysis indicates possibility of tail drag as a result of engagement, specify that a bumper or other suitable protection be provided in probable contact area.

5.16.5 Launch and recovery system repairability/maintainability. The landing gear system of an aircraft system shall be designed to provide a simple and reliable means to extend and lock the wheels and tail hook in position when the normal system has been damaged by hostile weapon effects. This is imperative for recovery of the aircraft aboard an aircraft carrier or a land station. Consideration shall be given to the location and accessibility of those components in the landing and launching systems that are most susceptible to primary and secondary damage mechanisms. Consideration shall be given to design of main landing gear struts and components that are interchangeable for either right or left installation to minimize the number of spare parts to be carried. The landing gear systems in aircraft are designed for ruggedness and hard use. The major elements of the main and nose gear struts and actuating linkages are generally resistant to small ballistic weapon effects and are readily changed if damaged by large threats. Items such as emergency pneumatic extension air bottles, however, can explosively shatter when impacted by a ballistic threat and can cause considerable secondary damage to nearby components and structure. Consideration shall be given to the design of such pressure vessels to minimize such reaction. Filament winding of nonmetallic material around an inner metallic air bottle is one example of a nonshatterable container. Attaching brackets for smaller components within the landing gear, nose gear steering, wheel brake, arresting gear, or drag chute systems shall be designed to be damage tolerant and reparable, rather than brittle and unrepairable when subjected to battle damage.

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5.17 Armor systems. Ideally, armor should defeat projectiles or fragments before damage can be inflicted on the component that the armor has been designed to protect. The basic mechanisms for defeat are the projectile breakup and/or absorption of the kinetic energy expended upon impact. All armor systems use these, or variations of these methods. Criteria have been developed to measure the energy absorption and the weight effectiveness of armor material and systems compared to a standard material. These criteria are called merit ratings. They include the protection (V_{50}) ballistic limit, the velocity merit rating (MR_V), and the weight merit rating (MR_W). These merit ratings are in common use, and most armor evaluations are related to them. Armor materials may be used singly or in combination to form armor systems, or they may be used in the fabrication of the aircraft structure. Material used as part of the aircraft structure is generally referred to as integral armor. Armor material added to the aircraft which does not generally perform a structural function is referred to as parasitic armor. Armor worn by personnel is categorized as body armor. Armor systems may be homogeneous or nonhomogeneous. The materials of which they are made may be opaque or transparent; they may be alloys or composites; and they may be machined, cast, laminated, or woven. The fabrication and processing techniques used may determine their resulting armor capability. In addition, how they are used and mounted can enhance their effectiveness. Specific uses of the various available armor materials are dictated by both their ballistic defeat properties and their nonballistic properties. There is no general catalog of materials by usage.

5.17.1 Definitions. Certain terms are used in context with armor materials and systems. Presented herein are a number of definitions of common usage.

5.17.1.1 Areal density. The areal density of an armor material is defined as the weight per unit area of a complete armor system expressed in pounds per square foot (psf) of surface area. (The weight is dependent on material density and thickness.)

5.17.1.2 Armor material. An armor material, as differentiated from an armor system is a basic material having those properties required to provide a measure of protection against projectile impact.

3.17.1.3 Armor system. An armor system represents some combination of one or more elements made of basic armor material (in some cases supplemented by nonarmor materials) to form an effective ballistic protection device.

5.17.1.4 Ballistic limits. Various definitions of ballistic limits are used to reflect a number of different test conditions and a variety of meanings as far as actual protection capability is concerned. In every case, the ability of an armor material to defeat a given threat is defined in terms of the degree of penetration of the armor by the projectile. The definition of what constitutes complete or partial penetration is of critical importance in differentiating between the various types of ballistic limits. Most commonly used in the past have been the Army ballistic limit, Navy ballistic limit, and protection ballistic limit. Of these three, the protection ballistic limit is

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the one most commonly used and is the type of ballistic limit reflected throughout this report, unless otherwise specified. Complete penetration occurs whenever a fragment or fragments from either the impacting projectile or the armor are caused to be ejected from the back of the armor with sufficient remaining energy to pierce a 0.020-inch-thick 2024-T3 aluminum alloy sheet placed parallel to and 6 inches behind the target. Any fair impact which rebounds from the armor plate, remains embedded in the target, or passes through the target, but with insufficient energy to pierce a 0.020-inch-thick aluminum witness plate, is termed a partial penetration. Transparent armor targets generally are set up for testing with a 0.002 in. thick aluminum foil sheet as witness material.

With this criterion, a ballistic limit is defined as a striking velocity of a kinetic-energy fragment or projectile below which partial penetrations of “the armor will predominate. This velocity is generally expressed as protection (V_{50}) ballistic limit, and is a critical velocity at which 50-percent complete penetrations and 50-percent partial penetrations of the armor target can be expected. This concept is shown schematically in Figure 5-188 along with an illustration of the Army and Navy ballistic limits.

The Army ballistic limit and Navy ballistic limit are discussed briefly herein, primarily for reference purposes. Under the Army ballistic limit criterion, a complete penetration occurs when light is visible through the penetration in the armor or when the nose of the projectile can be seen from the rear of the armor. This criterion for complete penetration is used to approximate the minimum velocity at which a projectile can produce a hole in the armor, yet not necessarily cause any fragments to be displaced to the rear of the plate. The Navy ballistic limit criterion for a complete penetration requires that the projectile or a major portion of the projectile pass through the plate. The Navy criterion for damage evaluation is used mainly for armor-piercing projectiles that contain an explosive filler.

5.17.1.5 Composite armor, Composite armor is an armor system consisting of two or more different armor materials bonded together to form a protective unit.

5.17.1.6 Experimental armor. Experimental armor is an armor material, composite, or configuration for which military specifications have not been established.

5.17.1.7 Fair impact. A fair impact results when an unyawed projectile strikes an unsupported area of a ballistic test sample at an undamaged location which is at least 3 calibers away from a previous impact, hole, crack, edge of sample, or spalled area. Only fair impacts are permitted for rounds used in determining the ballistic limit. This definition is applicable primarily to steel armor materials.

5.17.1.8 Fragment-simulating projectile (FSP). An FSP is a projectile of special shape and size designed for ballistic test firings intended to simulate the effect of typical fragments from high-explosive shells, usually of larger caliber than the FSP, on armor samples. Reference 259 contains the details on FSP'S used in ballistic testing.

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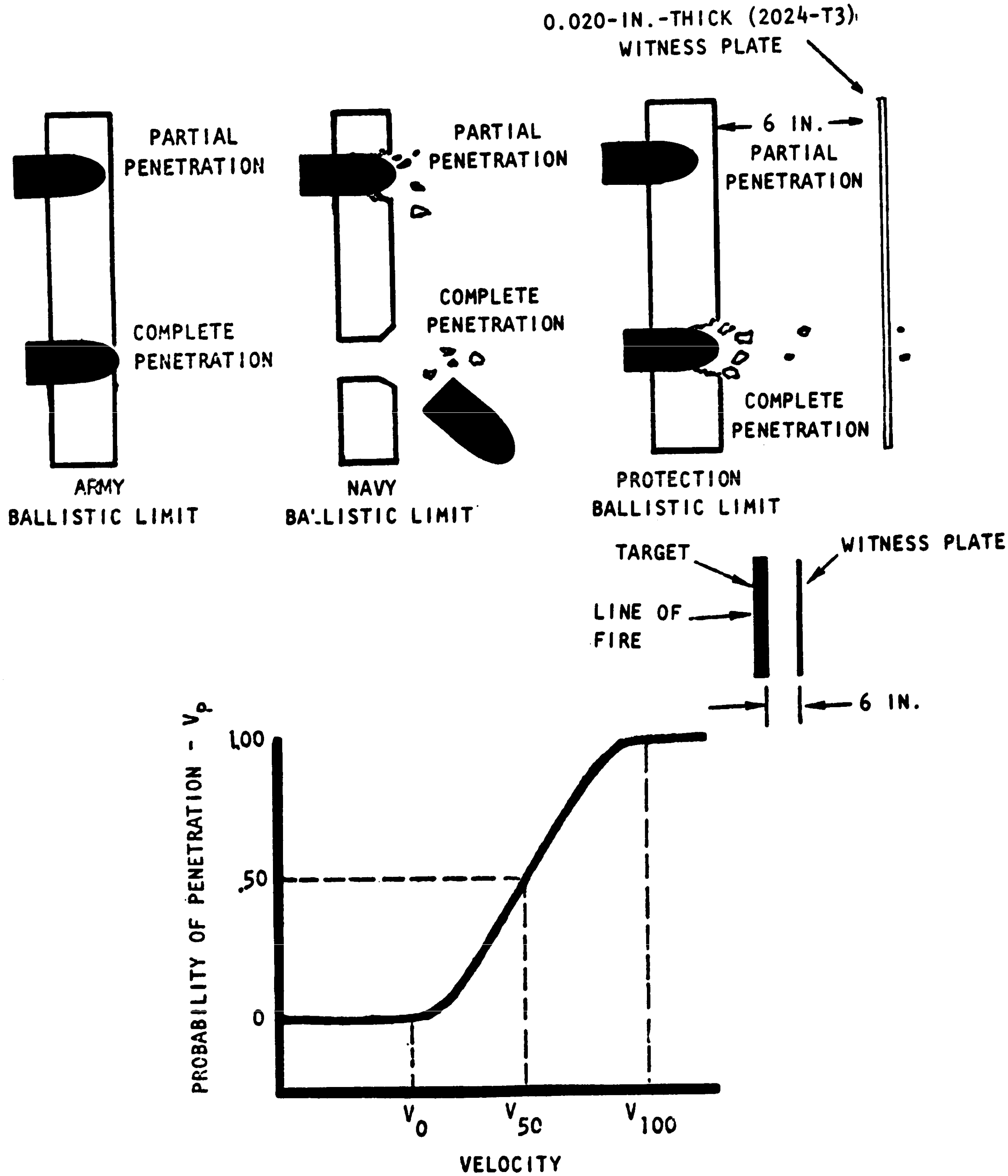

FIGURE 5-188. Ballistic limits.

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5.17.1.9 Full multihit capability. Full multihit capability is the ability of armor to sustain two or more hits within a distance of 3 calibers without loss in ballistic performance. A "caliber" is the diameter of the projectile.

5.17.1.10 Homogeneous armor. Homogeneous armor is armor made from a single material that is consistent throughout in terms of chemical composition, physical properties, and degree of hardness.

5.17.1.11 Lethality. Lethality is a measure of the destructive effect of a particular projectile on a given target under specified attack conditions.

5.17.1.12 Lightweight armor material. This is an armor material which will defeat a specific ammunition threat under a specific set of ballistic conditions at an areal density equal to or less than one-half that required by standard homogeneous steel armor.

5.17.1.13 Limited multihit capability. A limited multihit capability implies lesser degrees of armor protective ability than that provided by an armor having full multihit capability. The armor system suffers damage from an initial projectile impact that will not provide specified protection for a second projectile impact within a distance of 3 calibers.

5.17.1.14 Maximum vulnerable range. This is the range beyond which a specific threat is incapable of defeating a given armor.

5.17.1.15 Merit rating (velocity). Velocity merit rating (MRv), used primarily for preliminary screening of armor material candidates for a given application, is the ratio of the V_{50} ballistic limit obtained by test of the candidate armor (Reference 242) having the same areal density. Velocity merit rating is based on ballistic test at 0 degrees obliquity. In terms of an equation,

$$MR_v = \frac{V_{50} \text{ ballistic limit of candidate armor}}{V_{50} \text{ ballistic limit of homogeneous standard steel armor}}$$

NOTE : In the case of an FSP of .30 caliber and smaller, merit rating is measured with respect to Hadfield manganese steel (Reference 243).

5.17.1.16 Merit rating (weight). Weight merit rating (MRw) is usuallY based upon tests at close ranges and 0 degrees obliquity, but it can be based on various- obliquities when so specified. The weight merit rating is used for comparing the ballistic performance of candidate armor materials to the known performance of a standard steel armor (as specified for velocity merit ratings). In terms of an equation,

$$MR_W = \frac{\text{Areal density of standard steel armor}}{\text{Areal density of candidate armor}} (\times 100)$$

It is calculated for a point where both armors exhibit the same V_{50} protection ballistic limit.

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5.17.1.17 Minimum ballistic limit. The minimum ballistic limit is a value of ballistic limit, wherein the X subscript of the V_x ballistic limit (defined later) falls within an approximate range of 5 to 10. This represents a near-optimum practical value of ballistic limit, with only 5- to 10-percent probability of a complete penetration.

5.17.1.18 Obliquity. Obliquity is a measure, normally in degrees, of the extent to which the impact of a projectile on an armor material deviates from a line normal to the target. Thus, a projectile fired perpendicular to the armor surface has 0 degrees obliquity.

5.17.1.19 Overmatch. Overmatch is a term used primarily in association with steel armor, and indicates that the diameter of the impacting projectile is larger than the thickness of the armor plate.

5.17.1.20 Partial penetration. A partial penetration results from any fair impact that is not a complete penetration. More specifically, it is any fair impact that rebounds from the armor plate, remains imbedded in the target, or passes through the target, but with insufficient energy to pierce the 0.020-inch-thick 2024-T3 aluminum alloy witness plate.

5.17.1.21 Passive defense. The passive defense capability of an aircraft is that defense derived from its physical resistance to impact damage and includes basic structural strength, armoring, and certain basic design feature incorporating protection.

5.17.1.22 Percent weight saving. This was the means of measuring armor performance used prior to development of the merit rating concept; the method rated new armor materials by comparison of their areal densities to the areal density of steel armor required to provide equal protection. In equation form:

$$\textbf{Percent weight saving} = \frac{W_S - W_X}{W_S} \times 100$$

Where

W_S = areal density of steel required to provide equal ballistic protection

W_X = areal density of new material

5.17.1.23 Petalling. Petalling is the plastic deformation of a ductile material when struck by an impacting projectile or fragment, resulting in material being forced outward in leaflets or petal forms.

5.17.1.24 Protection (V_{50}) ballistic limit. The protection (V_{50}) ballistic limit is a computation made for each test condition on a given armor material by averaging six fair impact velocities comprising the three lowest velocities, resulting in complete penetration, and the three highest velocities resulting in partial penetration. A maximum spread of 150 fps is used between the lowest and highest velocities used in determining the ballistic limit.

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In cases where the spread between the lowest complete and highest partial velocities is greater than 150 fps, the ballistic limit is based on 10 velocities, five of which result in complete penetration and five of which result in partial penetration. In cases where the required number of complete and partial penetrations within 150 fps cannot be obtained because of insufficient armor sample or other reason, the protection (V_{50}) ballistic limit may be established by a four- or two-round test program. In the four-round program, the protection (V_{50}) ballistic limit is defined as the average of four fair impact velocities comprising the two lowest velocities resulting in complete penetration, and the two highest velocities resulting in partial penetration. A maximum spread of 150 fps shall be allowed between the lowest and highest velocities used in determining ballistic limits. In the two-round program, the ballistic limit is determined from one partial and one complete penetration within 75 fps.

All velocities used in determining the protection (V_{50}) ballistic limit are corrected to striking velocities.

5.17.1.25 Punching. Punching occurs when the armor fails in shear and a circular plug about the size of the attacking projectile is pushed from the back side of the plate.

5.17.1.26 Solid armor. Solid armor is all homogeneous and composite armor materials and systems having no airspace between elements.

5.17.1.27 Spaced armor. Spaced armor comprises all armor designs having spaces between armor elements.

5.17.1.28 Spalling. Spalling results when a layer of armor in the area surrounding the impact location is detached or delaminated from the armor, usually on the rear face.

5.17.1.29 Striking velocity. Striking velocity is the relative velocity between the target and the projectile at the instant of impact. It is normally expressed in feet per second (fps) and is determined from projectile initial (muzzle) velocity, range considerations, projectile aerodynamics and aircraft velocity.

5.17.1.30 Undermatch. Undermatch, a term used primarily in association with steel armor, indicates a relationship in which the diameter of the impacting projectile is less than the thickness of the armor plate.

5.17.1.31 Unyawed projectile. A projectile is considered to be unyawed when it strikes the armor test panel at an attitude such that its geometrical axis is within 5 degrees of its projector path.

5.17.1.32 V_X ballistic limit. This is any expression of ballistic limit wherein the X subscript denotes probability of complete penetration. For example, a V_{05} ballistic limit would be one at which the probability of complete penetration would be 5 percent.

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5.17.1.33 V_{50} ballistic limit. In general, this is a velocity at which the probability of penetration of an armor material is 50 percent.

5.17.2 Armor effectiveness criteria. Prior to the determination of criteria for armor effectiveness, the projectile threat mechanisms, as well as those mechanisms of the armor that defeat the threat must be known. Generally speaking, ballistic limits, merit ratings, and weight saving percentage values mean very little to a field commander. He needs to know the range within which the vehicle or aircraft is vulnerable to specific types of hostile weapons. To provide him with this information, the level of protection afforded by an armor system must be evaluated for expected realistic combat encounter conditions.

5.17.2.1 Armor defeat. Defeat of an armor material is normally defined in terms of the degree of penetration of the armor by a specific projectile. While this degree of penetration may be defined in varying ways, the basic question still involves consideration of what happens to the armor material under impact by the projectile. In the most basic terms, any one of four possible results may occur: (1) the projectile may perforate the armor, (2) the projectile may become partially imbedded in the armor, (3) the projectile may be deflected by the armor with little or no penetration occurring, or (4) upon impact the projectile breaks up. (Projectile breakup continues as the hardness of the armor and penetration pressure increases to a point where brittle fracture occurs.) In addition to these four basic penetration possibilities, various secondary or side effects can occur in specific situations. Included among these effects are punching, petalling, spalling, bulging, and cracking.

5.17.2.1.1 Side effects. Of primary concern in the case of side effects is the possibility that secondary fragments, possibly of a lethal nature, might be created in the process. Such secondary fragments, in some cases, would possess a damage potential greater than that of the original projectile because they would affect a greater area. A second result of these side effects might be a serious degradation of any capability of the material to sustain a second hit in the same general area.

5.17.2.1.2 Ballistic limit. The protection ballistic limit is a very meaningful measure of protection, particularly in ground warfare, because it defines the limiting velocity at which damage occurs beyond the armor, this damage being lethal to personnel. It can be determined quite readily by range personnel with a minimum of ambiguity. The Army ballistic limit, by contrast, does not include the energy absorbed in the final stage of penetrating the back surface of the armor. This energy may be a significant part of the total energy absorbed, or it may be very little depending upon the armor hardness, the test conditions, or the type of exit condition (spalling, punching, etc.). In general, the protection ballistic limit is very close to the Navy ballistic limit at low obliquities of attack, whereas the three types of limits may be essentially the same at high obliquities or when the projectile markedly overmatches the armor (projectile diameter is much greater than the plate thickness).

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5.17.2.1.3 Ballistic limit testing. In actual testing, a number of variables must be controlled or corrected for in order to obtain accurate ballistic limits. Velocity measuring equipment must be calibrated and its reliability assessed. The measured velocity must be corrected to striking velocity. It is necessary to determine and then use correction factors for the thickness and obliquity variations. In all terminal ballistic tests, it is important to use armor materials and ammunition of known metallurgical and mechanical properties and history. In addition, information on the behavior of the armor and ammunition should be reported by the testing organization. This type of information is extremely valuable in assessing the reliability of the data and in providing comparisons with similar ballistic data. The presence of spalling, punching, and cracking may indicate deficiencies in the quality of the armor. Projectile breakup may be caused by the quality of the projectile, or an ability of the armor that causes the projectile to shatter.

5.17.3 Materials. Classification of armor by major material types is as follows:

a. Metallic

b. Nonmetallic transparent

c. Nonmetallic opaque

d. Composite

General information is presented in the following paragraphs to acquaint the reader with the overall spectrum of armor material types. This material is available in Reference 123 and Reference 138.

5.17.3.1 Metallics. Metallic armors exist as specification armor, experimental armor, and spaced armor systems. Metals used in armor applications include steel, aluminum, titanium, magnesium, lithium, and beryllium. Magnesium, lithium, and beryllium are not available as specification armors. A discussion of these types follows.

5.17.3.1.1 Steel. Steel types used for armor include rolled, wrought, case-hardened, electroslag remelt, and dual hardness. Advantages in the use of steel include cost, availability, fabricability, and load-carrying ability. Disadvantages include weight and lack of corrosion resistance. Steels classified as specification armor include:

	Reference
Wrought homogeneous steel	242
Nonmagnetic rolled steel	243
Wrought high-hardness steel	254
Face-hardened steel	204
Roll-bonded dual-hardness steel	253

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5.17.3.1.2 Aluminum materials include cast and wrought aluminum alloy. Nonballistic advantages include weight, fabricability, availability, and corrosion resistance. Aluminum specification armor includes:

	Reference
Weldable aluminum alloy	250
Heat-treatable, weldable aluminum alloy	251
Armor, aircraft aluminum alloy-plates, deflector	215
Armor, aircraft aluminum alloy-plates, projector	216

5.17.3.1.3 Titanium. The advantages in using titanium are typical of all light metals. Typical titanium specifications for armor include:

	Reference
Weldable titanium alloy (6A1-4V)	252

5.17.3.1.4 Magnesium, lithium, and beryllium. Magnesium, lithium alloys, and beryllium armor have few specifications and are considered as experimental.

5.17.3.2 Nonmetallic transparent armor. Specifications for armor glass are in Table 5-XXXVII.

TABLE 5-XXXVII. Armor glass specifications.

Name	Specification	Reference Number
Glass and composite glass		
Bullet-resistant flat-laminated glass	MIL-G-5485	209
Laminated glass-faced composite	MIL-A-46108 (MR)	256
Acrylic		
AS-cast	MIL-P-5425	207
AS-cast modified	MIL-P-8184	219
Stretched	MIL-P-25690	248
Polycarbonate		
Plastic sheet, polycarbonate transparent	MIL-P-83310	266

5.17.3.3 Nonmetallic opaque armor. Nonmetallic opaque materials may be used as elements in composite armor. Included in these materials are aluminum oxide, boron carbide, nylon, boron, and fiberglass. Bonded and unbended ballistic nylon (Reference 241), boron woven roving fiberglass, bonded and unbended Kevlar may be used for protection against shell fragments and span. Kevlar is one of the most effective armor materials available today for defeating fragments.

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5.17.3.4 Composite armor. Most composite armor falls into the experimental category. Categories of composites include metal-metal, metal-ceramic, metal-organic, metal-organic-ceramic, and ceramic-organic. The specification for composite material is MIL-A-46103 (Reference 255).

5.17.4 Armor selection. To determine armor material needs, the designer must have the following information:

a. Aircraft affected
   (1) Type
   (2) Model
   (3) Serial number(s)

b. Protection to be provided for
   (1) Crewmembers
      (a) Pilot
      (b) copilot
      (c) Other
   (2) Aircraft component(s)

c. Nature of required installation
   (1) Permanently installed
      (a) Factory
      (b) Field (kit form)
   (2) Removable
   (3) Structural capabilities required
   (4) Nonstructural

d. Aircraft status:
   (1) New design
   (2) Undergoing major modification
   (3) Operational (in-service)

e. Extent of protection
   (1) Direction(s) (from rear, bottom, etc.)
   (2) Angle(s)

f. Threat to be defeated
   (1) Projectile type and size (e.g., caliber 12.7 MM API)
   (2) Impact velocity
   (3) Impact obliquity (worst condition)
   (4) Single or multiple impact capability

g. Design limitations
   (1) Allowable armor weight
   (2) Allowable effect on aircraft balance
   (3) Allowable restrictions (if any) on aircraft operation or performance

h. Logistic considerations
   (1) Cost limitations
   (2) Delivery schedule requirements

i. Special considerations (if/as applicable)

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5.17.4.1 Effective methods. Those efforts necessary for correct armor selection include the following:

a. Threat analysis.

b. An assessment of the protection level of the existing indigenous protection (existing aircraft structure and components) around the item to be protected for the directions of interest.

c. Design limitation review.

d. Determination of armor material/systems compatible with design limitations.

e. Determination of ballistic and applicable nonballistic characteristics of the candidate materials/systems. This includes determination of the multihit, span, and fragment prevention or protection required by armor use.

f. Selection of the candidate armor materials/systems that minimize overall aircraft/crew performance degradation, and determination of the cost impact of the candidates. The choice is generally based on producibility, maintainability, and cost and performance/cost trade-offs, after an armor configuration has been established.

g. Consideration of aircraft balance, armor application, fabrication, and installation factors.

5.17.5 Installation/fabrication. Improper installation of armor can degrade its effectiveness. Design in accordance with the guidelines listed herein is suggested. Where time limitations are specified by the procuring activity, due regard must be given to maximum allowable times for armor installation or removal. Airframe manufacturing tolerances should be taken into consideration to facilitate interchangeability of parasitic armor kits between individual aircraft.

5.17.5.1 Element design. In the design of satisfactory armor elements, due consideration must be given to a number of typical factors in addition to the weight limitations. The nature of these factors varies with the type of armor involved. Some of the more important of these factors as they relate to ceramic-plastic armor and to metallic armor are as follows:

a. Ceramic-plastic armor

(1) Armor panels should be designed, if possible, so that the overall dimensions will be a multiple of individual standard tile dimensions to minimize ceramic tile cutting, thereby reducing fabrication costs.

NOTE: It may be desirable to consider use of a monolithic facing in lieu of individual tiles where the ceramic element of the armor panel (curved or flat) can be produced within the current state-of-the-art. Such a procedure would provide definite advantages in ballistic

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protection capability, because the ballistic protection provided at or near tile joints normally is only about 85 percent of that provided at the center of the tile.

(2) Flat panels should be used wherever possible. Curvatures can be accommodated by use of monolithic panels as previously mentioned, or by faceting a series of flats.

(3) Individual elements must be designed with due regard to attachment and installation methods to be used.
NOTE : Through-bolting should be avoided wherever possible.

(4) Dynamic deformation (backing bulge) at impact should be accommodated by allowing a clearance between the backing surface and aircraft structure or equipment. This space allowance should be a minimum of 1.00 inch for .30 caliber armor and 1.50 inches for .50 caliber armor.

(5) A span shield material should be incorporated on the tile surface to contain the ceramic at impact.

(6) In any case where there is a possibility of error, the design should provide a positive means for insuring that armor is installed in proper orientation.

(7) A minimum of four support points should be used to attach each piece of armor.

b. Metallic armor

(1) The size of armor panels should be consistent with weight limitations for any single piece of armor, and it should be a function of location. In areas where installation or removal would be hampered by the existing structure and/or equipment, the weight should be reduced to a minimum.

(2) Shielding of the span should be accommodated by incorporation of span deflection plates or nonmetallic span shields, where applicable.

(3) In the case of dual-hardness or face-hardened steels, the design should provide a positive means of insuring that the armor is installed with the hard face outward (i.e., toward the impacting projectile).

(4) Allowances for dynamic deformation should be considered (similar to the ceramic-plastic armor).

(5) The design procedures used must consider the fabrication capability of the armor used. Table 5-XXXVIII presents fabrication data for three metallic armors.

5.17.5.2 Attachment methods. Satisfactory attachment design will require consideration of the type of armor materials involved, features of the aircraft mounting/backup structure, and nature of the planned attaching bracketry. Typical attachment methods for ceramic-plastic armors and for metallic armors differ as outlined herein. These attachment methods for the two armor types are illustrated in Figures 5-189 and 5-190, respectively.

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TABLE 5-XXXVIII. Fabrication data for metallic armor materials.

Parameter	High-Hardness Steel	Dual-Hardness Heat-Treated Steel	Dual-Hardness Ausformed Steel
Maximum Plate Size	0.250 in. thick, 33.5 x 72 in. 1.250 in. thick, 72 x 56 in.	66 x 96 in.	26 x 96 in., up to 2,000 lb
Minimum Radius of Curvature (for Typical Small-Arms	10 times thickness.	Approximately two times thickness in annealed condition.	3x9 in, depending on thickness.
Extent of Compound Curvature	7 in., deep dishes have been explosively formed.	Very small radius in both directions in anneald condition.	Unknown.
Ballistic Effects of Curvature	None.	Slight improvement.	None.
Tools Required for Cutting	EDM*	EDM	EDM
Welding Procedures Required	Austenitic stainless steel electrodes by MIG* or submerged arc techniques; or with low hydrogen ferritic electrodes.	Annealed condition: Hardex heat-treatable electrode gives ballistic joint. Heat-Treated Condition: Stainless steel electrode with 700°F preheat.	MIG* methods
Drilling	EDM	EDM	EDM
Recommendations for Attachment to Structure	Through-bolting.	Through-bolting.	Through-bolting.
Bolt Tension in Through-Bolting	Not important.	Not important.	Not important.
Panel Joining Methods	Welding or mechanical joints.	Welding or mechanical joints.	Welding or mechanical joints.
Ballistic Joints Between Panels	Cannot be achieved by welding unless material thickness is increased In heat-affected zone.	Can be achieved by welding with Hardex electrode in annealed condition.	Cannot be achieved by welding unless material thickness is increased in heat-affected zone.

*Electric Discharge Machine
*MIG - Metallic inert gas

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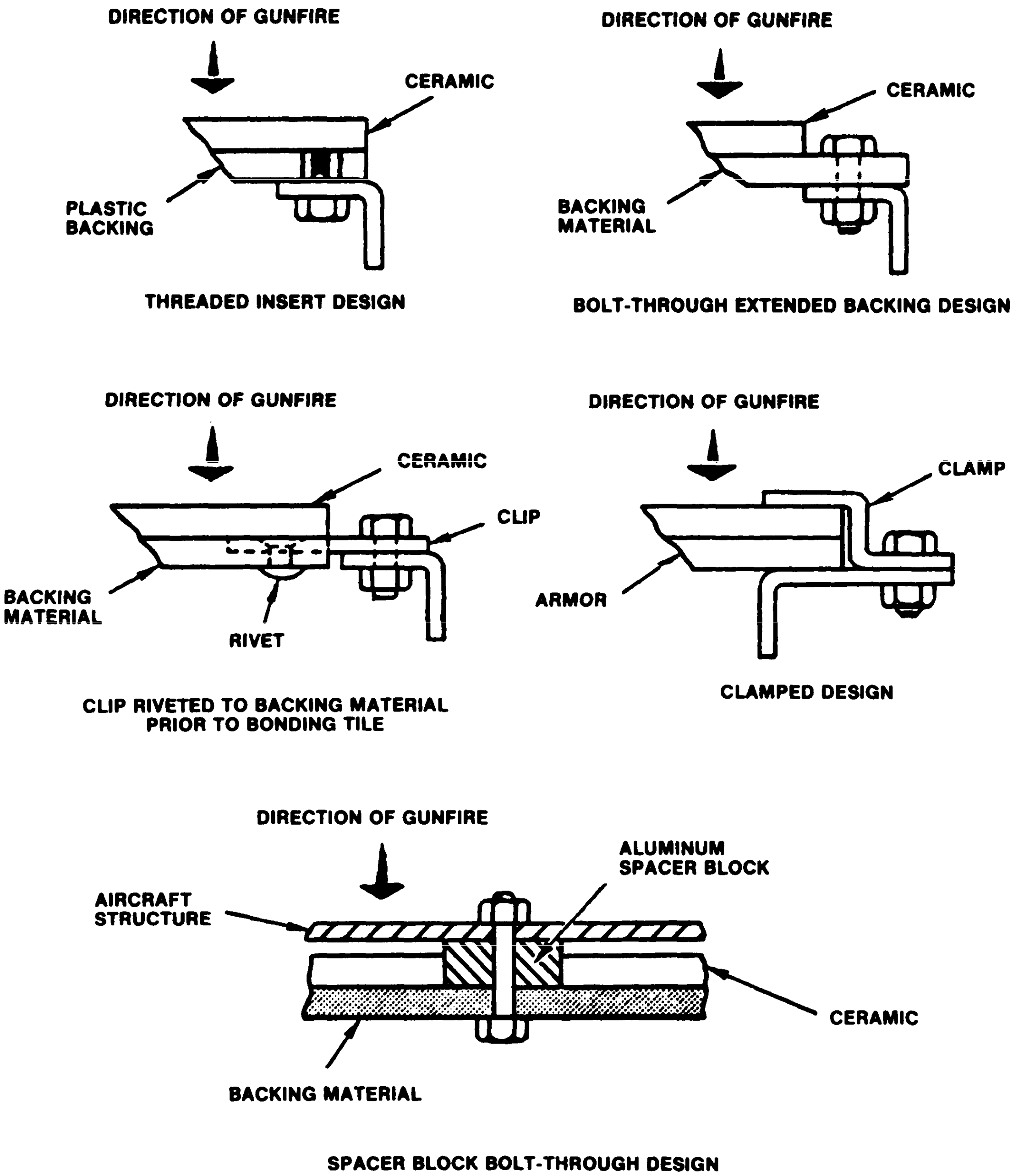

FIGURE 5-189. Ceramic-plastic armor attachment methods.

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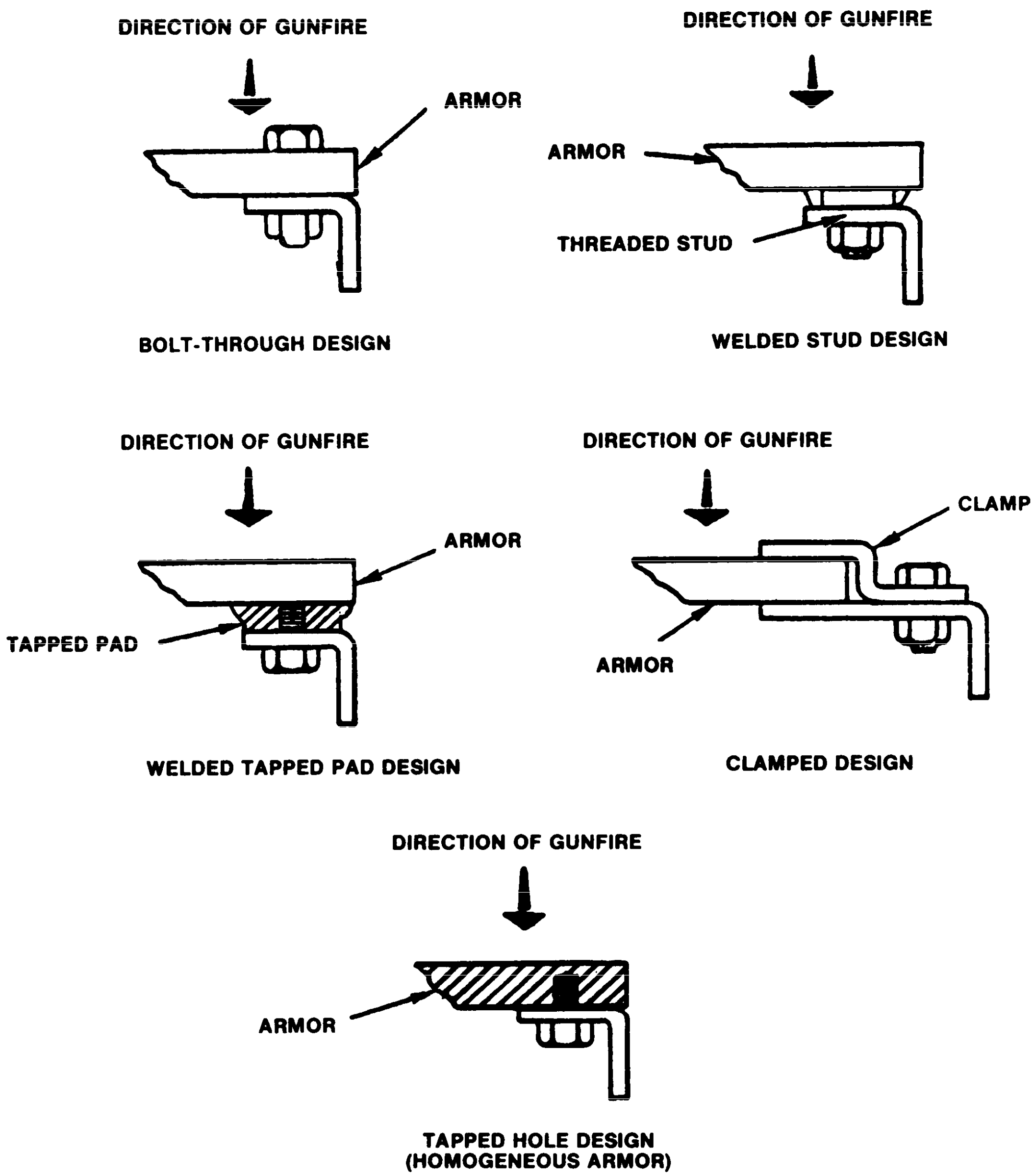

FIGURE 5-190. Metallic armor attachment methods.

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5.17.5.2.1 Ceramic-plastic armor. In general, attachment methods recommended for use with ceramic-plastic armor include the following:

a. Threaded inserts

b. Bolt-through extended backing material

c. Riveted bracketry attached to backing material prior to bonding of tile

d. Clamping

e. Spacer block bolt-through

5.17.5.2.2 Metallic armor. recommended attachment methods for metallic armor include:

a. Bolt-through design

b. Welded stud

c. Welded tapped pad design

d. Clamping

e. Tapped hole

5.17.5.2.3 Bracketry design. Bracketry for attachment of armor panels must be designed to meet specific flight and ballistic (dynamic) loading conditions. Crash loading must also be considered where applicable. Bracket design normally is based upon the most critical of these three conditions for the specific case at hand. The following basic considerations apply:

a. Flight loads - When designing to flight loads, the bracketry should neither yield below the limit load nor fail below the ultimate load.

b. Crash loads - When designing to crash loads, the bracketry should not fail below the crash load. Yield is of no consequence, provided it does not endanger personnel or interfere with emergency escape.

c. Projectile impact loads - When designing to projectile impact loads:
   (1) Bracketry may yield, but must not fail under limit load.
   (2) Standoff distance of bracketry should be such that no deflection or deformation of the armor or of bracketry will cause interference with any critical system function.
   (3) Bracketry must be sufficiently strong after being subjected to the limit load to withstand flight loads without deforming to the point of interference with critical systems. It is not necessary to design for crash loads after projectile impact, provided there is no danger to personnel.

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Although stress analysis based upon the foregoing requirements will be mandatory to verify the end design, certain approximations based on past experience can be used for purposes of preliminary evaluation. In general, experience has shown that brackets of 0.090-inch-thick 2024-T3 aluminum are commonly used in armor systems designed for protection against a .30 caliber threat. Similarly, 2024-T3 aluminum brackets of 0.125-inch thickness would be a good starting point in the design of .50 caliber armor installations. Test evaluation would be required to finalize this bracketry design because it would be difficult to analytically evaluate all the interacting factors, particularly for threat levels greater than .30 caliber.

5.17.5.2.4 Backup structure. A final factor to be considered in the design of an armor installation involves analysis of the requirements to be imposed upon backup structure to provide sufficient structural hard points for armor mounting. In new aircraft, the structure should be designed to support the required armor, whether it is to be built in initially or added later. In existing aircraft, structural modifications should be planned according to the following criteria:

a. When armor is added to a system in some way other than directly to the structure, the structural integrity must be maintained in accordance with original design conditions of flight loading, crash loading, or projectile impact loading.

b. When armor is attached directly to the backup structure, this structure should not:
   (1) Yield under limit load or fail under ultimate load for the flight load condition.
   (2) Fail under ultimate load for the crash load condition.

c. When designing for projectile impact loads, existing backup structure must be strengthened if necessary so that it will not yield under the projectile impact load. Structural reinforcement will be required under the following conditions (NOTE: Impact load refers here to the energy of the projectile specifically defined as the threat as it will affect the structure upon impact.):
   (1) If deformation of the existing armor backup structure after a projectile impact would cause interference with the system being protected.
   (2) If failure of the existing armor backup structure after a projectile impact would cause the armor to come loose and/or cause system interference.
   (3) If failure of existing primary airframe load-carrying structure that also serves as armor backup structure would occur after a projectile impact.
   (4) If the existing airframe primary structure that also serves as armor backup structure would yield after a projectile impact to the extent that the structure could not carry its design ultimate load.

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d. A structural reinforcement may be required under the following conditions:
   (1) If the secondary airframe structure that also serves as armor backup would yield after a projectile impact, but without system interference.
   (2) If failure of existing secondary airframe structure that also serves as armor backup structure would occur after a projectile impact, but without the armor coming loose and/or without system interference.
   (3) If the existing primary airframe structure that also serves as armor backup structure would yield after a projectile impact, but to such a minor extent that the structure would still be capable of carrying the design ultimate load.

e. In those cases in which a structural reinforcement is not required, the advantages and disadvantages of a reinforcement at the time of armor installation should be considered. The following general points apply:
   (1) If field level maintenance cannot be accomplished on the backup structures the reinforcement should be made.
   (2) If repair to the damaged backup structure after a projectile impact is estimated to be more extensive than the reinforcement prior to a projectile impact, the reinforcement should be made.
   (3) If the required reinforcement is extensive, but structural repair procedures are also extensive, and if it can be determined that spares are available, spares should be used in lieu of structural modification.

5.17.6 Armor protection against high explosives. Special consideration should be given to providing armor protection against high explosives. Using fragment data for the high explosive threat, theoretical V_{50} defeat values for selected armor materials are calculated at pertinent obliquity angles to establish required material and thickness criteria. Areal density, qualification status structural properties, environmental resistance, material availability and cost, and fabrication capabilities are significant factors that should be considered when selecting the armor system. Of these factors, the areal density value is considered to have the greater influence due to the limited amount of weight that can be tolerated by aircraft.

5.17.6,1 Protection against Soviet 23 mm HEI-T. The protection of the aircrew against the Soviet 23mm HEI-T projectile was investigated (Refer to Reference 109). This investigation indicated that protection can be accomplished for relatively modest penalties. The most important factor in the protection of the aircrew is to employ design features that cause the delay fuze time to be minimized and cause projectile detonation in the least distance. When this can be accomplished, the resulting fragments and blast effects can be defeated with minimum aircraft penalties. There is, however, very little verified data on the 23mm HEI-T delayed (MG-25) and superquick fuzes that is needed for future design applications. Also lacking is sufficient data on the fragmentation and blast characteristics of the projectile that is directly usable by aircraft designers. There is a lack of data on the

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response of ceramic-type armor to fragment impacts at high velocities. This includes not only the V_{50} data for zero and other angles of obliquity, but the residual velocity and mass of a penetrator (projectiles or fragment) for those conditions where the armor system has been overmatched and defeated.

5.17.6.2 Results. The results of the study, documented in reference 109, clearly support the feasibility of providing higher levels of ballistic protect ion. There are a number of technical areas that are considered to require further research to provide the detail design data and information essential to specific system application. The following are recommendations (also documented in reference 109), in descending order of priority, that will provide the information and validation required for operational usage.

a. The use of laminated Kevlar 49 material backing for boron carbide armor has not been optimized. It is recommended that additional research be conducted to determine the best type of Kevlar 49 weaves and areal densities required to achieve the lowest practical armor system weight. The choice and percentage of laminating resin should also be researched to insure that the optimum energy absorption of the armor system is obtained and that environmental factors are considered.

b. It is recommended that selected armor protection concepts be mocked up in an operational helicopter so that they can be flight tested for simulated combat encounters. This would provide field condition evaluation of each concept before any fabrication of the actual armor system.

c. There is a serious deficiency of ballistic limit (BL), threshold velocity (TV), and zone of mixed results (p) data on armor-piercing projectiles and high-velocity fragments for boron carbide ceramic armor composites. This information is essential for the calculation of V_{05} ballistic limit values that are being specified for aircrew ballistic protection in Army helicopter systems currently under development. It is recommended that this type of information be developed by a ballistic test program for the range of projectiles and fragments relevant to Army aircraft. Since this type of information is also required by the other military services, a joint program may be proposed for the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS). The penetration equations subcommittee would appear to be the responsible for such activity.

A design approach for providing protection of the aircrew in the AH-1G aircraft was extracted from reference 109 and since this data is classified it is ineluded in Volume 4 of this handbook. This data illustrates an armor protection system for high explosives.

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6. DAMAGE/PROTECTION PREDICTION DATA

6.1 Damage prediction. The consideration for damage prediction is two fold. The ability to determine how much damage has been generated by the threat terminal effects, and when sufficient damage has been generated as a result of response to weapon effects, in equipment/structure, to preclude satisfactory performance of its function. The damage effects generated by conventional weapons (nonnuclear weapons) are the result of the transfer of energy to the impacted element in the form of overstressing pressure and forces and/or thermal energy. When thermal energies and overstressing pressure or forces are imposed simultaneously, a synergistic situation results that may develop damage levels greater than the application of damage agents individually. The conventional weapon effects considered in this handbook include gun systems, rocket and missile systems and High Energy Laser (HEL) systems. The terminal damage effects of gun systems include (1) projectile impact and penetration with possible projectile breakup into fragments of core, jacket and contained incendiary materials, (2) the detonation of a projectile (warhead) with a contained high explosive charge, at or near the target surface, with attendent thermal shock and overpressure wave fronts, and detonation accelerated fragments (if added) and warhead casing fragments. The terminal damage effects of missile warheads include the by products of high explosive detonation and fragment generation which are similar to projectile warhead high explosive detonations. High Energy Laser terminal damage is the result of extremely high levels of energy contained in the directed beam of coherent visible or near visible light (present systems are in the IR spectrum) to capitalize on more efficient atmospheric propagation and target interaction. Presented herein are the major damage modes related to the appropriate terminal effects.

6.1.1 Ballistic damage effects.

6.1.1.1 Impact and penetration. Elements sensitive to impact and penetration damage include primary and secondary structural load elements, mechanical components, fluid containers, pressure containers, avionic components and crew members. The terminal effect agents capable of impact and penetration damage include projectiles (core and fragments) and fragments resulting from detonation of high explosive warheads. The damage modes for these sensitive elements are:

a. Structure
   (1) Loss of load carrying ability and/or stability
   (2) Loss of aerodynamic function

b. Mechanical Components
   (1) Cracking
   (2) Jamming
   (3) Shearing

c. Solid Explosive and Propellants
   (1) Explosion
   (2) Fire

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d. Fluid Containers
   (1) Leakage (loss of working fluid)
   (2) Explosion
   (3) Fire
   (4) Hydrodynamic ram effects

e. Avionic Components
   (1) Loss of electrical continuity and;or circuit function
      (a) Circuit opens
      (b) Circuit shorts

f. Crew Members
   (1) Lacerations
   (2) Loss of blood
   (3) Shock
   (4) Trauma
   (5) Vital organ damage

6.1.1.2 Warhead detonation (blast and fragmentation). The specific damage modes associated with blast effects are contingent on gross material deformation, loss of structural integrity and/or breakup resulting from shock waves, gross local temperature variations and penetration of structure by fragments and large magnitude overpressure pulses. These effects may occur either internally or externally. Components sensitive to these effects are listed below.

a. Structure
   (1) Loss of load carrying ability due to
      (a) Deformation
      (b) Breakup

b. Loss of aerodynamic function due to
   (1) Deformation
   (2) Breakup

c. Mechanical Components
   (1) Jamming-component or structural deformation
   (2) Component breakup

d. Solid Explosive and Propellants
   (1) Fire
   (2) Explosion

e. Fluid Containers
   (1) Leakage due to deformation or breakup
   (2) Hydrodynamic ram effects-Internal detonation, structural deformation
   (3) Secondary hazards (fire) in the presence of flammables

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f. Avionics
   (1) Loss of continuity/Circuit function due to opens and shorts from
      (a) Component deformation
      (b) Component breakup

g. Crew Members
   (1) Trauma from blast and shock

h. Secondary Hazards
   (1) Lacerations internal and external
   (2) Bleeding
   (3) Skin burns due to thermal effects

6.1.1.3 Incendiary effects. Incendiary effects are generated by various nonexplosive projectiles that contain incendiary materials, and high explosive warheads where the incendiary material is included either as part of the explosive mixture or as part of the casing fragmented by the detonation. Incendiary action can also be obtained from passive fragments impacting at high velocity. Incendiary action results in the initiation of fire or explosion in the presence of flammable or explosive materials. Flammable/explosive materials present in aircraft include:

a. Fuel

b. Solid explosive and propellants

c. Hydraulic fluids

d. Coolant fluids

e. Lubrication fluids

f. Oxygen

g. Furnishings

6.1.1.4 High energy lasers. The damage mechanism of high energy laser weapon effects is the depositing of an extremely high level of thermal energy on the surface of a target in a very short length of time. The damage sustained by a target is dependent upon the intensity and duration of the laser beam exposure, its "jitter" (wander from the aim point), the thermal absorption characteristics of the target material, and the material response to the energy deposited. The damage modes may include melting and burn through, vaporization, cracking and shattering of material surfaces, and creation of hot spots that may be capable of initiating secondary hazard conditions.

6.1.2 Ballistic threat. Methods of predicting the levels of damage to the aircraft depend on the comparison of the material response of the target element with a set of criteria for that element defining the level of damage causing loss of function. Simple criteria comparison methods have been used and

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accepted to determine Ballistic Threat functional disruption of some elements. Typical of this group are:

a. Projectile fragment impact effects on crewmen

b. Overpressure effects on crewmen

c. Incendiary effects on flammables

Criteria comparisons for some elements have been found to be inadequate for the prediction of functional disruption. Typical of this class are aircraft structures.

6.1.2.1 Structural damage prediction.

6.1.2.1.1 Projectile impact and penetration.

6.1.2.1.1.1 Direct effects. A program for the analysis and prediction of structural damage resulting from projectile and fragment impact and penetration was developed by the Air Force Flight Dynamics Laboratory (AFFDL) for use with the CDC computer and is published as "An Aircraft Structural Combat Damage Model". The Design Handbook contains the significant modeling data for mechanization of a computer analysis program and is published as an AFFDL Report (Reference 139). The Design Handbook is, in fact, a summary of the information presented in Reference 140. The design handbook is for use in predicting the effects of projectile impact on aircraft structure. It provides information on target penetration, damage size, and structural response following impact, along with predictions of the projectile post-impact state. Target penetration is represented by a ballistic limit equation, while the damage size is bounded by a pair of empirical curves. Structural response predictions are provided for both fracture at time of impact (impact fracture) and residual strength of impact damaged targets (residual static fracture). Projectile post-impact state is described in terms of trajectory and structural configuration. The predictions were developed for small-arms ammunition and are good for .30, .50 caliber and 20 mm projectiles on aircraft materials such as 7075-T6, 2024-T3, 2024-T81 aluminum and 6A1-4V titanium.

6.1.2.1.1.2 Induced effects (hydrodynamic ram). Another analysis program is available for the determination of hydrodynamic ram effect (fluid-structure interaction) generated within liquid containing structures, (i.e. fuel tanks as a result of impact and penetration by projectiles and fragmects. This computer analysis program is identified as BR-114R and is a modification of Northrop finite element computer code BR-1. The modification was developed by R.E. Ball for the Naval Post Graduate School, Monterey, California, to include fluid structure interaction. The theory and users manual are documented in NPS57B p74071 dated July 1974, and published by the Naval Post Graduate School Monterey, California (Reference 202). Several mathematical models of projectile and fragment empirical penetration data have been developed for use with hand or computer analysis. Description and usage data for these models are presented in section 6.2 of this volume.

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6.1.2.1.2 Warhead detonation. External Blast (overpressure only) - One analysis method is available for the estimation of in-flight aircraft vulnerability, a sub element of that analysis may be used to determine the structural response to HE blast of aircraft skin panels and cantilever sections. Using this data so developed an estimate of the threat induced point of incipient damage can be determined by comparison to the structural design limits. This analysis method is documented in Reference 141. The report was developed for the Aeronautical System Division, Wright Patterson Air Force Base.

6.1.2.1.2.1 Internal detonation (overpressure and fragmentation). A family of structural analysis programs for internal blast response are available by Northrop Corporation for the Air Force Flight Dynamic Laboratory based on a finite element analysis. A short description of these programs are presented below:

a. BR-1 - Finite Element Transient Response Analysis -- The BR-1 (Blast Response) finite element computer code that was developed to determine and predict the transient response of aircraft structures to the damage mechanisms associated with the detonation of high explosive (HE) projectiles internal to skin-rib stringer type structural compartment of an aircraft. Large deflections, large strains, nonlinear stress-strain relations, and material failure are accounted for in the structural response theory that was assembled in the development of the BR-1 code. Effects of fragmentation of high explosive projectiles on the impulse imparted to the structural compartment and on the loss of structural mass and stiffness because of penetration of fragments are accounted for. An available blast pressure loading computer program was used as the basis of the blast pressure loading subroutine in the BR-1 code. The results of sample problems that were executed with the BR-1 code are discussed. Experimental techniques are presented for obtaining test data to verify and/or support analytical predictions that may be obtained with the BR-1 code. This report is published in two volumes (Reference 142). Volume I is an engineer's manual that includes the development of the analysis and Volume II is a user's and programmer's manual for the BR-1 code.

b. BR-1A Computer Code for Transient Structural Response to Blast Loading of Aircraft Compartment - The BR-1A Structural Analysis program is a revision to the BR-1 program to include additional structural modeling capability (triangular plate) and to improve the basic program efficiency.

c. The BR-1A code is published as a supplement to BR-1 as an AFFDL Report (Reference 143).

6.1.2.2 Mechanical component damage. Damage prediction for mechanical components is generally limited to damage resulting from impact and penetration of projectiles or fragments. A technique that has been successfully used in the past was based on the premise that failure occurred on component wall penetration by the threat. Another method used for ballistically tolerant components is the determination of the residual load carrying capability of the

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component after projectile impact and penetration. The application of ballistic defeat/slowdown models presented in section 6.2 will provide adequate estimates of damage if case penetration is used as the criteria of disjunction. Determination of residual load carrying ability through the use of the lateral damage models contained in Reference 126, and comparison to required loads is sufficient to determine ballistically tolerant component disjunction.

6.1.2.3 Avionics damage.

6.1.2.3.1 Projectile fragment penetration. Most avionic equipment and components are a relatively light construction and sensitive as well to impulse loads. When avionics are housed in a walled container, the contained component will be damaged sufficient to cause failure if the projectile or fragment penetrates the wall of the container. Ballistic penetration equation are presented in section 6.2.1 which are applicable for determination of case penetration.

6.1.2.3.2 Blast shock. Explosion in the vicinity of avionics equipment (avionics boxes) can cause failure of contained equipment as a result of blast induced shock. An analytic technique and empirical criteria based on limited testing for prediction of damage to avionics boxes is contained in Reference 144.

6.1.2.3.3 Fire. Avionics equipment can be considered as not functioning satisfactorily if the external surrounding temperature causes the avionics components to exceed their upper operating range temperature limit.

6.1.2.4 Flammable materials. All flammable materials that are used in aircraft fabrication or carried in the aircraft during flight have design data which identifies the time-temperature combinations that result in the initiation of combustion. Comparison of these limits with the temperature developed by the threat will indicate whether fire damage results.

6.1.2.5 Aircrew disablement. The aircrew are subject to damage from several ballistic threat effects and associated secondary hazards. Included are:

a. Projectile/fragment impact

b. Projectile/fragment penetration

c. Blast effects
   (1) Fragments
   (2) Overpressure

d. Chemical/toxic effects of burning materials

Damage prediction data is presented as part of section 5.4 of Volume 1.

6.1.3 High energy laser damage. Currently there is no triservice endorsed method for damage prediction of military aircraft construction materials,

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consumables, or components from exposure to high energy laser weapon effects. The basic damage mechanism is the absorption of thermal energy by a target material that may produce melting, crazing, or burning. There is a basic difference between opaque and transparent materials in that the opaque materials absorb the energy initially in the very near surface region. For metallics, the level of incident energy required to produce burn through may be estimated by use of the following equation from Reference 83) (assuming normal incidence).

$$E = It = \frac{eL}{\alpha}(c\,\Delta tm + H_f)$$

where

E = incident energy density

I = incident flux (spatially uniform)

t = irradiation time

e = target material density

L = target thickness

α = surface absorptivity

c = specific heat

$\Delta T_m = T_m - T_o$

T_m = target material melting temperature

T_o = target material initial temperature

H_f = heat of fusion

This equation assumes the time for material penetration is short compared to irradiation time for material melting and reradiation and convection losses are small (Reference 83). The reradiation loss may be estimated by use of this formula:

$$I_r = ne\sigma T_s^4$$

where

I_r = reradiated flux

T_s = surface temperature

n = number of surfaces

e = surface emissivity

σ = stefan-boltzmann constant $(5.7 \times 10^{-12}$ W/cm^2 °I

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For convection, the rate of heat loss, g_c may be estimated as:

$$g_c = hA\Delta T_a$$

where

h = convective heat coefficient which is a function of the Reynolds and Porandtt numbers for the system

A = surface area associated with the value of h used

ΔT_a = difference between surface temperature and recovery temperature of flow medium (T_S - T_R)

For materials that ablate when subjected to high energy laser weapon effects, the following equation may be used (assuming normal incidence):

$$I = \frac{1}{\alpha} \frac{(LP}{\tau} (c\Delta Ta + Ha) + I_r)$$

Where

T_a = target material ablation temperature

H_a = material heat of ablation

$\Delta T_a = T_a - T_o$

For materials that are relatively thick and the thermal energy is absorbed in the very near surface region; that is, the depth over which energy is absorbed is small compared to the thermal penetration depth; and the time for energy to penetrate the target material is longer than the irradiation time; the following equation may be used to predict melting, crazing, and burns.

$$I = \frac{1}{2\alpha}\left[\frac{\pi KCP}{t}\right]^{1/2} \Delta T_S$$

Where

$\Delta T_s = T_s - T_o$

The methods shown are for preliminary estimating purposes only. Where more precise and current information is needed, consult with JTCG/AS for referral to specific government activities where research is being conducted in the areas of interest. There are a number of documents that contain more detailed and classified data on this subject. These are References 84 through 97.

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6.2 Ballistic defeat/slowdown. To properly evaluate the vulnerability or level of protection required for components within the airframe of an aircraft, it is essential to know the condition and velocity of a penetrator at impact. Since the aircraft structure and other subsystem components may be between the component of interest and the penetrator along the path of its trajectory, a method to calculate the sequence of events is needed. This section contains the penetration equations of solids and liquids sponsored by the JTCG/ME. They have been developed by the Penetration Equations Subgroup and have been documented in a Penetration Equaions Handbook. Only the basic penetration equations are provided in this handbook for use by the reader. For equation development and more definitive information, the reader is directed to the JTCG/ME Penetration Equations Handbook. This section is concerned only with nonexplosive projectiles and for Kinetic Energy penetrators. The geometry of a masking component or element can also affect the physical condition of a penetrator and its capability to pass through the material. The equations are structured to permit evaluation of the geometry of a component. The equations have been developed to be compatible with currently accepted vulnerability analysis practices in which the target is described as an assembly of components and the target attack is represented as a sequence of encounters with individual components. To the extent practical, the equations are expressed in terms of dimensionless parameters to make the choice of units for individual calculations flexible and facilitate the use of scaling principles.

6.2.1 Ballistic prediction. The basic interaction for which terminal ballistic prediction is required relates to an interaction between the impactor and a target component. The input data for a prediction are the description of the impactor, its state of motion, and a description of the target component. The output of the prediction is a new description of the impactor and a new state of motion. Currently, the equations do not allow a proliferation of encounters due to the fragmentation of the impactor and the component. This means that for impacts where breakup is known to occur, the prediction is a correlation between the original impactor and a major fragment of it. If the fragment is a small part of-the original impactor, this procedure causes the effect of multiple impacts to be disregarded. The output of one impact is the input for the next in a single sequence of impacts along a unique path through the aircraft target.

6.2.2 Equation parameters.

6.2.2.1 Impactors. The impactors to be considered are projectiles fired from aircraft or antiaircraft guns, and fragments from warheads that might employ uncontrolled fragmentation, controlled fragmentation, or preformed fragments. The projectiles may range in caliber from 7.62-mm to 57-mm and be of armor piercing (AP) or armor piercing incendiary (API) types. Fragments of interest may range in weight from a few grains to hundreds of grains.

6.2.2.2 Target components. The target components could be structural elements, avionic components, the walls of a fuel compartment, parts of the engine, etc. Aircraft components are comparatively thin with the great majority made from aluminum alloys or low-strength steels. Such components

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deform more readily than fragments and much more readily than the cores of AP and API projectiles. Impact results in intense forces of short duration. Very intense local deformation of the component occurs near the impactor but does not extend out more than two or three projectile diameters from the region of direct contact between impactor and component. The target components are often treated as plates, even though the component surface may be curved, because of the intense localization of the deformation. This tendency to localize the deformation in the component is most conspicuous at high impact velocities. Exceptions to this tendency for deformation to be localized occur for impacts against very thin plates and at lower velocities for which there are significant bending deformations at larger distance from the region of contact. This permanent flexure of the plate is called dishing.

6.2.2.3 Impact conditions. There is a range of impact conditions for which the projectile can not perforate the component. The projectile is either completely decelerated or ricochets from the component. The impact velocity at which the projectile just perforates the component is called ballistic limit. This velocity depends on the properties of the component and on the projectile obliquity and yaw. For sharp unyawed projectiles, the deformations of the component are particularly intense near the tip of the projectile and cause rupture and perforation by piercing the component. Blunt projectiles, most fragments, and sharp projectiles impacting with significant yaw tend to accelerate a small region of the component and thus to push out a plug. The dynamites of piercing and plugging are sufficiently different to require different descriptive procedures.

6.2.2.4 Above ballistic limit. Above the ballistic limit, the projectile emerges from the component with a new speed and, in general with changes in direction of travel and orientation of the projectile; the projectile is deflected most near the ballistic limit velocity and is deflected toward the normal to the back surface of the component. With increased exit speed the deflection very rapidly decreases.

6.2.2.5 Fragments. Although aircraft components are soft compared to AP and API projectiles, these components can strip off the jacket of an API round and are capable of breaking up the core of a projectile. Since fragments are more easily deformed than projectile cores, they may be significantly deformed by impact and reduced in weight. Failure processes that occur in the projectile core and in fragments are generally quite different. Projectiles tend to fail by brittle fracture. This means that cracks abruptly develop in the core without significant permanent changes of shape. For aircraft target components, this usually is brought about by bending moments applied to the core during impacts at obliguity. Fragments tend to fail by ductile failure in which there is intense deformation near the contact surface and the deformed material is wiped off as perforation proceeds.

6.2.2.6 Penetration equations features. The penetration equations needed for vulnerability analyses must summarize these phenomena in the form of relations between the initial conditions of an impactor and component and final conditions. Specifically, the final impact velocity, its current shape and size, and its continued ability to function as an incendiary agent or

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penetrator must be predicted from the original velocity at impact and its appropriate dimensions and the system parameters. The most desirable feature of the equations are that they predict the behavior of real projectiles and fragments by simple mathematical procedures with accuracy that is commensurate with other inputs to vulnerability analyses. For this reason the validity of the equations used should be demonstrated by comparison with experimental data.

6.2.3 Recommended equations. A set of equations has been selected that consists of two kinds of equations; first, equations that predict the state of the impactor for certain ranges of impact conditions; and second, those that determine the range of impact conditions for which specific equations of the first type apply. These equations are clearly interrelated and form a larger analytical procedure. This procedure has six parts which are as fol.-lows:

a. Input of data on the impactor and target data.

b. Determination of impactor presented area and shape.

c. Determination of the mode of perforation or ricochet.

d. Calculation of impactor's changes of motion.

e. Determination of impactor mode of failure.

f. Calculation of changes in the description of the impactor.

These divisions of the procedure also correspond to stages in the logical prediction progression. Equations for both fragments and projectiles follow these divisions, and the operations in each division are mathematically similar. There are sufficient input differences, and differences in the details of the operations to require separate treatment of projectiles and fragments.

6.2.3.1 List of equation symbols.

A_p Effective presented area of an impactor

B Brinell hardness of a material

C_b Constant in the ballistic limit equation for blunt projectiles

C_{bf} Constant in the ballistic limit equation for fragments

C_d Drag coefficient

C_f Shape factor for fragments

C_s Constant in the ballistic limit equation for sharp projectiles

C_2 Constant in the breakup equation for projectiles

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E	Elastic modules of target component (Young's Modulus)
E_c	Elastic modulus of core materials (Young's Modulus)
E_f	Elastic modulus of fragment material (Young's Modulus)
F	Mathematical function
F_i	Incendiary-functioning parameter
J	Ricochet parameter
K	Bulk modulus of target component material
K_f	Bulk modulus of fragment material
K_2	Ricochet constant
L	Length of an impactor
L_c	Length of projectile core
L_n	Projectile nose length
L_{nc}	Nose length of a projectile core
Q_1 through Q_{13}	Dimensionless constant (See 4.2.2.1.1)
R_n	Ogive radius of the nose of a projectile
R_{nc}	Ogive radius of the nose of a projectile core
T	Target thickness along a line perpendicular to the plate
U	Hugoniot speed
V	Relative impact speed of impactor with respect to the component at impact
V_a	Speed of aircraft with respect to its target with respect to a ground reference system.
V_c	Critical speed for shattering
V_d	Critical speed for deformation-mode mass loss
V_p	Speed of a projectile with respect to a ground reference system

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V_r	Exit speed of an impactor after perforation
V_{rr}	Exit speed of an impactor after ricochet
W	Weight of an impactor
W_c	Weight of a core (or portion of a core in case of prior break-up)
W_o	Reference weight for scaling factors - 100 grains
a	Ricochet parameter
b	Ricochet parameter
b_b	Constant in ballistic limit equation for blunt projectiles
b_f	Constant in ballistic limit equation for fragments
b_s	Constant in ballistic limit equation for sharp projectiles
c	Sound speed in a target element
c_f	Sound speed in a fragment
d	Diameter of a projectile or breadth of a fragment
d_c	Diameter of a core
d_x	Exit diameter or breadth
d_{cx}	Exit core diameter
f	Exponent of ballistic limit equations for fragments
h	Exponent of ballistic limit equations for fragments
k	Constant in ballistic limit equations
m	Ricochet constant
p	Impact pressure
q	Constant in mass-loss equation
v	Constant in mass-loss equation
s	Constant in mass-loss equation
t	Pulse duration
w	Width of fragment

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x	Distance of impactor travel
α	Nose angle (total angle or half angle)
α_c	Nose angle of core
β	Angle between penetrator axis and plate material
δ	Constant in yaw equation
η	Constant for deformation-mode mass loss equation
η_c	Constant for critical conditions for shatter
υ	Constant in yaw equation
θ	Obliquity of an impactor path with respect to a component, measured from the inward drawn normal to plate surface
θ_r	Obliquity of an impactor path after perforation, measured from the inward drawn normal to the plate surface
θ_{rr}	Obliquity of an impactor path after ricochet measured from the inward drawn normal to the plate surface
λ	Constant for breakup equation
λ_x	Constant for breakup equation for perforation
λ_r	Constant for breakup equation for ricochet
μ	Impact inclination of a flat surface
μ_c	Critical impact inclination of a flat surface
ρ	Specific weight of a target component
ρ_c	Specific weight of a core
ρ_f	Specific weight of a fragment
ρ_p	Specific weight of a projectile
σ	Ultimate strength of a target component (tensile strength)
σ_f	Ultimate strength of a fragment (tensile strength)
σ_c	Ultimate strength of core (tensile strength)
σ_y	Yield strength of a target component

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σ_{yf}	Yield strength of a fragment
τ	Compressive strength
ϕ	Yaw angle
ψ	Elevation angle
ω	Constant in yaw equation
Ω	Azimuth angle

6.2.3.1.1 Summary of dimensions constants. These relationships are developed in the JTCG/ME "Penetration Equation Handbook for Kinetic Energy Impactors (U)" 61-JTCG/ME-77-16.

6.2.3.2 Input and output variables. The basic interaction for which terminal ballistic prediction is required relates an impactor and a target component. The input data required for the prediction are a description of the impactor, its state of motion, and a description of the target component. The output of the prediction is a new description of the impactor and a new state of motion. Penetration equations are the correlations between the initial and final descriptions of an impactor and its initial and final state of motion. Table 6-I summarizes the required input and output variables and the categories of equations that are required for the correlation. The impactors description is divided into four parts: official designation, material properties, principal dimensions, and function capacity. In principle, the last three of these and the state of motion could be the object of a correlation for a given target. In current practice, only correlations of principal dimensions and predictions of special functioning on impact, such as incendiary functioning or high-explosive initiation, are carried out. It is assumed that there are no changes in material characteristics as the result of an impact against a target component.

6.2.3.3 Official designation. An official designation of a projectile (such as 20-mm API), in principle identifies the material properties, principal dimensions, and functional capacities of a specific projectile; but ambiguities are possible. Clearly, it is as fallacious to compare analyses done with different projectiles as it is analyses done with different equations. To avoid ambiguity, the identification of a projectile by an official designation should include a reference that relates the designation to a detailed description of the projectile, and the documentation of the analysis should explicitly state the striking mass and the core mass. For fragments, the important facts that are derived from the official designation of the warhead are the mode of fragmentation and the size of the fragment that it is intended to produce. It is essential that there be agreement on the mass and principle dimensions of the fragments used in any analysis. Fragment identification should include the mass and shape (controlled or preformed with cube, sphere,

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TABLE 6-I. Input and output variables.

Input-Output Variable	Equations
Projectile description	
Official designation	
Material properties	Equations of material
Density	degradation (currently
Moduli	not considered).
Strengths	
Principal dimensions	Equations of impactor
Major dimensions	Deformation and failure
Shape description	
Mass	
Functional capacity	Equations governing the
Incendiary	actuation of incendiary
Projectile state of motion	Equations governing the
Velocity	state of motion.
Obliquity	
Yaw	
Yaw rate	
Target description	External calculations
Identification	determine the next
Material properties	component.
Principal dimensions	

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parallelepipeds or diamond shape, uncontrolled with either compact or noncompact designation and with specified length-to-diameter radio (L/d). The Handbook for Metals (Reference 206) should be used as the reference for the correlation of the properties of an impactor to an official designation of the material.

6.2.3.4 Material properties. The material properties that are used in the descriptions of impactors and components are listed as follows:

Material Property	Symbol
Specific weight	ρ
Young's modulus	E
Bulk modulus	K
Compressive strength	τ
Tensile strength	σ
Elongation at failure (percent)	ϵ_a

No attempt is made in current predictions to account explicitly for degradation of the strength of the impactor material as a result of impact. The material constants for use in penetration equations are listed in Table 6-II.

6.2.3.5 Principal dimensions. The dimensional description of a projectile can be given to a high degree of accuracy by a comparatively small number of parameters since the shape is simple, known in detail, and nearly identical for all projectiles of a single official designation. The dimensional description of fragments is equally precise for preformed fragments, but becomes approximate for fragments formed by controlled fragmentation, and is a best estimate for natural fragmentation. Simplified representations of projectiles and fragments are shown in Figure 6-1. A set of descriptive parameters that cover current procedures and likely improvements in the completeness of the impactors description is listed in Table 6-III.

6.2.3.6 Impactor state-of-motion. The state-of-motion of an impactor is defined by its speed along its line of flight with respect to the component. The line-of-flight intersects the component and is specified by an obliquity angle that is measured with respect to the normal to the surface of the component at the point of intersection. The yaw angle is the angle between the line of flight and the longitudinal axis of the impactor. The state-of-motion of the impactor is defined with respect to a frame of reference that is centered at the target component. This state-of-motion includes. the motion of the aircraft and the impactor with respect to the warhead or gun that launched the impactor. Aircraft target shot line descriptions are developed with respect to a coordinate system which refers to longitudinal and vertical axes of the aircraft. Azimuth angle, Ω, (0 to 360°) measured in the plan view, is the angle

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TABLE 6-II. Material constants for equations

Alloy	B (BHN)	$(C_b)_1$ (ft/sec)	$(C_b)_2$ (ft/sec)	k (ft/sec)	b_b	C_s (ft/sec)	b_s
Steel							
	100	1,590		0	0.61	2,480	0.69
	150	1,805		0	.61	2,600	.67
	200	1,933		0	.61	2,760	.65
	250	2,041		0	.61	2,880	.63
	300	2,084		0	.61	2,980	.62
	350	2,041		0	.61	3,090	.62
Aluminum							
2024-T4	120	529	3,731	450	1.75	1,830	0.60
5083-M113	82	386	6,132	750	1.75	1,620	.63
5154-0	58	395	4,099	500	1.75	1,560	.64
X5356-0	65	458	2,926	350	1.75	1,630	.63
6061-T6	90	458	4,117	500	1.75	1,600	.63
7075-T6	150	628	3,153	375	1.75	1,900	.60
7039-T61	123	467	4,117	500	1.75	1,740	.61
Titanium							
6 Aℓ 4V	325	1,880	4,703	350	1.00	2,660	.75

between the aircraft longitudinal axis and the plan view projection of the relative attack trajectory, and increases counterclockwise from the nose. Elevation angle, ψ, is the angle (0 to ±90°) between the plan view projection of the relative-attack trajectory and the trajectory itself. [1] Since the projectile is always considered as moving toward and into the target, an attack azimuth defined by $\Omega = 0$ involves a frontal attack, and an attack elevation, ψ, defined as being positive is an attack from above. Since the aircraft target is moving with speed V_a so is the coordinate system. A frontal attack $(\Omega = 0, \psi = 0)$ produces a relative impact speed equal to the algebraic sum, $V_p + V_a$, of the aircraft and projectile speeds*; contrarily, an attack from the rear $(\Omega = 180, \psi = 0)$ produces a relative speed, $V_p - V_a$. In order to encounter the aircraft along a shot line defined by $\Omega = 90°$, $\psi = 0°$ or ($\psi = 90°$) (a beam or overhead relative attack trajectory) the projectile will have a relative

1 The penetration equations are applied accordingly to impactors on shot lines so defined.

* As measured with respect to the gun or warhead.

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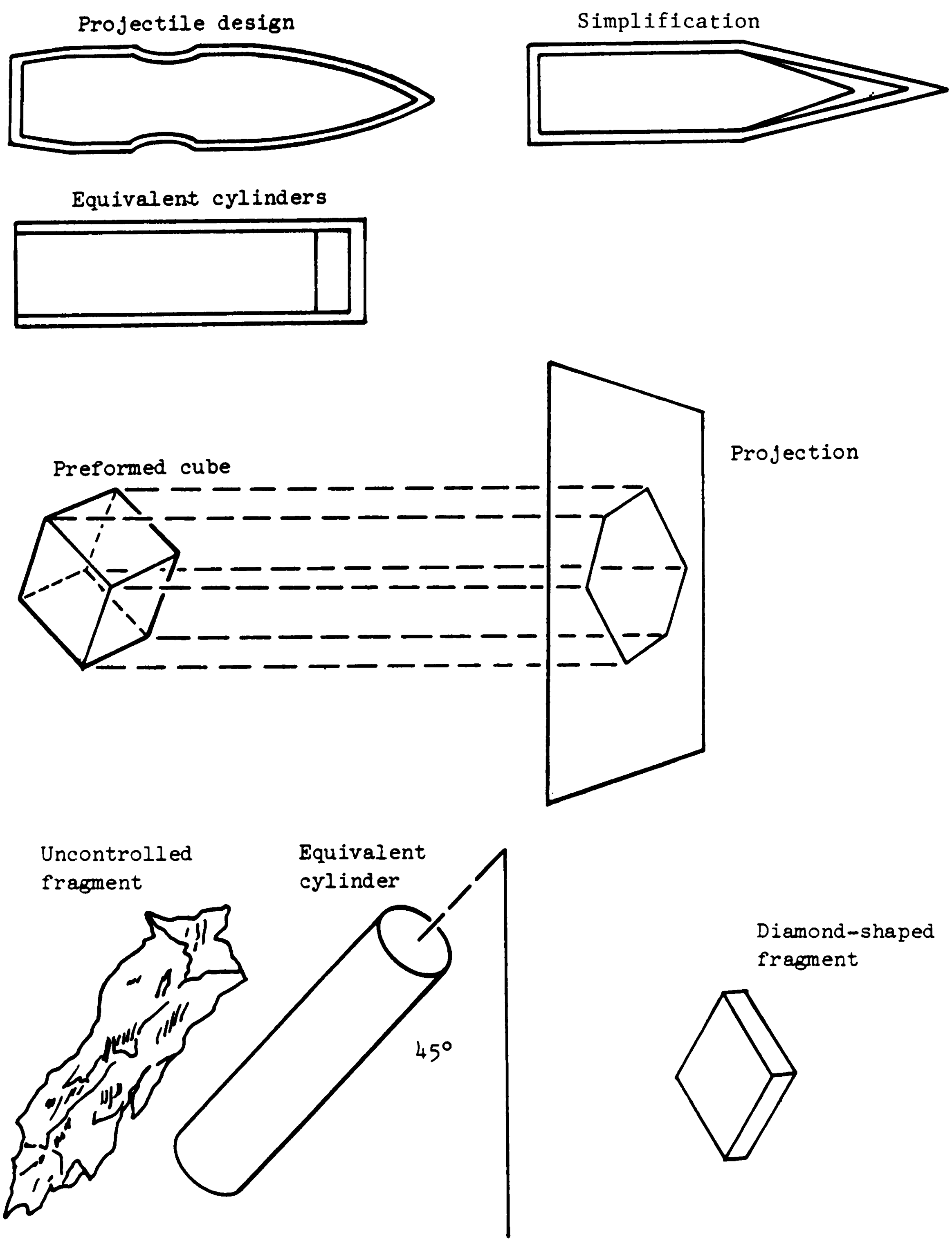

FIGURE 6-1. Impactor configurations

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TABLE 6-III, Description of impactors.

Parameter	Projectile	Projectile Core	Fragment
Major Dimensions			
Length	L	L_c	L
Diameter (breadth)	d	d_c	d
Width	-	-	w
Shape[a]			
Cone angle		c	-
Ogive radius	R_n	R_{nc}	-
Nose length	L_n	L_{nc}	-
Shape factor	-	-	C_f
Weight	W	W_c	W

[a]All projectiles are currently treated as cone-nosed projectiles.

speed of magnitude $(V_p^2 - V_a^2)^{1/2}$. More generally, the magnitude of the relative speed of the projectile with respect to the aircraft, along a specified shot-line, is given by:

$$v = V_a \cos \Omega \cos \psi + \sqrt{V_p^2 - V_a^2 \left(1 - \cos^2 \Omega \cos^2 \psi\right)}$$

Though unyawed with respect to its own trajectory, the projectile is yawed with respect to the relative trajectory (shot-line) along which it encounters the aircraft. Yaw influences the terminal behavior or projectiles in very significant ways and needs to be taken into account.

For a projectile which is not yawed with respect to its own trajectory, its relative yaw is:

$$\phi = \arccos \left[\frac{v^2 + V_p^2 - V_a^2}{2 \, v \, V_p} \right]$$

6.2.3.7 Target description. The target description, whatever form it may take, is equivalent to a set of planes of the aircraft that identify and locate the components of the target with respect to longitudinal and vertical

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axes. From this description the components encountered along a given shot-line are identified as their functional contribution to the target, vulnerability to impact, material properties, and principal dimensions. A component of the target is currently treated as a plate that has the thickness of the component at the point of impact so that the only relevant geometric properties are the orientation and the thickness. The material properties of the target are given by its specific weight P, Young's modulus E, bulk modulus K, compressive strength r, and tensile strength σ.

6.2.3.8 Projectile penetration equations. Figure 6-2 is a schematic representation of the interrelation of the stages and the principal computations that are performed for projectiles. The six stages form a loop so that the output of one complete prediction is part of the input for the next prediction. The third and fifth stages consist of equations and logical operations that serve to decide which equations in the fourth and sixth stages are right for predicting changes of motion and changes in the description of the projectile (i.e., changes in the dimensions and shape).

6.2.3.8.1 Data input. The data listed in Table IV are given as initial conditions, or as data on the current target and the output of a preceding impact. If these data are initial conditions then the information on the orientation of the shot-line with respect to the aircraft, the speed of the projectile, and the speed of the aircraft are converted to a speed and yaw with respect to the target components. When the data on the state-of-motion are the output of the preceding impact, the speed of the projectile is a direct equality of output to input:

$$V = V_r$$

where

V_r is the predicted residual velocity from the preceding impact.

Where $\Delta\phi$ depends upon the distance between components it is calculated by:

$$\Delta\phi = 180° - \sin^{-1} [\sin^2 \upsilon \ \sin^2 \delta + (\sin \upsilon \cos \omega \cos \delta + \cos \upsilon \ \sin \omega)^2]^{1/2}$$

$$\upsilon = 40°$$

$$\delta = (34° + 0.260\ \theta°)(0.9\ Q_7/Q_2)$$

$$\omega = 139° - 0.24\ \theta°$$

$$Q_7 = x/d \qquad Q_2 = 4\omega/\pi p d^3$$

where

x is the distance between components and d is the diameter of the projectile.

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$$\phi = \sqrt{\phi_r^2 + \Delta\phi^2}$$

where

ϕ_r is the yaw from the preceding impact.

The input data on the description of the projectile are either the initial values of the projectile parameters or the values for the preceding impact.

$$d = d_r \qquad d_c = d_{cr}$$

$$\alpha = \alpha_x \qquad \alpha_c = \alpha_{cx}$$

$$W = W_r \qquad W_c = W_{cr}$$

6.2.3.8.2 Presented area and shape determination. Two dimensional quantities that are needed in subsequent calculations are the ratios of target thickness to projectile diameter Q_1 and effective projectile length to diameter Q_2.

$$Q_1 = T/d$$

$$Q_2 = \frac{4W}{\pi \rho_c d^3}$$

If Q_2, which is the effective L/d, is greater than or equal to tan Ø the effective presented area is the oblique cross-section and does not depend on the length of the projectile:

$$A_p = d^2 \; [\pi/(4 \; | \cos \phi |)]$$

but if Q_2 < tan Ø the presented area includes the projectile length of the projectile and the total presented area is calculated by:

$$A_p = d^2 \left[\frac{4}{\pi \rho_c} (W/d^3) \; / \sin \phi / + \frac{\pi}{4} / \cos \phi / \right]$$

$$= d^2 \left[Q_2 / \sin \phi / + \frac{\pi}{4} / \cos \phi / \right]$$

The angle of the point of the projectile that is actually presented to the target component should include the effect of projectile yaw so that the presented angle is given by:

$$\gamma = \alpha + \phi$$

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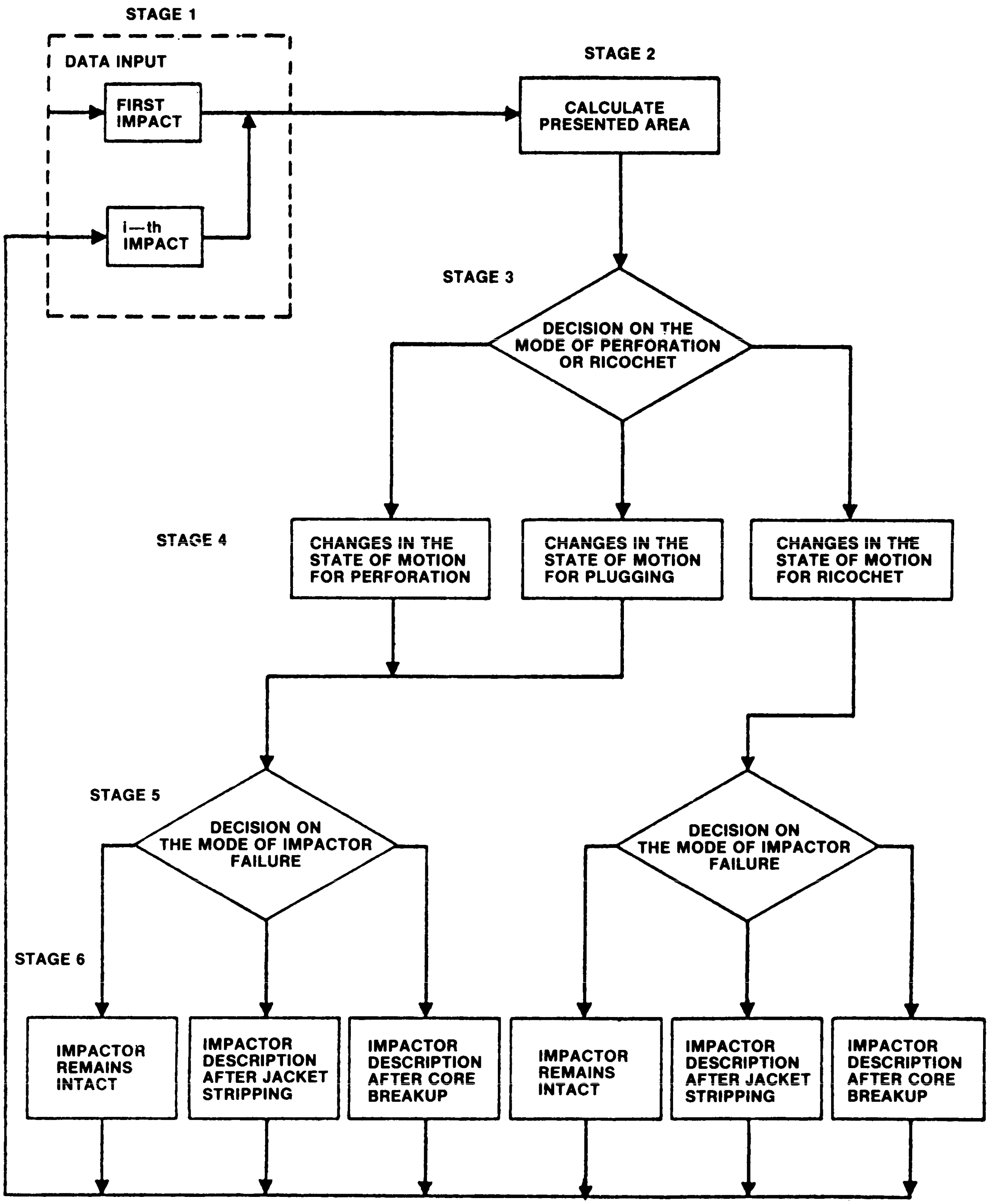

FIGURE 6-2. A schematic representation of stages and principal computations for projectiles.

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TABLE 6-IV. Input data.

Parameter	Overall Projectile	Core	Target
Material properties			
Elastic modulus		E_c	
Specific weight		ρ_c	ρ
Density		ρ_c/g	ρ/g
Tensile strength	σ_P	σ_c	α
Brinel hardness			B
Principal dimensions			
Length	L	L_c	
Nose Length	L_n	L_{nc}	
Thickness			T
Diameter	d	d_c	
Nose angle	α	α_c	
Weight	W	W_c	
Functional capacity			
Incendiary	F_i		
State of motion			
Speed, projectile	V_p		
Speed, aircraft	V_a		
Speed, in component frame of reference	V		
Yaw	ϕ		
Obliquity			θ
Azimuth angle of shotline	ψ		
Elevation angle of shotline			

g is the constant of the acceleration of gravity.

ρ_c has the value for steel in the constants given in this handbook.

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A schematic representation of the logic of this section is given in Figure 6-3.

6.2.3.8.3 Perforation and ricochet determination. In this stage there are two major decisions (1) between blunt and sharp attack of the target component, and (2) between perforation and ricochet. If the angle γ is less than 25°, the projectile is judged to be in a sharp attack of the component and the equation for the ballistic limit and the equations for residual speed and obliquity must be appropriate for a piercing mode of perforation. If this angle γ is greater than or equal to 25°, then the equations for ballistic limit, residual speed, and residual obliquity must be appropriate for plugging perforation.

In the sharp attack of a target component that is comparatively thick, the equation for the ballistic limit is a simple expression in terms of the parameters Q_1 and Q_2, but for thin components a correction must be made for the effect of localized deformations called petalling. The criterion for thinness is:

$$Q_1 < 0.5$$

The ballistic limit for sharp attack of thick targets is:

$$V_{50n} = C_s^* \left(Q_1^*/Q_2^*\right)^{b_s} = C_s \left[(T/d_c)/(4W_c/\pi \rho_c d_c^3)\right]^{b_s} \quad (5.1)$$

and the correction is:

$$V_{50n\ (corrected)} = C_S^* \left(Q_1^*/Q_2^*\right)^{b_s} \left[1 - \exp\left(3.2\right) \sqrt{Q_1^*}\ \right] \quad (5.2)$$

In the blunt attack of a target component very thin aluminum and titanium components required special treatment. For these components the ballistic limit is:

$$(V_{50n})_b = C_{b2} \left[\frac{4\rho_c T A_p}{\pi W}\right] = C_{b2} \left[\frac{4Q_1}{\pi Q_3}\right] \quad (5.3)$$

where

$$Q_3 = \frac{W}{\rho_c A_p d}$$

The condition for deciding that a component is thin is given by:

$$\frac{Q_1}{Q_3} < 0.0974$$

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and the ballistic limit for all other attacks by blunt projectiles is:

$$(V_{50n})_b = C_{b1}\left[\frac{4\rho_c TA_p}{\pi W}\right]^{b_b} + k = C_{b1}\left[\frac{4}{\pi}(Q_1/Q_3)\right]^{b_b} + k$$

Any of the values of V_{50_n} predicted by 3.1, 3.2, 3.3, or 3.4 are converted to the ballistic limit at obliquity by:

$$V_{50} = V_{50n} \sec\theta$$

A schematic representation of the decisions of this section is shown in Figure 6-4. The net effect of the major decisions of this section is to define three options among the modes of perforation and ricochet: (1) perforation by plugging, (2) perforation by piercing and (3) ricochet. The first and second options are chosen for $V > V_{50}$, and the third option is chosen for $V < V_{50}$.

6.2.3.8.4 Projectile change of motion. The equations for changes in the state-of-motion for the three options on the outcome of an impact are:

Perforation by piercing

$$V_r = \sqrt{V^2 - V_{50}^2}$$

$$\theta_x = \theta$$

Perforation by plugging

$$V_r = \sqrt{V^2 - V_{50}^2/(1 + Q_4)}$$

where

$$Q_4 = \frac{\rho A_p T}{W\cos\theta}$$

$$\theta_x = \theta$$

ricochet

$$V_r = V\sin\theta\sin^2\theta_{rr}$$

$$\theta_r = \pi - \tan^{-1}\left\{\left[\frac{JV\sin\theta\ \rho_c E_c/g}{\sigma_c}\right]\exp\left[-m(a-b)\right]\right\}$$

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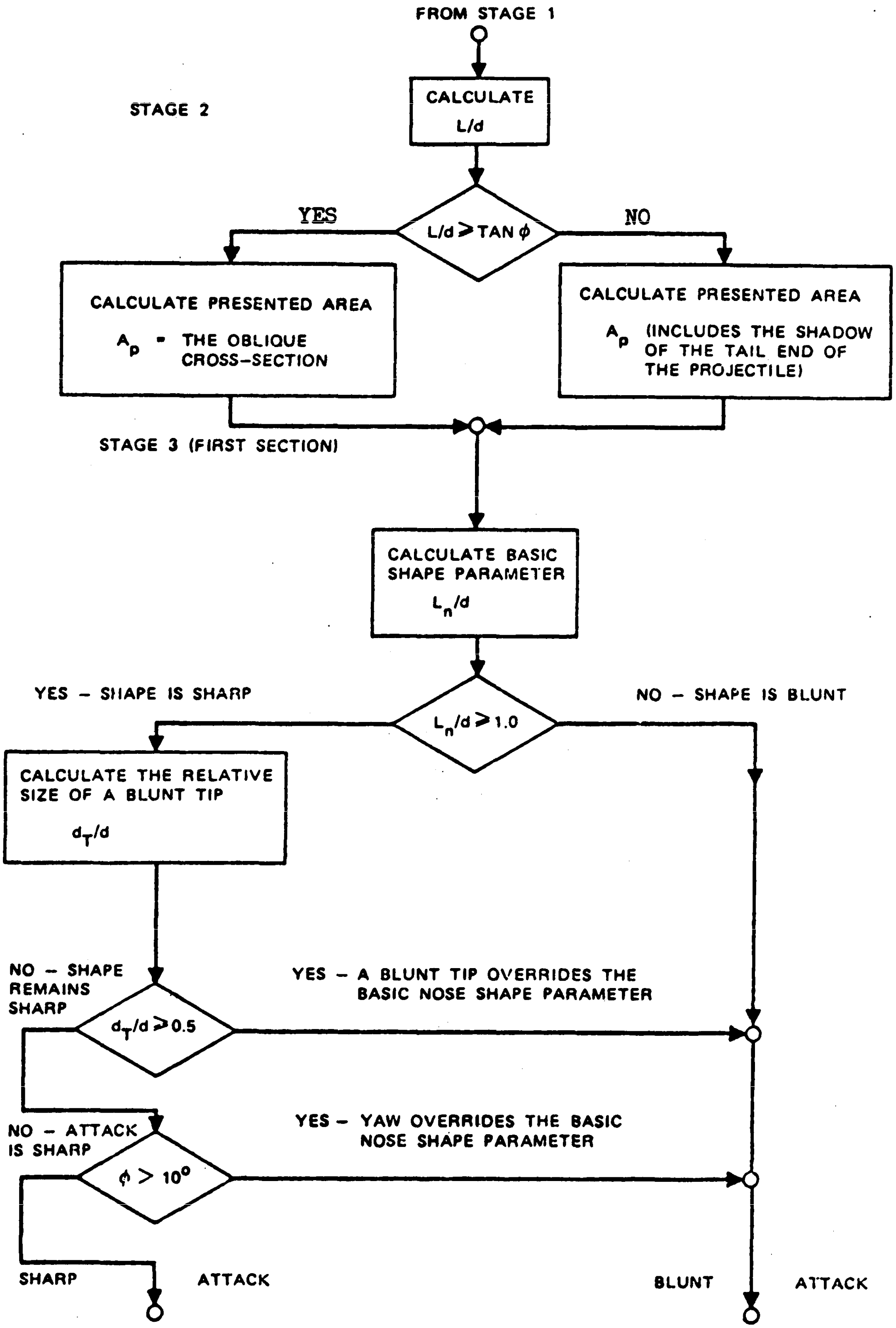

FIGURE 6-3. Presented area and determination of shape.

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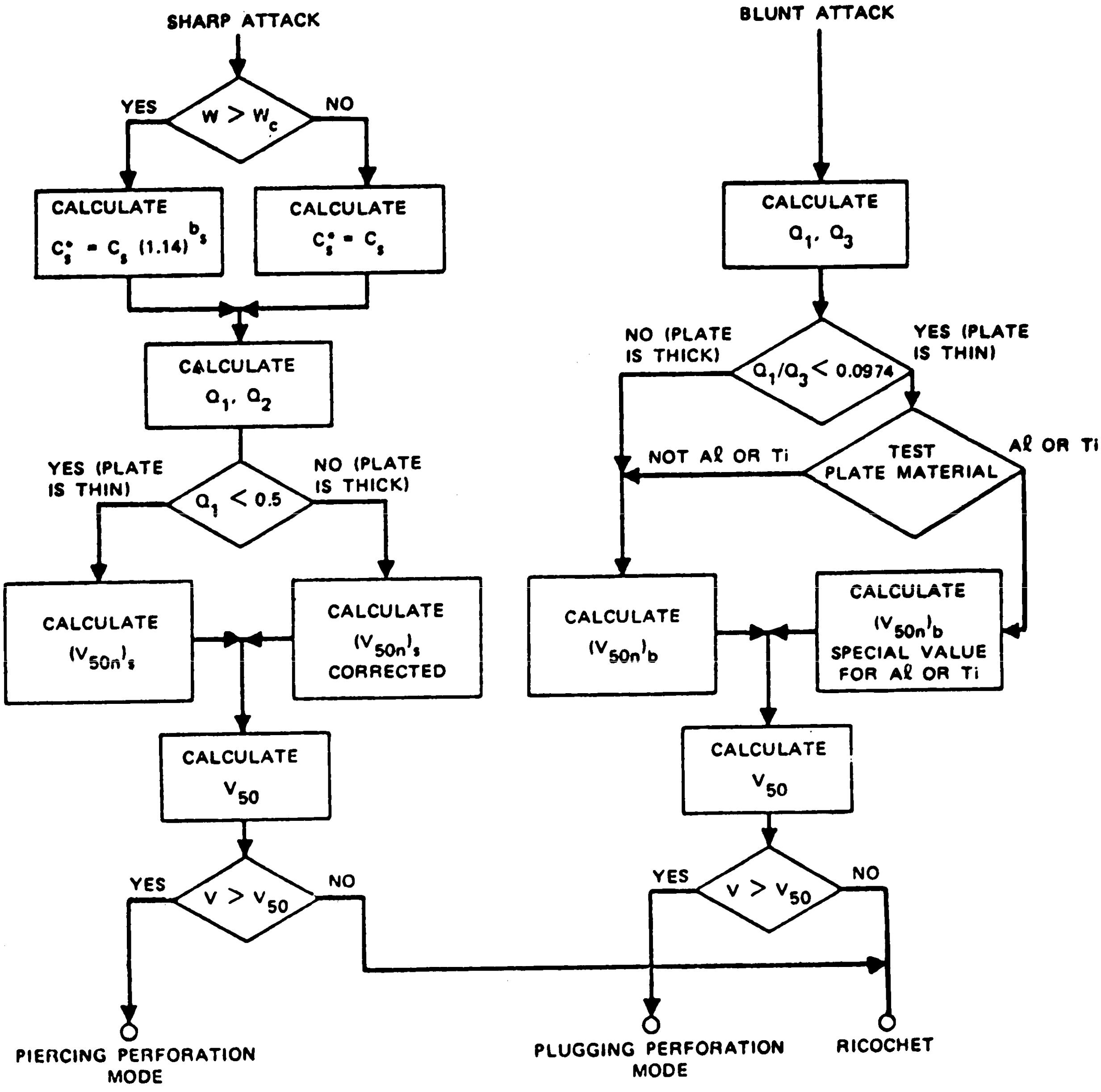

FIGURE 6-4. Decision on the Mode of perforation or ricochet.

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If a < b then the exponential term equals 1.0; a is given by:

$$a = \left\{ \left[\frac{(W/d^3)\ V^2\ \cos^2\theta}{g\sigma} \right]^{1/3} + K_2 \left[\frac{(W/d^3)\ V^2\ \cos^2\theta}{Q_1 g\sigma} \right]^{1/2} \right\}$$

The values of the dimensionless constants in these equations are the following:

	Steel Plate	Aluminum Plate
J	4.0	4.0
m	3.0	2.0
b	0.74	-0.50
K	0.29	0.29

6.2.3.8.5 Projectile failure modes. In this stage there are two major decisions: (1) between impact conditions for which breakup of the core takes place and impact conditions for which the projectile remains intact, and (2) between impact conditions for which the jacket is stripped from the core and impact conditions for which the jacket is intact. The decisions are considered in the order shown in Figure 6-5, the decision on breakup of the core first and then the decision on jacket stripping second and applied to both of the outcomes of the first decision.

The decision for core breakup depends on a quantity λ_x which is:

$$\lambda_x = \frac{16W_c\ V_{50n}^2\ \sin\beta}{\pi C_2 g\sigma_c d^3\ \cos\theta} = \frac{16Q_6\ \sin\beta}{\pi C_2\ \cos\theta}$$

for perforation, and a quantity λ_r for ricochet given by:

$$\lambda_r = \frac{16W_c\ V^2\ \sin\beta\ \cos\theta}{\pi C_2 g\sigma_c d_c^3\ \pi} = \frac{16Q_5\ \sin\beta\ \cos\theta}{\pi C_2}$$

where Q_5 and Q_6 are defined as

$$Q_5 = \left(\frac{W_c\ V^2}{g\sigma_c d_c^3} \right)$$

and

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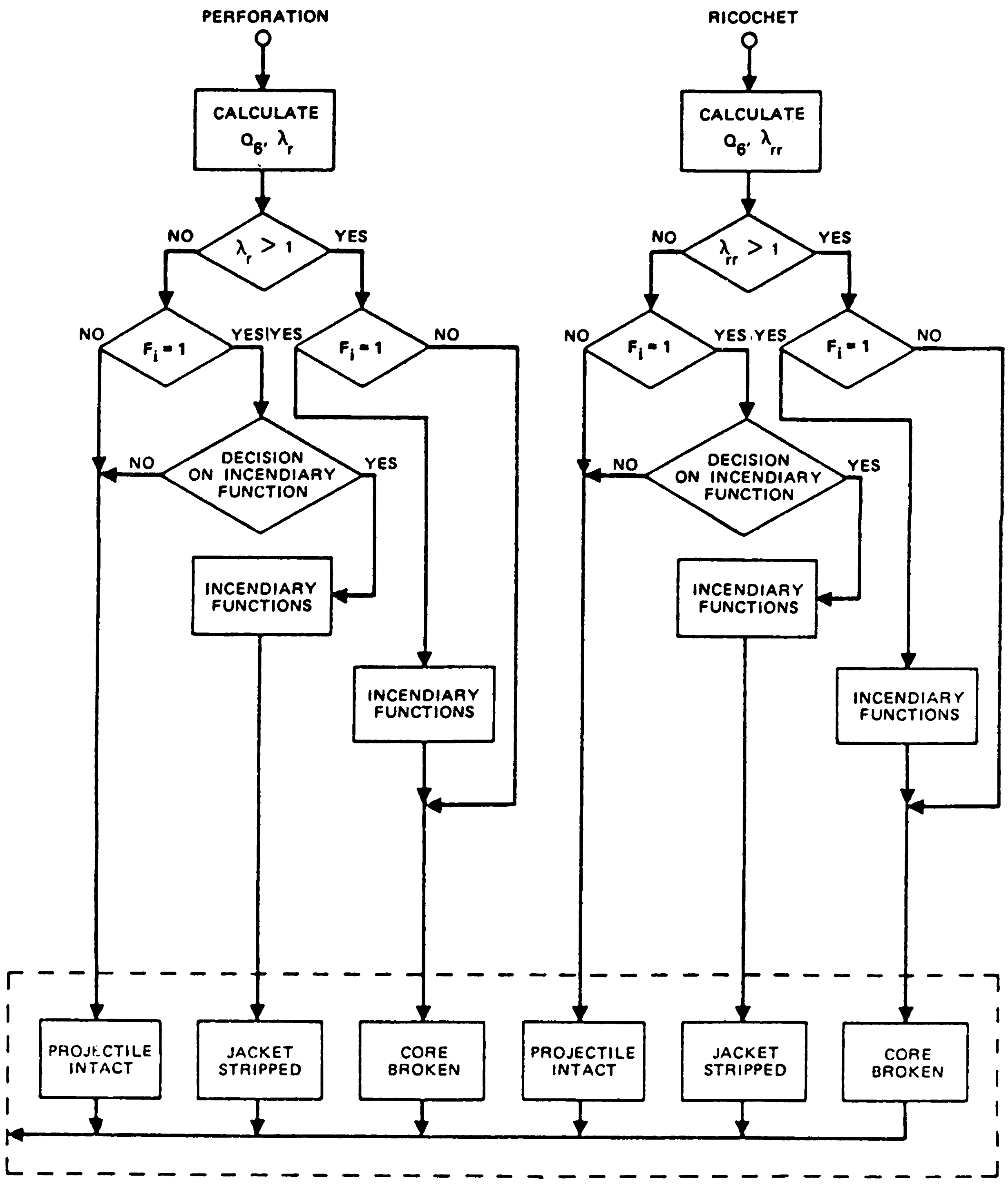

FIGURE 6-5. Projectile failure and incendiary functioning.

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$$Q_6 = \left(\frac{W_c \; V_{50n}^2}{g \sigma_c d_c^3} \right)$$

and

$$\beta = \cos^{-1} (\cos \theta \cos \phi)$$

and

$$C_2 = 11.2 - 0.022 \; B$$

If λ_x >1, the core of the projectile is broken; othewise the projectile remains intact following perforation. If λ_r >1, the core is broken; otherwise the projectile remains intact following ricochet.

6.2.3.8.6 Projectile physical changes. The decisions of the preceding stage select sets of correlations. The primary parameters for the expression of changes in the description of the projectiles are the core parameters because the changes in the description of the projectile are in terms of the description of the core; thus, jacket stripping reduces the overall projectiles parameters to the core parameters, and breakup reduces the overall projectile parameters to the parameters for the broken core.

Correlations

Intact projectile

$d_r = d$	$d_r = d$
$L_{nr} = L_n$	$L_{nr} = L_n$
$W_r = W$	$W_r = W$
$F_i = 1$	$F_i = 1$

Jacket stripped

$d_r = d_c$	$d_r = d_c$
$L_{nr} = L_{nc}$	$L_{nr} = L_{nc}$
$W_r = W_c$	
$F_i = 0$	$F_i = 0$

Core-broken

$d_r = d_c$	$d_r = d_c$
$L_{nr} = 0.0$	$L_{nr} = 0.0$

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$$W_r = W_c/2$$

$$L_r = Q_2^* d_c$$

$$F_i = 0.0$$

For perforations, these data and the data on the state-of-motion and the material properties of the projectiles are input for the next calculation. For ricochet, the trajectory for which calculations were being made is ended and these data are available for special calculation of the ricochet trajectory and the inclusion of the projectiles incendiary effects if applicable.

6.2.3.9 Fragment penetration equations. Figure 6-6 is a schematic representation of the interrelation among the main stages of the analytic procedure for fragments and the principal computations that are performed in each. As for projectiles, the six stages form a loop so that the output of one complete prediction is part of the input for the next prediction. Each stage has the same function as the comparable stage of the projectile procedure. The most conspicuous differences between the calculations for fragments and projectiles are: (1) in the form of input data, (2) the use of a single blunt perforation process for all fragments, and (3) the recognition of different failure modes for fragments of commonly used warhead materials.

Fragments from warheads may have sizes and configurations that result from the following:

a. Uncontrolled fragmentation of the warhead case.

b. Controlled fragmentation of the warhead case as the result of a scribed grid or other control process.

c. The use of preformed fragments.

The information available on the fragment may be limited to weight and material properties for the case of uncontrolled fragmentation, but will include three dimensions and shape factors for controlled and preformed fragments. The input parameters of Table 6-V list the relevant parameters for each type of fragment. For the initial calculation, information on the orientation of the shotline with respect to the aircraft, speed of the fragment, and speed of the aircraft are converted to a speed with respect to the target components by equation 1.1 (located in the section on equations for projectile). In general it is assumed that the yaw is not known; however, in the section concerned with the modes of failure of the fragment, provision will be made for calculation of failure modes that depend on favorable orientation of the fragment and for which a yaw value must be specified. When data on the state-of-motion is the output of a preceding impact, the speed of the fragment is a direct equality of output to input:

$$V = V_r$$

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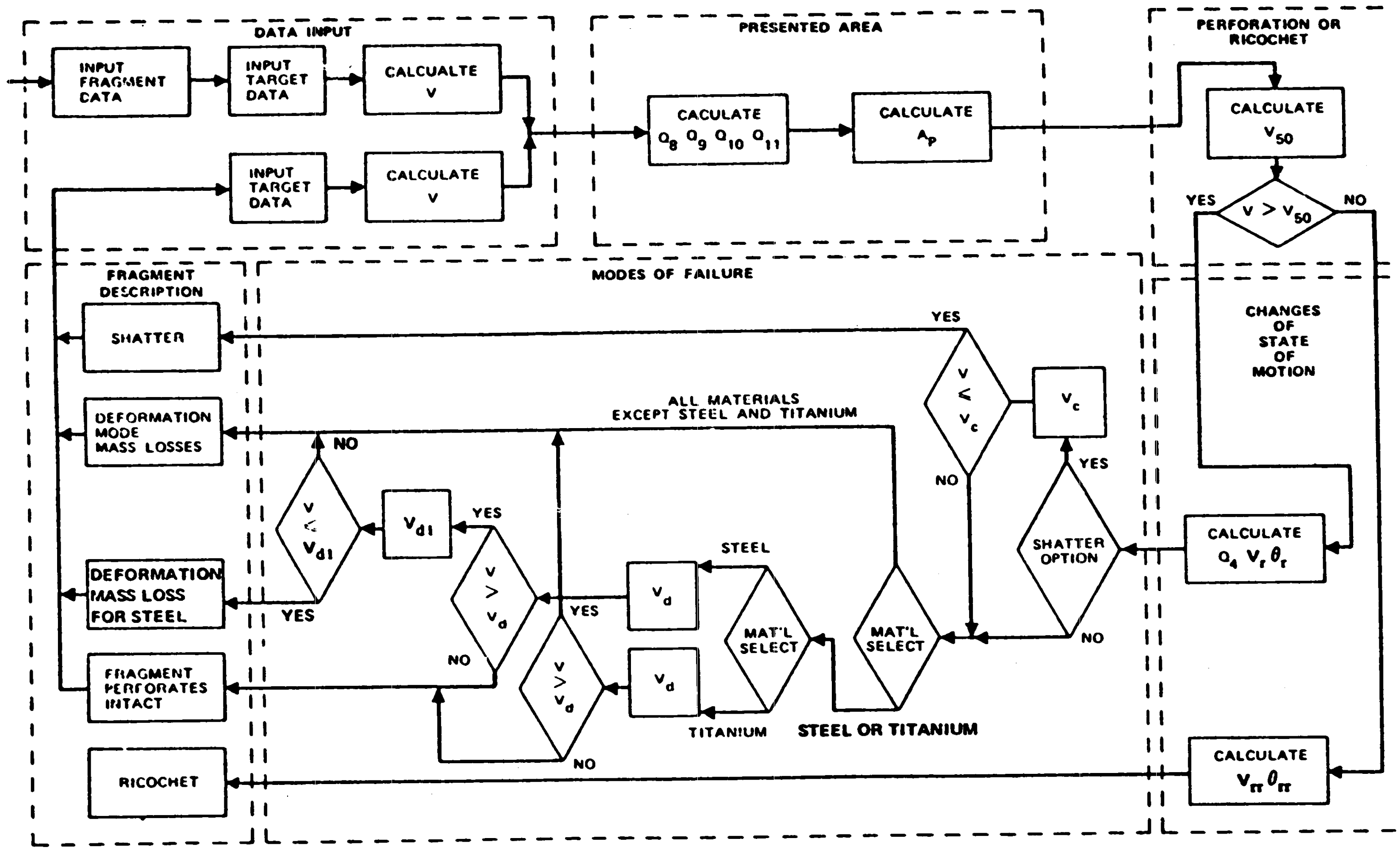

FIGURE 6-6. A schematic representation of the principal computations for fragments.

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FIGURE 6-V. Fragment parameters.

Parameter	Fragment	Target
Material properties		
Elastic modulus	E_f	E
Specific weight	ρ_f	ρ
Density	ρ_f/g	ρ/g
Bulk modulus	K_f	K
State of motion		
Speed, fragment	V_p	
Speed, aircraft	V_a	
Speed, in component frame of reference	V	
Yaw (special calculations only)	ϕ	
Obliquity	θ	
Azimuth angle of shotline	ψ	
Elevation angle of ahotline	Ω	

Principal dimensions	Uncontrolled		Controlled				Target
	Compact	Non-compact	Diamond	Sphere	Cube	ppd	
(Lateral dimension) d =	d	d	d	d	d	d	
Length L =	d	L	L	d	d	L	
Width w =	d	d	w	d	d	d	
Shape factor	C_f	C_f	C_f	C_f	C_f	C_f	
Weight	W	W	W	W	W	W	
Thickness							T

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where

V_r is the predicted residual velocity from the preceding impact.

The input data on the description of the fragment are either the initial values of the fragment parameters or the values for the preceding impact:

$$d = d_r$$

$$w = w_r$$

$$L = L_r$$

$$C_f = (C_f)_r$$

$$W = W_r$$

6.2.3.9.1 Presented area and shape determination. There are four dimensionless quantities that are needed in subsequent calculations and which can be computed from the data available at the start of the procedure. These are the following:

$$Q_8 = \frac{\rho_f T A_p}{W}$$

$$Q_9 = \frac{T}{L}$$

$$Q_{10} = \frac{V}{c_1} \text{ for } c_1 = \sqrt{\frac{E_f}{\rho_f}} = 16900$$

$$Q_{11}'' = \frac{\rho_f T A_p}{W_o}$$

where

W_o = 100 grains, 6.48 grams, 0.0143 pounds

The presented area of the fragment is calculated by the expression

$$A_p = C_f w d$$

This is the presented area of the fragment in its average orientation with respect to the barrier. The values of C_f for various shapes are as stated in Table 6-VI.

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TABLE 6-VI. Values of C_f.

Shape	C_f	Corresponding Geometric Formula
Uncontrolled		
Compact	1.262	$A_p = \frac{d^2\sqrt{2}}{2}\left(1 + \frac{\pi}{4}\right)$
Noncompact	0.707 L/d + 0.555	$A_p = \frac{d^2\sqrt{2}}{2}\left(\frac{L}{d} + \frac{\pi}{4}\right)$
Controlled		
Diamond shape	0.354	$A_p = \frac{wd}{2}\left(\frac{\sqrt{2}}{2}\right)$
Preformed		
Sphere	0.785	$A_p = \pi d^2/4$
Cube	1.50	$A_p = 3d^2/2$
Parallelepipeds	L/d + 0.5	$A_p = (L/d + 0.5)d^2$

6.2.3.9.2 Perforation and ricochet decision. In this stage the decision is made between perforation and ricochet. The ballistic limit is calculated by the equation

$$V_{50} = C_{bf}\left(\frac{\rho_f\ T\ A_p}{W}\right)^{-b_f} \sec^h\theta\left(\frac{\rho_f T\ A_p}{W_o}\right)^f = C_{bf} Q_8^{\ b_f} \sec^h\theta\, Q_{11}^f$$

The fragment perforates if $V > V_{50}$ and ricochets if $V < V_{50}$. All perforations are assumed to take place by the plugging process characteristic of blunt fragments.

6.2.3.9.3 Fragment state-of-motion change. Changes in the state-of-motion of the fragment are calculated by the equations for perforation by plugging

$$V_r = \sqrt{V^2 - V_{50}^2/(1 + Q_4)}$$

where

$$Q_4 = \frac{\rho_c A_p T}{W\cos\theta}$$

$$\theta_r = \theta$$

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The equations for ricochet of fragments is essentially the same as for projectiles

$$V_{rr} = V \sin\theta \sin^2 \theta_{rr}$$

$$\theta_{rr} = \tan^{-1} \left\{ \left[\frac{JV \sin\theta \sqrt{\rho_f E_f / g}}{\sigma_f} \right] \exp\left[-m(a - b)\right] \right\}$$

If a <b then the exponential term equals 1.0; a is given by:

$$a = \left\{ \left[\frac{(W/d^3)\ V^2 \cos^2\theta}{g\sigma} \right]^{1/3} + K_2 \left[\frac{(W/d^3)\ V^2 \cos^2\theta}{Q_1 g\sigma} \right]^{1/2} \right\}$$

Values of the dimensionless constants in these equations are as follows:

	Steel Plate	Aluminum Plate	Titanium
J	4.0	4.0	4.0
m	3.0	2.0	3.0
b	0.74	-0.50	0.49
K_2	0.29	0.29	0.29

6.2.3.9.4 Fragment failure modes. The decisions in this stage are between: (1) perforation of the fragment intact, (2) a deformation mode of mass loss, (3) a special deformation-mass loss calculation for steel, and (4) shattering of the fragment. For all materials a computation can be made as to whether or not shatter will occur as the result of a favorable orientation of a flat surface against the target. This is shown in Figure 6-7 as the initial decision. This decision is optional and is not an essential part of the prediction. It is included only to allow the option of estimating the effect of such impacts on vulnerability assessments as supplementary information. The conditions that are required for the shatter-mode failure of the fragment are a favorable orientation of the impacting surfaces, that the fragment impacting surface be essentially plane, and that a critical velocity is achieved. The critical impact orientation is given by

$$\mu_c = \sin^{-1} \left[\frac{V}{C_1} \cos\theta \right] = \sin^{-1} \left[Q_{10} \cos\theta \right]$$

where

V is impact velocity

C_1 is the sonic wave velocity in the fragment

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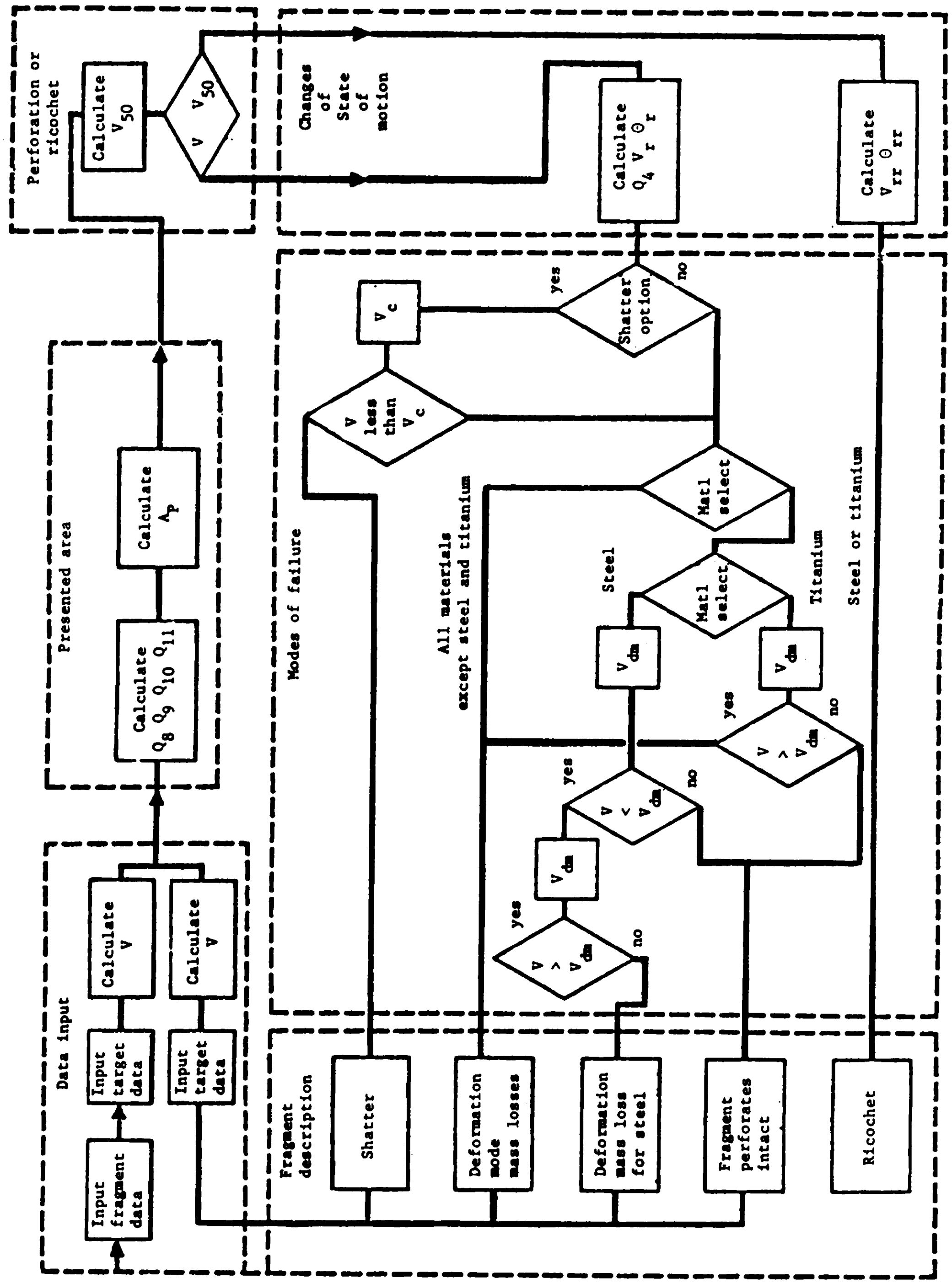

FIGURE 6-7. Initial decision if shatter will occur.

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The equation for the critical velocity is

$$V_c = \eta_c\,(1 + Q_{12}\,Q_{13})\sec\theta$$

where

$$\eta_c = 2{,}000\text{ ft/sec, } 610\text{ m/sec}$$

$$Q_{12} = \sqrt{\frac{K_{Fe}}{K}}$$

and

$$Q_{13} = \sqrt{\frac{\rho_{Fe}}{\rho}}$$

where the subscript Fe means the value for steel.

If $V > V_c$ the perforation results in shattering (provided that $\mu < \mu_c$) and If $V < V_c$ the perforation is further examined to determine whether it will result in deformation mode mass losses or remain intact.

6.2.3.9.4.1 Steel and titanium. Steel and titanium are treated separately in determining deformation-mode mass losses. Under certain conditions which are defined in the following paragraphs, these materials are assumed to undergo no mass loss, otherwise these are modeled by mass-loss equations in the next stages. All other materials are modeled by the mass-loss equations without an intact option.

The equation for the critical velocity separating impacts with fragment intact from deformation mode mass losses is:

$$V_d = \eta\left\{1 + [\cos\theta/(0.6T/L + 0.15)]\right\}$$

$$= \eta\left\{1 + [\cos\theta/0.6Q_9 + 0.15)]\right\}$$

This critical velocity is defined only for steel and titanium components for which the values of η are:

Steel η = 700 ft/see, 213 m/see

Titanium η = 1,000 ft/see, 305 m/see

For values of $V < V_d$ for either steel or titanium, the fragment remains intact. If for titanium the velocity is greater than the critical value, the mass loss will be computed by the principal mass loss equations. If for steel the velocity is greater than the critical value then a new value of the critical velocity V_{d1} is computed using η= 2,500 ft/sec or 762 m/see. If $V < V_{d1}$ the mass loss

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is computed using a special computation for steel and if $V > V_{d1}$ the mass loss is computed using the mass loss equations which apply to other plate materials,

6.2.3.9.5 Calculation of the changes in the description of the fragment. If the fragment remains intact:

$$L_r = L$$

$$W_r = w$$

$$d_r = d$$

$$W_r = W$$

$$(C_f)_r = C_f$$

If the fragment undergoes deformation-mode-mass losses:

$$W_r = W - WC_m \left(\frac{\rho T A_p}{W}\right)^q \left(\frac{V}{c_1}\right)^v \left(\frac{\rho T A_p}{W_o}\right)^t \sec^s \theta$$

$$= W - WC_m Q_8^q Q_{10}^v Q_{11}^t \sec^s \theta$$

$$L_r = d$$

$$w_r = d$$

$$d_r = d = \left(\frac{4W_r}{\pi\rho}\right)^{1/3}$$

$$C_f = 1.262$$

If the fragment shatters use the q, r, t, s, and C_m values from the table of shatter mode-mass lost constants. The values of q, r, t, and s in this table are the values for mild homogeneous steel. Values of C_m for materials not included in the table can be computed by the formula:

$$C_m = 1.59 \left[\frac{2}{(1 + Q_{14})}\right]^{0.761} Q_{15}$$

where

$$Q_{14} = \frac{(\rho c)_{steel}}{(\rho c)_{material}}$$

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and

$$Q_{15} = \frac{c_{steel}}{c_{material}}$$

and

$$c = \sqrt{\frac{E}{\rho}}$$

For the special case of steel fragments striking steel components at velocities between V_d and V_{dl}

$$W_r = W \left[1 - 0.1656 \left(\frac{V - V_d}{V_d} \right)^{1.42} \right]$$

$$L_r = d$$

$$w_r = d$$

$$d_r = d = \left(\frac{4W}{\pi\rho} \right)^{1/3}$$

$$C_f = 1.262$$

Material Constants for Equations are located in Table 6-VII thru 6-IX.

TABLE 6-VII. Ballistic limit constants.

Alloy	C_{bf} (ft/see)	b_f	h	f
Magnesium	784	1.076	0,966	-0.072
Aluminum alloy 2024 T3	1,354	0.941	1.098	-0.038
Titanium alloy	1,610	1.314	1.643	0.011
Face-hardened steel	2,268	1.397	1.747	-0.206
Mild homogeneous steel	2,644	0.963	1.286	-0.057
Hard homogeneous steel	3,164	0.963	1.286	-0.057

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TABLE 6-VIII. Deformation-mode mass loss constants

Alloy	Cm	q	v	t	s
Magnesium	0.503	0.197	1.519	0.088	-0.172
Aluminum alloy 2024 T3	2,838	0.306	1.901	-0.079	-0.362
Titanium alloy	0.224	1.748	0.459	-0.662	1.327
Face-hardened steel	1.066	0.256	0.483	-0.022	0.469
Mild homogeneous steel	1.569	0.165	0.761	-0.027	0.143
Hard homogeneous steel	1.816	0.371	0.880	-0.025	0.327

TABLE 6-IX. Shatter-mode loss constants.

Alloy	cm	q	z	t	s	Q_{14}	Q_{15}
Magnesium	0.70	0. 165	0.761	-0.027	00143	4.97	1.08
Aluminum alloy 2024 T3	1.01	0.165	0.761	-0.027	0.143	2.55	0.90
Titanium alloy	1.32	0.165	0.761	-0.027	0.143	1.49	0.85
Steels (all)	1.59	0.165	0.761	-0.027	00143	1.00	1.00

6.2.4 Liquid penetration equations. If a compartment is filled with a liquid then it is assumed that the liquid will have a significant effect on the state-of-motion of the impactor and the liquid itself is treated as a target component. The yaw of the projectile is assumed to be unchanged. The loss of velocity of the impactor is calculated by a drag equation.

$$V_r = V \exp\left(-[C_D A_p \rho_L x]/2W\right)$$

where

x is the distance between point of entry and point of exit of the impactor into the fluid

ρ_L is the specific weight of the liquid

A_p is the presented areas of the impactor

C_D is the appropriate value of the drag coefficient from TABLE 6-X

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TABLE 6-X. Values of drag coefficient.

Impactor	Drag Coefficient
Projectiles	If $x \leqslant 25$ cm, $C_D = 0.05 + 0.25 \sin^3$ If $x > 25$ cm, $C_D = 0.30$
Fragments	
Cubes	$C_D = 0.75$
Spheres	$= 0.50$
Diamond-shaped	1.10
Irregular, chunky	1.00
Irregular, long	0.80

Table 6-XI contains a listing of some common fluids used on military aircraft and their specific gravities.

6.2.5 Equipment penetration. Currently, there are no published data on the capabilities of common nonhomogeneous aircraft equipment or components to defeat or slow down penetrators. Some experimental work is in progress by the JTCG/AS. When such data are developed, it will be included in this section of the publication. The reader is advised to contact the JTCG/AS for the availability of data for the type of components or equipment of interest.

TABLE 6-XI. Common military aircraft fluids.

Liquid	Specific Gravity	Fluid Density (oz in.^{3})
Gasoline	0.76	0.439
Hydraulic oil (Reference 211)	.85	.491
JP-1	.80	.462
JP-3	.76	.439
JP-4 (0.751-0.802)	.79	.457
JP-5 (0.788-0.845)	.82	.474
Kerosene	.82	.474
Liquid oxygen	1.14	.659
Glycerine	1.27	.734
Water	1.00	.578

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6.2.6 Armor materials. The penetration analysis of armor materials is a highly specialized technology. It requires an interface with the Government activities engaged in the development and testing of armor materials. For basic armor system information, the reader is directed to paragraph 5.17 in this volume. For detailed information and data, the reader is directed to the appropriate military activities. These are:

a. Director

U.S. Army Materials and Mechanics Research Center,
Mass. 02172

b. U.S. Navy Weapons Laboratory
Dahlgren, Va.

Custodians:

Army - AV
Navy - AS
Air Force - 11

Review Activities:

Army - ME, MR, SG
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Air Forces - 26

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