MIL-HDBK-336-3
4 FEBRUARY 1983

MILITARY HANDBOOK

SURVIVABILITY, AIRCRAFT, NONNUCLEAR,

ENGINE-VOLUME 3

NO DELIVERABLE DATA
REQUIRED BY THIS DOCUMENT

FSC MISC

DEPARTMENT OF DEFENSE
WASHINGTON 25, DC

MIL-HDBK-336-3
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 procedures.

2. This publication was approved on 04 February 1983 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.

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 0) 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 system 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,

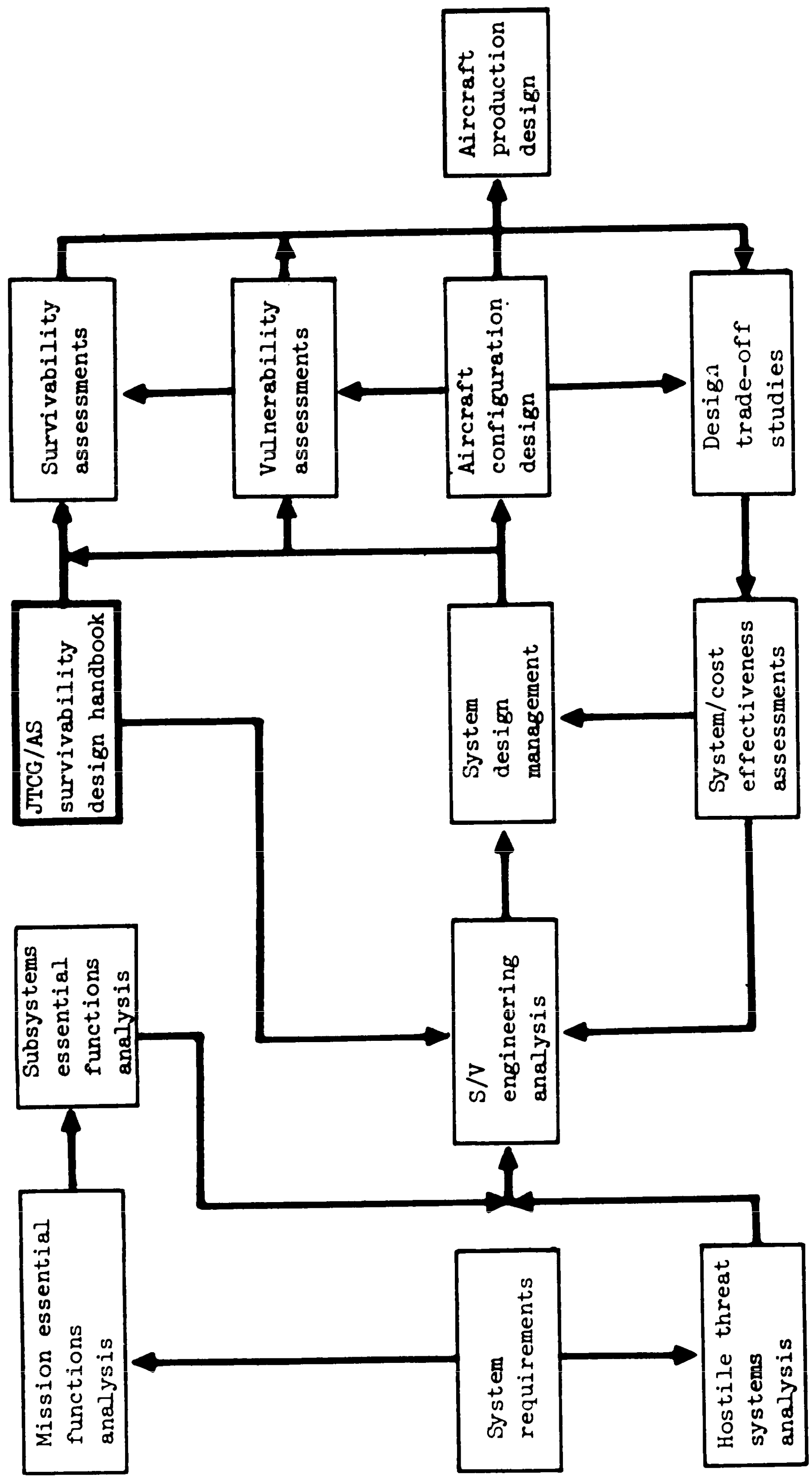


FIGURE 1. Handbook use in design process.

vulnerability assessment analysts, and survivability assessment analyst 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 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 throuqh the validation, full-scale development, production and operational phases of the aircraft system.

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 for antiaircraft artillery shells. The available body armor in 1942 was awkward and heavy and 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 APT 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 atte~ltion was also directed to the suppression of fuel fires in bomber aircraft. Ralsa 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 estinguishing systems in the fuel tank areas of some of their multiengine 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 Vul–nerability 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 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 nonnculear 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 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 non-nuclear 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 lightweight 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 non-nuclear 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 nodify 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 system 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, 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 air-frame 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 of 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. Rapid 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.

TABLE OF CONTEXTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

FIGURES

TABLES

This page intentionally left blank

1. SCOPE

1.1 General. This is the third 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 is concerned with. the design of aircraft engines and their components to enhance aircraft system survivability against hostile non-nuclear weapon threats. The objective of Volume 3 is to provide a ready reference containing design information on military aircraft engine and propulsion system survivability. It contains data on design techniques to reduce visual, infrared, radar, and aural detectability; and projectile and high-energy laser vulnerability of military aircraft engines and engine installations. The design techniques discussed range from combat- and test-proven systems, through development, laboratory, and breadboard equipment, to undeveloped concepts. Turbine engines are stressed, but piston engines are also presented.

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 subsystem 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.

This page intentionally left blank

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 reference 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)				

Ref. No.	Volume Number 1	2	3	4
29			X	
30		X	X	
31			X	
32		X	X	
33			X	
34			X	
35				
36				
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	

TABLE 2-I. 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		

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

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

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		
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		

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													

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	Elect. 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													

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	Elect. 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																		
(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

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	Elect. 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

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	Elect. 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																

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	Elect. 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													

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	Elect. 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														

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	Elect. 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																	

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	Elect. 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					

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

Ref. No.	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
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																		

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

Category / Ref. No.	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
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

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.

REFERENCES

REF NO.	REPORT NO.	TITLE
1	MIL-STD-2089	Aircraft Nonnuclear Survivability Terms, 21 July 1981
2	ADS-11A	Aeronautical Design Standard, Survivability Program - Rotary Wing, USAACSCOM, April 1976 (U)
3	(DELETED)	
4	AFWL-TR-75-223	ESP III - An Engagement Simulation Program, Volume I, Model Theory, AFWL, July 1976, (Secret), (ADCO06838L)
5	AFSC DH-2-7	System Survivability (U), AFSC, 5 November 1974, (Secret)
6	BRL-1796	Aircraft Vulnerability Assessment Methodology, Volume I - General, BRL, July 1975, (U)
7	61JTCG/ME-71-7-l	Magic Computer Simulation, Volume I - User's Manual, JTCG, July 1970, (U)
8	61JTCG/ME-71–7-2-l	Magic Computer Simulation, Volume II - Analyst Manual, Part I, JTCC, May 1971, (U)
9	61JTCG/ME-71-7-2-2	Magic Computer Simulation, Volume II - Analyst Manual, Part II, JTCG, May 1971, (U)
10	61JTCC/ME-71-5-l	Shot Generator Computer Program, Volume I - User's Manual, JTCG, July 1970, (U)
11	61JTCG/ME-71-5-2	Shot Generator Computer Program, Volume II - Analyst Manual, JTCG, July 1970 (U)
12	61JTCC/ME-71-6-l	Varea Computer Program, Volume I - User's Manual, JTCG, February 1971, (U)
13	61JTCG/ME-71-6-2	Varea Computer Program, Volume II - Analyst Manual, JTCG, February 1971, (U)
14	BRL-R-1779	Laser Vulnerability Methodology and Code - User's Manual

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
15	AFSC DH-2-9	Communist Air Defense (U), AFSC, Nov 1975 (Secret)
16	BDM/W-193-73-TR	TACOS II - Air Penetration/Ground Based Air Defense Operational Simulation - January 1972
17	BDM/H-74-015-TR	TACOS II - A Simplified Inputting Scheme - May 1974
	BDM/W-73/0025	QR-TACOS - Quick Response Tactical Air Defense Computer Operational Simulation - September 1973
19	TN-4565-16-73	Antiaircraft Artillery Simulation Computer Program - AFATL Program P001 - September 1973
20	61JTCG/ME-75-5	Dynamic Air-to-Air Model Computer Program, Volume I - User's Manual, JTCG, March 1975, (U)
21	61JTCG/ME-75-6	Dynamic Air-to-Air Model Computer Program, Volume II - Analyst Manual, JTCG, March 1975 (U)
22	JTCG/AS-74-D-003	Documentation of Survivability/Vulnerability (S/V) Related Aircraft Military Specification and Standards - June 1974
23	USAAMRDL-TR-71-41A	Survivability Design Guide for U.S. Army Aircraft, Volume I - Small-Arms Ballistic Protection, NAR, November 1971 (U) (AD891122L)
24	AFWL-TR-72-95	A Simplified Propagation Model for Laser System Studies, AFWL, April 1973, (U) (AD909426L)
25	MIL-E-5007A	Engines, Aircraft, Turbojet General Specifications For - July 1951
26	MIL-E-5007D	Engines, Aircraft, Turbojet General specifications For - October 1973
27	P-1077	Small Aircraft Engine Technology, An Assessment of Future Benefits IDA, Jan 1975 (ADA017379)
28	DELETED	

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
29	AFAL-TR-75-100	Proceedings of the 1975 Radar Camouflage Symposium, AFAL, December 1975, (Secret) (ADC006173)
30	MIL-E-8593A	Engines, Aircraft, Turboshaft and Turboprop, General Specifications For, October 1975
31	AFAL-TR-74-112	Calculation of Radar Cross Section, Volume I, User's Guide, AFAL September 1974, (Unclass.) (ADB004824L)
	AFAL-TR-74-112	Calculation of Radar Cross Section, Volume II, Computer Program Listings, AFAL, September 1974, (Unclass.) (ADB003471L)
	AFAL-TR-74-112	Calculation of Radar Cross Section, Volume III, F4 Aircraft Computations, AFAL, September 1974. (Secret) (ADC002351L)
32	AFAL-TR-19-220	Radar Cross Section Studies, Air Force Avionics Lab, September 1969, (Secret) (AD504142L)
33	AFAL-TR-71-69	Advanced Radar Analysis Techniques, AFAL, March 1971, (Secret) (AD514445)
34	AFAL-TR-71-390	Engine Radar Cross Section Study, AFAL, January 1972, (Secret), (AD520239L)
35	AFAL-TR-74-346	Engine Radar Cross Section Study, AFAL, May 1975, (Secret) (ADC002199L)
36	AFAL-TR-71-220	Forward Aspect Radar Camouflage Study (Phase III) (U) - October 1975 (Secret)
37	AFAL-TR-67-234	Mini-Inlet Investigation, AFAL, August 1967, (Secret) (AD385953)
38	MD62-70-17-2	GAM-77 Project Final Report (U) - November 1962 (Secret)
39	Off. Naval Res. Env. Res. Inst. Michigan U.	Compatibility of Turbofan IR Suppression and RCA Reduction (U) llth IRIS Symposium - February 1974 (Secret)
40	GE R76AEG468	Methodology for Trades of Passive/Active IRCM vs. Aircraft Survivability, June 1975 (Secret)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
41	GE R73AEG321	Turbine Engine IRS Program Spectral Calculation of Infrared Radiation From a Turbine Propulsion System as Intercepted by an Observer (U), Volume II - Analysis - December 1974 (Secret)
42	None	The First Fourteenth IRIS Symposium on Infrared Countermeasures (U) - 1962-1976 (Secret)
43	AAMRDL-73-59	Armored Aerial Reconnaissance System (AARS) Vulnerability Study (U), Lockheed, June 1974 (Confidential) (AD532039L)
44	Textbook	Pyrometry, McGraw-Hill Book Company, 1972,
45	S-114	Penetration of Defense by Helicopters (U), IDA, May 1963 (Confidential) (AD346102)
46	R-500-PR	Proceedings of the Second Symposium on Increased Survivability of Aircraft, (U) Rand Corp. Volume I - June 1970 (Secret)
47	None	Noise Control of Aircraft Engine, Noise Control Engineers Magazine – June-August 1975
48	None	Vulnerability of the TF3D-P-1 Turbofan Engine to Fuel Ingestion, April, 1975 (ADB008834L)
49	None	Vulnerability of TF41 Turbofan Engine to Fuel Ingestion. BRL Unpublished Notes, 1975
50	None	Problems Encountered in the Translation of Compressor Performance from One Gas to Another. Transactions of the ASME - May 1975
51	GE R75AEG010	Vulnerability Testing of Static and Operating T58 Engines with 23mm Armor Piercing Projectiles (U) - June 1975 (Confidential)
52	WADC-TN-57-257	Ingestion of 20mm API Nose Pieces by J73 Turbojet Engine - March 1957, (AD858248L)
53	DELETED	

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
54	None	Simulated Ballistic Impact on J65-W-16A Engine Combuster at Sea Level Static Conditions. Proceedings of the Symposium on S/V, Volume I - October 1975.
55	None	Propulsion System Survivability. A Status Report (U) Proceedings of the Symposium on S/V, Volume II - October 1975 (Secret)
56	GE TM71AEG1694	T58 Vulnerability: Army BRL Testing of Operating Engines (U) - July 1971 (Confidential)
57	DELETED	
58	FAA RD-70-51	Fire Protection Tests in a Small Fuselage Mounted Turbojet Engine arid Nacelle Installation, FAA, November 1970 (AD715442)
59	APL-TR-71-86	Ignition of Aircraft Fluids by Hot Surfaces Under Dynamic Conditions - November 1971 (AD734238)
60	DELETED	
61	ASD-XR-74-20	A-1 SEA Combat Damage Incident Analysis (U) September 1974 (Confidential) (AD532182L)
62	JTCG/AS-74-T-016	Backup Flight Control Design Considerations to Increase Aircraft Survivability, Naval Air Systems Command, March 1976, (Unclassified) (ADB011605L)
63	USAAMRDL-TR-73-62A	Design Guide Handbook for the Design of Ballistic-Damage-Tolerant Short-Fiber-Molded Aircraft Flight Control System Components. Volume I - Design Criteria, Concepts, Tooling, Fabrication, Testings and Evaluation, Army Air Mobility Research and Development Lab, August 1973, (Unclassified) (AD916279L)
64	USAAMRDL-TR-73-62B	Design Guide Handbook for the Design of Ballistic-Damage-Tolerant Short-Fiber Molded Aircraft Flight Control System Components. Volume II, Ballistic Data, Army Air Mobility Research and Development Lab, August 1973, (Confidential) (AD527899L)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
65	USAAMRDL-TR-76-6	Development of Design and Manufacturing Technology for Ballistic Damage Tolerant Flight Control Components, USAAMRDL
66	AFFDL-TR-67-53	Fly by Wire Techniques, AFFDL, July 1967, (Unclassified) (AD820427)
67	AFFDL-TR-70-135	Survivable Flight Control System Program Simplex Actuator Package, AFFDL, November 1970, (Unclassified) (AD877615)
68	AFFDL-TR-73-26	Design and Development of a Lateral Axis Integrated Actuator Package for Tactical Fighter Aircraft, AFFDL, February 1973, (Unclassified) (AD913510L)
69	AFFDL-TR-73-105	Survivable Flight Control System Supplement - Supplement for Survivable Stabilator Actuator Package Design and Analysis, AFFL, December 1973, (Unclassified) (AD917249L)
70	SAE-751041	Digital FBW Flight Control and Related Displays - November 1975
71	SAE-751044	Design Freedom Offered by Fly-By-Wire - November 1975
72	SAE-751046	Fly-by-Wire Flight Control System Design Considerations for Fighter Aircraft - November 1975
73	AFFDL-74-39	Survivability Assessment Guidelines for Flight Control Systems, Volume I, AFFDL, June 1974, (Unclassified) (AD922633L)
74	USMMRDL-TR-73-57A	Armored Aerial Reconnaissance System (AARS) Vulnerability Study - Volume I: Vehicle Design and Subsystem Studies, Army Air Mobility Research and Development Lab, March 1974 (Unclassified) (AD920760L)
75	AFWL-TR-73-44	Passive Laser Countermeasure Study (Applications) - Volume I, System Applications, AFWL, July 1973 (Secret) (AD527341L)
76	USAAMRDL-TR-72-64	Design Study of Low-Radar-Cross-Section Expendable Main Rotor Blades, Army Air Mobility, Research and Development Lab, March 1973 (Confidential) (AD526710L)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
77	USAAMRDL-TR-74-31	Low-Radar Cross Section OH-6A Helicopter Tail Rotor Blade, April 1974
78	NR-212-210	Quiet Attack Aircraft Program Overview - Volume I (U), May 1974 (Secret)
79	AHS Preprint NO. 1011	Survivability of the Sikorsky YUH-60A Helicopter, Presented at the 32nd Annual National V/STOL Forum of the American Helicopter Society, May 1976 (Unclassified)
80	USAARMDL-TR-72-2	Investigation of the Vortex Noise Produced by a Helicopter Rotor, February 1973
81	AFFDL-TR-71-22	A Guide for Predicting the Aural Detectability of Aircraft, March 1972
82	USAARMDL-TR-75-4	Ballistically Tolerant Rotor Blade Investigation, April 1975
83	USAMC-036-35-9709	Laser Systems Investigation (U), February 1974 (Secret)
84	FA-T74-3-1	Hardening of Acrylic and Polycarbonate Surfaces for Army Aircraft SARFA-PDS, February 1974 (Secret) (ADC002093L)
85	NRL-MR-3041	The Navy In-House Laser-Hardened Materials Development Program, Naval Research Lab, April 1973 (Secret) (ADC002137)
86	ARPA-JDR/A	Journal of Defense Research Series; Strategic Warfare, High Energy Lasers, Volume 4A, No. 1, (U) - May 1975 (Secret)
87	AFAL-TR-69-194	Investigatons of Laser Vulnerability and Defense Techniques, AFAL, November 1969, (Secret) (AD507239)
88	AFWL-TR-20-59	Material Effects of High Power 10.6 Micron Laser, AFWL, July 1970, (Secret) (AD510637L)
89	BRL-RN-1533	Laser Effects on the Seeker-Tracker of an AIM-9D (Sidewinder) Missile (U) - February 1971 (Secret)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
90	AFAL-TR-72-112	Laser Countermeasure Study, Air Force Avionics Lab, May 1972, (Secret) (AD520711L)
91	AFWL-TR-71-159	Material Effects of High Power Laser Radiation, AFWL, February 1972, (Secret) (AD523700L)
92	ASD/XR-73-5	Development of Weapon System Lethal Criteria, Volume I: F-111X-7, Aeronautical Systems Division, Wright-Patterson AFB, March 1973, (Secret) (AD525432L)
93	BRL-R-1643	Investigation of Target Vulnerability and Absorption Wave Phenomena Using the XLD-1 Laser (U) - April 1973 (Secret)
94	AFWL-TR-72-150	Response of Military Targets to Pulsed Loads, Volume II: Re-entry Vehicles, AFWL, May 1973, (Secret) (AD526187L)
95	MDCP04725	Threat Effectiveness Study - Special Report (U) - September 1973 MACAIR (Secret) (AD527792L)
96	AFWL-TR-74-100	Laser Digest, Spring 1974, AFWL, May 1974, (Unclassified) (AD919135L)
97	NASA-JPL-TR-32-1474	Sensitivity of Explosives to Laser Energy, April 1970
98	61JTCG/ME-73-7	Mission Available Kill Analysis of USAF Aircraft in Southeast Asia (U), August 1973 (Confidential)
99	NYAS, Vol. 125	Prevention of and Protection Against Accidental Explosion of Munitions, Fuels and Other Hazardous Materials, October 1968
100	BRL-CR-146	Characteristics of Plexiglass Fragments from Windows Broken by Airblast, Ballistic Research Labs, March 1974 (Unclassified) (AD919032L)
101	AFFDL-TR-67-64	Investigation of Passive Defense Provisions for Aircraft Crews and Passengers, AFFDL, March 1967 (Secret) (AD384309)
102	ASD-XR-71-25	Crew Station Metallic Armor Test and Analysis, Aeronautical Systems Division, Wright-Patterson AFB, September 1971 (Confidential) (AD518935L)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
103	AFFDL-TR-71-109	Integral Armor Study Volume I: Vulnerability Effects on Survivable Design, AFFDL, December 1971 (Secret) (AD525666L)
104	AFFDL-TR-71-1O9	Integral Armor Study Volume II: Effect of Vulnerability on Combat Effectiveness, F-4C and A-4E Aircraft, Book 1, AFFDL, December 1971 (Secret) (AD525667L)
105	AFFDL-TR-71-109	Integral Armor Study, Volume II: Effect of Vulnerability on Combat Effectiveness, F-4C and A04E Aircraft, Book 2, AFFDL, December 1971 (Secret) (AD525668L)
106	AFFDL-TR-71-109	Integral Armor Study, Volume IV: Integral Structure Armor for Close Air Support, AFFDL, December 1971 (Confidential) (AD525647L)
107	AFFDL-TR-71-109	Integral Armor Study, Volume V: Combat Vulnerability/Survivability Bibliography, AFFDL, December 1971 (Confidential) (AD525648L)
108	AFFDL-TR-68-5	Design Techniques for Installing Parasitic Armor, AFFDL, February 1968 (Confidential) (AD388597)
109	USAAMRDL-TR-74-83	Feasibility Analysis of Armor Materials for Protection of Aircrews, Army, Air Mobility Research and Development Lab, September 1974 (Confidential) (ADC000436L)
110	JTCG/AS-76-CM-001	Countermeasures Handbook for Aircraft Survivability - Volume I (Edited by Phillip Sandier), February 1977 (Secret - No Fern)
	JTCG/AS-76-CM-001	Countermeasures Handbook for Aircraft Survivability - Volume II (Edited by Phillip Sandier), February 1977 (Secret)
111	USANL-TR-70-32-CE	Review of the Development of Ballistic Needle-Punched Felt, October 1969
112	AMMRC-MS-74-2	Proceedings of the Fourth Symposium on Lightweight Armor, Army Materials and Mechanics Research Center, February 1974 (Confidential) (AD529772L)
113	USAAMRDL-TR-71-54	The Design, Fabrication and Testing of an Integrally Armored Crashworthy Crew Seat, January 1972

REFERENCES (continued)

REF NO.	REPORT NC.	TITLE
114	AMMRC-MS-69-02	Proceedings of Symposium on Lightweight Armor Materials (U), Army Materials and Mechanics Research Center, April 1969 (Confidential)
115	AFFDL-TR-70-43	Survivable Fuel Tank Systems Selection Technique R&D Design Handbook Report - March 1970
	AFFDL-TR-70-43	Survivable Fuel Tank Systems Selection Technique R&D Design Handbook Report - Volume II, AFFDL, March 1970 (Secret) (AD509605)
116	USAAVLABS-TN3	A Study of the Fuel/Air Characteristics in the Ullage of Aircraft Fuel Tanks - June 1970
117	USAAWABS-TR-68-78	Relative Vulnerability and Cost-Effectiveness Study of Transmission Oil Heat Rejection Systems - November 1968
118	BRL-TN-1652	Vulnerability of Small Caliber H.E. Ammunition to Projectile Impact (U) - April 1967 (Confidential)
119	BRL-MR-1994	Vulnerability of Bombs and Warheads of Bullets (U) - September 1951 (Confidential) (AD503992)
120	BRL-MR-567	Vulnerability of Bombs and Warheads of Bullets (U) - September 1951 (Confidential) (AD379944)
121	BRL-TN-158	Vulnerability of JATO Units to Single Fragments and Bullets (U) - January 1950 (Confidential) (AD378733)
122	AFFDL-TR-76-72	Aircraft Structural Design Handbook for Lower Cost Maintenance and Repair, August 1976
123	AMMRC-TR-76-15	Ballistic Technology of lightweight Armor, Army Materials and Mechanics Research Center, May 1976 (Confidential) (AD528792L)
124	None	USSTRICOM Data Base for Test and Eval. of Air Mobilitv Concepts - Tactical A/C Vul/Sur. (AV/S) in Varying Combat Situations (U), North Amer. Av. Inc., Col. OH 28 May 65, (Secret) (AD362034L)
125	AFFDL-TR-74-49	Survivable Combat Aircraft Structures Design Guidelines and Criteria – Final and Test Report, AFFDL, April 1974 (Unclassifiecl) (AD-BOO9385L)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
126	AFFDL-TR-74-50	Survivable Combat Aircraft Structures Design Guidelines and Criteria - Design Handbook, AFFDL, April 1974 (Unclassified) (ADB009386L)
127	AFFDL-TR-77-25	Fault Tolerant Digital Flight Control With Analytical Redundancy, AFFDL, May 1977 (Unclassified) (ADA045671)
128	USAAMRDL-TR-76-3	Evaluation of Contrast - Reduction Techniques, Army Air Mobility Research and Development Lab, April 1976 (ADC006316L)
129	MCIC-HB-01	Damage Tolerance Design Handbook Metals and Ceramics Information Center, Battelle Columbus Labs
130	Third Edition	Advanced Composite Design Guide, AFML, September 1976
131	AFFDL-TR-76-31	Numerical Analysis of Fuel Tank Penetration Dynamics (ADA02541)
132	AFFDL-TR-74-88	Payoffs for Controlled RCS Designs, Preliminary Assessment and Methodology, Boeing Aerospace Company, October 1974 (Secret)
133	Deleted	
134	Deleted	
135	USAAMRDL-TR-76-8	High Survivability Transmission System, May 1976 (ADA025930)
136	USAAMRDL-TR-76-22	CH-47C Vulnerability Reduction Modification Program - Fly-by-Wire Backup Demonstration, August 1976 (ADA030682)
137	USAAMRDL-TR-73-20	Manufacturing Methods Tech (MM&T) for Ballistic Tolerant Flight Control Components (AD766744)
138	AMCP-706-170	Engineering Design Handbook - Armor and Its Applications, Army Material Command, November 1973 (Secret) (AD530922)
139	AFFDL-TR-70-116	An Aircraft Structural Combat Damage Model Design Handbook AFFDL, November 1970 (Unclassified) (AD877920)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
140	AFFDL-TR-70-115	An Aircraft Structural Combat Damage Model Volume I, AFFDL, November 1970 (Unclassified) (AD877917)
	AFFDL-TR-70-115	An Aircraft Structural Combat Damage Model, Volume II: Appendices I, II, III, IV, and V, AFFDL, November 1970 (Unclassified) (AD877918)
	AFFDL-TR-70-115	An Aircraft Structural Combat Damage Model, Volume III: Appendices VI, VII, and VIII, AFFDL, November 1970 (Unclassified) (AD877919)
141	ASD/XR-72-7	Vulnerabilities of Aeronautical Systems to External Non-nuclear Blast Waves, Aeronautical Systems Division, February 1972 (Secret) (AD520562L)
142	AFFDL-TR-73-136	Effects of Internal Blast on Combat Aircraft Structures, Volume I: Engineer's Manual, AFFDL, January 1974 (Unclassified) (AD919970L)
	AFFDL-TR-73-136	Effects of Internal Blast on Combat Aircraft Structures, Volume II: User's and Programmer's Manual, AFFDL, January 1974 (Unclassified) (AD920058L)
143	AFFDL-TR-75-73	Effects of Internal Blast on Combat Aircraft Structures, Volume I: The BR-1A Computer Code for Transient Structural Response to Blast Loading of Aircraft Compartments, AFFDL, July 1975 (Unclassified) (ADB006777L)
	AFFDL-TR-75-73	Effects of Internal Blast on Combat Aircraft Structures, Volume II: Effects of Detonations of High Explosive Projectiles on Fracture of Metallic Aircraft Compartments, AFFDL, July 1975 (Unclassified) (ADBO06778L)
	AFFDL-TR-75-73	Effects of Internal Blast on Combat Aircraft Structures, Volume III: Response of Fuel-Force Aircraft Wing Compartments to Internal Blasts, AFFDL, July 1975 (Confidential) (ADC003551L)
144	NWC-TP-5467	Vulnerability of Enclosed Electronics to Blast, Naval Weapons Center, December 1972 (Confidential) (AD525645L)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
145	DELETED	
146	R71-8	Radar Cross Section Technology, McDonnel Douglas, August 1971
147	AFWL-TR-74-250	Project Delta, AFWL, October 1974 (Secret) (AD532086L)
148	BRL-MR-2420	Laser Vulnerability Analysis, Ballistic Research Labs, December 1974 (Secret) (ADC000609L)
149	AFFDL-TR-72-146	Gunfire Vulnerability Tests on light Control Actuators, Components, and Fluids, AFFDL, September 1973 (AD915312L)
150	BRL-MR-2717	Vulnerability of Domestic Aircraft Components and Titanium Substitutes, Test Series 3, BRL, January 1977 (Secret) (ADC009139L)
151	BRL-MR-2696	Vulnerability of Domestic and Foreign Aircraft Components, Test Series 1, October 1976 (Secret) (ADC008687L)
152	BRL-MR-2716	Vulnerability of Domestic and Foreign Aircraft Components, Test Series 2, BRL, January 1977 (Secret) (ADC009171L)
153	AFWL-TR-74-211	Aerospace Systems Laser Vulnerability Digest, Air Force Weapons Lab - Kirtland AFB, April 1975 (Secret) (ADC002361L)
154	R-75-10	The BRL/ADPA Report of the proceedings of ‘he Vulnerability/Survivability Symposium, Sponsored by BRL and ADPA (Ballistics and Vulnerability Division) at the Naval Amphibious Base, San Diego, October 1975
155	ASD-TR-77-20	Laser Countermeasures Assessment Study, April 1977 (Secret)
156	AIAA Paper No. 69-195	Problem of Helicopter Noise Estimation and Reduction, J. B. Ollerhead and N. V. Lowsen, AIAA, New York, N.Y., February 1969
157	TM-69-1-FDDA	Aural Detection of Aircraft, D. L. Smith and R.P. Paxson, AFFDL, WPAFB, September 1969 (AD859852)

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
158	DELETED	
159	DELETED	
160	AFFDL-TR-74-3	Failure Detection Through Functional Redundancy, Air Force Flight Dynamics Laboratory, January 1974
161	NADC-76-192-30	Backup Flight Control Design Procedures to Increase Survivability of Aircraft, Naval Air Development Center, June 1976 (ADB016418)
162	AFAPL-TR-73-124	Gross Voided Flame Arrestors for Fuel Tank Explosion Protection, Air Force Aero Propulsion Laboratory, February 1974
163	NADC-74227-50	Combat-Induced Failure Modes and Effects Analysis Methodology, Naval Air Development Center, October 1974, (Unclassified) (ADB008622L)
164	BRL-MR-2434	A Survey of Models Used within the Vulnerability Laboratory - Circa 1973, BRL, January 1975, (Unclassified) (ADB002042L)
165	BRL-MR-2366	A Desk Calculator Code For Predicting Fragment Penetration Performance Versus Single and Multiple Target Layers (AD9191396)
166	USAREUR PAM No. 30-60-1	Identification Guide, Part One, Weapons and Equipment, East European Communist Armies, Volume II, Artillery, 15 January 1973
167	JTCG/AS-74-T-008	Ballistic Damage Tolerant Flight Control System (AH-lG), NASC, December 1974 (Confidential)
168	AFFDL-TR-69-119	Research on Flight Control Systems - The Flow Difference Sensor, AFFDL, January 1970
169	NWC-TP-5915	Aircraft Fire Simulator Testing of Candidate Fire Barrier Systems, November 1976
170	No Number	Infrared Optical/Electro-Optical Countermeasures Handbook (U), Naval Air Systems Command, June 1974 (Secret)
171	AFSC DH1-6	Design Handbook for Aircraft Systems General, System Safety - Fourth Edition, 20 July 1974

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
172	WADC TR-52-35	Research on Flammability Characteristics of Aircraft Fuels, Wright Air Development Center, WPAFB, June 1952
173	AFAP-TR-71-7	Analysis of Aircraft Fuel Tank Fires and Explosion Hazards, Air Force Aero Propulsion Laboratory, March 1971
174	JTCG/AA-77-V-001	Aircraft Fuel Tank Environment/Threat Model for Fire and Explosion Vulnerability Assessments, Joint Technical Coordinating Group on Aircraft Survivability, (In Publication)
175	AFAPL-TR-70-65	Effects of Fuel Slosh and Vibration on the Flammability Hazards of Hydrocarbon Turbine Fuels With Aircraft Fuel Tanks, Air Force Aero Propulsion Laboratory, WPAFB, November 1970
176	D5-67-7	Investigation of Turbine Fuel Flammability Within Aircraft Fuel Tanks, Naval Air Propulsion Test Center, Aeronautical Engine Department, July 1967
177	AFAPL-TR-73-76	Vulnerability Assessment of JP-4 and JP-8 Under Vertical Gunfire Impact Conditions, Air Force Aero Propulsion Laboratory, WPAFB, December 1973
178	AFAPL-TR-75-93	Integrated Aircraft Fuel Tank Fire and protection Systems - Phase 1 and 2, Air Force Aero Propulsion Laboratory, 30 July 1975
179	Symposium Paper	Aircraft Applications of Halogenated Hydrocarbon Fire Extinguishing Agents, National Academy of Science Symposium, 11-12 April 1972
180	JTCG/AS-75-V-011	Bleed Air System Design and Vulnerability Assessment Procedures, Joint Technical Coordinating Group on Aircraft Survivability, December 1976 (ADB009823L)
181	JTCG-AS-75-V-O08	Required Minimum Elements of a JTCG/AS Vulnerability Assessment (U), December 1976 (Unclassified)
182	AFFDL-TR-76-34	Survivable Fuel Systems Design Properties (U), Air Force Flight Dynamics Laboratory, March 1976 (Confidential)

REFERENCES (continued)

REF. NO.	REPORT NO.	TITLE
183	BRL-1897	LV Methodology and Code-Analystts Manual (U), Ballistic Research Labs. July 1976 (Unclassified) (ADB012934L)
184	M73-115	Proceedings of the 1973 DoD Laser Effects/ Hardening Conference - Volume I: Damage and Vulnerability (U), Mitre Corporation (Project 809A), April 1974 (Secret)
185	JTCG/AS-74-V-003	Vulnerability Analysis of A-7D Aircraft to impacting 23-MM Heit and 57-MM HE Projectiles, SA-7 Missile Warhead, and a Proximity-Fuzed Surface-to-Air Missile (U), December 1975 (Confidential)
186	JTCG/AS-74-V-005	Development of Generic Hydraulic Actuator $P_{K/H}$ (Probability of Damage Given a Hit) Curves (U), December 1977 (Confidential)
187	JTCG?AS-75-V-10	Development of Generic Flight Control System $P_{D/U}$! (Probability of Damage Given a Hit) Curves, August 1977 (Unclassified)
188	AFATL-TR-75-13	ENDGAME Computer Program - Volume I: User's Manual (U), Air Force Armament Lab, May 1973 (Unclassified)
	AFATL-TR-75-13	ENDGAME Computer Program - Volume II: Analyst's Manual (U), Air Force Armament Lab, May 1975 (Unclassified)
	AFATL-TR-75-13	ENDGAME Computer Program - Volume III: Data Manual (U), Air Force Armament Lab, May 1975 (Secret)
189	BRL-MR-l317	Evaluation of Protection Afforded Personnel by Several Body Armors, Ballistic Research Lab, February 1961 (AD322492)
190	FSCT-381-5036	Effectiveness of Conventional AA Weapons – Part I: Soviet Block (U), U.S. Army Foreign Science and Technology Center, Washington, DC, May 1965 (Confidential)
191	FZM-12-4890-1	F-lllA/D Survivability Study, Project 5105-02, Final Report (U), General Dynamics, Fort Worth Division, Fort Worth, Texas, July 1967 (Secret)

REFERENCES (continued)

REF. NO.	REPORT NO.	TITLE
192	MIL-STD-499	Engineering Management, 1 May 1974
193	MIL-STD-2072	Survivability, Aircraft Establishment and Conduct of Program, For, 25 August 1977
194	MIL-STD-785	Reliability Program for Systems and Equipment Development and Production, 15 September
195	JTCG/AS-78-V-002	FASTGEN II Target Description Computer Program, January 1980
196	MIL-T-27422	Tank, Fuel, Crash Resistant, Aircraft, 13 April 1971
197	MIL-STD-1288	Aircrew Protection Requirements, Nonnuclear Weapons Threat, 29 September 1972
198	MIL-T-5578	Tank, Fuel, Aircraft, Self Sealing, 26 January 1981
199	ASD-TR-77-16	Generic Missile Warheads
200	AFSC DH 2-1	Airframe, 25 April 1977
201	AFSC DH 2-5	Armament, 10 December 1971
202	NPS 57B	Naval Post Graduate School, Monterey CA, R.E. Ball, Dept of Aeronautics, July 1974
203	AS-4449	Safety Requirements for Air Launched, Guided Missile Target Drone, Aircrew, Escape and Rocket Propulsion Systems
204	JAN-A-784	Armor, Steel, Plate, Rolled Face-hardened, 1/4 to 1.-1/8 Inches (U), (Confidential)
205	MIL-STD-1290	Light Fixed and Rotary-Wing Aircraft Crashworthiness, 21 July 1977
206	MIL-HDBK-5	Metallic Materials and Elements for Aerospace Vehicle Structures, 15 September 1976
207	MIL-P-5425	Plastic, Sheet, Acrylic, Heat Resistant, 28 September 1979

REFERENCES (continued)

REF. NO.	REPORT NO.	TITLE
208	MIL-H-5440	Hydraulic Systems, Aircraft Types I and II, Design and Installation Requirements for, 14 September 1979
209	MIL-G-5485	Glass, Laminated, Flat, Bullet-Resistant, 23 April 1971
210	MIL-G-5572	Gasoline, Aviation, Grades 80/87, 100/130, 115/145, 13 March 1978
211	MIL-H-5606	Hydraulic Fluid, Petroleum Base, Aircraft, Missile, Ordnance, 29 August 1980
212	MIL-T-5624	Turbine Fuel, Aviation, Grades JP-4 and JP-5, 16 June 1980
213	MIL-T-6396	Tank, Fuel, Oil, Water-Alcohol, Coolant, Fluid, Aircraft, Non-Self-Sealing, Removable, Internal, 30 August 1974
214	MIL-H-7061	Hose, Rubber, Aircraft, Self-Sealing, Aromatic Fuel, 6 June 1968
215	MIL-A-7168	Armor, Aircraft, Aluminum Alloy, Plates, Deflector
216	MIL-A-7169	Armor, Aircraft, Aluminum Alloy Plates, Projector
217	MIL-C-7905	Cylinder, Compressed Gas, Non-Scatterable, 14 December 1979
218	MIL-P-8045	Plastic, Self-Sealing and Non-Self-Sealing, Tank Backing Material, 22 February 1974
219	MIL-P-8184	Plastic Sheet, Acrylic, Modified, 15 November 1968
220	MIL-F-8785	Flying Qualifies of Piloted Airplanes, 5 November 1968
221	MIL-S-8802	Sealing Compound, Temperature-Resistant, Integral Fuel Tanks and Fuel Cell Cavities, High-Adhesion, 17 September 1980

REFERENCES (continued)

REF. NO.	REPORT NO.	TITLE
222	MIL-A-8860	Airplane Strength and Rigidity, General Specification for, 18 May 1960
223	MIL-A-008860	Airplane Strength and Rigidity, General Specification for, 31 March 1971
224	MIL-A-8861	Airplane Strength and Rigidity Flight Loads, 18 May 1960
225	MIL-A-008861	Airplane Strength and Rigidity Flight Loads, 31 March 1971
226	MIL-A-8863	Airplane Strength and Rigidity Ground Loads, for Navy Procured Airplanes, 12 July 1974
227	MIL-A-8864	Airplane Strength and Rigidity Water and Handling Loads for Sea Planes, 18 May 1960
228	MIL-A-8865	Airplane Strength and Rigidity Miscellaneous Toads, 18 May 1960
229	MIL-A-008865	Airplane Strength and Rigidity Miscellaneous Loads, 17 February 1977
230	MIL-A-8866	Airplane Strength and Rigidity Reliability Requirements, Repeated Loads, and Fatigue, 18 May 1960
231	MIL-A-008866	Airplane Strength and Rigidity Reliability Requirements, Repeated Loads, and Fatigue, 22 August 1975
232	MIL-A-8867	Airplane Strength and Rigidity Ground Tests, 18 May 1960
233	MIL-A-008867	Airplane Strength and Rigidity Ground Tests, 22 August 1975
234	MIL-A-8868	Airplane Strength and Rigidity Data and Reports, 8 February 1974
235	MIL-A-8869	Airplane Strength and Rigidity Special Weapons Effects, 18 May 1960
236	MIL-A-008869	Airplane Strength and Rigidity Nuclear Weapons Effects, 9 June 1971

REFERENCES (continued)

REF. NO.	REPORT NO.	TITLE
237	MIL-A-8870	Airplane Strength and Rigidity Vibration, Flutter, and Divergence, 18 May 1960
238	MIL-A-008870	Airplane Strength and Rigidity Flutter, Divergence, and Other Aeroelastic Instabilities, 31 March 1971
239	MIL-H-8891	Hydraulic Systems, Manned Flight Vehicles, Type III Design, Installation and Data Requirements for, General Specification for, 23 January 1978
240	MIL-F-9490	Flight Control Systems - Design Installation and Test of, Piloted Aircraft, General Specification for, 6 June 1975
241	MIL-C-12369	Cloth, Ballistic, Nylon, 17 August 1977
242	MIL-A-12560	Armor Plate, Steel, Wrought, Homogeneous (For use in and for Combat Vehicles Ammunition Testing), 28 April 1980
243	MIL-A-13259	Armor, Steel, Sheet, Strip and Fabricated Forms, Rolled, Non-Magnetic, For Helmets and Personnel Armor Requirements, 6 May 1966
244	MIL-A-18717	Arresting Hook Installations, Aircraft, 10 September 1979
245	MIL-D-19326	Design and Installation of Liquid Oxygen Systems in Aircraft, General Specification for, 18 October 1978
246	MIL-L-19538	Lacquer, Acrylic, Nitrocellulose, Camouflage (for Aircraft Use), 11 May 1970
247	MIL-E-22285	Extinguishing System, Fire, Aircraft, High-Rate Discharge Type, installation and Test of 27 April 1960
248	MIL-P-25690	Plastic, Sheets and Parts, Modified Acrylic Base, Monolithic, Crack Propagation Resistant, 15 November 1968

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
249	MIL-E-38453	Environmental Control, Environmental Protection, and Engine Bleed Air Systems, Aircraft and Aircraft Launched Missiles, General Specification for, 2 December 1971
250	MIL-A-46027	Armor Plate, Aluminum Alloy, Weldable 5083 and 5465, 10 June 1976
251	MIL-A-56063	Armor Plate, Aluminum Alloy, 7039, 18 August 1980
252	MIL-A-46077	Armor Plate, Titanium Alloy, Weldable, 28 April 1978
253	MIL-A-46099	Armor Plate, Steel, Roll Bonded, Dual-Hardness, 9 November 1976
254	MIL-A-46100	Armor Plate, Steel, Wrought, High-Hardness, 29 July 1977
255	MIL-A-46103	Armor, Lightweight, Ceramic-Faced Composite, Procedure Requirements, 31 March 1975
256	MIL-A-46108	Armor, Transparent, Laminated Glass-Faced Plastic Composite, 9 June 1975
257	MIL-P-46111	Plastic Foam, Polyurethane (for Use in Aircraft), 28 September 1978
258	MIL-L-46159	Lacquer, Acrylic, Low Reflective, Olive Drab, 6 June 1977
259	MIL-P-46593	Projectile, Calibers .22, .30, .50 and 20mm Fragment and Simulating, 12 October 1964
260	MIL-S-58095	Seat System, Crashworthy, Non-Ejection, Aircrew, General Specification for, 31 October 1980
261	MIL-B-83054	Baffle and Inerting Material, Aircraft Fuel Tank, 17 May 1978
262	MIL-T-83133	Turbine Fuel, Aviation, Kerosene Type, Grade JP-8, 4 April 1980
263	MIL-A-83136	Arresting Hook Installation Runway Arresting System, Aircraft, Emergency, 6 August 1968

REFERENCES (continued)

REF NO.	REPORT NO.	TITLE
264	MIL-H-83282	Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base, Aircraft, 22 February 1974
265	MIL-C-83291	Cover, Self-Sealing, Fuel Line, Aircraft, 28 February 1978
266	MIL-P-83310	plastic Sheet, Polycarbonate, Transparent, 17 January 1371

(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).

This page intentionally left blank

3. DEFINITIONS

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

This page intentionally left blank

4. GENERAL REQUIREMENTS

4.1 Description. Engine designs now in development and early production have certain characteristics which affect their survivability/vulnerabilitv. This section examines typical past and present designs, compares design requirements, and provides design trends data for a glimpse into the future. Today's engines, with higher rotating speeds, peak gas temperatures, and peak pressures, are rumored to be much more vulnerable than their predecessors. Analysis suggests that this is not true. Government engine design requirements specifications have become increasingly demanding since the 1950's, and the results are favorable to enhance survivability. The J79 was designed generally in accordance with MIL-E-5007A. The current specification generally applicable to new turbojet and turbofan engine designs is MIL-E-5007D. Table II is a comparison of the two specifications in which "D" requirements considered significant to improved survivability are listed and compared with the corresponding provision in the "A" specification (references 25 and 26). As table 4-I shows the "D" specification imposes hardware design and test requirements which ensure structural integrity, long life, damage tolerance, containment, fire protection, and no visible smoke engine features. Analysis and test requirements are included which provide insight into survivability areas of concern such as IR, RCS, noise, and projectile vulnerability. Nearly identical requirements are established in the present turboshaft and turboprop engine specification, MIL-E-8593A. Thus, current Government specifications include requirements important to engine survivability which are not mentioned in earlier specifications.

TABLE 4-I. MIL-E-5007, "A" vs "D" specification companion.

Item	"D" Requirement	"A" Requirement
Nonnuclear S/V	Consideration required	No requirement
Infrared radiation (IR)	Analyze and test	No requirement
Radar cross section (RCS)	Analyze and test	No requirement
Smoke	No visible smoke	No requirement
Noise	Minimize and test	No requirement
Containment	Demonstrate blade containment, fan, compressor, turbine	No requirement:
Disk burst speed	122% maximum speed	No requirement
Strength and life analysis	Analyze	No requirement
Structural life	Specified	No requirement
Engine pressure vessel	Demonstrate tolerance for twice operating pressure	No requirement
High-cycle fatigue life	1 to 3 billion cycles life required	No requirement
Low-cycle fatigue life	Specified testing required	No requirement
FOD	Design to tolerate demaged blades	No requirement
Bird ingestion	Demonstrate	No requirement
Sand ingestion	Demonstrate tolerance	No requirement

TABLE 4-I. MIL-E-5007, "A" vs "D" specification companion. (continued)

Item	"D" Requirement	"A" Requirement
Flammable fluid system	Fire resistant and fireproof lines and components	No requirement
Electrical power	Engine provided	Aircraft proved
Lube system	All engine provided. Operate 30 seconds with no oil	Tank and cooler not engine provided. Operate 10 seconds with no oil
Hydraulic system	All engine provided	No requirement

4.2 Current Technology. Figure 4-1 illustrates scaled side-by-side cross section comparisons of the J79 and F404 engine designs. The engines are in the same thrust class. The J79 is a combat-proven 1950's design which is still in production and operational service. The F404 is a new design currently under Navy development. The engines are each representative of the latest technology of their respective design periods. Compared to the J79, the F404 possesses the following:

a. Twenty-five percent shorter in length, and a smaller diameter; thus a smaller target

b. Eight fewer turbomachinery stages; three fewer variable vane stages

c. One-half the weight; equivalent speed, reduced rotating energy levels

d. Casing temperatures reduced 350°F; increased fire protection

e. Lower specific fuel consumption; less fuel tankage required

f. Short main shafts; no bearings or sumps under combustor

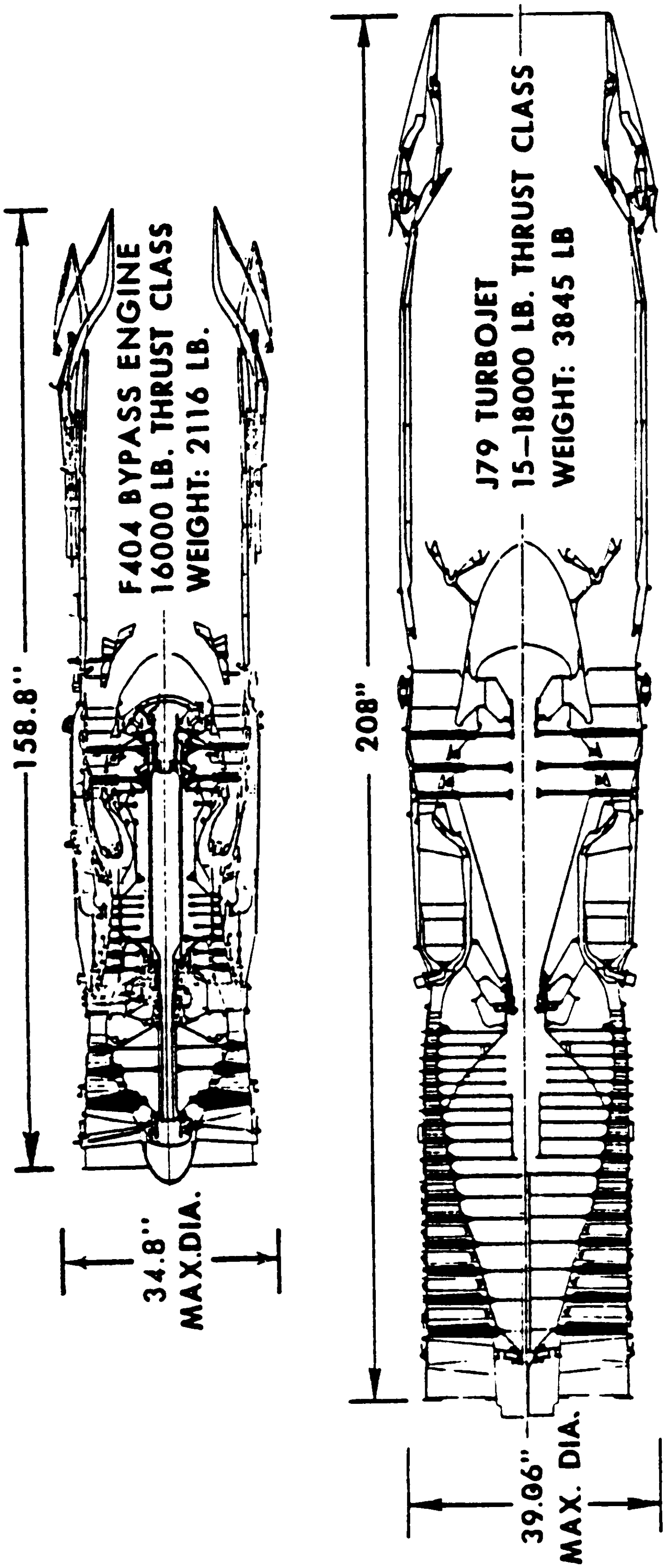


FIGURE 4-1. F404/J79 scaled cross-section comparisons.

4.3 Trends. Future engine designs will yield continuing improvements in performance with additional emphasis being placed on operational suitability, durability, and life cycle costs. Characteristics which promise highly survivable, reliable, easily maintained engines will be in demand and will be influenced by the performance trends described herein. A plot illustrating the benefits in reduced specific fuel consumption of increasing turbine inlet temperatures and engine pressure ratios is shown in figure 4-2. Figure 4-3 illustrates the benefits in horsepower per unit of airflow rate for the same independnet variables. The figures indicate that specific power and specific fuel consumption are, in general, improved by increasing pressure ratios and turbine inlet temperatures. As stronger, lighter-weight materials become available and more precise temperature measurement and control become possible (through developing pyrometry, electrical controls and turbine cooling technology), increased pressures and temperatures are forecast. Figure 4-4 indicates turbine inlet temperature trends. Figure 4-5 shows pressure ratio trends for turboshaft engines. Figure 4-6 shows pressure ratio trends for turbojet and turbofan engines. See reference 27 for source data.

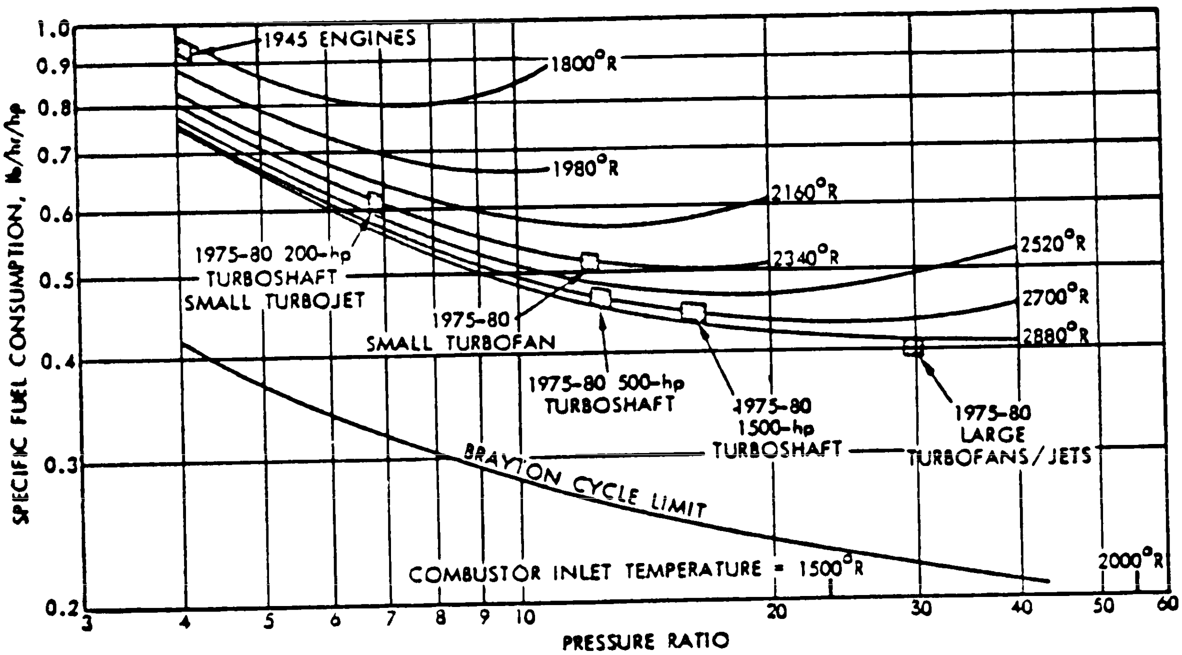


FIGURE 4-2. Engine design technology progress, specific fuel consumption.

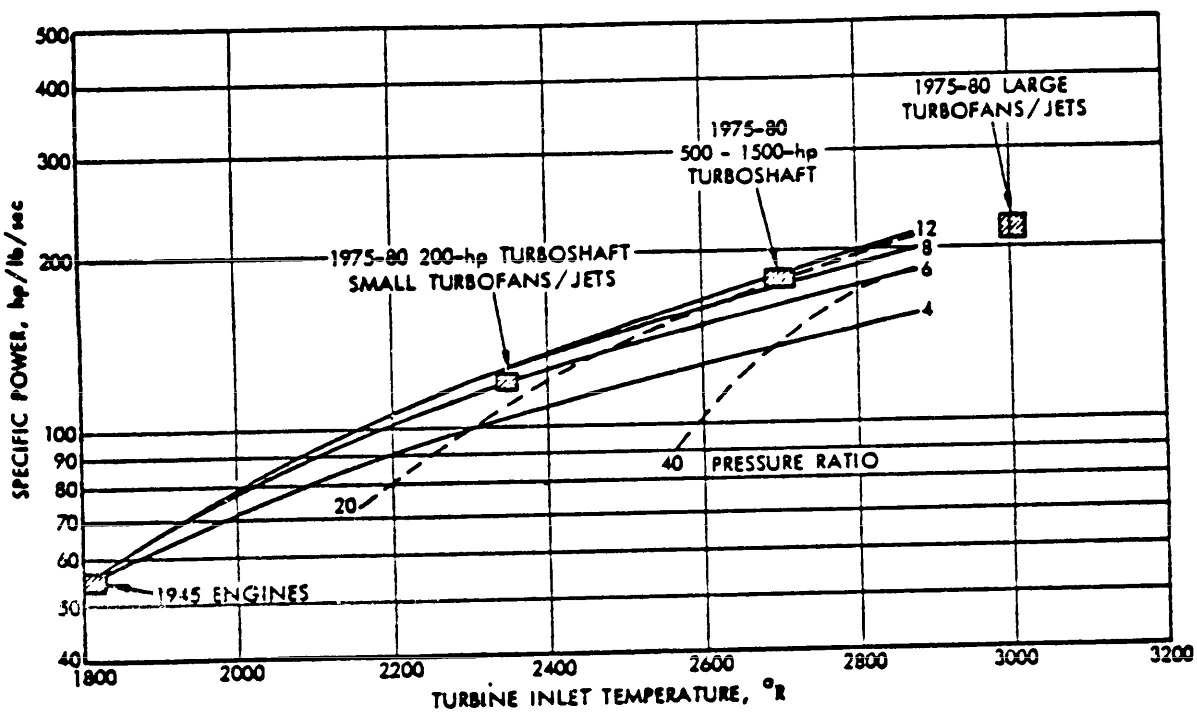


FIGURE 4-3. Engine design technology progress, specific power.

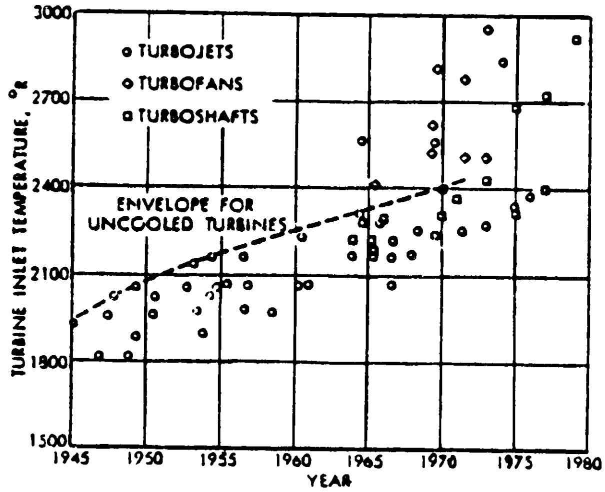


FIGURE 4-4. Engine design trends, turbine inlet temperature.

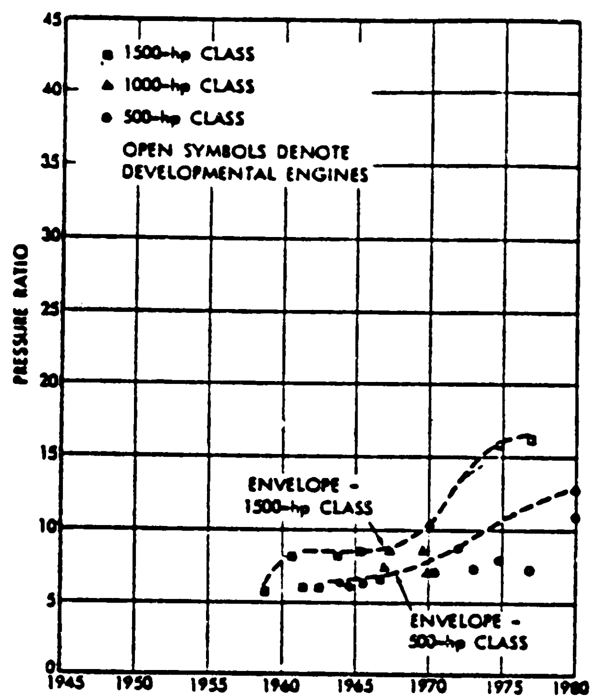


FIGURE 4-5. Trends, pressure ratio, turboshafts.

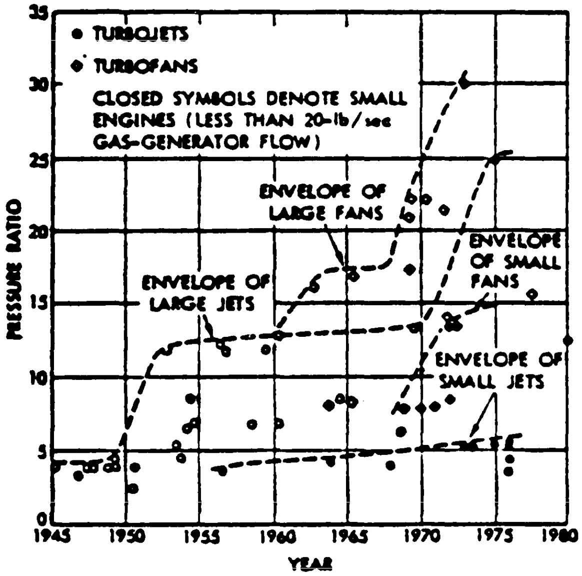


FIGURE 4-6. Trends, engine pressure ratio, turbojets, and turbofans.

5. DETECTABILITY REDUCTION

5.1 Description. This section presents a discussion of the contributions of the propulsion system to an aircraft's radar signature, infrared (IR) radiation signature, visible signature, and acoustic signature. See Reference 110, chapters 7, 8, 9, and 10. Since one or more of these observable characteristics are used by virtually every current or projected air-to-air and surface-to-air weapon for detection, tracking, fire control, guidance, or fuzing, they play a major role in determining the survivability of an aircraft in a threat environment. The engines and engine installations typically are major contributors to these signatures. The objective of this discussion is to assess the state-of-the-art for reduction of these contributions and to describe their interaction with each other and their impact on system design. The definition of survivability may be shown in the following equation:

$$P_S = 1 - P_K$$

The probability of survival is simply the probability of not being killed. The probability of being killed, P_K, can be expressed as:

$$P_K = (P_D \times P_C \times P_H \times P_L \times P_{K/H})$$

where

P_K = the kill probability.

P_D = the probability of being detected.

P_C = the conversion probability; i.e., the probability that the encounter will lead to a position where the threat weapon can be launched/fired.

P_H = the probability of the weapon (or its released fragments) hitting the target.

P_L = the probability of weapon launch

$P_{K/H}$ = the probability of killing the target given a hit.

The IR radiation signature always impacts both the P_C and P_H terms, and may sometimes influence the P_D term as well. The radar signature impacts the P_D term, but also influences the P_C and P_H terms. The visible and acoustic signature always impact the P_D term, but occasionally influence the P_C and P_H terms. These relationships are discussed at length in the following paragraphs. The $P_{K/H}$ term is primarily a function of the vulnerability of the target. The application of technology to reduce the $P_{K/H}$ term is the subject of section 6 of this volume.

This page intentionally left blank

5.2 Radar. The role of radar in modern electronic warfare has been expanding in application and sophistication since its introduction in the early days of World War II. As the word “radar” (radio detection and ranging) implies, its original function was to provide early warning of the approach of hostile forces. Today, ground-based and airborne radar systems are used to provide a wide variety of weapon system functions, including search, acquisition, tracking, fire control, guidance, and fuzing. However, all of these systems employ the following principle of operation: radio-frequency electromagnetic energy is emitted from a transmitter, reflected from a target, intercepted by a receiver, and the transmitted and received signals compared to describe some feature of the target. For most military applications, the target information most commonly sought is target location, direction of travel, and velocity (i.e., range, speed, bearing, altitude, etc), but in some cases the information also may include target identification.

5.2.1 Radar cross section. The parameter that describes the capability of a target to reflect radar signals is called the radar cross section (RCS). The precise technical definition of this parameter is cumbersome, and may be found in any standard textbook on radar theory and design, but for purposes of the present discussion, it may be thought of as the equivalent reflecting area of the target. It is expressed in units of area (usually meters squared) or in decibels (db) above some referenced area (usually decibels above one square meter), but is not necessarily equal to the physical or projected area. RCS is determined by the size and shape of the target, and by the electromagnetic properties (permittivity, permeability, and conductivity) of the materials from which it is made, and is a function of the radar frequency (or wavelength) and the orientation of the target with respect to the radar (i.e., the "viewing angle"). For many targets, the RCS is smaller than the physical cross section, because the target may transmit or absorb part of the incident radar energy, or may reflect part of the energy in a direction away from the radar transmitter/receiver, thus depriving the receiver of much of the echo. Other types of targets exhibit RCS levels considerably larger than their physical cross sections, due to a focusing effect of the reflected energy in the direction of the receiver. Because RCS affects the survivability of the target in a hostile radar environment in so many complex ways, technology for reducing or controlling RCS has been emphasized in recent development programs. An excellent overview of the relationships between RCS and survivability, and the state-of-the-art in RCS reduction/control, may be found in reference 29.

5.2.2 Range limitation. The nature of the target RCS impacts the performance of radar in several ways, but the most important effect is the establishment of a maximum range limitation. In very simple terms, a target with a large RCS is easy for the radar to "see," even at long ranges. If the target RCS is small, however, it must be much closer for the radar to “see” it. The RCS level also influences the effectiveness of jamming the other types of electronic countermeasures (ECM) used by the target. Jamming involves the deliberate broadcasting of electromagnetic energy by the target aircraft into the receiver of a hostile radar to saturate it with incorrect information or excessive electromagnetic noise, thereby making the true target echo indistinguishable by the hostile system. Jammer power requirements (and consequently, jammer weight requirements) to accomplish this are determined by the RCS level of the target; the lower the RCS level, the less jammer weight and power are required. Other countermeasures techniques, such as the use of chaff and decoys, are similarly enhanced by keeping the target RCS at a low level. See reference 110.

5.2.3 Threat description and RCS sources. Due to the varied roles of radar in modern electronic warfare, many different types of radar systems may affect the survivability of an aircraft. Generally, the most serious radar threats are those associated directly with attack ordnance, such as surface-to-air and air-to-air missiles, antiaircraft artillery, etc. However, any radar system capable of detecting the presence of the aircraft can also influence its survivability, as discussed in the preceding paragraph. A typical surface-to-air missile (SAM) system involves an acquisition radar, a tracking or fire control radar, a missile guidance radar, and a fuzing radar. Typical antiaircraft artillery (AAA) systems, which are frequently coordinated with SAM systems, utilize an acquisition radar and a tracking/fire control radar. Virtually all currently operational or anticipated interceptor, air superiority, and V/STOL fighter aircraft are equipped with some form of airborne fire control radar. The earlier designs are used primarily in conjunction with optical gun sights, while the more modern airborne intercept radars are used in conjunction with the fire control systems of both radar-guided and IR seeking air-to-air missiles (AAM). Radar-guided AAM's also use the airborne radar of the launching aircraft as a source of missile guidance information. Other types of military controlled radar systems which are indirectly associated with threat weapons include ground-based and airborne early warning radars, height finders, IFF, and GCI radars. Radars or other microwave emitters which are not directly related to any weapons system, but nevertheless could influence the detectability of a penetrating aircraft, include airport radars, beacons, navigation aids, microwave communication links, etc.

5.2.3.1 Mission detectability levels. Of course, the mission itself determines what radar threats must be considered and what detectability levels can be tolerated. A tactical aircraft such as a fighter-bomber, for example, would not be used against a foreign force except during overt warfare, so knowledge of an aircraft's presence in a given area is often of little consequence. A covert reconnaissance vehicle, on the other hand, must perform its mission without detection, so all radars must be considered threats. Furthermore, while the use of active ECM (jamming) may be a viable protective alternative for the fighter-bomber, a jamming signal would surely betray the presence of the reconnaissance vehicle, which makes passive protection (i.e., the reduction/control of RCS levels) the only viable protection scheme for such a vehicle.

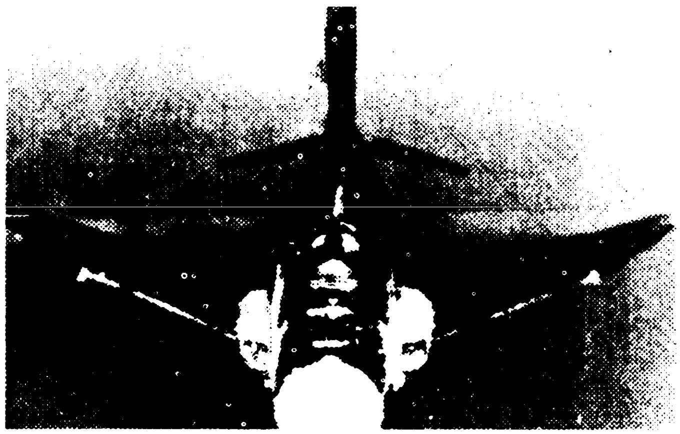
5.2.3.2 RCS signature, IR signature relationship. It is important to consider the aircraft RCS signature in relation to the IR signature and other observable characteristics, since it is quite common to find a mixture of radar threats, IR threats, and combination radar/IR threats in a typical modern electronic warfare environment. Many modern fighter aircraft, for example, carry a normal armament complement which includes both IR-guided and radar-guided AAM's, so that the pilot has a choice of which type of weapon to use against a particular target. Future threats are expected to be even more complex, integrating optical and acoustic detectors with the IR and radar systems.

5.2.3.3 Flare spots. Aircraft target geometry is rather complex and, consequently, some portions of the target contribute much more to the total RCS signature than others. Regions of very high reflection contribution are termed echo sources or "flare spots." Figure 5-1 presents flare spot photographs of a typical (F-4) aircraft. Flare spot photography (discussed in paragraph 5.2.5) is a qualitative technique for identifying echo sources, which show up as bright spots in such photographs. For the forward aspect, the engine inlet cavities are major echo sources. For the aft aspect, the dominant flare spots are those associated with the propulsion system; i.e., reflections from within the exhaust systems and the surrounding cavities. Thus, in order to achieve control over the aircraft RCS levels for these important viewing regions, contributions from the engine and its installation must be considered. Engine inlet and exhaust system cavities are also important echo sources on helicopters.

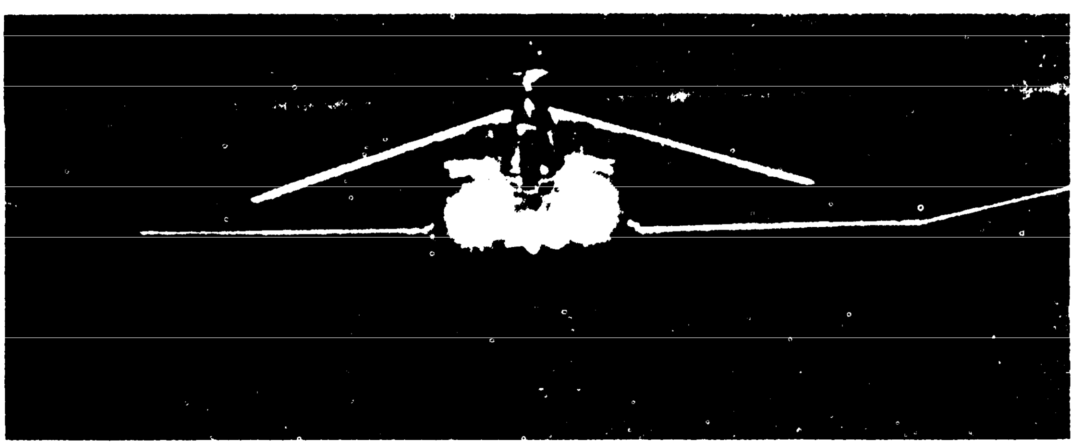
5.2.4 Engine requirements. The propulsion system has long been recognized as major echo sources, and recently RCS signature requirements have been included in engine specifications. The general specification for military turbojet and turbofan engines, MIL-E-5007D (reference 26), requires that, for future engines, inlet and exhaust system RCS levels shall be included in the prime item development specification, and measured as a part of qualification testing. The specific paragraphs (3.1.2.12 and 4.6.5.2, respectively) involved are quoted as follows:

a. "Radar cross section. The maximum radar cross section (RCS) of the engine inlet and exhaust systems, in terms of square meters over the frequency range from 2 to 18 GHz shall be specified in the engine specification. The median values of the RCS over 10 degree intervals shall be less than the specified value. The 10-degree intervals over which the median values are obtained shall extend, as a minimum, over the angular range of ±60 degrees in both azimuth and elevation as measured from the engine centerline at the inlet for the forward hemisphere and at the engine centerline at the exhaust position for the aft hemisphere. Where variable exhaust nozzle systems are used or IR suppression devices are incorporated in the nozzle system, the contractor shall specify RCS values for these devices in each mode appropriate to system operation. Any special provisions for reducing RCS shall be described in the engine specification."

b. "Radar cross section (RCS). The engine RCS shall be determined to substantiate the levels specified in 3.1.2.12 (the above quoted paragraph) of the engine specification by taking radar reflectivity measurements of the engine inlet and exhaust. The radar reflectivity determinations shall be conducted at an outdoor test site with the engine both static and operating. Prior to engine installation, the background shall be measured with all support columns in place and shall be at least 20 db below the ten degree median values measured. The calibration standard shall be a sphere or cylinder. RCS measurements shall be performed at a minimum of one frequency per octave over the specified frequency range and at those frequencies specified by



forward aspect cavities: Engine inlets, cockpit area and nose radar



Aft aspect: Engine exhaust cavities

FIGURE 5-1. Flare spot photographs, F-4.

the Using Service. The radar illumination field at the engine shall be probed and its variation in power density in the vertical plane of the engine shall be less than ±0.5 db about the mean value. sufficient data shall be taken to construct a table of median values of RCS over 10-degree intervals in the area bounded by ±60 degrees in both azimuth and elevation about the engine inlet centerline for the forward hemisphere and about the engine centerline at simulated exhaust nozzle operating positions for the aft hemisphere. The maximum RCS value for each hemisphere (fore and aft), expressed in square meters, shall be determined by obtaining the arithmetic average of the median values contained in the above referenced table."

The general specification for military turboshaft engines, MIL-E-8593A (reference 30), includes RCS sections corresponding to those of MIL-E-5007D and uses almost identical wording. it should be noted that neither of these general specifications establishes an engine RCS "requirement" that constrains or limits the engine design to a prescribed or specified RCS level; they simply require that the RCS levels resulting from the engine design process be identified, and subsequently verified by measurement.

5.2.4.1 Engine requirement applicability. Several problems have been encountered in applying these specifications (especially MIL-E-5007D) to new engine development programs. The most serious problem is the requirement that RCS measurements be performed on the engine, "both static and operating." As described in paragraph 3.1.3, RCS measurements have nearly always been made using accurate, lightweight static scale models of targets of interest, rather than on the actual target hardware, for very sound technical reasons, including the requirement that the target supporting structure present an extremely small RCS in order to preserve measurement accuracy. Consequently, most RCS measurement facilities are incapable of supporting either the weight of a large jet engine, or the forces which would be imposed by the operating engine thrust. Furthermore, the RCS contributions of typical engine designs are determined by the physical shape and materials, and are not significantly affected by pressure, temperature, gas flow, etc, so that an RCS measurement on an operating engine would provide information of only minimally greater value than a similar measurement performed on an accurately scaled static model of the engine. While RCS measurements on an operating engine are not a technical impossibility, the expense of developing a suitable facility has generally resulted in the ccncept being considered not cost effective. Consequently, in applying MIL-E-5007D specifications to new engine development contracts, RCS requirements normally permit measurements to be made on a static model. Another problem associated with the application of MIL-E-5007D is the requirement that the RCS contributions of both the "engine inlet and exhaust systems" be specified and measured. For most conventional aircraft, RCS contributions from the exhaust system cavity are directly and solely attributable to the design and structure of the engine hardware, but the RCS contribution from the engine inlet cavity results from interaction between reflections from the duct walls and from the engine face. Thus, the RCS contribution from the engine face is a function of the total aircraft installation, and cannot be separately identified as called for by the engine specification, MIL-E-5007D. Consequently, in applying this specification to new engine programs, the provisions of paragraphs 3.1.2.12 and 4.6.5.2 of MIL-E-5007D have typically been modified to delete any reference to inlet RCS.

5.2.4.2 Helicopter applications. For many helicopter applications, IR suppression devices are incorporated downstream of the engine exhaust hardware. Such devices are usually considered to be a separate component from the engine; however, the RCS contribution of the engine is greatly influenced by the geometry of such an IR suppressor. This means that the RCS provisions of MIL-E-8593A are meaningful for the aircraft measurements only if the engine and suppressor are regarded as a single, integrated system, and the imposition of an RCS specification on the engine hardware alone has limited value.

5.2.5 Design evaluation tools and techniques. Tools and techniques for the quantification and evaluation of the RCS characteristics of aircraft and other types of radar targets have been under development for several years. Knowledge of the RCS characteristics of hostile systems is a necessary input to the evaluation of the performance of friendly radar systems. With increasing emphasis on survivability as a factor in aircraft design, as indicated by the emergence of RCS requirements in specifications such as MIL-E-5007D and MIL-E-8593A, such tools and techniques have been adapted for the evaluation of friendly aircraft as well. Such techniques are necessary for the evaluation of competing designs on a survivability basis and, due to the particular significance of propulsion system components and installations as RCS contributors, specialized RCS evaluation tools and techniques are being developed for these echo sources. In general, there are two types of design/evaluation tools and techniques - experimental and analytic. The experimental approach involves direct measurement of RCS characteristics of physical targets, while the analytic approach involves prediction of RCS characteristics by application of electromagnetic theory and mathematics. Until the development of modern high-speed computers, the mathematical complexity of the analytical approach made the analysis impractical for all but the simplest of target shapes (flat plates, spheres, cones, etc). Consequently, the development of experimental techniques was initiated at a much earlier date, and has reached a more sophisticated stage of development.

5.2.5.1 Experimental technique. The RCS of a target may be determined experimentally by locating the target at some fixed and precisely known distance from a radar system of known performance characteristics (frequency, antenna gain, etc) and then measuring the ratio of received power to transmitted power. This ratio is directly proportional to the RCS of the target, and the system can be calibrated through the use of some “standard” target of known RCS (usually a cylinder or a sphere). Typically, the target is mounted on some type of pedestal that permits variation in orientation (pitch and azimuth) while maintaining constant range. If the target is large, then the range must be large in order to maintain uniform illumination of the target by the radar beam. This means that typical ranges on the order of 3,000 feet or more are required for high accuracy, and this implies an outdoor measurement facility. Of course, such a facility must be free of any other reflecting objects in the radar field of view, as the return from such objects would result in spurious background return (known as "clutter”) which would destroy the accuracy of the measurement.

5.2.5.1.1 Scale modeling. Many targets of interest are simply too large and/or heavy to handle for this type of measurement, so an alternative technique using a reduced scale model of the target is often used. Fairly small models often can be measured at ranges on the order of 50 to 100 feet without destroying measurement accuracy and, for range dimensions this small, the measurement can often be performed indoors, in a microwave anechoic (echo-free) chamber. The chamber must be anechoic to eliminate return from the walls of the chamber. This is accomplished by lining the walls of the chamber with radar absorbing materials (RAM).

5.2.5.1.1.1 Procedure. To scale up RCS measurements for a l/n scale model of the target, measure the model at n times the radar frequency of interest, and multiply the measured RCS levels by n^2 to get the full-scale RCS levels at the desired frequency. Care is necessary, however, in using scale models for RCS measurement purposes. For example, it is not always possible to measure at n times the frequency of interest. If n is very large (very small model), the required measurement frequency may be beyond the frequency range of the measurement facility and, in some cases, may be completely out of the microwave spectrum. This establishes a practical limit on the model scale, and for typical aircraft engine models and realistic threat frequencies, this limit is about 1/4 scale, with larger scales (1/3, 1/ $\sqrt{10}$, or 1/2) usually preferred.

5.2.5.1.1.2 Limitation. Another limitation on the use of scale models is the requirement that the real target and the scale model be completely reflective; i.e., where they neither absorb radar energy nor transmit radar energy through their surfaces. This means, in effect, that the technique can be used with accuracy only when both the target and the model have exclusively metallic surfaces.

5.2.5.1.1.3 Dimension-to-wave length ratio. Also, the principle requires that the same dimension-to-wave length ratio in the model at the measurement frequency be used as in the full scale target at the threat frequency. This means that dimensional accuracy must be preserved. Consequently, high-precision models are required, which are often quite costly; relaxation of model precision results in significant RCS measurement inaccuracies.

5.2.5.1.1.4 Full-scale RCS measurement. When full-scale RCS measurement is required, the target may either be the real hardware or an accurate full-scale model thereof. For targets such as turbine engine inlets and exhaust systems, it is usually better to use a model than the real hardware for two reasons:

a. The real hardware weight makes it impractical for use as a measurement target. To preserve measurement accuracy, all "background" echo must be minimized, including the echo from the target support structure. For this reason, support columns are usually made of low density, low reflectivity polyurethane foam, and such materials are incapable of supporting very large mechanical loads. RCS models are normally built of light weight materials, such as wood, fiberglass, etc., with their surfaces metallized with aluminum foil or conductive paint.

b. It is usually only the interior of the exhaust system or inlet cavity that is of interest as an RCS source, since the exterior of the nozzle is usually configured in such a way that it reflects energy away from the radar (thereby contributing nothing to the RCS), and the rest of the engine exterior is concealed within the fuselage or nacelle. If a real engine were used as a target, non-specular scattering sources on the exterior of the engine (pumps, gearboxes, fuel lines, flanges, bolts, etc.) would show up in the measurement, destroying the utility of the data.

5.2.5.1.2 Static measurements. The type of RCS measurements specified in 5.2.5.1.1.4 are known as "static" measurements, since they are performed with the range fixed. They may be performed on complete systems (such as aircraft or aircraft models) or on subsystems (such as the engine inlet or exhaust system). Generally, measurements on the complete system are needed for inputs to system survivability studies, but it is usually difficult to isolate the RCS contributions from a single flare spot (such as the engine exhaust system) with a complete system model. Consequently, separate measurements on isolated engine or nacelle models are also frequently required.

5.2.5.1.3 Dynamic measurements. Dynamic RCS measurements are performed with the target operating in its normal environment, such as a "fly-over" measurement of an aircraft in flight by a calibrated ground radar, or an in-flight "breaklock" experiment using a chase aircraft. Obviously, it is impossible to isolate the RCS contribution of a single flare spot with such a measurement. While such techniques may be quite valuable as a "proof of the pudding" evaluation of the total system, they are expensive and have little value in evaluating subsystem RCS characteristics.

5.2.5.1.4 Flare-spot photography. One other empirical technique that has some utility in RCS simulation is flare-spot photography. It is essentially a scaling technique, using a small scale model of the target, and a visible light source instead of a radar transmitter. The receiver/recorder is a simple camera. The photos are made in a closed chamber in which there is only one light source, and that source is placed in close proximity to the camera (a flash attachment on the camera is commonly used). The walls of the chamber, including the backdrop, have nonreflecting surface treatments. Figure 5-1 shows flare spot photographs of an F-4. When the target model is illuminated by the light source, it will affect the light energy much as the real target affects an incident radar beam; i.e., it reflects part of the energy back towards the source, and scatters or absorbs the rest. The treatment of the chamber walls makes the chamber "anechoic" in the visible spectrum, so the only light that reaches the camera is the reflection from the target. This reflected energy will paint an impression of the target on the film, in which areas of the target with high reflection (i.e., "flare spots") show up as bright areas. Some attempts have been made to quantify the results by relating the brightness of the film spots to strength of the echo, but the accuracy is too limited to be generally practical.

5.2.5.1.5 Static vs. simulation. Although the technique of static RCS measurement is well established and highly developed, it is a rather time-consuming process, and does not lend itself to rapid, inexpensive RCS evaluation of preliminary designs. Consequently, simulation methodology has been inadequate to satisfy the need for an RCS evaluation tool, as an aid in cycle and nozzle selection suitable for use during preliminary engine design.

5.2.5.2 Analytic technique. Recently, the emergence of an analytical RCS prediction computer model, GENSCAT (reference 31), has resulted in a potential method for solving the preliminary design problem. The GENSCAT program, developed by Northrop Corporation under USAF sponsorship, has the capability to predict RCS signatures for a variety of target geometries, including the external surfaces of aircraft (fuselage, wings, nacelles, empennage, etc.) and certain types of engine inlet cavities. The program was not designed for, and currently does not have the capability of predicting RCS signatures for exhaust system cavities; but with certain program modifications, the inlet RCS prediction model can be adapted for exhaust predictions. While the GENSCAT program has a high potential for becoming a useful preliminary design tool, considerable program development is required.

5.2.6 Suppression techniques and practices. Considerable technical effort, largely Government-sponsored, has been applied and progress made in the development of technology for the reduction or suppression of engine-related RCS signature contributions. Specific suppression techniques are generally classified CONFIDENTIAL, and quantified suppression levels achievable classified SECRET. The discussion that follows in this unclassified document is, therefore, very general. However, frequent references to classified documents are provided to identify sources of more specific information.

5.2.6.1 Overall parameters. The two overall parameters that determine the RCS of any target are its geometry (size and shape) and the electromagnetic properties (conductivity, permeability, and permittivity) of the materials from which it is made. Materials with very high conductivity (i.e., metals) are the strongest reflectors, while materials with low conductivity (i.e., electrical insulators) will tend to either transmit or absorb incident microwave energy. Shape is usually a more significant determinant of RCS level than size. Energy incident on a flat metallic surface such as a wing or fuselage side will tend to be reflected away from the source in mirror-like (i.e., specular) fashion for all angles of incidence except perpendicular to the surface, thereby contributing to the, radar echo only over very small ranges of aspect angles. Metallic cavity-shaped structures, on the other hand, tend to behave like "corner reflectors"; i.e., they tend to reflect all, or nearly all, of the energy entering the cavity back toward the source. Metallic cavity-shaped structures, such as engine inlets and exhaust systems, therefore, tend to be major RCS contributors over wide ranges of viewing angles.

5.2.6.2 Exploitation of low-reflection geometries and materials. Since the RCS of any target is determined by its geometry and its material properties, the key to RCS reduction for aircraft and other targets (including engine inlet and exhaust system cavities) is the exploitation of low-reflection geometries and materials with controlled electromagnetic properties, either singly or in combination. The most difficult flare spot to reduce has been the engine exhaust system cavity. This difficulty arises from the fact that (1) flexibility in geometrical configuration is often limited; and (2) the selection of materials with controllable electromagnetic properties that are capable of withstanding the high temperature, thermal shock, pressure, chemical, and acoustic environment of a modern turbine engine exhaust system is also limited.

5.2.6.2.1 Exhaust system geometry. Considerable progress has been made in the area of exhaust system RCS reduction, largely as a result of a series of programs performed by General Electric for the Air Force Avionics Laboratory under Project 691X (references 32, 33, 34, and 35). These programs included evaluation and development of both geometry-based and materials-based suppression schemes. In general, the exhaust system geometry is a much more significant determinant of the RCS characteristics than the materials properties. The geometry, of course, is determined primarily by the selection of the engine thermodynamic cycle and nozzle type. Although past practice has been to make such selection as early as the weapon system concept definition phase, before survivability against radar threats (and, consequently, the need for RCS specifications) is considered, certain geometries are characterized by much lower RCS levels than other geometries, and RCS level could be used as a factor in cycle/nozzle selection for any aircraft where survivability is weighed as importantly as range, payload, etc. The major geometrical properties of an exhaust system that influence its RCS levels are:

a. Size. The nozzle exit area is probably the most important determinant of RCS level. In general, two small exhaust systems will not exhibit the same RCS characteristics as one equivalent larger system; so a comparison of single-engine versus twin-engine systems will sometimes show an RCS advantage for the twin, and sometimes for the single installation, depending on the particular mission/threat definition considered.

b. Nozzle type. Many types of nozzles (plug, conical, asymmetric, etc) have been investigated, with a clear preference indicated for certain types over other types on an RCS basis. The details are classified as noted below.

c. Engine cycle. The mechanical structure at the forward end of the exhaust system cavity has been found to have a major impact on the RCS levels associated with the cavity. The geometry of such structures is primarily a function of the engine cycle; for example, it may be a row of turbine buckets in a dry turbojet; it may be a complicated augmenter; or it may be a variety of other metallic shapes depending on whether the engine is mixed, separated, or confluent-flow turbofan; a turboshaft; or a variable cycle engine.

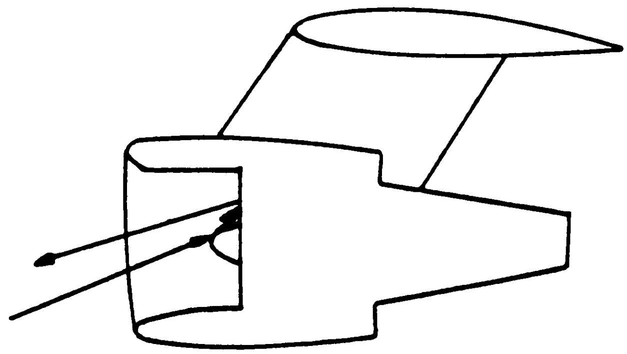
d. Symmetry. Recent investigations have addressed a wide variety of non-axisymmetric exhaust systems which exhibit nonsymmetric RCS patterns. Such patterns add a new dimension to the possibilities of geometry exploitation for RCS suppression and, again, selection of the "best" type of nozzle is very much a function of the specific mission/threat definition considered.

5.2.6.2.2 Exhaust system materials. Exploitation of special exhaust system materials is a valuable technique for RCS reduction. For current systems and/or retrofit suppression applications, use of special RAM is usually the only feasible approach, since there is little flexibility in changing the cavity geometry without significant effects upon the engine cycle and the mechanical design. Certain components within the exhaust system cavity are typically much more significant RCS contributors than others, so that knowledge of which components to treat with special materials for the most cost-effective RCS reduction is of critical importance. Classified details are discussed at length in references 32, 33, 34, and 35. Reference 35 also presents a summary of the current state-of-the-art in special materials for exhaust system RCS reduction.

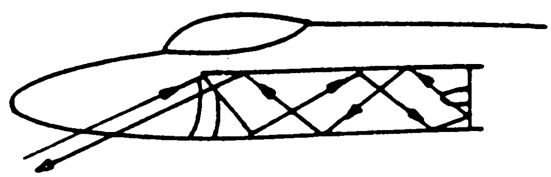
5.2.6.3 Engine inlet RCS reduction. The RCS characteristic of the engine inlet depends strongly on the installation geometry. Figure 5-2 shows that, for installations involving large-diameter engines and relatively short inlets, the RCS is dominated by direct reflections from the engine front face. For installations involving relatively long ducts and small-diameter engines, the RCS is dominated by reflections from the walls of the duct. For most other installations, the RCS results from interaction of the reflections from duct walls and engine face. The desirability of low-RCS inlet/engine cavities has led to a significant amount of technology development in this area, primarily under government sponsorship. A wide range of suppression concepts involving both geometry-based and materials-based techniques have been investigated and evaluated (references 36, 37, and 38). In general, these successful approaches have been limited to the duct-dominated and interaction-dominated cases; there has been little work done to develop RCS reduction technology for the engine-face dominated case. There is a significant need for improved technology in this area.

5.2.7 Trade-off factors. The traditional approach to aircraft/engine development has been to optimize the engine cycle and aeromechanical design to fulfill a given mission requirement without consideration of the RCS contributions of the engine components until after the engine configuration has been fixed. Then trade studies are performed to evaluate the feasibility of reducing the engine-related RCS signature contributions. Generally, the only feasible engine RCS reduction concepts within these ground rules involve the addition of special materials and/or structures to the engine, resulting in weight penalties and sometimes performance penalties to the propulsion system. Thus, on a system basis, improved survivability is obtained at the sacrifice of some mission capability. Such a trade is seldom considered cost effective, and engine RCS suppression is rarely implemented. If system trade-off studies involving engine RCS reduction are performed earlier in the development cycle, such as during the system definition phase, different results may be anticipated. System survivability against radar threats is not the result of RCS level alone. It is determined by a combination of factors, including RCS level, type of active ECM (jamming) used by the aircraft, maneuver capability, type of mission (high altitude versus low altitude, etc) and a variety of other factors. System trade studies performed early in the program may show, for example, that engine RCS level trades favorably with system weight if the RCS

Ž NACELLE
RCS is Engine-Dominated



Ž LONG DUCT
RCS is Airframe Dominated



Ž POD
RCS results from interaction
of Duct and Engine return

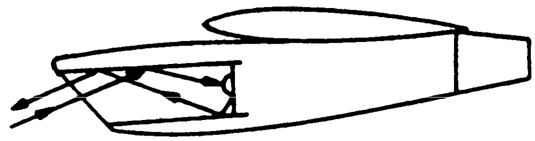


FIGURE 5-2. Inlet and engine face RCS.

reduction would permit a significant reduction in jammer power (and consequently jammer weight), requirements that would offset an attendant increase in engine weight. Experience has shown that many engine RCS reduction techniques also result in reduction of the IR signature, and vice versa (reference 39). Therefore, such system survivability trade studies should take into account all of the observable characteristics. It may be, for example, that a given technique, considered as an RCS reduction concept alone, is not cost effective, and that the same technique, considered as an IR suppression technique alone, is also not cost effective. Consideration of the same technique as a combination IR/RCS reduction concept, however, may indeed show cost effectiveness.

5.2.8 Technology need and voids. Although the state-of-the-art in engine RCS technology has progressed significantly over the past decade, several technology voids remain. System survivability trade studies performed early in the development process, as described in paragraph 5.2.7, are expected to lead to future higher survivability aircraft. However, current capability for performing the engine RCS portions of such studies is quite limited. While it is well known that such factors as engine cycle and nozzle selection have major impact on engine RCS levels, current knowledge of these effects is limited to only a few cycle/nozzle combinations previously investigated, and a broader data base is needed.

a. The capability of performing credible preliminary design trade-off studies to determine the optimum degree of RCS reduction (cost of RCS treatment, savings in active ECM) requires the development and compilation of a hard data base on RAM (materials) physical, environmental, electrical and cost parameters, and a MIL-type handbock. of application principles and directions for the vehicle designer.

b. An improved analytical RCS prediction tool is urgently needed to assist in the development of such studies. While efforts are currently underway to adapt the GENSCAT program for prediction of engine inlet and exhaust system RCS contributions, the program is very complex, requiring considerable setup time, and its accuracy is unknown, implying the need for verifying experimental data.

c. There is also a need for development of technology for reduction of the RCS contributions resulting from the engine front face.

d. Finally, there is a need for a better selection of special materials (especially RAM materials) for engine exhaust system RCS reduction. Current materials have marginal electromagnetic performance, do not perform at all threat frequencies, and are restricted to certain components by temperature limitations (reference 35).

This page intentionally left blank

5.3 Infrared Emissions. Both helicopters and fixed-wing aircraft emit and reflect IR energy. The emission of IR radiation by the aircraft is strongly dependent on the surface temperature and to a lesser degree on its surface emissivity and area (reference 40). Of the aircraft emitting surfaces, the hot engine exhaust surfaces are the dominant IR contributors over the aft hemisphere of the aircraft. Radiation from the engine exhaust gases such as H_2O and CO_2 and from the airframe surfaces are the principal contributors over the side and frontal hemispheres. The airframe reflection of the sun's radiation (sun glint) and earth's radiation (earthshine) are usually the dominant IR reflective sources over the side and bottom hemispheres because of the large viewable surface areas of the aircraft in these aspects. The reflective radiation may approach the contribution due to surface emissions during daylight operations.

5.3.1 Vulnerability to IR guided missiles. Radiation from these aircraft sources, even after attenuation by atmospheric H_2O, CO_2, CO, dust, etc, can be used for guidance of threat missiles. These missiles are designed to detect the contrast between the aircraft IR sources and the background and lock-on to the sources of greatest contrast. Utilizing this contrast, the missile flies a path to intercept and explode its warhead when it hits or gets in close proximity to the aircraft. Depending on the lethality of the missile warhead, the target aircraft may be disabled to the point where it cannot complete its mission. The missile is then said to have accomplished an aircraft "kill." Because of the ability of these IR guided missiles to accomplish an aircraft "kill," consideration is given in specifying requirements for military aircraft to assessing the IR levels of the aircraft. The specifications can either limit radiation levels under defined conditions or simply require IR signature assessment. In either case, the aircraft designer must use IR prediction and evaluation tools. The prediction techniques (reference 41) model the aircraft. IR sources are used to determine IR levels for specified flight conditions. This modeling capability is especially helpful in making aircraft design iterations to meet specified IR levels or in predicting in-flight signatures.

5.3.2 Passive countermeasures. Aircraft IR suppression design techniques (reference 42) include cooling exposed surfaces; hiding hot, hard-to-cool surfaces with other cooled surfaces; and absorbing the radiation impinging on cooled visible surfaces from hotter surfaces shielded from direct view. These "passive" countermeasures can, if used properly, increase the effectiveness of "active" countermeasures, to the point where detection can be avoided.

5.3.3 Active countermeasures. Active countermeasures include flares to decoy the missile away from the initial target aircraft or IR jammers such as amplitude modulated IR sources which cause the attacking missile to track a point in space other than the attacked aircraft. To be effective in deceiving the missile, these signals must exceed the IR signal level of the target aircraft by a factor of 2 or 3. Thus, if the target aircraft radiation is reduced, the IR flare level or jammer level can be decreased proportionately and still be effective in decoying the missile. Reducing the required output of the active countermeasures permits a reduction in the associated power requirements and, thus, in aircraft weight. This reduction may be traded against the extra weight required or aircraft performance loss by incorporating suppressors. For equal IR threat detectability, the trade may favor the use of suppressors.

5.3.4 Threat description. Threat missiles use the contrast between the target aircraft and background IR radiation levels for guidance. Most missiles are designed to guide on IR radiation in the wavelength band from approximately 2 to 5 microns (references 40 and 42).

5.3.4.1 Hot parts seeking missiles. The older missiles of the 1950-70 period used detectors sensitive to radiation in the 2- to 3-micron band (reference 40). The most intense sources of radiation in this wavelength band are the aircraft hot exhaust system components, including the last stage turbine blades, centerbody, and tailpipe walls. This, combined with the state-of-the-art of missile aerodynamic and fuzing technology, limited the missiles to near tail-on (±30 degrees) approaches. Such missiles were classified as hot parts seekers. Hot parts seeking missiles were designed to be either air-launched from an interdiction-type fighter aircraft or ground-launched from missile carriers or man-carried shoulder-held launchers. Launch ranges were limited to several miles because the detectors were uncooled and had difficulty distinguishing the target from the background and internal noise. Additionally, the launch range was limited by the size of the solid-propellant booster size.

5.3.4.2 Present missiles. Newer missiles (starting in 1970) use cooled IR detectors which reduce the internal detector noise and enable detection of radiation from the aircraft surfaces and engine exhaust CO_2 emissions in the 3- to 5-micron band (references 40 and 42). Because the missiles now have a source of aircraft radiation from whatever angle the target is viewed, the missiles are designed to attack aircraft from any direction. The missile propulsion systems are improved so that the missile can be launched at long ranges (5 to 10 miles) from the aircraft. Also, the fuzing system and warheads are proximity-fuzed so that the missile can achieve an aircraft kill with a near miss. Because of this all-aspect capability, such missiles are termed dogfight missiles and they can be employed by one aircraft attacking another to achieve a kill. Because of the aircraft sources which they utilize for tracking, they are classified as plume-hot parts seekers as contrasted to the earlier generation hot-parts-only-seeking missiles.

5.3.5 Requirements. The IR level requirements for engines of turbine-powered aircraft are specified in two documents: MIL-E-5007D for turbojet and turbofan engines, and MIL-E-8593A for turboshaft and turboprop engines. MIL-E-5007D provisions are typical. The following is quoted from MIL-E-5007D (3.7.10.3). "Infrared Radiation, The maximum IR levels for the following azimuth, elevation, bandpass, altitude, and engine power settings shall be submitted to the Using Service prior to PFRT:

a. Azimuth Angles: 0°, 5°, 10°, 15°, 20°, 30°, 40°, 60°, 90°, 135°, and 180°

(An extension of the centerline aft of the engine shall define the 0° azimuth and 0° elevation position. The 0° azimuth angle, 0° elevation angle and centerline are defined as being in a plane parallel to a level ground plane. If the radiation pattern is symmetrical about the centerline, a polar plot with a notation indicating symmetry may be used.)

b. Elevation Angles: 0°, 5°, 10°, 15°, 20°, 30°, 40°, 60°, and 90° (above and below horizontal).

c. IR Bandpass Conditions: 1-3 microns and 3-5 microns, 8-10 microns, 10-12 microns, and 12-14 microns.

d. Altitudes: Sea level, 36,089 feet; and the absolute for the engine.

e. Engine Power Settings: Maximum, intermediate; and maximum continuous.

The standard source used as a reference for both the radiation patterns and the measurement equipment shall be specified."

The following is quoted from MIL-E-5007D (3.7.10.3.1): "Infrared Suppression System, When an infrared suppression system is required by the Using Service, the maximum IR levels in accordance with 3.7.10 (MIL-E-5007D) with and without suppression shall be included in the engine specification. A description of the system shall be provided including method of actuation, operating limitations in the suppression mode, and fail-safe provisions. The detailed effects of the IR suppression operation upon thrust, SFC and other performance parameters shall be included in the engine performance computer program."

The following is quoted from MIL-E-8593A (4.6.5.3): "Infrared Radiation Test, Peak engine infrared radiation and radiation patterns shall be determined to substantiate the requirements of 3.7.10.3 (MIL-E-5007D). The IR signature shall be measured as total (hot parts + reflection + plume) effective radiation for the uninstalled engine. The infrared intensity and spectral response of the IR instruments shall be determined by calibration before and after infrared test measurement and these data shall be recorded. The measurement instruments shall be calibrated with a field standard IR source to determine their effective response to infrared radiation during the IR test. The standard source used as a reference for both the radiation patterns and the measurement equipment shall be specified. Atmospheric conditions (temperature, humidity, precipitation, cloud formation, meteorological range, sun location standard) and engine effective IR radiation shall be specified. The measurement technique shall be such that extraneous radiation from the background and external regions of the engine normally covered by aircraft structure is minimized. The engine shall be set up in an outdoor test facility and operated at the power conditions specified in 3.7.10.3. Each power condition shall be maintained until exhaust system component temperature is stabilized before taking IR readings. Infrared radiation measurements shall be taken at angles specified in 3.7.10.3 in the increments required to determine the peak radiation and overall emission patterns. Total IR signature shall be verified by band width radiometers, sensitive in the 1-3, 3-5, 8-10, 10-12, and 12-14 micron wavelengths. In addition, spectral measurements shall be made with a spectrometer having a resolution of at least 0.05 microns at each aspect angle from 0 to 180 degrees to identify the exhaust gas "plume" contributions. For engines incorporating special IR suppression system features, the above tests shall be accomplished with the engine running both in and out of the suppression mode."

The procedures for predicting and measuring the engine IR level are discussed in the next paragraphs. The IR levels of the engine are measured for specified engine operating conditions at various altitudes, external Mach numbers, and ambient air pressures, temperatures, and humidities. Predictions are made of the IR signature, IR level versus aspect angle, for the test engine cycle, ambient conditions and IR measurement ranges. These predictions are compared to the at-range measurements and the prediction procedure ability to model the engine IR emissions verified. Measurements are made of the engine cycle dependent exhaust system surface temperatures and exhaust gas exit conditions. These are used to verify the heat transfer modeling required to predict the exhaust system surface temperatures.

This modeling verification having been accomplished, engine cycle and exhaust system surface temperatures at the IR specification flight conditions are predicted. Source IR radiation signatures for the engine at these same flight conditions are also estimated. This predicted signature is then compared to the IR specification maximum levels or signatures to verify that the engine design does indeed meet the required IR levels.

5.3.6 Design evaluation tools and techniques. The IR prediction and measurement procedures have been developed as aircraft design evaluation tools for this purpose. SCORPIO is a typical IR aircraft prediction program which models aircraft IR sources and atmospheric attenuation (reference 41). As shown in figure 5-3, the IR prediction method is broken down into groups of computational steps or modules. Each module has a particular functional capability such as the AMFM module which models the airframe surface areas, emissivity, and temperature as viewed from specified chosen aspect angles. A second module (SIGNIR) is used to model the engine exhaust system areas, temperatures, and radiant interchange between these areas and the ambient environment. A third module (JETMIX) models the spatial distribution of engine exhaust products such as H_20 and $C0_2$ as they mix to lower temperature and concentrations with the ambient air. A fourth module (PLUMIR) models the IR emission and attenuation of the exhaust and atmospheric gases in the path between the aircraft hot components and exhaust gases and the observer location in space. A fifth module (TOTALR) calculates the available spectral radiant intensity (radiant energy per unit solid angle per unit wavelength, watts/steradian/micron) of the plume contributions and the airframe and engine hot parts spectral radiant intensity as transmitted through the intervening plume and/or atmospheric path to the observer. Other modules are available to calculate the missile utilization of this incident radiant energy and its contrast with the background spectral radiance and the range at which this radiant energy provides the needed signal to noise ratio for missile lock-on. Input for this defined IR modeling procedure are obtained from the aircraft design. Typical input quantities such as airframe geometry engine interior geometry, engine exhaust profile of temperatures and $H_20/C0_2$ concentration are shown in figure 5-3. This procedure is thus able to model the complete IR emissions of the aircraft.

5.3.6.1 Computations. For most computations, compromises must be made between real-world distribution of input parameters and those which the computational procedure has been set up to accept. Comparisons between

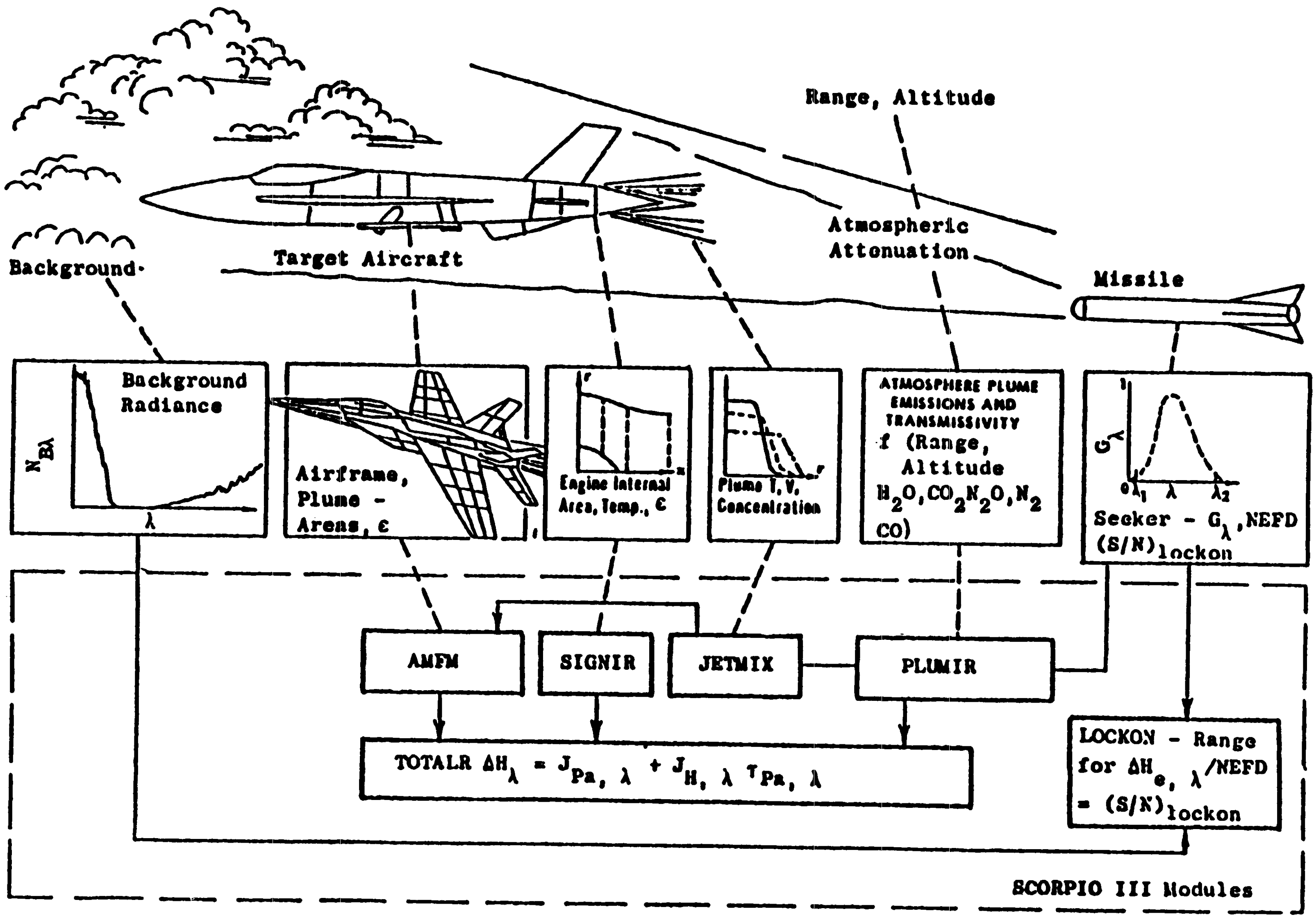


FIGURE 5-3. Overall aircraft - missile IR modeling.

predicted and measured IR levels for aircraft have shown that prediction errors as low as ±10 percent are achievable. However, this accuracy is achieved only if the real-world spatial distribution of input parameters closely match the assumed spatial distributions made for computational ease in the IR model. Thus, checks are usually made on the accuracy of the IR modeling made for each aircraft by comparing predicted with measured levels. This procedure of verifying the accuracy of the IR modeling requirement specification and testing takes a particular set of test conditions and then utilizing the verified prediction model to predict the engine IR levels for flight conditions which may be prohibitively costly or difficult to achieve. The IR measurement instruments such as radiometers and spectrometers are used to determine the radiation level of aircraft and engines.

5.3.6.2 Radiometers. Radiometers incorporate radiation detectors which integrate the product of spatial distribution of the incident radiation and spectral sensitivity of the combined optics detector and electronics over the wavelengths for which the radiometer is sensitive. The output signal from the radiometer is thus proportional to integrated effective radiation. Radiometers have a limited field of view and are sensitive to the incident radiation within the field of view. A superposition of a typical radiometer's field of view sensitivity contours on a turbofan engine is shown in figure 5-4. An overall engine target and calibration source setup for determination of engine radiation levels is shown in figure 5-5. From figure 5-4, it can be seen that most of the engine hot parts fall within the 100-percent sensi- The remaining engine components and the plume radiation positions relative to the radiometer sensitivity counters are also shown in figure 5-4. These relative positions of the radiation sources to the sensitivity contour change with the range and aspect angle from which the sources are viewed. A typical range of aspect angles for IR measurements is shown in figure 5-5. These differences need to be taken into account when interpreting IR measurements and comparing them to predicted IR radiation levels. Usually the radiometer is placed far enough from the engine so that the major radiation sources fall within the 90-percent sensitive contour, and differences between the actual and measured radiation levels are of the order of 10-percent.

5.3.6.2.1 Calibration of radiometers. Calibration of the radiometers to relate the output signal to the effective radiation level is carried out using field IR sources of known temperature, area, and emissivity and therefore calculable effective radiant intensity. These calibration sources are viewed at the same range as the engine IR so that atmospheric attenuation of the calibration source radiation is similar to that of the engine target radiation.

5.3.6.2.2 Comparison of predicted and measured engine radiation. A typical predicted arid measured engine radiation for a radiometer sensitive to radiation in the 2- to 3-micron band width is shown in figure 5-6. The predicted radiation level is seen to vary at most by about 20 percent from the measured values. This variation is typical of the accuracy achieved by radiometers in measuring engine IR sources.

FIGURE 5-4. Radiometer field of view sensitivity bands superimposed on a turbofan engine exhaust.

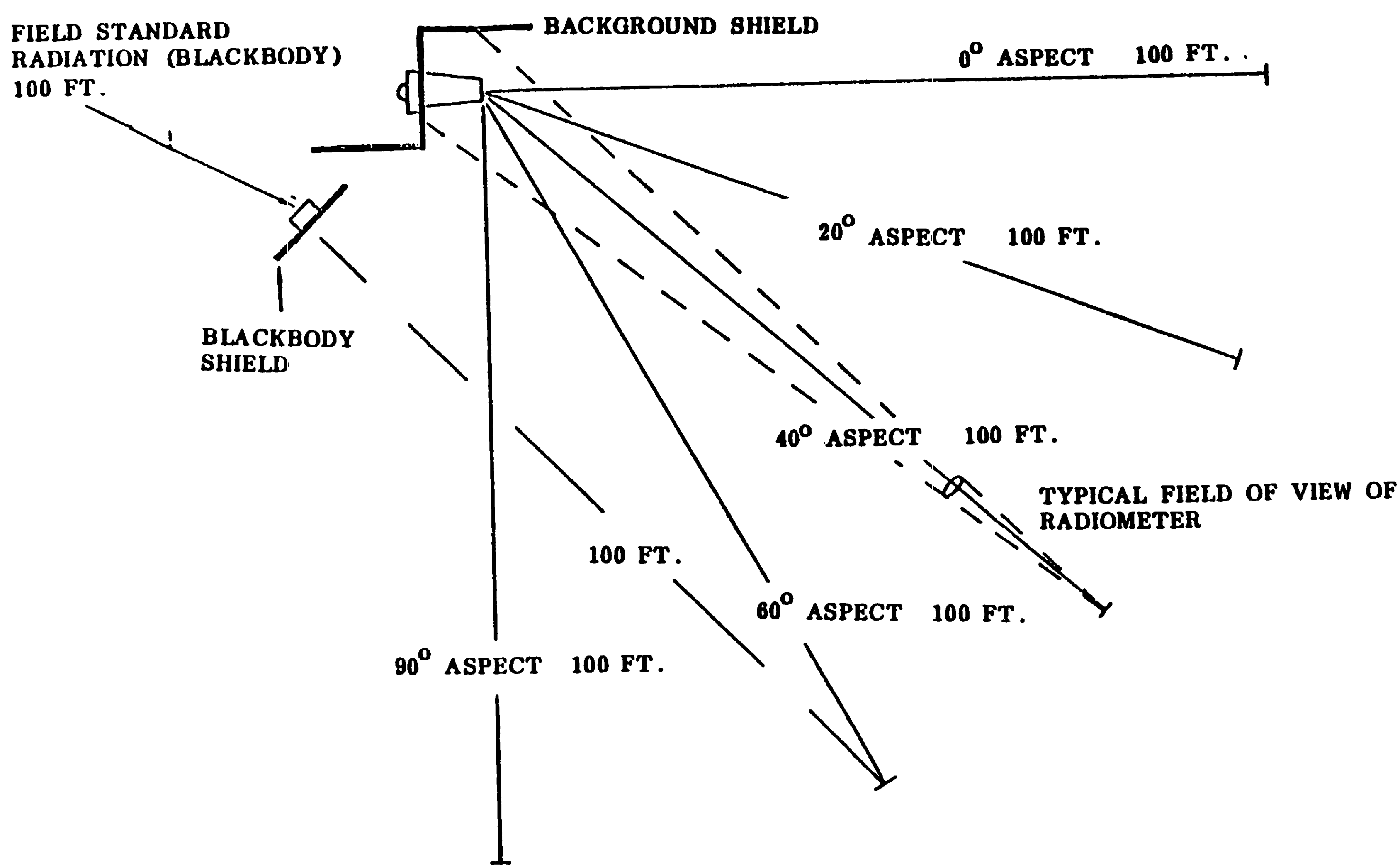


FIGURE 5-5. Turbofan engine IR signature measurement layout.

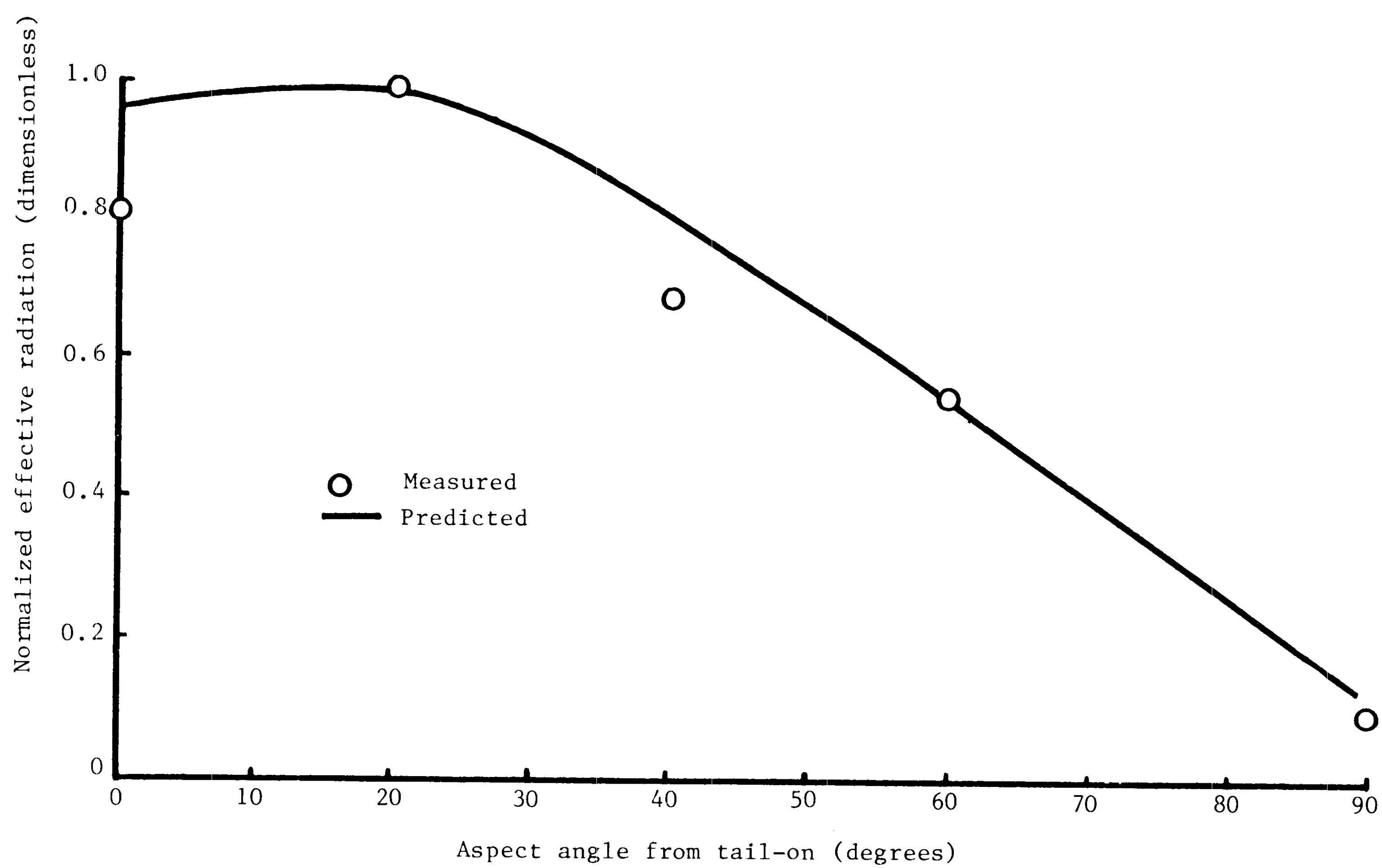


FIGURE 5-6. Measured and predicted IR signature comparison-separated flow engine.

5.3.6.3 Spectrometers. Spectrometers are used for evaluation of the spectral distribution of radiation from the target. These spectrometers are generally used at the same ranges and aspect angles from the engine as the radiometers. Typical field of view response sensitivity contours for a spectrometer are shown in figure 5-7 for optics used at a 1,000- and 500-foot range, respectively. The sensitivities and those of the radiometers are determined by laboratory calibrations prior to the engine measurements. The spectrometer response to incident attenuated radiation is checked periodically during the test by sighting the spectrometer at a source of measured temperature and known area and emissivity and range. This response is noted at wavelengths where no atmospheric attenuation is present and used to adjust the spectrometers pretest determined spectral sensitivity such as shown in figure 5-8 to give the response over the wavelengths to which the spectrometer optics and IR detector respond.

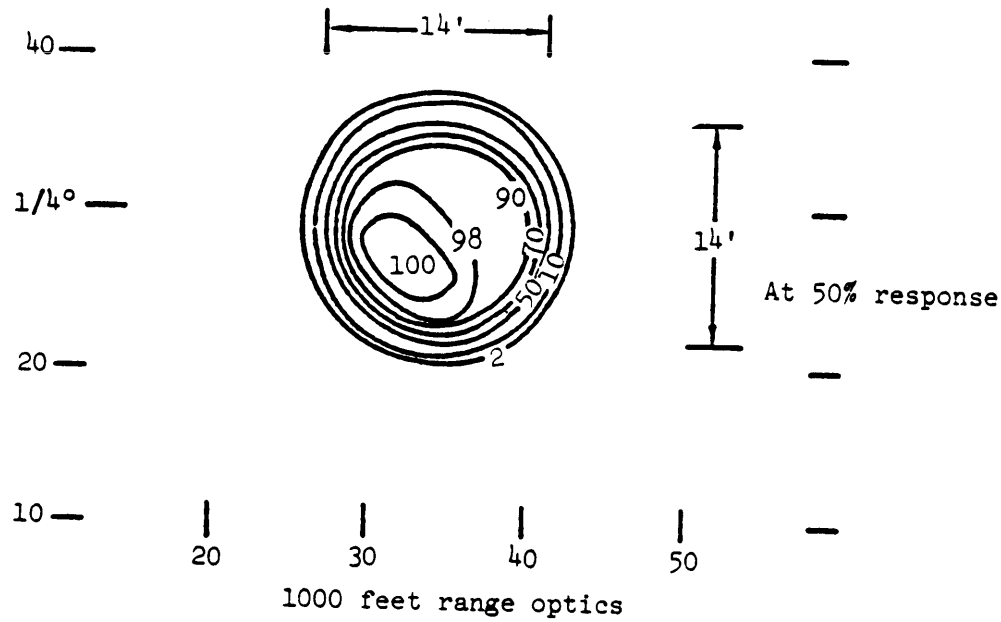
5.3.7 Control/suppression techniques and practices. In order to reduce the vulnerability of aircraft to IR seeking missiles, the aircraft designer uses IR control and suppression techniques. These techniques of control and suppression are referred to as passive techniques in that they reduce the level either over a given viewing zone or over all viewing zones.

5.3.7.1 Engine tailpipe and nozzle cooling. Control of the aircraft IR signatures is generally thought of in terms of reducing the angular extent of the spatial zones, say from ±90 degree to tail-on to ±20 degree to tail-on. This then forces the attacking aircraft (if we are considering air-launched missiles) to come in closer to tail-on to the target aircraft. This signature shaping can be accomplished by utilizing a technique such as engine tailpipe and nozzle cooling (reference 42) which leaves only the hot turbine and exhaust centerbody as major IR contributors.

5.3.7.2 Aircraft position. As will be explained further in the discussion on trade-offs for IR control and suppression, the narrower IR signature can be employed with fighter aircraft maneuvers to position the aircraft relative to the approaching missile so the radiation available to the missile is less than that needed to maintain guidance for a lock-on condition.

5.3.7.3 Cooling air. Engine hot parts emissions can be reduced by further cooling of the engine exhaust system hot components with cooler ambient air or, in the case of turbofan engines, with bypass air. Engine exhaust system components that may be cooled are the exhaust frame centerbody, flameholders, tailpipe, and nozzle walls. Cooling air may be pumped by external blowers or ejectors in the case of turboshaft engines or, for turbofan engines, from the fan flow. The cooling air is generally applied to the surface through cooling slots which combine impingement and convective cooling.

5.3.7.4 Blade shielding. For components such as turbine blades, which remain hot, cooled shields which block the view of the blades to an observer external to the exhaust system are used. Another method of shielding the blades from view is to incorporate a turn in the exhaust duct.



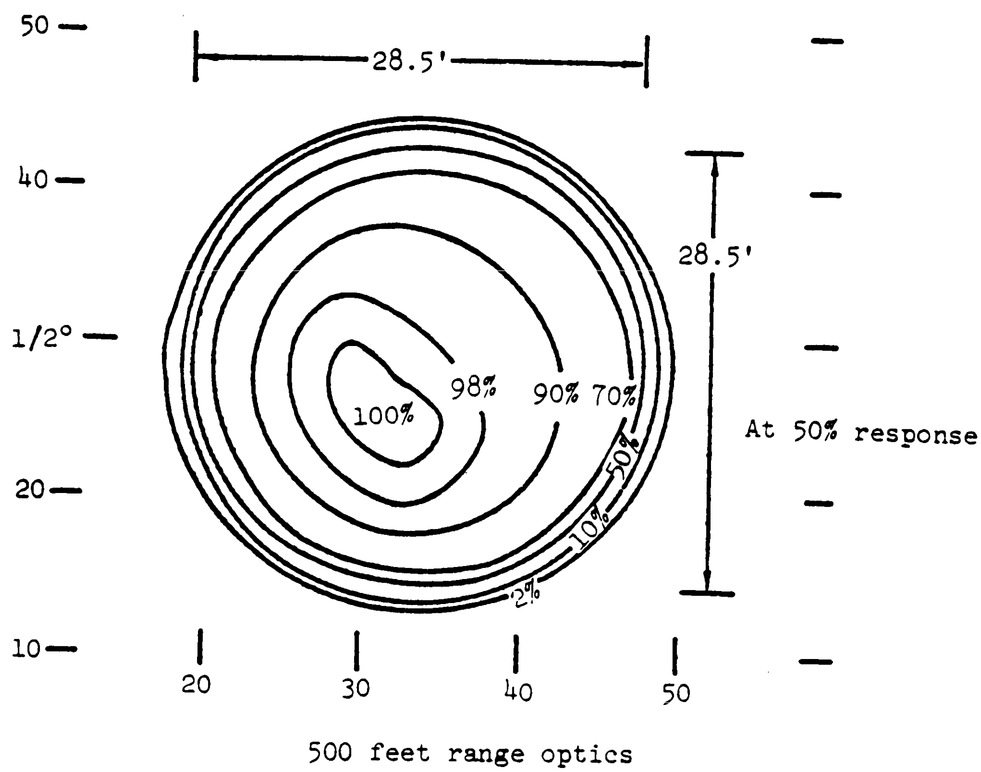


FIGURE 5-7. Spectrometer field-of-view response sensitivity plot in minutes of arc in azimuth or elevation.

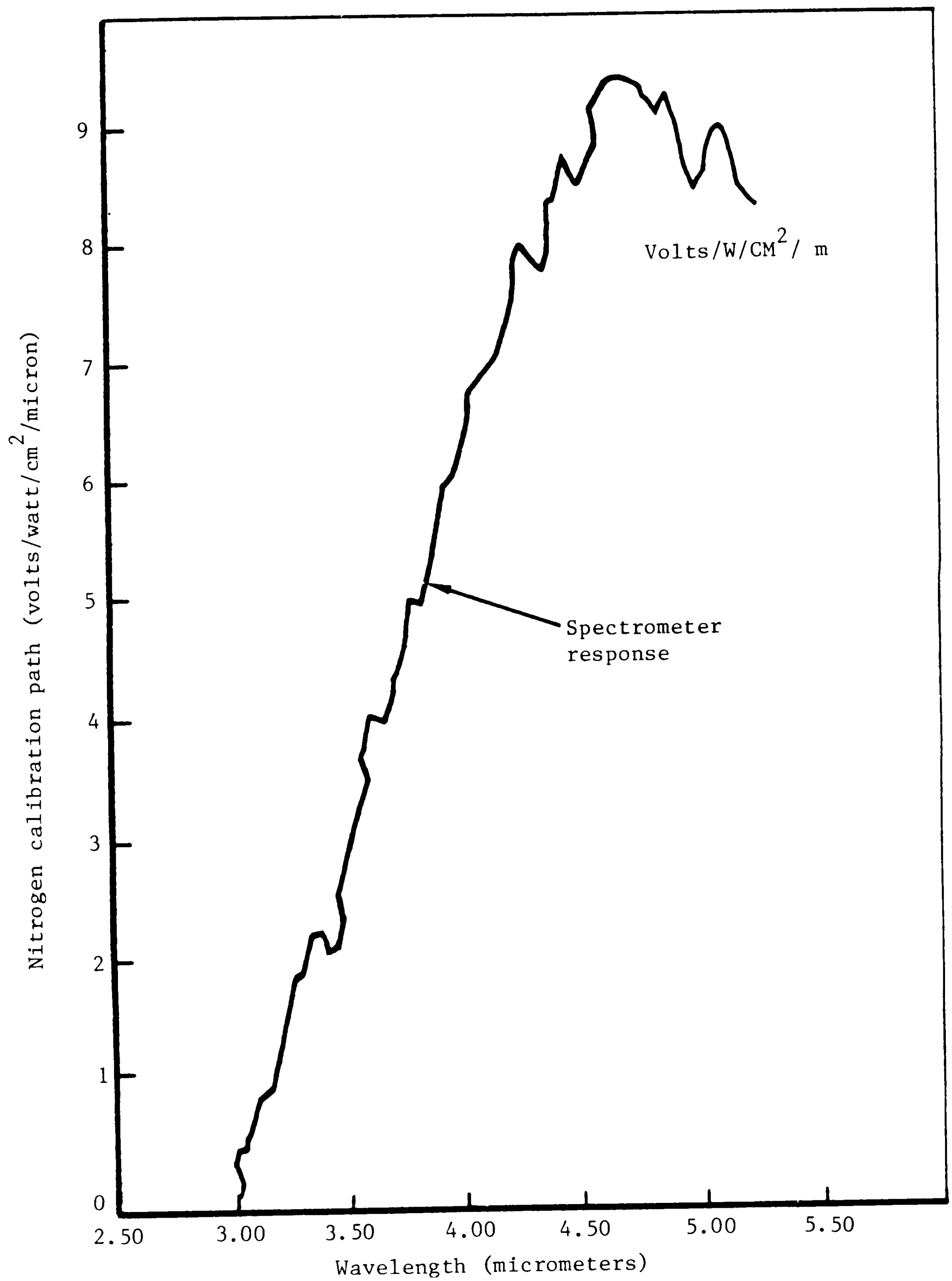


FIGURE 5-8. Laboratory-determined spectrometer response.

5.3.7.5 Absorbent materials. Further IR radiation reduction may then be accomplished by coating the cooled surfaces with IR radiation absorbent materials. These materials ideally should be diffuse reflectors which return half of the radiation toward the turbine, and reflect little of the remaining portion in the direction of the exhaust exit plane. In this way, the radiation is forced to have a larger number of reflections from the absorbing materials and thus a higher probability of absorption before leaving the exhaust duct.

5.3.7.6 Engine exhaust plume reduction. Suppression of engine exhaust plume IR radiation levels is most efficiently performed by reducing the gas temperature (reference 40) either before it leaves the exhaust system or as soon thereafter as possible. One technique used on turbofan engines which have a hot gas generator or core stream and a much cooler bypass or fan airstream is to employ a mixer to bring the hot and cool streams into contact just downstream of the turbine discharge plane and force these gases to mix in a constant or decreasing cross-sectional area duct prior to exit from the nozzle.

5.3.7.6.1 Ejectors. Another technique used to reduce the exhaust gas temperature by dilution with cooler air is to use ejectors which pump either engine bay compartment cooling air or ambient air into a coannular stream surrounding the hot core gas stream. This technique usually does not achieve as complete a mixing as is accomplished with the mixer in the turbofan engine, but still results in a considerable reduction in the exhaust gas temperature along the outer walls of the exhaust duct. The exhaust gas temperature in the case of the ejectors, however, increases from a low level near the walls to a maximum in the center of the exhaust gas stream.

5.3.7.6.2 Mixing of surface cooling flows. Further cooling of the turbine discharge gases occurs due to mixing of surface cooling flows with the hot gases, and this can result in some additional cooling of the gases near the walls.

5.3.7.6.3 Turning the exhaust gas (cross-flow). Still further plume radiation reduction can be obtained under flight conditions by turning the exhaust gas at an angle to the flight direction which effectively puts the plume in a cross flow. This cross flow, depending on the momentum of the ambient air cross flow relative to that of the plume, will cause rapid mixing of the ambient air with the plume and turning of the exhaust gas stream into the direction of the cross flow. In testing which has been conducted for helicopters, such a rapid decay of the exhaust temperature occurs that the exhaust gas core disappears within several diameters downstream of the exit plane and, in this case, little radiation is contributed by the exhaust gas external to the exhaust duct. The major contributor to gaseous radiation is the hotter unmixed gases inside the exhaust duct. Radiation from these gases is normally absorbed by the cooler exhaust gas products downstream of the exhaust plane. However, the cross flow bends the path of the plume such that the little optical depth of the cooler exhaust gases is available to absorb the radiation from inside the exhaust duct. This technique can only be used with a turboshaft engine where the energy in the exhaust jet is low.

5.3.7.6.4 Changing exit shapes. Another technique for reducing exhaust gas radiation is to make the exhaust duct transition from a round cross-sectional shape near the turbine discharge plane to an elliptical or rectangular shape at the exhaust exit plane. These exit shapes give more perimeter for the engine exhaust flow to mix with the surrounding ambient air. This exit shape also reduces the optical depth of the plume across the narrow dimension thus reducing radiation in this direction and reducing the presented area normal to the narrow dimension which also reduces the available plume radiation.

5.3.8 Trade-off factors. Trade-off of aircraft passive IR countermeasures such as for engine hot parts and plume IR reductions may be made against requirements for active countermeasures such as flares and IR jammers. The required weight and/or aircraft fuel reserves necessitated by control of the aircraft IR signature can be traded off against the reduction in weight or power associated with the active countermeasures carried by the aircraft.

5.3.8.1 Flares. Flares, as utilized for missile decoys, generally have a spectral integrated radiant intensity (J) ratio to target aircraft intensity (S) of three or more to be effective in decoying the missile away from the aircraft IR sources. For a typical mission and given aircraft engine radiation level, space and weight have to be allotted to carry the apparatus necessary to detect threat missile firings and to store and launch multiple flares. If the target aircraft radiant intensity, S, is reduced by a factor of 2 or 3, only one decoy flare is required rather than two or three previously needed. If this reduction is multiplied times the number of potential encounters (say 10) with threat missiles during the aircraft penetration of enemy territory, then a significant reduction in aircraft weight can be achieved, and the aircraft can still accomplish its intended mission and effectively decoy the enemy threat missiles. This flare weight reduction can be used to reduce the aircraft takeoff gross weight, or it can be traded for more fuel or traded against the increased weight or increased engine fuel usage due to incorporating passive IR reduction in the engine design. This trade is best made during the preliminary design of the aircraft when the aircraft budgeted weight for active countermeasures is still flexible.

5.3.8.2 Jammers. Control of the aircraft IR signature pattern such that the aircraft is only detectable by the threat missile over a small range of aspect angles near tail-on can result in a reduction of the need for all-aspect IR jammers. For instance, if four jammers with their associated weight and power requirements were required to provide active countermeasures against all-aspect missile attack, this requirement could be reduced to one jammer if the IR signature was controlled so that the threat missiles could only be fired at the aft hemisphere of the aircraft. Thus, a reduction in weight and power needed for this type of active countermeasure could be traded against the aircraft weight or increased fuel required to provide reduction of the IR signature.

5.3.9 Technology needs and voids. Aircraft technology needs and voids fall into several areas for IR emissions.

a. First, techniques need to be developed to quickly and cheaply predict the effects of engine design and IR signature control and reduction on the aircraft survivability to threat missiles for use in preliminary design studies. Available techniques are too time-consuming to set up and too costly to run in preliminary design studies where over several hundred different engine design iterations may be necessary. Efforts have been undertaken and some IR prediction methods for preliminary design usage are nearing completion. These techniques promise the ability to predict trends in the IR contributions due to the hot parts and plume and also to evaluate the IR effects of rudimentary methods of IR suppression such as engine component temperature reduction and nozzle shaping. More future work needs to be done to couple these IR prediction methods with engine cycle decks and determine if the methods are sensitive enough to aid in defining trends of IR radiation with variation in engine design parameters. Also, methods have to be developed concurrently to determine the effects of passive and active countermeasures on aircraft performance factors such as takeoff gross weight and life cycle costs. These determinate effects are needed to trade countermeasures versus aircraft takeoff gross weight and life cycle cost and an aircraft design chosen which can perform the intended mission with minimum probability of kill.

b. Another technology void is the absence of engine exhaust component designs which shield hot turbine blades from view using techniques such as cooled mixer shields. At present, effective shielding designs have not been included in engines employing mixers because the available designs have unacceptably high engine performance losses. However, analytical or experimental techniques are available which could be used to design the shielding-type mixers for considerably lower engine performance losses than achieved by past designs.

c. An additional technology void is the lack of predicting techniques to calculate the spatial distribution of exhaust gases for exhaust systems having an elliptical or rectangular exit cross-sectional shape. At present, prediction techniques are available for only axially symmetrical exhaust cross sections. However, with the apparent IR suppression advantages that the nonasymmetrical exhausts offer, the need is increasing for determining their overall attractiveness.

This page intentionally left blank

5.4 Visual Detection. Most airborne targets in Southeast Asia were detected visually. Optical devices were used to acquire and track targets and aim weapons. Engine contributors to visual detection include smoke, contrails, and at night, exhaust glow. During recent helicopter daylight pop-up experiments at ranges of 1,500 to 3,000 meters in which aural, dust cloud visual, and helicopter visual acquisition were compared, 83 percent of detections were through visual acquisition (reference 43). Engine exhaust smoke trails and contrails can be seen at distances where the aircraft itself is difficult to see. Night exhaust glow results from the incandescence of turbine hot parts which may be visible when sighting into the exhaust cavity. Table 5-I is a tabulation of hot parts glow with temperature (reference 44).

TABLE 5-I. Hot parts glow with temperature.

Tint	Temperature (°C)	Temperature (°F)
Lowest visible red	470	878
Dull red	600	1,112
Cherry red	700	1,292
Light red	860	1,562
Yellow	1,000	1,832
White	1,150	2,102

5.4.1 Countermeasures.

a. Design for flight at very low (nap of the earth) or very high altitudes.

b. Design engines which emit no visible smoke per current military specifications. Exhaust emissions are measured in accordance with SAE Aircraft Recommended Practice (ARP) 1179 and must not exceed a limit *set* to ensure no visible smoke when looking through the exhaust plume transversely. The limit is lower for large engines. Figure 5-9 illustrates typical test results for a current small turboshaft engine.

c. To prevent hot parts glow, hide or cool the hot parts. This can be done with an asymmetric or turned exhaust nozzle like that of the T58. Hot parts glow protection is an inherent fringe benefit of an IR suppressor.

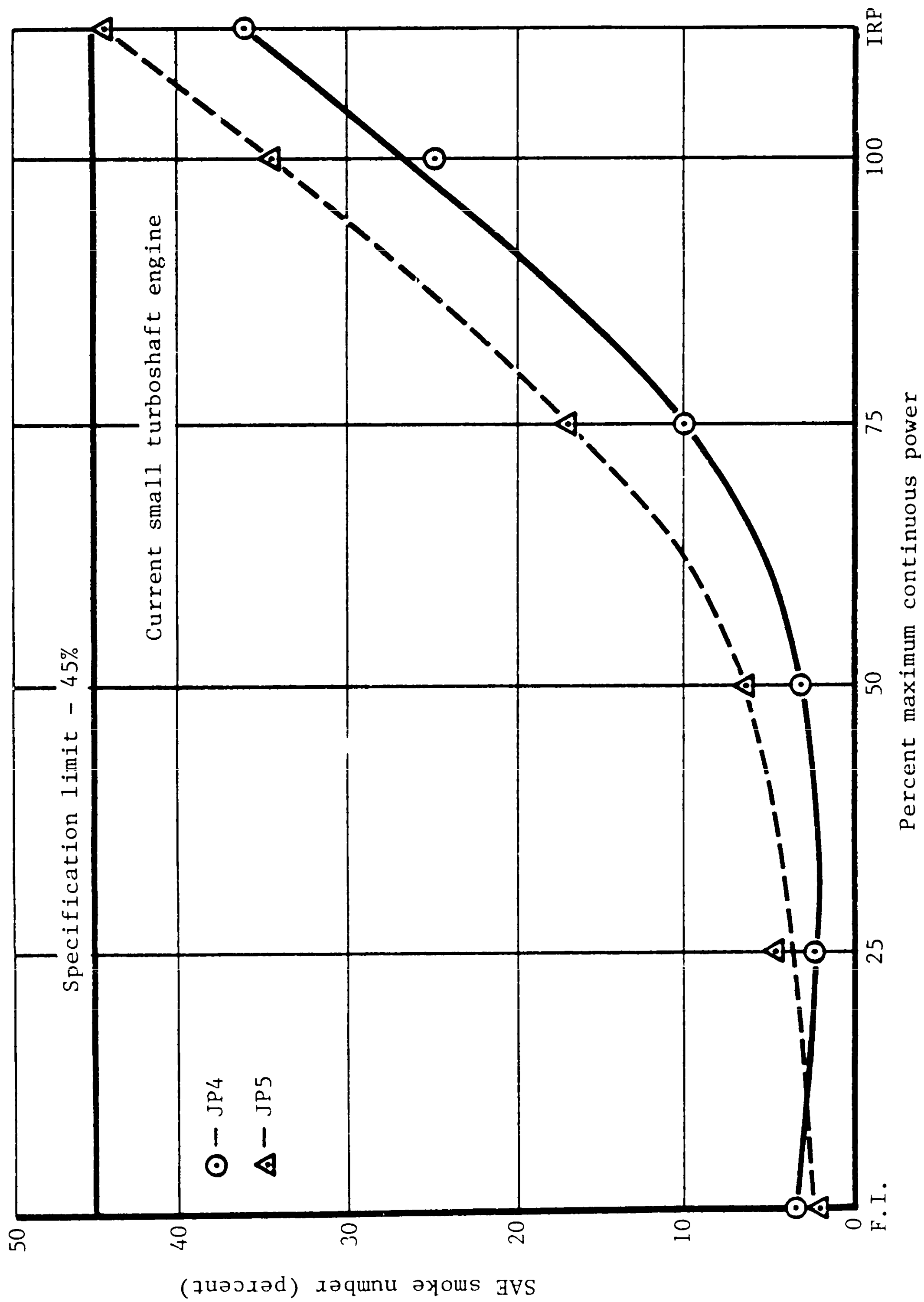


FIGURE 5-9. SAE smoke number versus engine speed.

5.5 Aural Detection. Aircraft are often heard before being seen by ground observers. Aural transmissions are not limited to line of sight. In general, engines contribute a large percentage of total aircraft noise. Low-flying helicopters can sometimes be heard as much as 30 seconds before they become visible; aircraft, several miles (reference 45). However, in daylight pop-up tests of four types of helicopters in which visual and aural acquisition were compared at ranges of 1,500 to 3,000 meters, initial detection occurred because of perceived noise in only 8 percent of the tests (reference 43). Moreover, under battlefield conditions, background noise from tanks, guns, and other aircraft and helicopters may prevent aural detection. See reference 110 for a more comprehensive discussion of this subject.

5.5.1 Noise levels. Piston engines and rotors are a major source of helicopter noise. For turbine power helicopters, rotors are the critical noise source (reference 46). Sound pressure level (SPL) is measured in decibels where:

$$db = 20 \log_{10} \left(\frac{P}{P_o}\right)$$

P is the measured pressure in dynes/cm^2 and P_o is a reference pressure level of 0.0002 dyne/cm^2 selected as being just audible in a pure tone at 1,000 cps. A "quiet" outdoor SPL would be 20 db. Doubling the SPL (sound power) increases noise levels 3 db. Twin-engine noise levels are 3 db greater than the noise level of a single engine alone. Sound levels decrease 6 db each time the distance from the source is doubled due to the expanding spherical wave front. This is in addition to atmospheric attenuation due to turbulence, absorption, etc. Vegetation attenuates sound. Additional factors to consider:

a. As regards helicopter noise levels, in low-altitude flybys at 200 feet range, helicopter SPL'S were measured at 80 to 100 db's. As regards fixed wing aircraft, boundary layer noise is substantial and may exceed, for example, propeller noise (reference 46).

b. The trend is toward specification of noise limits for turbine engines. For a small turboshaft engine at maximum power, a typical limit would be 92 db at a 200-foot radius.

c. High bypass fans have reduced noise levels (reference 47).

5.5.2 Noise reduction.

a. Fan inlet radiated noise may be reduced by:
   (1) Acoustically treating a conventional inlet.
   (2) Use of an accelerating inlet with a high subsonic threat math number with or without acoustic treatment.
   (3) Use of shielding by over-the-wing installation or other fuselage mounting arrangement (reference 47).

b. Exhaust noise can be reduced by using acoustic treatment panels. Panels in series have a greater combined effectiveness than the sum of the two separate effects. Series panels reduce noise substantially (reference 47).

c. Combustor and turbine noise reductions have been demonstrated by the use of acoustic treatment just downstream of the low pressure turbine (reference 47).

This page intentionally left blank

6. VULNERABILITY REDUCTION, SPECIFIC GUIDELINES

6.1 Description. This chapter presents information on problems and design techniques available to the engine designer to reduce military aircraft engine and propulsion system combat vulnerability to metal projectiles and high-energy lasers. The objective is to set forth possible design solutions to reduce the effects of engine projectile hits and laser exposure; i.e., possible burn-throughs, uncontained parts releases, uncontrollable fires, and complete power losses which, in turn, threaten the survivability of the aircraft and crew. The goal is to establish lightweight, low-cost, low-penalty alternatives to armor. Vulnerability is measured in vulnerable area units and is quoted for a specific viewing angle of the target relative to the threat path. Threat refers to the terminal characteristics of the attacking weapon. For projectiles, the terms are size, orientation, speed relative to the target, and explosive or incendiary characteristics. For high-energy lasers, the parameters are energy delivered, spot size, and dwell time. Knowing the threat, target size, and effects of a hit or exposure on any part of the target, the probability of disabling the target for a given hit or exposure can be assigned. The kill probability given a hit, $P_{K/H}$, times the presented area (Ap) is computed for each element. The products are incremental vulnerable areas (A_v), which are summed to provide total vulnerable area (A_v) for each view. In general, vulnerability can be reduced by the following:

a. Reducing target size and sensitivity

b. Providing a redundant element so that a failure of one element will not disable the system; for example, twin-engined aircraft

c. Stacking vulnerable targets one behind the other so that target area is reduced; for example, running fuel transfer lines through fuel tanks or putting oil pumps inside oil tanks

d. Shielding vulnerable targets behind less vulnerable targets; for example, locating the fuel control behind the starter

e. Armor

This page intentionally left blank

6.2 Inlets, compressors, and ingestion. Foreign object damage (FOD) and fuel ingestion are important to any discussion of engine combat vulnerability and so intimately involve the inlet, fan, and compressor sections of the engine as to require a discussion of these engine sections in one section. Hits on aircraft fuel tank walls common to engine inlet ducts release fuel into inlets for ingestion. Span from hits and particles from proximity-fused high-energy fragmenting shells are frequently ingested. All contribute to the combat FOD problem and point up the importance of the test results and design solutions discussed in the following paragraphs.

6.2.1 Fuel ingestion.

6.2.1.1 Fuel ingestion testing. Fuel ingestion tests have produced startling results and focused substantial interest on this combat hazard. Reference 48 reports Army Ballistic Research Laboratories (BRL) testing in which a test-stand stand-mounted operating TF30-P-1 turbofan engine was subjected to gross "dumped" and steady-flow fuel ingestion. The dumped release simulated the initial spurt of fuel from a holed fuel tank and the steady flow, the follow-on leakage. Steady-flow rates up to 39 gallons per minute were tolerated for 5 minutes in dry (no afterburner) operation. Dumped fuel releases of up to 2.25 gallons into the inlet resulted in visible momentary ignition of ingestion fuel and recoverable stalls. Engine damage resulted in some tests. Figure 6-1 and 6-2 illustrate the test setup for steady flow and dumped fuel releases, respectively. Figure 6-3 illustrates the engine's response to ingestion of 3 gallons of dumped fuel. Tables 6-I and 6-II summarize the steady flow and dumped fuel ingestion results, respectively.

6.2.1.1.1 TF30 Engine Installed in an A-7. A test run was made at China Lake in which 0.1 gallon of JP4 was dumped into an operating TF30 engine installed in an A-7. The engine stalled and, following shutdown, damage at the fan duct casing split line bolted connections was noted. A peak overpressure of 55 psi was measured in the inlet duct.

6.2.1.1.1.1 Water dumping. During the Army BRL TF30 fuel ingestion testing program, one test was conducted in which one-half gallon of water, instead of fuel, was dumped into the inlet. This test was performed to determine whether burning of the fuel ingestant was a cause or effect of the stalls. Introduction of the water resulted in a hard engine stall similar to those associated with fuel ingestion. This indicates that the stall is independent of the flammability characteristics of the ingestant.

6.2.1.1.2 TF41 engine testing. TF41 engine testing was similarly conducted with the following results. Reference 49 reports that under steady-state fuel ingestion conditions, fuel accumulated in the aft fan duct and tailpipe regions and caused one or more explosions, the backpressures of which caused the engine to stall. Fuel ingestion at a flow rate of 14.1 gallons per minute was survived for 5 minutes with a single explosion and moderate stall from which the engine quickly recovered with no apparent damage. Higher flow rates caused more frequent explosions and stalls. Dumped fuel releases of one pint of JP4 fuel

FIGURE 6-1. Engine operating in steady-flow test.

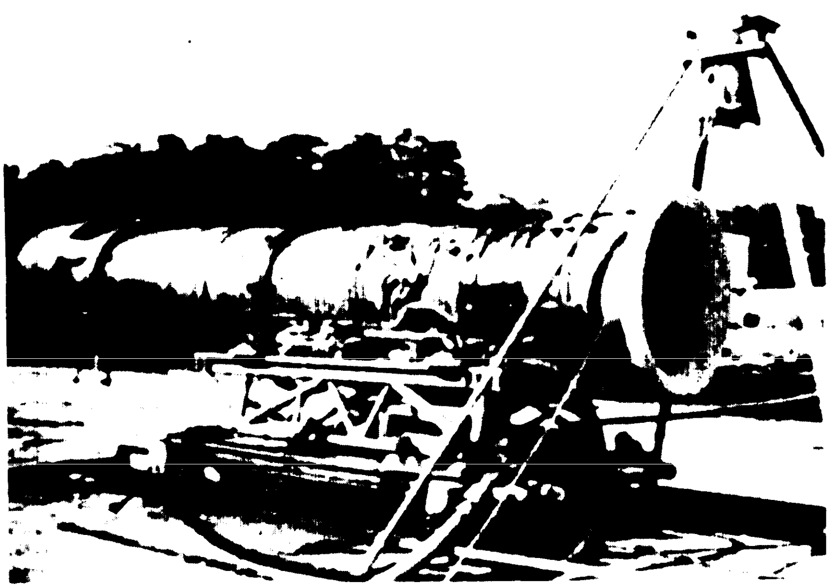
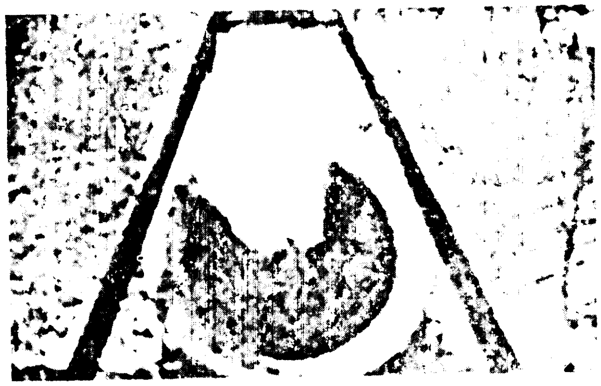
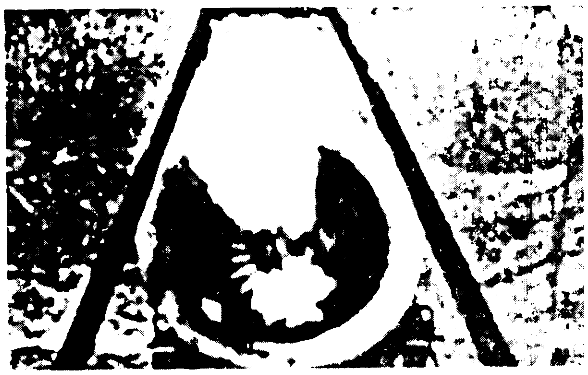


FIGURE 6-2. Dumped ingestion test setup.

a. Initial ingestant flow.

b. Fire observed in exhaust (t= 85 ms after ignition).



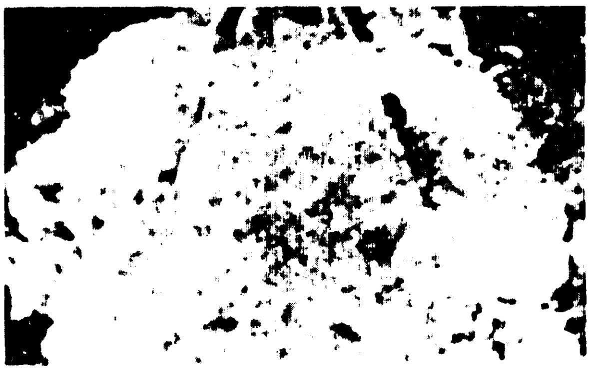


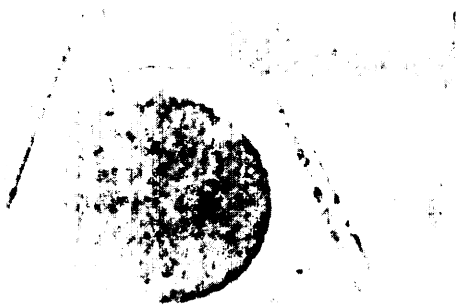
c. Fire at engine face from behind inlet guide vanes (t = 90 ins).

FIGURE 6-3. Ingested fuel flow and ignition as observed in 3-gallon test dump.

d. Overpressure wave emerged from the bellmouth (t = 95 ins).

e. Engine obscured by the ingestant fireball (t = 125 ins).





f. Fireball consumed by the engine; burning fuel sucked up from the ground (t = 1.2 seconds).

FIGURE 6-3. Ingested fuel flow and ignition as observed in 3-gallon test dump(continued).

TABLE 6-I. Summary, steady-flow fuel ingestion tests.

Run	Engine	Fuel ingestion			Engine conditions at start of ingestion						Throttle activity	Fuel leakage from engine	Effect on engine
		Rate (gal/min)	Duration (min/sec)	Quantity (gal)	F(lb)	T_5(°C)	N_1(%)	N_2(%)	P_{S4} (psig)	EPR			
1	647358	2	1/0	2	8.900	882	90	89.0	185	1.85	NRP steady	None observed.	No significant effect.
2	647358	6.7	5/40	37.9	9,000	937	91	90.5	185	1.87	NRP, A/B return to NRP	Mist from guide/ breather vents	NRP performance okay; torching; unstable N_1 and T_5 in A/B; delayed A/B cutoff. Engine survived.
3	647358	8.6	0/34	4.9	9,000	935	91	90	187	1.86	NRP steady	Heavy fog from guide/ breather vents.	Slightly unsteady performance in NRP; possible torching. Engine survived.
4	647358	18.7	5/0	93.5	9,000	938	91	90	185	1.87	NRP steady	Heavy fog from guide/ breather vents; moderate pumping through fan case seams.	Intermittent slight surges; gradually increasing T_5. Engine survived.
5	647358	24.3	0/35	14.2	9,000	962	91	90	184	1.85	NRP, A/B sub-NRP	Heavy fog from vents; heavy flow through fan case seams.	Moderately unsteady performance of NRP; some torching in A/B; normal response to A/B cutoff. Engine survived.
6	647358	25	6/30	162.7	9,100	932	91	90	186	1.86	NRP, A/B sub-NRP	Heavy fog from vents; extremely heavy flow in spurts through fan case seams.	Intermittent minor fluctuations; no torching at NRP; bright orange glow in exhaust in A/B, with high P_{S4} and N_1 and slightly unsteady performance; delayed A/B cutoff. Engine survived.

EPR = engine pressure ratio.
NRP = normal rated power.
A/B = afterburner.
N = rotor numbers.

TABLE 6-I. Summary steady-flow fuel ingestion tests (continued)

Run	Engine	Fuel ingestion			Engine conditions at start of ingestion						Throttle activity	Fuel leakage from engine	Effect on engine
		Rate (gal/min)	Duration (min/sec)	Quantity (gal)	F(lb)	T_5(°C)	N_1(%)	N_2(%)	P_{S4} (psig)	EPR			
7	647358	38	5/9	195.7	8,950	936	91.5	90.5	188	1.87	NRP, A/B	Heavy fog from vents; extremely heavy flow in spurts through fan case seams.	T_5 increased 50°C; F increased 200 pounds; noise level increased; possible torching with performance fluctuating while in NRP. Ingestion discontinued after 5 minutes, then restarted while A/B was selected. Light-off caused immediate severe stall, engine failure, blown duct seal, and pad fire. Engine was restarted and run successfully.
8	647358	36.8	3/20	122.6	8,600	975	90	90.5	170	1.84	Sub-NRP steady	Same as preceding.	Periods of fluctuating performance, followed by severe stall, blown duct seal, and pad fire after 3 minutes and 20 seconds. Engine stall caused internal blade damage. Pad fire caused further engine damage. Fan blade tips seized in delaminated case liner material.
9	647318	30	3/49	116	9,800	960	97	91	187	1.97	Military power, deceleration	Same as preceding.	Performance smooth at military power and through transition to below flight idle power. Engine survived.
10	647318	35.8	3/0	107.5	9,600	956	96	90.5	182	1.95	Military power steady	Same as preceding.	Performance smooth at first, then gradually developed serious instability. Engine was shut down to prevent failure.

EPR = engine pressure ratio.
NRP = normal rated power.
A/B = afterburner.
N = rotor numbers.

TABLE 6-II. Summary, dump fuel ingestion tests.

Run	Engine	Dumped quantity (gal)	Engine condition at start of ingestion						Throttle activity	Figure	Effect on engine
			F(lb)	T_5(°C)	N_1(%)	N_2(%)	P_{S4} (psig)	EPR			
1	674318	0.5	9,500	865	91	88.5	175	1.82	Not moved	...	Hard stall, followed by rapid recovery. Ingestant consumed by engine.
1A	647223	0.5	9,260	890	88.5	88	152	1.8	Not moved	23	Hard stall, followed by rapid recovery. F dropped to 2,000 pounds, remaining below critical thrust level for 0.45 second. Ingestant consumed by engine.
2	647318	1	9,500	887	90.5	88.5	170	1.82	Decreased slightly	24	Two severe stalls occurred within 15 seconds (N_1 dropped to 42% and 44%, respectively). Throttle was retarded slightly, and engine fully recovered. F fell below critical level for 7 seconds, returned for 4.5 seconds, fell below critical again for 3.6 seconds, then recovered.
3	647318	1.25	9,510	892	90.5	88.5	168	1.82	Decreased to idle	25	Initial severe stall (N_1 dropped to 60%) with F below critical for 2.6 seconds. About 1 pint of burning ingestant expelled from bellmouth and was not consumed. Subsequent performance with no throttle change was sluggish, with two minor and two major stalls. Recovery obtained after reducing throttle to near idle at t = 30 seconds.
4	647318	1.5	9,510	892	90.5	88.5	169	1.82	Decreased to idle	26	Entered sustained, severe stall (N_1 dropped to 40%), with F remaining below critical through t = 15 seconds. About 1 pint of burning ingestant was expelled from bellmouth. Performance remained poor, and a second stall occurred at t = 15.5 seconds. At t = 19 seconds, throttle was retarded to near idle, and recovery was quickly obtained.
5	647318	1.75	9,500	976	90.5	89.5	168	1.83	Not moved	27	Entered severe stall (N_1 dropped to 41%), with F below critical for 7 seconds. At least 1 quart of burning ingestant was expelled from bellmouth. Stabilized at low power (5,800 pounds F) after 11 seconds without throttle change; recovery to 9,000 pounds F began at t = 27 seconds and ended at t = 49 seconds.

EPR = engine pressure ratio.

N = rotor numbers

TABLE 6-II. Summary, dump fuel ingestion tests (continued).

Run	Engine	Dumped quantity (gal)	Engine condition at start of ingestion						Throttle activity	Figure	Effect on engine
			F(lb)	T_5(°C)	N_1(%)	N_2(%)	P_{S4} (psig)	EPR			
6	647318	2	9,510	985	90.5	89.5	156	1.84	Not moved		Initial severe stall in which N_1 dropped to 56%, with F below critical for 3 seconds. About 2 to 3 quarts of burning ingestant was expelled from bellmouth. Recovery complete in less than 12 seconds, but thrust was erratic during recovery.
7	647318	2.25	9,010	960	89	89	152	1.81	Not moved until shutdown	29	Initial severe stall in which N_1 dropped to 52%, with F below critical for 6.2 seconds, followed by second stall in which N_1 dropped to 41%, with F below critical for 6.6 seconds. About 3 to 4 quarts of burning ingestant was expelled from bellmouth. Resulting pad fire threatened engine fuel delivery line, and shutdown was accomplished at t = 17 seconds, while engine was beginning recovery. Recovery considered probable within 30 seconds after dump.
8	647318	3	9,150	981	90	89.5	158	1.81	Refer to effects	30	Initial severe stall in which N_1 dropped to 58%, with F below critical for 3 seconds. Sluggish recovery punctuated by repeated stalls over 7 seconds. About 1 to 1-1/2 gallons of burning ingestant was expelled from bellmouth. Performance leveled at 8,500 pounds F, with no throttle changes, when another stall occurred at t = 37 seconds. At t = 47 seconds, engine malfunctioned; maximum F dry was 6,800 pounds. Further advance of throttle caused A/B to operate. Engine blade damaged.
9	647223	3	10,000	800	87.5	85.5	185	...	Refer to effects	31	Entered sustained, severe stall (N_1 dropped to 34%). Engine dropped to subidle speeds and continued to "run" at this level for over 1 minute, despite throttle change to idle at t = 30 seconds. About 1 gallon of burning ingestant was expelled from bellmouth. With throttle still at idle, a sluggish recovery started at t = 82 seconds and was completed at t = 120 seconds with throttle advanced.
10	647223	0.25	10,000	887	90	88	166	1.86	-	32	One severe stall (N_1 dropped to 44%). F dropped to 2,000 pounds. Engine recovered in 11 seconds. Ingestant consumed by engine.

EPR = engine pressure ratio.

N = rotor numbers.

did not affect the engine. Release of 1 quart or more of fuel typically resulted in fuel slamming into the fan blades, splashing over the nose fairing, and apparently entering the high-pressure compressor. Stalls and overtemperatures resulted with fireballs out the inlet. The engine typically recovered with locked throttle and, in the process, the burning fuel was reingested. Ingestion of 1 quart of fuel was survived with a momentary stall, some damage, and thrust degradation. Ingestion of 1 gallon of fuel was survived with a momentary stall and 18 percent thrust loss. During testing, the stalls resulted in shock fronts out the 6-foot inlet duct and overpressures which were measured at various distances from the engine face. Overpressures as high as 73 psi were measured near the inlet duct bellmouth station, 61 inches upstream from the engine face. Peak pressures at the bellmouth throat tended to be slightly higher than those at the engine face, indicating some growth in intensity as the shock wave progressed, possibly due to ingestant combustion.

6.2.1.1.2.1 Testing in damaged A-7 fuelage. Testing involving a TF41 engine installed in a damaged A-7 fuelage was conducted at the Naval Weapons Test Center, China Lake, California. In this test, ingestion of one-half gallon of dumped fuel into the inlet of the operating engine resulted in a severe stall and measured 55 psi overpressures, which ruptured the inlet duct under the cockpit floor and released the ejection seat in the unoccupied cockpit.

6.2.1.2 Fuel ingestion analysis. As one possible explanation of the aforementioned test results, it is postulated that during the steady ingestion flow, the TF30 and TF41 fans centrifuged the ingestant out so that it was discharged down the fan duct and did not enter the core compressor. This reasoning is substantiated by the data presented in 4.1.3. In contrast, it is estimated that, in the dump tests, substantial fuel entered the core compressor and was ignited. For both the TF30 and TF41 engines, core compressor gas temperatures are sufficiently high to vaporize the ingested liquid fuel and form a substantial parcel of gas in the compressor with thermodynamic properties distinctly different from air. It is estimated that the effects on the compressor would be similar to severe inlet distortion. Under these conditions, a stall is to be expected. Reference 50 provides insight into this phenomenon with an analysis of these effects on compressor performance of ingesting other than the design working fluid. It is estimated that the stall results in a momentary gas flow reversal of direction and trespass of very hot combustor gases into the compressor. The flow breakdown also causes the ingestant residence time in the hot environment to be increased. This combination results in ignition of the ingestant. Stalls and ignition of the ingestant are forecast as a standard response mode when substantial fuel quantities are ingested by turbine engine compressors developing high-pressure ratios.

6.2.2 Fan centrifuging. When heavier-than-air foreign objects enter a high-speed rotating compressor flow path, they tend to be centrifuged radially outward and ride aft along the outing casing inner call. Typically, compressor sand ingestion damage is inflicted on the stage 1 rotor leading edges and then, in subsequent stages, concentrated on compressor blade tips and vane roots; i.e., surfaces adjacent to the casing. Turbofan engines tend to centrifuge foreign particles out into the fan discharge stream and minimize the risk of entry into the compressor flow path. Figure 6-4 illustrates this. Table 6-III presents test results for separation tests of this configuration which demonstrated separation efficiencies exceeding 95 percent; i.e., less than one in 20 of the particles released into the fan entered the compressor.

6.2.2.1 Percentage of airflow weight. Reference 26 requires that development engines demonstrate capability to function satisfactorily with up to 5 percent of their total airflow weight in the form of water as part of their qualification testing. This requirement is typical of that met by existing in-service contemporary engines.

6.2.2.2 Effects on compressor casing. One effect of ingesting liquids into compressors on turboshaft or turbojet engines or into core high-pressure compressors on turbofan engines is to tend to momentarily chill and shrink the compressor casing relative to the rotor. The ingestant is centrifuged out and rides aft along the casing inner wall. As the ingestant is heated and evaporates, it chills and reduces casing temperatures substantially. The casing shrinks relative to the rotor, and tip rubs with intense local heating may result. These considerations influence materials selection, coatings, and tip clearances in design.

6.2.2.3 Rainingestion. The fan stages of turbofan engines centrifuge liquid ingestants. In rainingestion qualification testing of a TF34-2 engine, 95 percent of the ingested water was centrifuged out by the fan and passed out the fan discharge duct. Only 5 percent of the ingestant entered the core.

6.2.3 Turboshaft engine inlet protection. Severe turbine engine compressor erosion damage caused by ingestion of sand clouds generated by helicopter main rotor downwash in forward landing areas were an important consideration in mission availability of helicopters and resulted in requirements for effective engine inlet protection in future Army engines. Figure 6-5 illustrates the T700 turboshaft engine with an integral inlet particle separator. Figure 6-6 is a separator schematic. Particle-laden air entering the engine inlet is given rotational velocity about the engine's axis by swirl vanes. The heavy high-inertia foreign particles are moved and held outboard by the resultant centrifugal forces. They pass into a scroll duct and are discharged overboard. The light low-inertia clean air particles are turned back inboard by inlet pressure forces and enter the compressor. The scroll duct flow is aspirated by a mechanically driven scavenge blower. The T700 separator has demonstrated good efficiency in removing sand and other foreign objects, and promises to reduce the risk of combat FOD in future aircraft. Other inlet protection devices such as barrier filters, nonswirl inertial separators, and banks of small plastic inertia swirl tubes have also been proven effective. Inlet protection discharge ducts should be designed to pass foreign objects which can get through the upstream openings.

6.2.4 Inlet design, other. The following paragraphs consider inlet design solutions other than those previously discussed.

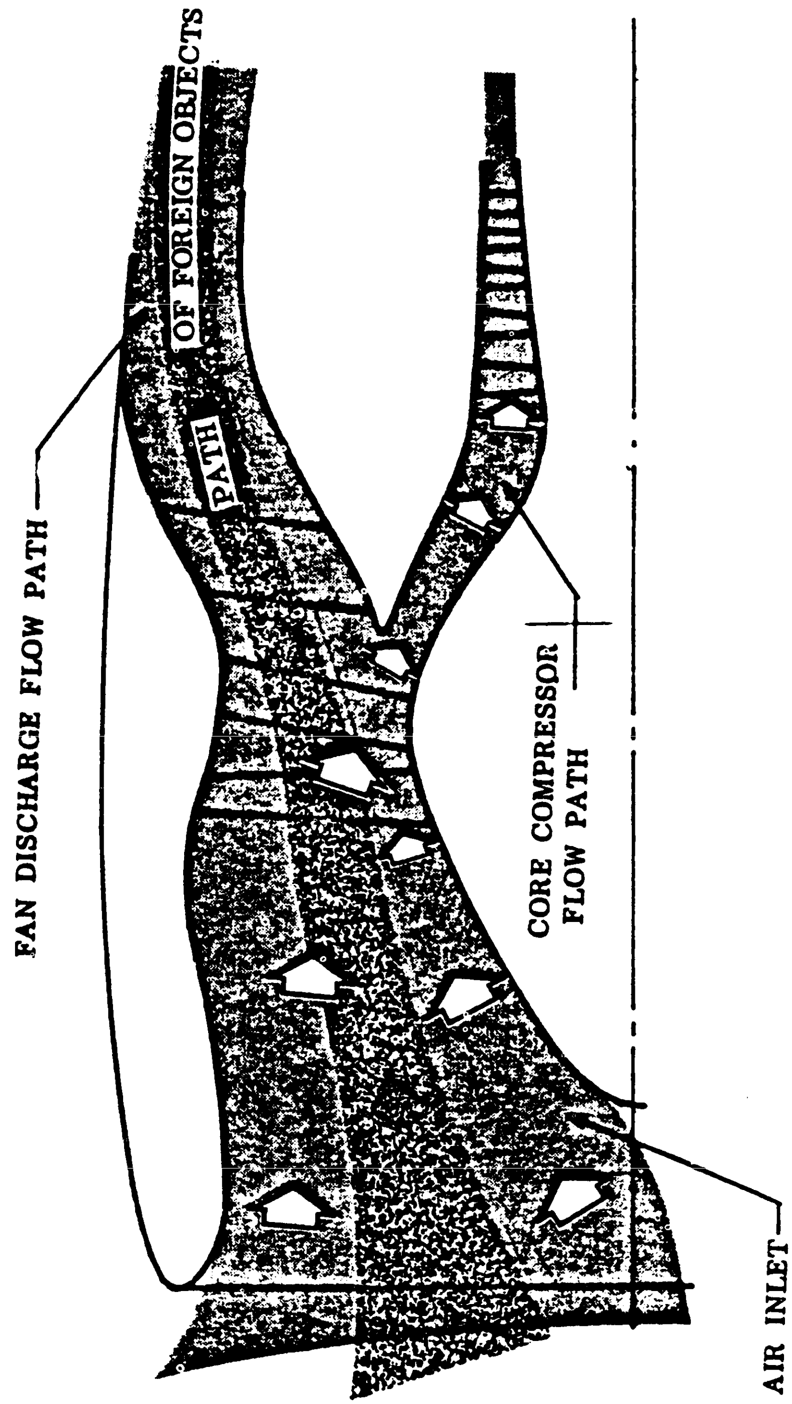


FIGURE 6-4. Turbofan centrifuging, foreign objects.

FIGURE 6-5. T700 turbofan engine with inlet particle separator.

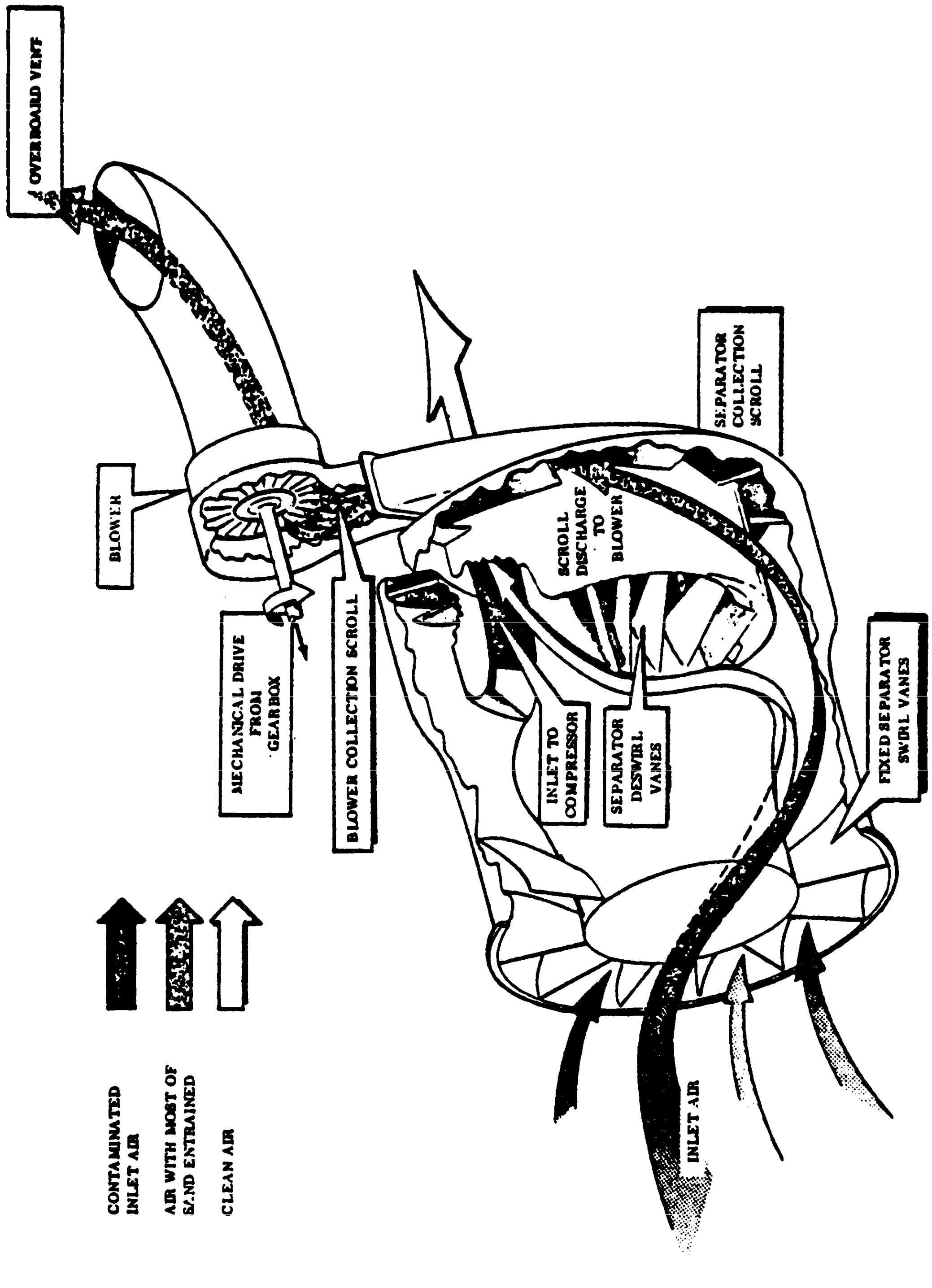


FIGURE 6-6. T700 type separator schematic.

TABLE 6-III. Turbofan centrifuging, foreign objects, test results.

Material	size (in.)	Fan speed (%)	Amount ingested (pieces)	Injection location measured radially outward from blade root	Separation efficiency (%)
Lead	0.174 dia.	42.5	5	0	Over 95
Aluminum	0.125 dia.	42.5	5	0	Over 95
Aluminum	0.125 dia.	65	110	0	Over 95
Lead	0.174 dia.	65	100	0	Over 95

6.2.4.1 Strength. The inlet frames and struts should be strong enough to take maximum expected foreign object impact and damage vibration loads without breakup or release of engine material into the flowpath. Bolted or riveted connections should be avoided. Cast or welded construction is preferred.

6.2.4.2 Inlet guide vanes. Inlet guide vanes tend to trap ingested foreign objects in the flowpath and prevent their expulsion out the inlet. Avoid the use of inlet guide vanes. If used, vanes should be securely supported at both ends and substantial axial spacing between the vane trailing edges and rotor blade leading edges provided to prevent contact under damage conditions.

6.2.4.3 Materials. The use of relatively soft materials such as aluminum or fiberglass instead of steel is encouraged. In the event of hit-induced material release, aluminum or fiberglass are more apt to provide released particles which the turbomachinery can tolerate without crippling damage.

6.2.5 Fan and compressor design. Fans and compressors provide relatively large target areas on the engine and are sensitive to hits. Holding the casing is possible with low-energy hits. Once inside, the engine performance and structural effects depend on stall margin, blade and vane size and hardness compared to the particle, and the structural soundness of the design.

6.2.5.1 Hit effects. Testing indicates that the most likely hit effects will be internal blade or vane damage. If the engine continues to run, heavy vibration is possible and it may result in secondary damage elsewhere; for example, a fuel line rupture or engine mount failure. For large projectiles impacting at high energy, massive structural damage resulting in complete thrust losses is a certainty. There is also a significant possibility of uncontained releases of high-energy parts. In two of four tests in which T58 engine compressors operating at top speed were hit with large projectiles fired at point blank range, all damage was contained In the other two, spool wheel segments were released; in one test, to land adjacent to the engine; in the other, some distance away. In these two tests, compressor flange bolts were broken and compressor casings expelled violently. (Reference 51). For small soft particles, damage may be insignificant. In 1957, an operating J73 accidently ingested two 210-grain (7,000 grains equal 1 pound) aluminum nose-pieces from 20 mm projectiles. Each carried an incendiary charge which burned in the engine. Yet, except for light compressor blade FOD, negligible damage resulted. (Reference 52) There are also numerous test results in which J57's and other engines have taken compressor hits and continued to function. Survivability of a compressor is measured by its ability to retain vanes under threat impact and to resist rotor blade damage caused by damaged vanes and foreign objects.

6.2.5.2 Design techniques. The following are fan and compressor design techniques to improve the combat survivability of aircraft:

a. Provide structural integrity in accordance with MIL-E-5007D or MIL-E-8593. Pertinent MIL-E-5007D requirements are outlined in table 4-I. Briefly stated, provisions include:
   Casing blade and pressure containment
   122% minimum burst speed
   Substantial design and fatigue life

b. Minimize target area by increasing stage loading and thus reducing the required number of stages.

c. Centrifugal compressors are preferred over axial compressors

d. Blades and vanes should be large and widely spaced.

e. Low aspect ratios (span/midchord ratio) are desirable

f. Rugged blade connections to disks or integral blade-disk (blisk) configuration should be specified

g. Integral multiple-vane segments are preferred over individual vanes

h. Hollow vanes are desirable

i. Variable-pitch stator vane stages should be minimized and, if necessary, actuated by mechanical links

j. All vanes should be shrouded

k. Tip-shrouded blades have increased tip footprint area for potential ease of containment, but at the penalty of higher blade kinetic energy at release. Unshrouded blades are preferred. Blade leading edges should be damage and erosion tolerant.

6.3 Combustors. Combustors are one of the major contributors to engine presented area. Modern engines are designed with through flow or reverse flow annular liners within which the fuel-air mixture burns. The liner is surrounded by compressor discharge air which flows into the combustion chamber through holes in the liner. The layer of compressor discharge air between the casing and liner is at slightly higher pressure than the combustor gases. Combustors are the hottest highest pressure location in the engines. Peak combustion gas temperatures exceed 3,000°F. Peak compressor discharge temperatures are typically in the 600° to 900°F range and are determined by inlet temperatures and compressor pressure ratio.

6.3.1 Types. Figure 6-7 is a Pratt and Whitney J60 cross section which illustrates its through flow can-annular combustor configuration and external fuel manifold location. Figure 6-8 is a GE T700 cross section and shows a through flow annular combustor configuration and external fuel manifold location. Figure 6-9 is a Lycoming AT170 cross section which illustrates a reverse flow combustor configuration and its fuel manifold location, Figure 6-10 is an exploded view of a T58 through flow annular combustor and illustrates its internal manifold.

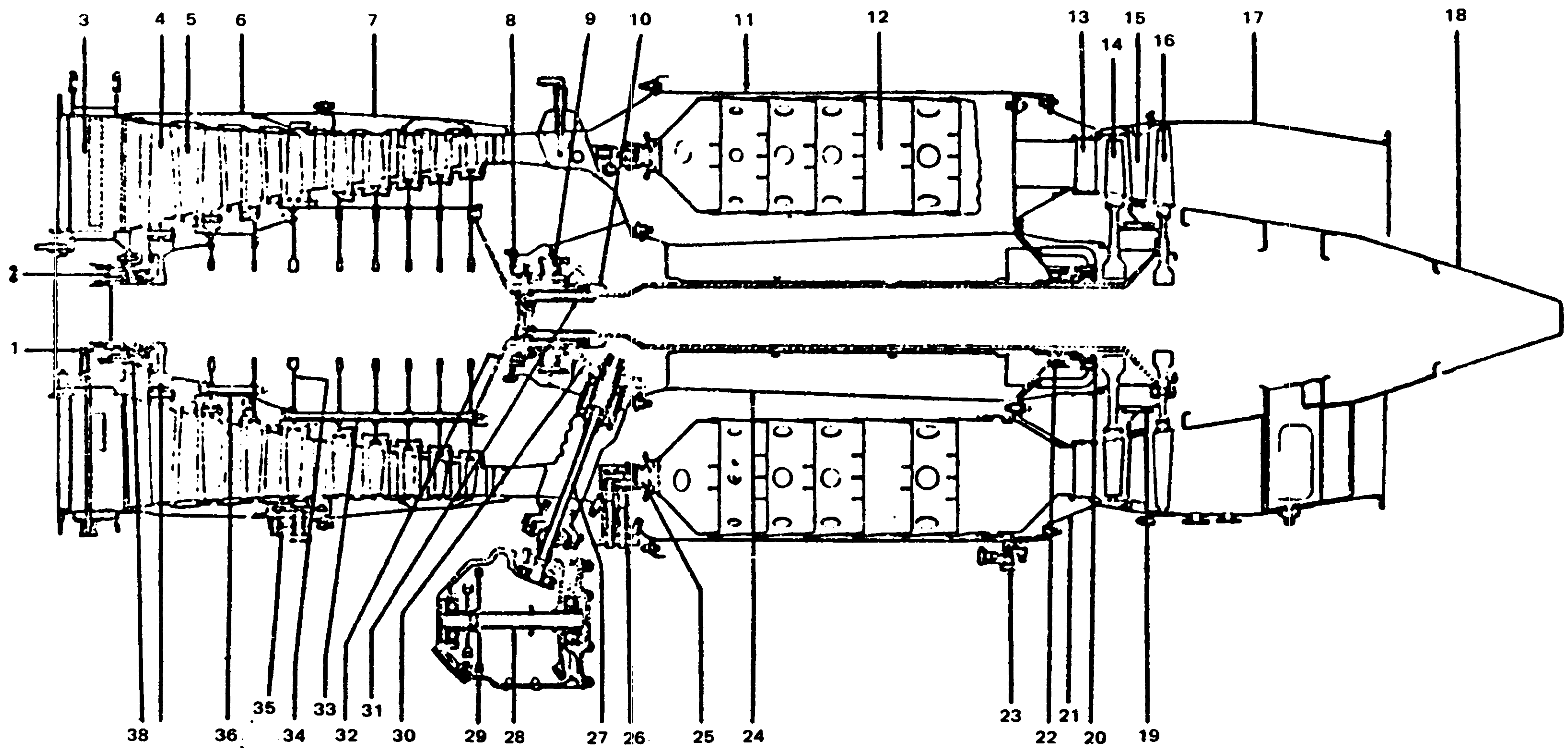
6.3.2 Low pattern factor. Combustors are carefully designed and developed to prevent hot spots. The objective is to minimize circumferential and radial gas temperature variations from the average; that is, achieve a low "pattern factor." A low pattern factor provides maximum performance and service life.

6.3.3 Nozzle replacement. Nozzle coking following shutdown and nozzle plugging from dirty fuel disrupt pattern factors and are potential concerns which make easy nozzle removal/replacement in the field attractive. To facilitate nozzle replacement, external fuel manifolds are often used rather than internal manifolds which reduce vulnerability.

6.3.4 Hit effects. Combustor casings are easily perforated, and high-obliquity hits often make large holes. Figure 6-11 is a photograph of a penetrator exit hole in a combustor casing from BRL vulnerability testing of an operating T64 engine. The high-obliquity entrance hole area was small; the exit hole was 8-in.^{2}. The engine rolled back immediately following the hit and was shut down. (Reference 52).

6.3.4.1 Hot plumes. J65 testing conducted at the Naval Air Propulsion Test Center, Trenton, N.J., demonstrated that holed combustors can emit hot plumes. Simulated hits on the J65 combustor, using a 4-inch hole (12.6 in.^{2} area) or a combination of 4- and 2-inch holes (15.7 in. 2 total area), resulted in flames emitted from the casing 3 to 10 feet in length, with temperatures reaching 1800°F at 6-inches from the perforations. The thrust loss from the initial normal ratio power setting was 15 percent. (Reference 54).

6.3.4.2 Compressed gas leakage. Perforated combustors leak compressed gas, and for large holes, excessive gas leakage occurs; energy to drive the turbines is reduced, and the engine rolls back and loses power. Using the relationship for choked flow through an orifice, the leakage flow for a given hole size can be determined.



1. No. 1 bearing oil nozzle
2. No. 1 bearing (roller)
3. Compressor inlet vane
4. Compressor rotor blade
5. Compressor stator-vane
6. Compressor inlet case
7. Diffuser case
8. No. 2 bearing seal
9. No. 2 bearing (ball)
10. No. 2 bearing oil scoop
11. Combustion chamber case
12. Combustion chamber
13. First stage turbine vane
14. First stage turbine
15. Second stage turbine vane
16. Second stage turbine
17. Exhaust case
18. Exhaust cone and strut
19. Turbine rotor inner seal
20. No. 3 bearing seal
21. Turbine case
22. No. 3 bearing (roller)
23. Combustion chamber fuel drain valve
24. Combustion chamber inner case
25. Fuel nozzle
26. Fuel manifold
27. Component drive tower shaft
28. Component drive gearbox main gearshaft
29. Component drive gearbox
30. Main component drive gears
31. Turbine shaft locking bolt
32. Compressor rear hub
33. Compressor rotor tierod
34. Compressor rotor disk
35. Compressor air bleed valve
36. Compressor tiebolt
37. Compressor front hub
38. No. 1 bearing seals

FIGURE 6-7. Pratt and Whitney J60 cross section.

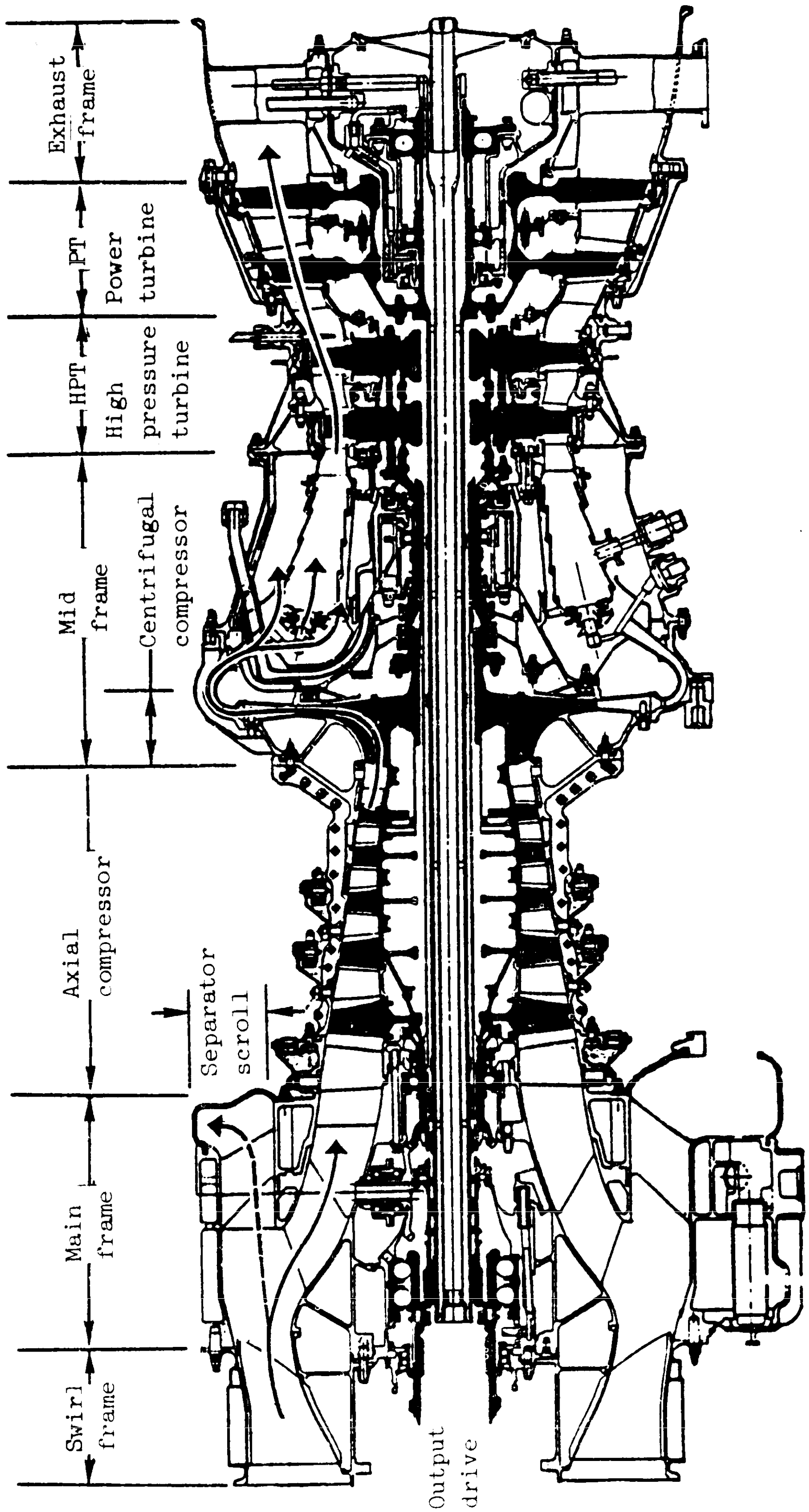


FIGURE 6-8. GE T700 cross section.

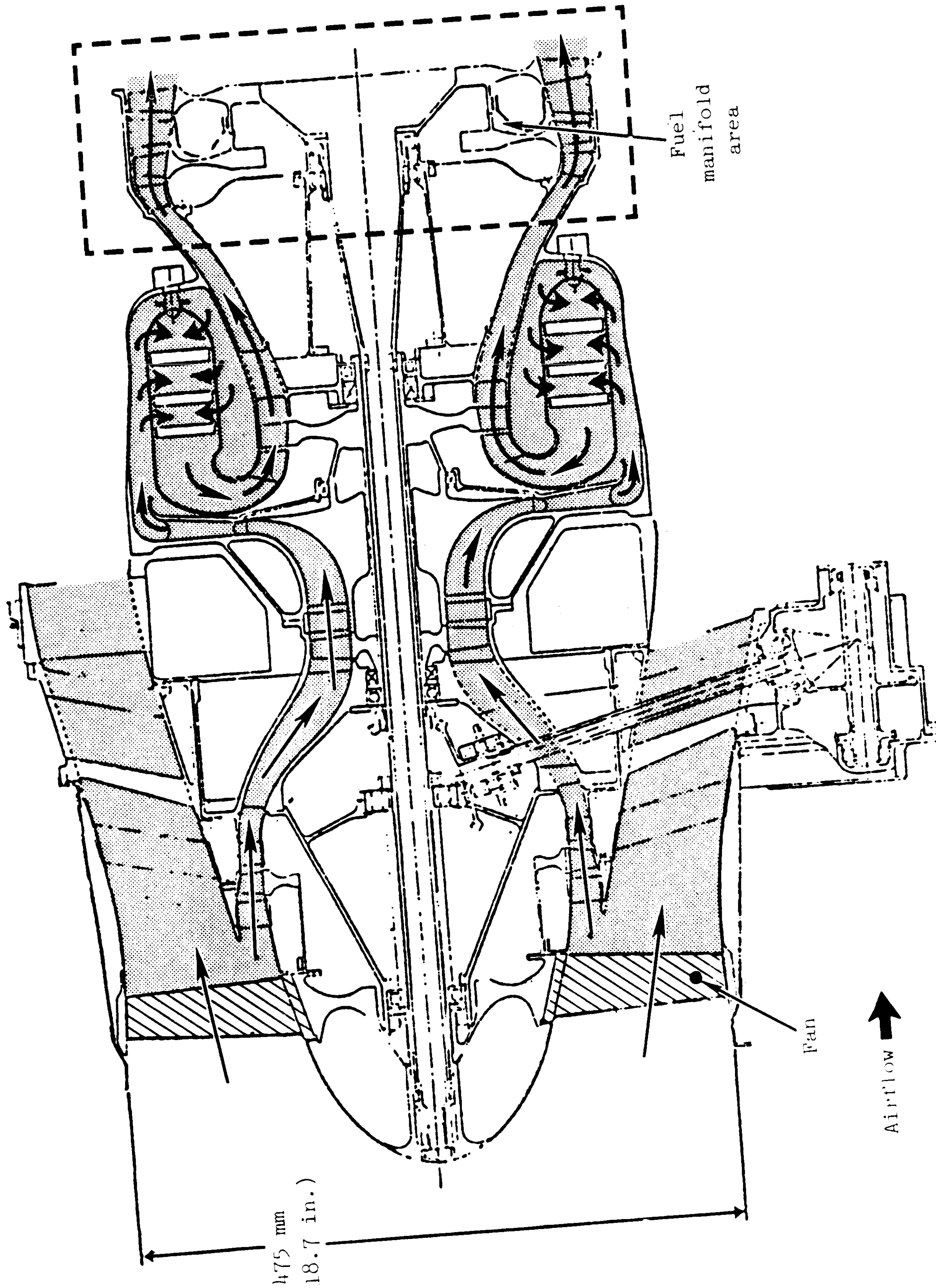


FIGURE 6-9. Lycoming AT170 cross section.

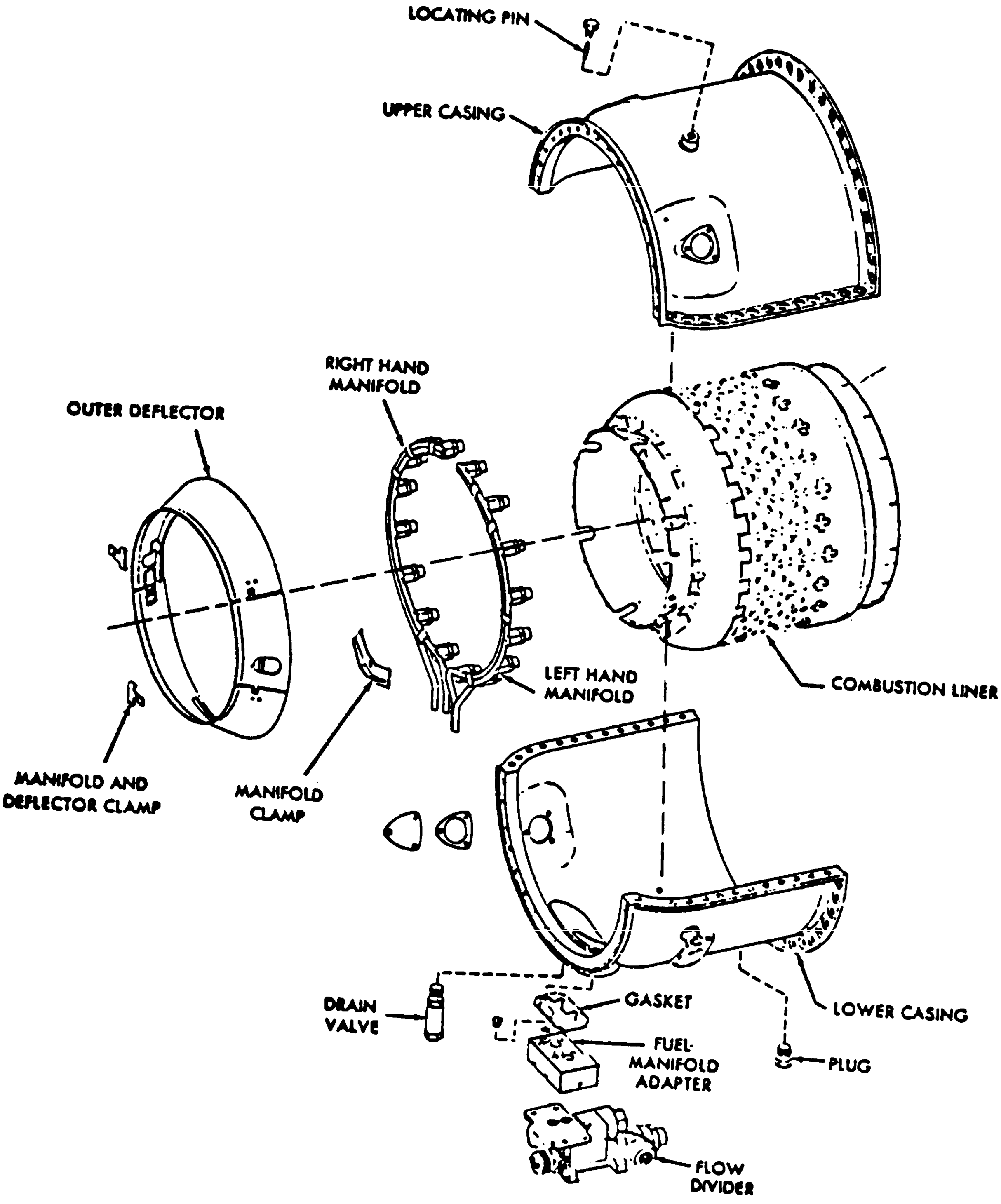


FIGURE 6-10. GE T58 combuster, expanded view.

FIGURE 6-11. T64-1 combustor casing exit hole.

$$W_L = \frac{0.53\ CAP_3}{\sqrt{T_3}}$$

Where:

W_L = leakage flow, lb/sec

C = orifice coefficient, assume 0.67

A = hole area, in.^{2}

P_3 = compressor discharge pressure, lb/in.^{2}

T_3 = compressor discharge temperature, °R

For constant-area holes and orifice coefficients, the preceding relationship shows that leakage flow increases with engine pressure ratio. Conversely, with a high-pressure ratio engine, a smaller hole is required to leak a given percentage of the total airflow.

6.3.4.3 Air leakage. It is postulated that all engines have roughly similar tolerance to air leakage; that is, similar schedules of percent bleed airflow versus percent thrust or power lost. It is estimated that a 12- to 18-percent bleed of maximum engine airflow will typically result in a 50-percent power (thrust) loss. For current high-pressure ratio engines, this occurs with relatively small hole area, much less than the 12 to 15 in.^{2} hole areas tolerated by the J65.

6.3.4.4 Summary. High-obliquity hits from even small threats make holes sufficient to cause rollback in high-pressure ratio engines. This sensitivity to holes reduces the probability of the engine emitting a destructively hot plume. It is estimated that plume is unlikely to occur with small holes and that plume emission and resultant damage are not an important consideration in high-pressure ratio engines. However, more facts are needed. Hits on fuel manifolds and nozzles result in immediate power loss kills. Momentary fires may also result. Combustors are typically “thin skinned” and offer little resistance to complete perforation. There is a risk that a projectile side-on combustor hit will kill an engine and the projectile will exit with sufficient energy to kill an adjacent engine.

6.3.5 Vulnerability reduction.

a. Design minimum-size combustors. As regards through flow or reverse flow combustors, through flow combustors permit a reduced engine diameter and reduced combustor section surface area. This means less high-obliquity area and, thus, reduced combustor vulnerable area. Reverse-flow combustors permit shielding and masking the turbine with the combustor and thus reduce vulnerable area. Figures 6-7 through 6-9 illustrate this.

b. Shield or thicken casings. Figure 6-12 illustrates simulated combustor casing configurations tested at BRL to determine the effects of double thicknesses, nylon blankets, and external ribs in reducing hole sizes. Although some variants on a standard single-thickness casing configuration resulted in modest reductions in hole size, the improvements were not great enough to stimulate further testing.

c. Use internal fuel manifolds.

d. Recommend location of sensitive aircraft components away from combustor areas.

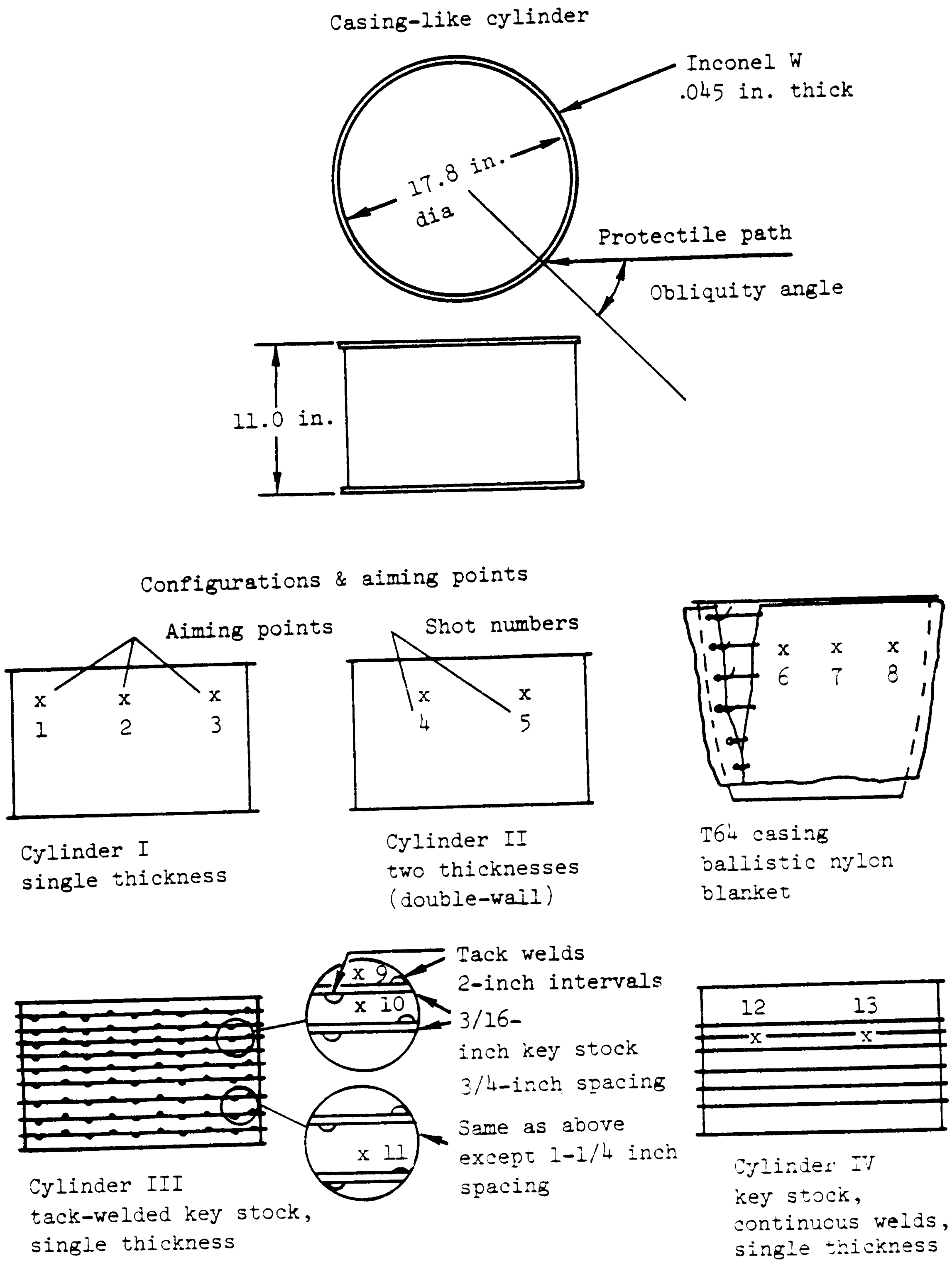


FIGURE 6-12. Test combustor casings.

6.4 Turbines. Turbines constitute substantial engine target area which is relatively sensitive to hits. Designs now emerging from development, feature the following: (1) generally increased rotational speeds; (2) more work per stage; (3) high temperature, high-strength materials; (4) air cooling; (5) lower aspect-ratio blades and vanes; and (6) increased demonstrated structural integrity and containment capability. Figure 6-8 illustrates the T700 low-aspect-ratio blades and vanes.

6.4.1 Hit effects. Hits typically cause blade and vane damage which results in released material, mechanical interference, jamming, and unbalance-induced vibration. Large threat hits cause immediate major power losses, with damage often contained. Damage was contained in two of three large-threat turbine hits on operating T58's during BRL vulnerability testing. (Reference 51)

6.4.1.1 Small-threat hits. Small-threat hits sometimes permit continued operation with damage-induced vibration which, in turn, may lead to more serious secondary damage. For example, in vulnerability testing, an operating T64 lost several power turbine buckets from a projectile hit. Severe vibration ensued, and the engine was shut down after 32 seconds of continued operation. Inspection disclosed that the tailpipe had been released and nearly all of the exhaust frame and bearing support weldments were broken. Similar testing and damage to a T58 caused vibration-induced shearing of all bolts securing the aft engine mount. At 1 minute after impact, the engine pivoted about the remaining forward mount and dropped to the deck of the test stand. Figure 6-13 shows the power turbine rotor damage. (Reference 55)

6.4.2 Vulnerability reduction. Damage tolerance increases with blade and vane size, material strength and toughness, improved structural integrity, and with few connections:

a. Integral one-piece stages are desired (except for the final stage turbine) alternatively, segments with two or more vanes are preferred to single vanes.

b. Hollow vanes which, when hit, produce only small pieces of debris are preferred over solid vanes.

c. Blades should be securely retained against axial displacement.

d. Integral blade tip shrouds are not desirable.

e. Static honeycomb abradable blade tip shrouds which pass small released particles with minimum blade tip damage are desirable.

f. Turbine cooling air passages routed deep within the engine to ensure reduced vulnerability to cooling air deprivation from low-energy hits are recommended.

g. Casing designed to contain a failed blade at maximum speed are designed. Casings so designed have contained multiple simultaneous blade releases.

h. Integral one-piece turbine blades and disks (blisks) are usually preferred.

i. Multiple pass cooling passages are undesirable for cooled stages.

FIGURE 6-13. Power turbine rotor damage.

6.5 Afterburner and Exhaust systems. Afterburners, used to provide large-thrust increases for short-term needs such as takeoff, fast acceleration, and supersonic flight, add substantial engine presented area, but need add only limited vulnerable area.

6.5.1 Hit effects. Afterburner casings are easily holed. Internal static gas pressures up to approximately 40 psig result in gas outflow from the hole into the surrounding engine bay. The leaking gas may consist of flow from the envelope of cool gas between the liner and casing or, for large holes during afterburner operation, may include hot combustion gases. Hot combustion gases leaking into the engine bay may damage the aircraft, and this contingency is not normally considered in bare engine vulnerability analyses. The engine is normally assumed to be invulnerable to holed casings.

6.5.1.1 Fuel lines. Afterburner fuel lines are normally kept filled during nonafterburner operation, and this is necessary to provide smooth, quick light-Offs. Hits on these lines may result in significant fuel leaks, even during nonafterburner operation.

6.5.1.2 Nozzles. Afterburners are designed with variable-area exhaust nozzles which are often actuated hydraulically. These nozzles are typically closed by hydraulic pressure and opened principally by aerodynamic forces. Working fluids used include oil and, for one design, fuel. A hit typically results in the nozzle failing open, and a substantial thrust loss occurs. With fuel pressure-powered nozzles a fire is likely.

6.5.2 Vulnerability reduction.

a. Reduced afterburner casing lengths.

b. Avoid use of flammable fluids in nozzle actuating systems.

c. Design nozzle actuating systems to be mechanically irreversible and, preferably, to fail closed.

d. Reduced fuel and hydraulic nozzle line sizes and flows to the minimum required.

e. Cluster and join separate fuel and hydraulic lines to reduce target area.

f. Recommend provision of quick-response overheat detectors in afterburner section of engine bay.

g. Advise aircraft designer to locate sensitive aircraft components and structure away from afterburner.

h. For turboshaft engines, exhaust systems are not generally considered vulnerable. Turning the exhaust flow or adding an infrared suppressor reduces vulnerability by adding shielding in the rear view.

6.6 Bearing and seals. Low-friction ball and roller bearings are normally used for all main and accessory gearbox bearings. Carbon and labyrinth air seals are used.

6.6.1 Hit effects. Hits on bearings and supports normally caused quick kills and may result in uncontained released parts. During BRL vulnerability testing, a direct hit was aimed at the gas generator rotor thrust bearing of a T58 operating at top speed. The engine heaved, emitted flame and small glowing particles out the entrance side, and stopped suddenly. Inspection revealed that the compressor casing was broken open with bolts sheared at the split line flanges. Figure 6-14 and 6-15 show the damaged engine and bearing, respectively. (Reference 55)

6.6.1.1 Lube system hits. The greatest cause of bearing damage in combat is from the effects of lube system hits and consequent lube deprivation and bearing distress. This is discussed in 6.8, Lube Systems.

6.6.1.2 Secondary Effects. Hits on seals result in leaking air or oil overboard or into cavities where secondary effects may result in a kill. Possible effects include venting very hot air into bearing cavities and other relatively cool cavities within the engine where heating of highly loaded rotating parts may result in reduced strength and failure.

6.6.2 Vulnerability reduction.

a. Minimize number of bearings.

b. Locate bearings so that they are shielded by heavy structural parts.

c. Locate bearings in relatively cool places in engine.

d. Use MSO vacuum melt steel bearing material and steel separators for maximum survivability from secondary damage.

e. Use squeeze film bearings to increase tolerance of bearing to unbalance.

f. Minimize sump sizes.

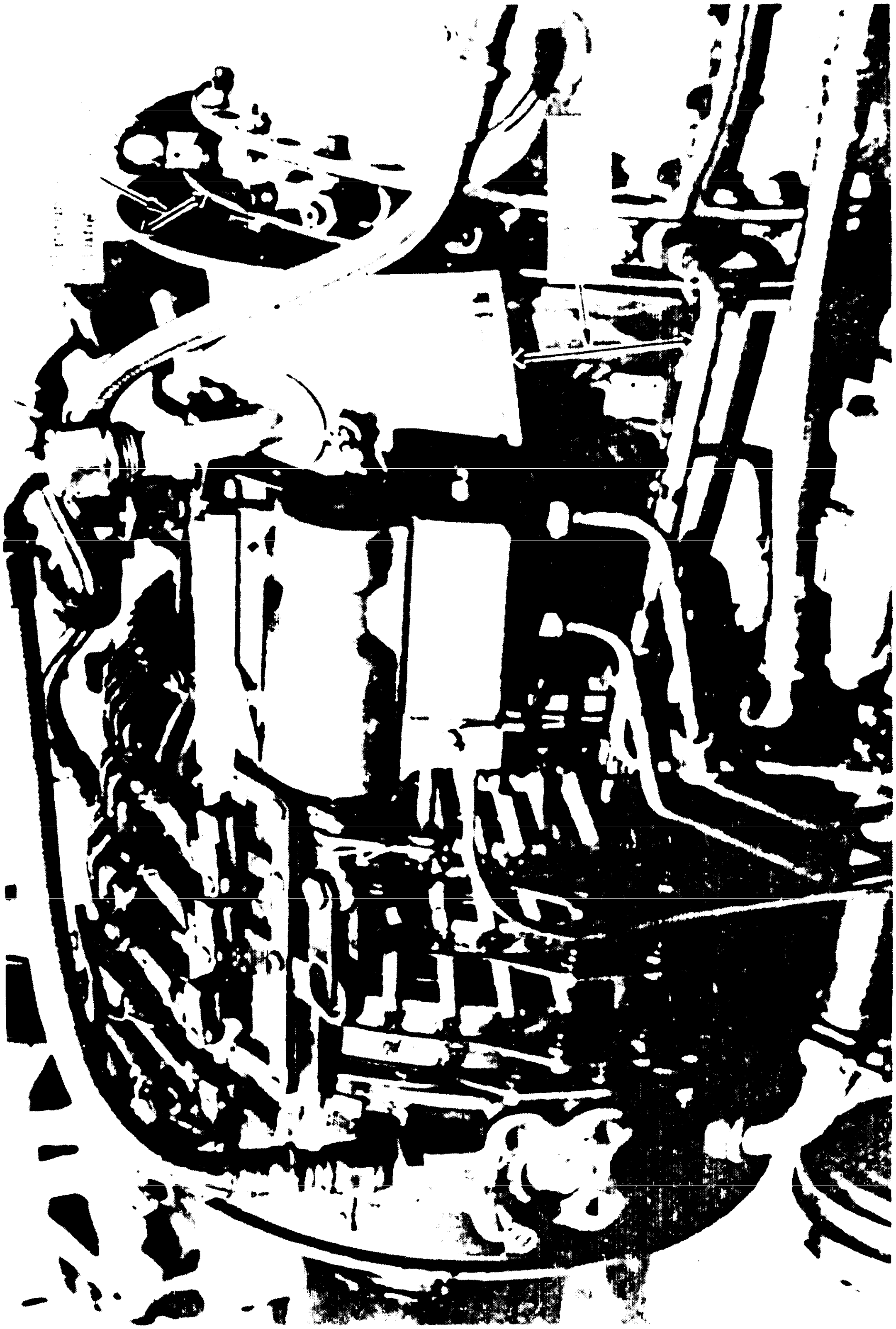


FIGURE 6-14. Gas generator thrust bearing hit damage.

FIGURE 4-15. Gas generator thrust bearing damage.

6.7 Fuel Systems. The engine fuel system components include the pumps, filters, fuel control and fuel pressure powered actuators, fuel oil coolers, 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 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).

6.7.1 Afterburner fuel systems. Afterburner fuel systems typically tap fuel filter, route it through a pump, control, and, possibly, fuel/oil coolers to the afterburner fuel manifold.

6.7.2 Fuel components. Fuel components are generally aluminum castings. For new designs, components and lines are often fire-resistant and will withstand 2,000°F for at least 5 minutes.

6.7.3 Hit effects. In general, all fuel components and lines can be easily perforated by even low-energy threats, and perforation results in an engine kill. Incendiary hits cause fires. Hits on low-pressure fuel system components can result in massive continuing fuel leaks or, alternatively, quick kill from fuel deprivation to the combustor. Hits on high-pressure fuel systems typically result in a drop in fuel pressure to less than the combuster air pressure, fuel deprivation to the combustor, rollback, and flameout. Metered fuel flow is generally proportional to compressor discharge pressure (combustor air pressure) and fuel pump output is generally proportional to pump seed; therefore, fuel available to the leak is reduced as the engine rolls back.

6.7.4 Vulnerability reduction.

a. Minimize fuel system area by reducing, integrating, and combining functions.

b. Reduce number of fuel components.

c. Minimize fuel component sizes.

d. Size pump to supply only as much fuel as engine can use.

e. Use electrical controls to schedule fuel in lieu of hydromechanical controls.

f. Require higher speed, smaller accessories.

g. Avoid use of fuel for hydraulic power transmission and cooling. Use mechanical linkages and air cooling.

h. Minimize volume of stored fuel in engine.

i. Use fire-resistant and fireproof lines.

j. Use suction fuel systems backed up as required by boost assist to reduce aircraft fuel line pressures and risk of fire, following aircraft fuel system bits. (Reference 56)

k. For helicopter engines, use top-mounted accessories.

l. Locate accessories so that lower vulnerability components such as starters, lube components, and accessory gearbox shield highly vulnerable fuel accessories.

m. Consider trade-offs of having turbofan accessories mounted on hot-core engine shielded by fan duct versus exposed cooler external fan duct location.

n. Locate fuel components to safeguard against ingestion and hot-surface ignition of leaking fuel. As regards hot-surface ignition, testing done by the FAA at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey, has demonstrated that the risk of hot-surface ignition from leaking JP4 fuel impinging on hot turbine engine casings is low. “In 97 tests, in which heat JP4 and other combustibles were sprayed for three minutes on the hot section casing of a J70 engine operating at Military thrust, ignition occured only 14 times. Engine casing temperatures in the impingement area ranged up to l,250°F, and leakage rates were as high as 500 pounds per hour at pressures up to 600 psi. Ignition occurred within two minutes of the start of leakage in only two tests. In both of these incidents, the nozzle. . . had slipped so that the fuel spray was directed toward the heat blanket which covered the turbine exhaust case . . . therefore, it was surmised that this hot surface ignition was caused by the leaking of fuel on the exhaust case underneath the blanket.” (Reference 58) Figure 6-16 and 6-17 from Reference 59 illustrate that the likelihood of hot surface ignition is influenced by fuel contact time and splash area. Figure 6-16 shows that if the leaking fuel is in contact with the hot surface for only a short time, higher temperature surfaces can be tolerated with no ignition. Contact time can be reduced by increasing engine ventilating airflow. Figure 6-17 shows that as leaking fuel target or "splash" area is reduced, higher surface temperatures can be tolerated.

o. Minimize number of connections, removable covers, and casings or fuel components. When hit, fuel components typically break open at connections, and this secondary damage increases fuel leakage rates over that leaking from the projectile holes. (Reference 51)

p. Minimize fuel line numbers, lengths, and line standoff distances from casings. Join and group lines to minimize exposed area. Use cored and internal passages. The Williams Research WR2-5C 125-pound thrust turbojet drone aircraft powerplant feeds fuel through the forward and main shafts to the combustor station. The high-speed shafts serve as a centrifugal fuel pump and sprays fuel through small shaft openings into the combustor. (See figure 6-18 and refer to reference 55).

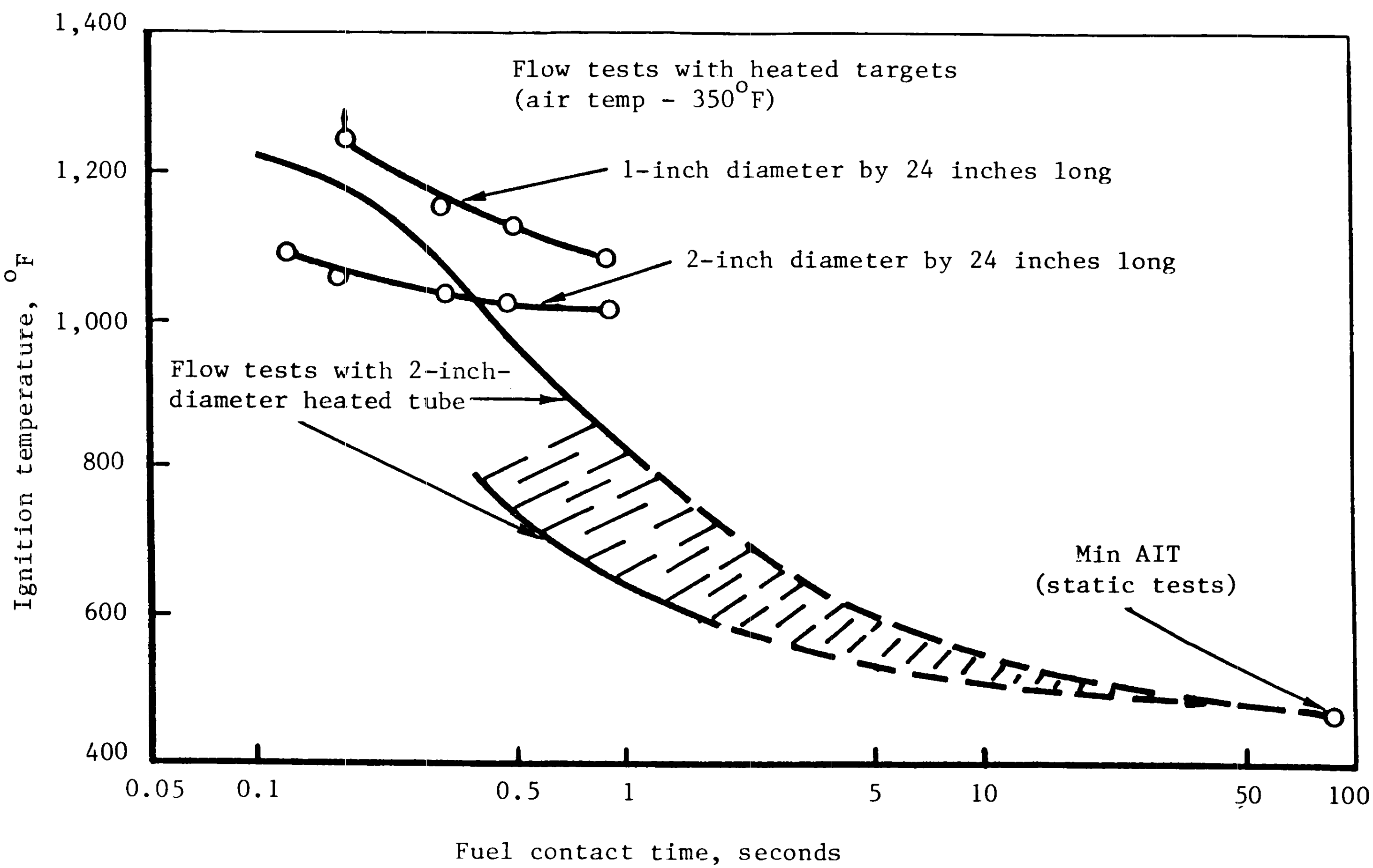


FIGURE 6-16. Variation of hot surface ignition temperature with fuel contact time, JP4.

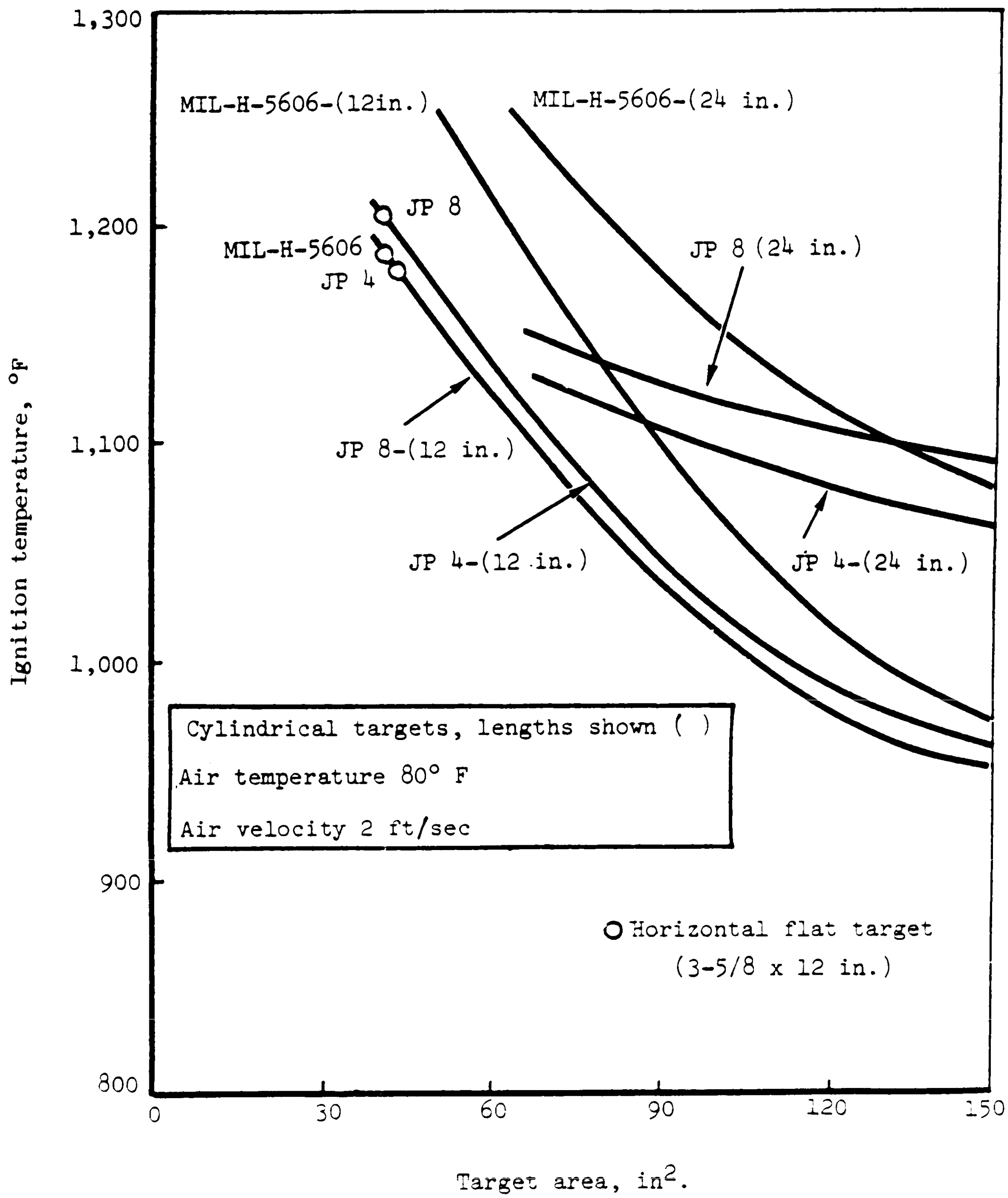


FIGURE 6-17. Hot surface ignition temperature versus target area.

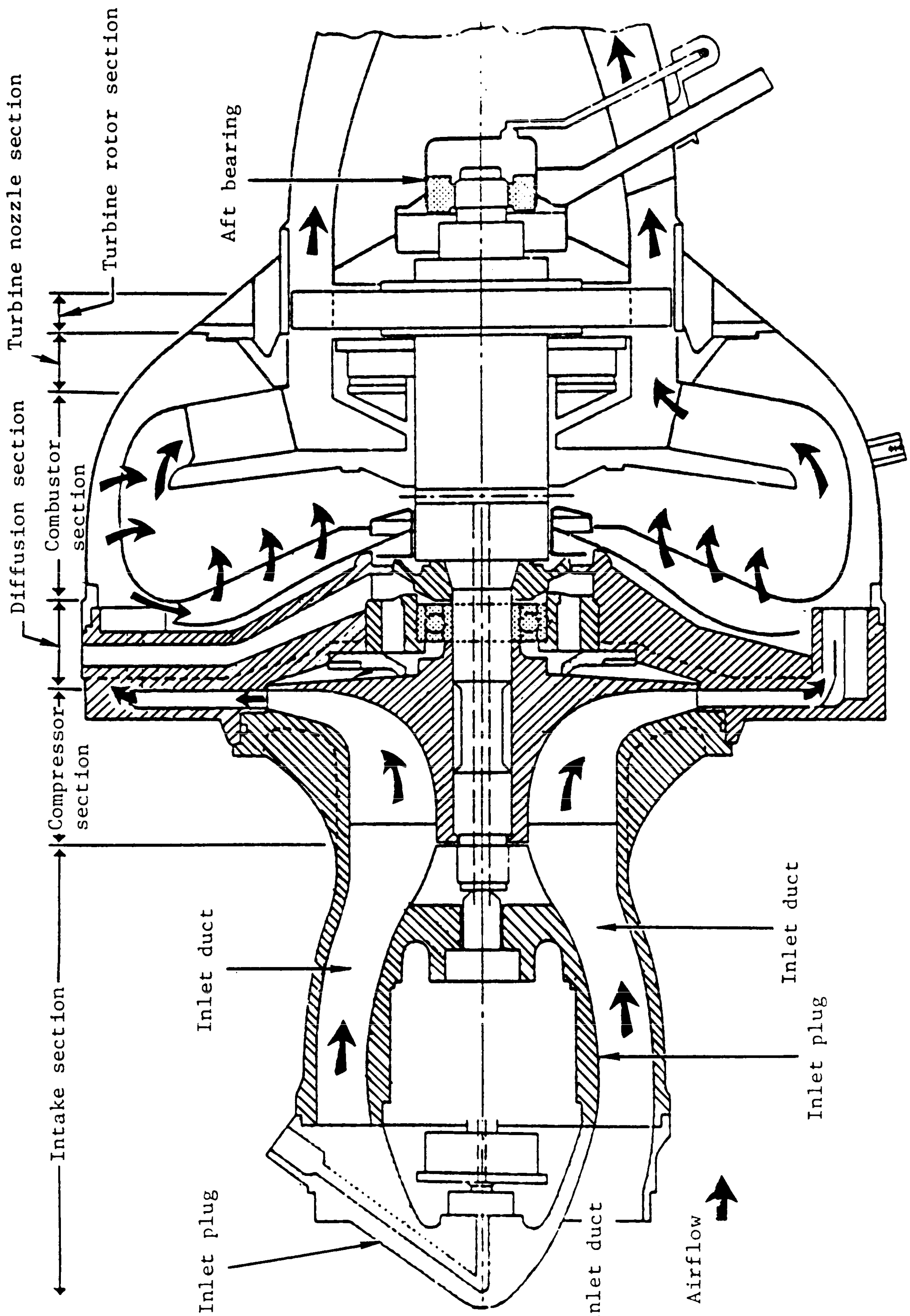


FIGURE 6-18. Williams WR2-5c turbojet engine cross section.

q. For multiengined installations, recommend airframe fire protection provisions, including engine isolation from one another, bay drainage, cooling air, and fire detection and extinguishing.

r. Avoid running fuel lines in rotor planes.

6.8 Lube and accessory gearbox systems. The engine lube system includes the tank, supply and scavenge pump, main filter, supply and scavenge lines, jets, and oil coolers. In older engines, tanks, and generally, some cooling are provided by the aircraft. In newer engines, the lube systems is entirely engine provided. The accessory gearbox provides mechanical drives for engine and aircraft-driven accessories such as pump, controls and alternators and a connection through which the starter can drive the engine. In new engines, lube components are usually fireproof; that is capable of withstanding 2,000°F for at least 15 minutes. With new high-efficiency, low fuel consumption engines, oil cooling is difficult because of limited fuel flow. Typically, fuel/oil cooling must be supplemented with air/oil cooling.

6.8.1 Pressures. Supply pressures between the pump and lube jets are usually approximately 40 psi; scavenge pressures between the scavenge pump outlet and the tank are perhaps 20 psi, and the tanks are generally slightly pressurized. The tanks have substantial expansion/deaeration space or other provisions for air/oil separation.

6.8.2 Tank dwell time. Typical tank sizes and flow rates result in tank dwell times of approximately 20 seconds; that is, the supply pump rate is approximately three times the tank useful oil capacity. In other words, the tank oil completes a circuit every 20 seconds.

6.8.3 Hit effects. Like the fuel system, all lube system lines and components can be easily perforated by even low-energy threats. Components are generally made of cast aluminum. Hits result in lube leaks and eventual oil deprivation to the bearings. With the tank oil completing a circuit every 20 seconds, all tank oil is evacuated quickly through a severed line or major leak, probably in less than 1 minute. For most engines, main bearings fail first under lube deprivation conditions. Gears are more durable. Bearings overheat and expand sufficiently to close up the clearances between the balls or rollers and the cages and races. Then the temperature shoots up, and bearing destruction occurs. In general, lube deprivation endurance life goes down with increasing load, added heat, and DN value. DN is bearing bore in millimeters times speed in rpm.

6.8.3.1 Lube deprivation testing. In BRL lube deprivation testing, the lube supply of a T58-1 engine operating at top speed was shut off. The engine continued to perform normally for approximately 14 minutes and then rolled back and was shut down. Postshutdown efforts to turn the rotors showed that the gas generator rotor was locked, while the power turbine rotor was free. Teardown inspection revealed that the gears were in good condition, while the bearings and seals were damaged. Figure 6-19 is a photograph of the gas generator thrust bearing. (Reference 55) This bearing is the highest DN ball bearing in the engine and is located at the compressor discharge station, where the thermal environment is adverse. It was operated at a DN value of 1.18 million during the test; that is, a relatively low DN. This 14-minute life and benign failure corroborates prior T58 engine testing in which 13 minutes endurance was demonstrated with a similarly benign failure response.

NOTE: COMPRESSOR REAR FRAME WAS CUT OPEN FOR ACCESS

FIGURE 6-19. Lube starvation test, gas generator thrustbearing.

6.8.3.1.1 New design. New engine design peak DN values typically exceed 2 million. Accordingly, deprivation endurance lives are reduced and special provisions are required to ensure even 5 minutes continued operation following a lube system hit.

6.8.3.2 Small threat hits on accessory gearboxes. In general, small threat hits on accessory gearboxes are assigned a relatively low probability of kill. Some inside wall areas of the accessory gearbox are wet with liquid oil, while other areas are relatively dry. In BRL testing on a T64 gearbox, holes in some areas produced significant oil leaks, while holes in other areas resulted in negligible leakage. AGB gear trains are normally configured with essential heavy loaded gears near the drive and less essential gears on the end of the train. Less essential accessories often have shear sections in their shafts so that if they are jammed by projectile damage the shaft will break and the undamaged AGB can continue to operate. BRL T63 testing has demonstrated an exception to this assumption of AGB low vulnerability. Impact by a small bullet anywhere on the T63 accessory gearbox released debris which blocked the lube pump inlet and caused the shaft to shear. "Thus with otherwise survivable gearing damage, the engine dies within 2 minutes due to lube starvation." (Reference 54)

6.8.3.3 Risk of fire. The risk of fire from lube system hits is estimated to be relatively small. The auto ignition temperature of oil is approximately 300°F higher than fuel. (Reference 58) However, given a supply line leak and ignition, all tank oil may be available to the fire.

6.8.4 Vulnerability reduction.

a. Continue to use integral engine-mounted lube systems which reduce lube system target area.

b. Use tank shapes and locations which minimize presented area.

c. Locate tanks so as to minimize risk of ingestion of leaking oil which may autoignite in engine and cause casing burn-through. Note, however, that oil seal leaks and ingestion have occurred in T700 development testing on several occasions, with no adverse effects.

d. Integrate and miniaturize the lube pump and filtering functions into one component to reduce lube system area.

e. Locate lube components to benefit from shielding by less critical components.

f. Require higher speed, smaller accessories.

g. Use cored passages, group and joint external oil lines into a single cluster, and use minimum line lengths, numbers of connections, and casing standoff distances.

h. Use fireproof lines and components.

i. Reduce number of bearings and sumps, lube flow rates, and tank capacity to minimum required.

j. Locate bearings in cool areas, and reduce loads.

k. Incorporate emergency lube system provisions which provide bearing lubrication and cooling capability following a lube system hit and thereby provide extended life for safe escape or safe landing.

1. The AF-lG aircraft has a system which senses airframe air/oil cooler leakage and shunts flow back to the T53 pump inlet, by-passing the cooler and preventing further leakage. The crew has sufficient engine life with no air/oil cooler to return home. (Reference 54)

2. An improved T53 system was demonstrated in which "3 way valves act upon oil pressure loss to shut off flow to all external lines and components and introduce an emergency supply of oil from a secondary tank which is beneficially located near the top of the side opposite the primary tank." (Reference 54)

3. The J65 and the SNECMA ATAR 09-series engine have air/oil mist systems for center and rear bearings which have redundancy features which ensure extended operation following a line hit. "Operation for at least 30 minutes at 95 percent speed is possible after impact damage either with reduced coolant airflow combined with normal metered oil flow or with fuel coolant airflow combined with residual non-flowing oil." (Reference 54)

l. Consider self-sealing lube tanks. Natural rubber used in many self-sealing materials cures with extended exposure to lube temperatures reached routinely in new engines. Under these conditions, the rubber will fail to react chemically with the leaking oil, and that contribution to sealing will not occur. However, the elasticity of self-sealing materials results in the hole closing mechanical action can result in greatly reduced leakage rates. Therefore, self-sealing should be considered.

6.9 Other systems.

6.9.1 Electrical systems. It is estimated that typical fuel-cooled electrical components can be perforated very easily. The risk of resulting fires has not been investigated however, and no fires have been reported to date. In general, engines are designed so that electrical power losses are not critical as regards an engine kill. Such losses typically result in, at worst, a modest performance penalty or reversion to a degraded level of control and performance. In the latter event, control of the engine may require significant attention from the crew, and this may be awkward in a combat situation. Also, probability and effects of shorts which cause electrical hardovers has not been adequately investigated.

6.9.2 Air systems. Compressed air is bled from engines for anti-icing, cabin pressurization, heating and ventilating, turbine cooling, engine seal pressurization, and engine balance piston (engine bearing load reduction) purposes. In general, bleed-air ducting is insulated to prevent the surface temperature from reaching a level which will provide an ignition source for leaking fuel or hydraulic fluid. Hits on turbine cooling lines can result in turbine blade overheating. For other lines, the risk is that severance will result in excessive gas leakage. Vulnerability to air bleeds can be reduced by:

a. Ducting required air internally through the engine.

b. Providing cored passages and minimizing line lengths for necessary external ducting.

c. Locating required valves close to bleed sources so that hits on downstream pipes do not result in leaks with valves closed.

d. Designing so that hit-induced leaks will not result in turbine overheating.

e. Designing so that hit-induced leaks will not result in excessive gas leakage and engine rollbacks.

f. Providing a precooler heat exchanger near the engine bleed port.

g. Providing a leak detector along the bleed air lines.

This page intentionally left blank

6.10 Piston engines. Piston engines power some remotely piloted vehicles, drones, and training aircraft. The A-1 aircraft used extensively in Southeast Asia was piston-powered. The engines currently used are typically designed with power sections consisting of two banks of air-cooled horizontally exposed cylinders and a direct or geared drive to a tractor propellor. The accessories section is located aft of the power section and is backed up by a vertical fire wall. Accessories section components include fuel pumps, filters and carbure-tors, lube, pump and filter, hydraulic pump, magnets, starter, generator, and cabin heater. Very carefully designed large-piston (3,500-shaft horsepower (shp)) engines produce 2 shp per pound of engine weight. Smaller engines pro-duce less than 1 shp per pound weight. Turbine engines produce much more - 4 shp per pound weight, or more.

6.10.1 Hit effects. Historically, piston engines have been judged relatively insensitive to hits. The sensitive fuel and oil accessories are shielded in the front view by the power section and can be shielded locally by less critical components, such as the starter. Compared to the turbine engine, pressures, temperatures, and speeds are, in general, a lot lower, and this is significant in reducing secondary damage effects. Some characteristics peculiar to piston engines are:

a. Piston engines can and have operated with holed cylinders.

b. Foreign object ingestion and damage, inlet distortion, and engine stalls do not occur in piston engines.

c. Piston engines do not release high-energy parts.

Reference 59 provides information on piston-powered A-1 aircraft combat damage incidents in Southeast Asia.

6.10.2 Vulnerability reduction.

a. Shield sensitive accessories and component with less sensitive com-ponents.

b. Use engine-driven suction fuel systems for aircraft to engine fuel transfer.

c. Minimize engine fuel line lengths and connection numbers.

d. Use self-sealing lube tanks and lines and fuel lines.

e. For manned twin-engine aircraft, recommend that engines be widely separated.

f. For manned twin-engine aircraft, recommend provision of adequate engine-out performance and full-feathering propellers.

g. For manned twin-engine aircraft, recommend provisions of fire-protec-tion equipment, including a firewall, shutoff valves, fire-detection system, and fire-extinguishing system.

This page intentionally left blank

6.11 Laser weapons. High-energy lasers which have the potential to transmit beams of intense energy to remote targets along straight lines at the speed of light are formidable future possible threats. Weapon terminal characteristics include wave length delivered power density, spot size, and dwell time; and, for pulsed devices, pulse rate. Target response variables include materials, pressures, initial temperatures, and burn-through response. Engine vulnerability to laser weapons is of interest. Specific detailed information can be found in references 147 through 154.

Custodians:
Army - AV
Navy - AS
Air Force - 26

Review activities:
Army - ME, MR, SG
Navy - MC
Air Force - 26

Preparing Activity:
Air Force - 11
(Project MISC-4363)

This page intentionally left blank

FOLD

DEPARTMENT OF THE AIR FORCE

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO. 73236 WASHINGTON D. C

POSTAGE WILL BE PAID BY THE DEPARTMENT OF THE AIR FORCE

Air Force Systems Command
Attn: ASD/ENESS
Wright-Patterson Air Force Base, Ohio 45433

OLD

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS: This form is provided to solicit beneficial comments which may improve this document and enhance its use. DoD contractors, government activities, manufacturers, vendors, or other prospective users of the document are invited to submit comments to the government. Fold on lines on reverse side, staple in corner, and send to preparing activity. Attach any pertinent data which may be of use in improving this document. If there are additional papers, attach to form and place both in an envelope addressed to preparing activity. A response will be provided to the submitter, when name and address is provided, within 30 days indicating that the 1426 was received and when any appropriate action on it will be completed.
NOTE: This form shall not be used to submit requests for waivers, deviations or clarification of specification requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waive any portion of the referenced document(s) or to amend contractual requirements.

DOCUMENT IDENTIFIER *(Number)* AND TITLE MIL-HDBK-336-3 Survivability, Aircraft Nonnuclear, Engine-Volume 3

NAME OF ORGANIZATION AND ADDRESS OF SUBMITTER

☐ VENDOR ☐ USER ☐ MANUFACTURER

1. ☐ HAS ANY PART OF THE DOCUMENT CREATED PROBLEMS OR REQUIRED INTERPRETATION IN PROCUREMENT USE? ☐ IS ANY PART OF IT TOO RIGID, RESTRICTIVE, LOOSE OR AMBIGUOUS? PLEASE EXPLAIN BELOW.

A. GIVE PARAGRAPH NUMBER AND WORDING

B. RECOMMENDED WORDING CHANGE

C. REASON FOR RECOMMENDED CHANGE(S)

2. REMARKS

SUBMITTED BY *(Printed or typed name and address — Optional)*

TELEPHONE NO.

DATE

DD FORM 1426 1 OCT 76 Replaces edition of 1 Jan 72 which may be used. S/N 0102-LF-001-4260