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REPORT JTCG/AS-74-T-002

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JTCG/AS

ENVIRONMENTAL AND OPERATING REQUIREMENTS FOR FIRE EXTINGUISHING SYSTEMS ON ADVANCED AIRCRAFT

J. D. McClure
R. J. Springer

November 1974

Approved for public release; distribution unlimited; statement applied November 1974.

Prepared for

JOINT TECHNICAL COORDINATING GROUP
FOR
AIRCRAFT SURVIVABILITY

FOREWORD

The work reported herein was performed under Air Force Contract F33615-73-C-2071 under the direction of the AFAPL (Air Force Aero Propulsion Laboratory), Wright-Patterson Air Force Base, Ohio. Mr. R. E. Cretcher (AFAPL/SFH) was the Air Force Project Engineer.

The work was sponsored by the JTCG/AS, as part of the 3-year TEAS (Test and Evaluation, Aircraft Survivability) program. The TEAS program was funded by Deputy Director, Research and Evaluation/Office of Deputy Director, Test and Evaluation. The effort was conducted under the direction of the JTCG/AS Technology Research and Development subgroup as Phase I of TEAS Element 5.1.1.7, *Advanced Fire Extinguishing System.*

This report is the culmination of Phase I of a four-phase program sponsored by the JTCG/AS and AFAPL to develop a fire extinguishment system for use on advanced combat aircraft. Phase II will concentrate on the development of a fire extinguishing agent that will operate effectively in the engine bay environment modeled as a result of Phase I. Phase III will develop an engine bay fire test simulator to be used to evaluate the effectiveness of the agents developed as a result of Phase II. Phase IV will result in the development of a flightweight fire extinguishment system for use in aircraft to be produced in the 1980s.

The contractor was the Fort Worth Operation of the Convair Aerospace Division of General Dynamics, Fort Worth, Texas. Mr. J. D. McClure (Program Manager) and Mr. R. J. Springer of the Forth Worth Operation conducted the study under the supervision of Mr. C. F. Crabtree, Design Group Engineer. Convair Aerospace consultants for the program include the following:

C. F. Crabtree
H. Skembare
Dr. J. V. Clifton
J. A. Cawthon
R. J. Green

The program spanned a period of 7 months, from 25 June 1973 through 25 January 1974, with 4 months for research and 3 months for documentation, review, and publication. This report was submitted in November 1973.

This technical report has been reviewed and approved.

DISCLAIMER

The estimates in this report are not to be construed as an official position of any of the Services or of the Joint AMC/NMC/AFLC/AFSC Commanders.

NOTE

Information and data contained in this document are based on the reports available at the time of preparation, and the results may be subject to change.

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Wright-Patterson Air Force Base

Environmental and Operating Requirements for Fire Extinguishing Systems on Advanced Aircraft, by J. D. McClure and R. J. Springer. Wright-Patterson Air Force Base, OH, AFAPL, for Joint Technical Coordinating Group/Aircraft Survivability, November 1974, 154 pp. (Report No. JTCG/AS-74-T-002, publication UNCLASSIFIED.)

Fire extinguishing systems for the advanced aircraft to 1980 will be required to operate efficiently over a wider range of environmental conditions than ever before. To determine what these environmental conditions will be for engine nacelles and adjacent compartments, a study was performed using an existing high performance aircraft. Using this aircraft, its operational parameters were extrapolated out to the advanced aircraft environment.

This study defines the environment in which the fire extinguishing system will be required to operate, primary and secondary fire zones, ignition sources, combustibles, and fire extinguishing agent requirements. Included are evaluations of effectiveness and limitations of the current state-of-the-art extinguishing systems as related to the normal and combat damage configurations. Fire extinguishing system requirements along with problem areas and recommendations for design alternatives for fire survivability of the future aircraft are identified.

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NOMENCLATURE

AFAMRL	Air Force Aerospace Medical Research Laboratory
AFAPL	Air Force Aero Propulsion Laboratory
ACGIH	American Conference of Governmental Industrial Hygienists
APU	auxiliary power unit
API	armor piercing incendiary
CDIC	Combat Data Information Center
FAA	Federal Aviation Agency
GD	General Dynamics
HEI	high explosive incendiary
ICC	Interstate Commerce Commission
JTCG/AS	Joint Technical Coordinating Group for Aircraft Survivability
NAS/NRC	National Academy of Science/National Research Council
NASA	National Aeronautical and Space Administration
SIT	spontaneous ignition temperature

INTRODUCTION

As aircraft and engine performance increase, the operating environments generated within the engine nacelles and adjacent compartments increase the fire hazard potential in these areas. The release of combustible fluids in these areas because of component failure or combat damage will result in a high probability of fire. This fire hazard must be controlled under these environmental conditions in the most efficient manner with the least operational penalty. In general, the vaporizable fire extinguishants used in available systems are thermally unstable above approximately 500°F and, being gaseous at temperatures above 170°F, can be readily carried away from the fire zone by airflow through the nacelle or compartment. The normal airflow pattern can be altered by skin and structural damage caused by projectile impact. In view of external engine case temperatures which could exceed the ignition temperatures of fuels and combustible fluids, and the higher airflow through these areas, agents with higher thermal stability and greater staying power are required to extinguish and prevent reignition of fires which may occur in these areas.

The objective of this program was to determine the requirements for a fire extinguishing agent(s) and distribution system capable of the suppression and control of flammable fluid fires in the high-temperature, high-airflow environment encountered in advanced aircraft. Key steps followed to achieve this objective consisted of:

1. Selection and definition of a baseline advanced aircraft configuration
2. Identification of the primary and secondary fire zones, ignition sources, combustibles, and their sources for the baseline vehicle
3. Identification of the baseline aircraft fire protection provisions
4. Definition of the environment in the engine nacelles and other selected compartments
5. Identification of the fire hazard potential of the baseline vehicle
6. Extrapolation of the baseline vehicle to an advanced environment
7. Identification of the effects of the 23-mm projectile combat damage on the environment in which an extinguishant is required to function
8. Identification of combustible fluids that are potential candidates for advanced aircraft applications to 1980
9. Assessment of the fire hazard potential in the advanced environment
10. Summation of engine nacelle environment/extinguishant for various aircraft
11. Evaluation of present fire extinguishants/systems in the high-temperature, high-airflow environment

12. Consideration of agent/system testing
13. Suggested design alternatives.

BASELINE AIRCRAFT

The Convair Aerospace Division, Fort Worth, Texas, operational F-111 aircraft (Figure 1) was chosen as the baseline vehicle for this program. The F-111 is a Mach 2.5 fuselage-mounted twin-engine fighter/bomber with demonstrated capabilities on the threshold of 1980 advanced aircraft. Selection of the F-111 aircraft as the logical baseline for this fire extinguishant program was based on the following considerations:

1. The F-111 flight regime extends to the threshold of the area of concern.
2. The aircraft is a high performance (high-temperature, high-Mach) operational vehicle.
3. More than 9,000 combat sorties have been flown.
4. More than 350,000 flight hours have been accumulated.
5. The aircraft has an outstanding fire safety record.
6. The aircraft has unique fire protection features.
7. The construction is modern.
8. The maturity of the aircraft is such that considerable data are available for use in evaluating the efficiency and characteristics of the design.

Fire protection provisions on the baseline aircraft include isolation, ventilation, restriction and separation, overboard venting and draining, detection, extinguishing, and combustible fluid shutoff valves. The fuselage-mounted engines are installed in compartments which have been treated as primary fire zones. Compartments outside of the engine bays where combustibles are routed are considered to be secondary fire zones. The F-111 onboard combustibles are JP-4 fuel, MIL-H-5606 hydraulic fluid, and MIL-L-7808 engine oil.

The F-111 airframe is divided into four fuselage sections. The forward fuselage section contains the nose radome, electronics bays, the crew module, and nose landing gear wheel well. The intermediate fuselage section contains the weapons bay and the forward fuselage tank. The mid-fuselage section, which extends aft to the engine firewall, contains the wing pivot support and main landing gear wheel well. The aft fuselage section contains the aft fuselage fuel tank, engine nacelles, structure for mounting the tail surfaces, and other system components. A general arrangement of the F-111 is shown in Figure 2. Figure 3 is an inboard profile drawing showing equipment location.

AIRCRAFT ENVIRONMENT

The F-111 aircraft is a two-place (side-by-side) fighter/bomber. The aircraft is designed for all-weather supersonic operation at both low and high altitudes. Mission capabilities include: long range, high altitude intercepts utilizing air-to-air missiles and/or guns; long range attack missions utilizing conventional or nuclear weapons as primary armament; and close support missions utilizing a choice of missiles, guns, bombs, and rockets. An automatic low altitude terrain-following system enhances penetration capability.

The Area Intercept mission presents the most severe exposure to aerodynamic heating for the baseline F-111 aircraft.[1] Figure 4 shows the variation in the adiabatic wall temperature and the ram temperature with time for the Area Intercept profile. Flight time at Mach 2.2 and 50,000 feet during this mission is sufficiently long so that most areas of the aircraft will reach steady-state temperatures. The equilibrium temperature varies with altitude but not significantly. Variation of equilibrium temperature at Mach 2.2 with altitude for a typical external location is given below.

Altitude, feet	Equilibrium temperature, °F
40,000	257
50,000	251
60,000	242

Skin temperatures during the Mach 2.2 cruise-climb flight are equal to the equilibrium wall temperature. Upper and lower fuselage skin temperatures are shown in Figure 5 for Mach 2.2 at 40,000 and 50,000 feet. Other F-111 maximum steady-state surface temperatures for Mach 2.2 are also shown in Figure 5.

Mach 2.5 at 50,000 feet altitude for 5 minutes represents the most severe aerodynamic heating condition for most regions of the F-111 aircraft. The upper and lower fuselage skin temperatures will reach equilibrium during the 5-minute dash. These temperatures are also shown in Figure 5.

ENGINE NACELLE

The F-111 engine nacelles (Figures 2 and 3) are designated as primary fire zones. Combustible fluids are adjacent to potential ignition sources in the presence of air. Traditional fire protection provisions of isolation, ventilation, restriction and separation (of plumbing), overboard venting and draining (for combustible fluid leakage), detection, extinguishing, and combustible fluid shutoff valves are incorporated in the engine compartments.

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[1] Convair Aerospace. *Aerodynamic Heating Analysis–F-111.* Fort Worth, TX, CA, 10 March 1965. (FZA-12-010A, publication UNCLASSIFIED.)

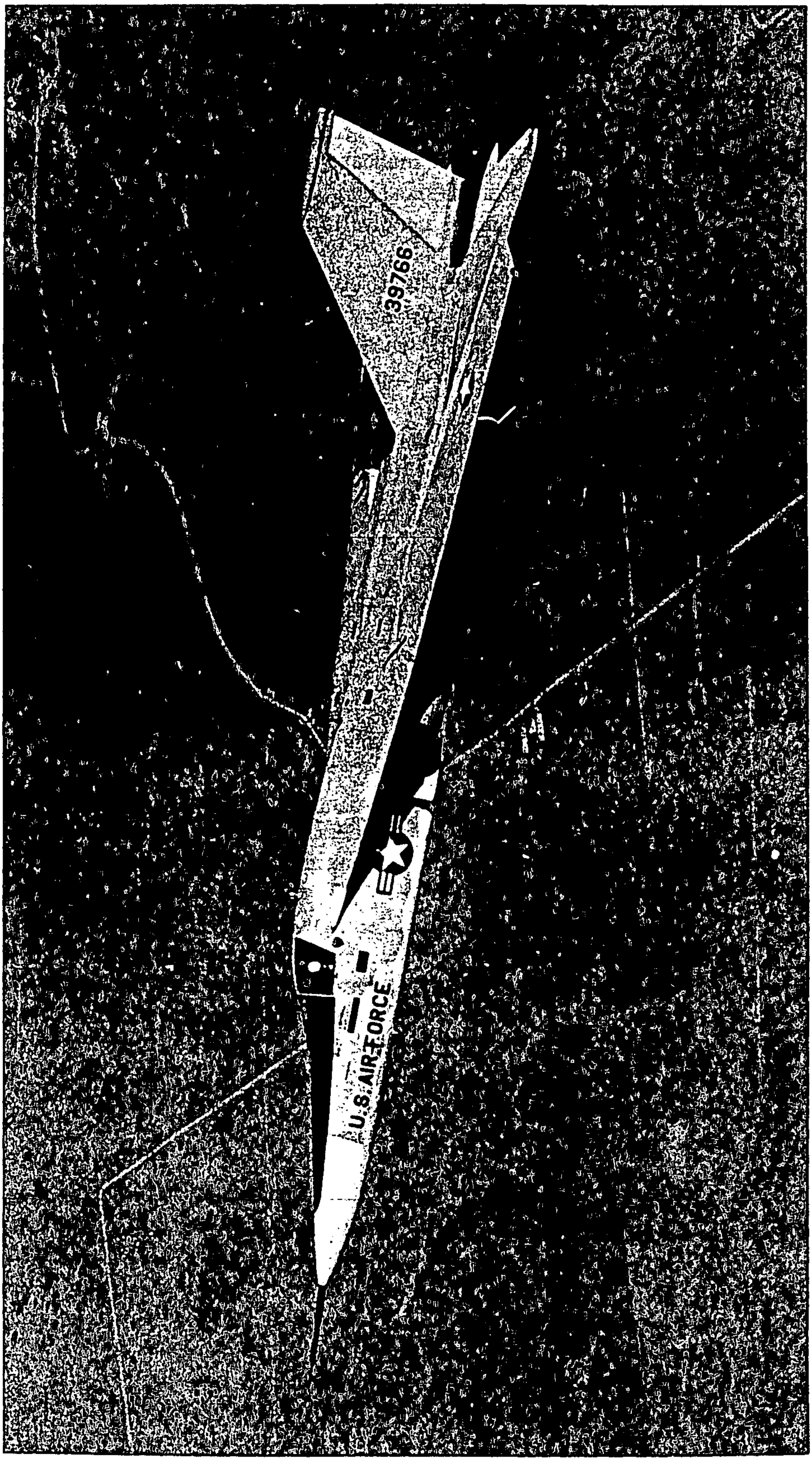

FIGURE 1. F-111 Aircraft - Baseline Vehicle.

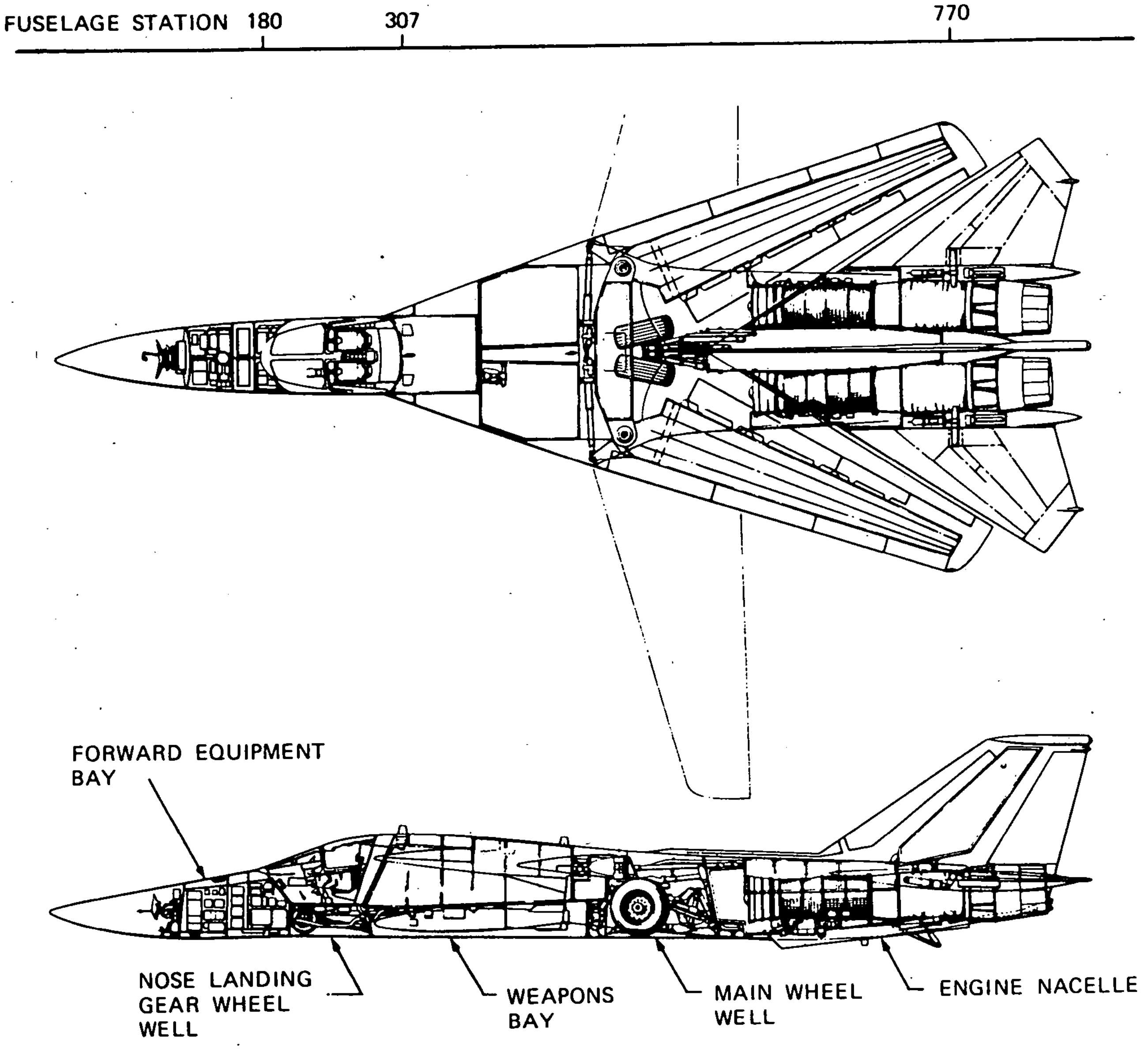

FIGURE 2. F-111 General Arrangement.

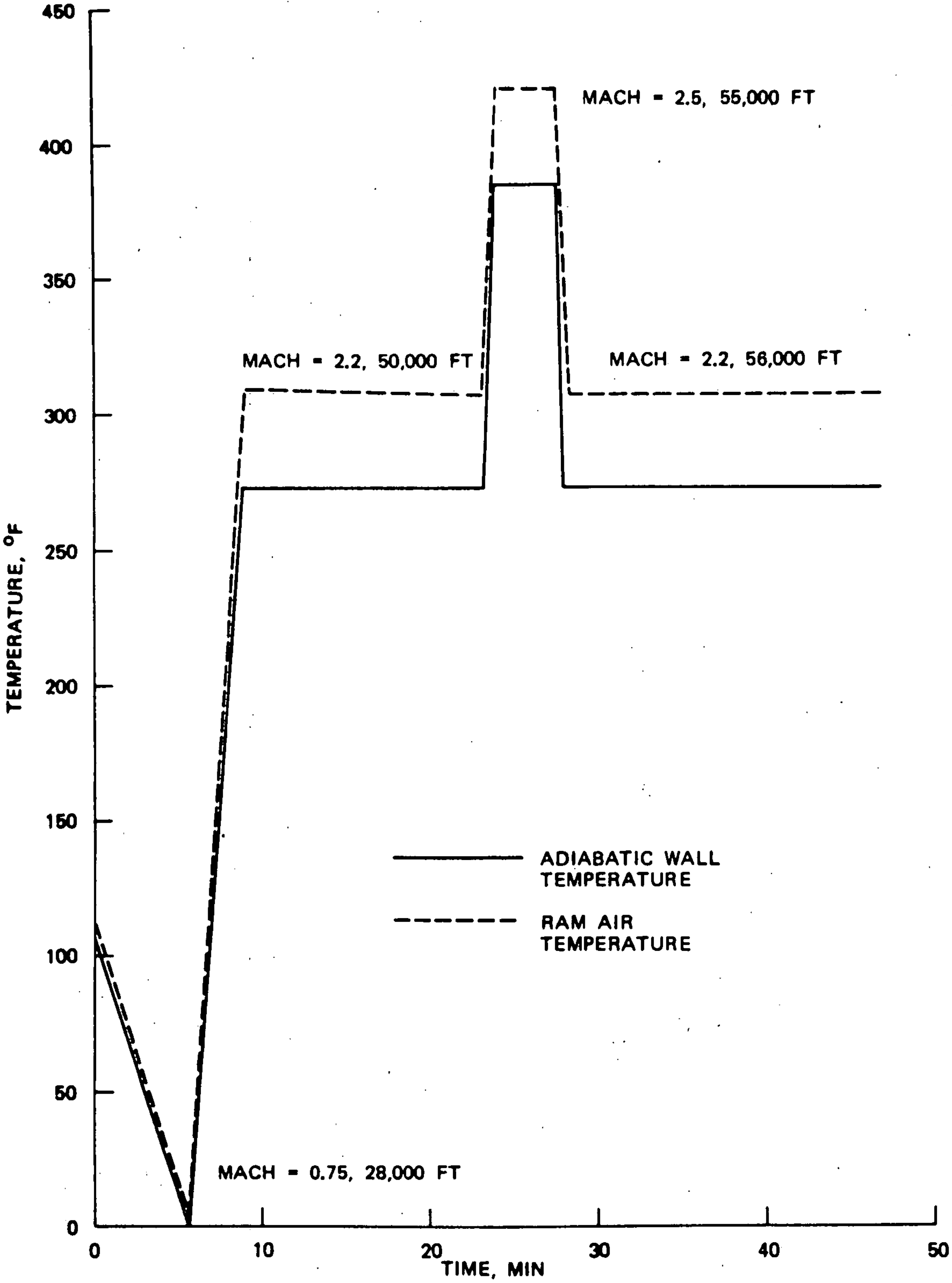

FIGURE 4. F-111 Area Intercept Mission Temperatures. (See Footnote 1).

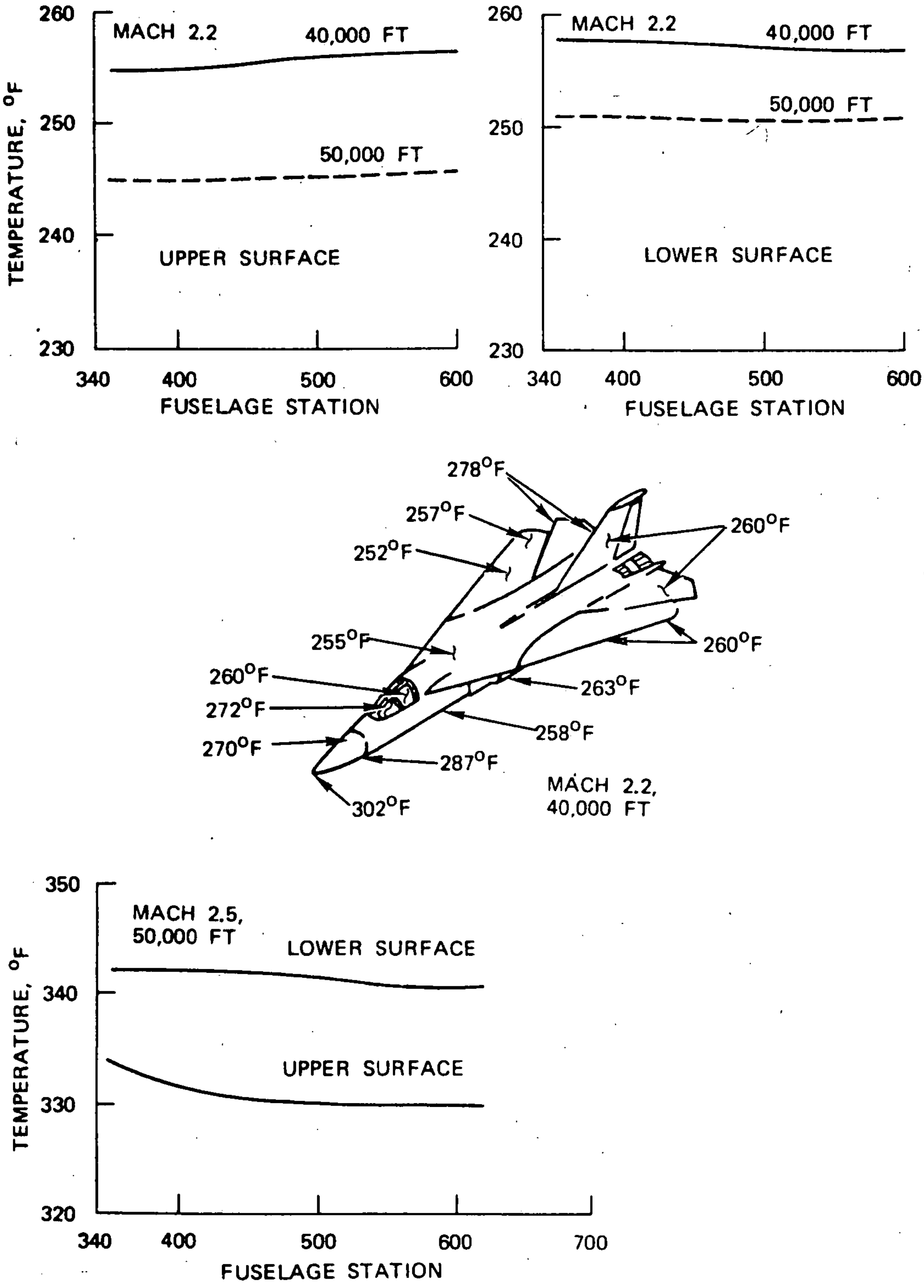

FIGURE 5. F-111 Fuselage Skin Temperatures. (See Footnote 1).

A novel fire protection design feature of the F-111 engine nacelle is the concept of the aerodynamic firewall, that is the effect of a transverse firewall to separate the hot and cooler engine sections is achieved without a physical barrier. Unidirectional ventilation airflow is used to prevent forward flame propagation as well as to remove flammable vapors from the nacelle. The engine compartment arrangement and ventilation are depicted in Figure 6. This ventilation concept recognizes the flame propagation speed of hydrocarbon combustibles in laminar and turbulent flow. If the ventilating air velocity is greater than the flame speed, a flame will move downstream until it reaches an area where velocity is equal to the flame speed. Sufficient airflow is provided in the baseline configuration to sweep a flame out the back of the nacelle. Adequate ventilation flow prevents forward flame propagation regardless of the source or location of combustible or ignition. If the air velocity is less than the flame speed, the flame will propagate upstream until it reaches an area where velocity is equal to flame speed. During ground operation, a bleed-air ejector is used to provide unidirectional ventilation and velocity. The ejectors are not required in flight because the ram velocity of secondary air provides sufficient ventilation and velocity. The unidirectional ventilation system provides at least 20 ft/sec ventilating flow at the forward end of the afterburner section for all operating conditions. This prevents any fire from propagating forward.

Engine nacelle flow area and volume are defined in Figures 7 and 8. Compartment air velocities were computed and are presented in Figure 9 for various conditions. Figure 10 provides nacelle airflow and pressure definition which was determined during F-111 flight testing.[2]

A vertical structural frame located at fuselage station 593 near the engine face isolates the engine compartment from the rest of the aircraft. Secondary inlet boundary layer ventilating air enters the nacelle through cutouts in this frame. Flapper doors (check valves) are hinged on the aft side of the frame to cover the cutouts for secondary airflow. If local nacelle pressure is less than secondary air inlet boundary layer pressure, the flapper doors will close and prevent nacelle flow or fire from spreading forward through the aircraft boundary layer system. During low-power F-111 ground operations, the flapper doors will be closed and nacelle ventilating air will be drawn into the nacelle from outside by hinged doors located on the forward engine access doors. All mechanical, fluid, and electrical connections to the engine are routed through the forward firewall with fireproof fittings.

Longitudinal firewalls in the engine compartment are Johns-Manville RF300 heat shield liners located on the compartment inboard sidewalls and the top of the compartments. These heat shield liners are corrugated but do not contain protuberances into the nacelle airflow to cause pockets which might act as flameholders. The longitudinal firewall is not penetrated by plumbing or connections in order to ensure positive sealing. The airspace between the longitudinal firewalls and fuselage skins is drained and vented.

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[2] Convair Aerospace. *Catagory I Propulsion System Flight Test Demonstration Report. Part III–F-111A Propulsion System Cooling Demonstration Report,* by T. S. Moore and D. M. Hancock. Fort Worth, TX, CA, December 1968. (FZM-12-5978-2, publication UNCLASSIFIED.)

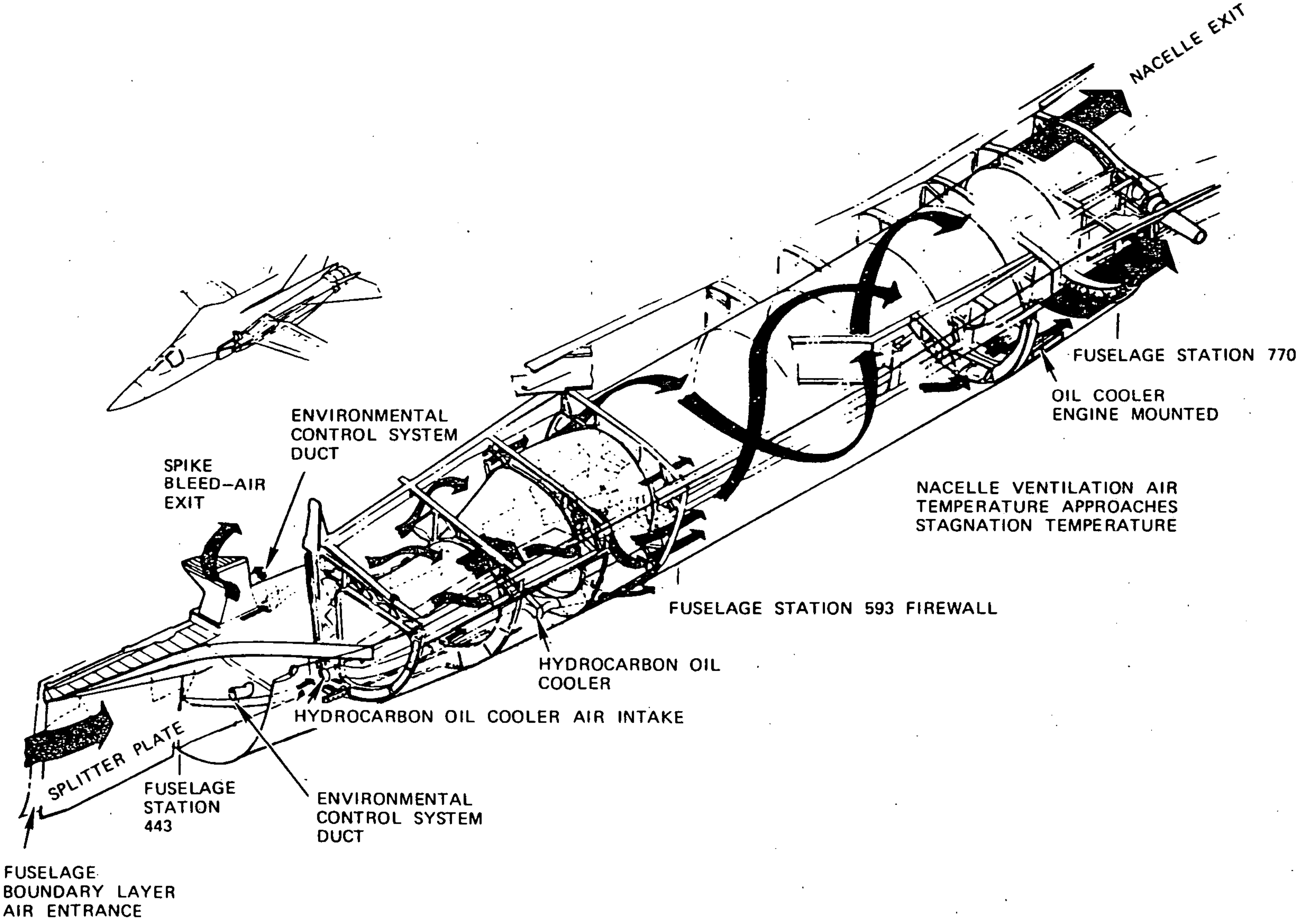


FIGURE 6. Baseline Engine Nacelle Ventilation.

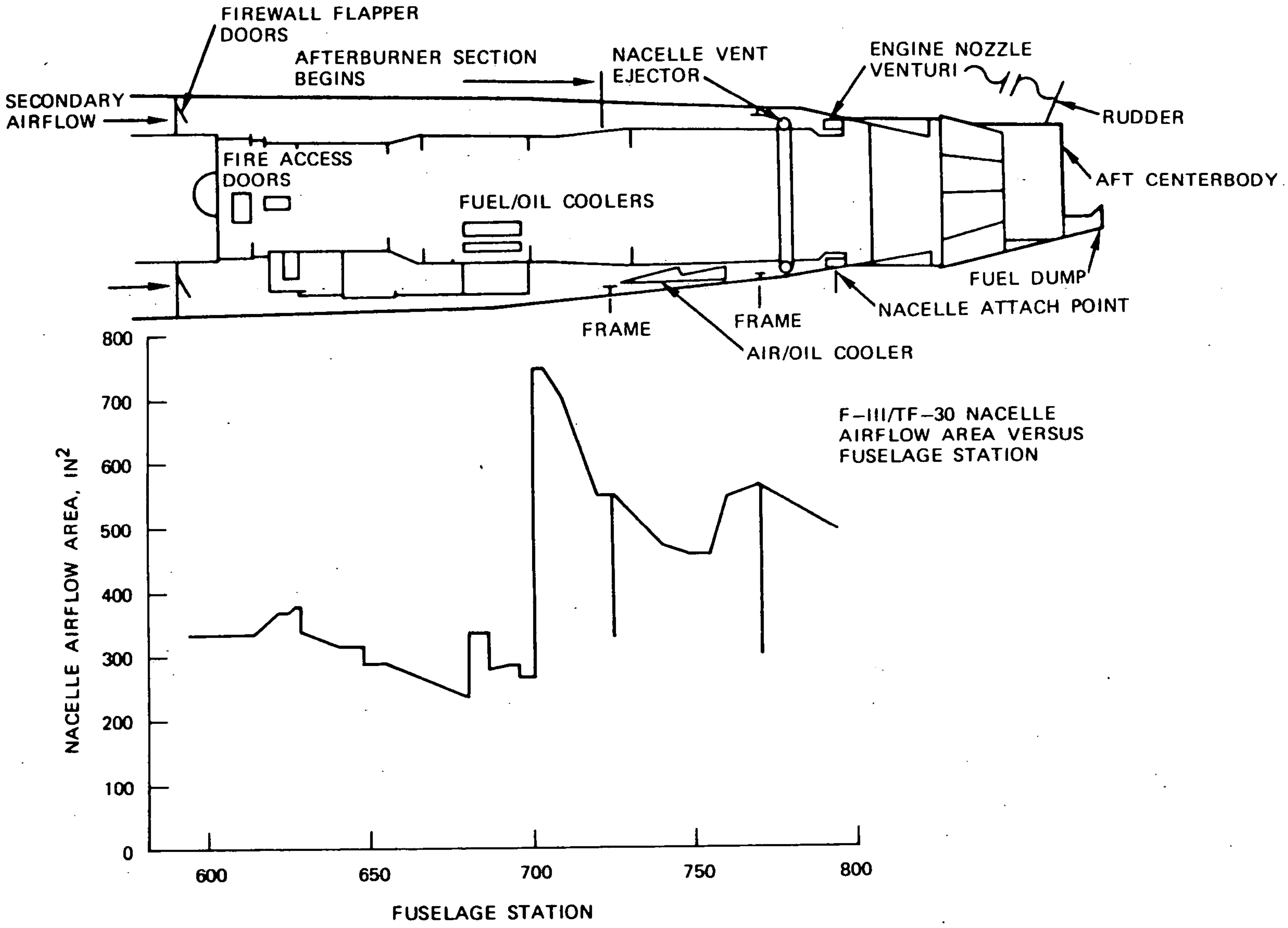


FIGURE 7. F-111 Nacelle Airflow Area.

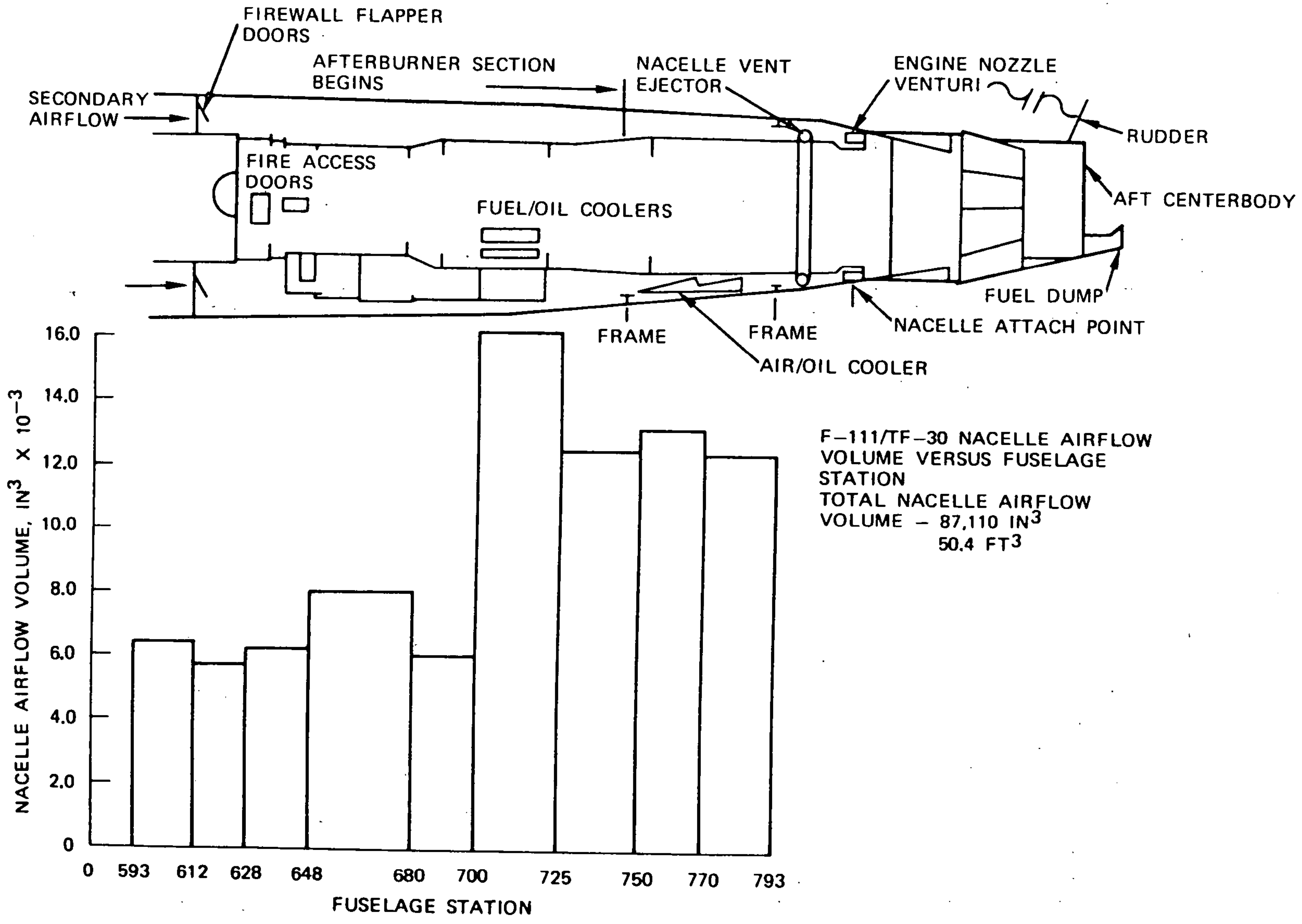


FIGURE 8. F-111 Nacelle Volume.

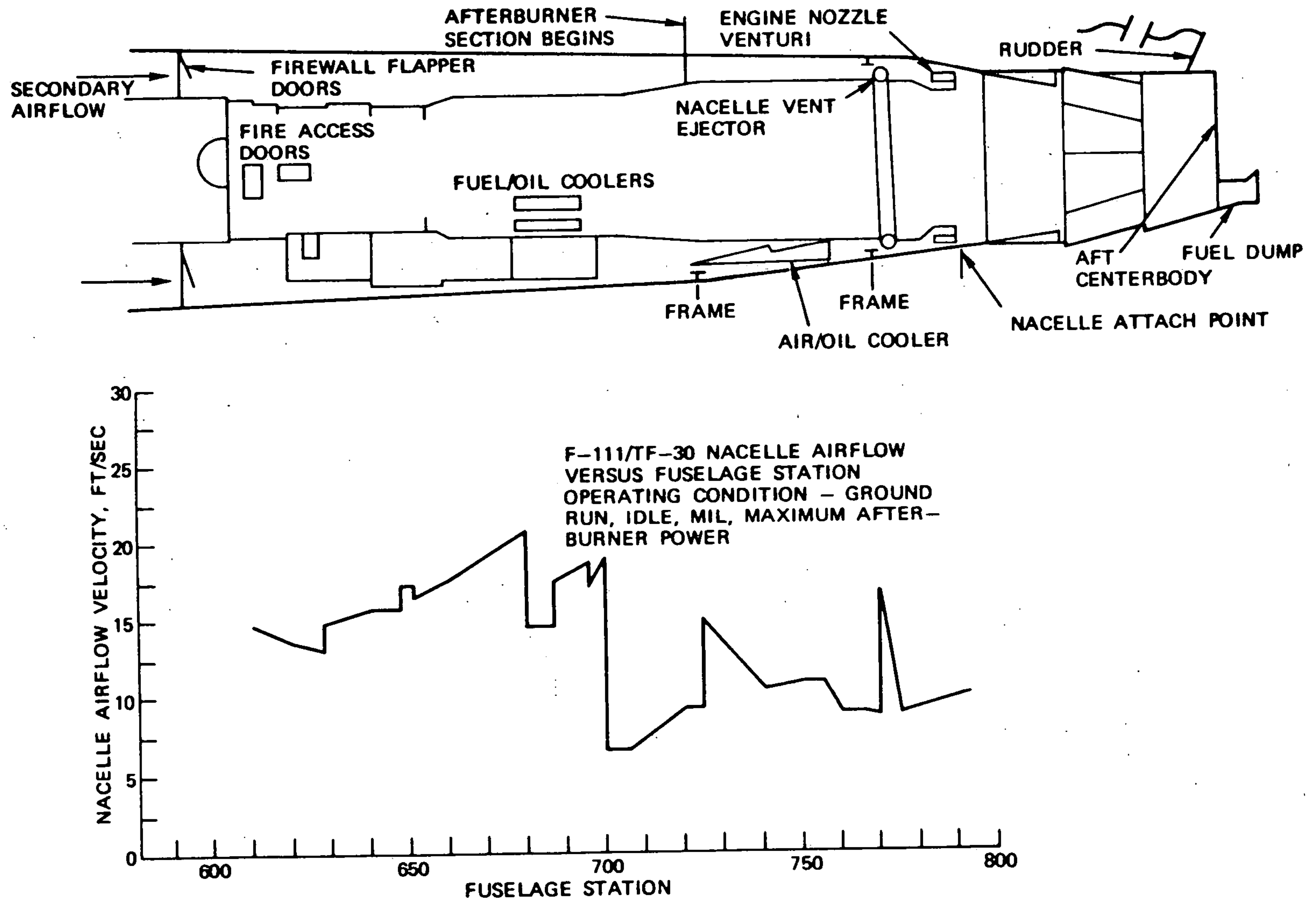


FIGURE 9a. F-111 Nacelle Air Velocity.

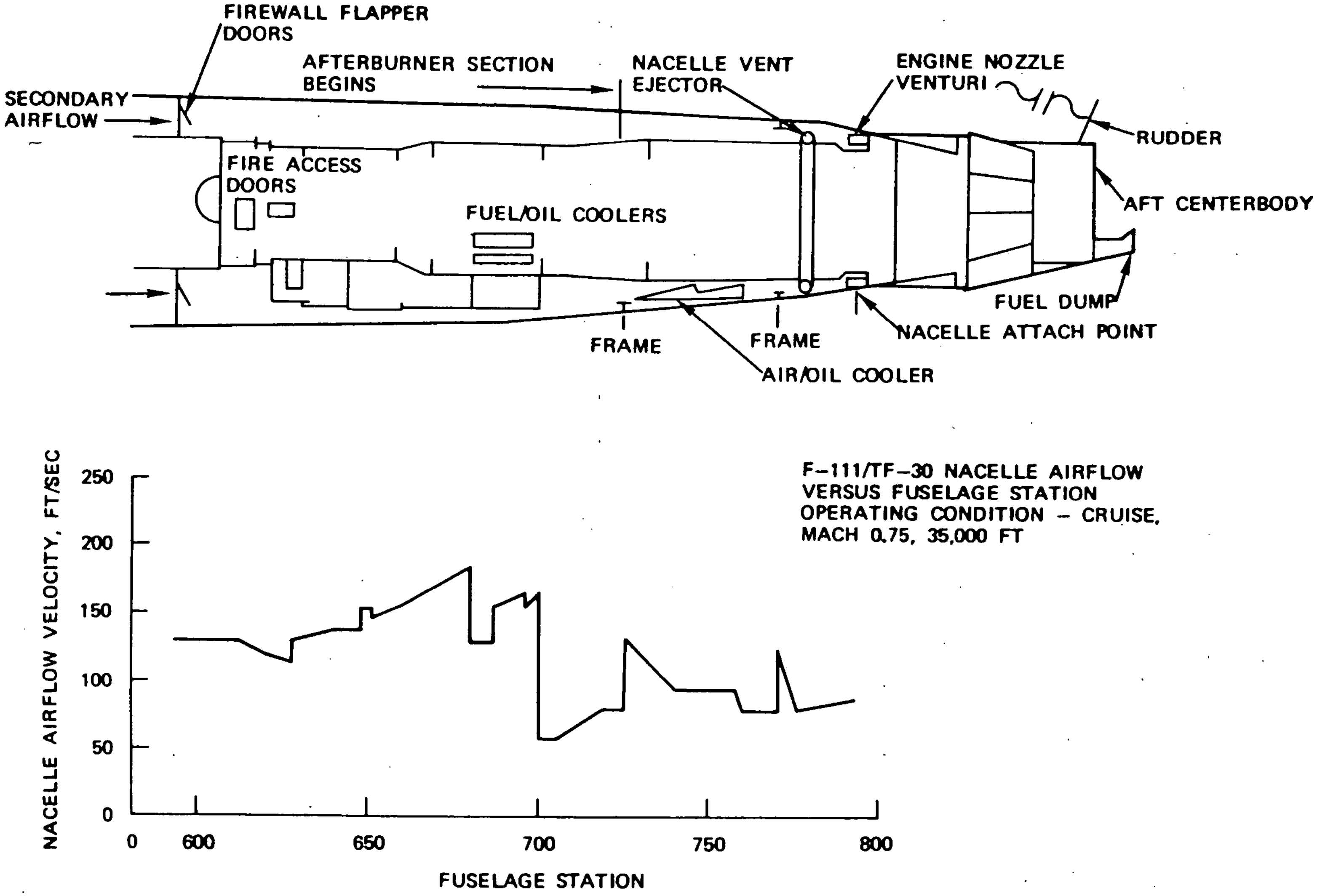


FIGURE 9b. F-111 Nacelle Air Velocity.

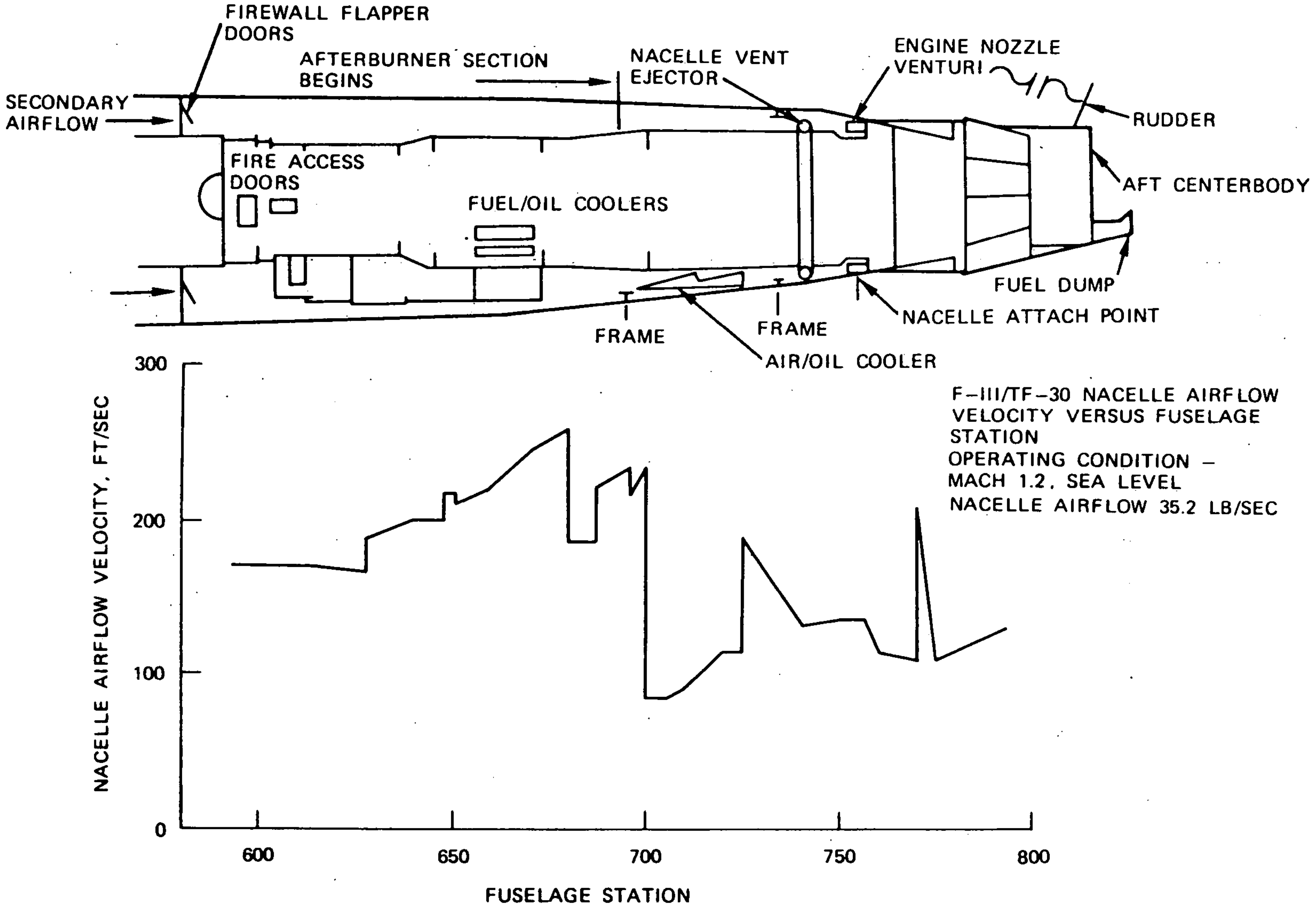


FIGURE 9c. F-111 Nacelle Air Velocity.

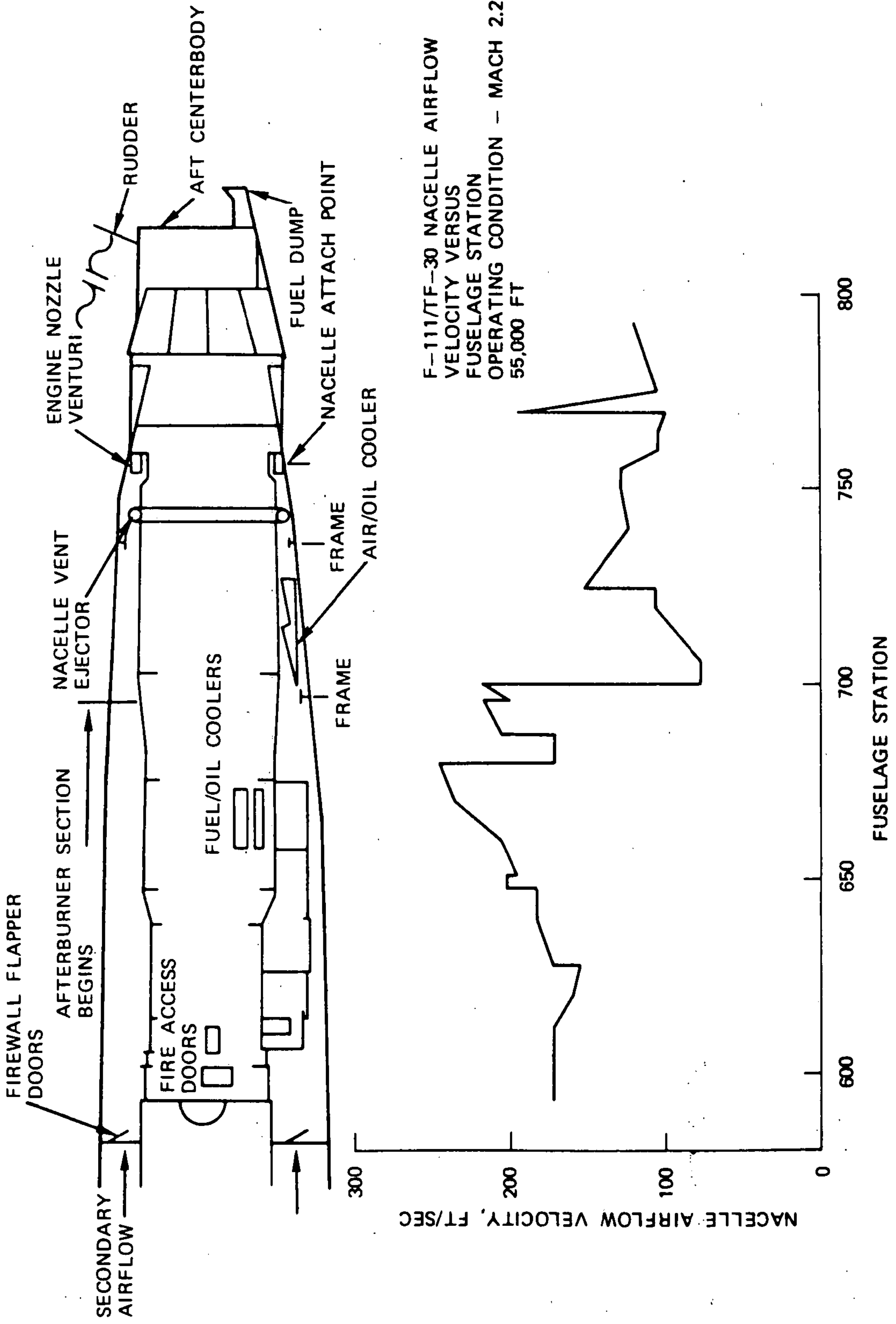


FIGURE 9d. F-111 Nacelle Air Velocity.

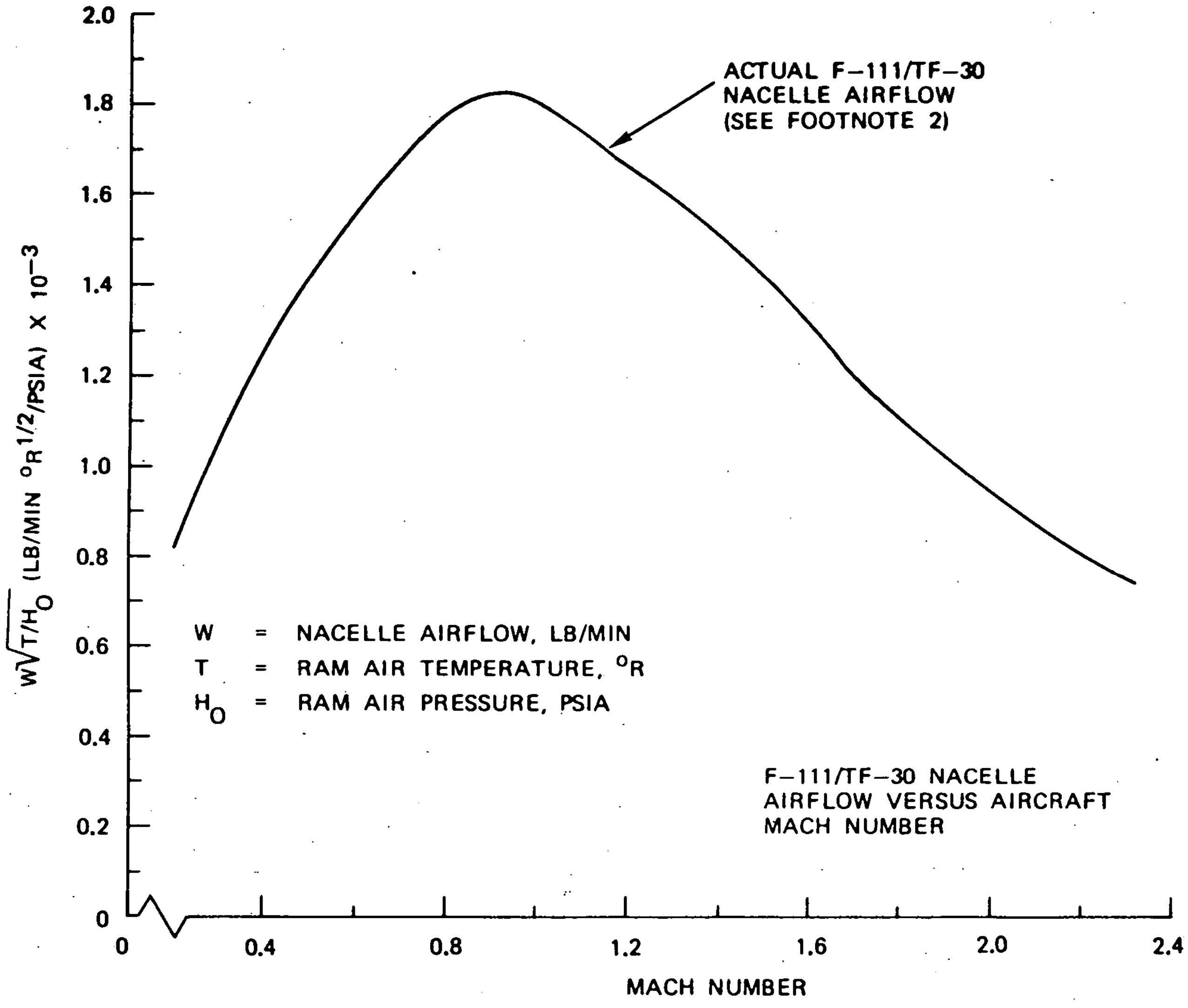


FIGURE 10a. F-111 Nacelle Airflow and Pressure.

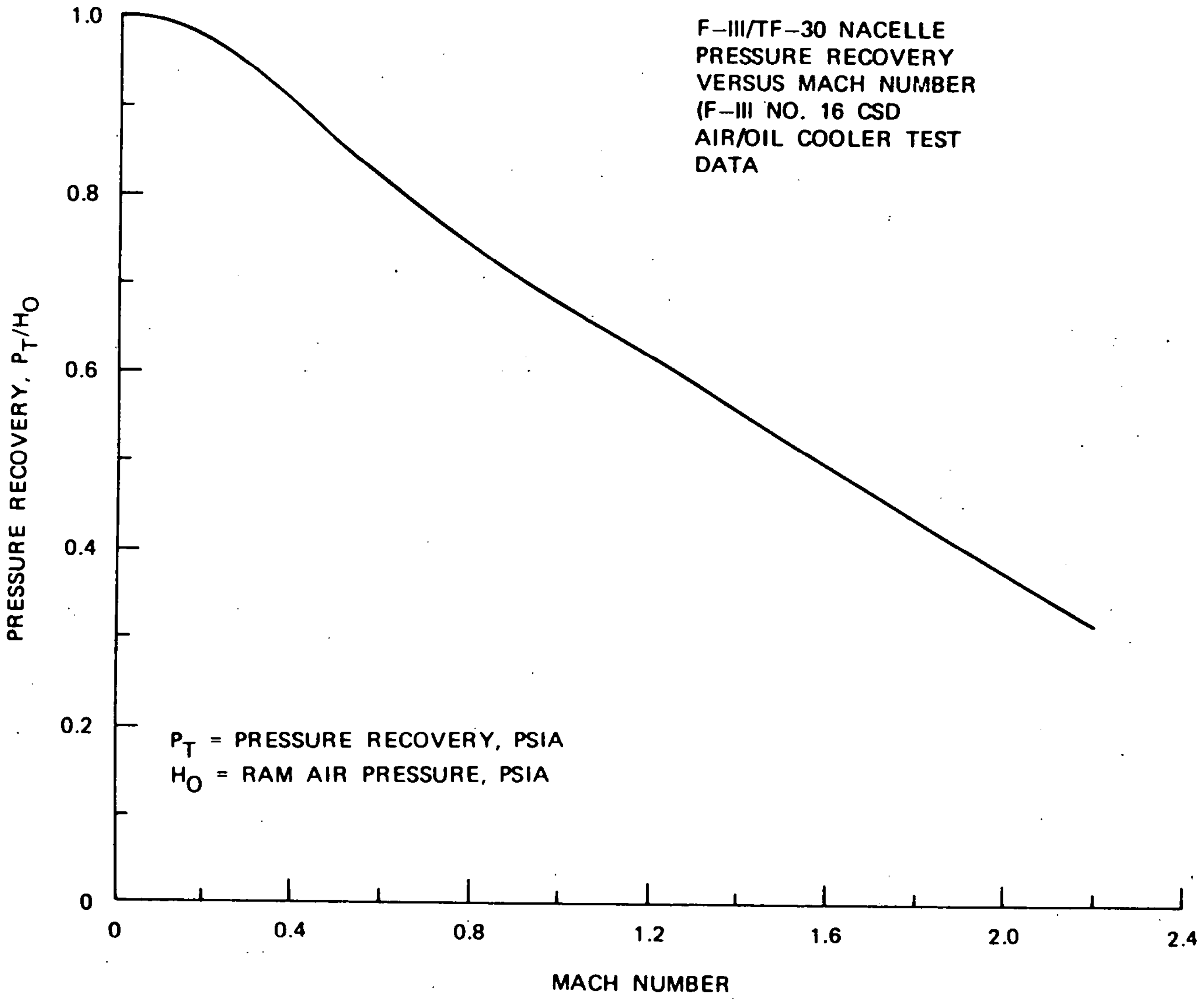


FIGURE 10b. F-111 Nacelle Airflow and Pressure.

The engine compartments are isolated from each other. Fuel shutoff valves for the engine supply lines are located in the main wheel well on the forward wall. The aircraft hydraulic fluid shutoff valves are located in the compartment just forward of the firewall at fuselage station 593. These shutoff valves (fuel and hydraulic) are actuated from the crew station.

Separate overboard drains are provided for the engine compartment. The engine seal drains are individually routed to a drain pan located on the bottom of the engine. These combustibles are drained overboard through a single opening on the nacelle bottom centerline.

Fuel is used as the hydraulic fluid for operation of engine components. Consequently, small high-pressure fuel lines are routed on all areas of the external engine case. The engine fuel supply line is routed through the forward firewall along the right side of the engine and terminates forward of the engine hot sections. Bleed air extracted for service use is routed along the left side of the engine and through the forward firewall. The bleed-air connection is on the opposite side of the firewall away from the fuel supply connection. The bleed-air duct in the engine compartment near the firewall is insulated.

Case temperatures of the F-111 ducted turbofan engine (Figure 11) are not excessive. Engine compartment air temperature, ram air temperature, and aircraft Mach number are defined as a function of time (Figure 12). For stabilized supersonic flight, compartment air temperature tracks ram air temperature and is generally about ram air temperature plus 30°F. Engine compartment structure temperatures are shown in Figure 13.

Without failure of electrical or mechanical components, the most likely source of ignition in the engine compartment is the 16th stage compressor bleed-air ducts utilized for aircraft service (2 1/2-inch outside diameter steel) and nacelle ventilation ejector (1 1/2-inch outside diameter steel). Maximum temperature of these ducts is approximately 1000°F. However, compartment air ventilation rates result in ignition temperatures of such magnitude that the bleed-air ducts are not ignition sources. The service bleed-air duct is routed across the top of the engine and forward along the left side of the engine to the firewall. The nacelle ventilation duct is routed aft from the service duct at approximately fuselage station 650 along the engine left side to approximately fuselage station 725. At this point the air pressure is regulated. The duct is routed under the engine and aft along the right side to an ejector ring at the aft end of the afterburner. Air flows in the ventilation duct downstream of the regulating valve only when the aircraft is on the ground.

The engine fire detection system (Figure 14) provides a visual warning of fire or overheat conditions that may occur in either engine compartment. The system includes two control units (one for each engine), two sensing element assemblies (one for each engine), two warning lamps, and three test switches. The sensing elements are routed through the engine compartments. When a high-temperature condition occurs, the resulting temperature rise causes the electrical resistance of the sensing element to decrease. The control unit senses the resistance and lights the fire warning lamp in the crew station.

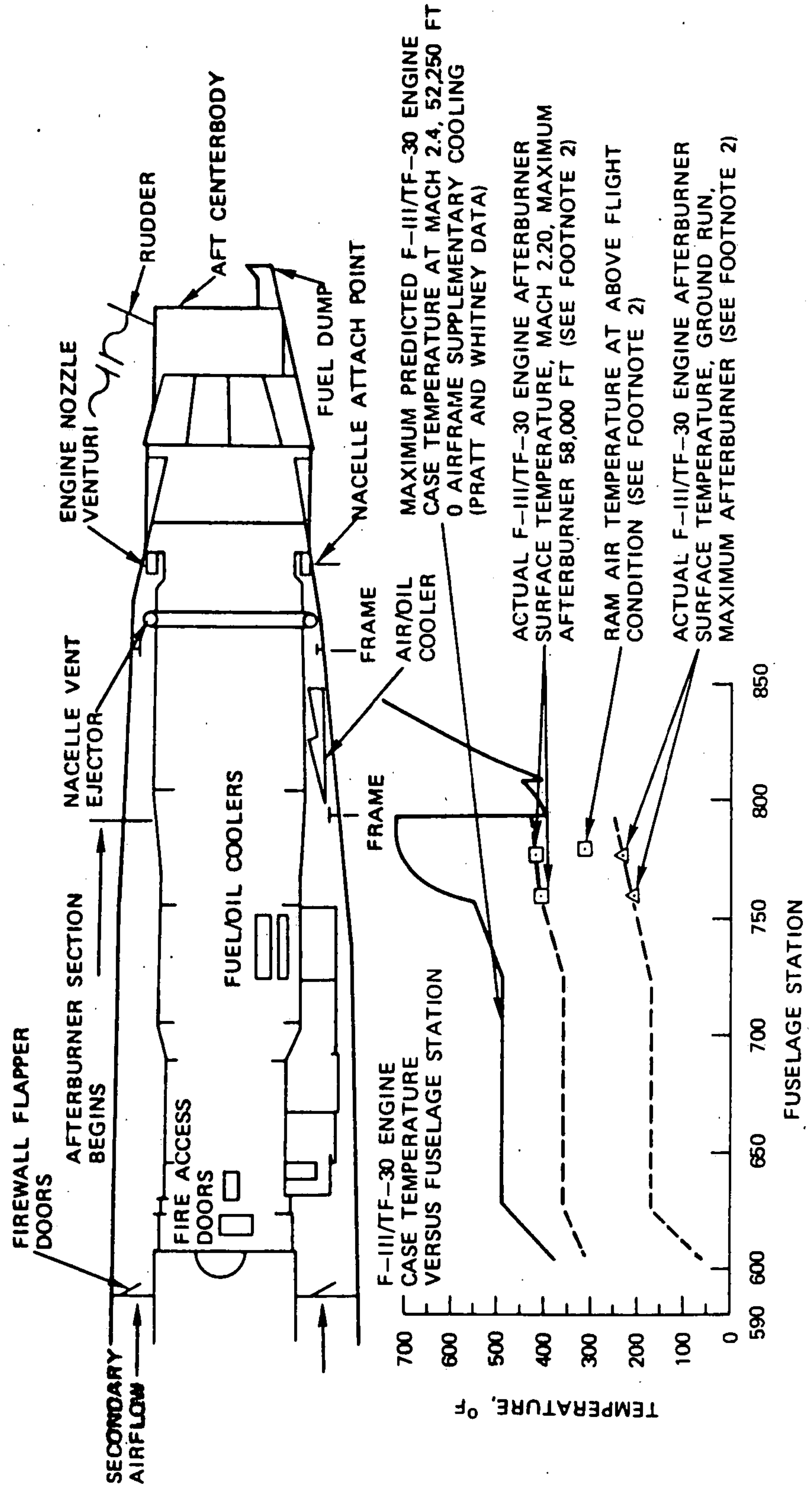


FIGURE 11. F-111 Engine Case Temperature.

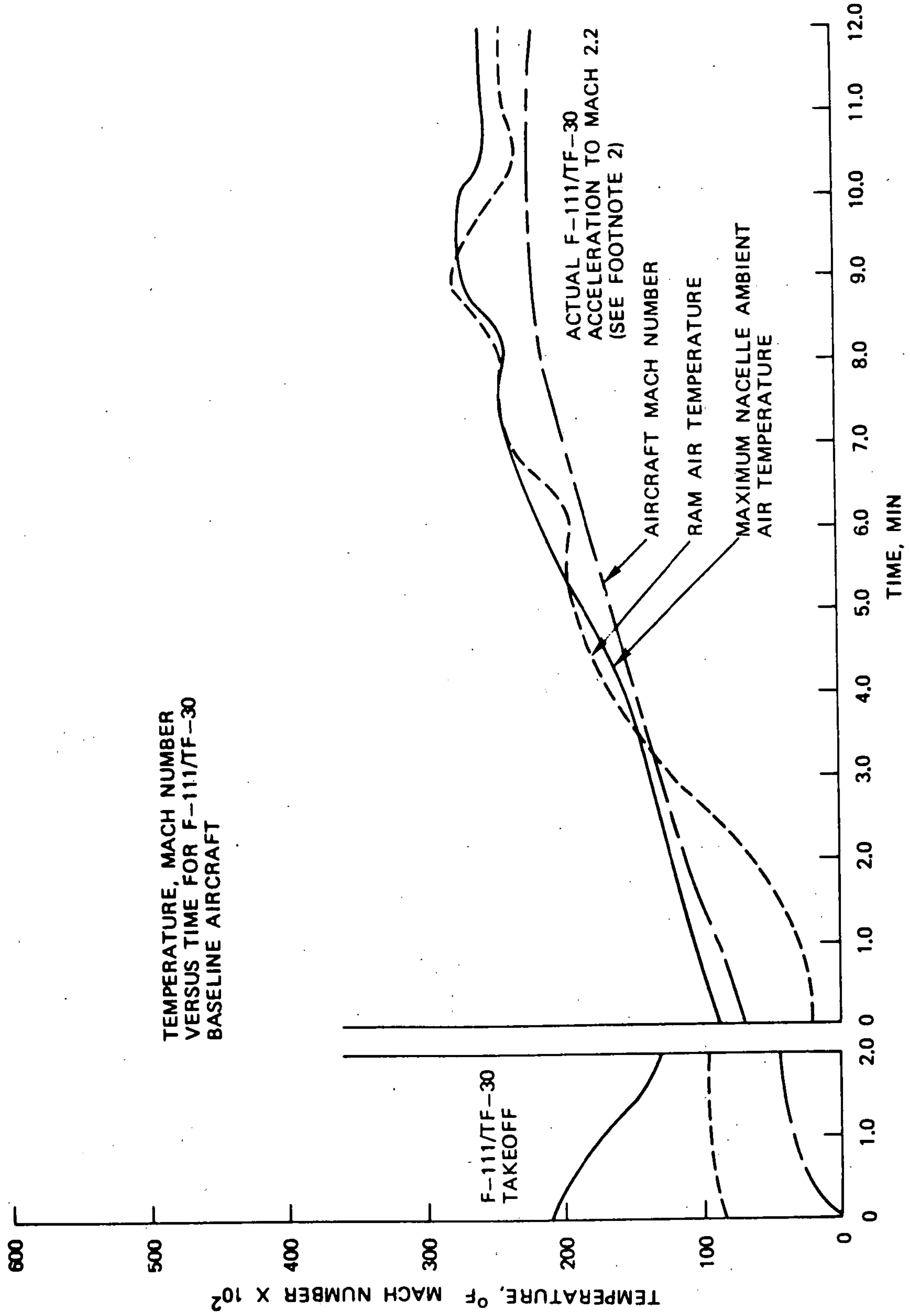


FIGURE 12. F-111 Nacelle Air Temperatures.

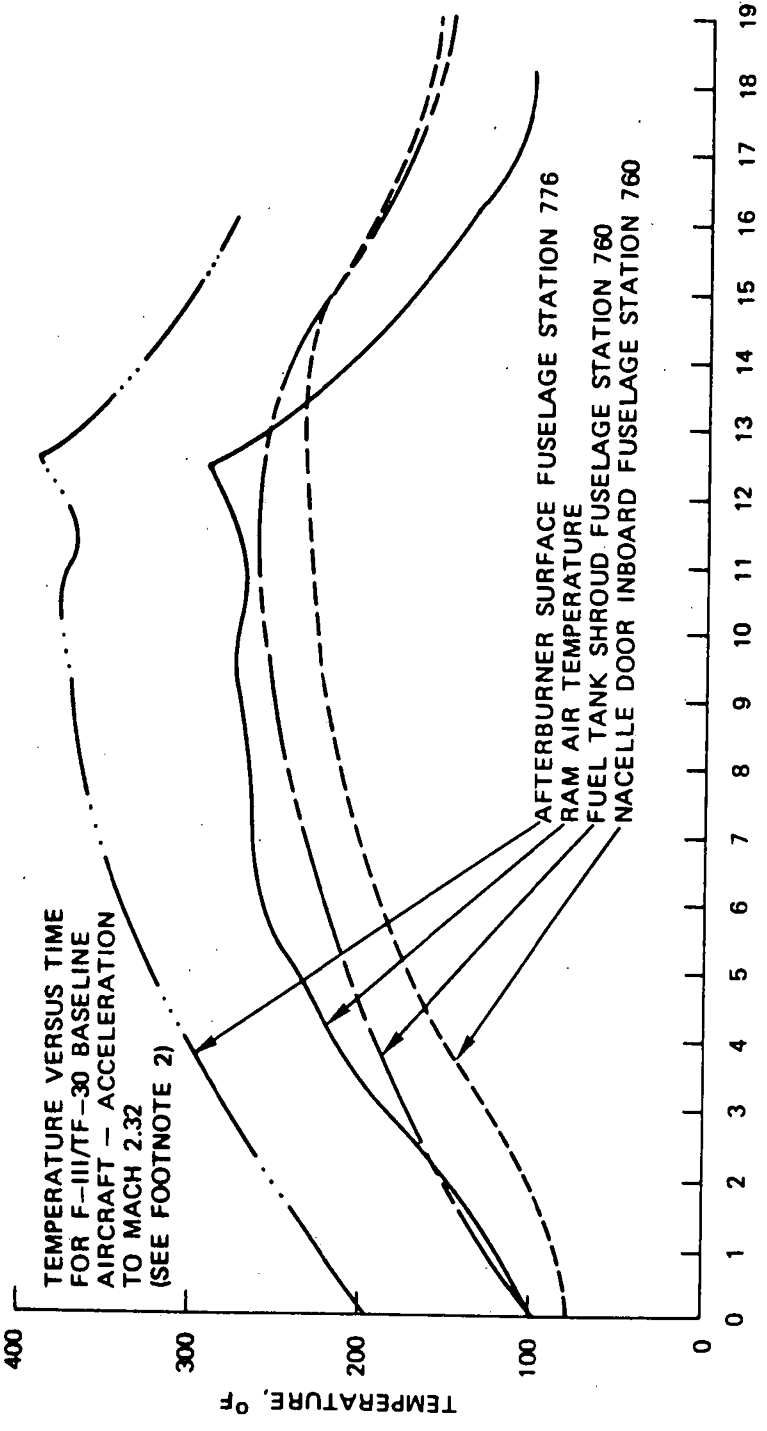
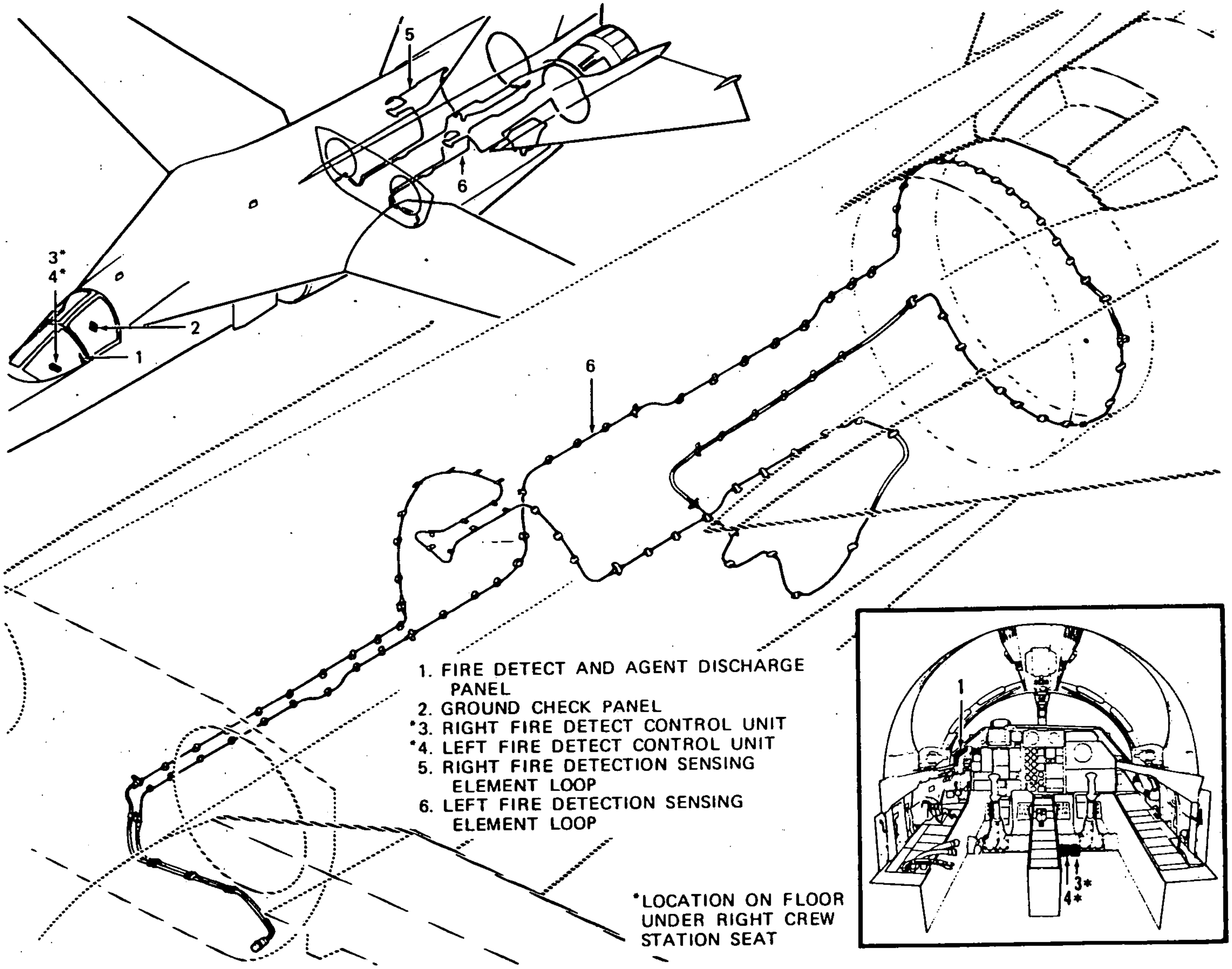


FIGURE 13. F-111 Nacelle Structure Temperature Examples.



1. FIRE DETECT AND AGENT DISCHARGE PANEL
2. GROUND CHECK PANEL
*3. RIGHT FIRE DETECT CONTROL UNIT
*4. LEFT FIRE DETECT CONTROL UNIT
5. RIGHT FIRE DETECTION SENSING ELEMENT LOOP
6. LEFT FIRE DETECTION SENSING ELEMENT LOOP

*LOCATION ON FLOOR UNDER RIGHT CREW STATION SEAT

FIGURE 14. Engine Fire Detection System Component Location.

An engine compartment fire extinguishing system (Figure 15) is provided. The system includes a fire extinguishing agent and container with a separate discharge valve for each engine, two fire pushbutton switches, and an agent discharge/fire detect test switch. The agent container is located in the bottom of the fuselage aft of the main wheel well. The agent container is a sealed-type storage tank weighing 23.2 pounds maximum when filled with dibromodifluoromethane agent. The container is designed for storage temperature between -65 and 160°F or service temperature between -65 and 275°F, with temperatures up to 290°F being permissible for short periods of time (5 minutes maximum). When the discharge valve for either engine is energized, an explosive cartridge ruptures a frangible disk releasing all of the agent to the selected engine. Crew action in the event of an engine compartment fire warning is as follows:

1. Retard throttle of affected engine to the off position.

2. Depress the fire pushbutton for the compartment indicating a fire. (This action arms the agent container cartridge and closes the hydraulic and fuel shutoff valves for the selected engine.)

3. Position the agent discharge switch to agent discharge. (This discharges the fire extinguishing agent into the engine nacelle selected by the pushbutton.)

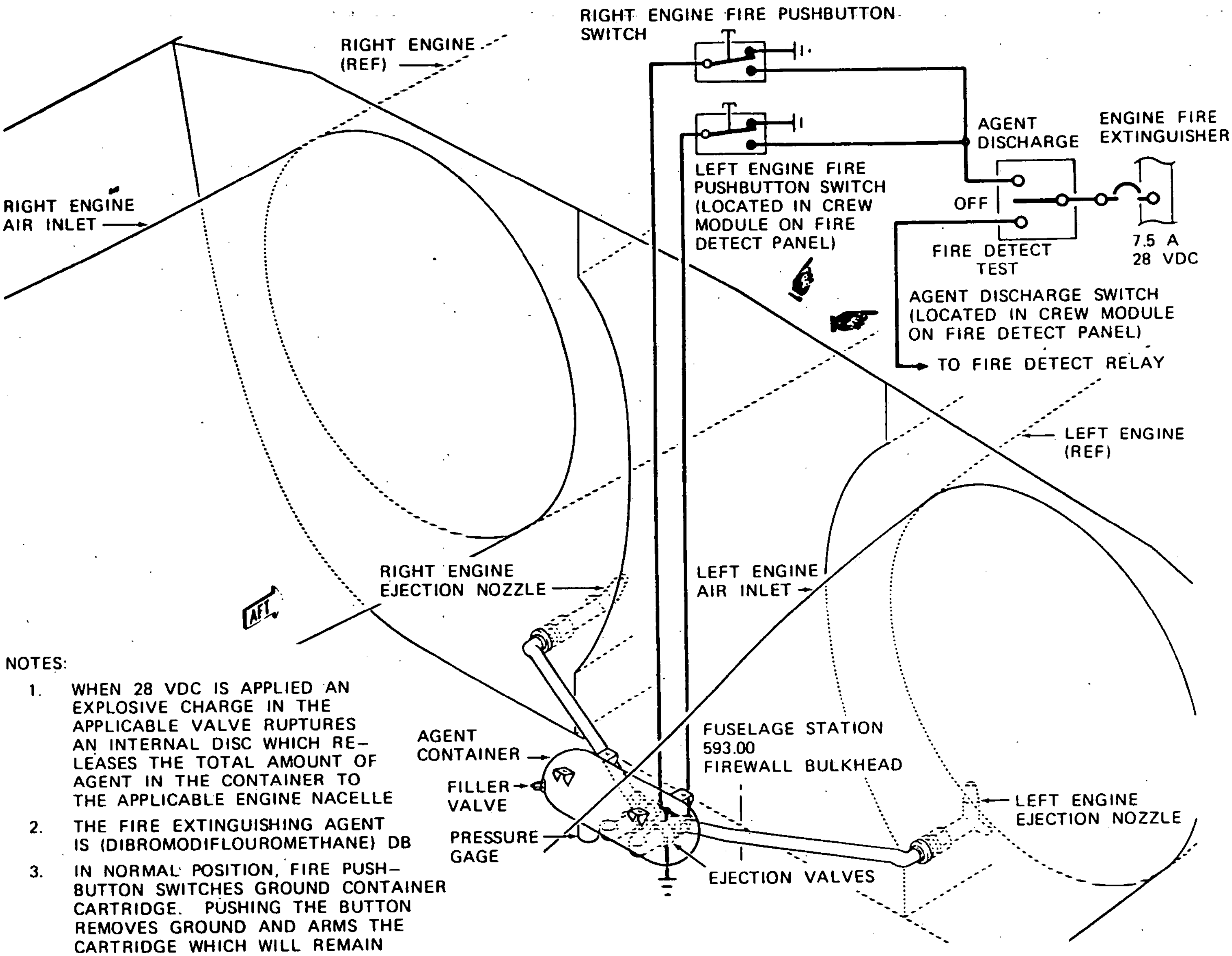
OTHER COMPARTMENTS

F-111 baseline aircraft secondary fire zones (Figure 16) include the forward equipment bay, cheek areas, weapons bay, main wheel well, and upper routing tunnel. Ventilation is utilized to reduce potential fire hazards in these compartments by removing flammable vapors, reducing the stay-time of flammable vapors, and reducing temperatures. The baseline F-111 aircraft ventilation paths of the secondary fire zones are shown schematically in Figure 17. The ventilation flow follows the following route:

1. Cabin and electronic cooling air discharges into the nose wheel well cheek areas and flows aft into the upper routing trough (via the vertical routing tubes) and into the weapons bay routing tunnel, the weapons bay proper (through holes in the forward tunnel), and the weapons bay cheek areas.

2. The weapons bay air enters the main landing gear wheel well and exits through cutouts at the outboard aft corners of the wheel well door.

3. The flow in the upper routing trough branches at the main landing gear wheel well—part flowing down into the main landing gear wheel well and during ground operations, part continues aft in the upper routing tunnel to exit at the aft centerbody louvers. Recent F-111 flight test experience has shown that during flight, ventilation airflow in the upper aft fuselage routing tunnel is forward. Air enters the routing tunnel through the louvers in the centerbody sides and flows around the rudder post and stabilizer and other nonsealed joints in the aft fuselage area. This air flows forward through the aft routing tunnel into the wing cavity area and is discharged overboard in the wing seal area.



NOTES:

1. WHEN 28 VDC IS APPLIED AN EXPLOSIVE CHARGE IN THE APPLICABLE VALVE RUPTURES AN INTERNAL DISC WHICH RELEASES THE TOTAL AMOUNT OF AGENT IN THE CONTAINER TO THE APPLICABLE ENGINE NACELLE
2. THE FIRE EXTINGUISHING AGENT IS (DIBROMODIFLOUROMETHANE) DB
3. IN NORMAL POSITION, FIRE PUSHBUTTON SWITCHES GROUND CONTAINER CARTRIDGE. PUSHING THE BUTTON REMOVES GROUND AND ARMS THE CARTRIDGE WHICH WILL REMAIN ARMED UNTIL BUTTON IS PUSHED AGAIN

FIGURE 15. Engine Fire Extinguishing System Schematic.

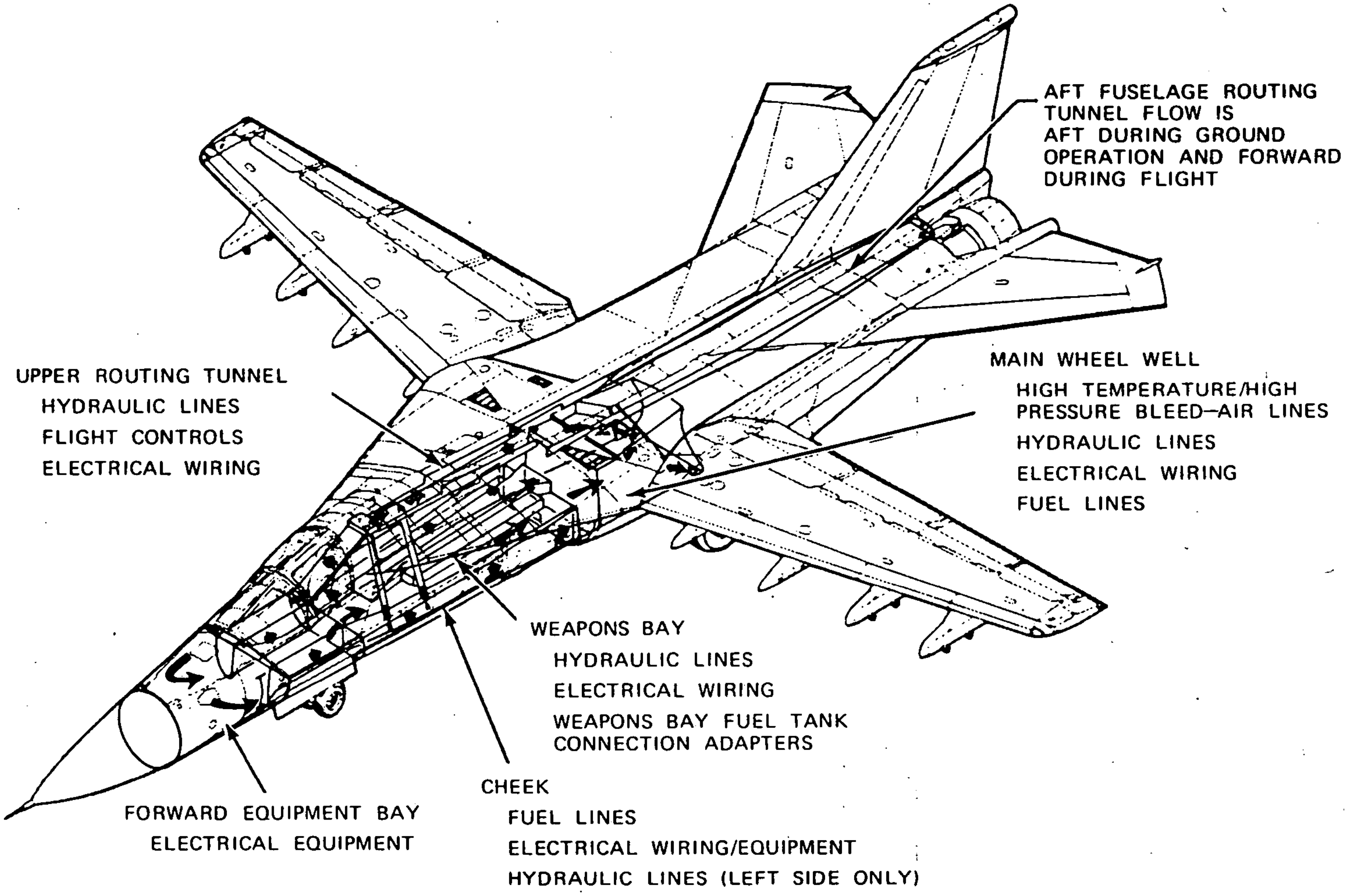
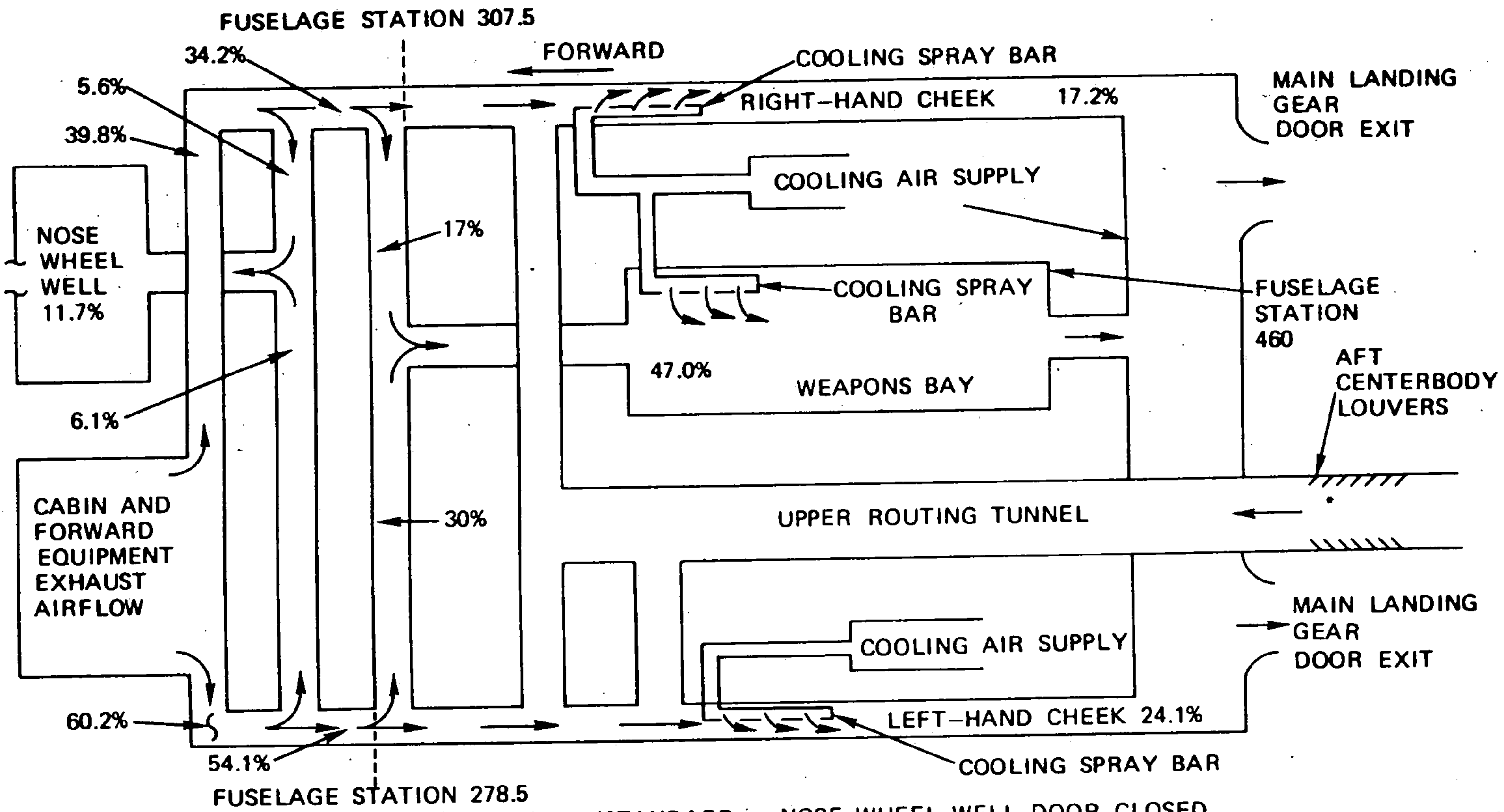


FIGURE 16. Baseline Aircraft Ventilation.



ESTIMATED STEADY-STATE AIRFLOW, LB/MIN (STANDARD DAY)

AIR SOURCE	MACH NUMBER 0.85	MACH NUMBER 1.20
CREW MODULE AND ELECTRONIC BAY	86	128
WEAPONS BAY SPRAY BAR	0	1.6
LEFT–HAND CHEEK SPRAY BAR	0.7	1.0
RIGHT–HAND CHEEK SPRAY BAR	0.7	1.0

NOSE WHEEL WELL DOOR CLOSED
AIRFLOW FROM CREW MODULE AND ELECTRONICS BAY FOR FLIGHT AT MACH 2.2 AND 49,000 FT WILL BE APPROXIMATELY 123 LB/MIN (MAXIMUM)

*FLOW IS FORWARD DURING FLIGHT AND AFT DURING GROUND OPERATIONS

FIGURE 17. Aircraft Ventilation Airflow Split Estimate.

Figure 17 also defines steady-state airflow rates for specified conditions with the nose landing gear closed. Air temperature in the F-111 internal compartment is a function of the amount of cooling air supplied to the bays as well as the flight conditions. Equipment bays are cooled to maintain a maximum compartment air temperature of 150°F.

The inadequacy of ventilation as the only fire protection provision in the secondary fire zones became apparent during F-111 flight test and operational program.

A main wheel well overheat detection system was added to provide the crew with a visual warning of an overheat condition. Sensing elements (Figure 18) are routed through the main wheel well in critical areas primarily adjacent to bleed-air ducting. When a high-temperature condition occurs, the resulting temperature rise causes the electrical resistance of the sensing elements to decrease. A control unit will sense the decrease in electrical resistance and illuminate the wheel well hot caution lamp.

A weapons bay and cheek area fire detection system (Figure 19) was added to provide the crew with a visual warning of an overheat/fire condition. The system consists of a control unit, sensing elements, two switches, and a red warning lamp. When a high-temperature condition occurs, the resulting temperature rise causes the electrical resistance to decrease. The control unit senses the decreased resistance of the sensing elements and the warning lamp in the fuselage fire pushbutton will light to provide a warning to the crew.

A fuselage fire extinguishing system was added to permit the crew to extinguish a fire in the cheek and stabilization glove areas and the weapons bay. The system consists of a pushbutton switch, an actuating toggle switch, 11.25 pounds bromotrifluoromethane extinguishing agent charged to 600 psi with dry nitrogen at 70°F, 378 in^3 agent container, and necessary piping. To actuate the system, a crew member must depress the pushbutton and then place the toggle switch to agent discharge position. This action discharges the extinguishing agent from the container located in the left aft corner of the nose wheel well. The container is immediately forward of the aft nose wheel well bulkhead at fuselage station 269.6. The agent is discharged from nozzles in the weapons bay and the left and right cheek areas. Ventilation air carries the agent throughout the weapons bay, cheek areas, and routing tunnels.

Forward Equipment Bay

The forward equipment bay (Figure 16) contains electronics equipment which, under failure conditions, could arc and spark creating an ignition source. Since combustibles are absent from this area of the aircraft, this area has a very low fire hazard potential.

Cheek Areas

The cheek areas are located as shown in Figure 16. The left-hand weapons bay cheek is used as a routing tunnel for the hydraulic system, fuel system, throttle controls, and electrical system. Between fuselage stations 278.5 and 307.5, the aircraft electrical power cables exit from the corseted weapons bay tunnel into the left-hand cheek and are routed forward.

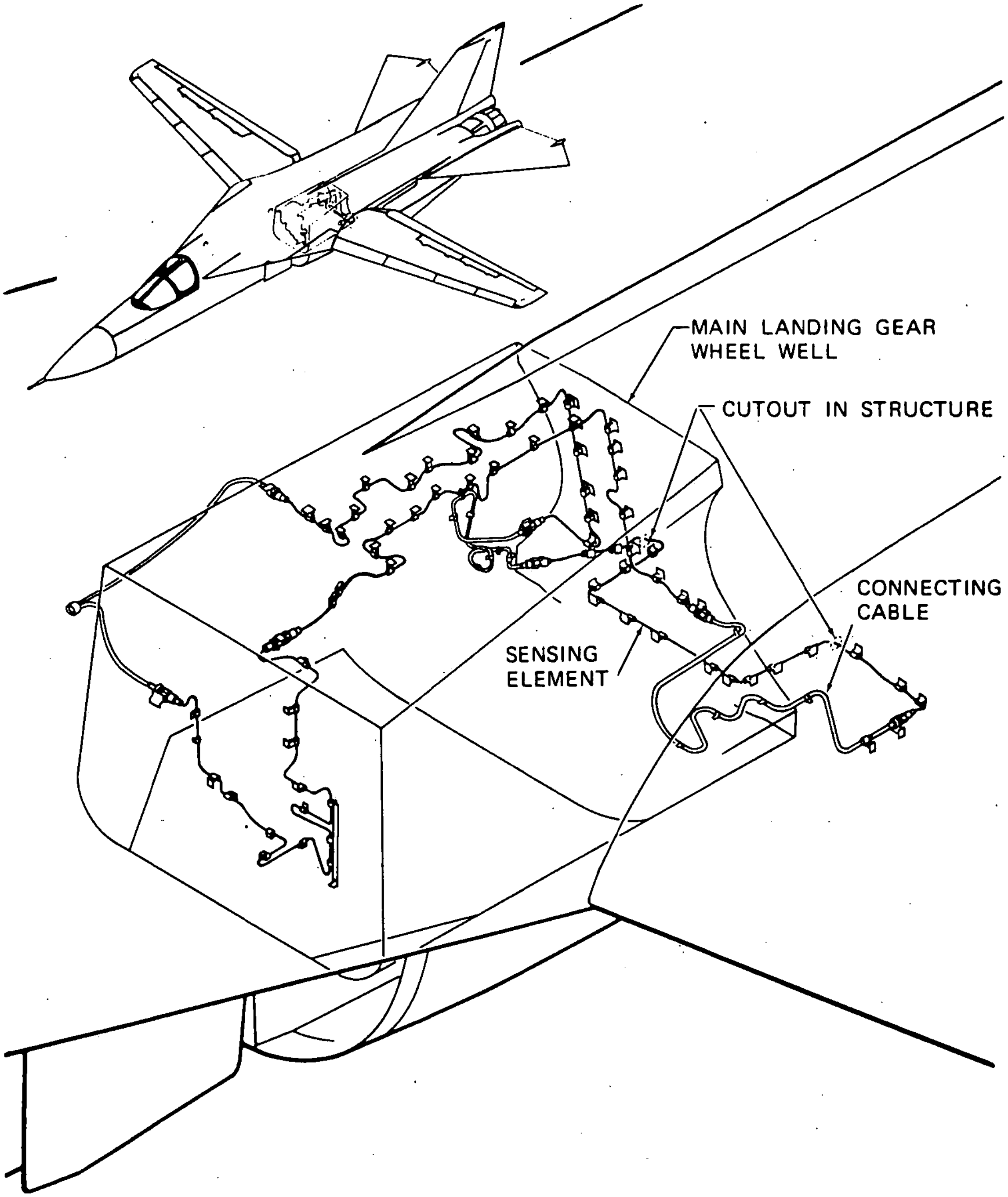


FIGURE 18. Wheel Well Overheat Detection System Location.

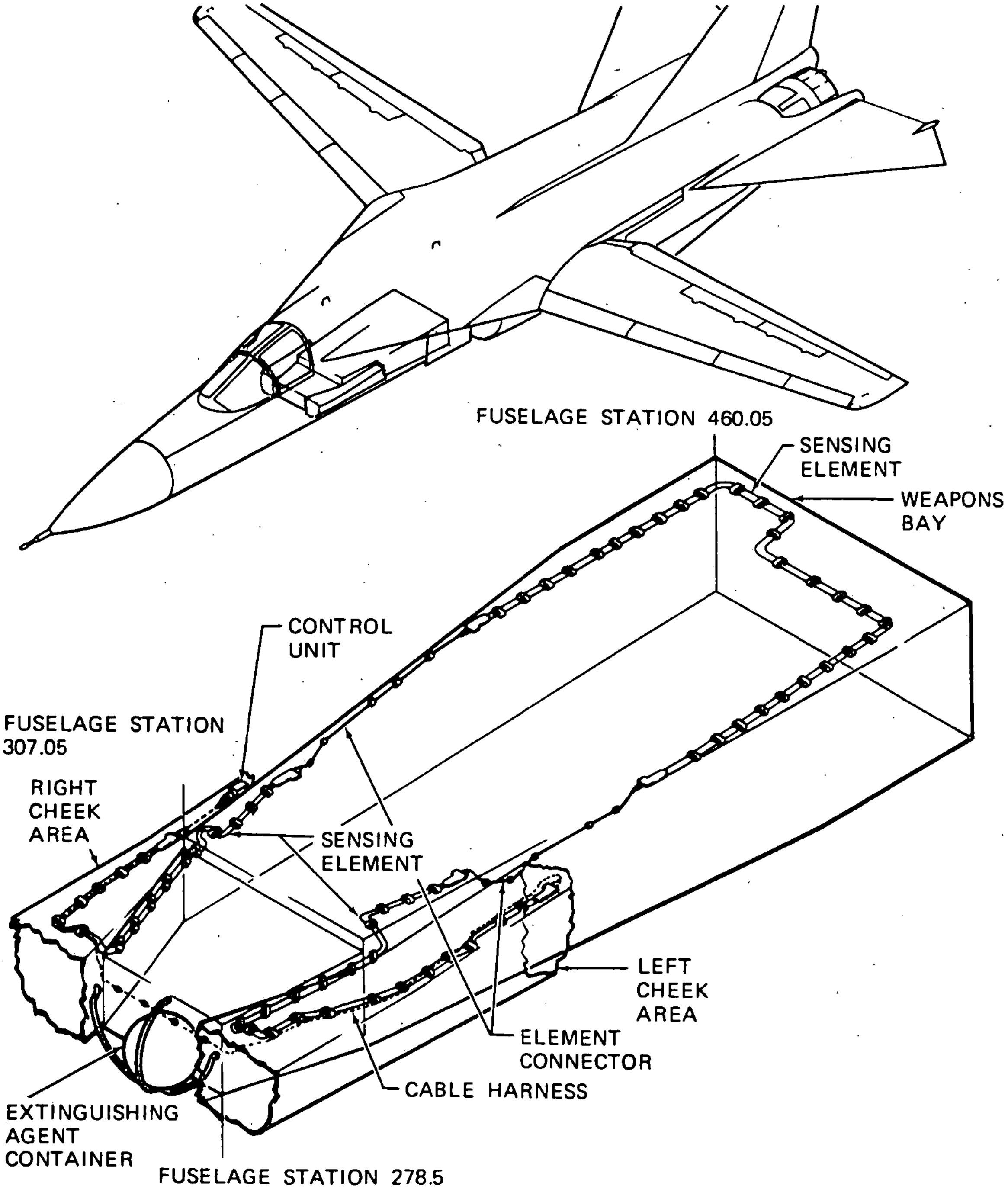


FIGURE 19. Weapons Bay, Cheek, and Stabilization Glove Fire Detection and Fire Extinguishing System.

Fuel lines in the left-hand cheek are the 3/8-inch-diameter precheck line and the 3-inch-diameter aircraft refuel line. The refuel line enters the cheek area for about 2 feet forward to the single-point refuel adapter at fuselage station 370. The precheck line contains fuel during the entire flight. The refuel line will contain fuel until approximately 20 minutes after the wing tanks are empty.

Small nose landing gear hydraulic lines are routed along the bottom of the left cheek. A fuel tank is located directly above the cheek. The electrical wiring and equipment in the left cheek is located forward of the refuel line. The precheck fuel line and small hydraulic lines are routed through the area containing electrical wiring and equipment. Because of the isolation of potential ignition sources from the sources of combustible vapors, the left-hand cheek area aft of approximately fuselage station 364 has a low fire hazard potential.

The right-hand weapons bay cheek area is used as a routing tunnel for air pressure sensing lines, electrical system, and electrical equipment storage. A defuel line enters the right cheek area for about 2 feet forward to the defuel adapter at approximately fuselage station 364. This line will contain fuel under pressure as long as the aircraft fuel pumps are on. Electrical wiring is routed along the cheek area below the fuel line. A fuel tank is located above the cheek.

Airflow in the cheek bays are temperature controlled to 150°F maximum. Predicted structure temperatures within the cheek area are presented in Figure 20. Another example is a longeron (Figure 20) which forms the lower surface of the cheek area. The cheek frame/longeron temperatures are representative of those expected at Mach 2.2 and 50,000 feet in the region where the cheek is cooled to 160°F. Temperatures shown at fuselage stations 448 and 420 are typical of the uncooled cheek areas. Transient temperatures at Mach 2.5 and 50,000 feet are shown in Figure 20.

Weapons Bay

The weapons bay is located as shown in Figures 2 and 16. The irregular-shaped compartment extends from fuselage stations 287.5 to 460.5. Maximum width is approximately 60 inches and maximum height is approximately 30.1 inches. Total gross volume of the weapons bay is approximately 125 ft^3. Figure 21 is a simplified sketch of the F-111A weapons bay showing adjacent areas.

The weapons bay contains potential sources of combustible vapors. These sources are:

1. Direct leakage from the fuel tanks above the bay
2. Indirect leakage from the fuel tanks into the routing tube through the cheeks and into the weapons bay
3. Leakage from hydraulic lines and components.

Potential sources of ignition are the gun and main power cables routed along the top of the bay.

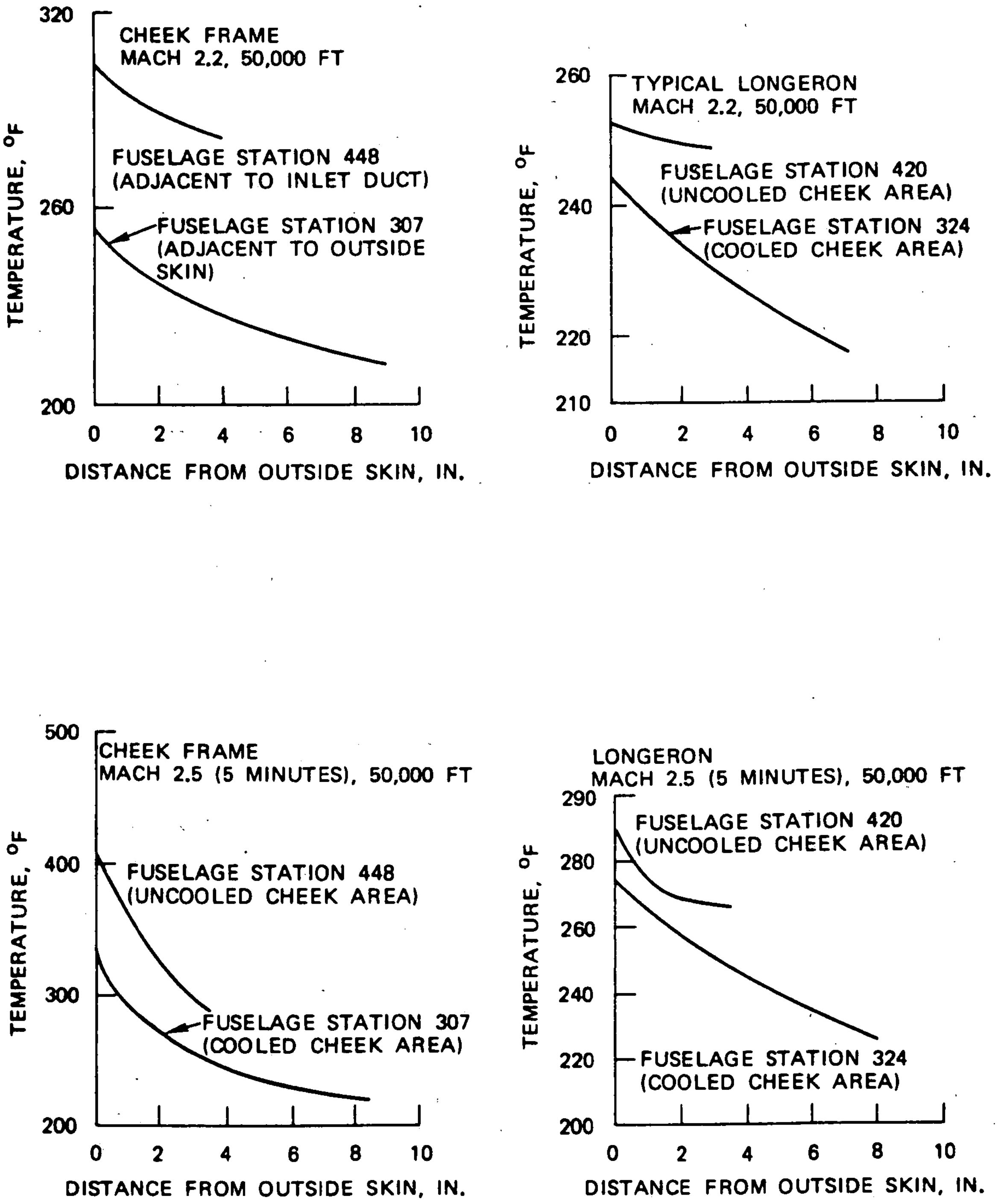


FIGURE 20. Example Temperature Distribution Estimate in F-111 Cheek Area. (See Footnote 1).

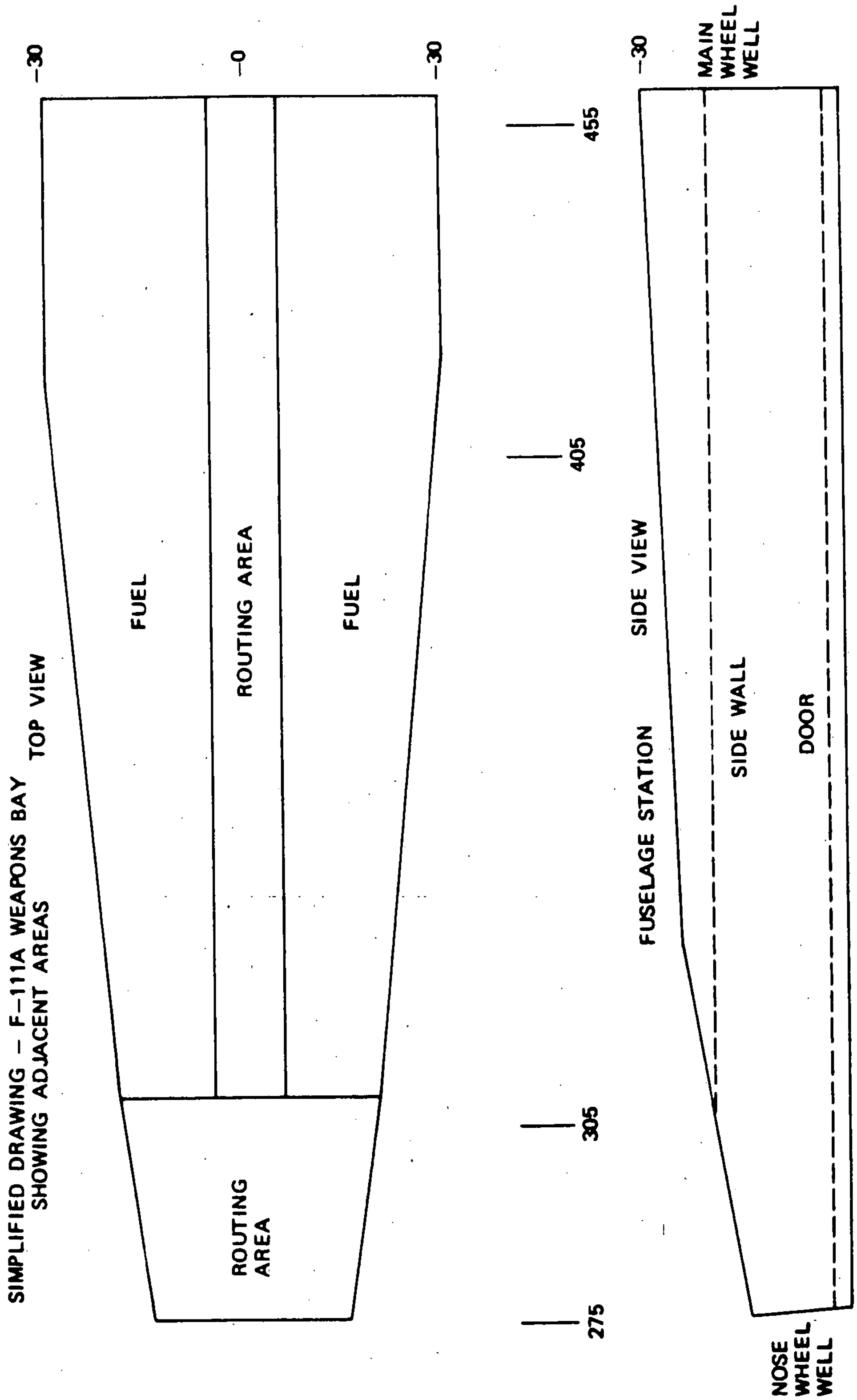


FIGURE 21. Weapons Bay Schematic.

The weapons bay has a temperature control which controls the flow of cooling air to prevent the bay temperatures from exceeding 150°F. This cooling air is used only when the bay temperatures approach 150°F. Operation of the cooling air at all times would add an undesirable bleed-air penalty to the aircraft performance and range parameters.

Figure 22 presents estimated weapons bay wall temperatures for the F-111 Area Intercept mission.

Main Wheel Well

The main wheel well (Figures 2 and 16) is located aft of the weapons bay. This compartment contains potential sources of combustible vapors from:

1. The fuel lines routed along each side
2. The numerous hydraulic components and plumbing
3. The fuel tanks located immediately forward, above, and aft of the compartment.

An abundant supply of air is available, since the major portion of the environmental control system discharge flows through this area. Potential sources of ignition are:

1. Engine bleed-air duct leakage
2. Main power cables and secondary wiring.

The main landing gear wheel well is not fireproof nor is it isolated.

The most severe aerodynamic heating occurs during continuous flight at Mach 2.2. The Mach 2.5 dash for 5 minutes is not of sufficient duration to cause significant temperature rise in the wheel well area. The adiabatic wall temperature is 270°F. The maximum air temperature after being used for cabin and electronic equipment cooling is 150°F. The maximum predicted temperature of the air exiting the main wheel well is 238°F.

Upper Routing Tunnel

The upper routing tunnel (Figure 16) from the capsule glove to the wing box contains flight control system and electrical harnesses.

The upper routing tunnel aft of the wing box is used for:

1. Flight control system
2. Hydraulic service to the tail components

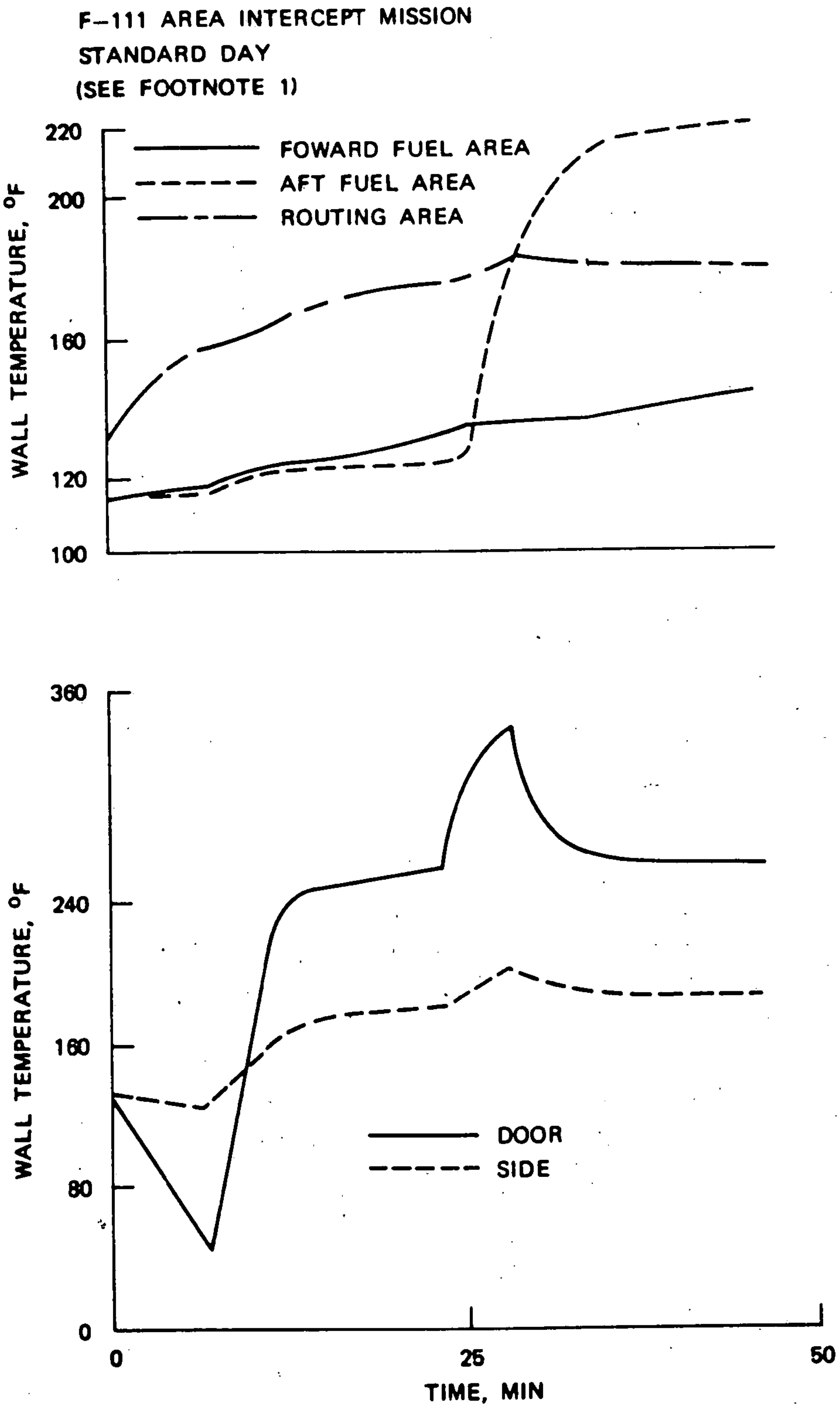


FIGURE 22. Weapons Bay Wall Temperature Estimates.

3. Fuel line interconnecting aft fuselage tanks with upper trap tank

4. Secondary electrical wires to the tail of the aircraft.

The possibility of a fire originating in this area is very remote.

At Mach 2.2 and 50,000 feet, the maximum predicted top routing tunnel temperature is 240°F in the region from fuselage stations 674 to 770. This temperature is reached after the adjacent fuel tank has emptied. Temperatures in the top routing tunnel forward of fuselage station 674 will be less than 240°F because of the cooling effect of fuel tanks and cooled compartments below the tunnel. Maximum top routing tunnel air temperature is predicted to be 270°F at the end of 5 minutes at Mach 2.5 and 50,000 feet. Recent flight test experience has shown that the tunnel airflow is forward during flight with velocity more than 20 ft/sec. The tunnel air temperature was approximately 150°F at Mach 2.2.

Nose Wheel Well

The nose wheel well is located as shown in Figure 2 and is 32 inches wide, 71 inches long, and 24.2 inches high. Potential sources of combustibles are hydraulic lines and components. Maximum air temperature in the nose wheel well is 192°F.

Crossover Area

The engine fire extinguisher container (Figure 15) is mounted in the crossover area (fuselage stations 573 to 593) immediately aft of the main wheel well. This compartment is bounded on the top and aft end by fuel tanks, by the inlet duct cavity on each side, in front by the main wheel well, and on the bottom by panels exposed to the outside air temperature and to aerodynamic heating. Hydraulic lines and insulated bleed-air ducts are routed through this compartment. The maximum temperature of the bleed-air duct insulation is 400°F. This compartment is not sealed; however, there is not any forced ventilation. Maximum predicted temperature for the fire extinguishing container, valve, or cartridge is 230°F (Mach 2.2, 30 minutes). It has been assumed that ambient air temperature in the compartment reaches adiabatic wall temperature (270°F).

FUEL SUBSYSTEM DESCRIPTION

A description of the F-111 fuel system is provided as a basis for part of the combat damage environment analysis conducted. Also included is a description of the A-7 aircraft fuel system which is used in defining the combat damage environment.

F-111 Fuel System Description

The F-111 fuel subsystem (Figure 23) consists of forward and aft integral fuselage tanks, two integral wing tanks, an integral vent tank, and the associated fuel pumps, controls, and indicators. During normal operation, the left engine receives fuel from the forward tank and the right engine receives fuel from the aft tank. Fuel from the wing tanks is

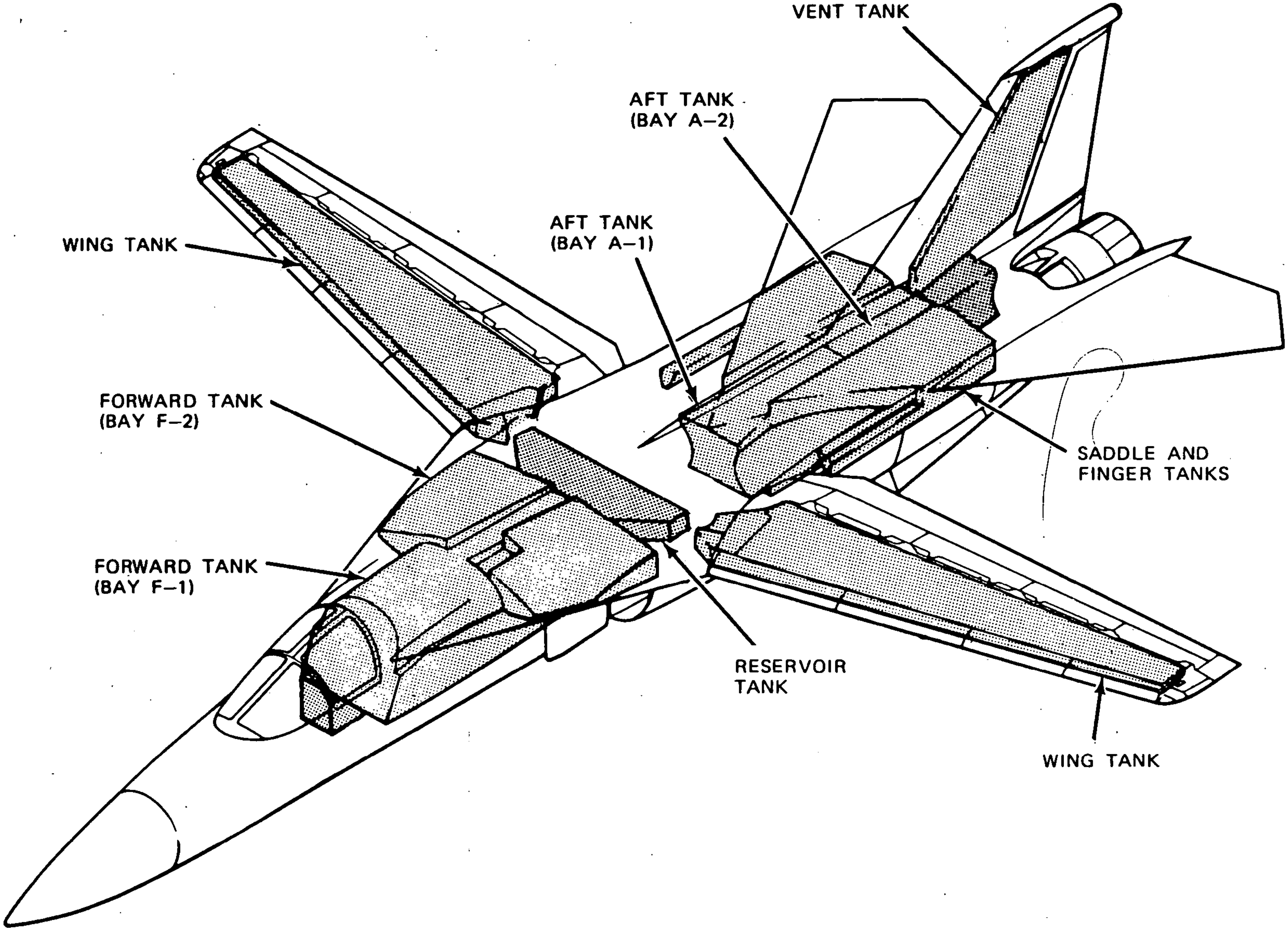


FIGURE 23. F-111 Fuel Tank Arrangement.

transferred to the fuselage tanks before being delivered to the engines. Provisions are made for air refueling from a boom-type tanker aircraft, and single-point refueling is provided for ground servicing.

The fuselage tanks are divided into compartments; the forward tank is divided into bays F-1 and F-2, and a reservoir tank. The reservoir tank includes the fuel contained in the wing carry-through box. Flapper valves allow fuel to flow from bay F-1 to F-2, and bay F-2 to the reservoir tank.

The aft tank is divided into bay A-1, which includes the centerline tank as well as two saddle and finger tanks, and bay A-2. Interconnecting standpipes and check valves allow fuel to flow from bay A-2 to A-1; ejector pumps transfer the fuel from the saddle and finger tanks to A-1.

The vent tank provides space for the expansion of fuel in the system when all tanks are fully serviced. Booster pumps in the fuselage tanks are provided for engine feed and transfer of fuel from the aft to forward tank. The fuel tank quantities for both full and 60% full evaluations (used for the combat evaluation) are shown in Table 1.

TABLE 1. F-111 Fuel Loading.

Tanks	Full, pounds	60% full, pounds	Remaining %
Wing	5,060	0	0
Reservoir	2,696	2,696	100
F-1	7,717	1,930	25
F-2	8,025	8,025	100
A-1	6,854	6,854	100
A-2	2,400	146	6
Total	32,752	19,651	60

The fuel tank walls will reach maximum steady-state temperatures when tanks are dry during Mach 2.2 of the Area Intercept mission. Predicted tank-wall temperatures based on dry-wall, steady-state assumptions are as follows:

1. Tank walls formed by external skins:

   a. Upper skin temperature = 245°F.

   b. Lower skin temperature = 252°F.

2. Tank walls adjacent to engine heated areas:

   a. 392°F maximum.

A-7 Aircraft Fuel System Description

The fuel supply subsystem for the A-7 aircraft consists of forward, mid, and aft fuselage tanks, a sump tank, an integral wing tank, and the associated fuel pumps, controls, and indicators. The location of these tanks on the aircraft is shown in Figure 24.

The fuel supply subsystem operates so that the fuel supply tanks feed the sump tank and the sump tank provides the engine feed. Fuel is moved from the supply tank to the sump tank by means of ejector pumps and gravity flow. The main fuel pump is a dual-element, high-pressure pump.

Provisions are included for aerial refueling from a boom-type tanker; single-point refueling is provided for ground servicing. The fuel tank quantities for both full and 60% full, which were used for the combat evaluation in *Combat Damage Evaluation*, are shown in Table 2.

TABLE 2. A-7 Aircraft Fuel Loading.

Tanks	Full, pounds	60% full, pounds	Remaining %
Right-hand forward	562	562	100
Left-hand forward	562	562	100
Right-hand mid	475	475	100
Left-hand mid	475	475	100
Aft	2,015	2,015	100
Sump	494	494	100
Wing	4,680	976	21
Total	9,263	5,559	60

FIRE INCIDENTS SUMMARY

A summary of actual F-111 fire and overheat incidents is presented in Table 3. These data provide a realistic basis for selecting typical failure modes and situations for evaluating fire hazard potential and extinguishing systems for present and future advanced aircraft. A comprehensive report[3] provided fire and explosion information for use in the investigation and analysis of aircraft fires/explosions.

Failure of bleed-air ducts in the F-111 engine compartment has resulted in damage to the nacelle but not because of fires or explosions. Afterburner fuel line failures and afterburner pump failures have resulted in engine compartment fires which have been detected by the fire warning system. The ignition source for these fires was the afterburner exhaust gases. Pilot action of retarding the throttle below afterburner settings removed the ignition source and shut off the supply of fuel.

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[3] Air Force Aero Propulsion Laboratory. *Fire and Explosion Manual for Aircraft Accident Investigators*, by Joseph M. Kuchta. Wright-Patterson AFB, OH, AFAPL, August 1973. (AFAPL-TR-73-74, publication UNCLASSIFIED.)

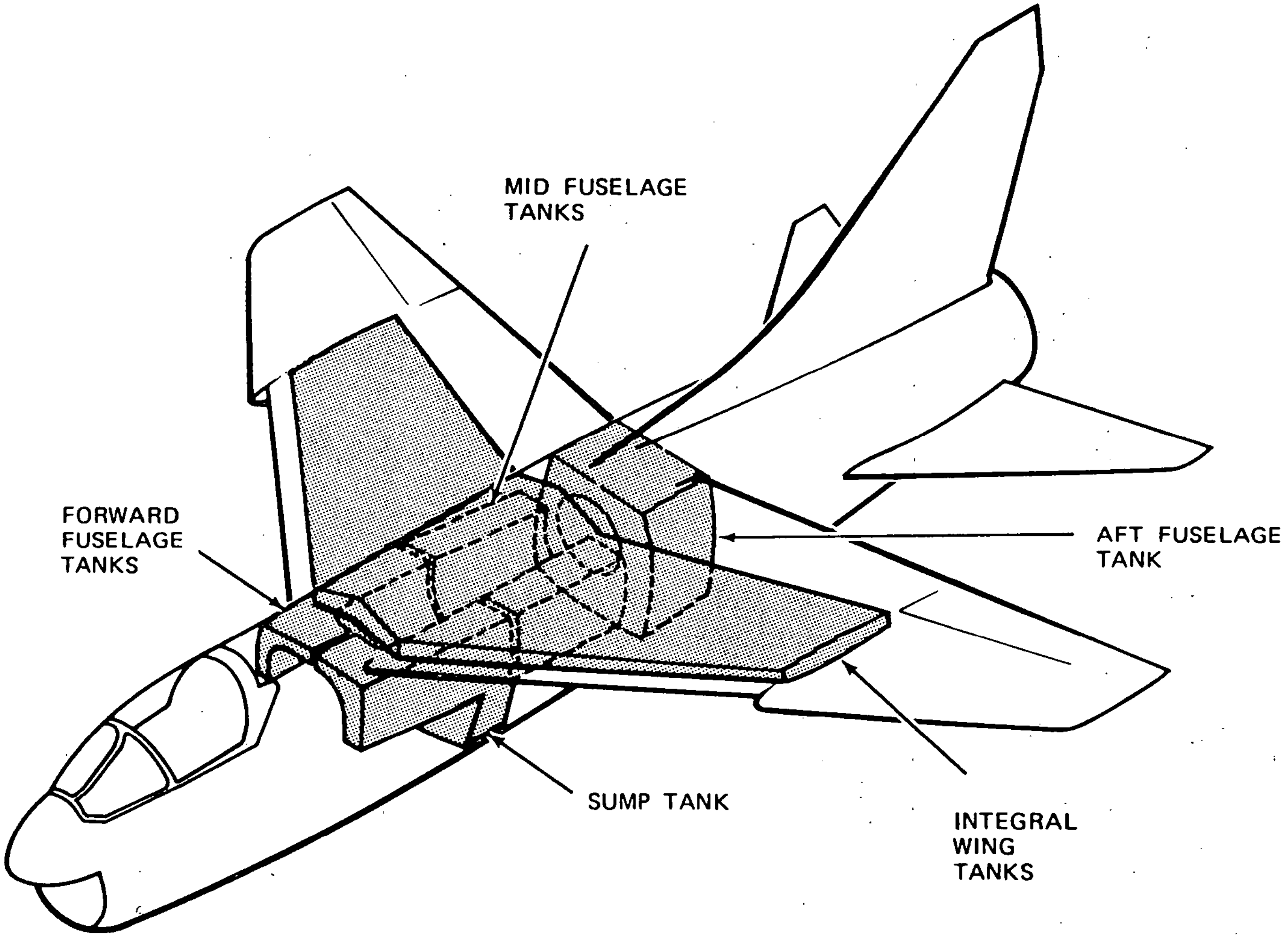

FIGURE 24. A-7 Integral Fuel Tank Locations.

TABLE 3. Fire Incidents – F-111 Summary.

Type incident	Cause	How detected	Results	Date and aircraft serial No.
Overheat	Bleed duct failure	Oil hot light	Nacelle damage	11-12-69 67-097
Overheat	Bleed duct failure	Postflight inspection	Nacelle damage	11-06-69 67-057
Overheat	Bleed duct failure	Oil hot light	Nacelle damage	06-28-72 67-051
Overheat	Bleed duct failure	Loud noise and oil hot light	Nacelle damage	03-25-72 67-066
Overheat	Bleed duct failure	Throttle sticking	Nacelle damage	12-03-71 67-069
Overheat	Bleed duct failure	Postflight inspection	Nacelle damage	02-23-71 67-061
Fire (fire warning light went out on retard from afterburner (agent not used))	Afterburner zone 1 fuel line failure	Fire warning light	Nacelle panel damage	04-21-72 66-058
Fire (fire warning light, shutoff fuel, discharged agent)	Afterburner zone 1 fuel supply line broke at case	Fire warning light	Nacelle damage and minor heat damage to engine	11-18-71 70-2378
Overheat	Broken clamp engine bleed duct	Oil hot light (went out with engine in afterburner; generator warning light came on)	Nacelle damage	12-02-69 67-7193
Fire	Stuck afterburner fuel pump drain check valve	Fire warning light	Nacelle damage	09-27-67 65-5710

TABLE 3. (Contd.)

Type incident	Cause	How detected	Results	Date and aircraft serial No.
Fire (ground run hanger)	Turbine bolts not installed	Engine stall	Turbine disintegrated and cut fuselage and wing, spilling fuel (loss of aircraft)	02-03-72 70-2407
Overheat	Bleed-air line failure	Fire warning light	Nacelle damage	03-22-71 67-064
Overheat	Bleed-air line failure	Fire warning light	Nacelle damage	10-21-70 67-159
Overheat	Clamp bolt failure on bleed-air line	Wheel well overheat light	Wheel well damage	06-29-70 66-016
Overheat	Bleed-air line failure	Oil hot light	Nacelle damage	07-10-69 67-062
Fire	Engine high compressor disintegration	Engine stall and fire warning	Severe damage to nacelle and aft fuselage	08-06-70 68-044
Fire in engine boundary layer duct and wheel well	Bird strike	Visual and fire warning – nacelle wheel well overheat light	Loss of aircraft	05-15-73 68-008
Fire	Fuel tank cap came off – fuel entered spike bleed and aft centerbody	Loss of aircraft control	Loss of aircraft	06-18-72 67-082
Overheat	. . .	Oil hot light	Nacelle damage	68-091
Electrical fire	Electrical malfunction behind camera magazine	Pilot's panel visual	Damage to electrical component	67-089

TABLE 3. (Contd.)

Type incident	Cause	How detected	Results	Date and aircraft serial No.
Overheat	Coupling in nacelle	Oil hot light	Nacelle damage	68-081
Overheat (ground)	Engines run on trim pad minus environmental control section duct	Wheel well hot light	Damage in wheel well	11-06-70
Fire	Inlet splitter plate attachment failed	Fire warning by element at fuselage station 770	Glove fuel tank punctured; fuel ingested into engine and boundary layer; fire in speed-bump area	01-04-67 63-9777
Fire	Splitter plate loss	Tower noted	Left wing root damage and loss	10-30-69 66-012
Flash fire (explosion)	Unknown	Phase inspection	Fuselage area heat damage at base of vertical fin	08-05-71 67-118
Major fire	Cracked afterburner hydraulic pump case	Fire warning light, left engine	Nacelle and engine damage	05-04-73 67-053
Fire and crash	Fuel leak from left engine pressurization and vent valve	Fire warning light, left engine	Hard over right rudder destroyed rudder mechanical linkage, loss of control	01-11-73 68-024
Fire	Discrepancies recorded in environmental control section	Wheel well hot light	Burned environmental control section in wheel well	02-27-73 72-1443

TABLE 3. (Contd.)

Type incident	Cause	How detected	Results	Date and aircraft serial No.
Fire	Material factor, fuel system	Left engine run	Unknown	12-09-68 67-060
Fire, left-hand engine nacelle	Ruptured diaphragm on constant speed drive valve	Fire warning light	Unknown	10-30-68 63-9773
Fire	Engine -- poppet valve stuck open	Fire warning light	Large quantity of fuel discharged in nacelle through drain line	09-27-67 65-5710
Internal engine fire on the ground	Hydraulic line broke (inlet spike)	Ground observation	Spike hydraulic fluid entered engine and ignited; ground run	03-07-68 63-9776
Fire (no warning light)	Gun rounds cooked off	Cookoff and fire reported by chase aircraft	Hydraulic system and control damaged, loss of aircraft	01-02-68 65-5701

Failure of the right-hand engine compressor on F-111E No. 54 (serial No. 68-044) ruptured the case (inboard side) and shrapnel cut engine wiring, bleed-air ducts, and aircraft fuel tank. Fuel from the ruptured aft tank entered the right nacelle and a fire resulted. Ignition could have occurred from cut electrical wiring, sparks from the failed high-energy rotating machinery, or high-temperature internal engine parts. The fire was confined to the mid-outboard area of the right nacelle. The flame did not propagate forward; smoke and heat damage occurred in the lower firewall area. Insulation on the electrical wiring at the firewall was not consumed. The nacelle doors were burned in the upper outboard area. The speedbump area immediately aft of fuselage station 770 was burned extensively. The fire alarm was signaled by either the elements on the 725 frame or the speedbump. Figure 25 shows the fire damage and burn patterns. The first indication of a problem was a right-hand engine compressor stall. After the stall, the right nacelle fire warning light illuminated. The crew initiated fire procedures and discharged the agent. Total time from compressor stall to fire light on agent discharge--fire light out was approximately 40 seconds.

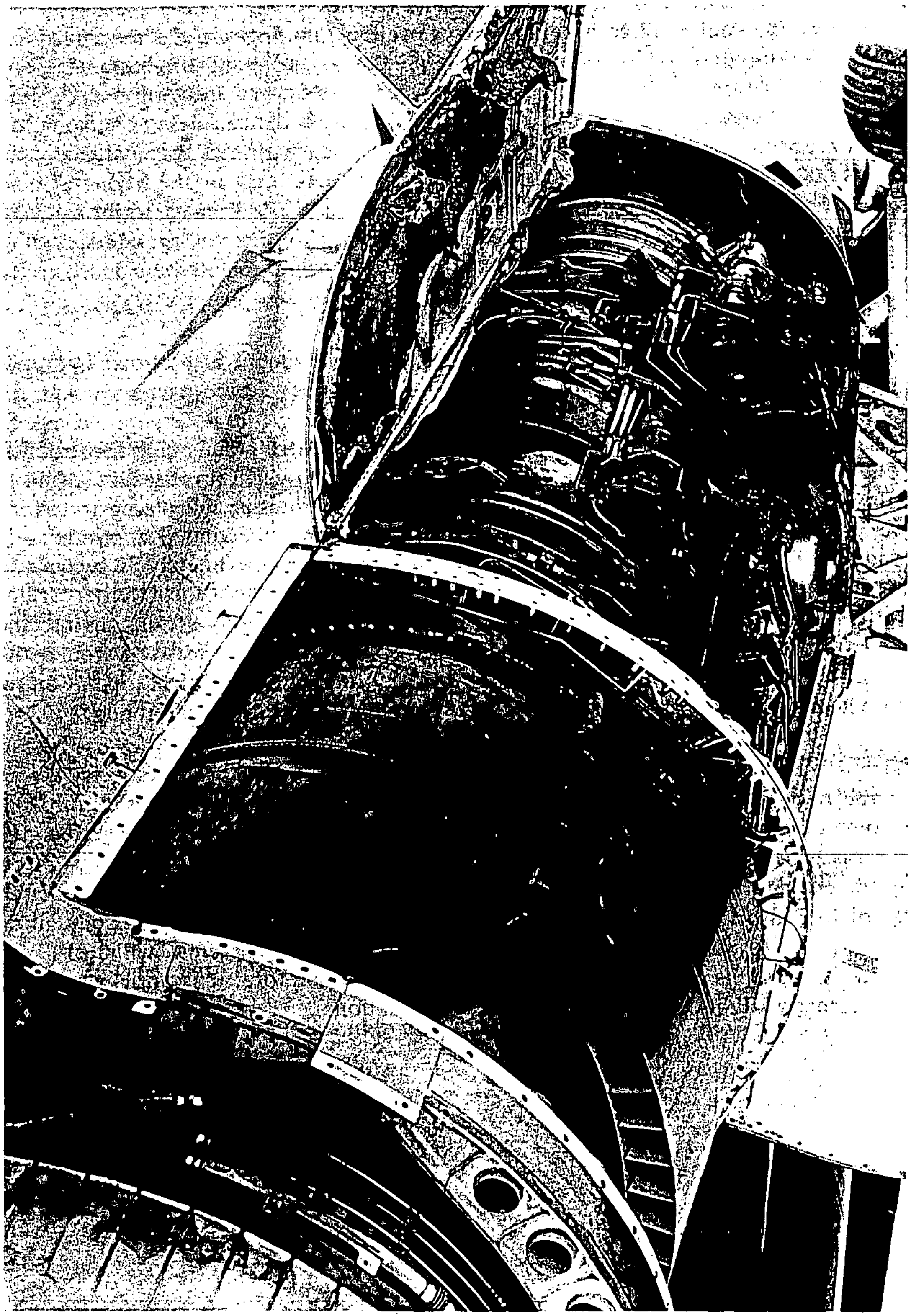

FIGURE 25. Nacelle Fire Pattern.

Failure of the right-hand boundary layer splitter plate attachment on F-111A No. 12 (serial No. 63-9777) resulted in separation of a large portion of the splitter plate from the aircraft. Part of the splitter plate penetrated the glove fuel tank forward of the engine inlet. Fuel from the punctured tank entered both the primary air inlet and the boundary layer bleed passages. The fuel ingested by the primary air inlet passed into the engine. Fuel ingested by the boundary layer bleed system streamed through the nacelle cavity and exited through the secondary air exit. The fuel leaving the secondary air exit was ignited by the afterburner and resulted in damage to the speedbump structure aft of the engine exhaust nozzle. The fire detection elements forward of fuselage station 770 frame gave the warning. Shutdown of the engine removed the source of ignition and stopped the fire. As a result of the 770 structural frame acting as a flameholder, fire detection elements were added to the nacelle panels immediately aft of the frame.

Failure of F-111A No. 98 (serial No. 67-053) left-hand engine afterburner hydraulic fuel pump resulted in a fire in the lower nacelle area. Fuel was released from a crack in the pump and was apparently ignited by the afterburner. The in-flight fire resulted in damage to the left-hand engine, nacelle, afterbody, aft fuselage flight controls, and equipment routing areas. The left-hand fire warning light illuminated on go-around when throttle was advanced to afterburner zone 2. The throttle was retarded out of afterburner and placed to cutoff. The fire pushbutton was depressed and agent discharge switch actuated approximately 30 seconds after the warning light came on. The light went out approximately 30 seconds to 1 minute after the agent discharge switch was actuated. Examination of the external surface of the aft fuselage centerbody revealed evidence of flame flow directly aft and up into the left-hand aft centerbody louver. The fire propagated internally, going forward around the base of the vertical fin resulting in intense heat damage to the rudder control tubes. Corrective action is presently being taken to eliminate this flame path into the centerbody.

Table 4 was developed to illustrate aircraft response to engine fuel ingestion and fuel leaks in the nacelle and exhaust area. If large streams of liquid fuel are ingested into the engine, some of the fuel will be centrifuged to the fan duct section and some ingested into the basic gas generator. The ingested fuel being composed of fine drops or mist, will on entering the engine inlet, pass on through the fan duct and gas generator. Ingestion of large amounts of fuel into the engine gas generator will probably result in a compressor stall or engine burn-through/failure if the condition remains undetected. The crew will most likely detect these conditions and perform engine shutdown. Therefore, it is anticipated that maximum damage will be loss of the engine for this situation.

TABLE 4. Probable F-111 Response to Fuel Ingestion/Leaks.

Damage mode	Military power	Afterburner
Fuel ingested into engine inlet	Maximum damage is loss of one engine.	Maximum damage is loss of one engine.
Fuel ingested into secondary air inlet (boundary layer)	No fire. Engine compartment temperature less than SIT (spontaneous ignition temperature) of JP-4.	Engine compartment temperature less than SIT of JP-4. Afterburner exhaust will ignite fuel. Fire damage to speedbump and centerbody.
Fuel ingested into engine and secondary air inlet	Maximum damage is loss of one engine.	Maximum damage is loss of one engine and fire damage to speedbump and centerbody.[a] Afterburner exhaust will ignite fuel.

[a] If fire enters centerbody through the centerbody louvers, damage to rudder control tubes and loss of hydraulic system may result in loss of aircraft. Corrective action has been taken to eliminate this flame path into the centerbody.

A review of 195 F-4 incident/accident reports during a 1968 *F-4C Operational Safety Study*[4] yielded a total of 12 fire histories. These engine fires or fire warnings resulted from the following known causes:

1. Engine material failures – turbine and compressor rotors, fuel manifold, afterburner, signal line, and engine case split-line leaks
2. Engine cavity fuel line failures – bellows in fuel feed line
3. Chafing – wire bundle and hydraulic line
4. Bleed-air duct leaks.

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[4] Convair Aerospace. *F-4C Operational Safety Study*. Fort Worth, TX, CA. 2 February 1968. (FZM-5020, publication UNCLASSIFIED.)

ADVANCED ENVIRONMENT

The extension of aircraft flight envelopes into the high supersonic and hypersonic ranges, such as those defined in Figure 26, will result in air and skin temperatures that may exceed the SIT of one or more of the onboard combustibles. Traditional fire protection systems will not provide adequate protection in these environments at all times. The regime of concern for this study, as related to future advanced aircraft/fire protection system requirements, is up to 1980. The baseline F-111 aircraft is on the threshold of these requirements. Extension of the baseline F-111 Area Intercept mission to higher Mach numbers within reason of advanced aircraft to 1980 provides a basis for analysis and evaluation of advanced aircraft/fire extinguishing systems. Possible advanced intercept mission points are shown in Figure 27. Mach 2.8 and 60,000 feet altitude provides a realistic extrapolation point for the purposes of this study. Present TF-30-type turbofan engine and JP-4 fuel will be applicable and realistic for the objectives of this program. Extrapolation to higher Mach numbers introduces variables such as the applicability of a turbofan engine, JP-4 fuel, etc. Adiabatic wall temperatures and ram air temperatures for the extrapolation to Mach 2.8 and 60,000 feet are 480 and 537°F, respectively.

A discussion concerning the aircraft environment for a Mach 3 supersonic transport is contained in AFAPL (Air Force Aero Propulsion Laboratory), Wright-Patterson Air Force Base, Dayton, Ohio, report AFAPL-TDR-64-105.[5] The basic flight plan consists of a 3,500-nmi journey with a cruising altitude of 70,000 to 80,000 feet. The maximum temperatures predicted were about 640°F at Mach 3.0. Surface temperatures between 450 and 600°F were estimated for the Mach 3.0 aircraft.

ENGINE NACELLE ENVIRONMENT

The F-111 engine nacelle temperatures are related to ram air temperatures. Increasing flight speeds to Mach 2.8 will result in correspondingly higher nacelle temperatures. Figure 28 illustrates the nacelle air temperature profile that would be expected. An estimate of several component temperatures are provided in Figure 29. Considering a correlation between actual and predicted engine case temperatures for Mach 2.2 flight, it has been estimated that TF-30-type afterburner surface temperatures would be approximately 660°F. The nacelle ventilation air velocity predicted for Mach 2.8 is shown in Figure 30. This velocity is greater than that for the Mach 2.2 flight profile but is of the same order of magnitude.

The engine case temperatures for a turbofan engine will be significantly less than those for a turbojet engine. Figure 31 provides an illustration of the order of magnitude of engine case temperatures for a high Mach turbojet engine.

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[5] Air Force Aero Propulsion Laboratory. *Fire Protection Research Program for Supersonic Transport.* Wright-Patterson AFB, OH, October 1964. (AFAPL-TDR-64-105, publication UNCLASSIFIED.)

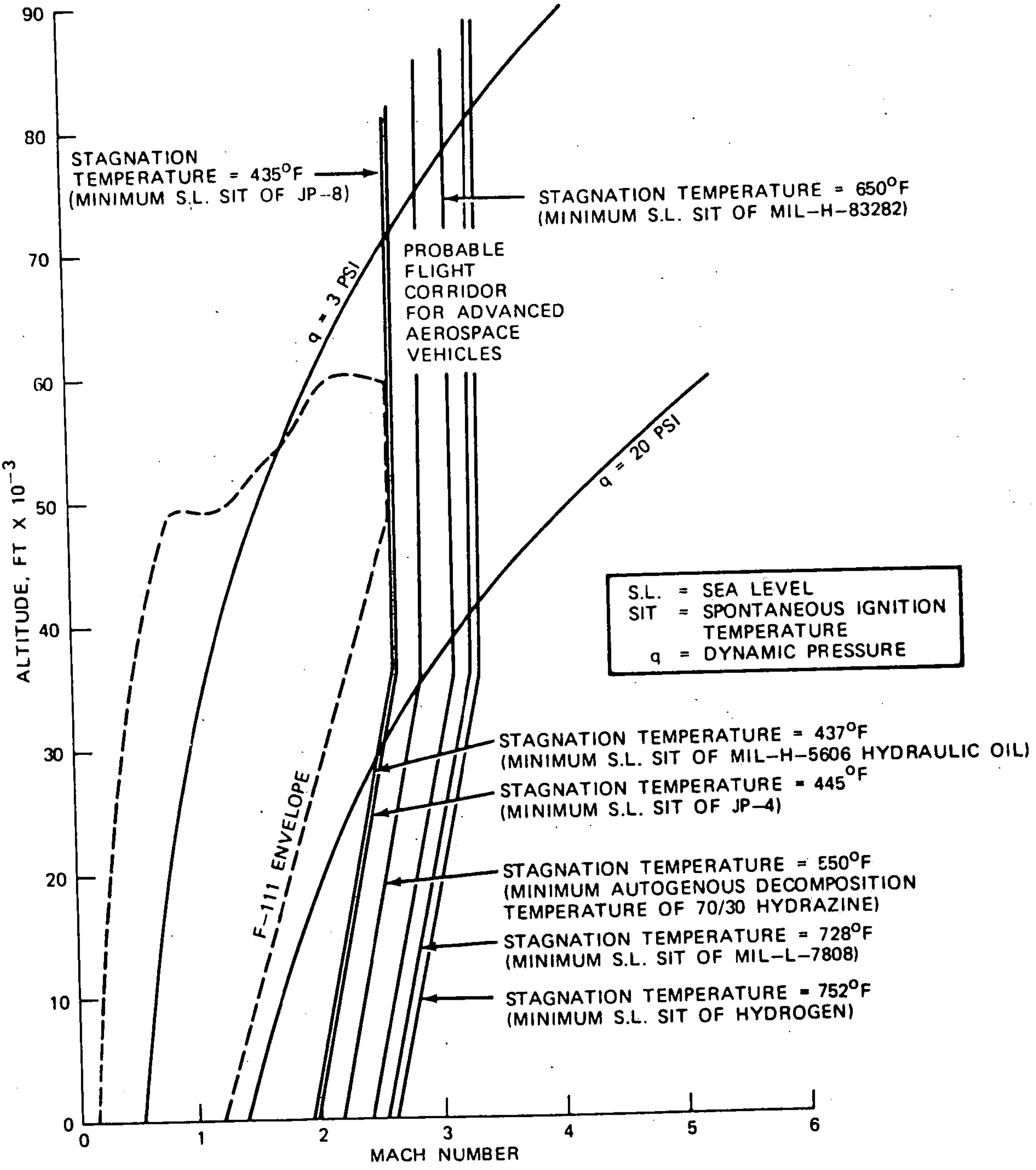

FIGURE 26. Operational Regimes Which Will Require Advanced Design for Fire Protection in Next Generation High Performance Vehicles.

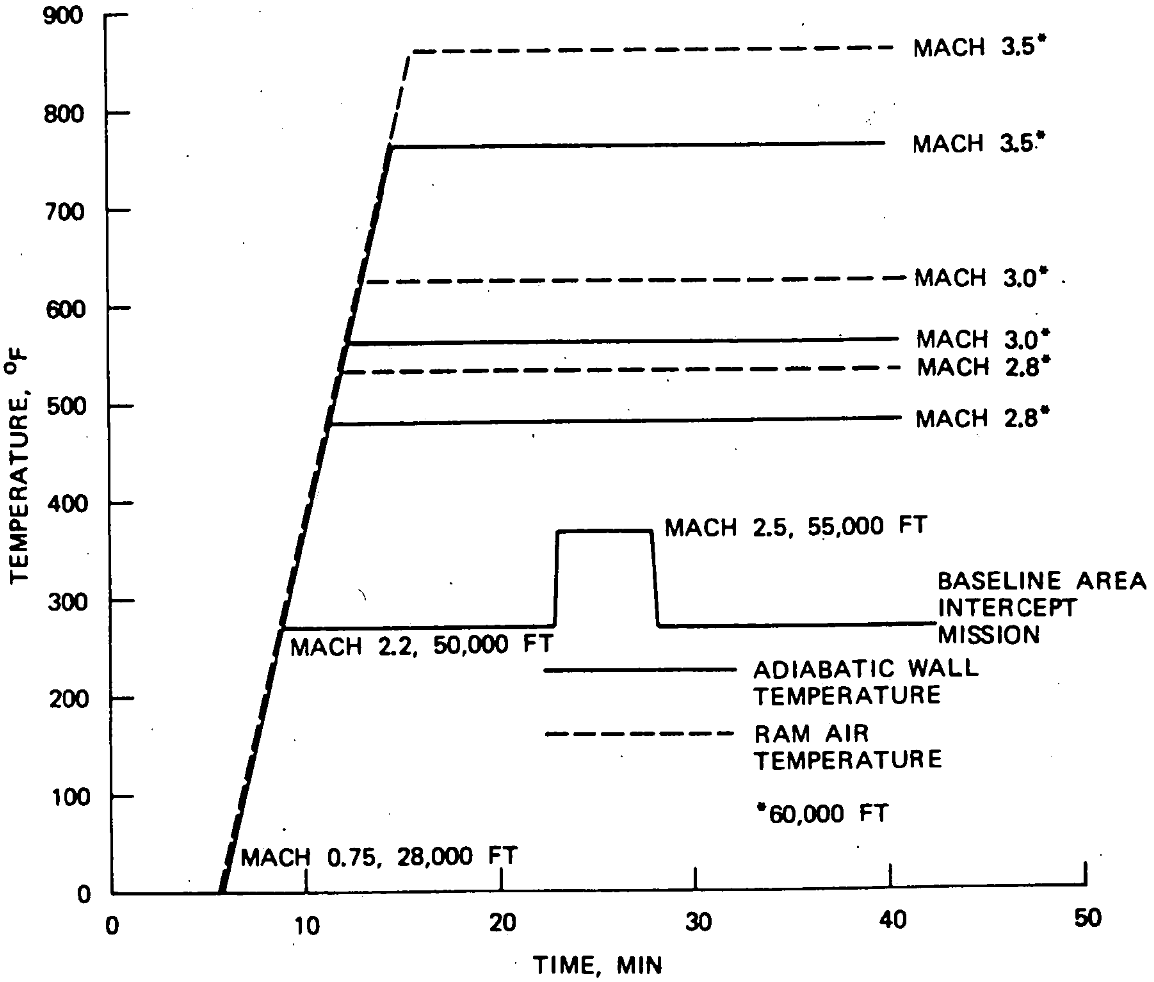

FIGURE 27. Advanced Area Intercept Missions.

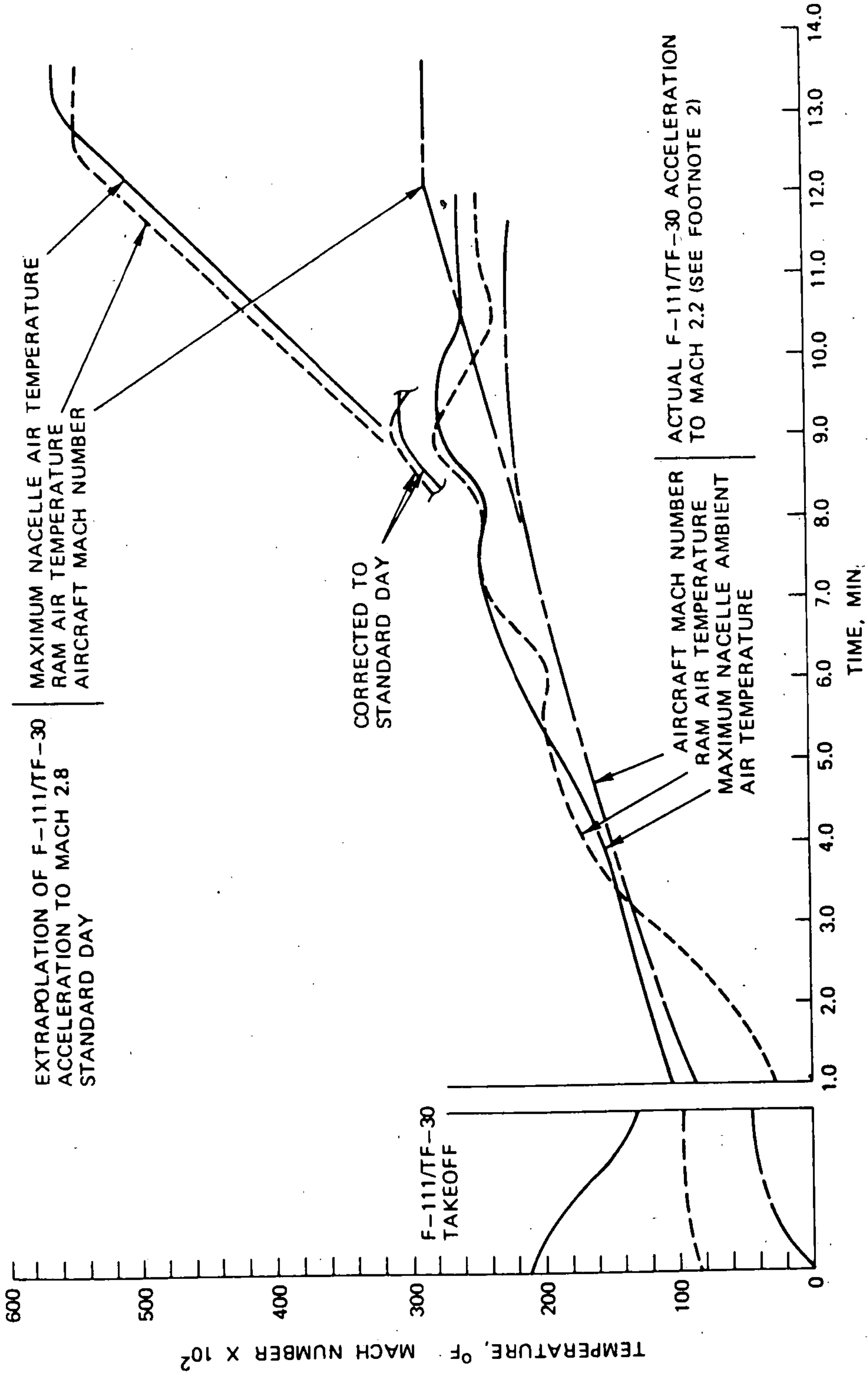

FIGURE 28. Estimated Nacelle Air Temperature Example for Advanced Environment.

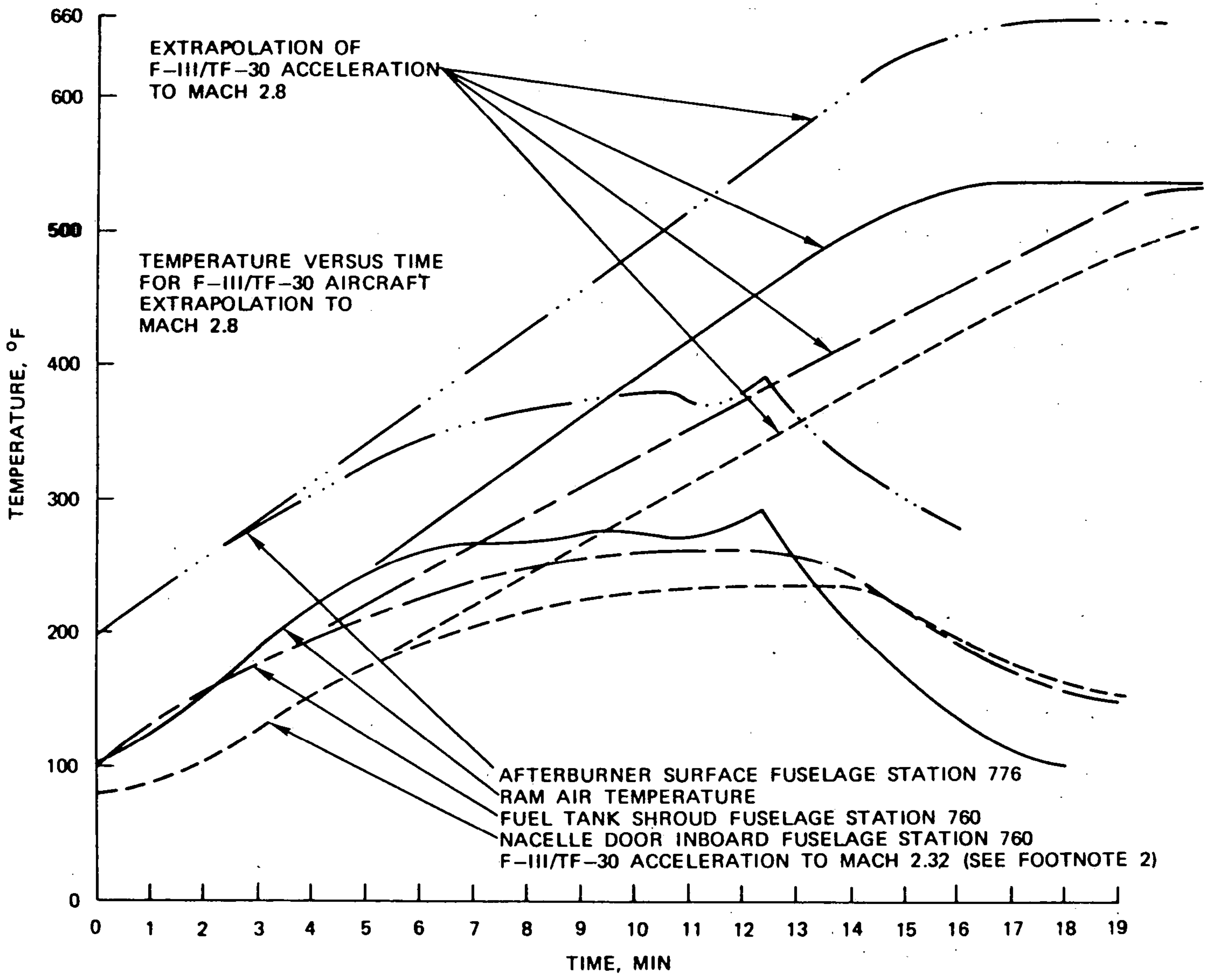

FIGURE 29. Estimated Nacelle Structure Temperature Example for Advanced Environment.

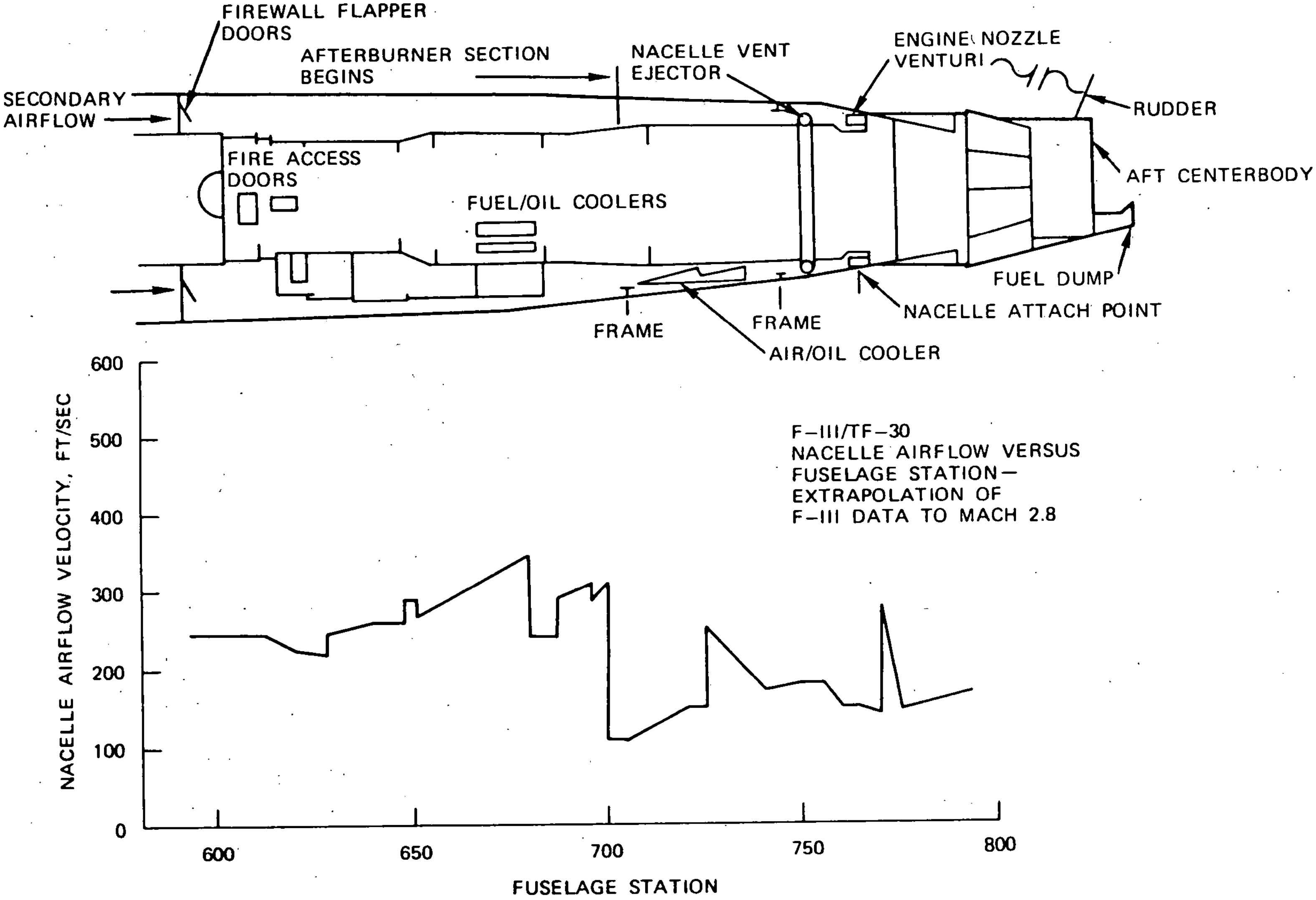

FIGURE 30. Estimated Nacelle Air Velocity for Advanced Environment.

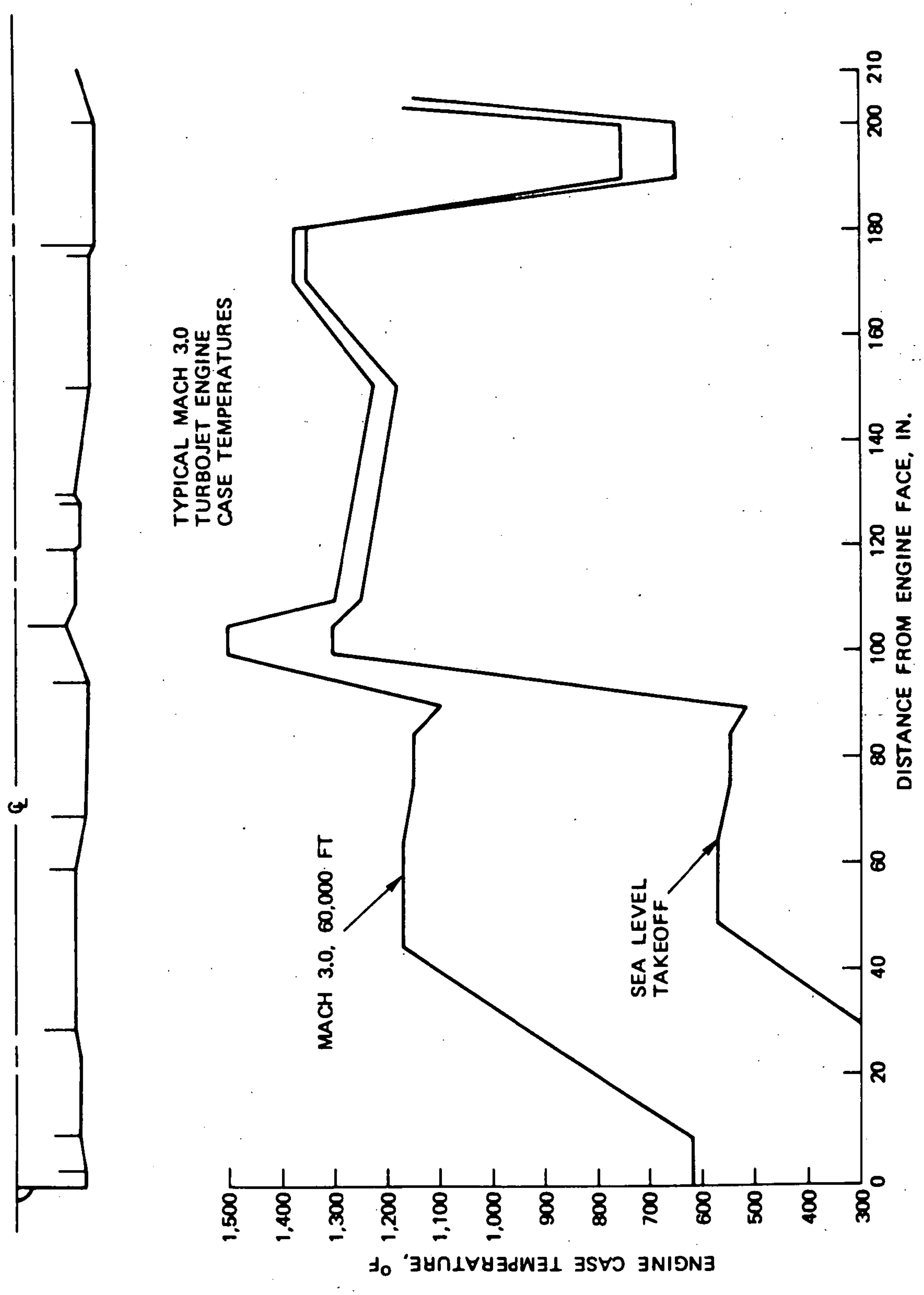

FIGURE 31. Example Turbojet Engine Case Temperature.

In addition to the fire protection tactics employed, a factor that must be considered is the cost of developing engine-driven accessories to meet the requirements of a high-temperature environment. Two alternatives to developing high-temperature equipment are (1) locating in a remote area that has a lower temperature and (2) providing cooling air to the equipment.

OTHER COMPARTMENT ENVIRONMENTS

A summary of the environments expected in selected F-111 compartments is provided in Table 5. Considering electronic requirements and the cost of increasing the electronic equipment operating temperature range, it is logical to assume that electronic equipment storage areas will continue to be cooled to 150°F maximum air temperature. The same would be valid for weapons stored in the internal weapons bay compartment. This cooling air will be supplied by the aircraft environmental control system. These compartment skin and structure temperatures will increase as the aircraft speed increases.

COMBUSTIBLES

Improved aircraft fluids will be developed and available for future advanced aircraft; however, it is expected that current combustible fluids such as those used on the baseline F-111 will be applicable to use in advanced aircraft to 1980. Jet engine fuels in use at this time include JP-4, JP-5, Types A and A-1. It is anticipated that fuels of this type will be used in future aircraft that can operate to approximately Mach 4.5. A recent fuels and lube study for AFAPL[6] concluded that existing fuels and lubricants are feasible for use in Mach 3+ and Mach 4+ interceptors. Above this speed, alternate cryogenic fuels such as methane and hydrogen will be considered. JP-8 is a candidate fuel for replacement of the current jet fuels because of its apparent enhancement of aircraft combat survivability. This fuel appears to have an advantage from a fire protection standpoint. It has been shown that JP-8 is generally less susceptible than JP-4 to fire and explosion induced by gunfire, and structural damage should be less than that with JP-4.[7] The adoption of any new fuel must include other factors such as cost, logistics impact, operational problems (engine exhaust gas visibility, relight at altitude, performance, cold weather starting, etc.), and energy resources and allocations.

MIL-H-83282 is a candidate hydraulic fluid for future use and it offers improved fire resistance over the presently used MIL-H-5606 fluid. Some flight testing using MIL-H-83282 hydraulic fluid in an F-4 aircraft has been conducted but the higher viscosity of this fluid has a deleterious effect on aircraft operation that has not been resolved.

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[6] Pratt and Whitney. *Fuels and Lube Study for AFAPL*. East Hartford, CT, 31 May 1973. (GP 73-126, publication UNCLASSIFIED.)

[7] Air Force Aero Propulsion Laboratory. *Vulnerability of Dry Bays Adjacent to Fuel Tanks Under Horizontal Gunfire*, by Robert Clodfelter. Wright-Patterson AFB, OH, March 1973. (AFAPL-TR-72-83, publication UNCLASSIFIED.)

TABLE 5. Environment Summary–Other Hazardous Areas.

F-111 extrapolated to Mach 2.8 at 60,000 feet

Area	Area cooled	External adiabatic, °F	Estimated compartment air temperature, °F	Estimated airflow, lb/min	Airflow restrictions	Combustibles	Comment
Nose wheel well	Yes (not regulated)	480	252	15	Nose landing gear, fire extinguishant bottle	Hydraulic fluid	Adjacent to fuel tank
Weapons bay	Yes	480	150 maximum	53	Weapons, routing along top of bay	Hydraulic fluid	Fuel tank located above Temperature regulated to 150°F to protect weapons
Right-hand cheek	Yes	480	150 maximum	21	Electronic equipment	None	Fuel tank located above Compartment regulated to 150°F to protect electronic equipment
Left-hand cheek	Yes	480	150 maximum	30	Electronic equipment	Hydraulic fluid fuel	Fuel tank located above Compartment regulated to 150°F to protect electronic equipment

TABLE 5. (Contd.)

F-111 extrapolated to Mach 2.8 at 60,000 feet

Area	Area cooled	External adiabatic, °F	Estimated compartment air temperature, °F	Estimated airflow, lb/min	Airflow restrictions	Combustibles	Comment
Main wheel well	Yes (not regulated)	480	311 maximum for exit air	109	Main landing gear, hydraulic reservoirs, hydraulic valves/plumbing, environmental control section, equipment, pneumatic bottles, bleed-air ducts, fuel lines	Hydraulic fluid fuel	Air temperature not regulated Tire design limit is 275°F with higher temperatures permissible for short time period dependent on heat sink available
Crossover compartment	No	480	480	0	Not applicable	Hydraulic fluid	Fuel tank adjacent Insulated bleed-air line in compartment Engine compartment fire bottle located in compartment
Aft fuselage routing tunnel	No	480	480 maximum	>20 ft/sec	Flight controls, hydraulic lines, actuators, fuel lines, environmental control section ducts	Hydraulic fluid fuel	Area is ventilated, airflow is forward during flight

The ignition characteristics of JP-4, JP-8, MIL-H-5606, MIL-H-83282, and MIL-L-7808 have been determined under conditions simulating an aircraft compartment.[8] These ignition temperature tests were performed by injecting the selected aircraft combustibles onto heated steel targets under various airflow conditions in an 8-inch-diameter tube. Ignition temperature data were obtained at various air velocities less than 10 ft/sec with compartment air temperatures of 80 and 350°F, and cylindrical and rectangular targets. Generally, the following statements were found to be true:

1. The ignition temperatures increased with increasing air velocity.

2. The ignition temperatures of the fluids were noticeably higher than their minimum autoignition temperatures which were determined in uniformly heated vessels.

3. The larger diameter targets ignited the JP-8 and JP-4 fuels at about the same temperature under the various flow conditions used.

4. With the air preheated to 350°F, it was demonstrated that the target temperature required for ignition is lower than with air at room temperature.

Higher ignition temperatures were obtained with MIL-H-83282 as compared to MIL-H-5606. For example, with compartment air preheated to 350°F, air velocity of 5 ft/sec, and with a 2-inch-diameter by 24-inch-long steel target, the ignition temperature of MIL-H-5606 is approximately 1150°F and approximately 1250°F for MIL-H-83282.

These tests provided not only a needed comparison between the various fluids but ignition temperature data simulating conditions more realistic of those found in aircraft compartments. Additional simulation tests such as these are needed for higher compartment air temperatures and velocities in order to more accurately assess the fire hazard for future advanced aircraft. Also, more accurate fire hazard assessment could be defined if these simulation tests were arranged to include altitude effects.

Ram air temperature is the highest temperature that can result from aerodynamic effects alone. For flight speeds where this temperature is below the lowest SIT (usually the sea level value) of the combustibles involved, aerodynamic effects cannot independently result in an ignition source. A critical flight Mach number for fire protection can be defined as the flight Mach number at which the ram air temperature for flight in standard atmosphere at 36,000 to 90,000 feet equals the minimum SIT.[9] This approach results in a conservative evaluation of aerodynamic effects, since altitude and other parameters which increase ignition temperature are not included. For flight beyond the critical Mach number, more detailed fire hazard analysis is required. Table 6 presents the critical Mach number for several aircraft combustibles as determined in EER-FW-1203[9] with several additional candidate combustibles added. For flight Mach numbers which exceed these critical values, a new

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[8] Air Force Aero Propulsion Laboratory. *Ignition of Aircraft Fluids by Hot Surfaces Under Dynamic Conditions*, by Strasser, Waters, and Joseph M. Kuchta. Wright-Patterson AFB, OH, November 1971. (AFAPL-TR-71-86, publication UNCLASSIFIED.)

[9] Convair Aerospace. *Explosion/Fire Protection for Compartments Susceptible to Leakage of Combustibles on Advanced Aerospace Vehicles*, by Skembare and Springer. Fort Worth, TX, CA, 31 December 1971. (ERR-FW-1203, publication UNCLASSIFIED.)

regime of fire protection is entered and the traditional fire protection provisions must be carefully evaluated. The free-stream air approaches stagnation conditions when it is ingested for compartment ventilation. Hot-surface ignition temperatures will continue to decrease as air temperature is increased. The situation can arise where a compartment surface is heated to a temperature above the combustible ignition temperature by contact with the ventilating airflow. At this point, conventional ventilation becomes a questionable fire protection tactic.

TABLE 6. Critical Flight Mach Number for Fire Protection.

Combustible	Minimum SIT, °F	Mo[a]
JP-4	445[b]	2.55
JP-5	435[b]	2.53
JP-6	450[b]	2.57
JP-8	435[b]	2.53
MIL-H-5606	437[b]	2.53
MIL-H-83282	650[c]	3.02
MIL-L-7808	728[b]	3.18
Hydrogen	752[b]	3.23
Methane	1000[b]	3.68
Hydrazine (70/30)[d]	550[e]	2.81

[a] Flight Mach number at which ram air temperature for flight in standard atmosphere at 36,000 to 90,000 feet altitude equals the minimum SIT.

[b] AFAPL-TR-73-74 (see Footnote 3, page 45).

[c] Military Specification MIL-H-83282.

[d] 70% hydrazine and 30% water by weight.

[e] Sundstrand data.

SUMMARY OF VARIOUS AIRCRAFT

An Engine Nacelle Fire Extinguishant Environment Summary has been prepared utilizing available data. This summary, in Table 7, provides a general view of nacelle environments for military and commercial aircraft. Also included is the type of fire extinguishing agent utilized, if any. This summary illustrates that most of the present United States aircraft utilize agent 1301 (CF_3Br). The foreign-manufactured supersonic transport (Concorde) utilizes agent 1211 ($CBrClF_2$). Also illustrated is the fact that many single-engine aircraft do not employ fire extinguishing agents for nacelle fire protection. Several of the United States military aircraft (B-58, B-52, KC-135) with wing-mounted pod-type engine nacelles do not incorporate fire extinguishing agents. Table 8 summarizes compartments other than the engine nacelle and provides examples of other areas that presently utilize an extinguishing agent.

TABLE 7. Engine Nacelle Fire Extinguishant Environment.

Aircraft/ propulsion system	Type of propulsion system	Design speed	Maximum engine case temperature	Maximum engine nacelle ambient temperature	Maximum nacelle structure temperature	Maximum engine bleed-air temperature	Engine nacelle air velocity/flow	Engine nacelle airflow volume	Engine nacelle air volume changes	Fire extinguishant	Fire agent capacity
Baseline aircraft/ propulsion F-111/TF-30 operating: ground maximum afterburner			274°F (hot day) at afterburner section, fuselage station 776	232°F (hot day)	211°F (hot day	840°F (hot day) at inner fuel tank shroud	7 ft/sec minimum 21 ft/sec maximum 2.67 lb/sec		0.86/sec	1202 CF_2Br_2	12.65 pounds
Baseline aircraft/ propulsion operating: cruise, Mach 0.75, 35,000 feet		M_o 2.5	113°F at 39,300 feet	86°F at 39,300 feet	46°F at 39,300 feet at inner fuel tank shroud	685°F at 39,300 feet (hot day)	59 ft/sec minimum 185 ft/sec maximum 6.98 lb/sec	50.4 ft^3	6.2/sec		
Baseline aircraft/ propulsion operating: Mach 1.2 at sea level			303°F	243°F	203°F	980°F	84 ft/sec minimum 264 ft/sec maximum 35.2 lb/sec		8.7/sec		
Baseline aircraft/ propulsion operating: Mach 2.2	Ducted turbofan		420°F afterburner section	270°F afterburner section	265°F inner fuel tank shroud	1005°F	78 ft/sec minimum 248 ft/sec maximum 6.5 lb/sec		9.3/sec		
Baseline aircraft/ propulsion data extrapolated to Mach 2.8, 60,000 feet			660°F afterburner section	556°F afterburner section	537°F	1215°F	110 ft/sec minimum 348 ft/sec maximum 6.09 lb/sec		12/sec		

TABLE 7. (Contd.)

Aircraft/ propulsion system	Type of propulsion system	Design speed	Maximum engine case temperature	Maximum engine nacelle ambient temperature	Maximum nacelle structure temperature	Maximum engine bleed-air temperature	Engine nacelle air velocity/flow	Engine nacelle airflow volume	Engine nacelle air volume changes	Fire extinguishant	Fire agent capacity
Baseline aircraft/ propulsion data extrapolated to Mach 3.0, 60,000 feet			734°F after-burner section	640°F	632°F	1300°F	144 ft/sec minimum 453 ft/sec maximum 6.26 lb/sec		15/sec		
High performance Mach 3.0 aircraft	Turbojet	M_0 3.0+	1510°F at 60,000 feet 1300°F at sea level takeoff								
YF-16	Ducted turbofan with after-burner	Mach 2 class	450°F	300°F after-burner section	275°F	~1100°F	2.5 lb/sec (1.87 lb/sec at 0.9 Mach)	54.1 ft^3	2.9/sec (1.4/sec)	1301 CF_3Br	
Sabreliner JT 12A-8	Turbojet	Mach 0.8					Ventilated			1301 CF_3Br	
C-5A TF-39-GE-1	High bypass turbofan	550 mph maximum					Ventilated			1202 CF_2Br_2	Charged with nitrogen
727/JT-8D	Turbofan	0.92					Not ventilated	Not applicable	Not applicable	1301 CF_3Br	Charged 600 psi with nitrogen
B-58/J-79	Turbojet with after-burner	Mach 2.0	1220°F	440°F	980°F at Mach 2.0 high altitude	800°F	~0.3 Mach $\gg$ 20 ft/sec 10 lb/sec			None	None
F-105 J-75-P-19W	Turbojet with after-burner	Mach 2 class					Ventilated			1202 CF_2Br_2	None - system deactivated

TABLE 7. (Contd.)

Aircraft/ propulsion system	Type of propulsion system	Design speed	Maximum engine case temperature	Maximum engine nacelle ambient temperature	Maximum nacelle structure temperature	Maximum engine bleed-air temperature	Engine nacelle air velocity/flow	Engine nacelle airflow volume	Engine nacelle air volume changes	Fire extinguishant	Fire agent capacity
F-104/J-79	Turbojet with after-burner	Mach 2 class	1220°F	~350°F		800°F	~20 to 25 lb/sec			None	None
KC-135 J-57 TF-33	Turbojet and turbofan	530 mph cruise								None	None
Martin B-57 J-65	Turbojet									1011 CH_2BrCl	
B-57F TF-33	Turbofan						Ventilated			1202 CF_2Br_2	
F-100/J-57	Turbojet with after-burner						Ventilated			None	None
T-37/J-69	Turbojet	425 mph maximum								None	None
F-4/J-79	Turbojet	M_o 2.2	1220°F at turbine casing				Ventilated			None	
F-106/J-75	Turbojet	M_o 2.0	1150°F at 35,000 feet M_o 0.90	Ram air temperature	~ ram air temperature		Ventilated (reversed on ground)			None	
AH-1J/ T-400	Turbo-shaft	207 mph	188°F	~250°F		~435°F	Ventilated			Engineering Change Proposal to add 1301 extinguishant	
S-3A/TF-34	Turbofan	500 mph	~400°F at sea level	~170°F at sea level			0.8 ft/sec minimum ~33 ft/sec maximum 1 lb/sec	21.09 ft^3		No fire extinguishant system	

TABLE 7. (Contd.)

Aircraft/ propulsion system	Type of propulsion system	Design speed	Maximum engine case temperature	Maximum engine nacelle ambient temperature	Maximum nacelle structure temperature	Maximum engine bleed-air temperature	Engine nacelle air velocity/flow	Engine nacelle airflow volume	Engine nacelle air volume changes	Fire extinguishant	Fire agent capacity
F-15/F-100	Ducted turbofan with after-burner	Mach 2.5	~ram air temperature ± 25°F	~ram air temperature	Compartment air-flow not required for structural cooling	1100°F	2 lb/sec at cruise (Mach 0.8)	84 ft^3	Minimum six per minute at speeds above Mach 0.55	1301 CF_3Br	6.6 pounds charged 600 psi with nitrogen at 75°F
C-141/ TF-33-P7	Ducted turbofan	Cruise 505 mph					Ventilated			1202 CF_2Br_2	Charged 600 psi at 72°F with nitrogen
DC-9 JT-8D	Turbofan	Cruise at 565 mph								1301 CF_3Br	
DC-10, CF-6, or JT-9D	High bypass turbofan	Mach 0.85 cruise		<250°F			Ventilated			1301 CF_3Br	
BAC-111/ Spey Mk 505-14 or Mk 506-14		Mach 0.86					Ventilated			1211 1301 on American Airlines	Two 6-pound charged bottles per engine
A-7/TF-30 and TF-41	Turbofan	Subsonic	~ram air temperature				0.5 lb/sec			None	None
T-38/J-85	Turbojet with after-burner	Mach 1.2 class								None	None
B-52/J-57 and TF-33	Turbojet and turbofan	650 mph								None	None

TABLE 7. (Contd.)

Aircraft/ propulsion system	Type of propulsion system	Design speed	Maximum engine case temperature	Maximum engine nacelle ambient temperature	Maximum nacelle structure temperature	Maximum engine bleed-air temperature	Engine nacelle air velocity/flow	Engine nacelle airflow volume	Engine nacelle air volume changes	Fire extinguishant	Fire agent capacity
F-102 J-57	Turbojet with after-burner						Ventilated			None	None
F-14A TF-30	Turbofan with after-burner	Mach 2.3 class								None	None
Convair 990/ CJ 805-2	Turbofan (aft fan)	0.86 cruise	270°F	262°F	<262°F	Insulated ducts	Ventilated			1301 CF_3Br	
Concorde SST/593 Mk 602		M_o 2.2								1211 $CBrClF_2$	Two 16-pound containers per pair of engines (two-shot system)
Convair 880 CJ 805	Turbojet	0.86 cruise	270°F	~225°F		Insulated ducts	Ventilated			1301 CF_3Br	5.5-pound bottle

TABLE 8. Fire Extinguishant Summary–Hazardous Areas Other Than Engine Nacelles.

Aircraft	Area	Extinguishant	Capacity	Comments
F-111	Weapons bay and cheek areas	1301 (CF_3Br)	11.25 pounds	Maximum air temperature of bottle storage area (nose wheel well) is 192°F. Maximum temperature of air in weapons bay and cheek areas is 160°F. Electronic equipment is stored in cheek areas.
A-7		None		
AH-1J		None		
BAC-111	APU (auxiliary power unit) enclosure	1211 ($CBrClF_2$)	2 pounds	Single-shot charged extinguisher discharged electrically from flight deck.
DC-10	APU enclosure	1301 (CF_3Br)		Two-bottle/two-shot system for aft engine also serves the APU unit with two-shot capability.
880	Cargo bay	CO_2		
990	Cargo bay	CO_2		
F-102		None		
F-106		None		
YF-16		None		
B-58		None		
C-5A	APU enclosure	1011 ($CBrClF_2$)	2 quarts	Two (1-quart) bottles pressurized with 150 psi air at 88°F. Fire extinguishant bottles for APU located in right-hand wheel well pod.
	Flight deck, cargo hold, and troop compartment	1011 (Type A20 portable)	10 extinguishers	10 portable hand-held/ operated extinguishers located throughout aircraft.

TABLE 8. (Contd.)

Aircraft	Area	Extinguishant	Capacity	Comments
KC-135	Cargo bay	1011 (Type A20 portable)	Five extinguishers	Five portable hand-held/operated extinguishers located in forward and aft emergency equipment panels and in cargo door.
727	APU enclosure	1301 (CF_3Br)	2 pounds	Single-shot bottle charged with nitrogen.

COMBAT DAMAGE ENVIRONMENT

The fire protection tactics employed for normal flight operations may not provide adequate protection in the environment created by combat damage. Gunfire can inflict damage to aircraft structure, mechanical/electrical components, combustible fluid components and lines, fuel tanks, and propulsion system, etc. No area on the aircraft is immune from either direct damage or the effects of damage (fluid leakage to other areas, etc.). A descriptive base of actual damage created by the 23-mm projectile was obtained by a review of A-10 gunfire test results and F-4 (Air Force and Navy) battle damage/loss reports from the CDIC (Combat Data Information Center). This review illustrated the fact that 23-mm projectiles may inflict a variety of damages depending on many variables. Some of these variables include:

1. Where the aircraft is hit
2. Direction of projectile at impact
3. When the projectile explodes
4. The relation of equipment location to projectile entry
5. The number of hits
6. The fluid level when entering tanks
7. Void spaces around fuel tanks
8. Compartment volume
9. Type of structure, skins
10. Thickness of skins

11. Foam installation

12. Passive fuel tank protection.

One of the problems involved in designing aircraft fire protection systems or defining fire extinguishant requirements, considering combat damage, is the very large number of damage conditions that may occur even when considering only one type of threat. The problem is magnified if one considers multiple hits. A rational goal in vehicle and fire protection/extinguishant design would be to prevent a single hit by a 23-mm API/HEI (armor piercing incendiary/high explosive incendiary) from resulting in loss of the aircraft. It was evident from review of the A-10 gunfire test results that passive steps can be taken to reduce the vulnerability of aircraft to the 23-mm threat.

A review of CDIC F-4 and A-7 data indicates that the 23-mm projectile, upon entry, creates damage to the aircraft structure ranging from a hole approximately 1 inch in diameter at the penetration point to jagged holes such as 2 by 3, 6 by 10, and 4 by 6 inches, or completely blowing off an access panel. Skins may be deformed such that they could create local flameholders or even scoops to direct airflow into a compartment or redirect airflow within a compartment. One case was observed where a 23-mm projectile entered a compartment creating a 1.12- by 3.0-inch hole on entry and an irregular-shaped 15- by 24-inch hole in a nearby external skin when the shell apparently exploded inside the compartment. Several examples of damage inside compartments were reviewed. Fragments cut holes in bulkheads and inner skins, damaged wire bundles, and penetrated hydraulic lines, fuel cells, and hot air lines. Damage created by exiting projectiles/fragments ranged from several small holes/cuts to larger openings 3 by 6 and 8 by 20 inches. In one case, where the shell apparently exploded below the wing, an area approximately 2 ft^2 was damaged. Numerous holes were created by fragments and the wing skin was loose and hanging down. Several feet of the top side of the wing were damaged by fragments passing through the wing. Another type of damage created by the 23-mm projectile was penetration into areas where fragments or damaged components could enter the engine inlet. Foreign object damage to an engine can range from minor blade nicks to complete engine failure, which in turn can create additional damage and fire hazards. It should be noted that one limitation of the CDIC data review is the lack of detailed damage data concerning lost aircraft. Review of the data does indicate that compartments (particularly those on the bottom or lower areas of the aircraft) containing combustible fluid lines, reservoirs, or other containers or compartments adjacent to fuel tanks are candidates for fire extinguishing systems if protection from the 23-mm threat is to be considered.

An analysis, assuming a single 23-mm hit of selected compartments in the F-111 aircraft and the A-7 engine compartment, was conducted to assist in defining the environment in which a fire extinguishing agent is required to function. The sources of combustibles are identified, leakage rate calculated, and possible leakage paths, ignition sources, and components affected. Results of this analysis are summarized in Tables 9 and 10. Combustible fluid leakage from unpressurized fuel tanks is based on a minimum damage condition of a single 1-inch-diameter hole.

TABLE 9. Potential F-111 Fire Hazards Due to Combat Damage (Supersonic Aircraft, Twin-Engine, Afterburning).

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source (see Note 1)	Other components affected
Engine compartment	Forward fuel tank - bay F-1 - damage to side/top/bottom	Side - 3.0 gal/min Top - 0.8 gal/min Bottom - 4.4 gal/min (see Note 2)	Fuel from damaged bay flows into engine inlet and secondary air inlet and along aircraft fuselage (see Note 3)	Heat from afterburner exhaust ignites fuel exiting from nacelle compartment (see Note 3)	Hydraulic lines/ components in tail area, if fire spreads (see Note 4)
	Forward fuel tank - bay A-2 - damage to side/top	Side - 12.8 gal/min Top - 3.2 gal/min (see Note 2)	Same as above	Same as above	Same as above
	Forward fuel tank - glove area - damage to bottom	Bottom - 9.0 gal/min (see Note 2)	Fuel from damaged glove flows along aircraft fuselage and enters engine inlet and secondary air inlet (see Note 3)	Same as above	Same as above
	Aft fuel tank - saddle and finger area - damage to side/top/bottom	Side - 6.4 gal/min Top - 1.6 gal/min Bottom - 9.0 gal/min (see Note 2)	Fuel from top/side flows along aircraft fuselage; fuel from bottom flows into secondary air passage (see Note 3)	Same as above	Same as above

TABLE 9. (Contd.)

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source (see Note 1)	Other components affected
Engine compartment (contd.)	Aft fuel tank - bay A-1 - damage to side/bottom	Side - 11.5 gal/min Bottom - 23.0 gal/min (see Note 2)	Fuel from side damage flows into secondary air passage; fuel from bottom flows along aircraft fuselage	Heat from afterburner exhaust ignites fuel exiting from nacelle compartment (see Note 3)	Hydraulic lines/components in tail area, if fire spreads (see Note 4)
	Aft fuel tank - bay A-2 - damage to side/bottom/rear	Side - 1.6 gal/min Bottom - 2.3 gal/min Rear - 1.6 gal/min (see Note 2)	Fuel from side flows into engine and secondary air passages; fuel from bottom/rear flows along aircraft fuselage (see Note 3)	Same as above	Same as above
	Reservoir tank - damage to side/top/bottom	Side - 6.4 gal/min Top - 1.6 gal/min Bottom - 9.0 gal/min (see Note 2)	Fuel from side/bottom flows into secondary air inlet; fuel from top flows along aircraft fuselage (see Note 3)	Heat from afterburner exhaust ignites collected fuel (see Note 3)	Hydraulic lines/components in tail area, if fire spreads (see Note 4)
	Fuel feed lines - reservoir to engine - damage to line in engine compartment	98 gal/min with 20 psi on line (see Note 2)	Fuel flows into nacelle compartments (see Note 3)	Heat from afterburner exhaust ignites fuel exiting from nacelle. Incendiary in projectile ignites fuel in nacelle (see Note 3)	Same as above Engine/hydraulic equipment in nacelle

TABLE 9. (Contd.)

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source (see Note 1)	Other components affected
Engine compartment (contd.)	Engine compartment - compressor section/ combustion chamber/ turbine area - progressive damage to the area hit and attendant damage to fuel/hydraulic lines	98 gal/min with 20 psi pressure on fuel line 75 gal/min with 3,000 psi pressure on hydraulic line (see Note 2)	Fuel and hydraulic fluid from damage flows down nacelle (see Note 3); fuel also flows into nacelle compartments	Heat from afterburner exhaust ignites fuel exiting from nacelle. Incendiary in projectile ignites fuel in nacelle (see Note 3)	Hydraulic lines/ components in tail area, if fire spreads (see Note 4). Engine/ hydraulic equipment in nacelle
	Utility system pump/lines in engine compartment - damage to pump or lines	75 gal/min with 3,000 psi on hydraulic equipment (see Note 2)	Hydraulic fluid from damage flows into nacelle compartments	Incendiary in projectile ignites collected combustibles	Engine/fuel lines in nacelle
Weapons	Forward fuel tank - bay F-2 - damage to bottom	Bottom - 18 gal/min (see Note 2)	Fuel from bottom flows into wheel well	Sparks from damaged electrical wiring; incendiary from projectile	Armament, etc., in weapons bay
Weapons bay	Forward fuel tank - glove area - damage to front of area	Front - 6.3 gal/min (see Note 2)	Fuel from front of tank down inner skin of fuselage into weapons bay	Incendiary from projectile	Armament, etc., in weapons bay
Wheel well	Forward fuel tank - glove area - damage to front of area	Front - 6.3 gal/min (see Note 2)	Fuel from front flows internally to wheel well	Incendiary from projectile	Landing gear, hydraulic equipment

TABLE 9. (Contd.)

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source (see Note 1)	Other components affected
Wheel well (contd.)	Reservoir tank - damage to top/ bottom	Top - 1.6 gal/min Bottom - 9.0 gal/min (see Note 2)	Fuel from tank flows internally into wheel well	Incendiary from projectile	Landing gear, hydraulic equipment
	Main fuel feed line aft to reservoir tanks - damage to line	98 gal/min with 20 psi on line (see Note 2)	Fuel from line flows into wheel well	Same as above	Same as above
	Fuel feed lines - reservoir to engine - damage to line	98 gal/min with 20 psi on line (see Note 2)	Fuel from line flows into wheel well	Same as above	Same as above
	Engine fuel shutoff valves - damage to valves	98 gal/min with 20 psi on line (see Note 2)	Fuel from valve flows into wheel well	Same as above	Same as above
	Primary/utility hydraulic reservoir filters, etc., in wheel well or immediate vicinity - damage to components	75 gal/min with 3,000 psi on hydraulic line (see Note 2)	Fuel from hydraulic components collects in wheel well	Sparks from damaged electrical wiring; damage to bleed-air duct; incendiary from projectile	Same as above
Upper routing tunnel	Hydraulic damper servos, accumulators, lines, valves; power generator lines, valves damaged	75 gal/min with 3,000 psi on line (see Note 2)	Hydraulic fluid from damaged components flows in tunnel	Sparks from damaged electrical wiring; incendiary from projectile	Wiring and hydraulic components

TABLE 9. (Contd.)

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source (see Note 1)	Other components affected
Fuselage right-hand cheek area	Liquid oxygen converter punctured	Not applicable	Liquid oxygen vaporizes	Incendiary from projectile	. . .
Fuselage left-hand cheek area	Precheck fuel line severed	0.8 gal/min (same for fragments)	Fuel from damaged line spreads in cheek area	Sparks from damaged electrical wiring; incendiary from projectile	Wiring and electronics equipment

Notes:

1. The projectile is a potential ignition source for all cases shown.

2. If HEI projectile detonates before it impacts designated equipment, the resultant fragments will cause leakage rates ranging from a fine spray up to 3/4 (same for hydraulics) the quantities shown for projectiles.

3. Fuel flowing into engine inlet may cause compressor stall, abnormal engine operation, or engine burn-through/failures causing loss of engine.

Fuel flowing into the secondary air inlet is discharged from the nacelle in the engine exhaust area and collects on the speedbump and centerbody where it can be ignited by heat from the afterburner exhaust.

Fuel flowing along the fuselage collects on the speedbump and can be ignited by the afterburner exhaust.

If in nonafterburner power setting, propulsion system will not provide an ignition source.

4. Fire on the speedbump, if undetected, can spread along fuel paths when aircraft attitudes disrupt normal airflows along aircraft surfaces.

TABLE 10. Potential A-7 Fire Hazards Due to Combat Damage (Subsonic Aircraft, Single Engine, Nonafterburning).

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source	Other components affected
Engine compartment	Wing fuel tank - inboard of inlet - damage to bottom	Bottom - 2.6 gal/min (see Note 1)	Fuel from damaged tank flows into engine inlet duct (see Note 2)	Incendiary in projectile can ignite fuel (see Note 3)	None
	Forward fuel tank - inboard of inlet - damage to side/ bottom	Side - 12.8 gal/min Bottom - 18.0 gal/min (see Note 1)	Same as above	Same as above	Same as above
	Mid-fuel tank - inboard of inlet - damage to side/ bottom/top	Side - 13.2 gal/min Bottom - 19.0 gal/min Top - 3.3 gal/min (see Note 1)	Same as above	Same as above	Same as above
	Aft fuel tank - inboard of inlet - damage to side/ bottom/top	Side - 19.6 gal/min Bottom - 28 gal/min Top - 4.9 gal/min (see Note 1)	Same as above	Same as above	Same as above
	Sump fuel tank - inboard of inlet - damage to top	Top - 4.4 gal/min (see Note 1)	Same as above	Same as above	Same as above
	Fuel line, pumps, filters, controls, PC-3 hydraulic pump - damage to components	98 gal/min with 20 psi pressure in fuel lines; 75 gal/min with 3,000 psi in hydraulic lines (see Note 1)	Fuel/hydraulic fluid from damage flows into engine compartment cavities	Utility cooling air dump - 715°F; incendiary from projectile ignites fuel/fluid	Fuel, hydraulic, oil components in engine compartment

TABLE 10. (Contd.)

Fire hazard area	Source of combustible fluid	Leakage rate from projectile hit	Leakage path	Ignition source	Other components affected
Engine compartment (contd.)	PC-1 and -2 hydraulic pumps - damage to pumps	75 gal/min from hydraulic components (see Note 1)	Fuel/hydraulic fluid from damage flows into engine compartment cavities	Incendiary from projectile ignites fluid	Fuel, hydraulic, oil components in engine compartment
	Oil lines, tank pump, filter - damage to components	19.5 gal/min from 40 psi oil components (see Note 1)	Oil flows from damaged components into engine compartment cavities	Incendiary from projectile ignites oil	Fuel, hydraulic, oil components in engine compartment
	Engine compressor/combustor/turbine sections - progressive damage to the section hit and resultant damage to fuel/hydraulic/oil components	-98 gal/min with 20 psi on fuel component; -75 gal/min with 3,000 psi on hydraulic components; -19.5 gal/min with 40 psi on oil components (see Note 1)	Fuel/hydraulic fluid/oil flows from damaged components into engine compartment cavities	Incendiary from projectile ignites fuel/fluid/oil	Same as above

Notes:

1. If HEI projectile detonates before it impacts designated equipment, the resultant fragments will cause leakage rates ranging from a fine spray up to 3/4 (same for hydraulics and oil) the quantities shown for projectiles.

2. Engine compartment cooling air enters through three small holes in the outside skin under the wing trailing edge (each side). Any fluid leakage from the wing may enter the engine area.

3. Fuel flowing into inlet duct could be ignited by incendiary; however, airflows will *blow out* fire.

Fuel flowing into engine inlet may cause compressor stall, abnormal engine operation, or engine burn-through/failures causing loss of engine.

Damage to aircraft combustible lines and containers, and the resultant fluid flow and patterns may range from small fragment penetration holes producing a fine mist/spray to complete destruction of the container or line resulting in depletion of the container contents and/or pumping a system dry. The varied types of damage could also result in leakage rates from fuel tanks of sufficient magnitude to create severe aircraft balance problems and fuel depletion.

Another result of 23-mm projectile damage is alteration of the airflow and airflow patterns. Projectile damage to an external skin may be such that flameholders are formed inside the compartment or air scoops created by torn skin. Also, the openings may permit the entry or exit of air dependent on local compartment environment and aircraft flight condition. Single hits of minimum damage (1-inch diameter or slightly larger) will not likely create an appreciable effect from airflow variation. Larger openings can result in significant airflow changes. Local hot spots may be created in a region around the damage. Skin temperatures in these areas may reach total temperatures. A brief, general discussion of the effects of damage on temperature is provided in AFAPL-TDR-64-105 (see Footnote 5, page 54).

In a compartment such as the F-111 nacelle, a 1-inch-diameter or slightly larger hole would not have an appreciable effect on the compartment airflow or airflow patterns. Large damage areas of several square feet could result in substantial nacelle ventilation airflow being directed overboard and loss of the agent. Temperatures in the nacelle compartment would not be increased since compartment air temperature is essentially equal to ram air temperature.

An analysis of the effects of combat damage on fire extinguishant agent quantity and agent stay-time is presented in *Assessment of Fire Hazard Potential in Advanced Environment.*

ASSESSMENT OF FIRE HAZARD POTENTIAL IN ADVANCED ENVIRONMENT

This section defines an advanced environment which was extrapolated from the baseline aircraft environment. No test data were found which would indicate hot-surface ignition temperatures with the combined effects of environmental conditions such as pressure at altitude, ambient air temperature, and airflow velocity. In order to assess fire hazards, it was necessary to extrapolate known test data to the indicated environmental conditions. The hazards based on this approach are assessed in the following sections.

ENGINE NACELLE

The advanced engine nacelle environment which was extrapolated from the baseline aircraft environment was defined in *Advanced Environment*. Fire hazard assessment examples in the advanced environment are shown in Table 11 for the F-111 aircraft. Engine components referred to in Table 11 are identified and shown in Figure 32.

TABLE 11. Example: F-111/TF-30 Engine Nacelle Fire Hazard Assessment for Advanced Environment.

Environmental conditions Mach 2.8/60,000 feet	Source of combustible	Possible ignition source	Fire hazard assessment	Fire detection suppression	Comments
Ram air temperature (standard day): 537°F Engine case temperature (afterburner section): 660°F Nacelle ambient temperature: 556°F	Leaking fuel into nacelle from Fuel line ④ Fuel tank	Ambient air	Minimum SIT with nacelle air pressure of 3.8 psia (equivalent altitude 32,000 feet): 820°F (Figure 33) (velocity effects not included)	No fire hazard	. . .
		Hot surfaces Engine case Nacelle structure Engine bleed duct ①	Hot-surface ignition temperature Lower limit: 820°F - still air Upper limit: 1720°F (820°F + Δ 900°F air velocity effects, Figure 33)	Possible fire hazard	Testing required to determine actual effects from air velocity

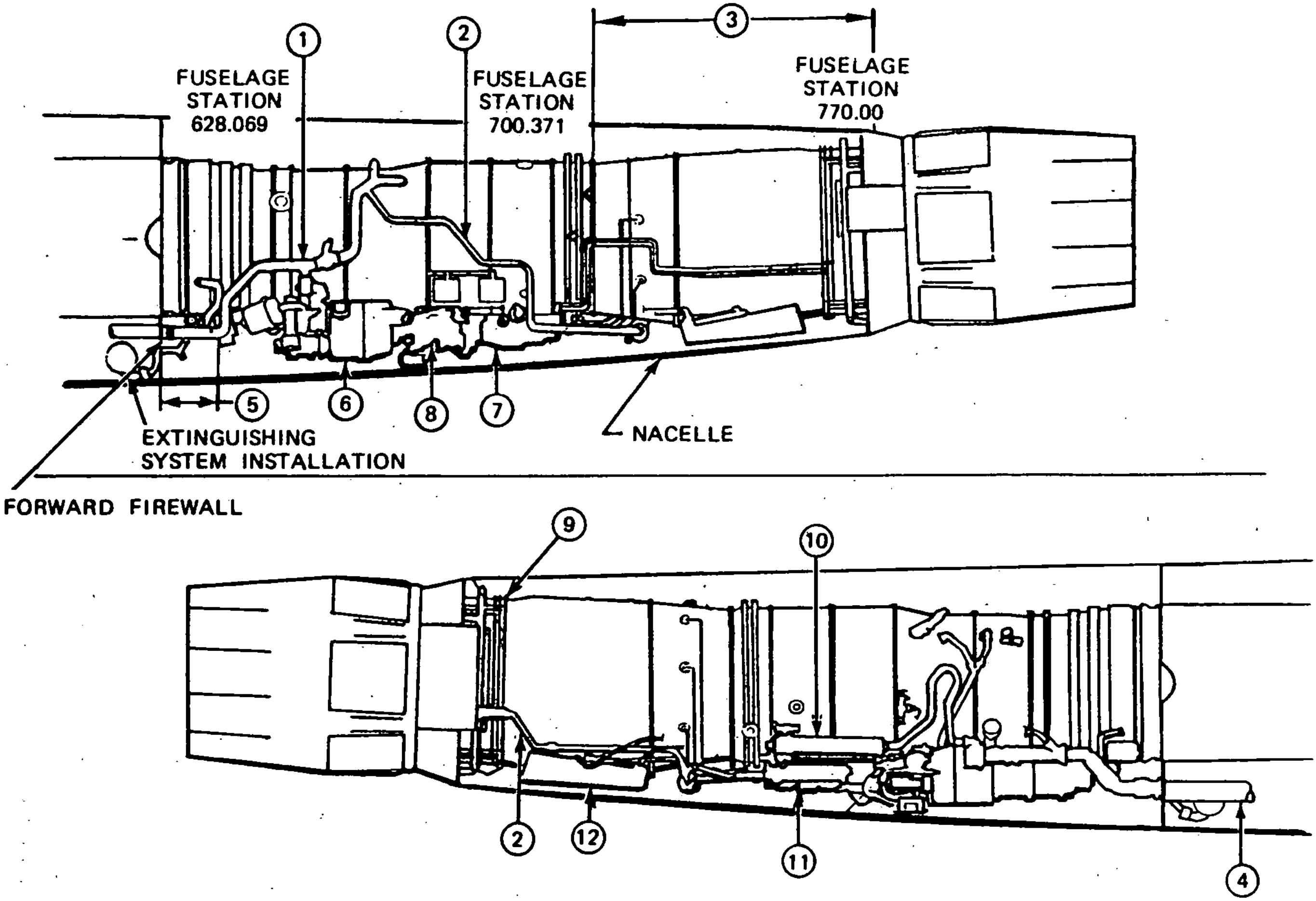
TABLE 11. (Contd.)

Environmental conditions Mach 2.8/60,000 feet	Source of combustible	Possible ignition source	Fire hazard assessment	Fire detection suppression	Comments
Nacelle structure (inboard fuel tank shroud): 537°F Nacelle airflow velocity: 110 to 348 ft/sec Nacelle air pressure: 3.8 psia	Fuel leaking into nacelle from Fuel line ④ Fuel tank Main and afterburner fuel controls ⑦ and ⑧ Afterburner fuel line ⑨ Afterburner and main fuel oil coolers ⑩ and ⑪	Afterburner exhaust gas temperature in excess of 3000°F	Nacelle air velocity prevents forward propagation of flame. The high velocities tend to blow out the fire	Fire detected, pilot moves throttle out of afterburner and turns off fuel supply valve and ignition source with no fuel and/or ignition source flame tends to be extinguished	The effectiveness of the present type of fire extinguishing system is questionable with high nacelle air velocities of 348 ft/sec
Engine bleed duct temperature: 1215°F	Hydraulic fluid leaks into nacelle from hydraulic lines Fluid removed by nacelle drains	Ambient air	Minimum SIT with nacelle air pressure of 3.8 psia (equivalent altitude 32,000 feet): 1020°F (Figure 34) (velocity effects not included)	No fire hazard	. . .

TABLE 11. (Contd.)

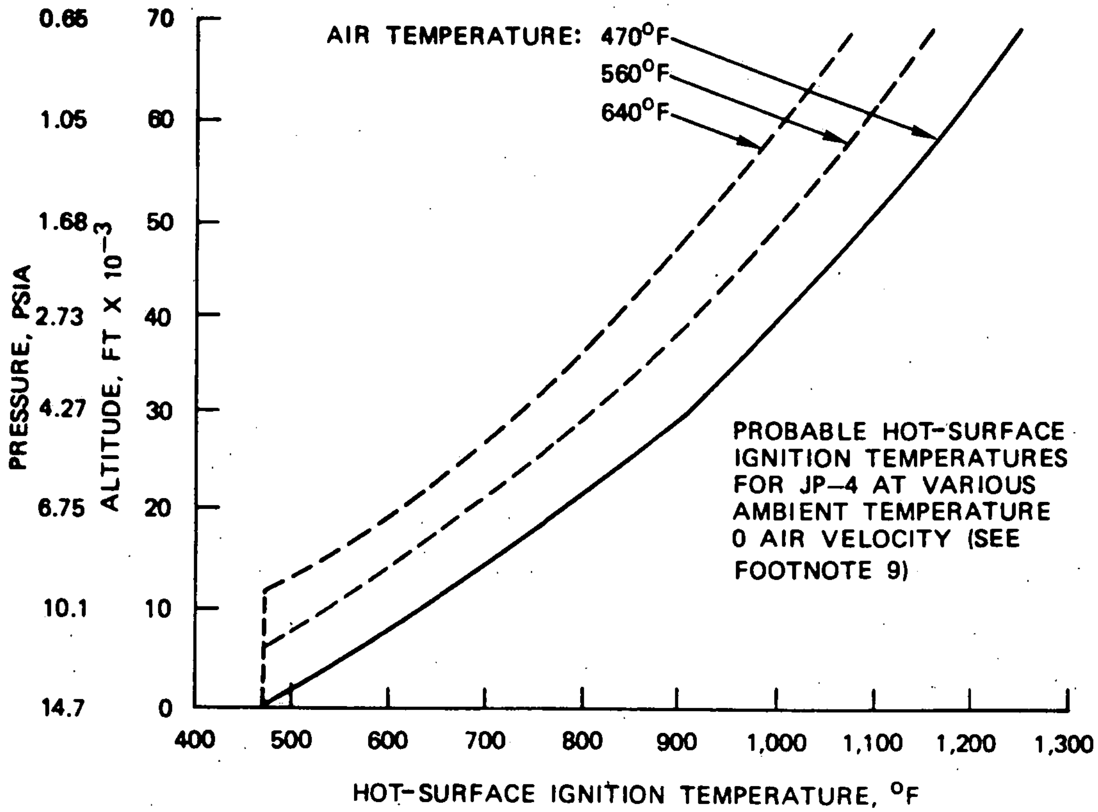
Environmental conditions Mach 2.8/60,000 feet	Source of combustible	Possible ignition source	Fire hazard assessment	Fire detection suppression	Comments
Fuel - JP-4 Hydraulic fluid - MIL-H-5606	Hydraulic fluid . . . (contd.)	Hot surface Engine case Engine bleed duct ①	Hot-surface ignition temperature Lower limit: 1020°F - still air Upper limit: 1820°F (1020°F + Δ 800°F air velocity effects, Figure 34)	No fire hazard Note: Verification testing recommended	Testing required to determine actual effects from air velocity
	Hydraulic fluid leaks in nacelle from lines or hydraulic pump and is discharged out of nacelle at engine exhaust	Afterburner exhaust gas temperature in excess of 3000°F	Nacelle air velocity prevents forward propagation of flame. The high velocities tend to blow out the fire	Fire detected Pilot moves throttle out of afterburner and shuts off hydraulic shutoff valve Flame is extinguished with no combustibles	The effectiveness of the present type of fire extinguishing system is questionable with high nacelle air velocities of 348 ft/sec

Note: ○ Indicates component on Figure 32.



1	ENVIRONMENTAL CONTROL BLEED DUCT	6	GEAR CASE
2	NACELLE VENT BLEED LINE – USED FOR GROUND VENTILATION ONLY	7	AFTERBURNER FUEL CONTROL
		8	MAIN FUEL CONTROL
3	AFTERBURNING SECTION	9	AFTERBURNER FUEL LINES
4	FUEL SUPPLY LINE	10	AFTERBURNER FUEL/OIL COOLER
5	SECTION OF BLEED LINE INSULATED OPPOSITE SIDE OF FUEL LINE ROUTING	11	MAIN FUEL/OIL COOLER
		12	AIR/OIL COOLER

FIGURE 32. F-111 Engine Installation.



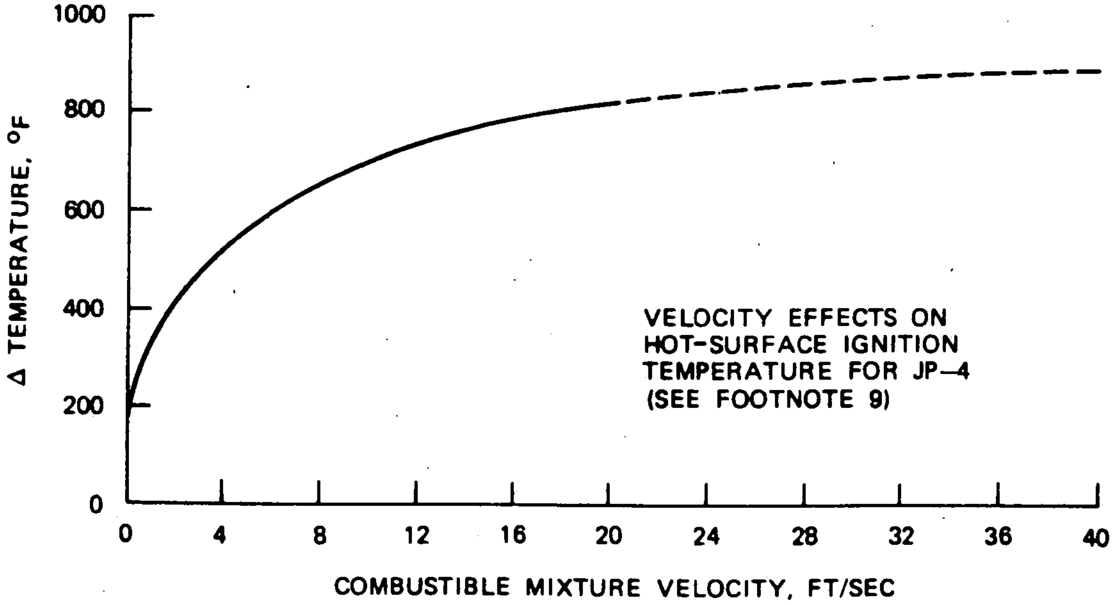
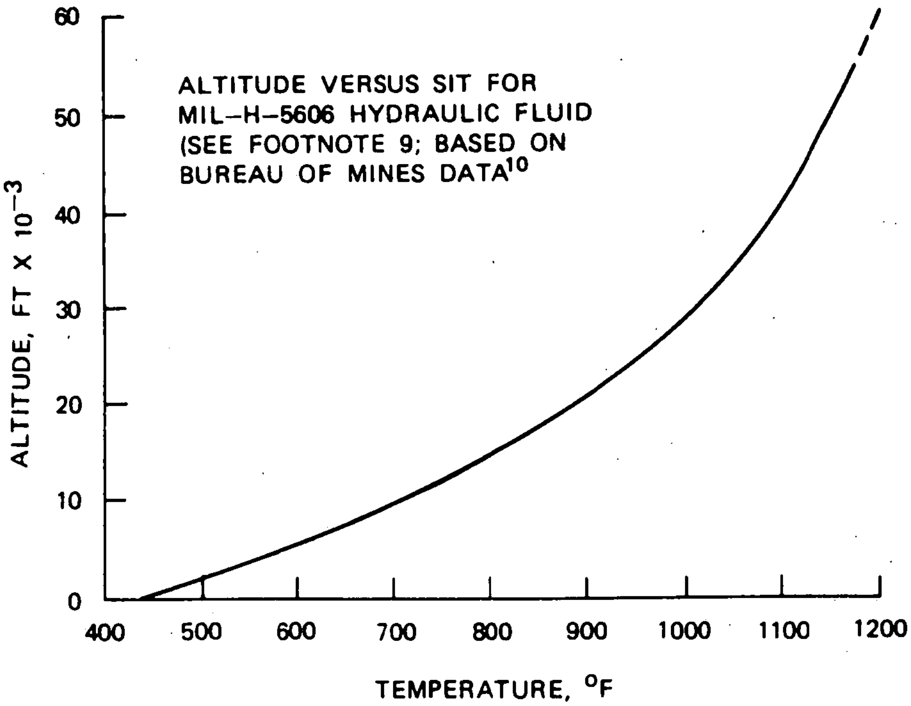


FIGURE 33. Ignition Temperature Data for JP-4.



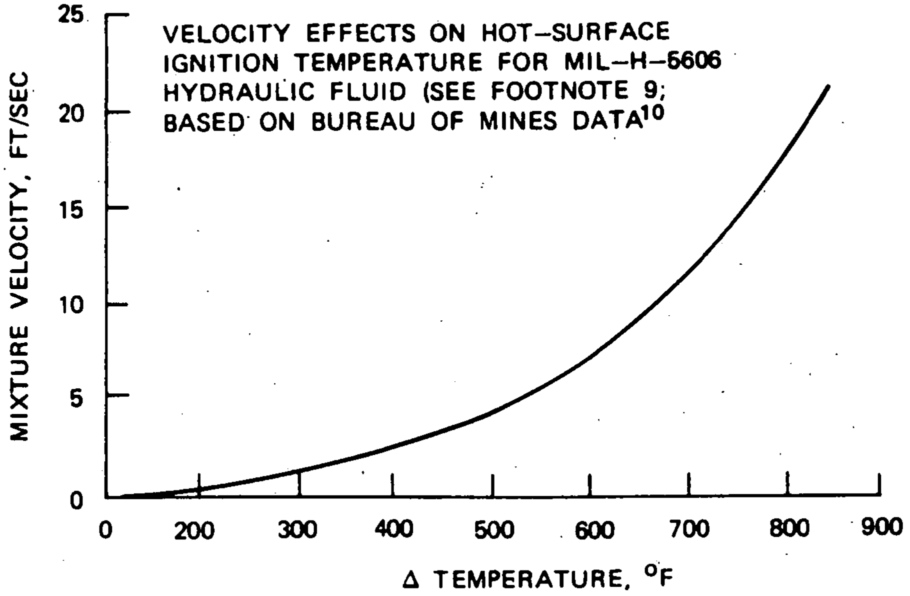


FIGURE 34. Ignition Temperature Data for MIL-H-5606.

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[10] Wright Air Development Center. *Research on the Flammability Characteristics of Aircraft Fuels*, by G. W. Jones. Wright-Patterson AFB, OH, January 1956. (WADC-TR-52-35, Supplement 4).

In determining hot-surface ignition temperatures, it is necessary to take into account the actual pressure level in the nacelle rather than the altitude of the aircraft. By extrapolating test data to the ambient temperature indicated as suggested in EER-FW-1203 (see Footnote 9, page 64), and assuming that the velocity effects were additive, the hot-surface ignition temperature for JP-4 was determined as shown on Figure 33. This approach takes into account the effects of ambient air temperature, pressure, and air velocity. Based on this approach, a lower and upper limit for hot-surface ignition temperature for JP-4 was determined. The lower limit with zero air velocity effects is 820°F (Figure 33) for the conditions shown in Table 11. This ignition temperature is based on data from testing a heated surface in a 30-inch-diameter steel pipe with a test volume of 12.3 ft^3. The upper limit of 1720°F is based on the 820°F with zero airflow plus a Δ 900°F from velocity effects shown in Figure 33. This indicates that the 1215°F bleed-air duct may be an ignition source. Therefore, testing is recommended to determine the actual air velocity effects on the hot-surface ignition temperature at the specified conditions.

A slightly different approach was taken in determining the hot-surface ignition temperature for MIL-H-5606 hydraulic fluid. These test data used were based on the crucible test in which the combustible mixture temperature and the ambient air temperature were the same. Again, as in the previous example, it was assumed that velocity effects are additive. Using these data (Figure 34), the upper and lower hot-surface ignition temperatures were determined. The lower limit, with zero air velocity effects, is 1020°F. The upper limit of 1820°F is based on the 1020°F with zero airflow plus a Δ 800°F from velocity effects (Figure 34) for the conditions shown in Table 11. As can be seen, the 1215°F bleed duct may be an ignition source for a MIL-H-5606 combustible mixture. Testing is also recommended to determine the effects on the hot-surface ignition temperatures at the specified conditions.

OTHER COMPARTMENTS

In Table 12, selected areas other than the engine nacelle are listed and the fire hazards are evaluated. As indicated, environmental conditions other than at the high-altitude, high-speed conditions such as the low-altitude supersonic flight may dictate design considerations to protect hazardous areas. For example, based on the TF-30/F-111 environment, engine bleed-air temperatures can reach 1000°F at low altitude supersonic flight. Uninsulated bleed-air ducts could cause a hazard in static compartments with no airflow. The bleed-air ducts in the baseline aircraft crossover area are insulated. A leaking bleed-air duct that heats up the structure in other compartments results in a possible ignition source as indicated in Table 11. Again, as in the nacelle, testing is recommended to determine the actual ignition temperatures in the high-temperature environment.

DATA REQUIRED

The testing recommended above should include additional investigation of jet fuel flammability characteristics at altitude. A review of literature indicates the existence of a region where what is known as *cool* flames can occur. A cool flame is defined as a self-sustaining reaction, with the evolution of light, and a small increase in temperature and pressure. This reaction will continue without resulting in a flame if heat does not build up to raise the temperature to the critical value. The cool flame reaction can be a hazard in that it may serve to initiate a normal flame if the environmental conditions change.

TABLE 12. Example: F-111 Fire Hazard Assessment—Other Hazardous Areas—Advanced Environment.

Area	Condition	Hazard evaluation	Comments
Crossover compartment	T_{air} = 480°F (static) T_{aw} = 480°F (external skin) Ambient pressure Leaking bleed-air duct temperature = 1215°F MIL-H-5606 leak in compartment JP-4 leak in compartment	SIT for MIL-H-5606 at sea level = 435°F SIT at 60,000 feet = 1200°F (Figure 34) As compartment air temperature increases, hot-surface ignition temperature of MIL-H-5606 approaches SIT Hot-surface ignition temperature of JP-4 at 60,000 feet = 1180°F (Figure 33)	Skin temperature is not an ignition source. 1215°F bleed-air duct may be a hazard at specified conditions. Testing under specific conditions is required to determine or verify actual ignition temperatures. Bleed-air temperature can reach 1000°F at low altitude/supersonic conditions. Uninsulated bleed-air ducts would present a hazard at this condition. Therefore, bleed-air ducts must be insulated in static air compartments. The bleed-air ducts in the baseline aircraft crossover area are insulated.
Nose wheel well	T_{air} = 252°F T_{aw} = 480°F P = ambient + 0.25 psi = 1.296 psi Ventilation in compartment	$T_{aw} <$ SIT for MIL-H-5606 and JP-4 at 60,000 feet	No fire hazard.

TABLE 12. (Contd.)

Area	Condition	Hazard evaluation	Comments
Main wheel well	Maximum T_{air} = 311°F T_{aw} = 480°F P - 1.296 psi Ventilation in compartment	$T_{aw} <$ SIT at 60,000 feet for combustibles Failed or leaking bleed-air duct can heat adjacent structures/components to 1215°F maximum Minimum hot-surface ignition with 0 airflow (Figures 33 and 34) MIL-H-5606 = 1180°F JP-4 = 1130°F	Skin temperature is not an ignition source. Baseline vehicle bleed-air ducts are insulated. Maximum external insulation temperature = 400°F. Bleed-air ducts require insulation to prevent hazard at low altitude/ supersonic flight. 1215°F surfaces may be hazardous. Testing required to determine ignition temperature and effects from air velocity.
Weapons bay	T_{air} = 150°F T_{aw} = 480°F P = 1.296 psi Ventilation in compartment	$T_{aw} <$ SIT at 60,000 feet for combustibles	Compartment cooled to protect weapons. Skin temperature is not an ignition source
Cheek areas	T_{air} = 150°F T_{aw} = 480°F P = 1.296 psi Ventilation in compartment	$T_{aw} <$ SIT at 60,000 feet for combustibles	Skin temperature is not an ignition source.

FIRE EXTINGUISHANT AGENT/SYSTEM EVALUATION IN THE HIGH-TEMPERATURE, HIGH-AIRFLOW ENVIRONMENT

Engine fire extinguishing systems are generally installed on multiengine aircraft. Also, fire extinguishing systems have been installed in compartments which contain combustible fluid lines, reservoirs, or they have been placed adjacent to fuel tanks. Fire extinguishing agents utilized for these applications are usually of the halogenated hydrocarbon type because of their greater fire suppression effectiveness compared to other agents (e.g., CO_2). Their physical properties have enabled an overall reduced system weight. The principal halogenated agents presently utilized for these applications in the United States are dibromodifluoromethane (CF_2Br_2) and bromotrifluoromethane (CF_3Br). In Europe, the current principal agent is bromochlorodifluoromethane (CF_2BrCl). Dibromotetrafluoroethane ($CBrF_2CBrF_2$) is a leading candidate for higher temperature applications. Table 13 provides a comparison of selected physical properties for the agents.[11,12] CF_2Br_2 is utilized for fire suppression in the F-111 nacelles and CF_3Br is utilized for fire suppression in certain F-111 fuselage compartments. Agents installed in other aircraft are included in the summary of various aircraft presented in Tables 7 and 8. The F-111 nacelle may be regarded as a high airflow compartment and is therefore a good example for evaluation or comparison of present and candidate agents to determine their capabilities or limitations. An evaluation of halogenated fire extinguishant agents should include the following considerations:

1. Toxicity
2. Thermal stability
3. Corrosion
4. Storage
5. Quantity requirements
6. Stay-time
7. Effectiveness.

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[11] Wright Air Development Center. *A Study of Vaporizable Extinguishants.* Wright-Patterson AFB, OH, January 1960. (WADC-TR-59-463, publication UNCLASSIFIED.)

[12] National Fire Protection Association. *The Halogenated Extinguishing Agents.* Boston, MA, NFPA, October 1954. (NFPA Q48-8, publication UNCLASSIFIED.)

TABLE 13. Comparison of Agent Properties.

Agent	Bromochloromethane	Dibromodifluoromethane	Bromotrifluoromethane	Dibromotetrafluoroethane	Bromochlorodifluoromethane
Chemical formula	CH_2BrCl	CF_2Br_2	CF_3Br	$CBrF_2CBrF_2$	CF_2BrCl
Halon number	1011	1202	1301	2402	1211
Boiling point, °F	153	73	-72	117.5	25
Freezing point, °F	-124	-223	-282	-166.8	-257
Molecular weight	129.4	209.8	148.9	259.9	165.4
Critical temperature, °F	531	388.7	152.6	418	309
Critical pressure, psig	953	593	574	500	595
Liquid density, (lb/gal) 70°F	16.1	19	13.1	18.0	15.3
Liquid density, (lb/gal) 130°F	15.4	17.9	10.4	17.1	14.2

TOXICITY

The possibility of accidental discharge of an agent during carrier operation or while the aircraft is in an enclosed hangar creates the necessity for consideration of a low toxicity agent. A relative comparison of agent toxicity using the Underwriters' Laboratories classification and results of the US Army Chemical Center lethal concentrations tests for exposure to rats are presented in Table 14 (see Footnote 11). These two comparisons correlate in the relative ranking of the agents with 1301 being the least toxic and 1202 the most toxic. The toxicity of some fluorocarbon agents have been evaluated by the AFAMRL (Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio).[13] The toxicologic evaluation of some members of the fluorocarbon series suggested the following:

1. The pharmacologic properties do not differ substantially from one member of the series to the next.

2. Differences are primarily the concentration to which the subject must be exposed to elicit a given response.

3. Evidence is available that there is no appreciable cumulative effect of repeated exposure.

Threshold limit values and emergency exposure limits were also evaluated in the AFAMRL letter.[13] For compounds where this information did not exist, reasonable estimates were made for use as guidelines. These comparisons are presented in Table 15.

The Underwriters' Laboratories, Army Chemical Center, and AFAMRL evaluations all rated 1301 as the least toxic of the four agents under consideration. The Underwriters' Laboratories and Army Chemical Center rated 1202 as the most toxic whereas the AFAMRL estimated that 2402 is more toxic than 1202. The 1202 and 2402 agents were estimated to have the same threshold limit value but 2402 was estimated to require less concentration for the emergency exposure limit.

Toxicity will be a factor in the selection and application of future advanced fire suppression systems. A logical goal in the development of future fire extinguishing agents would be that any new agent should be less toxic than 1301 as defined in Table 15. Agent 1301 is colorless and odorless and when discharged, it is difficult to detect by normal human senses. Considering toxicologic factors, a desirable feature would be to have an agent that has a distinguishable odor and/or color such that normal human senses could readily detect the presence of the agent in the event of accidental discharge.

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[13] Air Force Aerospace Medical Research Laboratory. *Toxicity of Fluorocarbons.* Wright-Patterson AFB, OH, AFAMRL, 3 March 1971. (Publication UNCLASSIFIED.)

TABLE 14. Relative Comparison of Agent Toxicity.

Agent	Underwriters' Laboratory classification[a]	Approximate lethal concentration, ppm for 15-minute exposure of rats[b]	
		Natural vapors	Decomposed vapors
1301	6	800,000	14,000
2402	5	126,000	1,600
1211	5	324,000	7,650
1202	4	54,000	1,850

[a] Underwriters' Laboratory classification of comparative life hazard of fire extinguishing agents based on a relative numbering system of 1 for highest toxicity and 6 for lowest toxicity.

Classification 4 - Gases or vapors which in concentrations of the order of 2 to 2 1/2% for periods of order of 2 hours produce serious injury.

Classification 5 - Gases or vapors much less toxic than Group 4 but more toxic than Group 6.

Classification 6 - Gases or vapors which in concentrations up to about 20% by volume for durations of order of 2 hours do not appear to produce injury.

[b] Research by Army Chemical Center.

TABLE 15. Fluorocarbon Exposure Limits, ppm.[a]

Compound	Threshold limit value	Emergency exposure limit
Bromotrifluoromethane (Freon 1301, F 13B1)	1,000[b]	60,000[c]
Bromochlorodifluoromethane (Halon 1211)	(1,000)	50,000[c]
Chlorobromomethane (Halon 1011, CB)	200[b]	(10,000)
Dibromodifluoromethane (Halon 1202)	100[b]	(3,000)
Dibromotetrafluoroethane (Halon 2402)	(100)	(1,000)
Dibromotrifluoroethane (Halon 2302)[d]	(100)	(1,000)

[a] AFAMRL letter (see Footnote 13).

[b] ACGIH (American Conference of Governmental Industrial Hygienists).

[c] NAS/NRC (National Academy of Science/National Research Council).

[d] Nothing is known of the toxicity of Halon 2302 and therefore it should be treated as extremely toxic until proven otherwise.

Notes:

1. Numbers in parentheses in the body of the table are unpublished values which represent estimates for use as temporary guidelines only until such time as documented values become available.

2. Threshold limit value = chronic daily exposure.

3. Emergency exposure limit = short duration (5 minutes) time limit. Subjective symptoms may become apparent - nausea, headaches, etc.

4. Values for Halon 2402 and 2302 are projected.

AGENT STABILITY

The Halon fire extinguishants available for present fire suppression systems are, in general, thermally unstable above 500°F. For example, initial decomposition of these agents occurs between 620 and 860°F after relatively short exposure times to these temperatures.[14, 15, 16] Test data presented in WADC-TR-59-463 (see Footnote 11) illustrate the significant agent decomposition that occurs at temperatures above 500°F. Agents ranked in order of decreasing thermal stability are: Halon 1301, 1211, 2402, and 1202. The following thermal stability limits for 1301, 1202, and 1211 have been defined considering the high vapor pressure of 1301 and 1211 and thermal decomposition of 1202 (see Footnote 5, page 54).

Agent	°F
1301	500
1211	400
1202	350

Agent storage containers may be located in compartments cooled by air from the vehicle environmental control system. However, this situation will not be practical in all cases because of various variables, some of which are engine locations, space allocation, environmental air available, and weight penalties. There are a large number of compartment combinations/conditions in which an agent may be stored. The thermal environment will depend on aircraft aerodynamic heating, other heat sources within the compartment, ventilation flow in the compartment, heat capacity of the agent and container, and heat sink available such as structure and adjacent fuel tanks. A general, analytical discussion of aerodynamic heating, transient heating effects, local flow properties, and extinguishant heating is provided in AFAPL-TR-65-124.[17] For general guidance in relating the agent stability to the aircraft environment, two conservative stabilized conditions may be assumed. These two conditions are:

1. Temperature of agent stored in an uncooled, nonventilated compartment reaches adiabatic wall temperature.

2. Temperature of agent in an uncooled, ventilated (either by design or resulting from damage) compartment reaches ram air temperature.

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[14] Air Force Aero Propulsion Laboratory. *Development of High Temperature Fire and Explosion Suppression Systems*, by Gillis and Cutler. Wright-Patterson AFB, OH, AFAPL. (AFAPL-TR-69-115, publication UNCLASSIFIED.)

[15] E. I. Du Pont deNemours and Co., Inc. *Stability of Fire Extinguishing Agents at 600°F.* Wilmington, DE, November 1959. (KSS-2446, publication UNCLASSIFIED.)

[16] E. I. Du Pont deNemours and Co., Inc. *Stability of Freon® FE1301 and Freon® 114B2 Fire Extinguishing Agents at 500°F.* Wilmington, DE, November 1967. (KSS-6048, publication UNCLASSIFIED.)

[17] Air Force Aero Propulsion Laboratory. *Investigation of Fire and Extinguishing System Requirements for Advanced Flight Vehicles*, by Landesman, Klusmann, Minich, and Christensen. Wright-Patterson AFB, OH, AFAPL, January 1966. (AFAPL-TR-65-124, publication UNCLASSIFIED.)

For these conditions, a critical Mach number for halogenated agent stability is defined as the flight Mach number at which adiabatic wall temperature or ram air temperature for flight in standard atmosphere at 36,000 to 90,000 feet altitude equals the agent stability temperature limit. The critical flight Mach number for halogenated agent stability has been calculated for several conditions and is presented in Table 16. For advanced aircraft flight beyond the critical Mach number, detailed agent heating analysis and storage container design evaluation are required as the conventional system becomes questionable.

TABLE 16. Critical Flight Mach Number for Halogenated Agent Stability.

Decomposition/thermal stability temperature,° F	Critical Mach number based on adiabatic wall temperature	Critical Mach number based on ram air temperature
620	3.1	3.0
350	2.4	2.3
400	2.6	2.4
500	2.8	2.7

Various agent/metal compatibility tests have been conducted in the high-temperature environment to determine the stability of the agents and effects on different storage container materials. The products of decomposition of the halogenated agents include acids which may have a corrosive effect on metals. In general, the tests conducted cannot be directly compared or correlated because of the different test methods, conditions, agents, and materials utilized. An agent/metal compatibility summary of selected high temperature tests is shown in Table 17. This summary is divided into two parts, one showing the effects on certain test metals and the other describing the effects on the agent. Basically, the tests are conducted by subjecting a test metal and agent to a specified test temperature/time condition.

Results of the 600°F and 25 hours testing with agent 1301 indicates that Inconel has the least effect on agent decomposition and exhibits the least corrosion. The rate of penetration for mild steel and stainless steel 316 was 4.4 and 2.3 times the rate for Inconel. The percent agent decomposition for mild steel and stainless steel 316 was 5.8 and 4.0 times the decomposition for Inconel. The agent did not change appearance for the 600°F/25-hour test using a pyrex test tube without a metal sample present, but 0.02% decomposition of agent occurred.

Results of the 500°F and 100 days testing indicate agents 1301 or 2402 are less compatible with 4130 steel. Also, AM362 steel with agent 2402 is less compatible.[18]

A Du Pont test using agent 1301 with stainless steel 321 resulted in 0.018% agent decomposition after 25 hours at 450°F and 0.23% after 25 hours at 700°F.[19]

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[18] E. I. Du Pont deNemours and Co., Inc. *Capability of Candidate Fire Extinguishing Agents With Metals at 500°F.* Wilmington, DE, October 1966. (KSS-5712, publication UNCLASSIFIED.)

[19] E. I. Du Pont deNemours and Co., Inc. *High Temperature Stability Tests of "Freon" Fluorocarbons With Titanium and Stainless Steel.* Wilmington, DE, May 1963. (KSS-4311, publication UNCLASSIFIED.)

TABLE 17. Agent - Metal Compatibility Tests Summary - High-Temperature Environment.

Agent	260 days[a] - 248°F[b]		25 hours - 600°F[b,c]			2 months - 500°F[d]	100 days - 500°F[e]				2000 hours - 400°F[f]
	Steel (dry)	Steel (wet)	316	Mild steel	Inconel	AM362	302	304	AM362	4130	Inconel, 316, 347
						Effect on material					
1301	0.9	91	630 slight tarnish	1200 darkened, slight corrosion	270 slight tarnish	Black film on surface, no corrosion noted on metal surface	Slight tarnish	Very slight tarnish	Slight tarnish	Black film	
1202	0.8	62									Thin film or scale weakly bonded
1211	1.1	82									
2402	1.5	140				Black film on surface, slight corrosion on surface	Slight tarnish	Slight tarnish	Very slight tarnish	Slight film	Black film
						Effect on agent % decomposition - (appearance change)					
1301	(No change)	(No change)	1.6 (red-orange)	2.3 (no change)	0.4 (no change)	0.4	0.16 (none)	0.12 (none)	0.36 (none)	0.82 (tube wall very slight etched)	
1202	(Color changed but not to the yellow or light amber color)	(No change)									(Slightly acidic, slightly darkened)

TABLE 17. (Contd.)

Agent	260 days[a] - 248°F[b]		25 hours - 600°F[b,c]			2 months - 500°F[d]	100 days - 500°F[e]				2,000 hours - 400°F[f]
	Steel (dry)	Steel (wet)	316	Mild steel	Inconel	AM362	302	304	AM362	4130	Inconel, 316, 347
	Effect on agent % decomposition - (appearance change)										
1211	(No change)	(No change)									
2402	(Color changed but not to the yellow or light amber color)	(Changed between yellow or light amber and dark amber or black)				0.1 (light yellow color)	0.11 (light yellow)	0.08 (light amber)	0.39 (tube wall very slight, white film)	1.5 (none)	Darkened slightly acidic, black precipitate

[a] AFAPL-TDR-64-105 (see Footnote 5, page 54).

[b] Metal penetration, (in/mo) x 10^{-6}.

[c] Pratt & Whitney Brochure GP 73-126 (see Footnote 6, page 61).

[d] AFAPL-TR-72-83 (see Footnote 7, page 61).

[e] AFAPL-TR-71-86 (see Footnote 8, page 64).

[f] AFAMRL letter (see Footnote 13, page 93).

Many of the present fire extinguishing agent containers are manufactured of 4130 steel. Tests at elevated temperature (Table 17) indicate that more compatible agent/metal combinations may be selected for future advanced aircraft applications. Based on the available test data reviewed, halogenated agent storage containers in high-temperature environments should be manufactured from stainless steel or Inconel. Where specific test data are not available, testing should be conducted to determine suitable agent/metal combinations. Service testing of systems should also be conducted to determine specific application time limitations.

It is doubtful that fire extinguishant agent storage temperatures in service will exceed 500°F for the advanced aircraft up to the 1980 time period. The test data and literature review indicate that agent 1301 will be compatible with this environment considering only decomposition and corrosive effects. Agent 2402 should be compatible with selected corrosion resistant steels for use at 500°F. The agent exhibited relatively small decomposition in 500°F tests for 100 days. Service life testing is required to determine appropriate life factors.

Near-term advanced agent development should include thermal stability and compatibility with corrosion resistant steels criteria for temperatures of approximately 500°F+. Ideally, the agent would not exhibit decomposition or corrosion effects (with corrosion resistant steels) greater than 1301 or 2402. The acceptability of cleanup problems will depend on the function of the agent and/or reliability of the fire detection system. In addition to the engine and aircraft materials presently utilized, an advanced agent should not create corrosion problems or reactions when discharged into a compartment with candidate advanced aerospace structural metals. An example of candidate metals as a function of Mach number is provided in Table 18 for a typical advanced interceptor.

STORAGE

Storage containers for the vaporizable fire extinguishant agents must be capable of withstanding the pressure resulting from the agent vapor plus the partial pressure of the charging gas. In a high-temperature environment, high pressures are developed within the container. The current military specification for container design is MIL-C-22284. This specification is for spherical containers and in general, requires conformance to ICC (Interstate Commerce Commission, Washington, DC) Specification No. 4DA.

The F-111 fuselage fire extinguishing spherical container is a realistic example used to evaluate the effects of operating in the higher temperature environment. The volume of this container is 378 in^3 and is filled with 11.25 pounds of 1301 agent charged to 600 psi at 70°F with nitrogen. Proof pressure is 2,600 psi. The container fill ratio is calculated as follows:

$$\text{Fill ratio} = \frac{\text{Volume of agent}}{\text{Volume of container}} \times 100 = 52.5\%$$

TABLE 18. Candidate Structural Metals for Use in Advanced Aircraft—Typical Interceptor.

Metals	Mach number/stagnation temperature, °F					
	2.5/420	3.0/590	3.5/860	4.0/1150	4.5/1140	5.0/1740
Aluminum						
2219	X					
Titanium						
β III	X	X				
6Al-4V	X	X				
6Al-2S_n-4Z_r-6M_o	X	X	X			
6Al-6V-3S_n	X	X				
Steels						
PH 14-8 M_o	X	X	X			
PH 15-7 M_o	X	X	X			
PH 13-8 M_o	X	X	X			
Super alloys						
Inconel 718			X	X	X	
Rene 41, HS188				X	X	X
Udimet 500					X	X

The following are data obtained from an actual sample container:

1. Material - 4130 steel
2. Minimum thickness - 0.065 inches
3. Outside diameter - 9.22 inches
4. Yield strength - 128,000 psi
5. Tensile strength - 144,000 psi
6. Burst - 3,800 psi.

The pressure developed in containers for specified agents at various fill ratios as a function of temperature may be obtained from data published in the literature[20] or calculated by assuming an ideal gas and utilizing Dalton's Law. Stress in spherical containers may be calculated as follows:

$$\sigma = \frac{1.2\ PD}{4\ t}$$

where

σ = stress

P = pressure

D = outside diameter

t = wall thickness

1.2 = weld efficiency factor

The following are sample container pressure and wall stress estimates for the present F-111 fuselage container at various temperatures.

Temperature, °F	Pressure, psi	Wall stress estimates, psi
193	1,330	56,596
252	1,820	77,448
500	3,787	161,151

The sample container-calculated stress at 2,600 psi proof pressure is 110,640 psi. This proof pressure is approximately two times the pressure developed at 193°F which is the maximum expected compartment air temperature for F-111 stabilized Mach 2.2 flight. The present container-calculated wall stress for a temperature equal to 500°F is greater than the proof pressure stress and approximately equal to burst level stress of the sample container. For the above example, if the temperature is 500°F and it is desired to maintain a proof pressure of twice the working pressure and the stress at proof pressure below 70,000 psi, then the calculated wall thickness will increase from 0.065 to 0.3 inch. This represents a weight increase of approximately 19 pounds over the sample container.

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[20] Aeronautical Systems Division. *Study on Minimization of Fire and Explosion Hazards in Advanced Flight Vehicles.* Wright-Patterson AFB, OH, ASD, October 1961. (Lockheed Report 15156; ASD-TR-61-288, publication UNCLASSIFIED.)

As an alternative to the higher pressures, the fill ratio may be reduced. This will increase container volume and diameter if the agent quantity remains constant. Volume increase or additional space allocation requirements can be of significance on high performance aircraft. The effects of reducing the fill ratio to maintain a given container pressure level can be illustrated by additional evaluation of the above F-111 fuselage sample container. Arbitrarily assume that the fill ratio is to be reduced from 52.5 to 25% and the quantity of agent remains constant at 11.25 pounds, and the maximum pressure developed is 1,330 psi (approximately 1/2 of sample container proof pressure). The container volume required for this condition is approximately 792 in^3 (approximately 11.5 inches inside diameter) or approximately twice the baseline sample volume. The weight increase over the baseline sample container is approximately 11 pounds based on the assumption of maintaining stress at proof pressure below 70,000 psi. In addition to the increased weight and space requirements, a limiting factor is the maximum allowable temperature to maintain the desired pressure level. The above specified pressure and fill ratio with 1301 agent corresponds to a temperature of approximately 252°F. If agent 1202 were substituted in the baseline F-111 fuselage container and the same weight of agent maintained (11.25 pounds), the pressure developed at 500°F would be approximately 3,228 psi. This is less than that developed with 1301 but it still is a high pressure that will result in significant penalties.

The F-111 engine nacelle fire extinguishant container is located in an enclosed crossover area compartment which is located on the bottom of the aircraft between the main wheel well and the engine nacelles. The volume of the cylindrical container is 385 in^3 and is filled with 12.65 pounds of 1202 agent charged to 600 psi at 70°F with nitrogen. If the temperature reaches 500°F, the internal pressure will be approximately 3,465 psi.

CLOSED COMPARTMENT

The effect of inadvertent aircraft compartment venting (e.g., due to possible battle damage) on the quantity of vaporizable fire extinguishing agent required for effective fire extinguishing over a specified period of time is considered for a closed compartment (no ventilation).

Condensation of Agent

In this analysis, it is assumed that the agent is loaded in sufficient quantity to provide a 6% homogeneous volumetric concentration in the compartment at an initial compartment air pressure of standard sea-level static (2,116.2 psfa) and an initial compartment temperature of 100°F (560°R). The agent selected for purpose of study is dibromodifluoromethane (CBr_2F_2), Halon 1202, which is a good example of the halogenated extinguishants. The choice of a 6% concentration for 1202 is justified by the following.

The flammability limits of several Halon agents are reported in WADC-TR-59-463 (see Footnote 11) and pertinent data are shown in Figure 35. The peak of a flammability curve plot is defined as the minimum volumetric concentration of agent (vapor state) at which no mixture of fuel and air is flammable. This volumetric concentration (curve peak) is listed for several agents and the flammability curves for two popular agents (Halon 1202 and 1301) relative to an n-heptane fuel/air mixture are shown in the graph.

FLAMMABILITY PEAKS

HALON	VOLUME, %	FLAMMABILITY PEAK WEIGHT OF AGENT, gm
1202	4.2	39.37
2402	4.9	56.87
1301	6.1	40.57
1211	9.3	68.71

NOTE: AGENT CONCENTRATIONS INDICATED ARE BASED ON N–HEPTANE AIR MIXTURES AT ROOM TEMPERATURES AND AT 300– TO 500–MM TOTAL PRESSURES

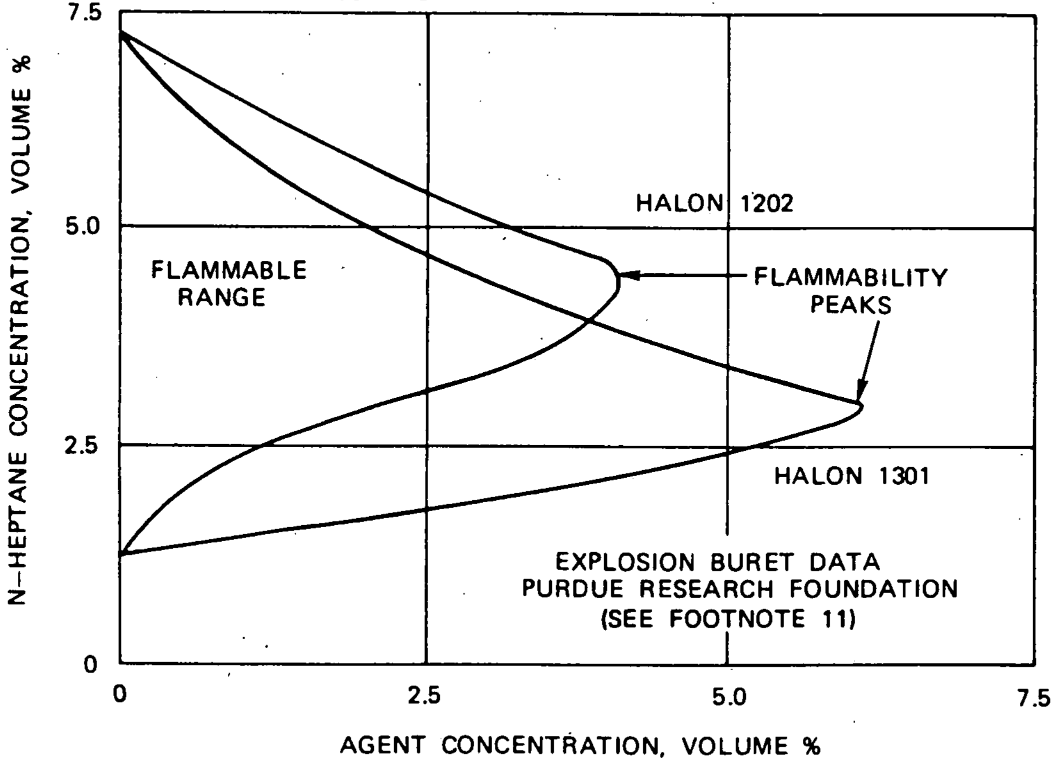


FIGURE 35. Flammability Limits for Representative Halogenated Extinguishing Agents.

One accepted explanation (see Footnote 11) for the behavior of a vaporizing halogenated liquid agent in extinguishing fires is that the halogens and halogen-containing compounds react with free radicals, e.g., the hydrogen atom, in the combustion process in such a manner as to terminate flame propagation. For these agents to be effective, they must therefore be dispensed in a vapor state to obtain a homogeneous mixture of proper concentration. If a desired quantity of agent is dispensed into a venting compartment where the local conditions (pressure and temperature) are changing rapidly, agent vapor condensation may occur and thus alter the agent concentration over a finite time period. This effect and the basic assumptions are examined in the following analysis.

1. Halon 1202 loaded to provide a 6% volumetric concentration at an initial compartment air pressure (before injection) of standard sea-level static and an initial compartment temperature of 100°F.

2. Complete vaporization and homogeneous mixing of agent and air upon injection.

3. Mixture properties (molecular weight, gas constant, specific heats, etc.) are those determined by conventional means for a mixture of ideal gases.

4. An isentropic expansion to ambient conditions (due to compartment venting) from an initial mixture pressure composed of the sum of the partial pressures of the ambient air (at any altitude) and the agent at the selected mixture temperature--the actual process will lie between the isentropic and isothermal, but the isentropic will give a conservative result.

An analysis was made over a range of flight altitudes with the further assumption of three different initial mixture temperatures. These are: (1) a constant temperature of 100°F (560°R)--here it is hypothesized that due to the mass of surrounding structure, the ambient temperature in a reasonably pressure-tight compartment will not change appreciably with a fairly rapid increase in flight altitude, (2) a temperature corresponding to the ambient temperature at altitude--(an extreme limiting case), and (3) a temperature of 0°F (460°R), which represents an intermediate case. The initial mixture properties which are considered invarient with altitude are as follows:

Mixture constituents	Halon 1202 and air	
Mixture molecular weight	39.82	
Mixture gas constant	38.80	$\left\{\frac{lb_f - ft}{lb_m - {}^\circ R}\right.$
Mixture specific heat ratio	1.320	

The steady-state results of an isentropic expansion from the assumed conditions is shown in Figure 36, where the final partial pressure of the agent is compared with the saturation vapor pressure of the agent at the final mixture temperature and plotted as a function of altitude for the three initial temperature cases. Saturation vapor pressure of the agent was taken from results presented in WADC-TR-59-463 (see Footnote 11) and reproduced in Figure 37.

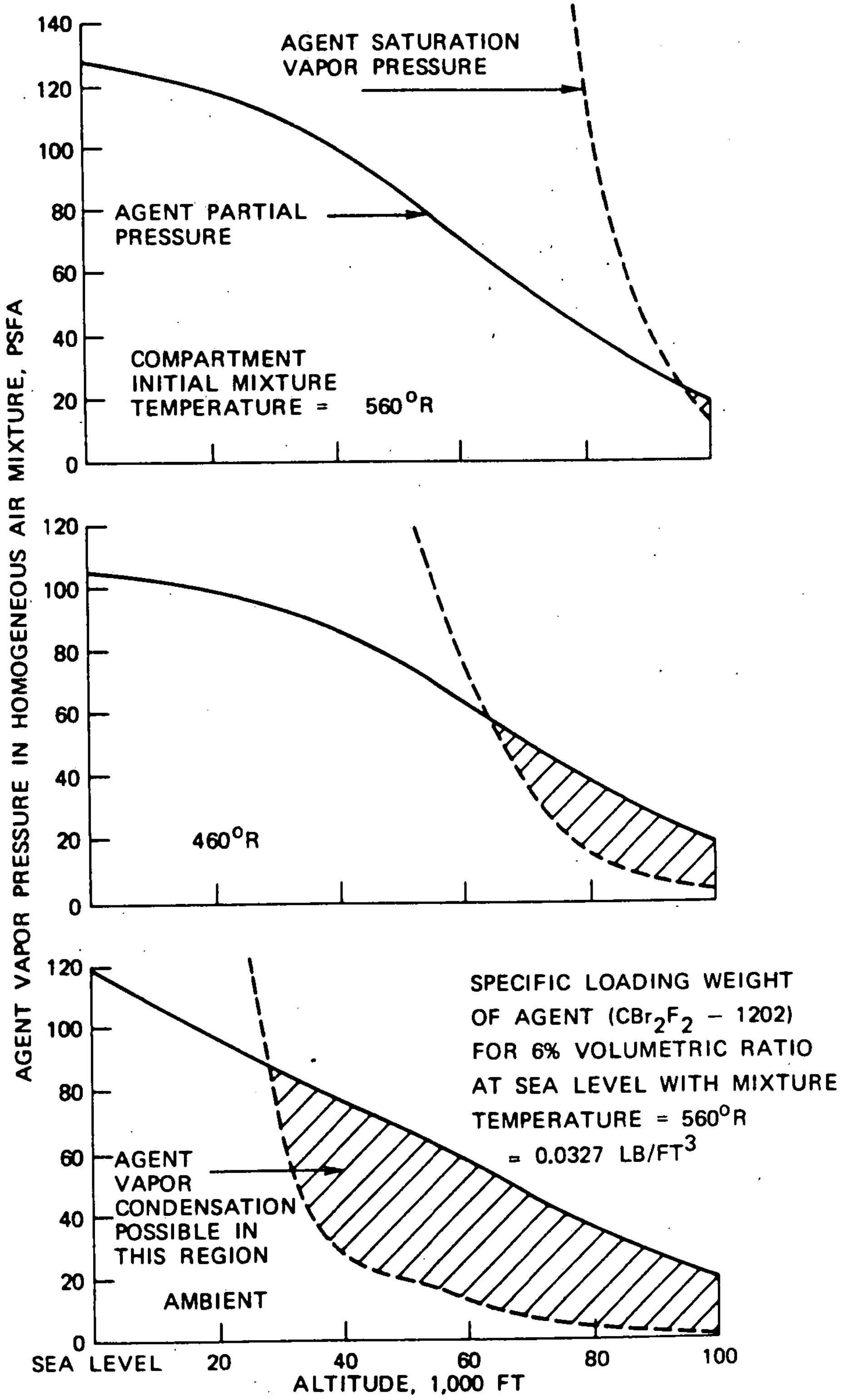


FIGURE 36. Comparison of Agent Vapor Pressure After Isentropic Expansion With Agent Saturation Vapor Pressure at Mixture Temperature.

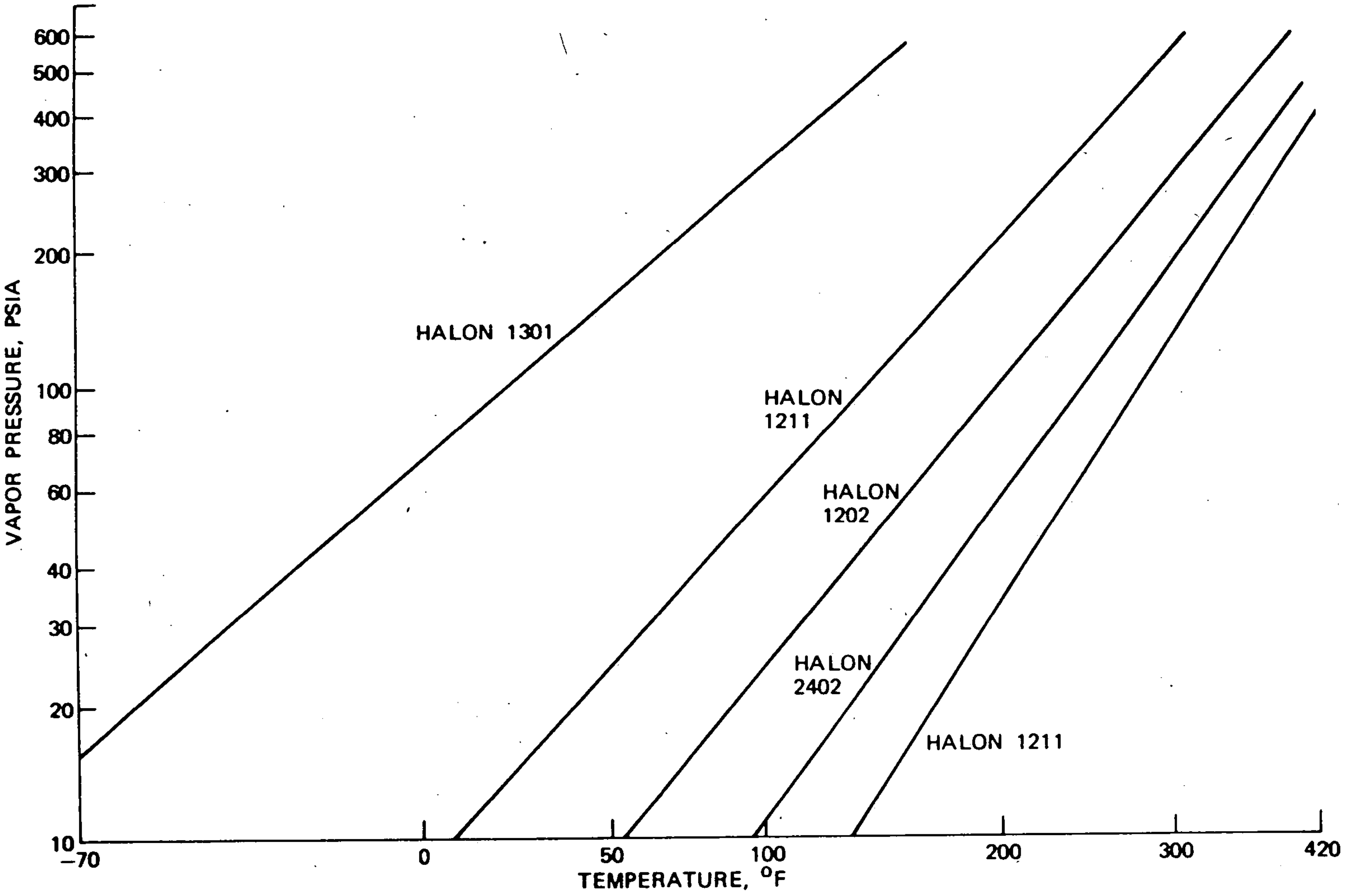


FIGURE 37. Vapor Pressure - Temperature Relation of Several Halogenated Extinguishing Agents.

The results depicted in Figure 36 show that agent condensation is indeed possible (indicated by a saturation vapor pressure lower than the agent partial pressure) but will happen only under the most severe conditions of high altitude and low initial mixture temperature. Also, in a mixture of gases, a state of supersaturation is often attained in a sudden expansion and condensation (a time- and foreign-contaminate-dependent process) will not be initiated immediately upon one of the constituents passing into the liquid phase.

In view of these results however, additional examination is appropriate. Two questions should be answered: (1) if condensation does occur, will the agent remaining in a saturated mixture be sufficient to satisfy the 6% volumetric concentration requirement and (2) is condensation initiated before or after the required stay-time is reached? Stay-time is defined as the amount of time after agent injection during which the desired agent concentration is to be maintained. For the applications of interest, 1/2 second is a minimum requirement.

To answer the first question posed above, the two cases in Figure 36 that indicate significant ranges of possible agent vapor condensation (initial mixture temperature of 460°R and ambient) were examined in further detail. The results are shown in Figure 38 where the specific volume required for a 6% concentration of the agent vapor after expansion at each altitude condition is compared with the specific volume of the agent vapor that would be contained in a saturated mixture. The results indicate that if all excess agent above that required for a saturated mixture were condensed in the expansion process, the agent left in the vapor phase would be more than enough to meet the 6% volumetric concentration requirement.

After this result, an answer to the second question posed has no relevance for the cases selected for examination in this study.

The case of 40,000 feet altitude and ambient initial mixture temperature (Figure 36) was examined and the results, in terms of agent partial pressure and agent saturation vapor pressure, are plotted versus time in Figure 39. The variable parameter (A/V) shown in the figure is the ratio of vent area and compartment volume and depicts the relative effect of vent area on the time required for expansion. It is of interest to note from the data of Figure 39, that at the initial mixture conditions (near-time zero) for the case in point, the agent partial pressure is greater than the agent saturation vapor pressure, which implies possible vapor condensation at the initial conditions. However, the noncondensed vapor (agent) will still provide Ce (volumetric concentrations) > 6% as shown in Figure 38. The design concentration will be maintained until the agent partial pressure decays to ambient pressure. During this time, flow will be out of the hole. After the agent mixture pressure reaches ambient, the agent concentration may decrease below the design concentration at a rate dependent on the type of hole and local flow conditions. The example in Figure 39 shows that for damage resulting in A/V = 0.100, the agent partial pressure decays to ambient before 0.5 second has elapsed. An A/V ratio of 0.004 for the above example will provide the desired concentration for more than 0.5 second. The conclusions reached in this part of the study are as follows:

1. Halon 1202 loaded to provide a 6% volumetric concentration for sea-level discharge will also provide at least a 6% concentration when discharged under altitude conditions and with compartment venting.

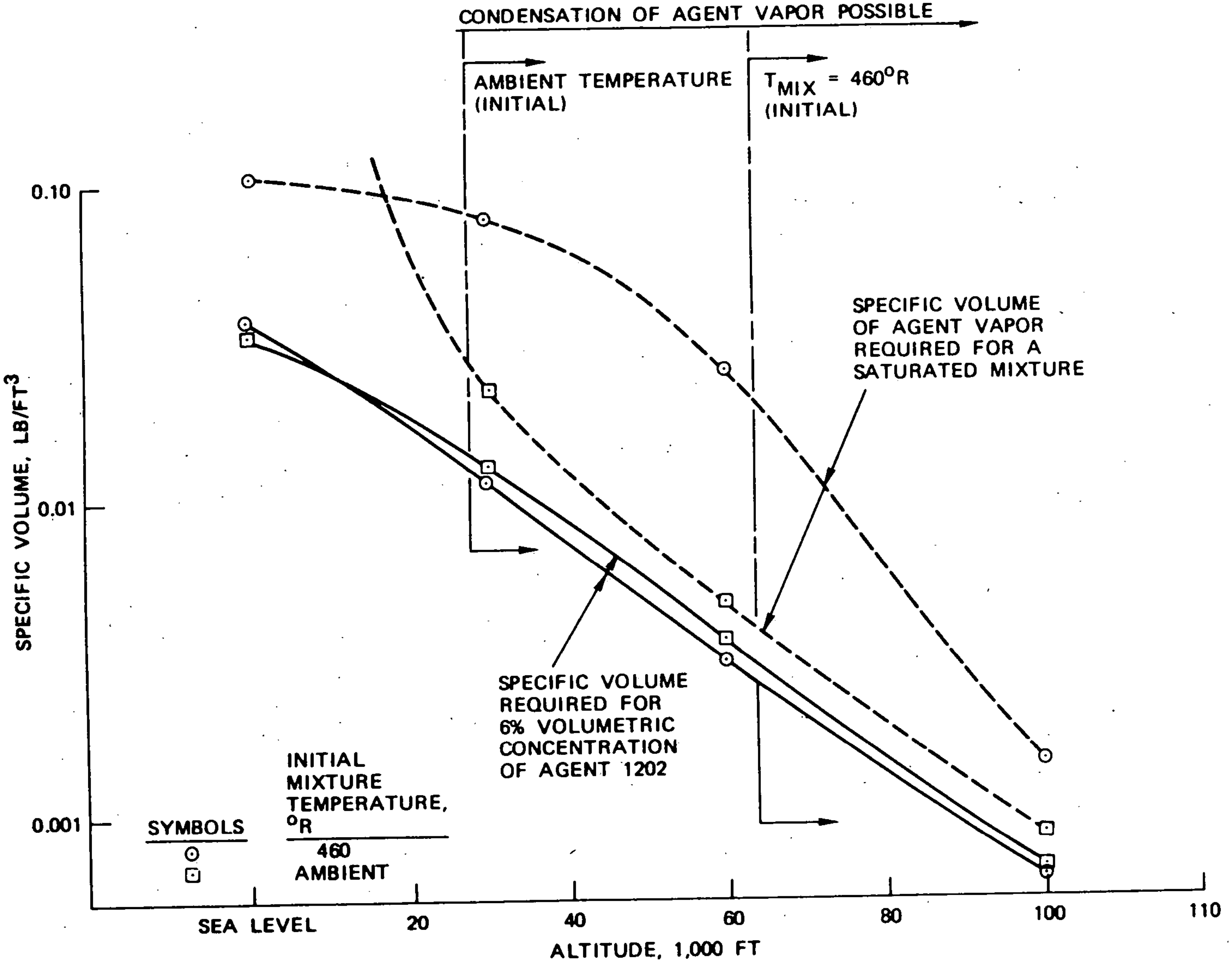


FIGURE 38. Comparison of Specific Volume of Agent 1202 Vapor Required for a 6% Volumetric Concentration and for a Saturated Air/Vapor Mixture.

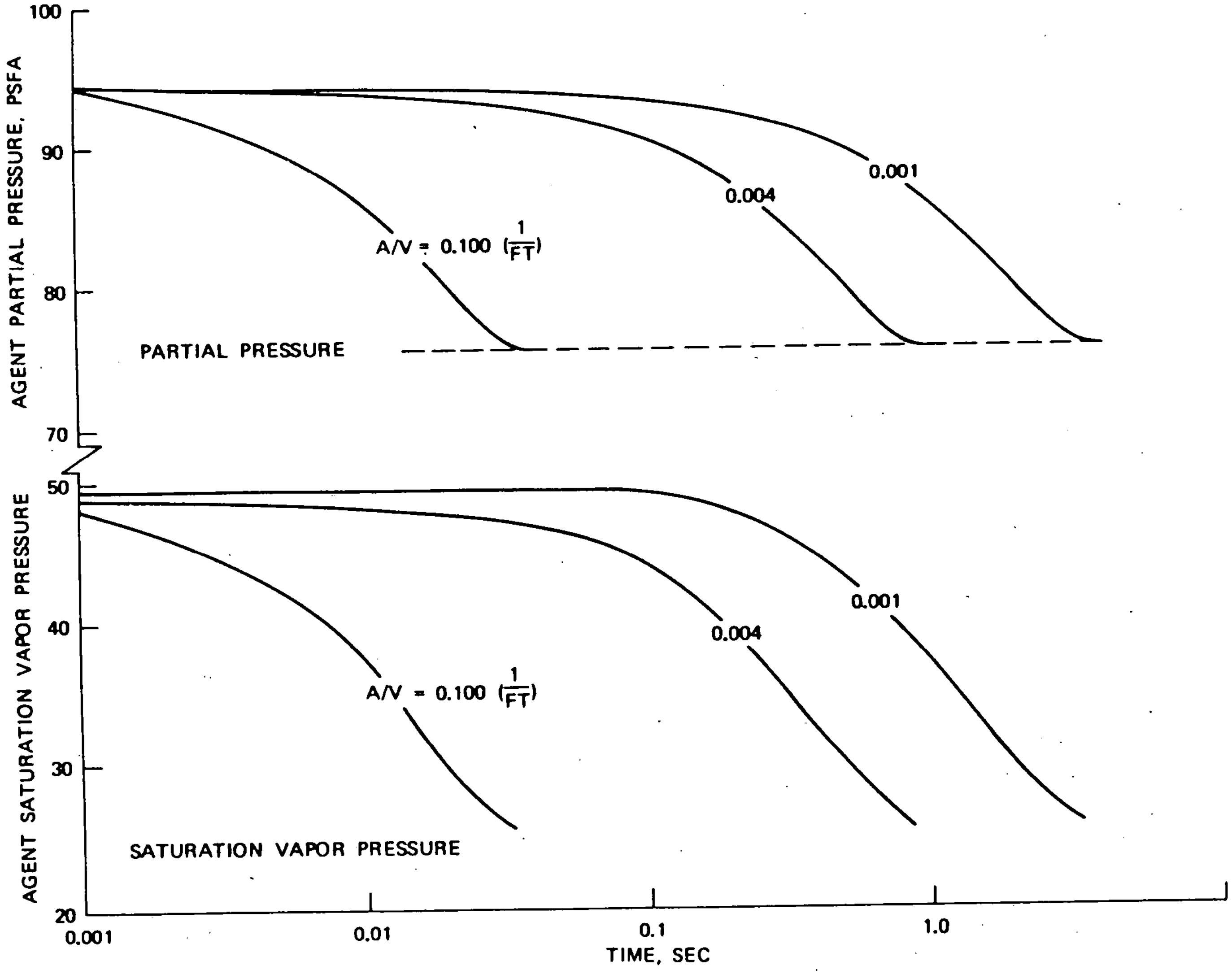


FIGURE 39. Time History of Agent 1202 Vapor Pressure and Saturated Vapor Pressure During an Isentropic Expansion to Ambient at 40,000 Feet Altitude.

2. At high altitude and with low initial mixture temperature, compartment venting may induce some agent vapor condensation; however, the volumetric concentration will remain above the required minimum.

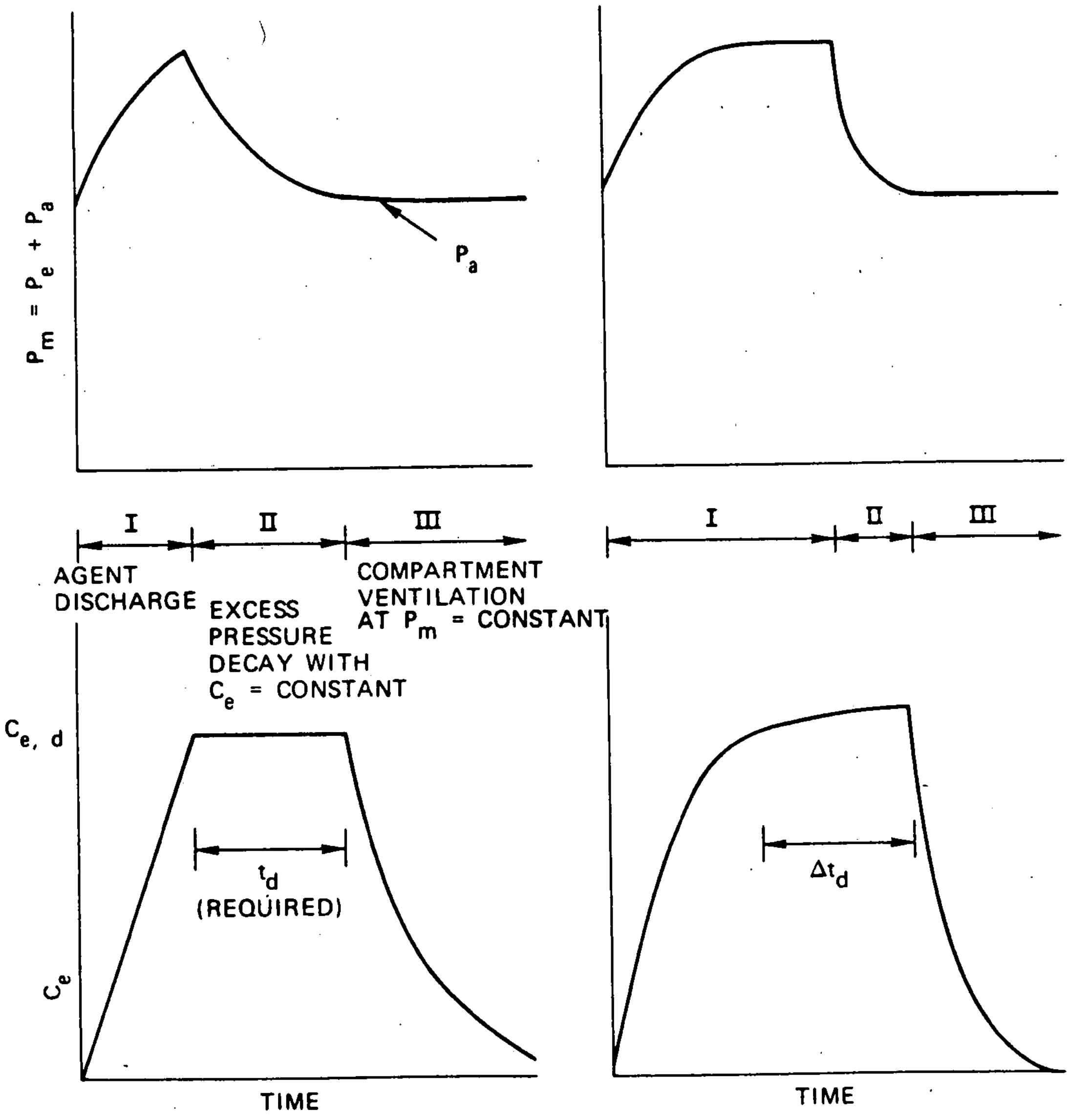
Quantity of Agent

In this section, attention is directed to the quantity (mass) of agent and the agent discharge time required to maintain an agent concentration (volumetric) of 6% for a period of 1/2 second in a compartment that has some battle damage. The battle damage is considered to be in the form of holes in the compartment walls that may allow ventilation and a compartment fire.

Figure 40 shows the physical characteristics of interest during and immediately following agent discharge into a normally closed (nonventilated) compartment that has openings in the walls due to battle damage. Figure 40a illustrates the behavior for small values of opening area (A) to volume (V) ratios. During discharge, the mixture pressure (P_m) and agent concentration (C_e) increase while a part of the mixture flows out of the compartment. After discharge termination, the mixture or compartment pressure decays to a value near the external pressure depending on the nature of the external flow conditions. During the period of mixture pressure decay, the agent concentration will remain constant and equal to the design value ($C_{e,d}$) since there is no mixing of the external air with the mixture in the compartment, only flow out of the compartment. Following the pressure decay process, when the compartment and external pressures are equal, mixing between the compartment mixture and external air may occur depending on the local external flow conditions and the size and shape of the openings. If there is negligible mixing with the external air, the agent concentration in the compartment will remain constant. However, with mixing, the agent concentration in the compartment will decrease; this is the most likely situation and the one to be considered for design purposes.

Figure 40b illustrates the behavior when the ratio A/V is large. The only difference from the small A/V case is that during agent discharge, the mixture pressure will reach a maximum value and remain constant when the rate of agent (mass) ($\dot{m}_e$) discharge equals the rate at which the mixture (mass) ($\dot{m}_m$) flows out of the compartment openings. Approximately the same peak pressure is needed for both cases in order to produce the required agent concentration. However, compartments with larger openings (A) will require larger quantities of agent to be discharged over longer periods of time.

For design conditions, the agent concentration in the compartment will be considered to decrease below the design value as soon as the compartment pressure decays to the local external pressure and external air is allowed to enter and mix with the contents of the compartment. The entry of air can be prevented only if the compartment pressure is maintained greater than the local external pressure by the discharge of a sufficient quantity of agent. Therefore, for design conditions, it is necessary to determine the quantity of agent and the time of discharge so that the required agent concentration (0.06) can be maintained for the required period of time (1/2 second). This will require that the compartment pressure be maintained at a value greater than the local external pressure for a period of 1/2 second after the desired agent concentration is attained.



(a) Small A/V

(b) Large A/V

FIGURE 40. Physical Characteristics of Pressure and Concentration in a Closed (Normally) Compartment During and Immediately Following Agent Discharge.

Analytically, the physical process within the compartment that occurs during and immediately following agent discharge can be treated by considering a mass balance on (1) the total amount of mass in the compartment and also (2) the mass of agent within the compartment. The agent and air are assumed to be perfectly mixed. Such mass balances yield

$$\frac{d(\rho_m V)}{dt} = \dot{m}_e - \dot{m}_m \tag{1a}$$

$$\frac{d(\rho_e V)}{dt} = \dot{m}_e - C_e \frac{\overline{M}_e}{\overline{M}_m} \dot{m}_m \tag{1b}$$

where

ρ_m = mixture density

ρ_e = agent density

$\overline{M}_e$ = agent molecular weight

$\overline{M}_m$ = mixture molecular weight

Considering the flow out of the compartment to be isentropic and the process within the compartment to be isothermal, Eq. 1a,1b can be written as

$$\frac{dP_m}{dt} = \frac{R_m T_m}{V} \left\{ \dot{m}_e - \gamma\sqrt{\frac{2}{\gamma - 1}} \frac{A}{\sqrt{\gamma_m R_m T_m}} \; P_m \left(\frac{P_o}{P_m}\right)^{1/\gamma} \sqrt{1 - \left(\frac{P_o}{P_m}\right)^{\frac{\gamma-1}{\gamma}}} \right\} \tag{2a}$$

$$\frac{dP_e}{dt} = \frac{R_e T_m}{V} \left\{ \dot{m}_e - \frac{P_e}{P_m} \frac{R_m}{R_e} \sqrt{\frac{2}{\gamma - 1}} \; \frac{\gamma A}{\gamma_m R_m T_m} \; P_m \left(\frac{P_o}{P_m} \right)^{1/\gamma} \sqrt{1 - \left(\frac{P_o}{P_m} \right)^{\frac{\gamma-1}{\gamma}}} \right\} \tag{2b}$$

where

P_e = agent pressure

R_e = agent gas constant

T_m = mixture temperature

R_m = mixture gas constant

γ = specific heat ratio

Time did not permit the numerical solution of Eq. 2a,b. However, approximate solutions will provide considerable insight into the physical process. First, consider the initial part of the agent discharge process when the agent concentration increases from 0 to the design value of 6% which corresponds to an agent partial pressure of 0.94 psia when the air partial pressure is 14.7 psia and the mixture temperature is 1000°R. Equation 1a, describing the compartment mass balance, can be expressed as

$$\frac{d(\rho_m V)}{dt} = \dot{m}_e - \dot{m}_m \tag{3}$$

or

$$\frac{V}{R_m T_m} \Delta P_m = \int_0^t (\dot{m}_e - \dot{m}_m) dt$$

Now, for the design opening size, as p_m increases from 14.7 to 15.64 psia, $\dot{m}_m$ increases from 0 to $\dot{m}_e$; p_m is a maximum when $\dot{m}_e = \dot{m}_m$. If $\dot{m}_m$ is considered to vary linearly from 0 to $\dot{m}_m$, the average value of $\dot{m}_m$ during the period Δt_1 is $\dot{m}_e/2$. Thus

$$\Delta t_1 \cong \frac{V \, P_{e,d}}{R_m T_m (\dot{m}_e/2)} = 0.007 \; V/\dot{m}_e$$

Figure 41 gives values of Δt_1 for representative values of V and $\dot{m}_e$.

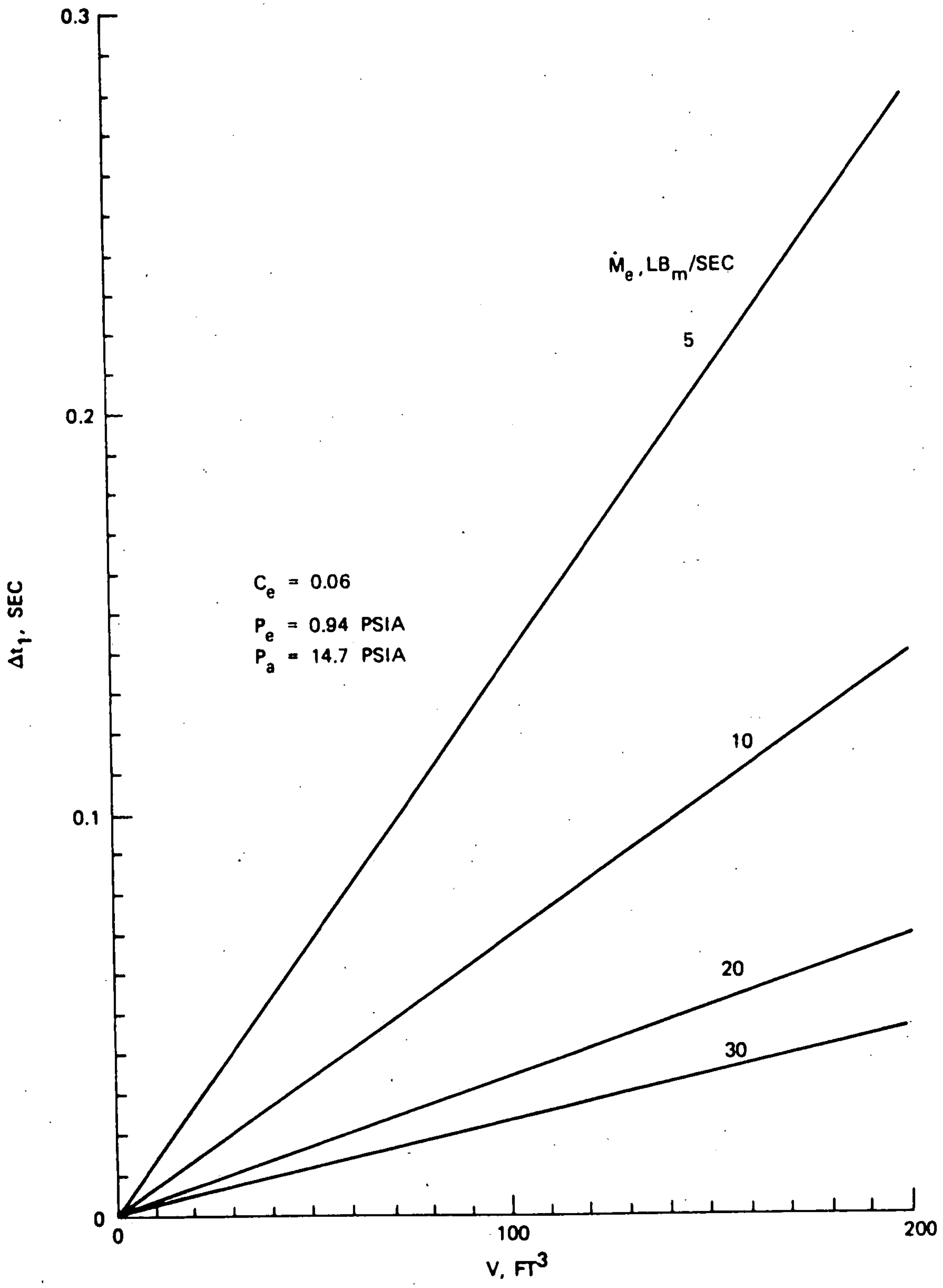


FIGURE 41. Time to Establish the Desired Agent Concentration.

The second part of agent discharge process occurs when the agent discharge rate ($\dot{m}_e$) is equal to the flow of mixture ($\dot{m}_m$) from the compartment ($dp_m/dt = 0$). It is of interest to estimate the rate of agent discharge that will equal the flow of mixture through various size openings (A) when the mixture pressure and temperature are 15.64 psia and 1000°R, respectively and the external pressure is 14.7 psia. For the constant pressure (p_m) part of the process, Eq. 2a yields

$$\frac{\dot{m}_e}{A} = \gamma \frac{2}{\gamma-1} \frac{P_m}{\sqrt{\gamma_m R_m T_m}} \left(\frac{P_o}{P_m}\right)^{1/\gamma} \sqrt{1 - \left(\frac{P_o}{P_m}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (4)$$

or

$$\frac{\dot{m}_e}{A} = 22.4 \text{ lb}_m/\text{sec - ft}^2$$

Figure 42 gives values of $\dot{m}_e$ for representative opening sizes (A).

The third and last part of the process involves the period following agent discharge termination when the compartment pressure decays to local external pressure. It is of interest to determine the period of time (Δt_3) for the compartment to decay from the peak value to the local external value. Equation 2a yields

$$\frac{d(\rho_m V)}{dt} = -\dot{m}_m \qquad (5)$$

or

$$\Delta t_3 \cong \frac{V}{A} \sqrt{\frac{\gamma-1}{2}} \frac{1}{\sqrt{\gamma_m R_m T_m}} \left\{ \frac{(P_{m,max} - P_o)}{\bar{P}_m \left(\frac{P_o}{\bar{P}_m}\right)^{1/\gamma} \sqrt{1 - \left(\frac{P_o}{P_m}\right)^{\frac{\gamma-1}{\gamma}}}} \right\}$$

Figure 43 gives the time period (Δt_3) for representative values of V/A.

The information shown in Figures 41, 42, and 43 can be combined to yield the quantity (mass) of agent required to maintain a 6% volumetric concentration, or greater, for 1/2 second. The rate of agent discharge (Figure 42) is that required to equal the mass of mixture flowing out of the compartment through the opening having area A. In terms of the available information, the time of discharge ($\Delta t_{discharge}$) is (1) that time required to establish the required (design) agent concentration, Δt_1 of Figure 41, plus (2) 1/2 second of discharge to maintain the required agent concentration, minus (3) the time of pressure decay (Δt_3) during which the required agent concentration is maintained without agent discharge. Analytically, the required agent mass (M_e) is expressed as

$$M_e = \dot{m}_e \, (\Delta t_1 + 0.5 - \Delta t_3)$$

Figures 44 and 45 give the agent mass and time of discharge, respectively. Figure 46 gives the time periods, Δt_1 and Δt_3.

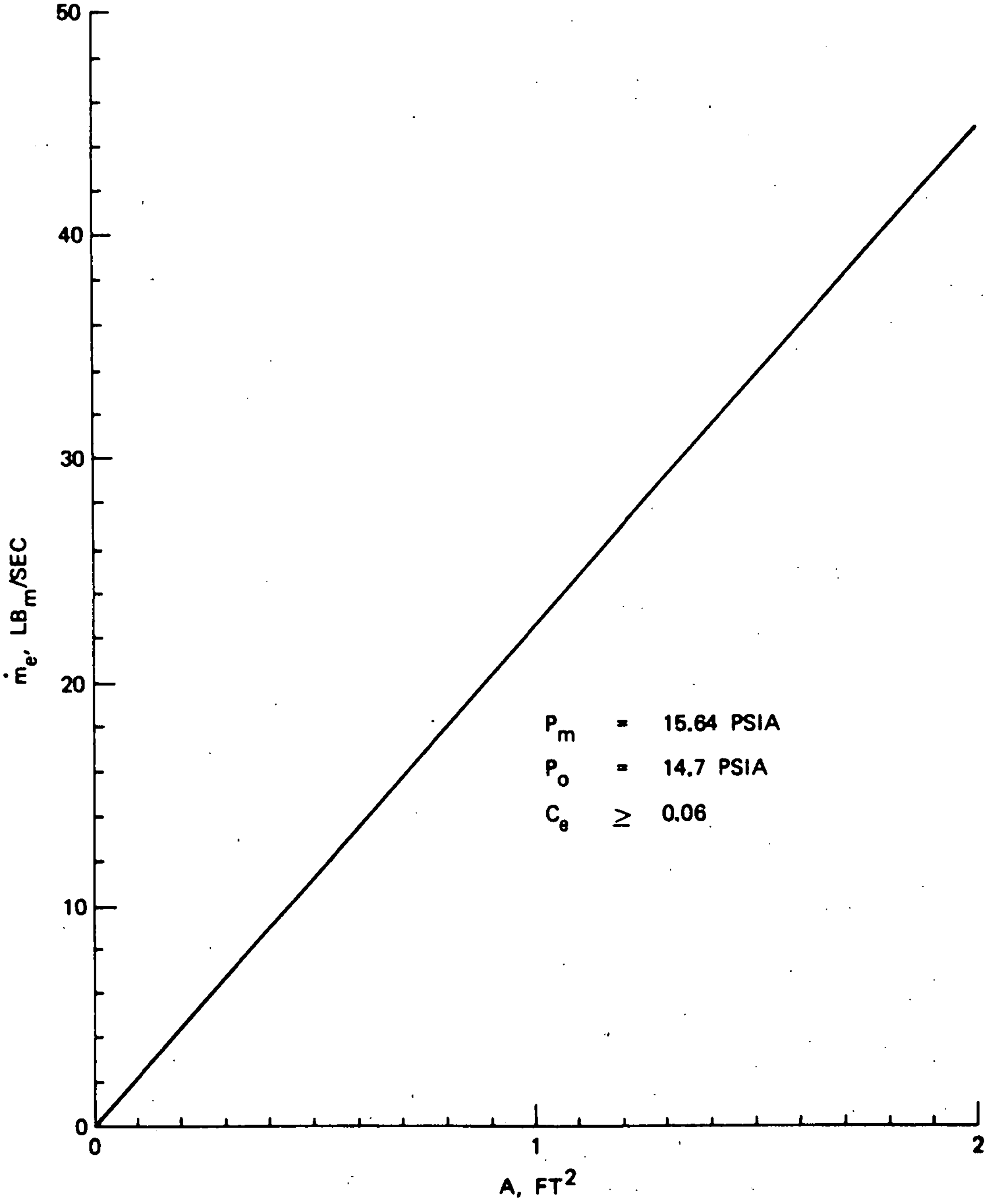


FIGURE 42. Mass Flow Rate of Agent Required to Equal the Mass Flow Rate of the Mixture Out of the Opening.

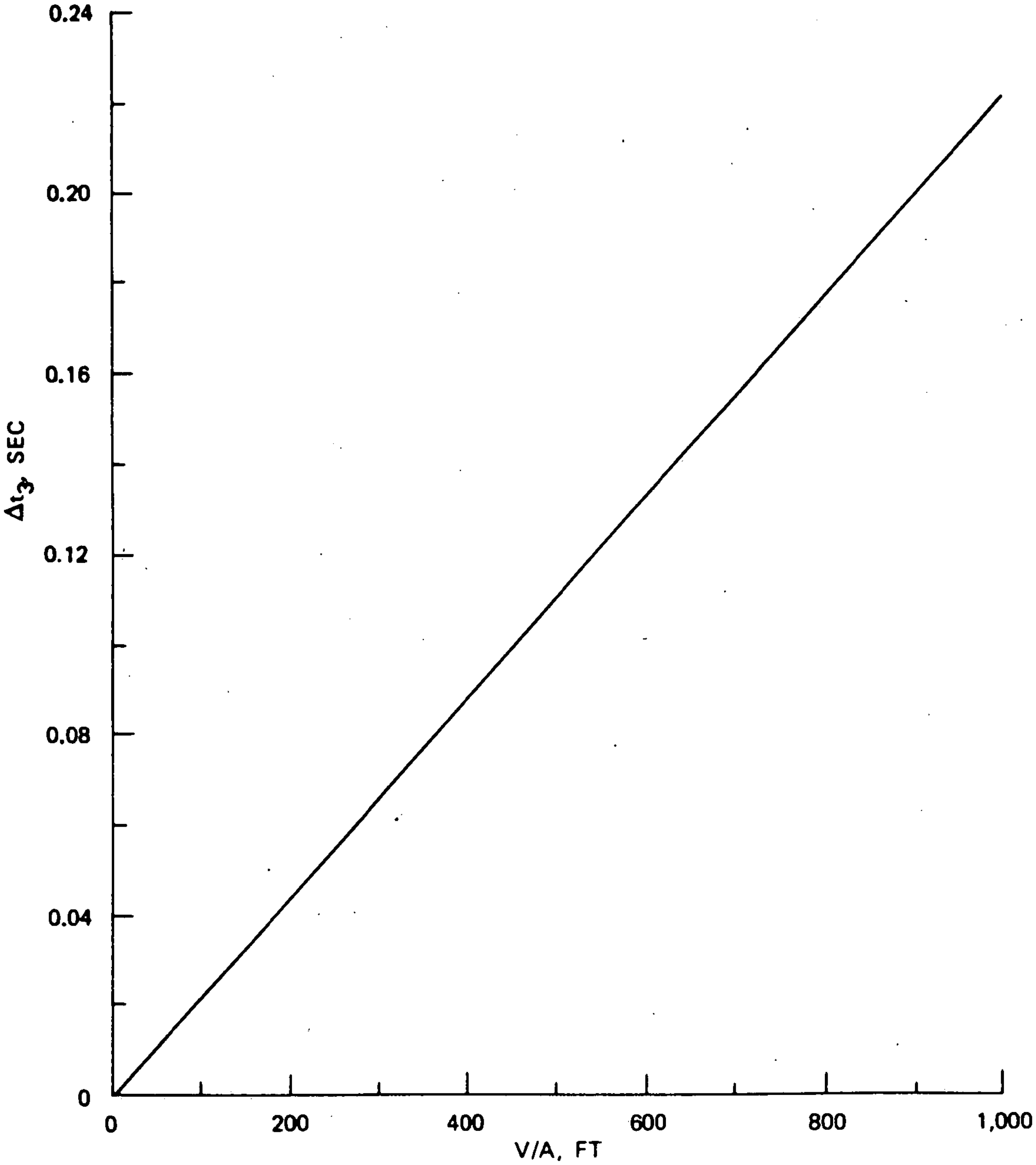


FIGURE 43. Time for the Compartment Pressure to Decay from 15.64 to 14.7 psia.

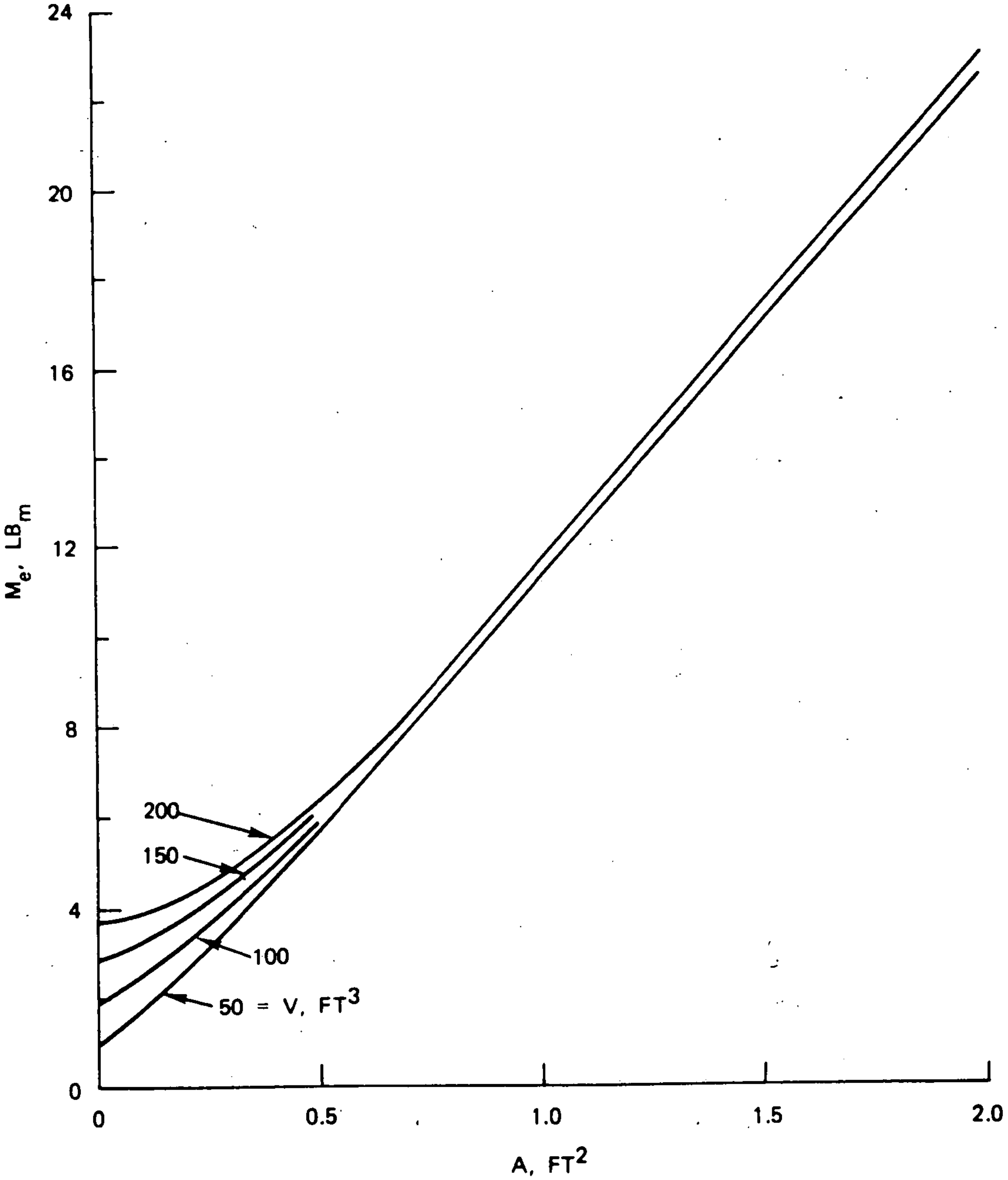


FIGURE 44. Amount of Agent Required to Maintain a 6% Volumetric Concentration for 0.5 Second in a Normally Closed Compartment That Has Openings With Area (A) Caused by Battle Damage.

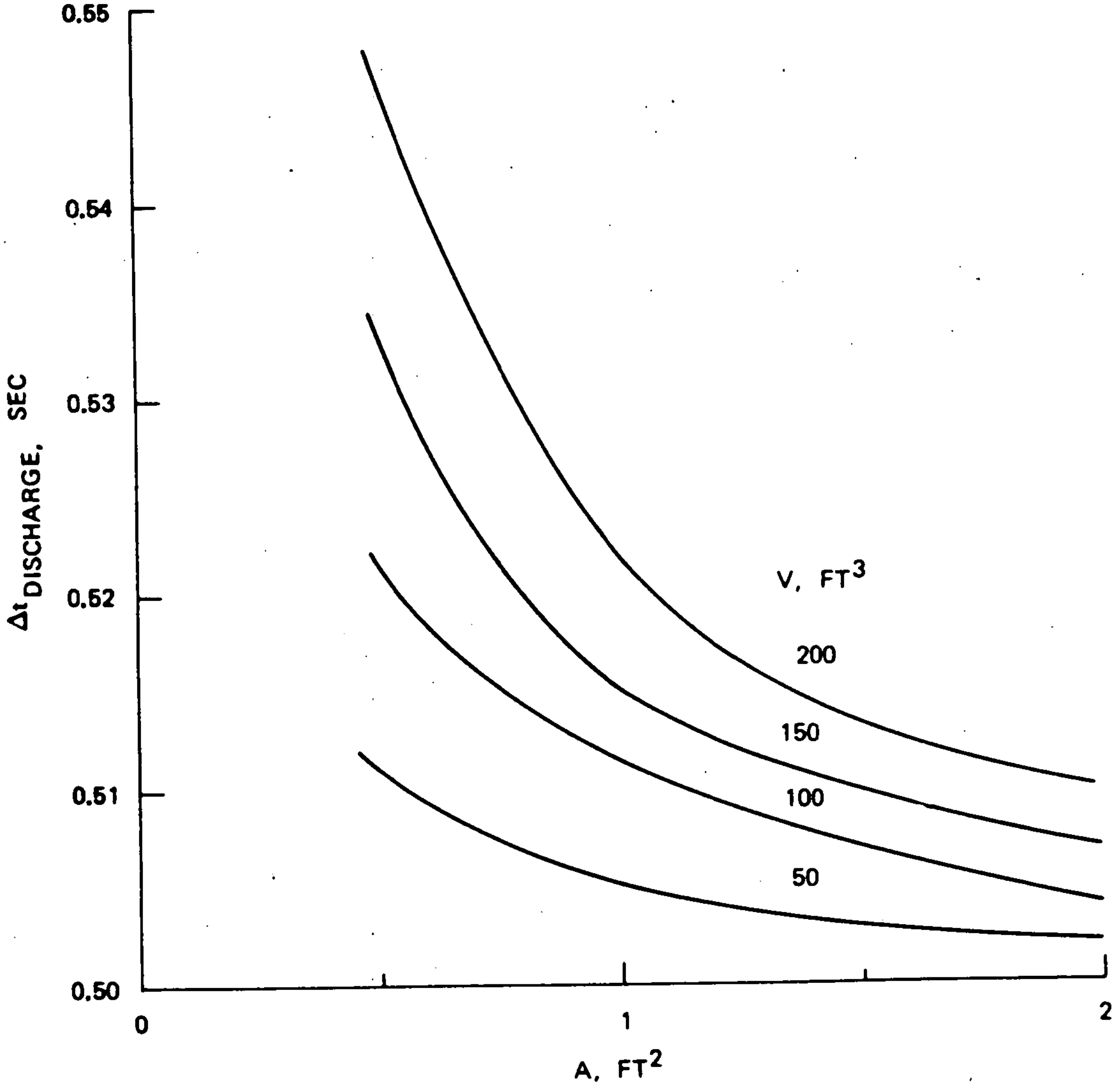


FIGURE 45. Required (Minimum) Time of Agent Discharge at the Mass Flow Rate Given in Figure 42.

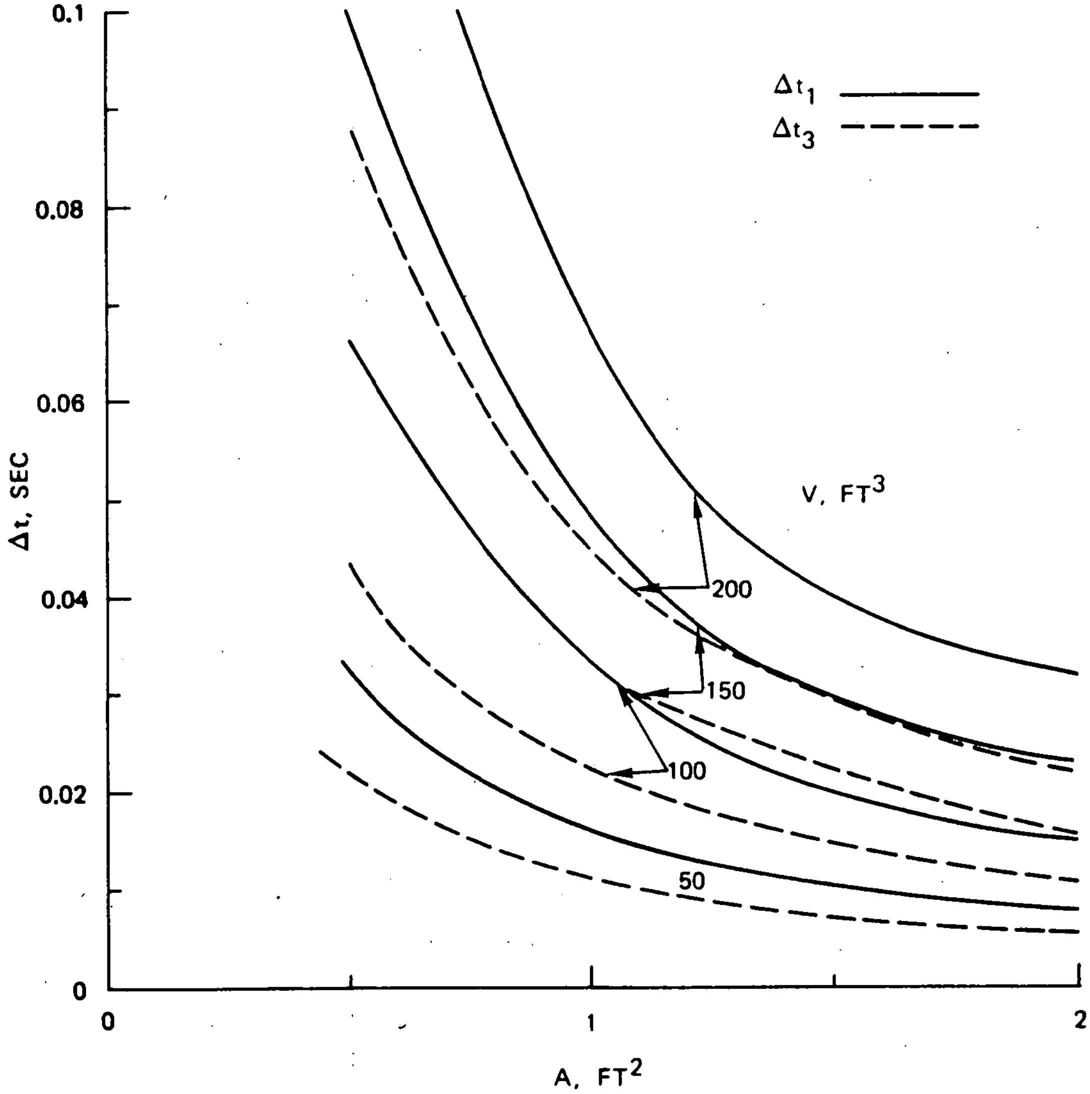


FIGURE 46. Approximate Lengths of Time to Establish the Required Agent Concentration, (Δt_1), and the Time for the Excess Pressure Decay (Δt_3).

Recognize that in the stated information on the agent mass flow rates, the time of agent discharge and the total amount of agent are estimates that have been based on an approximate analysis of Eq. 2a,b. These equations should be integrated numerically to more accurately determine the required mass of agent and the time of discharge for various compartment volumes (V) and opening sizes (A). The approximate analysis does, however, provide considerable insight into the physical behavior of the agent discharge into such compartments that have battle damage.

The primary conclusion of this analysis is that, for design type battle damage involving holes of 1 to 2 ft^2 in compartments up to about 200 ft^3, the times (1) to establish the required concentration in the compartment and (2) for the excess compartment pressure to decay, are small compared with the required stay-time of 1/2 second. This means that the rate (mass) of agent discharge is equal to the rate at which the mixture flows out of the compartment through the openings and the time of discharge is only slightly greater than 1/2 second; a conservative estimate is about 0.6 second.

Figure 44 shows that the amount of agent required to maintain a low (e.g., 6%) volumetric concentration for a given time period increases more rapidly with damage hole size than with increasing compartment volume.

The physical behavior of air-agent mixtures, containing small concentrations of any of the agents, is expected to be essentially the same as the Halon 1202 air mixture considered in the above analysis. Therefore, the required mass of other agents such as Halon 1301, the mass rate of discharge, and the time of discharge will be essentially the same as the Halon 1202, providing a 6% concentration of Halon 1301 is maintained for 0.5 second. This conclusion is based on the recognition that the rate of flow of air-agent mixture out of the compartment is the dominant part of the process and the mass flow rate of agent is sized to equal the mass rate of flow of mixture out of the compartment for a period of 0.5 second.

VENTILATED COMPARTMENTS

The questions to be answered in this section concern:

1. The amount of fire extinguishing agent required to produce the desired agent concentration for a specified period time.

2. The relative stay-time of the various agents, i.e., the length of time that a given weight of agent discharged in a certain time will maintain the agent concentration, within the given volume, equal to or above the required concentration.

3. The effect, qualitatively, of battle damage (additional openings in the volume that may permit additional ventilation) on the amount of agent required for fire extinguishing.

These questions will be considered in the following paragraphs.

Quantity of Agent

Consider first the quantity of agent required for the case without battle damage. Paragraphs that follow will contain some qualitative discussion of the effects of battle damage on the required amount of agent. The amount of agent required to extinguish a fire in a ventilated compartment depends on (1) the amount and nature of the ventilation flow through the volume and (2) the required concentration of agent in the volume for a required period of time.

Since the required concentration and length of time is defined for the many candidate agents, the quantity of a given agent will depend primarily on the amount of ventilation air flowing through the volume under normal conditions and the nature of the flow, i.e., whether the flow is choked at the inlet or exit or neither. However, regardless of the nature of the flow, the maximum (upper limit) amount of agent required can be calculated by considering the ventilation flow to be choked at the inlet or, more simply, that the ventilation airflow rate does not change when the agent is discharged into the volume. This approach will yield the correct total amount and concentration of agent for the choked inlet condition and somewhat larger than the required concentrations and amounts of agent when the inlet is not choked. For example, when the inlet is choked and remains choked during the agent discharge process, the amount of air flowing through the inlet will remain constant and the correct quantity of agent and time of discharge can be determined to provide the required agent concentration for the required period of time. Alternately, when the inlet is not choked, the discharge of the agent will cause the inlet flow to be reduced. If the required amount of agent is based on the nonchoked inlet flow, the actual concentration of agent will be greater than required since the inlet airflow during agent discharge will be somewhat less than that immediately prior to agent discharge.

For a given agent, it is required that a certain agent concentration exist throughout the entire volume of interest for a specified period of time. The total amount of agent is therefore the amount required to initially fill the volume with the required concentration, plus the amount required to maintain this concentration for the desired period of time. Analytically, this total amount (mass) of agent (M_e) can be conservatively written as

$$M_e = \rho_e \left(\frac{\dot{m}_{a,o}}{\rho_{a,o}} \right) \Delta t + \rho_e V \qquad (6)$$

where

ρ_e = agent (extinguishant) density

Δt = required period of time that the desired agent concentration is to be maintained

V = Volume of the compartment

$\dot{m}_{a,o}$ = mass flow rate of ventilation air flowing through the compartment

$\rho_{a,o}$ = density of air prior to agent discharge

The agent density can be expressed as

$$\rho_e = \frac{P_e \overline{M}_e}{RT} = \frac{p\,C_e\,\overline{M}_e}{RT} \qquad (7)$$

where

p = mixture pressure

C_e = concentration of agent

M_e = molecular weight of agent

R = gas constant

T = mixture temperature

Figure 47 gives the required quantity of agents CF_3Br and CF_2Br_2, based on the stated equation, for design conditions involving sea-level flight at Mach 1.2. The stated equations for M_e and ρ_e are the same as those given in AFFAPL-TDR-64-105 (see Footnote 5, page 54). The above discussion is intended to provide some basis for the following discussion and analysis.

The total time of agent discharge is defined as

$$t_d = \frac{M_e}{\dot{m}_e} = \Delta t + V/\dot{V}_{a,o} \qquad (8)$$

where Δt = 1/2 second. For most conditions of interest, the time of discharge is slightly greater than 1/2 second. For example, given a compartment volume of 100 ft^3 and a ventilation flow rate of 500 ft^3/sec, the time of discharge will be 0.7 second.

Stay-Time of Agents

At design conditions, the stay-time of the agent is equal to the design stay-time or 1/2 second. At off-design conditions, where the ventilation airflow rate through the compartment is less than that at design conditions, the concentration of agent in the compartment will be greater than the design value and the stay-time will be somewhat greater than 1/2 second. Consider for example, a case in which the ventilation airflow rate is considerably less than the value at design conditions (the maximum flow rate); this approach will give an upper limit on the stay-time. Figure 48 illustrates the mixture (agent and air) pressure (p_m) and agent concentration (C_e) in the compartment during the period of agent discharge and immediately following agent discharge.

At conditions where the ventilation airflow rate ($\dot{m}_{a,o}$) is less than the design value, the mixture pressure and agent concentration continue to increase during the agent discharge (Phase 1 in Figure 48) and attain maximum values at the time of discharge termination; the maximum concentration being considerably greater than the design value. Following

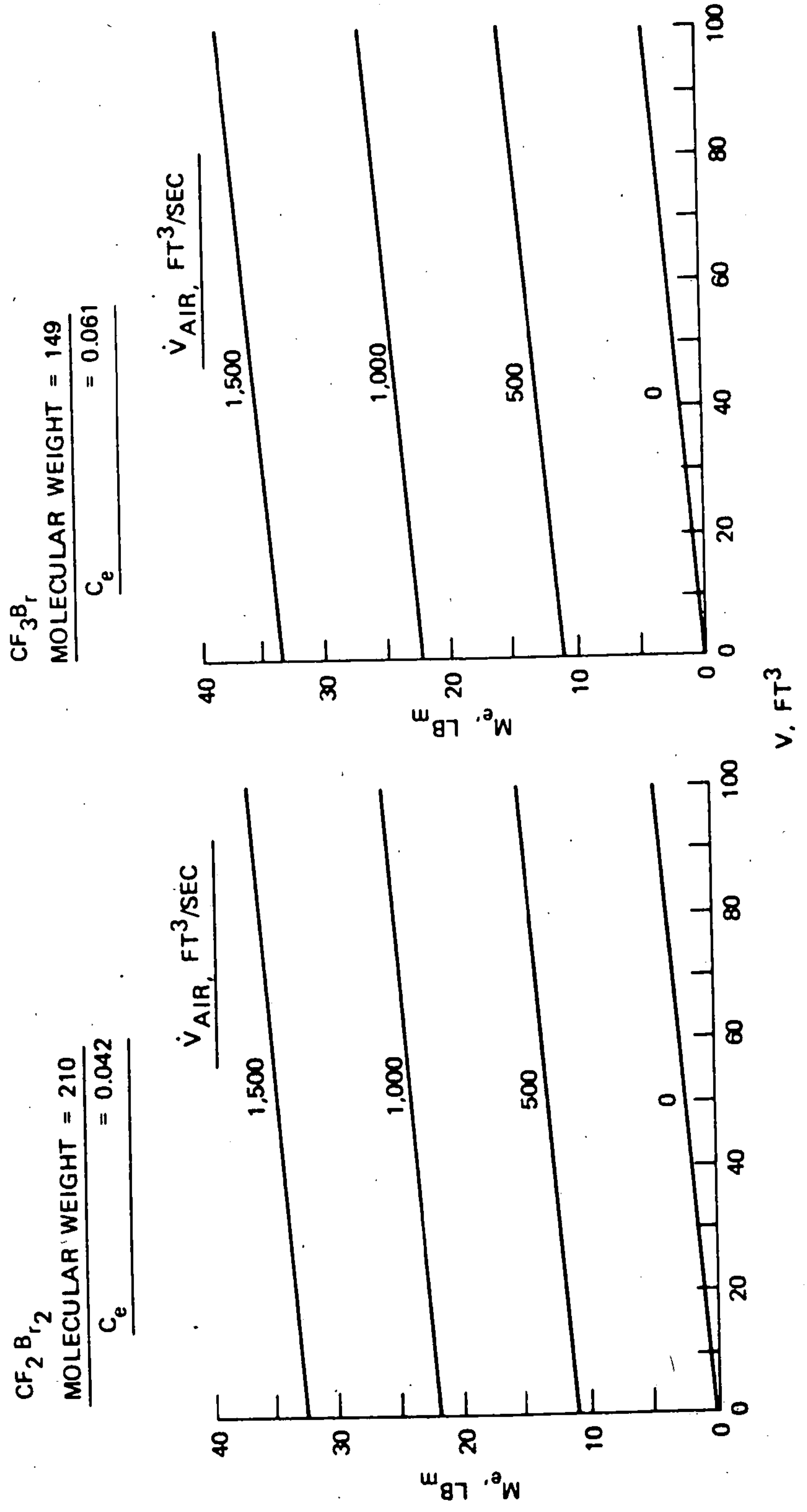


FIGURE 47. Weight of Fire Extinguishing Agent.

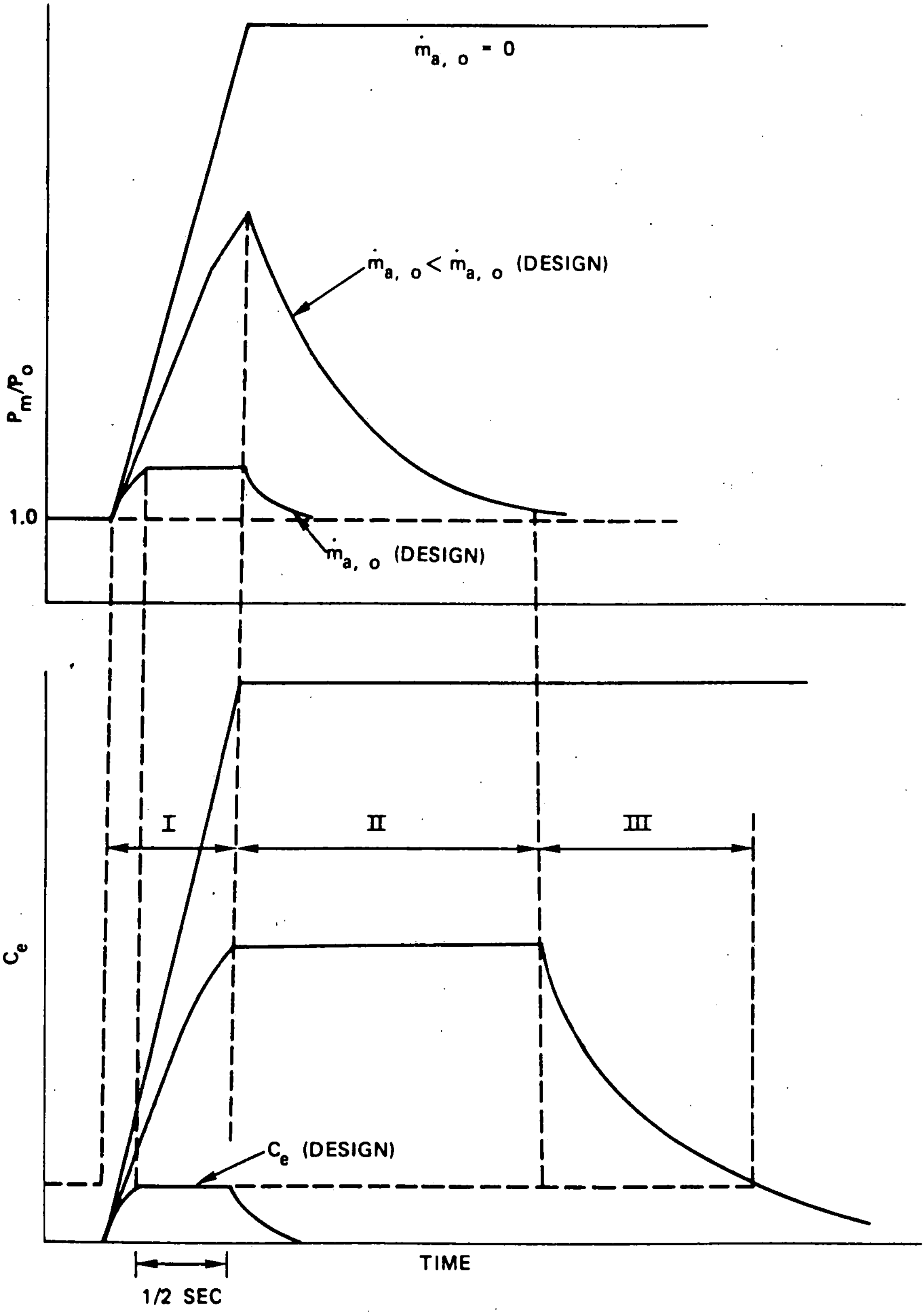


FIGURE 48. Physical Characteristics During and Immediately Following Agent Discharge in a Ventilated Compartment.

discharge, the mixture pressure decays to the compartment pressure (Phase II in Figure 48) prior to agent discharge. During Phase II, the concentration will remain essentially constant and equal to the maximum value since there will be zero or very little ventilation air entering the compartment; the mixture total pressure is greater than that of the air attempting to ventilate the compartment. When the mixture pressure decays to the original pressure, external air will again ventilate the compartment (Phase III in Figure 48) and the agent concentration will begin to decrease.

Estimates of the length of time of Phases I, II, and III are described below. The time period (Δt_1) for Phase I is essentially 1/2 second, since the total discharge time for design conditions is only slightly greater than this. The length of time of Phase II (Δt_2) is that required for the mixture pressure to decay from its maximum value ($p_{m,i}$) to the original value (p_o). This can be treated analytically by considering the rate of change of the mass of mixture in a compartment having volume (V) which is equal to the rate at which mass (of mixture) flows out of the compartment ($\dot{m}_{m,i}$). Analytically, this is written as

$$\frac{d(\rho_m V)}{dt} = -\dot{m}_m \tag{9}$$

The mixture will flow isentropically out of the compartment through the compartment openings. Within the compartment, the process can be either isentropic or isothermal; the actual process will be somewhere between the two. For engine nacelle compartments, however, the process within the compartment is expected to be closer to the isothermal case. For these conditions, Eq. 9 can be expressed as

$$\frac{dp_m}{dt} = \frac{-A}{V} \frac{\sqrt{\gamma R T_m}}{\sqrt{\overline{M}_m}} \, p_m \left(\frac{p_o}{p_m}\right)^{1/\gamma} \sqrt{\left(\frac{2}{\gamma-1}\right)\left[1 - \left(\frac{p_o}{p_m}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{10}$$

when

$$\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \leq \frac{p_o}{p_m} \leq 1$$

and

$$\frac{dp_m}{dt} = \frac{-A}{V} \frac{\sqrt{\gamma R T_m}}{\sqrt{\overline{M}_m}} \, p_m \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{11}$$

when

$$\frac{p_o}{p_m} < \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

Integration of Eq. 10 and 11 yield the period of time for the Phase II part of the process.

$$\Delta t_2 = \frac{-V}{A}\sqrt{\frac{\gamma-1}{2}}\sqrt{\frac{\overline{M}_m}{\gamma R T_m}}\int_{p_{m,i}}^{p_o} \frac{dp_m}{p_m\left(\frac{p_o}{p_m}\right)^{1/\gamma}\sqrt{\left[1-\left(\frac{p_o}{p_m}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \qquad (12)$$

when

$$\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \leq \frac{p_o}{p_m} \leq 1$$

and

$$\Delta t_2 = \frac{-V}{A}\sqrt{\frac{\overline{M}_m}{\gamma R T_m}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \ln\left(\frac{p_{m,i}}{p_o}\right) \qquad (13)$$

when

$$\frac{p_o}{p_m} < \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

At high altitudes, the mixture pressure (p_m) will in many cases be greater than

$$p_o \Big/ \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

which means that choked flow through the exits will exist until the mixture pressure decreases to this value. Nonchoked flow will exist during the latter part of this process. For this case, both Eq. 12 and 13 must be evaluated and the individual Δts added, i.e.,

$$\Delta t_2 = \Delta t_2 \text{ (Eq. 12)} + \Delta t_2 \text{ (Eq. 13)}$$

The initial mixture pressure ($p_{m,i}$) is written as $p_{m,i} = p_{e,i} + p_{a,i}$, where $p_{e,i}$ and $p_{a,i}$ are the initial partial pressures of the agent (extinguishant) and air, respectively. Considering a closed compartment, the upper limit of the initial partial pressure of the agent is

$$p_{e,i} = \frac{M_e R T_m}{\overline{M}_e V} \qquad (14)$$

Phase III (Figure 48) involves the process of ventilating, with air, a compartment that initially contains an agent with concentration $C_{e,i}$. The length of Phase III (Δt_3) is the time for the agent concentration to decrease as a result of ventilation from an initial concentration ($C_{e,i} = p_{e,i}/p_{m,i}$) to the design value ($C_{e,d}$). The Phase III time period (Δt_3) is determined by considering a mass balance involving only the agent, i.e.,

$$\frac{d(\rho_e V)}{dt} = -\dot{m}_e = -\rho_e A \upsilon \tag{15}$$

Considering (1) the temperature of the mixture, including the agent, to remain constant and (2) the volumetric flow rate into and out of the compartment to be equal, Eq. 15 can be written as follows in terms of the agent concentration,

$$\frac{dC_e}{dt} = \frac{-C_e}{V} \frac{\dot{m}_{a,o}}{\rho_{a,o}} \tag{16}$$

or

$$\Delta t_3 = \frac{V \rho_{a,o}}{\dot{m}_{a,o}} \ln \left(\frac{C_{e,i}}{C_{e,d}} \right)$$

A physically reasonable upper limit on the stay-time of an agent can be computed for a case representative of an F-111 type aircraft flying at Mach 2.2 and 55,000 feet. The engine nacelle is ventilated with air flowing at the conditions listed below:

$m_{a,o} = 7\ \mathrm{lb_m/sec}$

$\upsilon = 250\ \mathrm{ft/sec}$

$p_{a,o} = 3\ \mathrm{psia}$

$\rho_{a,o} = 0.0105\ \mathrm{lb_m/ft^3}$.

The engine nacelle has an outlet area of 60 in^2 and a volume of 50 ft^3; inlet check valves prevent reverse flow when the nacelle compartment pressure is greater than that of the air attempting to flow into the nacelle through the inlet. Consider the agent to be CF_2Br_2 which has a molecular weight ($\overline{M}_e$) equal to 210, and as a gas at a temperature of 700°R, has a ratio of specific heats (γ) equal to 1.10. At design conditions ($\dot{m}_a = 35\ \mathrm{lb_m/sec}$ at Mach = 1.2, sea level), the quantity of agent required to produce an agent concentration of 6% for a period of 1/2 second is 15 $\mathrm{lb_m}$.

The Phase I time period (Δt_1) will be essentially 1/2 second.

After agent discharge, the maximum initial partial pressure of the agent $p_{e,i}$ (Eq. 14) is 10.7 psia and the initial mixture pressure $p_{m,i}$ is 13.7 psia. The agent partial pressure has been estimated for a limiting case of zero flow out of the compartment during the time of agent discharge. Actually some of the mixture, including the agent, will flow out of the compartment during agent discharge which will cause the partial pressure of the agent to be less than the computed value and the air partial pressure to be less than 3 psia. The upper limit values will, however, suffice for the purpose of this example. The flow from the nacelle will be choked until the mixture pressure decreases to

$$p_m = p_{a,o} \Big/ \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 5.1 \text{ psia}$$

Equation 13 gives the Δt_2 for the choked flow part of the Phase II process.

$$(\Delta t_2)_1 = 0.40 \text{ sec}$$

Equation 12 gives the Δt_2 for the nonchoked flow part of the Phase II process.

$$(\Delta t_2)_2 = 0.24 \text{ sec}$$

The total time for the Phase II process is therefore

$$\Delta t_2 = 0.64 \text{ sec}$$

The time period of the Phase III (ventilation) part of the process (Eq. 16) is

$$\Delta t_3 = 0.19 \text{ sec}$$

Finally, the estimated stay-time during which the agent concentration is greater than the design value (6%) is

$$t = \Delta t_1 + \Delta t_2 + \Delta t_3 = 1.33 \text{ sec}$$

This time period represents a physically reasonable upper limit on the agent stay-time for a typical ventilated nacelle during flight conditions where the ventilation flow is about 20% of the maximum (agent design) value. Since there is flow out of the compartment during agent discharge (that was not accounted for), the peak mixture pressure and the corresponding agent stay-time will be somewhat less than the estimated values. A review of (1) the equations in this section describing the agent discharge and decay process and (2) the example calculation, shows that there is little that can be done to significantly increase the stay-time of the type agents being considered other than releasing a much larger quantity of agent over the desired, longer stay-time or shutting off the ventilation. The use of different agents having different molecular weights and different ratios of specific heats will not significantly increase the stay-time beyond the value computed in the above example. For example, if at the design condition it is desired to increase the stay-time to 1 minute, the total amount of agent required would be equal to 1,562 pounds versus the 15 pounds for 1/2 second.

Effects of Battle Damage on the Required Quantity of Agent

With respect to compartment ventilation and the required amount of fire extinguishing agent, battle damage consists mainly of additional holes in the compartment and a corresponding fire. These additional holes will normally act as inlets and/or exits that tend to increase the amount of ventilation within the compartment. At design conditions, the increased ventilation can reduce the agent concentration to a value less than the effective concentration, if the quantity of agent does not provide for some degree of battle damage. In future aircraft designs, consideration should be given to providing a quantity of fire extinguishing agent that will provide the effective agent concentration for both malfunction fires and fires caused by battle damage with some reasonable degree of increased ventilation. An increase in ventilation (mass flow rate through the compartment) by a factor of two will create a need for about twice as much agent at design conditions.

At off-design conditions, the ventilation is less than that at design conditions. Therefore, the agent concentration during discharge is greater than that at the design conditions. For the example considered in the previous section, the agent concentration had a peak value of about 78%. For this case, the amount of ventilation could be increased by a factor of about five, or the size of the openings due to battle damage could be about four times greater than the normal exit area ($4 \times 60 = 240$ in^2), and the agent concentration will still equal the design value.

MILITARY SPECIFICATION REVIEW

The high rate discharge system is defined in MIL-E-22285. This specification requires a concentration of at least 6% by volume in all parts of the affected zone. This concentration shall persist in each part of the zone for at least 0.5 second at normal cruising conditions. The high rate discharge system requires that the agent be discharged in 1 second or less. The agent quantity is based on the use of bromotrifluoromethane (CF_3Br).

The conventional discharge system is defined in MIL-E-5352. This specification requires that the agent be discharged in 2 seconds or less. The quantity of agent required is based on bromochloromethane (CH_2BrCl).

The fire extinguishant system for the F-111 engine nacelle was based on the requirements of MIL-E-22285 except dibromodifluoromethane (CF_2Br_2) was used.

The formula used was

$$W = 0.02V + 0.25W_a$$

where

W = weight of agent, pounds

W_a = pounds of air per second passing through the zone

V = net volume of the zone in cubic feet (gross volume of the zone less the volume of major items of equipment)

This formula is specified for a smooth nacelle interior regardless of airflow. This is applicable to the F-111 engine nacelle.

The formula for determination of the quantity of Halon agents required can be derived from the following general formula which is based on the ideal gas laws.

$$W = \frac{P\ C\ M_e}{RT}\left[\frac{W_a}{\rho_a}\ t + V\right]$$

where

W = weight of extinguishant

P = absolute pressure, lb/ft^2

C = percent concentration by volume required to extinguish flame for 1 ft^3 of volume

M_e = molecular weight of extinguishant

R = universal gas constant

T = ambient temperature, °R use 520 for standard conditions

W_a = mass flow rate of air passing through zone, lb/sec

ρ_a = density of air at standard conditions

V = flow volume, ft^3

t = discharge time for agent (use 1 second)

For a specific extinguishant such as Halon 1301 at standard day conditions with a 6% concentration, the formula reduces to

$$W = 0.308W_a + 0.024V$$

This does not agree exactly with the specification formula, $W = 0.25W_a + 0.02V$. However, it gives reasonable assurance of how the formula was derived. It should be noted that the quantity of agent required is determined only by flow rate and volume of the compartment.

With the general formula, one can determine the required quantities of different agents to put out a given flame. Based on known percent of concentrations required for each agent and molecular weights, a comparison of required agent quantities can be made.

Table 19 shows a comparison of various agent quantities required based on each agent's characteristics. These quantities shown are for selected F-111 flight conditions.

As can be seen, the derived formula ($W = 0.308W_a + 0.024V$) for Halon 1301 gives equal or higher quantities than with the general formula.

TABLE 19. Military Specification Review.

Fire extinguishant quantities required based on F-111 flight parameters

Flight condition	Fire extinguishant agent					
	Halon 1301 specification[a] formula, pounds	Halon 1301 general[b] formula, pounds	Halon 1301 derived[c] formula, pounds	Halon 1202 derived[c] formula, pounds	Halon 2402 derived[c,d] formula, pounds	Halon 1211 derived[c] formula, pounds
Idle	1.68[e]	0.19[e]	2.03[e]	1.96[e]	2.83	3.43
M_o .2, sea level	3.13	3.81	3.84	3.75	5.42	6.55
M_o .75, 35,000 feet (cruise)	2.76	2.54	3.35	3.27	4.72	5.77
M_o 1.2, sea level	10.41	12.88	12.79	12.58	18.21	22.00
M_o 2.2, 55,000 feet	2.63	2.24	3.20	3.13	4.52	5.52
M_o 2.8, 60,000 feet	2.53	2.05	3.14	3.00	4.34	5.30
M_o 3.0, 60,000 feet	2.68	2.16	3.26	3.07	4.43	5.41

[a] Quantity based on Specification MIL-E-22285 formula, $W = 0.25W_a + 0.02V$.

[b] Quantity based on general formula, $W = \frac{P\ C\ M_e}{RT}\left[\frac{W_a}{\rho_a}t + V\right]$.

[c] Quantity based on derived formula (general formula reduced to standard conditions). Derived formulas for indicated agents are:

Halon 1301 (CF_3Br) - $0.308W_a + 0.024V$; $C = 0.06$ (Specification MIL-E-22285)
Halon 1202 (CF_2Br_2) - $0.303W_a + 0.023V$; $C = 0.042$ (NFPA pamphlet Q48-8, see Footnote 12, page 91)
Halon 2402 (CF_2Br_2) - $0.439W_a + 0.033V$; $C = 0.049$ (see Footnote 12)
Halon 1211 ($CBrClF_2$) - $0.539W_a + 0.040V$; $C = 0.093$ (see Footnote 12)

[d] Halon 2402 may not be practical for high rate discharge systems because of its high boiling point (117.5°F).

[e] The quantity increases to 2.52 pounds if the alternate specification formula is used ($W = 0.05V$).

The general or derived formula gives a 24% greater quantity of agent than the specification formula based on the same conditions (12.88 pounds for general formula and 10.41 pounds for the specification formula).

The information in Table 19 indicates that the required quantities are almost equal for Halon 1202 and 1301 to put out a given flame (at cruise--3.27 pounds for Halon 1202 and 3.35 pounds for Halon 1301). This is followed by Halon 2402 which requires 4.72 pounds and Halon 1211 which requires 6.55 pounds.

Fire extinguishing systems designed to MIL-E-22285, require that the quantity of agent be based on normal cruise conditions of the aircraft. A review of the operating conditions for the TF-30/F-111 indicates that if the normal cruise parameter was used the quantity of agent would be approximately 1/4 that determined for the condition of maximum airflow (2.76 pounds based on nacelle airflow at cruise conditions and 10.41 pounds based on nacelle airflow at Mach 1.2 sea level). It is evident that the design condition should be based on Mach 1.2 sea level rather than at normal cruise conditions for maximum fire protection.

Another factor that should be considered is the effect of battle damage on the required quantity of agent. For example, as discussed in *Ventilated Compartments*, at design conditions the increased ventilation, due to battle damage, can reduce the agent concentration to a value less than the effective concentration. This condition will exist if the quantity of agent does not provide for some degree of battle damage.

The ambient temperature, in which the agent is discharged, was found to be a factor in the required agent concentration to inhibit flame propagation. A review of literature indicates that the present agent concentration factors are based on room ambient air temperature conditions. Results of tests conducted to determine effect of ambient air temperature on flammability peaks of various fire extinguishing agents with isobutane (C_4H_{10}) fuel-air mixture is presented in NFPA Q48-8 (see Footnote 12, page 91). The following information taken from the referenced report indicates that the ambient air temperature directly affects the agent concentration required to inhibit flame propagation (flammability peak). For Halon 1301:

Ambient air temperature	% concentration required
-78°C (-109°F)	3.25
+27°C (80°F)	4.7
+145°C (293°F)	7.3

The above review indicates that the present method, defined in MIL-E-22285, for determining the quantity of agent required may not be adequate for the advanced aircraft environment which includes combat damage considerations.

F-111 AGENT CONCENTRATION/DISTRIBUTION TESTS

Fire extinguishing agent concentration/distribution tests were conducted at GD (General Dynamics), Fort Worth, Texas, to evaluate the F-111 nacelle (February 1969) and fuselage compartment (October 1972) design. These tests were conducted on the ground utilizing the Statham Gas Analyzer (12 channels). Walter-Kidde Co., Inc., Bellville, New Jersey, furnished and operated the instrumentation in compliance with GD test plan.

F-111 Nacelle Test

Original intentions were to test the F-111 nacelle agent concentrations by an in-flight discharge of the system at a cruise condition with special onboard instrumentation to record agent concentrations in the engine nacelles. The flight test was replaced with a ground evaluation test based on considerations of the F-111 propulsion system design. Considerations in favor of the ground test were:

1. The TF-30 engine is a ducted turbofan and a film of cooling air passes the length of the afterburner. External engine surfaces remain relatively cool in flight. This eliminates a major ignition source for possible nacelle fires found in many other aircraft. Nacelle air temperatures are primarily a function of ram air temperature (which is directly related to aircraft flight Mach number) plus a small increment due to engine heat.

2. The F-111 propulsion system design provides very high nacelle unidirectional ventilation air velocity for all flight conditions. For example, at cruise (0.75 Mach, 30,000 feet), air velocities range from 59 to 185 ft/sec in the nacelle with 6.98 lb/sec flow rate. During ground operation, engine bleed air is utilized in ejectors around the engine to pump air through the nacelle. The unidirectional high air velocities/flow creates the effect of a transverse aerodynamic firewall. Since in-flight nacelle air velocity greatly exceeds the flame propagation velocity, a nacelle fire would either be blown out the aft end, or, in case of a protrusion acting as a flameholder, the flame would be held stationary until the combustible fluid is shut off thereby preventing a sustained in-flight fire.

3. The test instrumentation to sample and record extinguishing agent concentration would not provide meaningful or accurate results during an in-flight test. Equipment location on the aircraft would require excessive sampling tube lengths (up to 30 feet) and the high airflows and velocities would adversely affect response and accuracy. Development of instrumentation suitable for a flight test might be necessary. At the high airflows, orientation of the sensing line to the airflow is a problem requiring special attention.

4. Installation of the sampling and recording equipment in the F-111 would be a large task.

Conditions for the nacelle ground test were as follows:

1. 2.6 lb/sec nacelle airflow
2. 100°F nacelle air temperature
3. 14.45 psia nacelle pressure.

The agent quantity (discharged) was based on much greater airflow condition for Mach 1.2 flight at sea level. From the oscillograph trace analysis, it was determined that only one channel fell short of 6% concentration by volume for 1/2 second. Correction of the test data for transducer response time (time lag that occurred before the transducer responded on the oscillograph trace after the gas sample entered the sensing line) resulted in all 12 channels indicating 6% or greater agent concentration by volume for 1.5 second.[21] Results of the test are shown in Figure 49. The agent was discharged satisfactorily into the nacelle and satisfactory concentration and duration of the agent was obtained.

F-111 Fuselage Compartment Test

A ground test to determine the concentration and duration of the F-111 fuselage fire extinguishing agent (1303) in the weapons bay and cheek and glove areas were conducted.[22] Conditions for the tests were as follows:

1. Aircraft supported on jacks with weapons bay and wheel well doors closed to simulate in-flight condition. Landing gear retracted, all external paneling installed.

2. The aircraft environmental control section and external air supply to the aircraft ram-air inlet were operated to provide cooling and ventilation air to the given areas as in actual flight. An A/M 32C-60 starter cart was connected to the engine-start connection to provide airflow to the environmental control section airflow. Approximately 100 lb/min of airflow were provided for distribution throughout the fuselage cooling and ventilation system. In flight, maximum steady-state airflow of approximately 128 lb/min occurs at 1.2 Mach at sea level. This is the design condition establishing 11.25 pounds of agent.

The agent was discharged satisfactorily into the appropriate fuselage areas. Results of the tests are shown in Figure 50. Satisfactory concentration and duration of the agent were obtained in each of the areas.

DESIGN ALTERNATIVES

Design alternatives for the design of the fire extinguishing systems are proposed for further investigation to improve the fire survivability of advanced aircraft. These recommendations are for fire extinguishing systems that operate in the high-temperature, high-airflow environment. Following is a list of design approaches for high-temperature environments in the 500°F and greater magnitude and airflows above 1 lb/sec.

1. Insulate or cool storage containers
2. Pyrotechnic generated gas discharge fire extinguishant

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[21] Convair Aerospace. *Airframe–Fire Extinguishing System–Ground Functional Test*, by N. R. McDonald. Fort Worth, TX, CA, 14 March 1968. (FGT-5428, publication UNCLASSIFIED.)

[22] Convair Aerospace. *Airframe–Fire Extinguishing System–Weapons Bay; Cheeks, and Glove Areas–Simulated Flight Conditional Functional Tests*, by J. O. Bishop and N. R. McDonald. Fort Worth, TX, CA, January 1973. (FGT-5766, publication UNCLASSIFIED.)

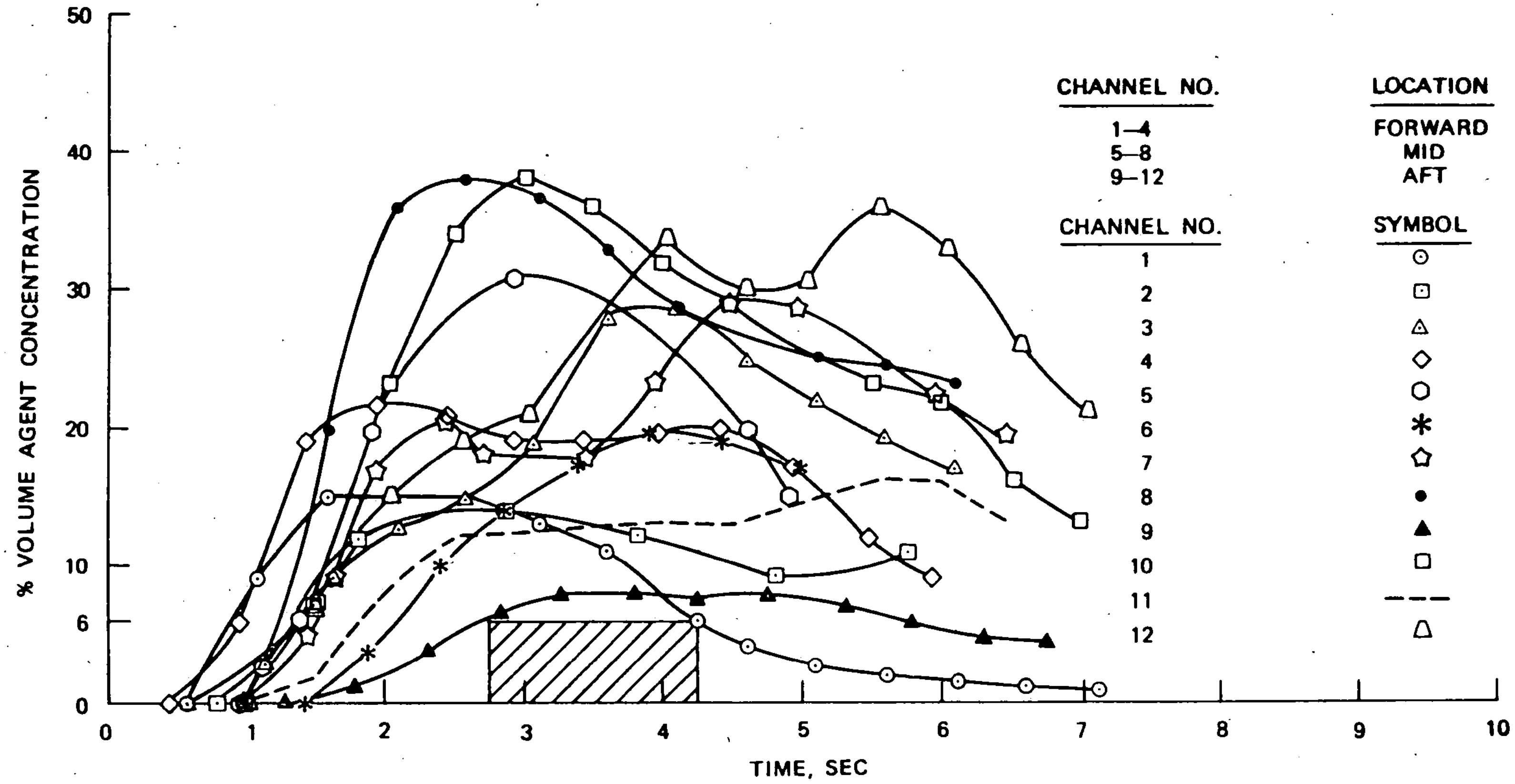
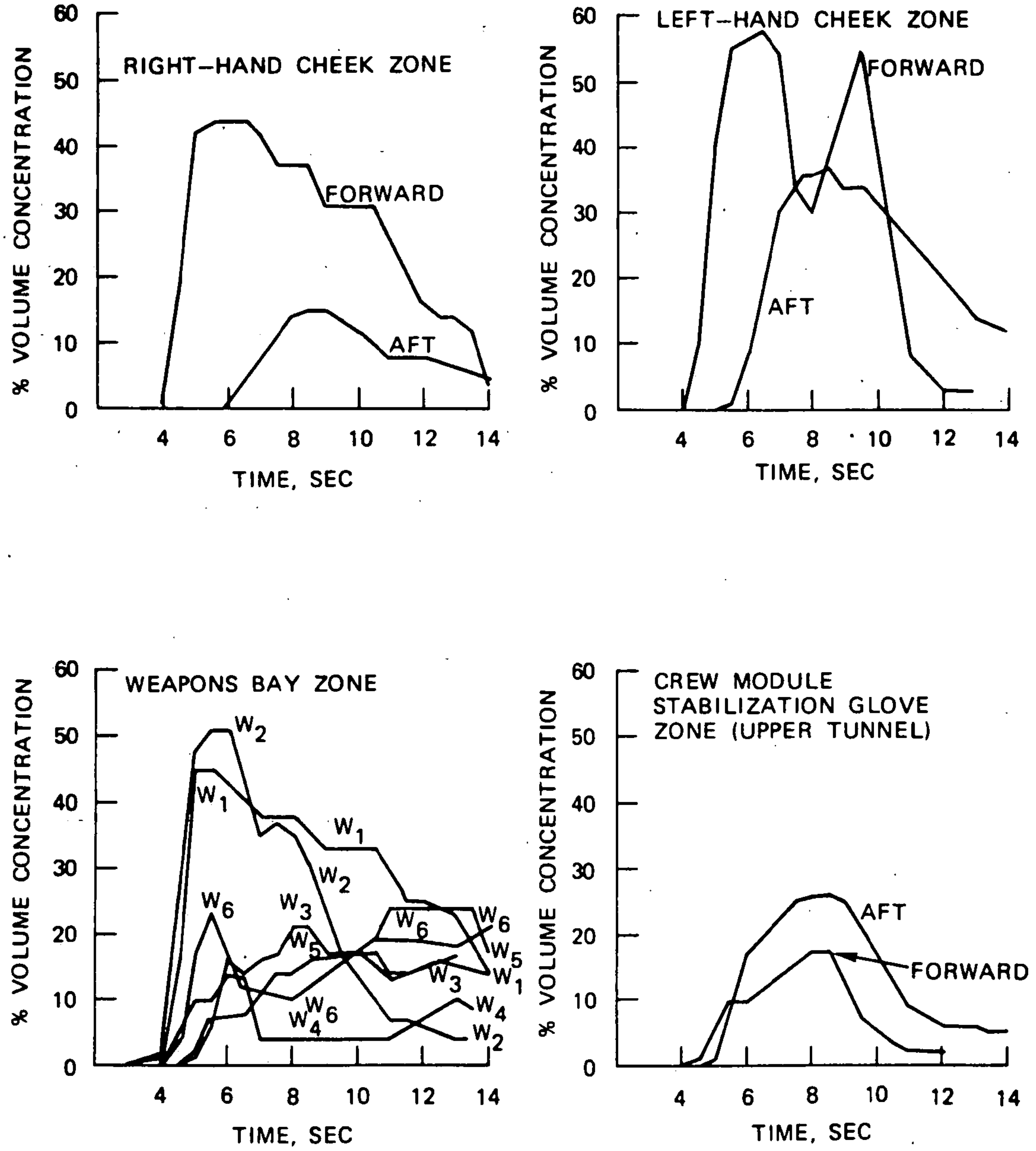


FIGURE 49. F-111 Nacelle Fire Extinguishing Test Results.



CHANNEL NO.	LOCATION IN WEAPONS BAY
W_1	LEFT, FORWARD
W_2	RIGHT, FORWARD
W_3	MID, LEFT
W_4	MID, RIGHT
W_5	AFT, LEFT
W_6	AFT, RIGHT

FIGURE 50. F-111 Fuselage Fire Extinguishing Test Results.

3. Combination scheme of agent and foam
4. Coatings form a thermal barrier when heated
5. Fire resistant inflatable bags in fire zones
6. Hazardous vapor detectors
7. Dry powder extinguishing agents.

INSULATE OR COOL FIRE EXTINGUISHING STORAGE CONTAINER

Some of the attractive halogenated extinguishants have low boiling points which generate high pressures when exposed to high-temperature environments. This problem could be resolved by either making very strong tanks to withstand the high pressures or by insulating the tanks to maintain low temperatures. From a weight cost and safety consideration standpoint, it appears that maintaining the temperature of the extinguishant below a given temperature is a more straightforward approach.

Several attractive insulation materials that are presently available are reviewed in AFAPL-TR-65-124 (see Footnote 17, page 96). These were narrowed down to *Superex* and *Dyna-Quartz*, the properties of which can be obtained from Johns-Manville Aerospace Products. A promising insulation candidate for high temperature aircraft applications is the all-metal (stainless steel) *LOW-Q* product developed by Hughes Aircraft. This insulation material is available in various densities and has insulating properties at the high temperatures much better than some of the current products.

PYROTECHNIC GAS GENERATORS

In order to discharge an agent in a given time at -65°F as well as at high temperatures, the agent in the container is pressurized with nitrogen gas to some given pressure at room temperature. This pressure can be 400 to 600 psi to ensure that the contents of the container are discharged in a given time at -65°F. Some Halon agents such as Halon 1301 have a boiling point of -72°F. The temperature-induced pressure from Halon 1301 is such that, at normal fill densities, pressures of 3,700 psi can be generated at 500°F. This pressure can be reduced by going to a lower fill density (reduced amount of agent per given volume of container). This results in the use of a larger container for any given quantity of agent. This is undesirable from a weight and space allocation standpoint. Therefore, an agent with a high boiling point would be desirable because at the high temperatures the induced pressure would be less. However, the high boiling point does not give the vaporization needed at low temperature to discharge the agent. These considerations led the Walter-Kidde Co. to develop a high-temperature pyrotechnic gas discharge fire extinguisher system.[23]

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[23] Air Force Aero Propulsion Laboratory. *Investigation of Pyrotechnic Generated Gas Discharge Fire Extinguishing System,* by M. deRouville and L. V. Hebenstreit, Walter Kidde and Co., Inc. Wright-Patterson AFB, OH, AFAPL, May 1968. (AFAPL-TR-68-47, publication UNCLASSIFIED.)

COMBINATION SCHEME OF AGENT AND FOAM

One of the problems with the present Halon-type fire extinguishing agents is the short stay-time of the agent concentration in a high-temperature environment. This short duration stay-time can result in the failure of the agent to extinguish a fire or result in reigniting a fire once extinguished. It would, therefore, be desirable to use a fire extinguishing agent that has the ability to remain in this environment a longer period of time.

One approach would be to develop foam-extinguishing liquids that have the following characteristics:

1. Foaming agent expanding to many times its original size when injected into a fire area
2. Foam particles which resist separation after expansion, thereby increasing the stay-time in the high-airflow environment
3. Inhibit combustion action
4. Thermal stability at high temperature
5. Noncorrosive
6. Minimum cleanup time after use
7. Minimum weight of system.

There has been some development done in this area. AFAPL-TR-71-21[24] describes the development of halogenated hydrocarbon foam (halofoam) extinguishants by Arthur D. Little, Inc., Cambridge, Massachusetts. The formulation of this agent consisted of surfactants that provided good foaming action in combination with propellants of Halon 1301 and nitrogen gas. The results of testing indicated that the foams were more effective firefighters than the use of bromochloromethane in the A-20-type hand fire extinguisher.

COATINGS FORM A THERMAL BARRIER WHEN HEATED

In any fire survivability design program it is not only desirable to have a good fire extinguishing system to put out a fire but also one to prevent the ignition source from starting a fire. It is suggested that a good fire extinguishing system, in combination with fire and thermal protection materials, would be a worthy objective of fire survivability studies of the advanced aircraft. This leads us to the consideration of ablative coatings in areas that could reduce fire hazards. It appears, that of all the developed ablative coatings, the recently developed intumescent coatings show the greatest promise for use in advanced aircraft.

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[24] Air Force Aero Propulsion Laboratory. *Development of Halogenated Hydrocarbon Foam (Halofoam) Extinguishants*, by S. Atallah, H. L. Buccigioss, I. J. Arons, and J. R. Valentine, Arthur D. Little, Inc. Wright-Patterson AFB, OH, AFAPL, April 1971. (AFAPL-TR-71-21, publication UNCLASSIFIED.)

Intumescent coatings contain chemicals which release gases when exposed to high heat. These gases are trapped in the thin-film coating, causing it to expand up to 200 times its original thickness. These coatings fight fire by forming a heat barrier provided by the expanded char layer. This layer has extremely low thermal conductivity. In addition, some of these coatings release water vapor and carbon dioxide, providing some fire-quenching action. As heat increases, the char layer eventually reaches a temperature high enough so that it reradiates much of the heat. Although intumescent coatings do not ordinarily extinguish a fire, in small spaces they can swell to fill the void completely, thus removing oxygen from the fire. This can be applicable to aircraft fuel and hydraulic lines, which are often routed through small confined spaces. In a NASA (National Aeronautic and Space Administration, Ames Research Center, Moffett Field, California), test with a 12- by 5.5-inch simulated enclosure, a pair of 2-inch lines (simulating fuel lines) were run through it. The ends and one side of this test section were coated, and a pan containing 200 cc of JP-4 jet fuel was placed in the section and lighted. The coating expanded and filled the entire section before 30 cc of the fuel had burned.

An important advantage of this type of fire protection scheme is that it does not give false alarms and is not energized unless it is needed, virtually giving 100% reliability. Considerable development in these types of coatings has been done by the Avco Systems Division, Lowell, Massachusetts.

One characteristic this material must exhibit is its ability to withstand the high airflow environment. At Convair Aerospace, limited testing of this material for application on an advanced aircraft indicates that the Avco intumescent coatings, Flamarest 1400X, forms a strong char and will withstand airflows in excess of 30 ft/sec. Results of this testing can be found in a Convair Aerospace report. [25]

RESISTANT INFLATABLE BAGS IN FIRE ZONES

In order to sustain a flame, fuel and oxygen must be present. If any of these are removed the flame would be extinguished. Therefore, with the space age development of fire resistant materials, another design alternative would be to install compact, lightweight, inflatable fire resistant bags in strategic areas where fires could exist. When a fire is detected, these bags could be inflated to fill voids thus depriving the flame of oxygen. In addition, these bags could be inflated with an inert gas such as nitrogen or some other fire extinguishing agent. It would also be possible to sequence the operation by allowing the bags to inflate, then, at some predetermined event or time, the fire extinguishing agent could be released to ensure that the flame was extinguished.

A review of literature indicates that firefighting fluorocarbon elastomers have been developed for use in protecting combustible materials such as certain plastics. One recently developed coating, tested on aluminum and epoxy glass laminates, is reported to be able to prevent penetration of a 2000°F flame for 15 minutes. Present and prospective applications include suits for auto race drivers, aircraft interiors, and draperies. It also appears that these material coatings could be used on fire resistant inflatable bags for fire extinguishing purposes.

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[25] Convair Aerospace. *Intumescent Paints–Avco's Flamarest 1400X and 1600–Quick Evaluation of,* by H. P. Owen. Fort Worth, TX, CA, October 1973. (Publication UNCLASSIFIED.)

HAZARDOUS VAPOR DETECTORS

It becomes evident, when reviewing improved fire extinguishing systems for advanced aircraft, that there are a significant number of design parameters that are required to be covered. Since it is difficult to cover all conditions in a design, a consideration for a hazardous condition warning system in combination with the fire extinguishing system would aid in giving greater safety factors in these aircraft. It would be desirable to know when potential fire hazards such as combustible mixtures exist. Knowing of this type of condition, prescribed actions could be taken to prevent a fire or explosion from occurring. One method of predicting a hazardous condition would be the use of a hazardous vapor detector to signal the presence of combustibles in designated compartments.

Hazardous vapor detectors are further described in EER-FW-1203 (see Footnote 9, page 64).

DRY POWDER EXTINGUISHING AGENTS

Dry powder-type extinguishants offer another alternative in the high-temperature, high-airflow of the advanced aircraft. Some of the advantages of this extinguishant are:

1. The agent has essentially no vapor pressure.
2. A properly chosen agent will be thermally stable.
3. The agent can be low in toxicity.
4. Higher fill ratios are obtainable because the agent does not expand.
5. Cost of the powder is inexpensive compared to the halogenated hydrocarbons.
6. It is believed that a dry powder is more effective in a fire situation involving high airflow velocities. The dense particles will not be swept out as easily as the volatile extinguishant. The Ansul Co., Marinette, Wisconsin, found that powders were extremely effective in extinguishing high flow natural gas fire.[26]

Graviner Inc. has investigated the use of potassium cryolite dry powder as a potential extinguishant for use in ambient temperatures up to 300°C (572°F). The testing with cryolite dry powder on puddle fires with airflow velocities in the range of 1.5 to 8.5 ft/sec is described in Graviner report D641.[27] Test results indicated that the potassium cryolite was at least 4.5 times as effective as MB (methyl bromide) on a weight concentration basis. One important factor with the powder is the carrying velocity necessary to avoid particle fallout from the gas flow. However, they expect with higher airflow velocities above 6 ft/sec, the dropout would be low. Particle size used was in the range of approximately 24 to 250μ with 90% in the 24μ size.

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[26] Ansul Company. Marinette, Wisconsin. (Technical Bulletin No. 32, publication UNCLASSIFIED.)

[27] Graviner (Colnbrook) Limited. *Dry Powder Requirements of Puddle Fire.* October 1969. (Report No. D641, publication UNCLASSIFIED.)

TECHNIQUES FOR EVALUATION OF AIRCRAFT FIRE EXTINGUISHING SYSTEMS

The most common method of evaluating aircraft fire extinguishing systems that use Halon fire extinguishing agents is to use a Statham Analyzer and oscillograph recorder which simultaneously measures the gas concentration variation with time at all affected fire zones. This equipment is a design by Statham Instruments Inc., Oxnard, California, and is based on a development described in Air Force Exhibit TSEPE-8E-4-A,[28] dated 31 January 1947, and further described in FAA (Federal Aviation Agency, Washington, DC) technical development report No. 403 entitled *Aircraft Installation and Operation of an Extinguishing Agent Concentration Recorder.*[29] The Statham Analyzer is a device that pulls a gas sample through heated porous elements by a vacuum pump. The pressure drop established across these elements varies as a function of viscosity and volumetric flow. The device is calibrated for air and the extinguishing agent used. This is accomplished in a manner so that a direct reading of percent relative concentration can be obtained from the curve recorded on an oscillograph. This relative concentration can be converted to percent by volume or percent by weight using the curves appearing in the FAA technical development report No. 403.[29]

There is some question if accurate data can be obtained during desired flight operations with present equipment that would require excessive sampling tube length with required heating. In addition, where there are high airflows, the effects of measurement response and accuracy are questionable.

The sampling and recording equipment on board the aircraft requires considerable effort to install. Existing weapons bay data packages have to be removed, sampling tubes routed, and provisions made for remote operation of the analyzers and recorders.

Due to the above problems, most testing of fire extinguishing systems is conducted on the ground in lieu of flight testing.

In many cases, it is desired to test the effectiveness of a fire extinguishing agent by actual testing during flight. Simple, lightweight, low cost methods of determining agent concentration are desired. Recently there has been increased activity in developing techniques for monitoring environmental pollutants. This is nothing more than a determination of the concentration of a specific undesired material in the air. It appears that this activity could be related in determining the desired concentration of a particular material such as a fire extinguishing agent. Therefore, it is suggested that research in pollution monitoring could be used in developing improved low cost, airborne-type equipment for determining fire extinguishing concentration.

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[28] Air Force Exhibit. 31 January 1947. (TSEPE-8E-A, publication UNCLASSIFIED.)

[29] Federal Aviation Agency. *Aircraft Installation and Operation of an Extinguishing Agent Concentration Recorder.* Washington, DC, FAA, September 1959. (FAA Report No. 403, publication UNCLASSIFIED.)

The study of fire extinguishing system reveals that the criteria used for determining the requirements for a fire extinguishing agent is based on factors that do not represent the actual application. For example, the agent concentration specified in a fire extinguishing system per MIL-E-22285 requires a concentration of 6% by volume of Halon 1301 in all affected zones for 0.5 second. The percent concentration by volume of agent was established at room temperature conditions. A review of literature indicates that the minimum percent concentration of agent necessary to render a fuel-air mixture nonflammable is directly proportional to the ambient air temperature. Fire suppression at high ambient temperatures may not be effective if design concentration is based on room temperature data to extinguish a fire under these conditions.

A review of the literature on fire extinguishants deals in specified areas that do not relate entirely to an actual flight condition. The effectiveness of agents are relative to each other under so-called standard fire conditions. It appears that all of the actual parameters possible must be brought together to evaluate the effectiveness of a fire extinguishing system. The following approach is suggested in developing a technique for evaluating a fire extinguishing system.

1. Establish a fire survivability model of design requirements based on all presently known parameters that affect fire hazards and suppression.

2. Develop a computer program model with all known variables such as
    - a. Engine nacelle classification (podded and airframe-mounted, geometry)
    - b. Nacelle airflow
    - c. Nacelle ambient air temperature
    - d. Combustible characteristics
    - e. Nacelle air pressure
    - f. Nacelle flow pattern
    - g. Hot surface temperatures.

3. With all known variables, build a 1/4 scale model. Vary parameters to determine
    - a. Hot surface ignition temperature hazards
    - b. Flight conditions fire/explosion most likely to occur
    - c. Determine airflow patterns
    - d. Make adjustments in computer program
    - e. Based on results of model testing, select fire extinguishing agents for effectiveness.

4. Confirm computer model program and scale-model concepts with actual full-scale fire initiating and suppression system testing. Make adjustments necessary to above program and finalize variable inputs to be used for subsequent computer and scale-model programs. Once this model testing is verified, subsequent variable inputs would result in optimum fire extinguishing systems without actual full-scale fire initiating and suppression testing.

CONCLUSIONS AND RECOMMENDATIONS

The F-111 aircraft provides a good example for the evaluation of present vaporizable fire extinguishing agents and the establishment of criteria for the development of new fire suppression systems to operate in the high-temperature, high-airflow environment.

The presently developed self-pressurization fire extinguishing systems will not be efficient over the storage environment temperature range of -65 to 500°F.

Attractive vaporizable fire extinguishing agents, which are effective at -65°F, develop extremely high pressures at the high ambient temperatures thus resulting in system weight penalties.

There are only a limited number of the currently vaporizable agents that are marginally, thermally stable at the high ambient temperatures expected in the advanced aircraft. This may be partially overcome by insulating storage containers, locating containers in cooled compartments, or utilizing other special designs. Based on the available test data reviewed, halogenated agent storage containers in high-temperature environments should be manufactured from stainless steel or Inconel.

A closed (nonventilated) compartment, designed to provide 6% volumetric concentration of Halon 1202 for sea level, will also provide at least 6% concentration for a minimum of 0.5 second for damage conditions of A/V (ratio of vent area and compartment volume) ratio slightly less than 0.1 ft^{-1} when discharged at altitude with compartment venting. Damage conditions of $A/V = 0.004\ ft^{-1}$ will provide the desired concentration for a time greater than 0.5 second.

In normally closed compartments with battle damage involving holes of 1 to 2 ft^2 in compartments of up to about 200 ft^3, the times to (1) establish the required concentration in the compartment and (2) for the excess compartment pressure to decay, are small compared with the specification required stay-time of 0.5 second. The rate of flow of air-agent mixture out of the compartment is the dominant part of the process and the mass flow rate of the agent is sized to equal the mass rate of flow of mixture out of the compartment for the required stay-time. The amount of agent required to maintain a low (e.g., 6%) volumetric concentration for a given time period increases more rapidly with damage hole size than with increasing compartment volume.

At design conditions for ventilated compartments, the stay-time of the agent is equal to the design stay-time or 0.5 second for current specifications. At off-design conditions where the ventilation airflow rate through the compartment is less than at design conditions, the concentration of an agent will be greater than the design value and the stay-time will be somewhat greater than 0.5 second. For an F-111-type aircraft flying at Mach 2.2 and 55,000 feet, a reasonable upper limit on the stay-time (time at which the concentration is 6% or greater) of a typical agent (1202) discharged into the engine nacelle is approximately 1.33 seconds.

For ventilated compartments, little can be done to significantly increase stay-time of the type of agents currently in use other than releasing a much larger quantity of agent over the desired longer stay-time, or shutting off the ventilation. The use of different vaporizable liquid agents having different molecular weights and different ratios of specific heats will not significantly increase the stay-time beyond the estimated values presented. At design conditions, increased ventilation due to damage can reduce agent concentration to a value less than the effective concentration if the quantity of agent does not provide for some degree of battle damage.

With respect to propulsion installation fire prevention design criteria, the extension of aircraft flight into the higher supersonic and hypersonic regime requires additional research into fire hazard definition. Ignition temperature research is needed for the present and future aircraft combustibles at high temperature conditions. This definition should include the effects of ventilation and altitude (pressure) with high ambient temperatures. Additional variables such as compartment volume, surface area, ignition source, and geometric shape should be included. The anticipated operating and environmental conditions under which fire/explosion protection equipment for advanced aircraft will be required to operate are contained in Tables 11 and 12 of this report. This data are based upon an extrapolation of the base line (F-111) aircraft environment.

It would also be highly desirable to develop simulation test capabilities to evaluate fire suppression systems before production of the aircraft. Testing early in the vehicle program is not conducted due to unavailability of equipment and cost. Practical low cost, simulation test methods would provide early evaluation of systems and the effects of a particular design (compartment roughness, restrictions, etc.). Also, simulation testing might include fire hazard evaluation (including failure and combat damage) and fire suppression capabilities for the critical conditions anticipated. This testing becomes more desirable and significant for the advanced aircraft operating in high-temperature, high-airflow environment.

An integrated design approach is recommended for fire/explosion protection of future aircraft. In addition to the traditional tactics employed (isolation, draining, venting, separation, etc.), the following are offered as suggestions to enhance the survivability of future aircraft operating in the high-temperature, high-airflow environment.

1. Consider fire/explosion hazards for normal operation, failure modes, and combat damage conditions in initial vehicle design efforts.

2. Establish failure and combat damage criteria for fire/explosion suppression and survivability. Develop design aids, checklists, and manuals to assist aircraft designers.

3. Develop, test, and incorporate combustibles with improved fire/explosion resistance.

4. Develop advanced fire extinguishants and fire suppression systems capable of functioning in a high-airflow environment and in a high-temperature/high-airflow environment to suppress a fire and prevent its reignition by hot surfaces or other residual ignition sources.

5. Design smooth engines and nacelles of low volume and cross-sectional area. Eliminate protuberances in the nacelle that can become flameholders.

6. Provide for unidirectional ventilation to purge compartments of vapors, increase ignition temperatures, and provide aerodynamic firewall.

7. Develop, test, and incorporate special coatings which provide greater fire resistance and insulating properties.

8. Provide rapid detection of fire or hazard. Consider use of vapor detectors for early identification of hazard.

9. Consider the effects of projectile damage in the selection of compartment structural materials and design concepts.

10. Initiate a study program to define and develop high-temperature, high-airflow integrated nacelle designs and design guidelines for fire/explosion survivability in the normal condition, failure modes, and combat damage environment of 23-mm API/HEI projectiles.