
Chapter 2: HISTORY OF FIRE SUPPRESSION IN AIRCRAFTⁱ

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ⁱ The content of this chapter has been approved for public release by the Naval Air System Command (NAVAIR), per NAVAIR public release authorization control numbers 063-06, SPR07-005B, and SPR07-005D.

2.1 FIRE THREATS TO MILITARY AIRCRAFT

Safety and survivability drive the requirements for fire suppression in aircraft. Whereas safety is concerned with mitigation of hazards associated with system or component failures or human error, survivability relates to susceptibility and vulnerability to threats directed at the aircraft. A fire is deemed a safety-related fire when it results from component failures, which may be due to inadequate design, a mechanical failure mechanism such as fatigue, or maintenance error, and results in either a flammable fluid contacting an always-present ignition source, or the failures themselves provide both the flammable fluid and the ignition source. Fires that relate to aircraft survivability are those that are ballistically induced in areas on an aircraft that, if not protected by some means, are vulnerable to fire or even explosion. Extensive literature compilations by the National Advisory Committee on Aeronautics (NACA) summarize investigations since 1922 of aircraft fire problems, fire prevention measures, fire detection, fire suppression, fuel tank explosion hazards, and inerting. These indicate that what was then the War Department had been addressing the field of aircraft fire protection at least as early as 1927.^{1,2} In 1938, just prior to World War II, the issue of in-flight power-plant (engine compartment) fires led to the Civil Aeronautics Administration (CAA) expanding its fire test program to include fire extinguishing to mitigate the hazards associated with these fires.³ Review of the combat data from World War II indicated that, in order, damage to engines, cooling and lubrication subsystems, fuel system, and flight control systems were to likely lead to aircraft loss, and that the majority of aircraft lost were on fire.⁴

Surveys conducted after World War II documented the obvious need for lower volatility fuels and separation of flammable fluid-carrying components from ignition sources with the engine emphasized as the principal ignition source.⁵ It was also then recognized that during flight the fuel-air mixture within fuel tanks could be alternately combustible and noncombustible, depending upon flight conditions. However, engine failures were still found to be the most frequent cause of flammable fluid ignition by an ignition source in flight.⁶ It is no surprise that years later, analysis conducted by the United States Navy (USN) indicated a similar outcome: non-combat in-flight fires, i.e., safety-related fires, occurred predominately in engine compartments, as illustrated in Figure 2-1.

The combat environment exposes military aircraft to ballistic and higher-level threats that, until recent years, have not been experienced in U.S. commercial aviation.⁷ These threats can be incendiary or non-incendiary. The military conflicts in Korea and Southeast Asia and analysis of aircraft combat loss data from those conflicts indicated that the fires due to fuel-system-related damage were becoming the predominant fire vulnerability, as aircraft were lost mainly due to hits on the fuel system.⁴ Analysis of aircraft losses suffered during the Vietnam conflict indicated generally that half were due to fuel fires and explosions, and that half of those were attributable to fuel explosions in dry bay areas on aircraft.⁸

As illustrated in Figure 2-2, dry bay areas along with the fuel tank ullage, which can itself contain a flammable fuel-air mixture, are vulnerable to ballistic threats.ⁱⁱ From the aircraft survivability design perspective, the fuel tank ullage and dry bay compartments contribute to an aircraft's ballistic vulnerable area. Incendiaries released from a ballistic round that penetrate the ullage can result in ignition of fuel vapor. A ballistic round entering into a dry bay adjacent to a fuel tank, and that also penetrates a fuel tank or other flammable fluid component, can cause fuel to leak and be ignited within the dry bay when incendiaries are released.

ⁱⁱ Dry bays are void areas on aircraft adjacent to fuel tanks or can be areas containing flammable fluid-carrying components.

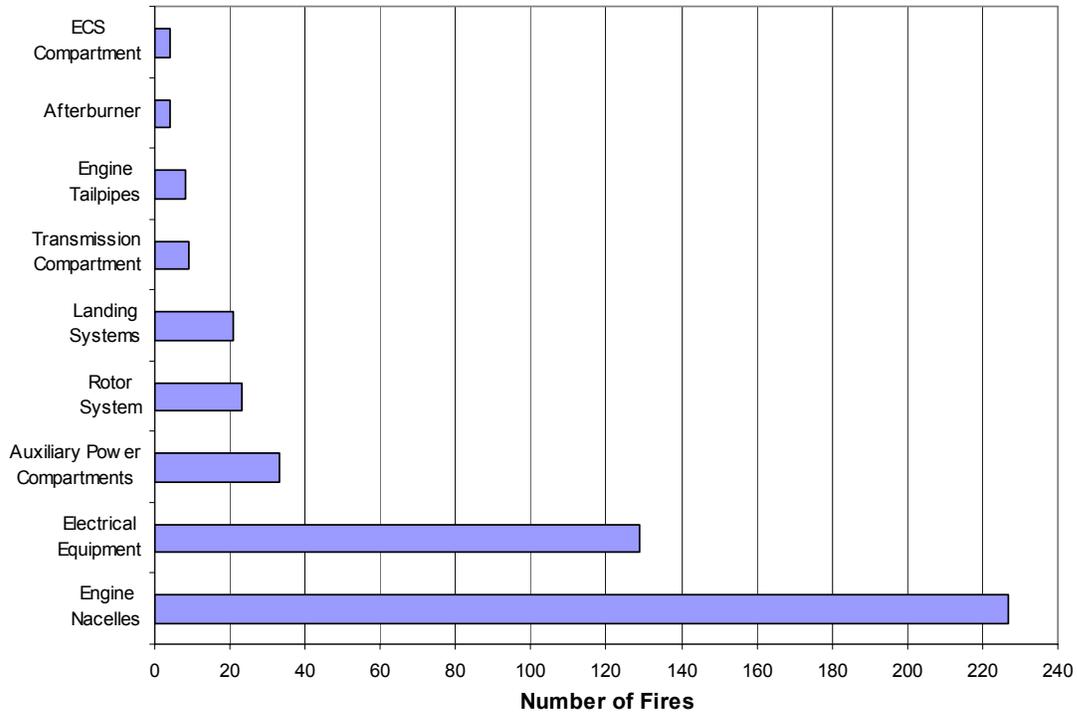


Figure 2-1. Significant Non-combat Fire Locations on U.S. Navy Aircraft 1977-1993.^{9, iii}

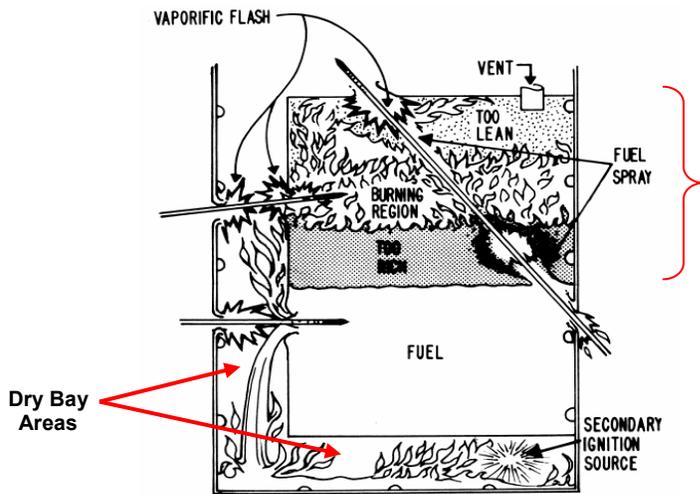


Figure 2-2. Combustion Threats in and Around an Aircraft Fuel Tank.⁴ (Reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

ⁱⁱⁱ Forty-nine percent (49 %) of the fires represented in the electrical equipment bar in Figure 2-1 occurred on one aircraft platform type within the aircraft cabin and were readily extinguished by either securing electrical power to that equipment or by use of on-board portable fire extinguishers. Also in Figure 2-1, ECS is an acronym for Environmental Control System.

Table 2–1 provides a generalized evolution of tactical and rotary aircraft vulnerability based on live fire testing (LFT) vulnerability assessments for armor-piercing incendiary (API) threats.^{iv} Though aircraft vulnerable areas have decreased over the years, as depicted notionally in Figure 2-3, fuel systems remain a significant vulnerability issue and drive the need for vulnerability-reduction measures such as fire suppression for aircraft dry bay compartments as well as for engine compartments.

Table 2–1. Evolution of Aircraft Vulnerability Based on Live Fire Test Vulnerability Assessments (API Threats).^{iv}

Aircraft Category, System	Vulnerable Area Percentage	Vulnerable Area Percentage
Tactical Aircraft	1960s through 1970s	Current
Crew	8 %	10 %
Propulsion	54 %	5 %
Flight Controls	11 %	5 %
Fuel System	25 %	75 %
Structure	1 %	2 %
Other	1 %	3 %
Rotorcraft	1980s	Current
Crew	1 %	3 %
Propulsion	< 1 %	2 %
Drive System	15 %	20 %
Flight Controls	38 %	33 %
Fuel System	30 %	42 %
Structure	16 %	-
Other	-	< 1 %

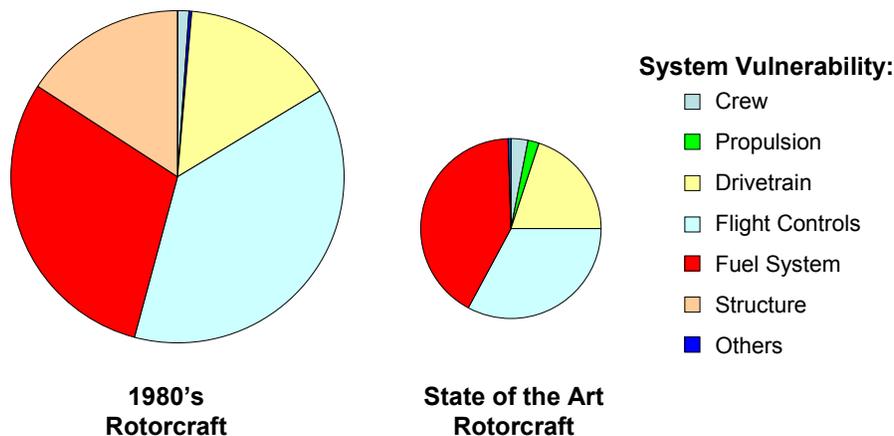


Figure 2-3. Illustration of Notional Reduction in Overall Rotorcraft Vulnerable Area.

^{iv} Figure 2-3 and the percentages in Table 2-1 were provided by the Naval Air Warfare Center Weapons Division, Aircraft Survivability, and are printed with permission of the Naval Air Systems Command.

The susceptibility of aircraft to engine fires combined with the combat vulnerability to fuel-system-related fires cannot be overstated. Based on United States Air Force (USAF) experience, the combined historical cost from 1966 through projected cost through 2025 of aircraft loss due to fire from both operational and combat losses has been estimated as over \$30 billion. The cost to provide fire suppression for that same period has been estimated at less than \$1 billion.¹¹ Chapter 10 provides further discussion of life cycle cost of aircraft fire protection.

In terms of personnel safety, the fire risk is obvious. However, in terms of crew survivability in combat, the need for fire suppression takes on an added dimension. Figure 2-4 shows known ejection locations of U.S. Navy aircrewmembers who subsequently became prisoners of war (POW) during the Vietnam conflict, and Figure 2-5 shows locations of Navy rescues of Navy aircrewmembers during that conflict.¹² It had been estimated that the difference in terms of time was typically 5 min flight time between ejection locations and rescue locations. Thus the ability to provide fire suppression capability to address both predominant operational failure threats as well as combat threats is likely to increase aircrew survival and recovery.

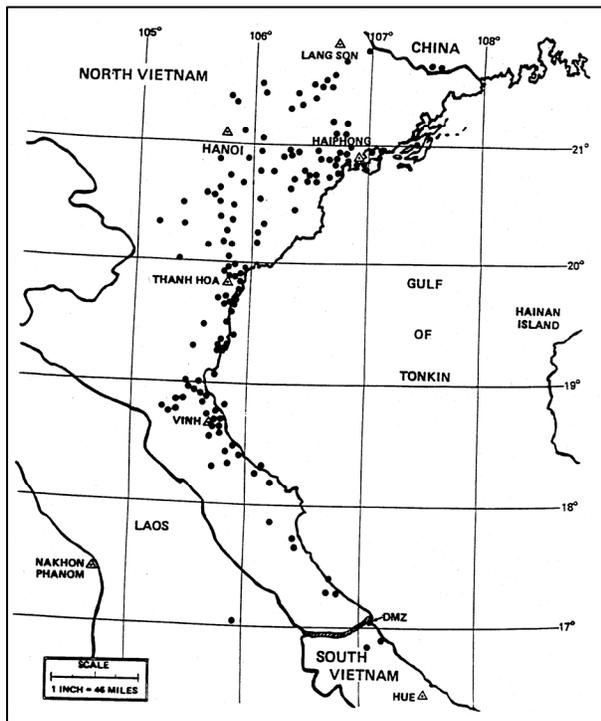


Figure 2-4. Known Ejection Locations of Navy Aircrewmembers Who Became POWs During the Southeast Asia Conflict.¹²

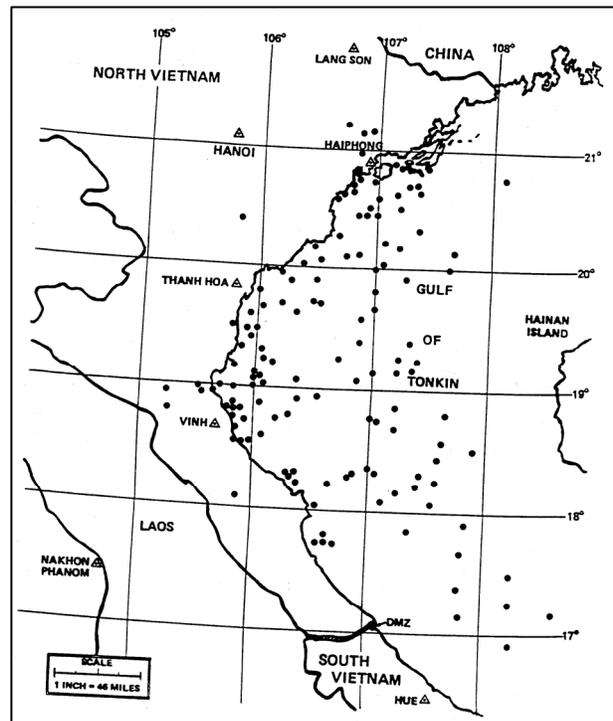


Figure 2-5. Locations of Navy Rescues of Navy Aircrewmembers During the Southeast Asia Conflict.¹²

The remainder of this chapter describes not only the aircraft compartments that were the primary focus of the United States Department of Defense's Next Generation Fire Suppression Technology Program (NGP), but also provides general summaries of all the various types of compartments on aircraft for which halon fire suppression has been implemented. This has been done so that the reader is reminded that, although the focus of the NGP addressed those compartments for which, statistically, the fire threat

has been the greatest, the work of the NGP is likely to influence in the future how fire suppression is applied for other aircraft compartments that may require protection.

The next section includes a brief discussion on various techniques for fuel tank ullage fire suppression, which was the subject of an exploratory effort during the NGP. This is followed by a summary of the NGP's investigation into the types of fires experienced in the compartments that were the focus of the NGP: engine nacelles, auxiliary power unit (APU) compartments, and dry bays. In particular, this section provides expanded discussion on the topic of temperature and historical experience related to fire suppressant releases relative to outside air temperature (OAT) and the nacelle temperature environment. Next, brief descriptions are provided for the fire suppressants that have been used on aircraft prior to the efforts to identify halon alternatives that commenced after production curtailments driven by the U.S. Clean Air Act of 1990 and amendments to the Montreal Protocol. Throughout this entire section, the word "halon" is used to denote any of the halogenated fire suppressants that have been used in aircraft fire suppression, except where the particular halon type is noted specifically. Finally, a brief overview of the Halon Alternative Technology Development Program (TDP) is provided to familiarize the reader with the "near-term" halon alternatives identified for use in aircraft fire suppression applications, their benefits, and their limitations, which led to the need for the NGP.

2.2 PROTECTED COMPARTMENTS ON AIRCRAFT

The predominant implementation of halon-1301-based fire suppression on aircraft has been for fire protection of powerplant-type compartments. These compartments are those that contain engine-type equipment that require flammable fluids (aviation fuel, hydraulic fluid, and lubrication oil) to generate propulsion power, such as a turbojet engine that generates thrust power for a fighter jet or a turboshaft engine that generates shaft power to turn a propeller on a turboprop aircraft or turn rotors on a helicopter. Powerplant compartments include engine compartments, which are referred to as nacelles, but depending on the type of aircraft, e.g., transport, cargo, fighter, or helicopter, may also include additional types of powerplant-type compartments such as APU compartments. Also, depending on the type of aircraft, halon 1301 has been utilized to provide fire suppression for other compartments, such as dry bays, cargo compartments, avionics compartments, weapons bays, and fuel tanks. Although the final focus of the NGP was to address halon alternative fire suppression for engine nacelles, APU compartments and dry bay compartments, the intent of this section is to familiarize the reader with these compartments as well as other types of compartments for which fire suppression has been provided on military aircraft.

From the aircraft designer's perspective, "fire extinguishing" implies that a system is to be designed to extinguish a fire without subsequent reignition, whereas "fire suppression" implies that reignition can occur but that the system will suppress the fire until a safe landing can be achieved. However, the phrase "fire suppression" is used widely throughout aviation as well as in the NGP and its publications to mean fire extinguishment, except where specifically explained otherwise. The latter convention is followed in this chapter as well, except where noted otherwise.

2.2.1 Engine Nacelles

Engine nacelles are the physical compartments on aircraft that house the engines. These compartments may be integral with the fuselage or mounted externally to the aircraft's wings. An example of a turboshaft engine is illustrated in Figure 2-6. The engine itself is physically complex, containing ribs,

tubing for fuel and bleed air, electrical harnesses, and externally-mounted accessory components (e.g., oil pump). Integration of an engine into an aircraft nacelle increases greatly the geometric complexity about an engine, as components and systems that must interface directly with the engine will also reside within the nacelle. Adding to the complexity of the installation are the dynamic conditions that exist within the nacelle during aircraft operation. Engine surface temperatures can exceed 538 °C. Ventilation airflow is required through the nacelle to ensure engine and accessory component performance is not degraded and is effected by incorporation of air inlets and outlets on the nacelle structure. Depending on the type of aircraft and flight conditions, nacelle mass airflow rates for DoD aircraft that have been fielded have ranged from under 0.23 kg/s (0.5 lbs/s) to in excess of 14 kg/s (30 lbs/s) for a fighter aircraft dash operation.^{13,14} When the combined integration is considered, the nacelle becomes a geometrically-complex, turbulent compartment capable of sustaining fire. Additionally, components within the nacelle and the engine components themselves provide for potential flame holders, recirculation zones, and for potential areas of stagnation.

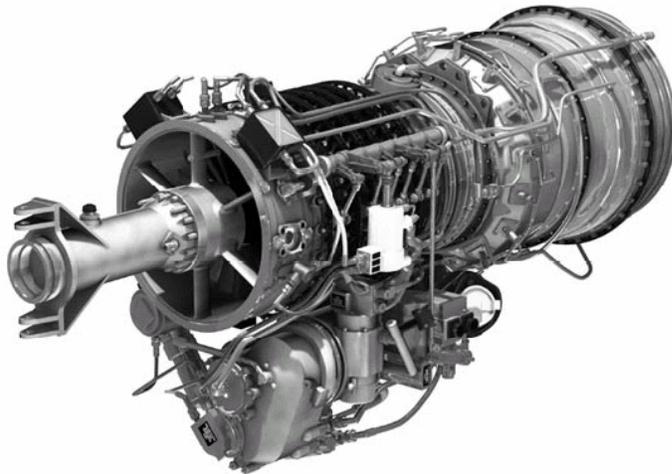


Figure 2-6. Example Turboshaft Engine.

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Figure 2-7 is an example of a military aircraft engine nacelle. As shown in Figure 2-8, the typical nacelle fire suppression system installation consists of one or more fire suppressant bottles, located external to the nacelles, connected to a directional control device that interfaces to distribution plumbing that routes discharged suppressant to the nacelles. This system may also be designed to deliver suppressant to an APU compartment. Discharge is effected by the pilot in the cockpit: an electrical signal causes activation of a pyrotechnic cartridge actuated device (CAD) to rupture a burst disk on the bottle to effect suppressant release. These systems are typically designed to provide a specified suppressant concentration level (6 % for halon 1301)^v throughout each protected compartment for a minimum of 0.5 s. Figure 2-9 shows a fire suppression system installation for an engine nacelle in which the suppressant bottle is located in a compartment adjacent (and external) to the nacelle. Though not typical in currently fielded DoD aircraft, the fire suppression system bottle may also be located within the nacelle, as shown in Figure 2-10, increasing nacelle complexity.

^v Throughout this chapter, where percentages are indicated in discussions related to suppressant concentrations, they are always referring to concentration by volume.



Figure 2-7. A Fighter Aircraft Engine Nacelle.
(Printed with permission of the Naval Air Systems Command.)

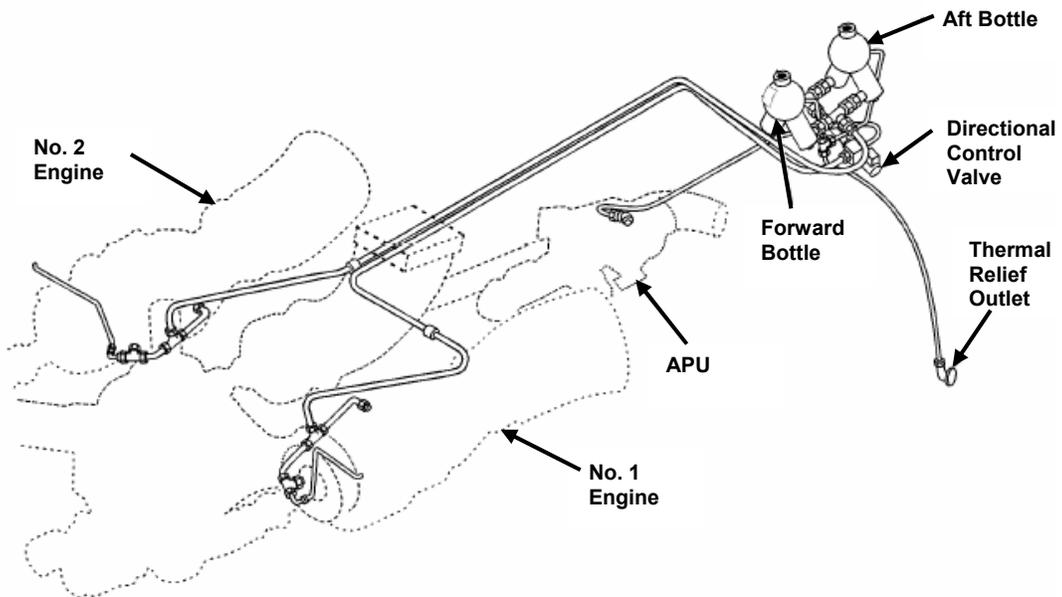


Figure 2-8. Diagram of an Aircraft Fire Suppression System Installation.⁸



- CAD
- Fire Suppressant Bottle (Mounted in Compartment External to the Nacelle)
- Discharge Line from the Bottle
- Nacelle Air Inlet Structure
- Distribution Line within Nacelle
- Distribution Line Outlet

Figure 2-9. An Aircraft Engine Nacelle Fire Suppression System Installation, Suppressant Bottle External to the Nacelle.

(Printed with permission of the Naval Air Systems Command.)

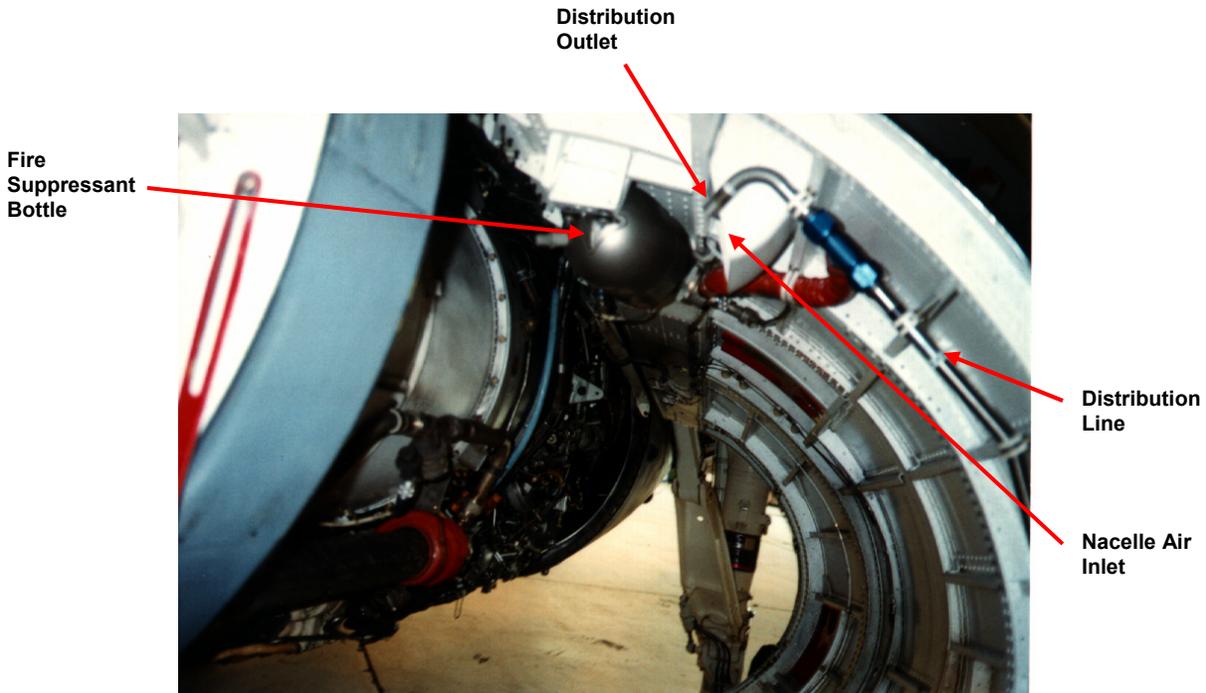


Figure 2-10. An Aircraft Engine Nacelle Fire Suppression System Installation, Suppressant Bottle Within the Nacelle.

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2.2.2 Other Powerplant-type Compartments

In addition to engine compartments, DoD military aircraft may contain other types of powerplant compartments for which a fire suppression capability is provided, either dedicated or shared with another fire suppression system on the aircraft. The most common compartment that falls into this category is that containing the auxiliary power unit (APU). On some aircraft this compartment may also be referred to as the auxiliary powerplant (APP) or the gas turbine compressor (GTC) compartment. These units may be miniature turbines or other power generating equipment, but are typically smaller than the normal jet engine propulsion systems. These units furnish electrical power when engine-driven generators are not operating or when external power is not available, and they may be used to provide emergency power to all or some of the aircraft subsystems in the event of an in-flight engine shutdown.^{vi} These units function and generate power independently from the normal aircraft engine systems. On the ground, the power output from the APU is used to generate power to drive a starter unit for engine starting.

^{vi} Because aircraft power for the fire suppression system may not be available during startup, one fielded rotorcraft model actually employs a manually activated fire bottle for its APP compartment. A cable is run from the cockpit fire bottle actuation mechanism, referred to as the T-handle, through overhead cabin compartments, around a two-pulley system, and into the discharge port of the bottle.

In addition to or instead of a dedicated APU compartment, there are fielded DoD aircraft that contain an accessory compartment or secondary power system (SPS), or in the case of a rotary aircraft, a gearbox compartment. These compartments may contain the APU or other equipment utilized during ground engine starting and aircraft operation such as a Jet Fuel Starter (JFS) or an Airframe Mounted Accessory Drive (AMAD). Like engine nacelles, each of these compartments is likely to have ventilation airflow to ensure proper component performance and, like the main aircraft engines, components like the APU are potential ignition sources and their integration into the aircraft can present geometric complexities with respect to fire suppressant distribution. Figure 2-11 is an example of an APU installation on a transport aircraft. Figure 2-12 is an example of a fighter aircraft accessory compartment. Figure 2-13 is an example of an aircraft gearbox compartment that also contains an APU. Figure 2-14 is an example SPS installation on a fighter aircraft. Integration of an APU or similar component into an aircraft accessory, gearbox, or other powerplant-type compartment results in a complex compartment in which fire may be sustained, due to either a component failure or, in the case for some aircraft as will be described later, because the compartment is vulnerable to ballistically induced fires.

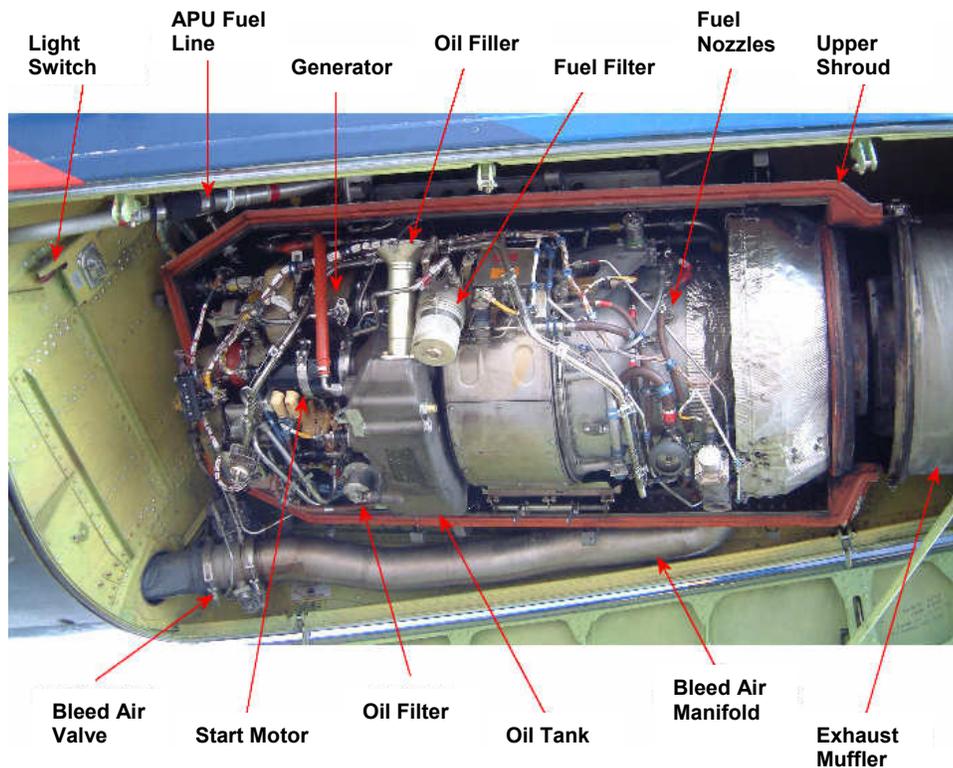


Figure 2-11. A Transport Aircraft Auxiliary Power Unit Installation.^{15, vii}
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^{vii} Several DoD aircraft models are variants of commercial transport aircraft. Such aircraft are referred to within the DoD as commercial-derivative aircraft.

Fire Suppressant
Bottle

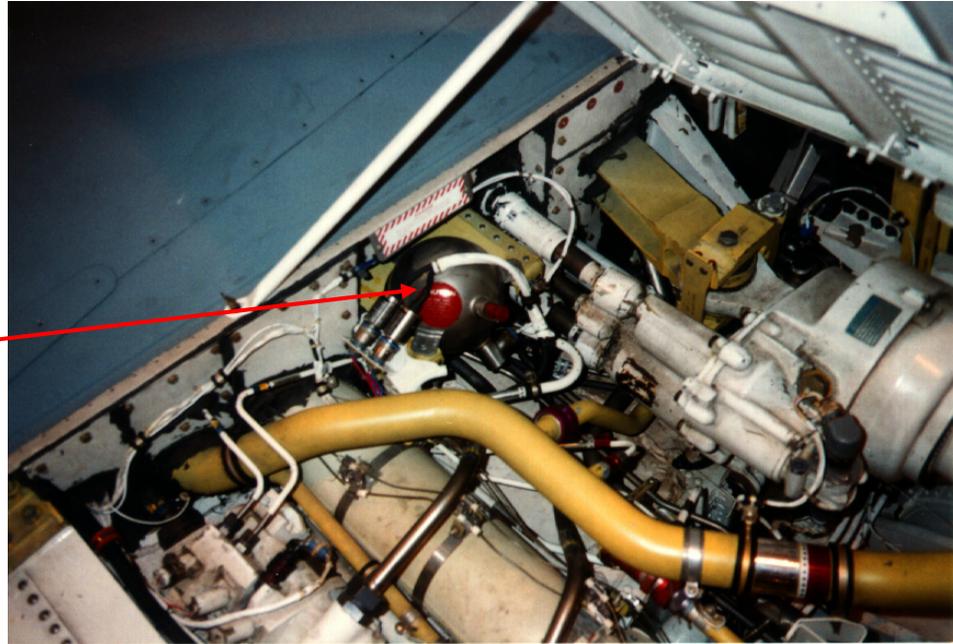


Figure 2-12. A Fighter Aircraft Accessory Compartment With Fire Suppression System Installation.
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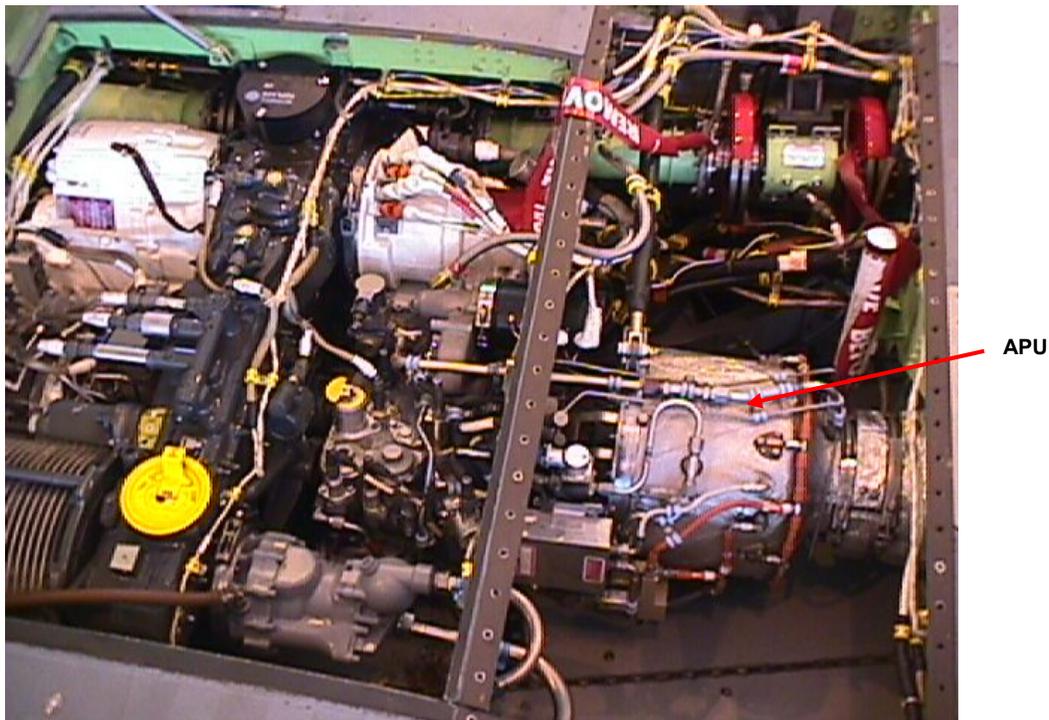


Figure 2-13. An Aircraft Gearbox Compartment with APU.
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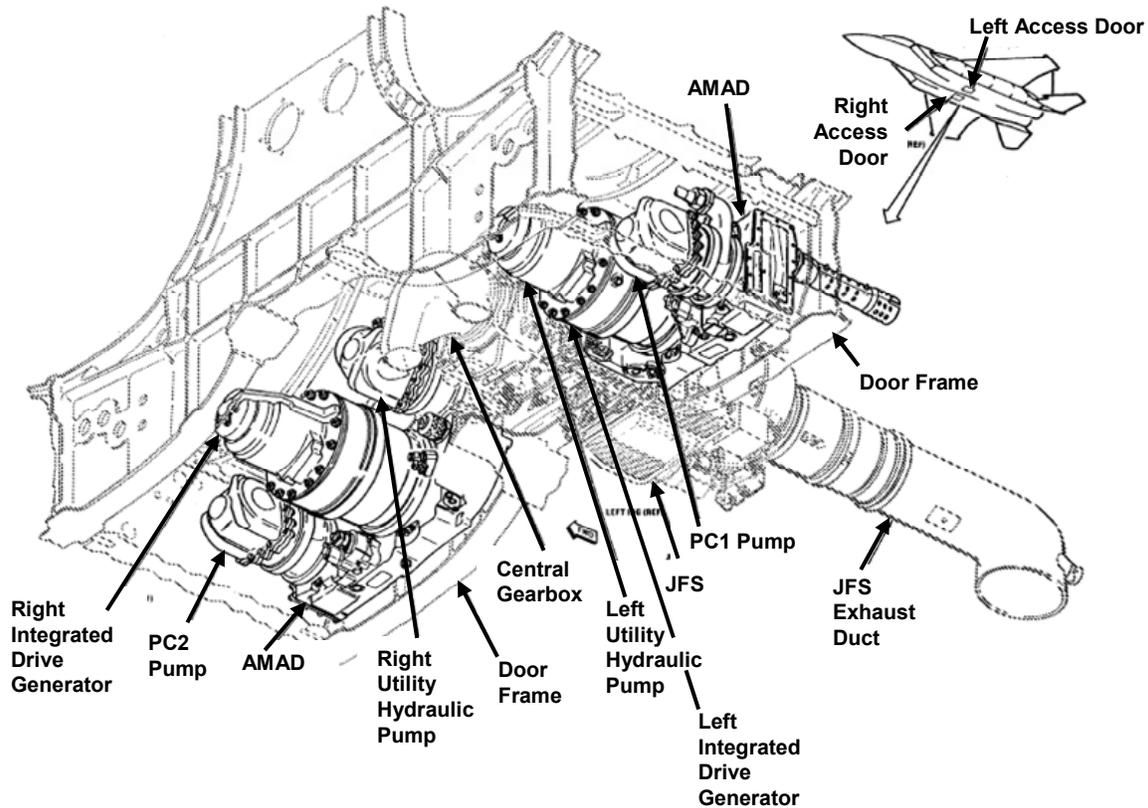


Figure 2-14. A Secondary Power System (SPS) Installation.¹⁶
 (Component callouts spelled out or simplified for clarity.)

2.2.3 Dry Bay Compartments

Dry bay compartments, or simply dry bays, are compartments on aircraft adjacent to fuel tanks or are compartments in which flammable-fluid-carrying components are located. The compartments adjacent to fuel tanks may contain other equipment, such as avionics equipment, or may be, for the most part, empty. There may or may not be ventilation airflow. If not empty, a dry bay can be geometrically complex, and if there is some ventilation airflow, the compartment may be turbulent. One study identified generally four types of dry bays: wing leading/trailing edge, wing midchord, fuselage fuel cell boundary, and fuselage forward and aft equipment bays.¹⁷ Ballistic threats such as armor-piercing incendiary (API) rounds or high-explosive incendiary (HEI) rounds can penetrate a fuel tank or fuel-carrying component, effecting release of flammable fluid into a dry bay. The incendiary released by the round from the penetration can then ignite the fluid-air mixture. The damage inflicted by a ballistic round may also result in damage to an aircraft system that can result in a secondary ignition source, such as heated metallic fragments or arcing from a damaged electrical harness. Figure 2-15 illustrates that dry bay compartments may be located within the fuselage as well as in wing areas that surround a fuel tank. Figures 2-16 through 2-18 provide examples of actual aircraft dry bay compartments. Figure 2-16 illustrates a dry bay compartment adjacent to a fuel tank whereas Figures 2-17 and 2-18 show dry bay compartments that also contain flammable-fluid carrying components.

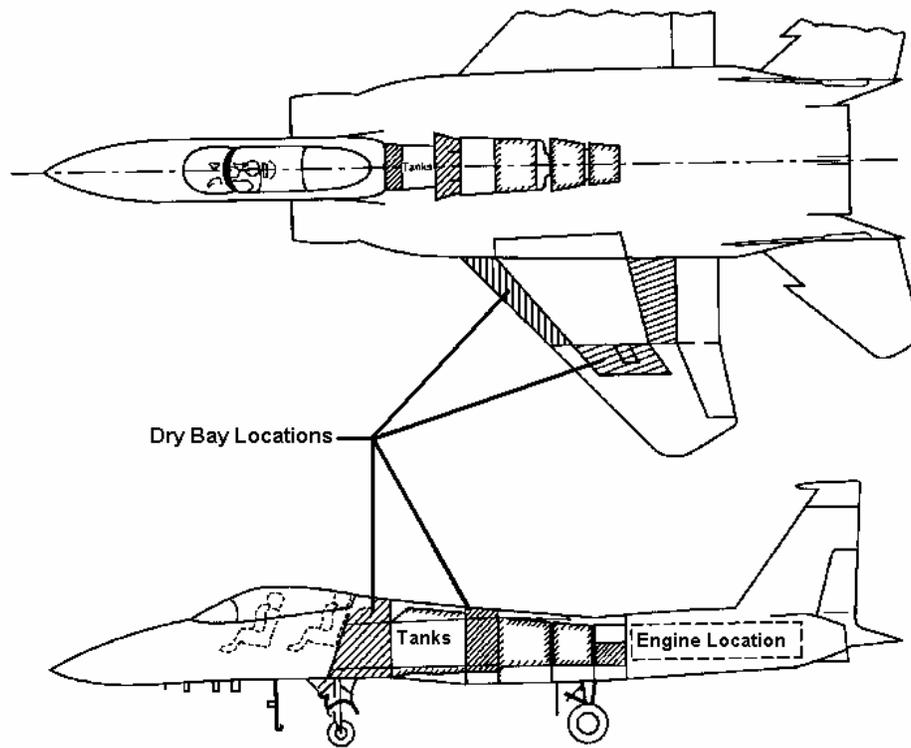


Figure 2-15. Typical Dry Bay Locations in a Fighter Aircraft.¹⁸

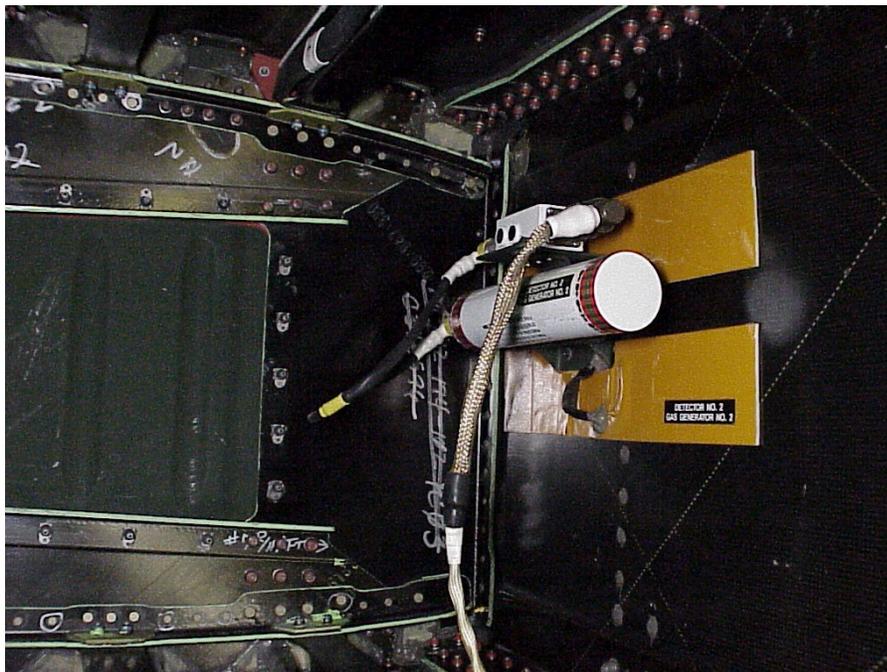


Figure 2-16. A Dry Bay Compartment Adjacent to a Fuel Tank; Fire Detector and Fire Suppressor Installed within the Dry Bay Compartment.

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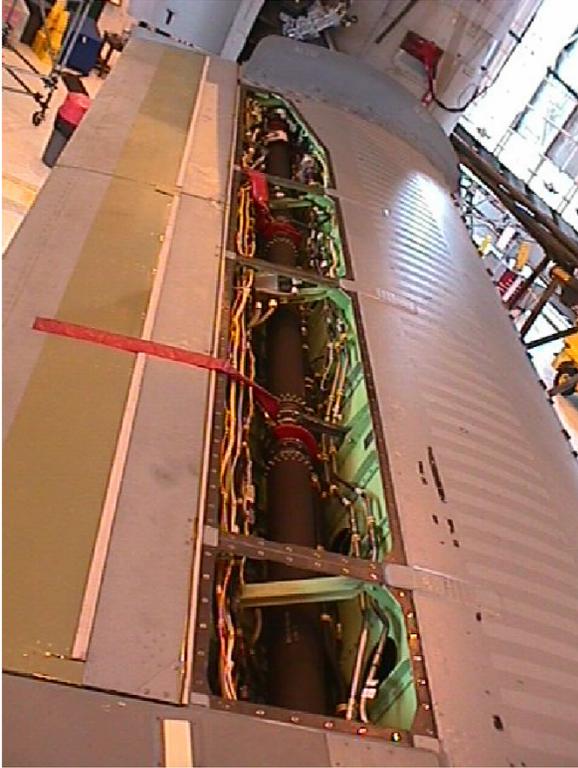


Figure 2-17. Top View of a Wing Dry Bay Containing Drive, Hydraulic, and Electrical Systems Components.

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Powder Panel

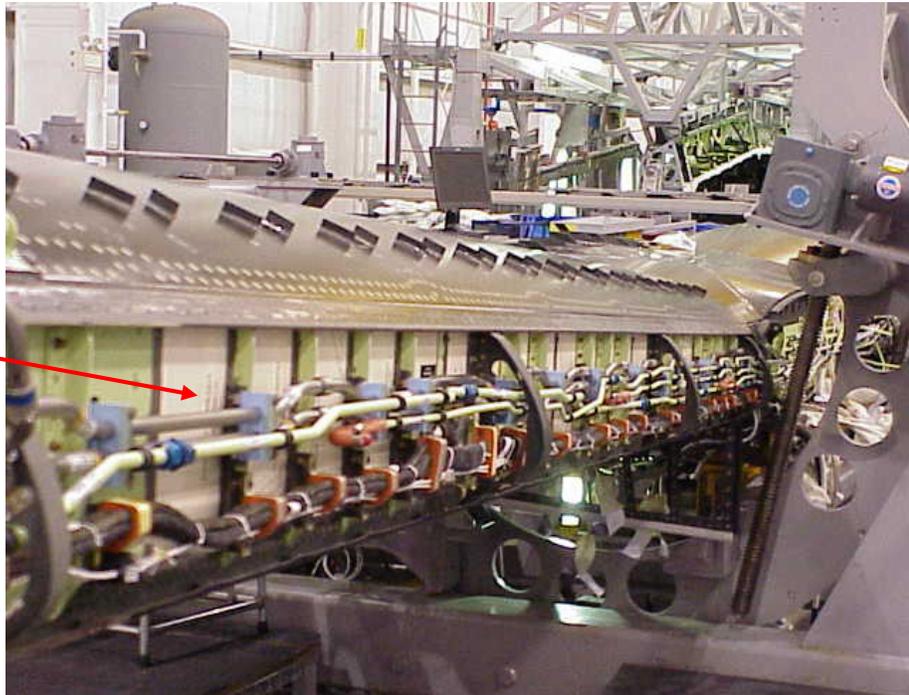


Figure 2-18. A Wing Leading Edge Dry Bay Containing Hydraulic and Electrical Systems Components, Leading Edge Structure Removed.

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There are active and passive approaches for suppressing dry bay fires. An active dry bay fire protection system must be capable of detecting a fire on a time scale of less than 10 ms and suppressing the fire within a few hundred milliseconds. In the truest sense, fielding of halon 1301 fire suppression systems for protection against ballistic threats in dry bay compartments on military aircraft has been limited: no DoD aircraft have such dry bay fire protection systems, but halon 1301 dry bay fire suppression is known to be installed on United Kingdom CH-47 Chinook helicopters.^{19, viii} Like halon systems designed to protect engine nacelles, the fire bottles used for dry bay fire suppression on the CH-47D helicopters also utilize a pyrotechnic device to rupture a burst disk on the bottle to effect suppressant release, but the bottles are automatically activated upon receipt of a signal from a pressure transducer – an initiator on the bottle also effects discharge.²⁰ Figure 2-19 depicts the components of this type of system, which is referred to as the COBRA system.^{ix} The bottles are much smaller than those fielded for nacelle fire suppression systems, and the time to discharge agent is on the order of 10 ms, compared to typically 1 s for a nacelle fire bottle.²¹ There are, however, DoD aircraft platforms for which halon 1301 is utilized to protect a powerplant or other type of compartment but in reality the protected compartment is a *quasi* dry bay compartment that is vulnerable to a ballistically induced fire; i.e., these compartments are either located adjacent to a fuel tank or they contain flammable-fluid-carrying components. For a few DoD platforms, those halon 1301 fire suppression systems are also intended to provide protection against dry bay fires.¹⁷

Passive techniques have been the predominant fire protection approach for aircraft dry bays on DoD aircraft, which have been implemented either by installation of a physical material to defeat the flame front, such as reticulated polyether foams and rigid foams, or by installation of panels adjacent to the compartment that, if ruptured by a ballistic projectile, release a powder suppressant to quench incendiaries released by the projectile. (In Figure 2-18, powder panels can be seen installed on the wing spar.) Performance limitations of this latter method were investigated under the NGP and resulted in development of new design techniques that dramatically improve powder panel protection capability.²² This is described further in Chapter 9.

2.2.4 Cargo Compartments

Cargo compartment fire suppression systems are typically installed on commercial transport aircraft, though there is at least one DoD aircraft equipped with this type of system, the C-5, an Air Force cargo transport aircraft.²³ Such systems are designed to provide a minimum knock-down concentration followed by a sustained minimum flooding concentration to suppress a fire that continues to burn until a safe landing is made. Such systems typically provide for 60 min of suppression capability. Thus unlike a fire suppression system designed to extinguish a nacelle, other powerplant, or dry bay fire, the protection philosophy for a cargo compartment is true fire suppression.

^{viii} In Reference 32 it is stated "...the F22 dry-bay protection scheme...incorporates multiple 'bottles', using halon 1301, to provide appropriate coverage." This statement infers that DoD USAF F-22 aircraft use halon 1301 for dry bay fire suppression. Space and electrical wiring provisions are installed on delivered F-22 aircraft in the event it is decided in the future to install dry bay fire suppression system components. Though the system was designed for use of halon 1301, research conducted for this Chapter confirmed (Reference 19) that, as of the writing of this book, no F-22 aircraft are fielded at this time with halon 1301, i.e., no dry bay fire suppression system components are installed.

^{ix} During research conducted for this book, it could not be confirmed if "COBRA" is an acronym, nor could it be confirmed why the system was assigned such a name. Literature provided by the system supplier indicates that it simply refers to the snake.

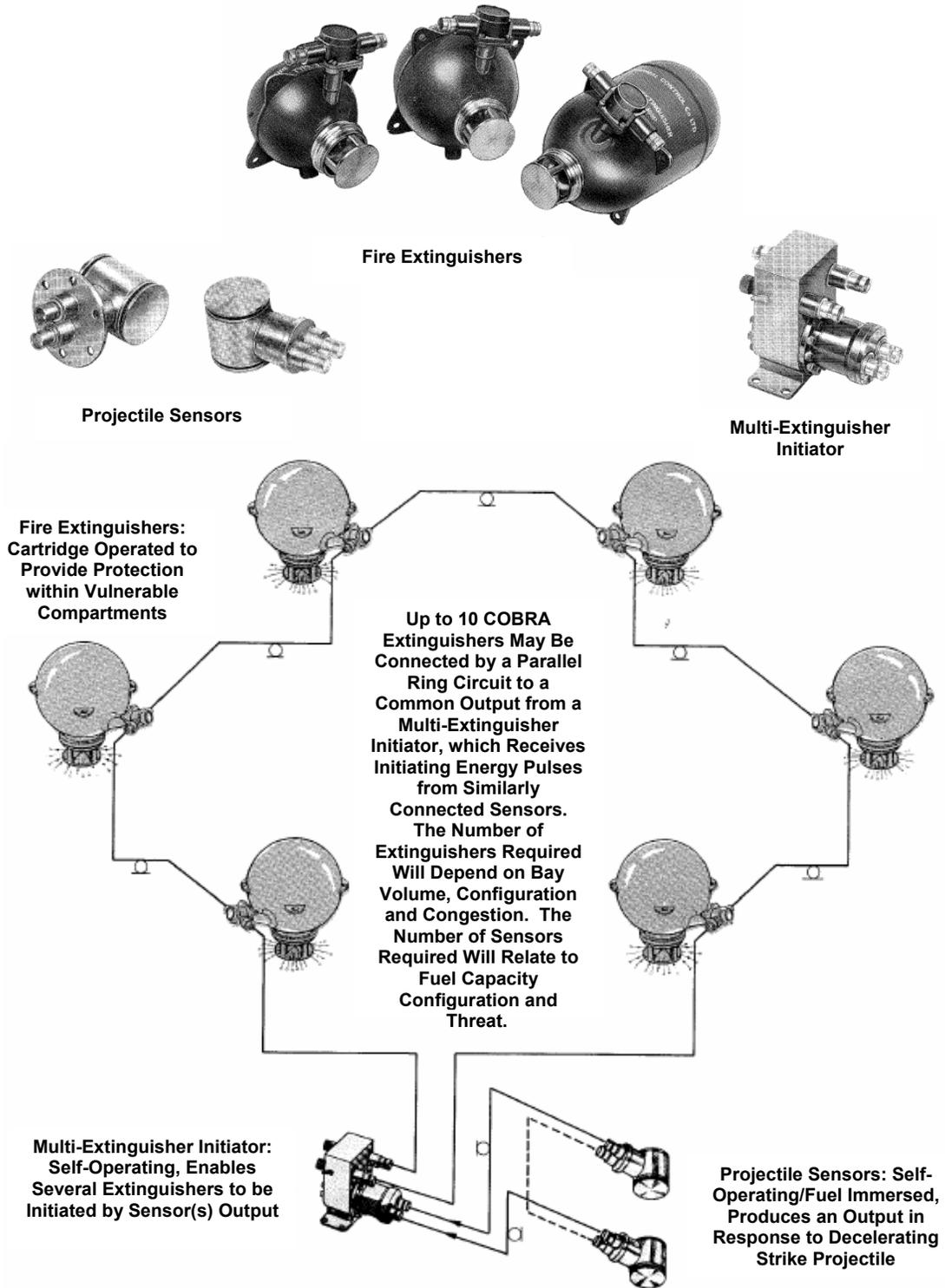


Figure 2-19. Non-DoD Aircraft Halon 1301 Dry Bay Fire Protection System.^{24,25}
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The diagram in Figure 2-20 is an example of a cargo fire suppression system installation on a transport aircraft. Such systems today utilize halon 1301 for fire suppression. In the case of an engine nacelle or APU compartment fire, the fuel source is shut off from either of those compartments prior to effecting agent discharge; whereas in a cargo compartment, the fire may be deep-seated and not removed from its flammable material source. The amount of agent installed to provide extinguishing capability to protect engine nacelles may be relatively small compared to that required for the cargo compartment. For example, on C-5 aircraft, there are four halon 1202 bottles (6.8 kg agent each) for engine fire suppression, whereas 17 halon 1301 bottles (31.75 kg each) are installed for cargo compartment fire suppression. Though the focus of the NGP did not include cargo compartment fire suppression, extensive research and testing into application of halon alternatives for these compartments has been conducted by the FAA's Fire Safety Branch at the Hughes Technical Center.

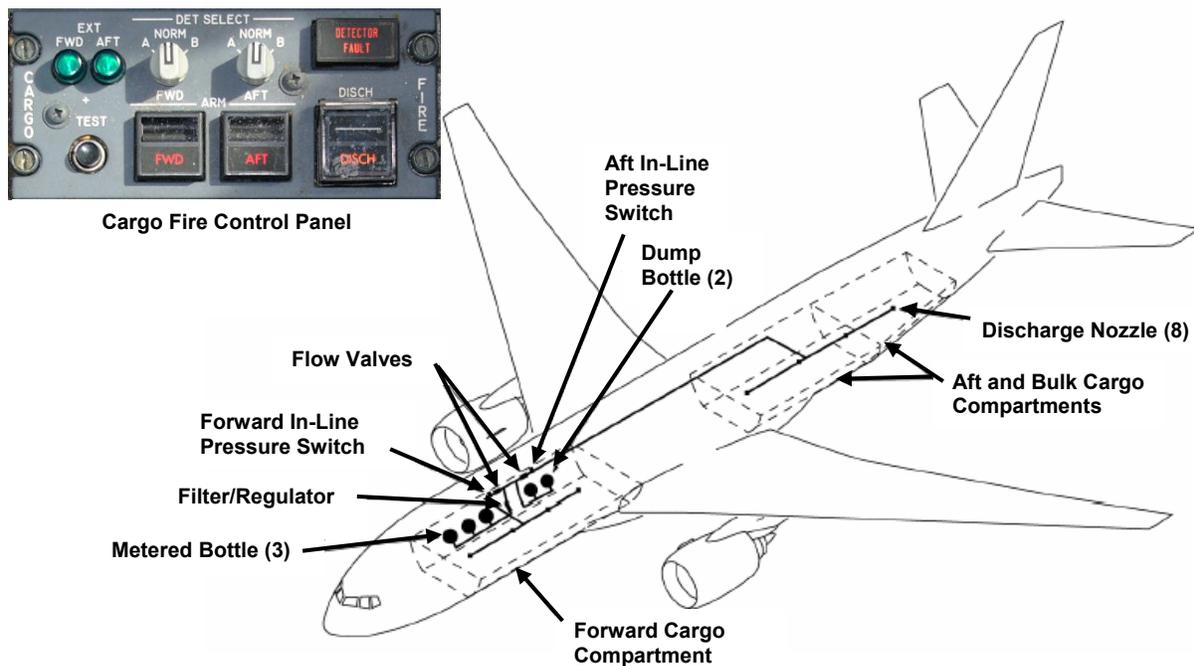


Figure 2-20. Diagram of a Cargo Fire Suppression System Installation on a Transport Aircraft.^{26,27}

(Photograph of panel reprinted with permission of the author.¹⁵)

2.2.5 Other Compartments

During the development of an aircraft design, safety hazard and vulnerability analyses will identify potential fire threats aboard the aircraft in compartments other than powerplant-type, dry bay and, if applicable, cargo compartments. (The vapor space within fuel tanks is a separate case that is described in the next section.) Design solutions are then pursued to mitigate the likelihood of a catastrophic fire and implement ballistic vulnerability reduction measures if needed, which typically considers isolating potential ignition sources from flammable fluid or other flammable sources. If the risk for fire cannot be mitigated to an acceptable level, a dedicated fire suppression system will be installed to protect the compartment (or if not, the risk is accepted). Examples of such compartments on DoD aircraft are, or

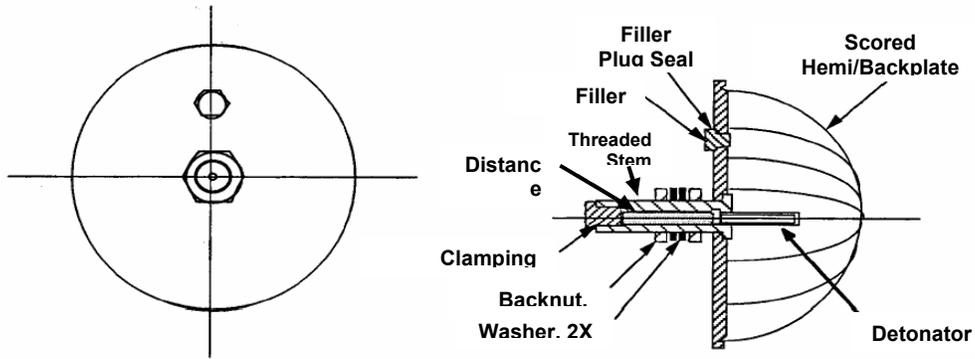
were, the fuselage fire protection system installed on F-111 aircraft to protect the cheek and stabilization areas and weapons bay, the C-5 avionics compartment fire suppression system, and the A-6E/EA-6B aft equipment bay fire protection system. All are, or in the case of retired aircraft were, halon 1301 systems. The certification requirement for engine nacelle halon 1301 fire suppression systems was applied to certify the A-6E/EA-6B aft equipment bay system, and that requirement was likely applied to certify the other systems on the C-5 and F-111. Thus it follows that certification requirements developed for any agent or technology developed by the NGP for engine nacelle fire suppression would likely become certification benchmarks, or likely starting points for such benchmarks at minimum, for systems installed to protect most compartments on aircraft except for dry bays and cargo compartments. The exception for dry bay compartments is that although viable technologies for dry bay protection were developed under the NGP, certification for those systems will likely still be accomplished through live fire ballistic testing, as is done currently in accordance with live fire testing legislation. The exception for cargo compartments is the unique knock down and flooding suppression requirement, which was not addressed by the NGP.

2.2.6 Fuel Tank Ullage

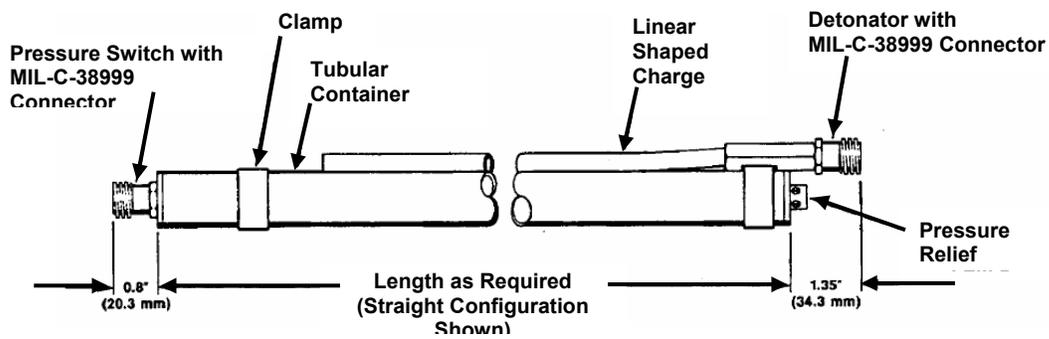
In contrast to dry bay compartments, fuel tanks are sometimes referred to as wet bays. The fuel tank ullage is that portion of the fuel tank volume not occupied by liquid fuel but contains an air and fuel-vapor mixture. From an operational safety perspective, though the potential for a fuel tank fire/explosion hazard exists on every aircraft due to a system or component malfunction or failure, safety has not been the requirements impetus for implementing ullage protection on DoD military aircraft. (Relatively recent activity has been conducted to reassess and develop such protection for commercial aircraft.^{28,29,30}) The case for military aircraft is primarily, like dry bay fire protection, one of vulnerability reduction for combat survivability. Though there are several military platforms that incorporate some type of active ullage protection system, only three DoD aircraft have utilized halon 1301 to provide fuel tank inertion, the USAF F-16 and F-117 aircraft and the United States Navy (USN) A-6E, which is no longer in service.

No research was performed under the NGP to identify or develop potential alternatives to halon 1301 for fuel tank inerting. However, the NGP did compile and appraise techniques for fuel-tank ullage suppression of fire and explosion, which had been previously developed and fielded.³¹ That work identified the following technologies that can be installed within the ullage itself to discharge a suppressant upon detection of the fire/explosion flame front: scored canister system (SCS), linear fire extinguisher (LFE), and the Parker Reactive Explosion Suppression System (PRESS). Existing design guidance on fuel system fire and explosion suppression also identifies an additional technology, the Fenwal cylindrical suppressor.²⁰ Of these, only the cylindrical suppressors utilized a halon fire suppressant (halon 1011) and were fielded on several aircraft, one of which was the USAF F-105. These suppressors were also utilized on some commercial transport aircraft (Boeing 707 and 747-100 models) in surge tanks to prevent ground fires entering the wing. These systems were designed to provide fire protection, not explosion protection.^{32, x} The SCS utilized pentane to create a fuel-rich environment and was also fielded on several platforms. The PRESS technology used water plus a brine additive to reduce the water's freezing temperature below -54 °C (-65 °F) and has not been fielded. Figure 2-21 illustrates the SCS, LFE, and cylindrical suppressor devices.

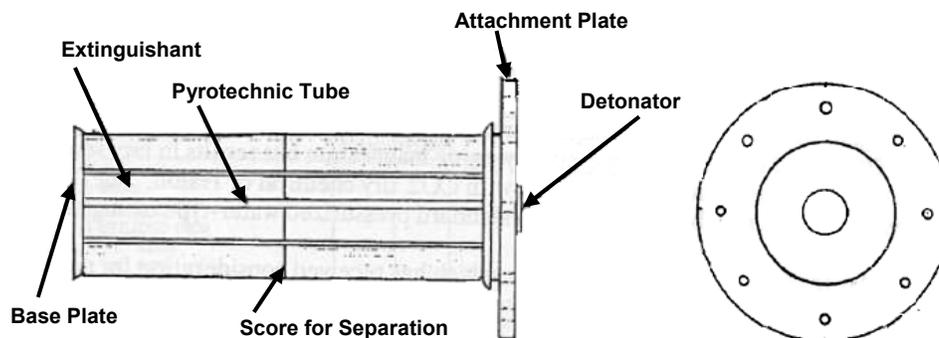
^x Reference 32 suggests that this type of fire suppression was installed to protect against fires initiated by lightning strike.



(a) Scored Canister³¹
(Reprinted with Permission of Kidde Aerospace.)



(b) Linear Fire Extinguisher³³
(Reprinted with Permission of Meggitt Safety Systems, Inc.)



(c) Cylindrical Suppressor²⁰
(Reprinted with Permission of Kidde Aerospace.)

Figure 2-21. Illustration of Ullage Fire/Explosion Protection Devices.

An additional technique identified during the NGP investigation was the nitrogen-gas-inflated ballistic bladder (NIBB) system, a double-walled fuel cell that is filled with nitrogen. Interestingly, this technique requires an on-board inert gas generation system (OBIGGS) to provide the nitrogen gas. The NIBB system has not been fielded on any DoD aircraft, whereas OBIGGS itself is fielded on several aircraft (C-17, MV/CV-22, F-22, UH-1Y, AH-1Z, and AH-64) to provide nitrogen-enriched air to inert the fuel tank ullage. OBIGGS is being considered for the USN's multi-mission maritime aircraft, to be designated as the P-8 aircraft.³⁴ The C-5 and the SR-71 had implemented liquid nitrogen inerting systems for ullage protection. In the SR-71 aircraft, a supersonic aircraft, the inerting system was implemented because of the high skin and fuel tank wall temperatures generated during supersonic flight, i.e., aerodynamic heating effected by supersonic flight could cause walls to become an ignition source for fuel vapor in the ullage.³⁵ The use of nitrogen as an inerting and fire suppression agent is described later in this chapter.

The NGP investigation classified the various ullage protection techniques into three categories: active (system is always providing a required level of protection), reactive, and passive. Active techniques fielded currently are halon-based inerting and OBIGGS. Engine exhaust has also been used as an ullage inerting agent - the Russian-built Ilyushin IL-2 Sturmovik cooled and piped engine exhaust gases into its fuel tank ullage spaces.⁴ Some earlier DoD aircraft also incorporated ullage inerting using exhaust gas (B-50 aircraft) as well as CO₂ and dry ice (B-47 and B-36 aircraft), but these techniques were discontinued because of technical problems.³⁶ Reactive techniques would integrate a detection system and a suppression system utilizing the LFE, SCS, PRESS, or cylindrical suppressor technologies. Passive techniques involve installing material within the fuel tank itself to prevent an overpressure by extracting heat from a flame front. There are primarily two materials that have either been fielded or at least have been demonstrated by the DoD as viable for providing passive fuel tank ullage fire protection: reticulated (porous) polyurethane foam and aluminum mesh. Polyurethane foam has been used in numerous DoD platforms for years (A-7, A-10, F-15, F/A-18, C-130, and P-3), whereas aluminum mesh has not been implemented on DoD aircraft.

During the NGP, non-NGP investigations were performed into the use of trifluoroiodomethane (CF₃I) as a replacement for halon 1301 in the F-16 fuel tank inerting system. A diagram of the F-16 inerting system is shown in Figure 2-22 and is a typical halon 1301 inerting system design implementation. The system also includes a 400-watt heater to maintain a constant halon reservoir pressure over the entire operating temperature envelope for the aircraft, as the reservoir was located in a wheel well area. A heater had also been part of the inerting system installed on A-6E aircraft.

Preliminary analysis and testing indicated CF₃I was a promising alternative to halon 1301, as it was initially concluded that only minor airframe system modifications would be required.^{37,38} However, CF₃I had been previously removed from consideration for use in engine nacelle, APU, and dry bay applications on DoD aircraft due to toxicity and materials compatibility concerns, as well as due to its relatively high boiling point.^{xi} Subsequent review later concluded that CF₃I was inadequate as a replacement for halon 1301 in the existing F-16 system due to its higher boiling point and resultant reduced delivery pressure at low temperatures.³⁹ Additional conclusions were that:

^{xi} CF₃I is listed as one of many acceptable halon alternatives for use in unoccupied spaces on the Environmental Protection Agency's (EPA) Significant New Alternatives Program (SNAP) list, and a minimum performance standard of 7.1 % volumetric concentration is being developed for its use for nacelle fire suppression in commercial aircraft, as determined under the Engine Nacelle Halon Replacement Program conducted by the FAA. That program also developed minimum performance standards for use of HFC-125 (17.6 % volumetric concentration) and FK-5-1-12 (6.1 % volumetric concentration). Boiling points for HFC-125 and FK-5-1-12 are -48 °C and 49 °C, respectively.

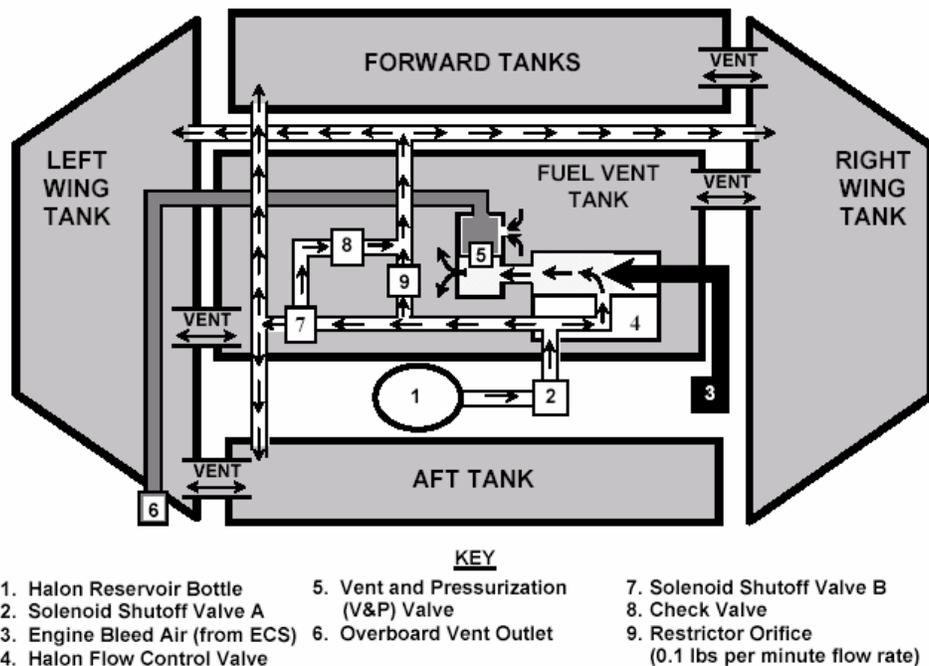


Figure 2-22. F-16 Aircraft Inerting System Diagram.⁴⁰

- More flight qualification testing would be required on the materials compatibility of CF₃I before it could be recommended as a replacement for halon 1301. CF₃I is more chemically reactive than halon 1301, which could lead to metal corrosion or elastomer failure. It was indicated that it may be possible to specify materials that could be used in service with CF₃I after such testing.^{xii}
- CF₃I is more toxic than halon 1301. It was indicated that under equivalent operational conditions, it would be considered unwise to replace a chemical with one that is 20 times more toxic, and that more rigorous toxicity testing of CF₃I would provide a more quantitative estimate of its toxicity in realistic exposure scenarios.^{xiii, xiv}

^{xii} During design evolution of an aircraft and its systems and subsystems, assessment of materials compatibility is typically completed well prior to conduct of flight qualification testing. The rationale for recommending materials compatibility evaluation for CF₃I as part of flight qualification testing was that it could degrade the fit, form, or function of any of the components that it contacts, and that it could introduce a contaminant or a degradation product into the fuel tank and fuel that produces damage. Due to the number of components involved, the extent of attack required to interfere with the operation of different components could vary. Thus it was assessed that it is virtually impossible to account for all possibilities in a laboratory and that engineering testing and evaluation would be required before CF₃I could be fully qualified for use.

^{xiii} An aircraft fuel tank as well as an engine nacelle or an APU-type compartment is a normally unoccupied space. For such spaces, this means it is permissible to use fire suppressants whose design or certification concentrations that are in excess of the Lowest Observed Adverse Effect Level (LOAEL).

^{xiv} The LOAEL, which represents the volumetric concentration of a substance that can induce cardiac sensitization in testing using beagle dogs, is reported for halon 1301 and CF₃I as 7.5 % and 0.4 %, respectively. The 20 factor was derived by the ratio of the halon 1301 LOAEL to the CF₃I LOAEL (i.e., 7.5/0.4). Though cardiac sensitization LOAEL was one of several CF₃I issues reviewed, the fielding of a suppressant whose LOAEL is significantly below a system certification concentration is not without precedent in the DoD. USAF C-130J and USN KC-130J aircraft, which are still being procured as of the

- The ODP of CF₃I is highly dependent upon the altitude and latitude at which it is released. It was calculated that CF₃I usage onboard an F-16 aircraft could be between 13 % and 167 % as damaging to the ozone layer than use of halon 1301, or, in other words, ozone depletion from F-16 application of CF₃I could be as small as one-eighth that of halon 1301 (at lower altitudes) or as large as one and two-thirds times as damaging as halon 1301 (at higher altitudes). However, even for conservative choices, CF₃I use onboard an F-16 would be a Class I ozone-depleting substance if significant amounts are released above 6.1 km (20,000 ft), and the US Clean Air Act bans use of Class I substances.

Subsequent NGP modeling of ODP associated with the use of CF₃I in engine nacelle and APU-type applications is described in Chapter 7. This study was conducted using the same chemical transport model, but updated with the latest representation of atmospheric chemistry and dynamics. The results of the modeling indicated the ozone depletion effects would not be significant for CF₃I use in engine nacelle and APU-type applications.⁴¹

2.3 TYPES OF FIRES EXPERIENCED

Both occurrence and suppression of fire on board an aircraft are probabilistic. Although obvious, assessment of such probabilities plays a role in determining whether a fire suppression system is implemented, or if implemented, the type of system, active or passive, and if implemented whether that system will provide protection under all flight and mission conditions. The level of protection implemented then becomes a risk trade for the program manager(s) responsible for the development, production, and fielding of a military aircraft.

Such trades receive additional attention from program managers, since they are most often applied when considering the need to implement fire suppression systems beyond those normally required by an aircraft specification for safety (i.e., engine nacelle and APU compartment) or those necessary to achieve desired vulnerability reduction (i.e., dry bay compartments). In short, such trade efforts are difficult to sell to a program manager, since they increase aircraft weight, cost, and complexity. It is no surprise that this would be case, since during the formulation of the NGP strategy it was found that majority of the types of fires experienced in DoD military aviation, as listed in Table 2-2, were types related to engine nacelle and dry bay compartment fires. This provided the NGP with an overarching view from which to investigate further the characteristics of fires within engine nacelles and dry bay compartments.

The primary aircraft design considerations are weight, performance, and cost. Key aircraft performance parameters (KPPs) include range, speed, and drag, all of which are impacted by weight. The aircraft program manager(s) and aircraft design engineers are always seeking the lowest weight possible for any system on the aircraft. For example, established fire suppression system specifications may require a redundant nacelle fire suppression capability. The reality may be that the aircraft just cannot physically accommodate the installation of an additional fire suppression agent container, or a risk trade analysis may be performed to assess the risk of not implementing the additional bottle, which will include a probabilistic analysis for failure to suppress the fire leading to loss of the aircraft and fatalities (in other words, what is the risk of not implementing redundancy to save weight). If it is decided to accept that

writing of this book, utilize halon 1211 for engine nacelle and APU fire suppression. The LOAEL for halon 1211 is 1.0 %, or 7.5 times higher than the value for halon 1301. Chapter 6 provides additional information regarding the cardiac sensitization protocol and the development of physiologically-based pharmacokinetic (PBPK) modeling of potential human exposure to halon alternative suppressants. Halon 1211 is also a Class I Ozone Depleting Substance (ODS).

risk, the requirement to provide the redundant capability will be removed or waived. Vulnerability analyses that effect whether or not dry bay and ullage fire protection are implemented is also probabilistic – analysis will assess probability of kill (aircraft loss) given a hit. Vulnerability reduction techniques are assessed for weight and performance, with performance assessed both from the vulnerability reduction perspective and aircraft performance perspective (for example, is it necessary to design a fuel cell so that all sides are completely self-sealing, or can weight be reduced by electing to employ self-sealing only on those sides or a portion of those sides having the greatest vulnerability).

Table 2-2 Tabulation of Aircraft Fire Types.⁴²

Service	Fire Type	Location	Fuels	Suppression Time	Fixed System (F) or Hand-Held (H)	Occupied Compartment at Discharge (Y or N)
US Army	Fuel spray	Engine nacelle	JP-4 or JP-5	seconds	F	N
US Army	Stack fire	APU exhaust	JP-4 or JP-5	seconds	F	N
US Army	Turbine jet fire	Helicopter engine nacelle	JP-4 or JP-5	≈ 5 s	F, H	N
Tri-Service	Explosion	Dry bay	JP-8, hydraulic fluid	≈ 10 ms	F	N
Tri-Service	Turbine jet fire	Engine nacelle	JP-4, JP-8	≈ 5 s	F	N
USAF	Electrical	Compartment	Plastics	< 30 s	H	Y
USAF	Wall fire	Cargo bay	Paper, plastics, chemicals	≈ 5 min	F (H)	Y
USN	Fuel spray	Engine	JP-4, JP-5, JP-8, hydraulic fluid	seconds	F	N
USN	Fuel spray	Crew compartment	JP-4, JP-5, JP-8, hydraulic fluid	< 30 s	H	Y
USN	Electrical	Crew compartment	Insulation, plastics	< 30 s	H	Y
USN	Turbine jet Fire	Engine nacelle	JP-4, JP-5, JP-8, hydraulic fluid	10 s to 20 s	F	N
USN	Rapid growth	Dry bay	JP-4, JP-5, JP-8, hydraulic fluid	≈ 50 ms	F	N

The relevance of trade analyses that evaluate requirements, weight, and performance relates directly to the residual fire threat for the aircraft after all design considerations have been addressed to the extent possible or practicable, e.g., drainage provisions for leaked flammable fluid, separation of fuel sources from potential ignition sources, tolerance of components to fire or hardening, and fire containment, which themselves are subject to weight trades prior to or in consideration with implementing fire suppression. As a precursor to its research activities, the NGP conducted a review to characterize the nature, frequency, consequences, and severity of fires for which halon-based fire suppression systems have been fielded on DoD aircraft.⁴³ With the knowledge acquired from this review as well as from various studies conducted during the TDP, studies performed coincident with the NGP and presented at Halon Options

Technical Working Conferences (HOTWC), and continuing work by the FAA's Fire Safety Branch and the International Halon Replacement Working Group (IHRWG), the characteristics of all types of aircraft fires have been described.^{xv} The remainder of this chapter discusses fire characteristics for areas specifically addressed by the NGP, engine nacelles, APUs and dry bay compartments, plus it includes a similar discussion on ullage fire/explosion characteristics.

2.3.1 Safety-related Fires

As described in the beginning of the chapter, an aircraft fire is deemed a safety-related fire when it results from component failures, which may be due to inadequate design, a mechanical failure mechanism such as fatigue, or maintenance error, and results in either a flammable fluid contacting an always-present ignition source, e.g., a hot engine case, or the failures themselves provide both the flammable fluid and the ignition source. These types of fires occur in flight or on the ground. The two most common types of fire hazard in the engine nacelle are a direct consequence of the means of fuel delivery and the failure mode that permits fuel to leak, i.e., either a spray fire or a pool fire.¹¹ A mechanical failure in the component path within the nacelle that provides fuel to the engine can either result in a fuel spray or the pooling of fuel. Examples of these types of failures are a cracked fuel line, or a fuel line or system component that was improperly installed and allows fuel to leak. An additional fire hazard associated with the aircraft engine nacelle is that even after extinguishment is achieved, a strong potential exists for reignition of the fire from hot surfaces on the engine. Hot surface reignition remains a threat as long as fuel vapor and air can come in contact with sufficiently hot surfaces. This concern prevails in flight as well as on the ground during or after engine shutdown. After engine shutdown, for a brief period, the engine case temperature and nacelle free volume temperature can actually increase due to engine temperature soak-back effected by removal of ventilation airflow that would occur with the engine operating. It is possible then that a small leak, which does not result in an in-flight fire, could result in a nacelle fire on the ground during engine shutdown. If the compartment is wetted with the flammable fluid, or if the fluid has pooled, the resulting ground fire event can impart extensive damage.

Given that dry bays may contain flammable fluid carrying components, such as fuel and hydraulic lines and hydraulic fluid reservoirs, and potential ignition sources such as bleed air ducts, safety-related fire events may also occur in these compartments. Even though the probable majority of dry bay fires over the lifetime of a particular military aircraft will result from ballistic threats, other events can result in a dry bay fire, such as an overheated electrical generator, arcing generated by failed electrical circuits or wiring, or damage induced by some other form of impact such as a bird strike.

In-flight Fires

In-flight engine fires can result in catastrophic loss of an aircraft and fatalities if the aircraft has only a single engine, or if there are multiple engines and the fire goes undetected and suppression is not attempted until the fire has effected damage to the aircraft that results in loss of lift or thrust or the aircraft fails to execute a safe landing, or if the nacelle fire suppression system cannot suppress the fire even if activated immediately after a fire warning is provided to the pilot and there is subsequent catastrophic damage or failure to execute a safe landing. A qualitative assessment of pilot reaction was conducted by

^{xv} As of the writing of this book, information related to work conducted by the FAA Fire Safety Branch and the IHRWG can be found at <http://www.fire.tc.faa.gov>.

the NGP and estimated that 95 % of the time pilot reaction was characterized as *normal*, meaning that the pilot response followed typical emergency procedures for effecting agent release without delay. After receipt of a fire warning, the pilot isolated the affected compartment to remove fuel flow to that compartment, armed the fire suppression system, confirmed that the fire warning persisted and had some secondary indications of the fire condition, and then discharged the suppressant into the compartment.⁴⁴ During the TDP, extensive review of fire incident and mishap data was conducted to evaluate effectivity of currently fielded halon 1301 fire suppression systems aboard USN aircraft.^{45,46} That review revealed that 55 % of fixed-wing fire events occurred in flight, yet for rotorcraft only 35 % had occurred in flight. An additional significant finding was that in-flight effectivity of the nacelle halon fire suppression systems was 76 % for fixed-wing aircraft, yet just 47 % for rotorcraft. It is important to bear in mind that these percentages are overall numbers for each of the aircraft types. However, they infer that the different nature of fixed-wing and rotorcraft designs and the missions these aircraft are required to fly influence different fire threats from an operational safety perspective.

The most surprising finding in these studies was that related to the redundant fire suppression capability on most rotorcraft and several fixed-wing aircraft. For rotorcraft, it was found that this capability was not utilized frequently, and when utilized it was successful in suppressing fire less than 10 % of the time. Usage on fixed-wing aircraft was also infrequent, except on P-3 aircraft.⁴⁷ In those cases, the reserve capability was successful 67 % percent of the time. The rationale derived from the rotorcraft events was that as a fuel-fed fire continues to grow after the first discharge, it is not likely that there would be successful suppression by the time the pilot effects the second discharge, which is delayed since the pilot has spent time coping with the emergency.⁴⁷ This rationale has been applied to support implementation of non-redundant halon-alternative nacelle fire suppression capability on the USN UH-1HY and AH-1Z rotary aircraft models. (However, no rationale is provided in the USN fixed-wing analysis that describes the 67 % success rate of the redundant capability on P-3 aircraft.) Contrasting the USN effectivity analysis was analysis performed by the U.S. Army, where frequency of use and effectivity of the redundant fire suppression capability on their rotorcraft between 1985 and 1995 indicated an overall higher percentage of in-flight nacelle fires on aircraft with nacelle fire suppression systems and a much higher effectivity of the redundant fire suppression capability.^{48,49} Given that Army and Navy analyses included similar model rotorcraft, these outcomes suggest that service-specific missions may have an impact on nacelle fire occurrence and the ability to suppress nacelle fires for similar aircraft models. As of the writing of this book, it is planned to revisit and update the U.S. Army and USN data in support of halon alternative nacelle fire suppression efforts under a joint U.S. Army-USN program for H-60 model helicopters (i.e., U.S. Army Blackhawk and USN Seahawk helicopters).⁵⁰

Ground Fires

Aviation mishap data from the DoD safety centers typically classify mishaps by whether the mishap occurred in flight; if not in flight then whether intent for flight existed; or whether the mishap occurred on the ground and there was no intent for flight, such as during a ground maintenance engine turn operation. Fire mishaps that fall into the intent-for-flight-existed category typically occur on the ground (e.g., a rotorcraft engine nacelle fire that occurs during rotor turns prior to takeoff). Also, fires that occurred on aircraft while on a ship's deck were also considered as ground fires. Both nacelle fires as well as internal engine fires have been experienced within the DoD. An internal engine fire can occur during startup or shutdown and may be a result of improper procedures, a component failure, or severe ambient conditions such as high winds while at sea. In the case of improper starting procedures or severe ambient conditions,

the engine does not ignite properly during startup and excess fuel is dumped into the engine combustor. The fuel can be blown into the turbine and tailpipe, subsequently igniting. In the case of a mechanical failure, a fuel line may rupture, a pressure and drain valve may fail, or the engine bearings may fail. Fuel can accumulate in the combustor, turbine, or tailpipe and may subsequently ignite. These internal fires are colloquially referred to as tailpipe fires.⁵¹

The reviews described in the previous paragraph revealed that 65 % of rotorcraft fires occurred on the ground, whereas for fixed-wing aircraft this number was 45 %, and the aggregate effectivity of the nacelle halon fire suppression systems was similar for each aircraft category: 65 % for fixed-wing aircraft and 64 % for rotary aircraft. APU fires occurred primarily on the ground, and their frequency of occurrence was noted to be far less than that for nacelle fires. Effectivity of halon fire suppression in APU compartments was even higher, though fire events were indicated for two aircraft platforms only – 100 % effectivity was found for P-3 APU fire suppression, and 75 % for H-53 APU fire suppression. Similar to ground nacelle fire suppression events, there is reduced or minimal airflow within an APU compartment during a fire suppression event.

Effectivity vs. Optimization vs. Over-design

The extension of the preceding to the NGP relates to its efforts in the development and validation computational fluid dynamics (CFD) models for nacelle fires and nacelle fire suppression. Those efforts considered the complex physics of fire, suppressant discharge and transport, the effects of compartment clutter on transport and distribution, and the effects of ventilation airflow on the behavior of fire and suppressant distribution. That effectivity of current nacelle halon fire suppression systems would be lower for in-flight events correlates with the NGP focus to develop CFD modeling capabilities to optimize nacelle fire suppression system designs for the dynamics of in-flight conditions. The need for a design optimization capability cannot be overstated when considering that even with halon 1301 as the suppressant and *normal* pilot reaction to effect agent discharge, the overall effectivity of halon 1301 nacelle fire suppression systems was still less than 80 %. It is this dichotomy that challenges an overarching assertion formulated during the TDP and that has prevailed during the NGP that halon 1301 nacelle fire suppression systems are over-designed. Rather, whether a system is either over-designed or not optimized is more appropriately assessed on an aircraft-by-aircraft basis. In any event, the CFD capability developed under the NGP provides a tool for use in conducting such assessments.

2.3.2 Ballistically-induced Fires

Fires that relate to aircraft survivability are those that are ballistically induced, usually during enemy combat. That combat projectiles could induce fire within an aircraft dry bay or fuel tank ullage with catastrophic results has never been unique to U.S. military aircraft. Imperial Japanese Navy design policies during the later part of World War II not only required carbon dioxide (CO₂) for nacelle fire suppression, but also for protection of fuel cells and alcohol tanks on aircraft; and structural spaces surrounding fuel cells were to be air tight, structural and weight limitations permitting. The CO₂ systems protecting fuel cells were to be automatic, and because of combat experience in which hits on aircraft with alcohol tanks resulted in fires, an automatic CO₂ system was to be implemented for the spaces surrounding the alcohol tank, i.e., a reactive dry bay fire protection system; a pilot-activated system was to be implemented for discharge into the tank itself.⁵² There is evidence that a concept for implementing active dry bay fire protection was being pursued by the Imperial Japanese Navy at the latter stage of

World War II (Figure 2-23) and was planned to be an automatic system utilizing CO₂ as the fire suppression agent. What was being investigated then still applies today, in that aircraft remain vulnerable to ballistically-induced fires in dry bays and in the fuel tank ullage. These types of fires are summarized below without the intent of describing all of the damage effects that could be effected by a ballistic projectile or without describing the functioning characteristics of various projectiles. Though it is possible for a ballistic projectile strike into another compartment to effect a fire, e.g., within an engine nacelle, dry bays and the fuel tank ullage remain the most vulnerable to ballistically-induced fires. Taking into consideration that a delay of only several hundred microseconds may occur before an HEI projectile functions after impact, the response time of any reactive ullage or dry bay protection system to detect the combustion event is typically on the order of microseconds. Whether this delay is longer is a function of several variables, including the thickness of the aircraft material that the projectile must penetrate and impact obliquity angles.⁴³

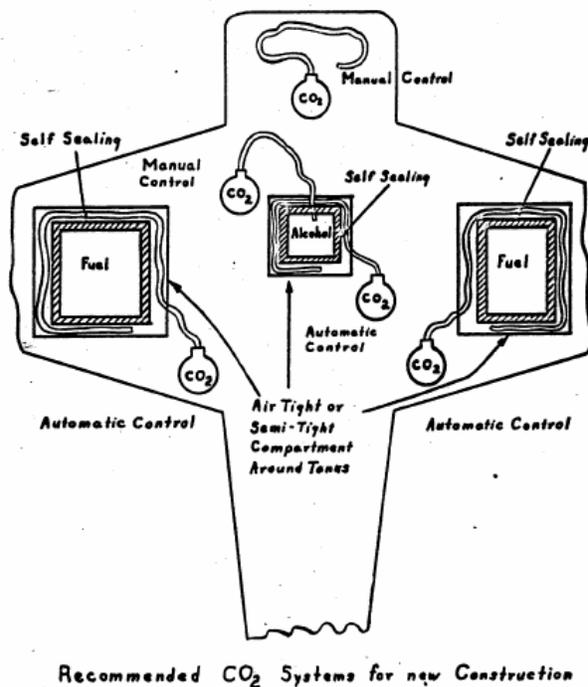


Figure 2-23. Imperial Japanese Navy Dry Bay and Ullage Fire Suppression System Concept, Late World War II.⁵²

Dry Bays

During aircraft dry bay live fire testing, the effects of wet-to-dry and dry-to-wet penetrations into the aircraft are characterized as follows. The wet-to-dry penetration is one in which the projectile first penetrates a fuel cell, travels through the fuel, and exits into dry bay. As the ballistic projectile travels through the fuel it creates an overpressure in the fuel cell. During exit, fuel may either leak or mist and can be ignited by hot spall; by pyrophoric, incendiary or tracer components of the projectile; or by an on-board ignition source, such as hot gases from penetrated bleed air lines, hot metallic surfaces (e.g., surfaces of bleed air or other hot gas ducts), or arcing electrical lines. The dry-to-wet penetration is one in which the projectile first enters into the dry bay and then penetrates either a fuel cell or a flammable fluid carrying component resulting in either leaking or misting fluid, or spall from the projectile will

damage such components sufficiently to effect a leak or mist, particularly if the damage to a system or component is one that operates at high pressures. In either case, fluid entering the dry bay can be ignited.

Ullage

Various ideas to describe the ullage combustion by an electrical discharge are all based on the notion of a critical flame kernel or bubble. Experiments reveal that the initial disturbance created by the electrical discharge must exceed a minimum volume in order for the flame to become self-sustaining. Experimental observations show that this volume is often toroidal in shape for a spark generated between bare electrodes. Ullage ballistic testing performed by the USN described the ullage combustion process as two-stage, free-radical, branched-chain reactions, depending upon the ignition source. For a spark ignition source that is produced by a component failure within the ullage, it was described that in the first stage a *seed* of free radicals is produced, which in turn produces a blue flame front throughout the ullage fuel vapor/air mixture. That mixture then transitions rapidly to the second stage in which free radicals react with one another and produce a stable though accelerating set of molecules that are the products of combustion and can lead to explosion. This process can take place within a few hundred milliseconds, as depicted in Figures 2-24 and 2-25.^{xvi} The functioning of an HEI ballistic projectile within the ullage will cause a violent reaction that, instead of a two-stage reaction, directly produces the products of combustion.⁵³

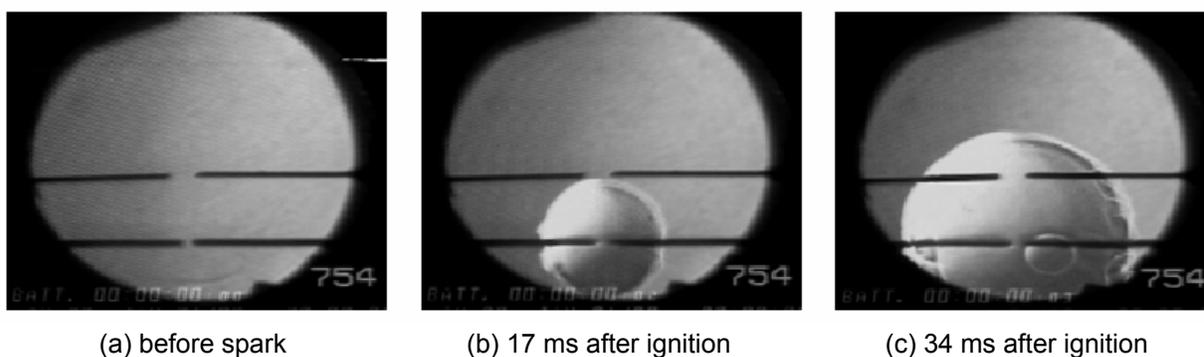


Figure 2-24. Ignition and growth of a flame in 7 % H₂, 1.4 % C₃H₈ Jet A Simulant Mixture at 295 K (22 °C) and 84.1 kPa (0.83 atm).⁵⁴

2.3.3 Spray Fires

A cracked high pressure fuel, lubricant or hydraulic fluid line, or a cracked flammable fluid system component, such as a motor housing, can supply a steady spray of fuel for a fire stabilized behind obstacles in an engine nacelle. Small droplets quickly evaporate, and the momentum from the spray efficiently entrains the air necessary for combustion. The fuel-air mixture is ignited when it contacts a hot surface, or the mechanism that effected the failure mode can provide the ignition source, such as arcing onto a flammable fluid line as can occur when an electrical harness chafes against the line.

^{xvi} For the process depicted in Figure 2-25, the spark source was a J-57 engine igniter that produced a spark from a capacitance discharge of 19 J of energy. The photographs in Figure 2-25 were provided by the Naval Air Warfare Center Weapons Division, Aircraft Survivability, and are reprinted with permission of the Naval Air Systems Command.

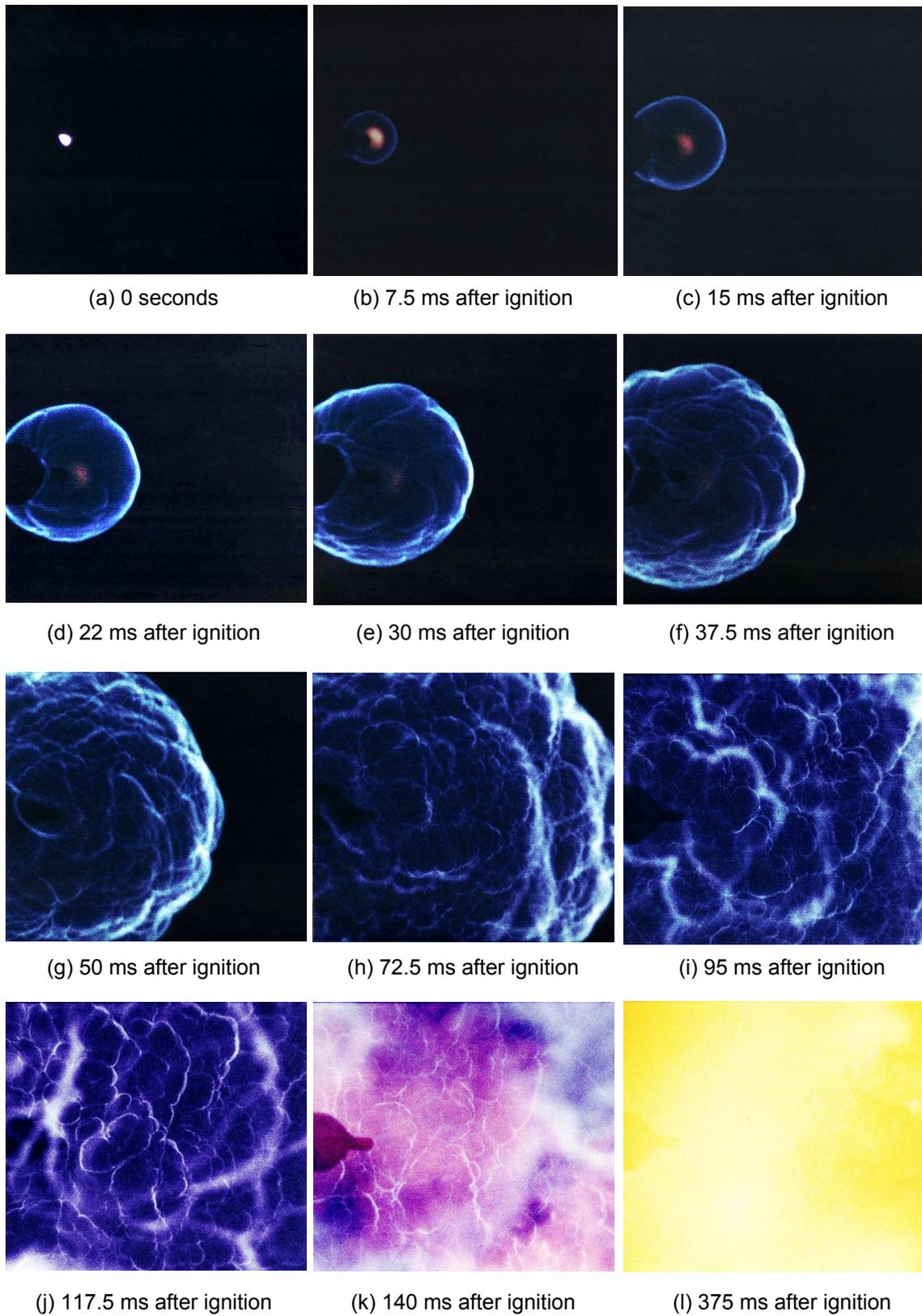


Figure 2-25. Spark-Initiated Ullage Combustion Process.

Extinguishment of the burning spray can occur if a critical amount of suppressant entrains into the combustion zone, or if the flammable fluid flow is cut off, thereby reducing the pressure effecting the spray, and the combustion is allowed to starve, or the combination of reduced flammable fluid flow and ventilation airflow provides sufficient strain. In addition to the flammable fluid system pressure and ventilation airflow, spray fire flame stability may also be influenced by ventilation airflow temperature, the type of flammable fluid, and the fire suppressant type.

2.3.4 Pool Fires

A pool fire can occur if failure of a flammable fluid line or component releases sufficient quantity of flammable fluid, which cannot drain away from the compartment and thus collects to form a pool. Ignition may occur by contact with a hot surface or by the mechanism that effected the failure mode, which could include a ballistic projectile. If there is ventilation airflow, such as within an engine nacelle, the stability of a pool fire can be greatly enhanced if an obstacle at the leading edge of the pool is present. In some nacelle configurations, obstacles in the form of structural ribs or other bluff bodies are present at locations where combustible liquids may puddle and fail to drain in a timely manner. Pool fire flames are believed to have a premixed structure and are more stable than the diffusion structure of spray flames, and both types of flame are believed to be less stable (more easily extinguished) at high airspeeds. Figure 2-26 depicts the sequence of events leading to a stabilized pool fire within a dry bay compartment having relatively low ventilation airflow.

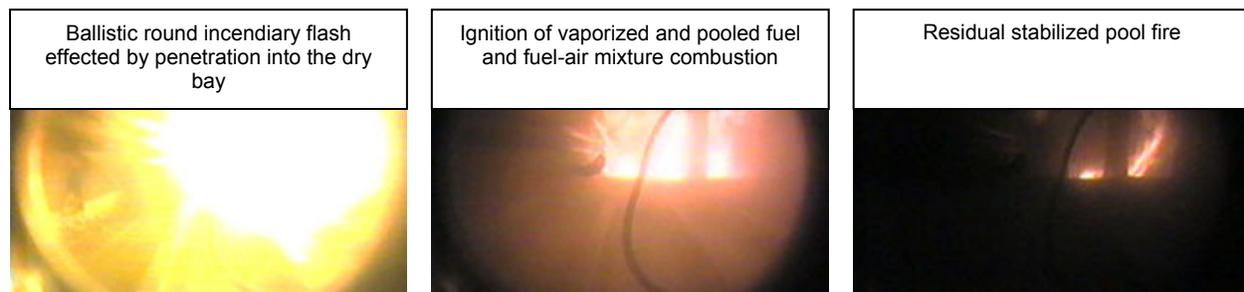


Figure 2-26. Stabilized Pool Fire Formation within an Aircraft Dry Bay Compartment.

Lab-scale fire suppression tests have shown that the stabilizing effect of a baffle in front of a pool fire can be very significant. Test results show that under similar airflow and baffle height conditions, a baffle-stabilized pool fire is dramatically more difficult to extinguish than a baffle-stabilized spray fire where the baffle is located in the middle of the flow field. Nacelle fire testing performed by the CAA and then later during the TDP has shown that occluded pool fires are more difficult to suppress than spray fires. The CAA reported that suppression mass quantity greatly increased with the presence of transverse structural ribs situated in the lower part of nacelles tested. This was attributed to difficulties in extinguishing pool fires between structural ribs. Later testing of three nacelle fire scenarios, fuel spray fire, burning of fuel as it flows as a thin film over a hot surface, and a burning pool of fuel, showed that greater suppressant concentrations were required for the hot surface and pool fire conditions than for spray fires.⁵⁵ That greater suppressant concentrations were required to suppress pool fires was again reconfirmed during the TDP in which it was found that stability of pool fires required larger suppressant concentrations and longer characteristic suppressant mixing times to achieve suppression due to recirculation zones. Pool fires were again found more difficult to suppress than spray fires during a nacelle fire test program for the USAF F-22 aircraft.⁵⁶

2.3.5 Fire Characteristics

Flame Temperature

The fire triangle and fire pyramid are often used to describe the basic components of fire. In the fire triangle, the three sides are typically indicated as fuel (or substance that will burn), oxygen, and temperature (i.e., sufficient heat to initiate and sustain combustion). The four surfaces of the pyramid indicate a fourth component: chemical chain reactions involving free radicals, which are necessary for the reaction (hence combustion) to be sustained. For hydrocarbon fuels (which include aviation fuels), the reaction is usually written as $\text{Fuel} + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2$. The net heat release for the reaction is referred to as the heat of combustion, and this can be used to estimate the maximum possible flame temperature, or the adiabatic flame temperature.⁵⁷ The net heats of combustion for JP-4, JP-5 and JP-8 aviation fuels used on DoD aircraft are within the range of 40 kJ/g to 45 kJ/g. As illustrated in Figure 2-27, the maximum flame temperature occurs when the equivalence ratio is one. The equivalence ratio is the actual fuel-air ratio divided by the stoichiometric fuel-air ratio. The fuel-air ratio is simply the ratio of the mass of fuel supplied to the mass of air supplied. In stoichiometric combustion, there is complete conversion of carbon and hydrogen to CO_2 and H_2O , with no leftover oxygen. Thus, the stoichiometric fuel-air ratio is the ratio of the mass of fuel supplied to the mass of air supplied for which the stoichiometric condition is satisfied.

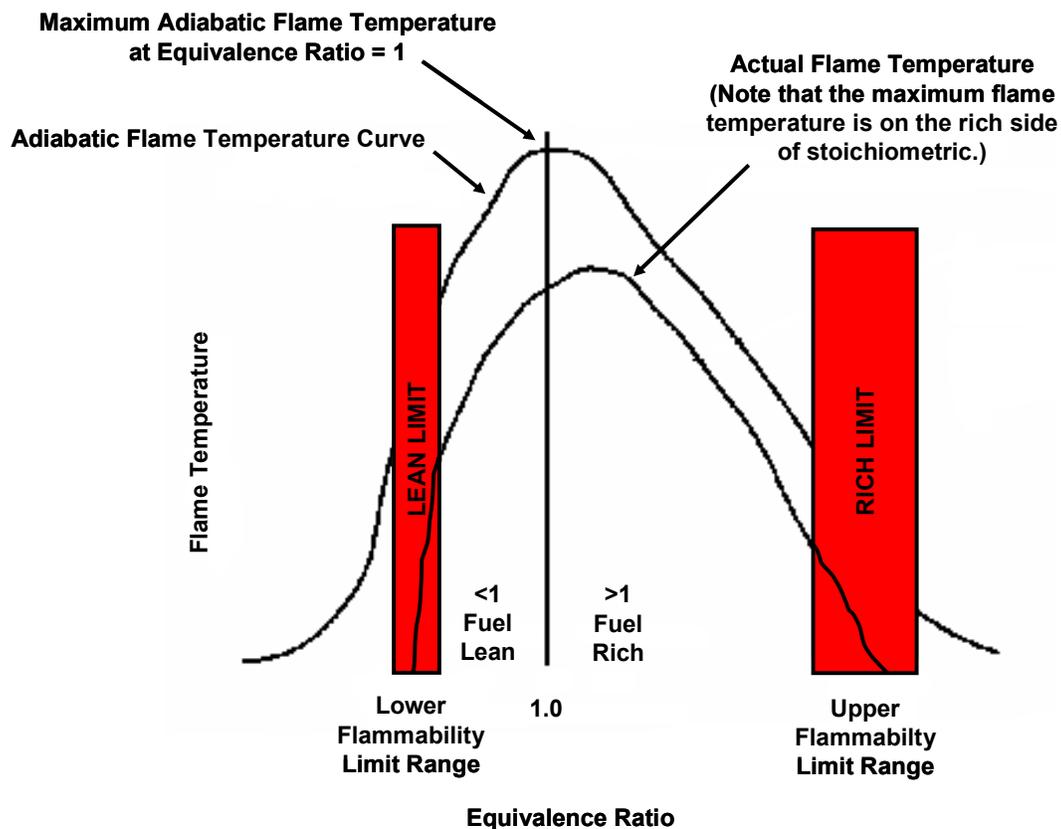


Figure 2-27. Flame Temperature vs. Equivalence Ratio.⁵⁸

(Reprinted with permission by AFP Associates, Inc.)

In reality, the adiabatic flame temperature is not attained, particularly for highly-ventilated compartments such as engine nacelles as well as for dry bay compartments, as they may also be ventilated and have leakage (i.e., they are not completely sealed – openings such as drain holes may be present). Also, complete combustion of leaking fuel is not assured in the event a fire occurs in nacelle or dry bay compartments. It is not uncommon to find residual fuel or hydraulic fluid in these areas after a fire event. Thus, as illustrated in Figure 2-27, the actual flame temperature will be less than the adiabatic flame temperature, but the maximum flame temperature occurs on the fuel-rich side of an equivalence ratio of unity, as greater fuel mass available results in greater energy and heat release.

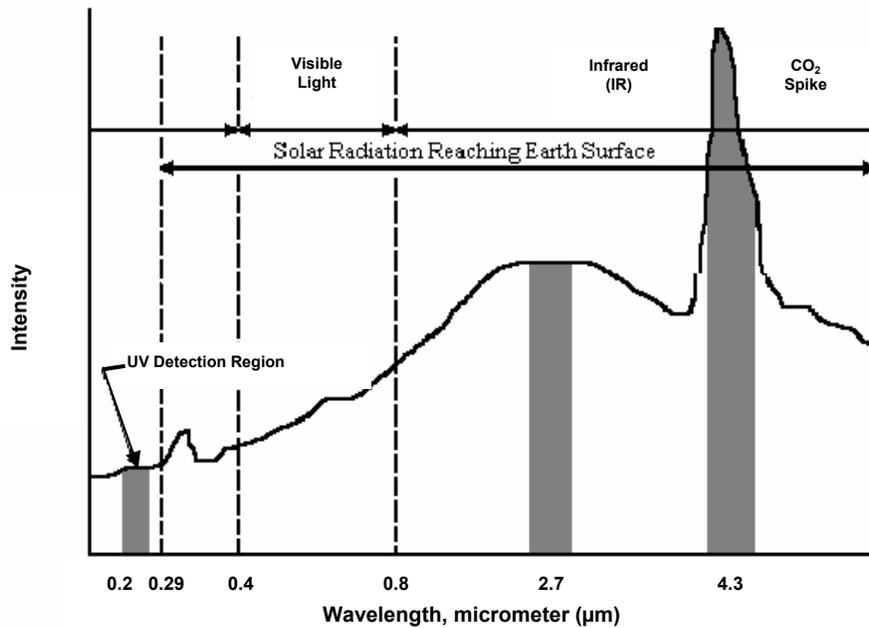
In work to determine the spectral characteristics for fire detection by optical fire detectors, it was shown that ultraviolet emissions from JP-4 flames increased with increasing altitude and that the ultraviolet (UV) power emitted at 10.7 km (35,000 ft) by the burning fuel was nearly double that emitted at sea level. Thus UV detection must be sensitive for the sea level condition. The power emitted at visible and near-infrared wavelengths decreased at higher altitude. Thus visible/near infrared detection must be sensitive at high altitude. The visible/near-infrared emission spectra are due to hot carbon particles in the diffusion flame, while the energy emitted at ultraviolet wavelengths is associated with the electronic transitions of free radicals in the flame. It is believed that as altitude is increased (and pressure decreases) the reduction in the available oxygen to sustain the combustion process may result in an increase in the density of these radicals, and thus stronger emissions of the ultraviolet radiation. In contrast, the reduction in oxygen pressure, as occurs with increasing altitude, may reduce the flame temperature and thus the intensity of the visible/near-infrared radiation emitted by the carbon particles.⁵⁹ Typical hydrocarbon flame and burning JP-4 fuel emission spectra are shown in Figure 2-28.

The relevance of the preceding discussion is that requirements for fire tolerance, thermal fire detection, optical fire detection, and ultimately fire suppression are related to temperature (and exposure at that temperature). Fire zone components are required to withstand exposure to a minimum flame temperature of 1093 °C (2000 °F) and minimum heat input (heat flux density) of 9.3 Btu/ft²-s (10.6 W/cm²) for 15 min. This temperature is also the DoD fire warning requirement threshold for continuous-loop thermal fire detectors used in many engine nacelles and APU compartments for fire detection, whereas optical fire detection for dry bay compartment fires are typically sensitive to the 4.3 μm wavelength (i.e., the CO₂ spike) associated with JP-type aviation fuel fires.

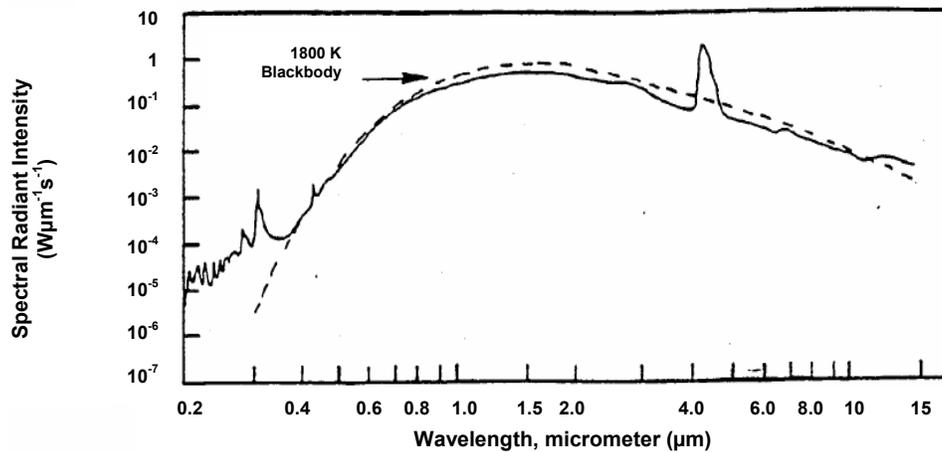
Deflagration vs. Detonation

Deflagrations and detonations are distinguished by flame front velocity. Detonations involve supersonic burning velocities and are more likely to occur in oxygen than in air, whereas deflagrations are characterized by subsonic burning velocities.⁶⁰ Research and testing has clearly proven that nacelle, dry bay, and ullage fire events are deflagrations. Detonations and deflagrations may or may not lead to a (sustained) fire. When the combustion rate of energy release is rapid and there is a large increase in pressure, referred to as overpressure, it may be sufficiently large enough to damage or destroy portions of the aircraft structure and is referred to as an explosion. Aviation fuels typically deflagrate with overpressures normally less than 1380 kPa (200 psi).⁴ In one series of ullage fire testing conducted at a simulated high altitude, with a pressure of 58 kPa (8.4 psia) and 21 % oxygen, an initial flame velocity measure from film was observed to be 3.35 m/s (11 ft/s).⁵³ If a combustion wave propagates throughout the ullage with near stoichiometric fuel/air mixture, a pressure increase of over 790 kPa (100 psig) or

eight times atmospheric pressure is theoretically possible.⁴³ Photographic evidence from full-scale dry bay testing indicates that turbulent flame speeds are below 300 m/s (984 ft/s).^{xvii}



(a) Typical Hydrocarbon Fire Emission Spectrum⁶¹



(b) Emission Spectrum of Burning JP-4 Fuel above 35,000 ft⁵⁹

Figure 2-28. Hydrocarbon Flame Emission Spectra.
(1800 K = 1527 °C = 2780 °F)

^{xvii} The speed of sound is 340.29 m/s at sea level.

Turbulence

Turbulence within an aircraft engine nacelle or dry bay compartment is influenced by a variety of factors. The obvious is ventilation airflow through the compartment. The geometry of the compartment will also influence whether there are localized regions of higher ventilation airflow velocity, recirculation, or stagnation. Structural members (ribs, frames, longerons), subsystems equipment (engine and accessory components, bleed air ducts, flammable fluid components and lines, electrical components and harnesses), and mounting hardware (clamps, brackets), collectively referred to as bluff bodies or clutter, will effect complex flow fields within nacelle or dry bay compartments and also provide locations for flame holders or pooled fuel. Estimation of the increase of the Reynolds Number as change occurs in a recirculation zone of premixed gases burning in the wake a bluff body was known previously to support turbulence conditions.⁵⁵ (The Reynolds Number is used for determining whether flow is laminar or turbulent.) Estimation of the Reynolds Number at the air inlet of an engine nacelle indicates this area to be highly turbulent even prior to consideration of clutter-enhanced mixing.⁶² Though ventilation airflow through an engine nacelle may be assumed to be longitudinal throughout the annular volume, it is also possible that ventilation airflow will in some places be found to be circumferential about the engine and even contain areas of reversed flow. An engine nacelle fire is typically a turbulent diffusion flame stabilized behind an obstruction in a moderately high-speed airflow that was typically found to range from 0.57 kg/s (1.25 lb/s) to 1.25 kg/s (2.75 lb/s).⁴³

The primary design purpose of ventilation airflow through a nacelle is to provide cooling for the engine to ensure desired engine performance and not degrade operation of other subsystem components located in the nacelle, though in the case of the F-111 aircraft the nacelle design imparted unidirectional ventilation airflow to also prevent flame propagation as well as remove flammable vapors.⁶³ The number of air exchanges per unit time (volumetric air flow divided by net volume) depends on the aircraft design and may be as high as one per second.⁴³ Though nacelles are unique for each aircraft, the intended forward-to-aft nacelle ventilation airflow characteristic is typical. Dry bay compartment sizes, ventilation requirements, and geometries differ greatly from aircraft to aircraft, and thus turbulence within a dry bay compartment may or may not be more complex than within an engine nacelle. Figure 2-29 provides a contrasting example of this when compared to Figure 2-26. Both depict fires within a dry bay compartment. Whereas Figure 2-26 suggests a relatively benign turbulent environment, Figure 2-29 provides an example of a highly turbulent environment.

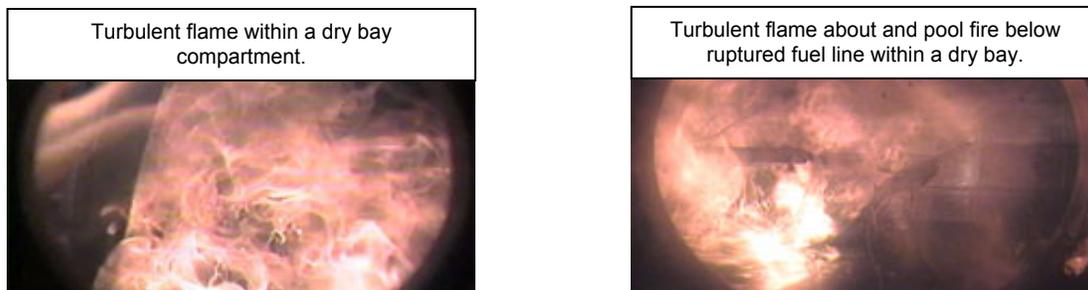


Figure 2-29. Turbulent Fire within Aircraft Dry Bay Compartments.

The same physical and environmental characteristics that contribute to turbulence will also influence flame strain, suppressant distribution, and suppressant effectiveness (and dilution), as the time required for an agent to entrain into the recirculation zone is a key parameter in the effectiveness of suppression with respect to baffle-stabilized flames. In computational fluids dynamics (CFD) modeling and model validation testing performed by the NGP, success or failure in extinguishing nacelle fires was largely correlated with the ratio of the rate of injection of suppressant to the total inflow rate into the nacelle (that is, ventilation airflow plus suppressant flow). For a suppression system that is not an optimized design (it is possible for an un-optimized system to pass a certification test), turbulence can effect inhomogeneities and failure to suppress a fire. If regions of the flow field exist where the suppressant concentration is locally below the value that leads to suppression, there can be failure to completely suppress a fire, since small pockets of fire can quickly propagate through the remaining premixed gases in the nacelle leading to accelerated burning under certain conditions and catastrophic results.⁶⁴

2.3.6 Aircraft Operational Temperature Environment⁴⁴

As discussed previously, temperature is the primary basis of current aviation requirements for fire detection and component tolerance to fire. Temperature is also a variable with regard to the potential for ignition of a fuel-air mixture, the amount of energy to ignite a flammable mixture, suppressant performance capability, and, in the case of hot surfaces within an engine nacelle, reignition, which is discussed separately in this chapter. Given a constant initial pressure, it has been established previously that a non-flammable fuel-air mixture may become flammable for some period of time if its temperature is elevated sufficiently.⁶⁵ Additionally, as shown in Figure 2-30, it had been established previously for halon 1301 that the peak flammability limit, the suppressant inerting concentration in air at which no mixture of fuel and air is flammable, can increase with temperature.^{66, xviii} Lab-scale testing during the TDP with halon 1301 and several halon alternative suppressants also indicated similar trending as shown in Figure 2-31.¹³

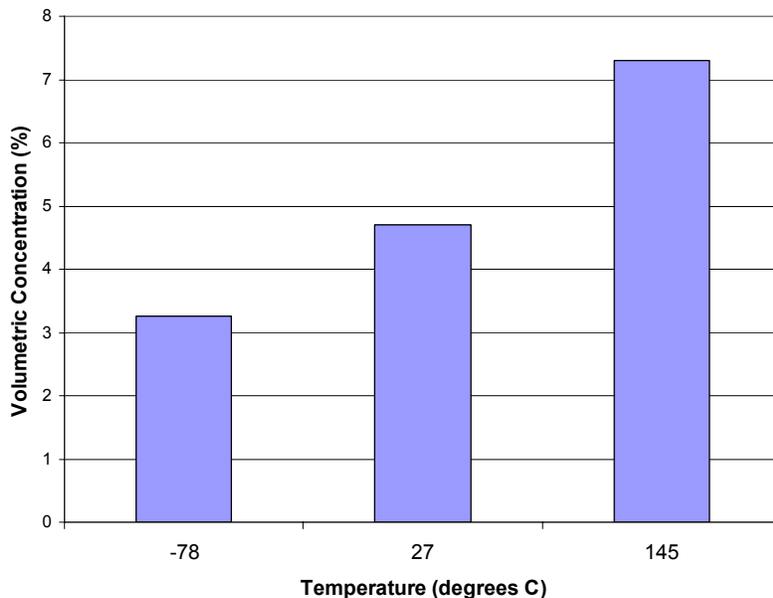


Figure 2-30. Variation in Halon 1301 Peak Flammability Limits for Isobutane with Temperature.

^{xviii} The certification requirement for halon-1301-based nacelle fire suppression systems is suggested to be founded, per Reference 132, on the 6 % inerting concentration determined by the Purdue Research Foundation, whereas halon-1301-based fuel tank inerting systems have been designed to maintain even higher concentrations (e.g., 20 %).

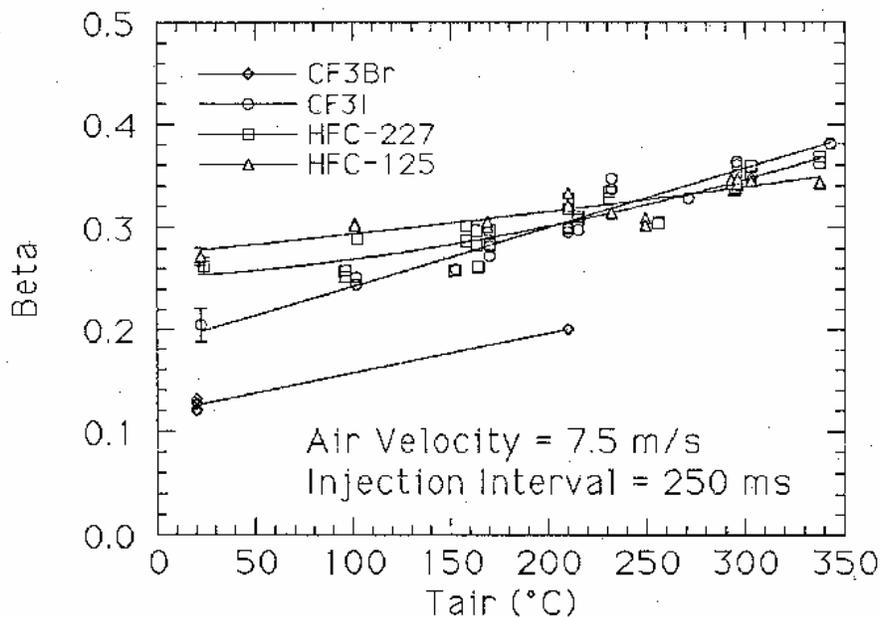


Figure 2-31 Variation in Halon 1301 and Three Halon Alternative Mass Fractions (Beta) Required to Suppress JP-8 Spray Flames with Temperature.¹³

(Beta is the ratio of the mass flow of the suppressant to the total flow of suppressant and air.)

What were not established until the NGP was the correlation of historical fire experience with outside air temperature (OAT) and altitude and how that correlates with suppressant low-temperature requirements. The temperature data that was previously indicated as design requirements but is currently promulgated as design guidance to define the low and high temperature extremes for DoD aircraft systems are worldwide air environments (WWAE), which represent conditions having a 1 %, 5 %, 10 % and 20 % frequency of occurrence.⁶⁷ In commercial aviation, standard climate profiles from the Joint Aviation Regulation (JAR) define temperatures based on arctic, temperate, tropical, intercontinental, and standard-day conditions.⁶⁸ (Note: there is no design guidance or DoD/JAR climate profile for altitude environments below 60 degrees south latitude, the Antarctic.) Figure 2-32 plots these climates vs. the WWAEs used for DoD acquisition programs. Figure 2-33 depicts the worldwide land environments provided as design guidance for DoD aircraft systems, which categorizes four land environment types: basic, hot, cold, and severe cold.⁶⁷

The relevance of the aircraft temperature envelope requirement to on-board fire suppression systems that utilize a chemical suppressant, i.e., the engine nacelle and APU fire suppression systems on DoD aircraft, is that the low temperature extreme defined for the envelope has historically been applied to substantiate the boiling point requirement for the fire suppressant, which is predominantly halon 1301. Thus in the context of the WWAEs, a boiling point requirement based on halon 1301 would provide for in-flight fire suppression under atmospheric conditions down to temperatures consistent with arctic-like temperature conditions.

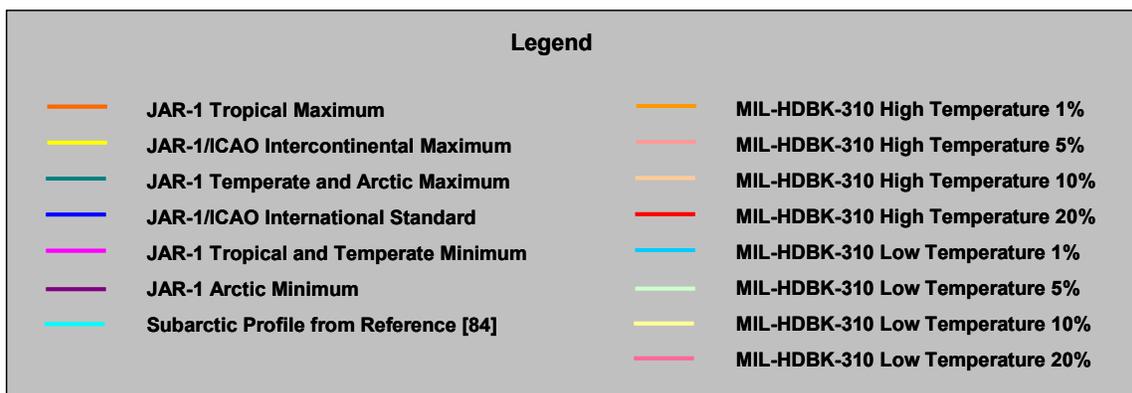
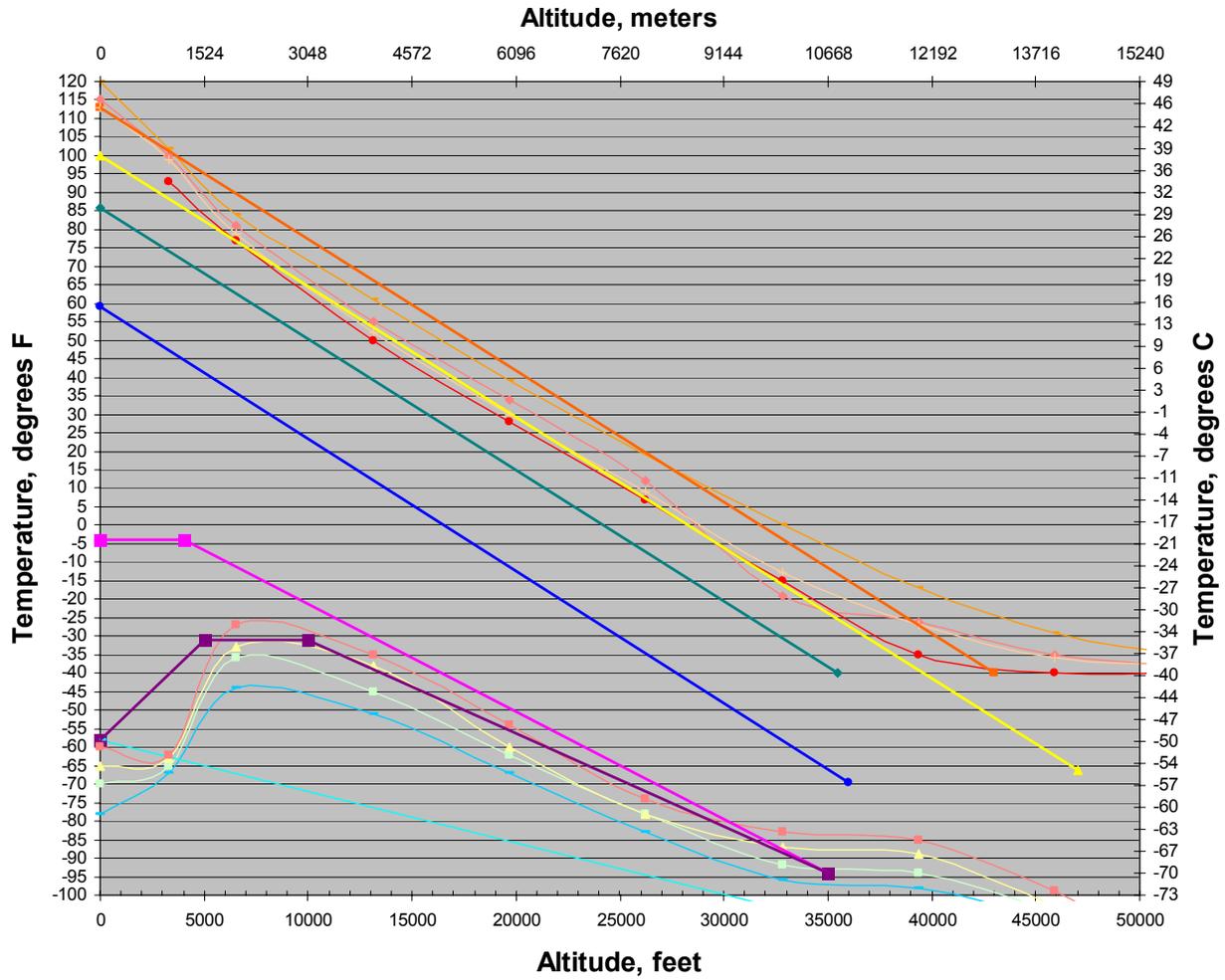


Figure 2-32. Commercial Aviation Standard Climates vs. DoD WWAE Design Guidance.

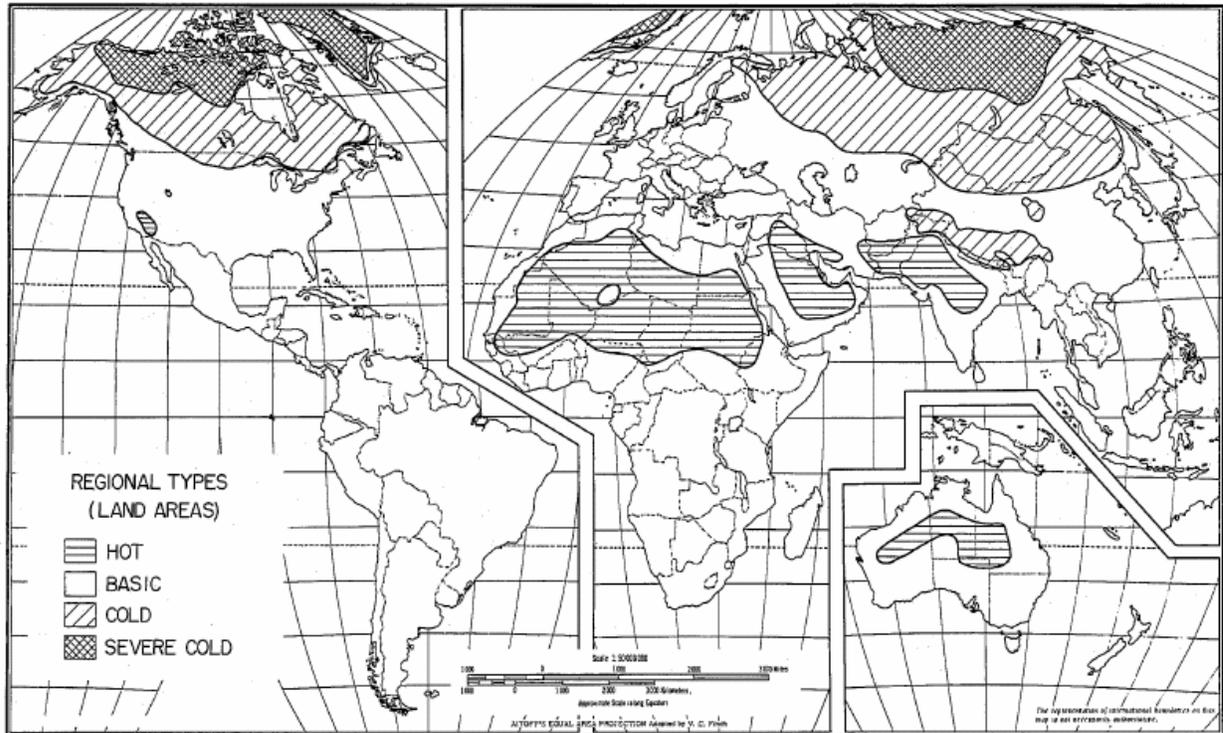


Figure 2-33. DoD Land Environment Design Guidance.⁶⁷

With regard to ground fire suppression, land environments indicated as cold or severe-cold climates are the likely environments in which cold-soak conditions prior to aircraft startup would exist. The DoD design guidance indicates a low-temperature 1 % frequency of occurrence of $-46\text{ }^{\circ}\text{C}$ ($-50\text{ }^{\circ}\text{F}$) for cold land environments and a low-temperature 20 % frequency of occurrence of $-51\text{ }^{\circ}\text{C}$ ($-60\text{ }^{\circ}\text{F}$) for severe-cold land environments. Designers of legacy aircraft would develop fire suppression systems whose requirements were tailored to halon 1301 properties to likely assure fire suppression performance at such temperature conditions.

Boiling point (or T_b) of a fire suppression agent has been used as one of the criteria to guide the search for new halon alternative chemical fire suppressants during the NGP.⁶⁹ Currently, this criterion is $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$). It was also one of the parameters considered during the TDP, which identified HFC-125 as the best near-term alternative to halon 1301 for use in aircraft nacelle fire suppression system applications. However, even during the TDP it was recognized that, when operational contexts were considered such as the likely temperature environment within an operational engine nacelle at the time of suppressant discharge, the typical low temperature performance requirement could be a candidate for a performance trade. Minimum nacelle operating temperatures were indicated to range from below $-18\text{ }^{\circ}\text{C}$ ($0\text{ }^{\circ}\text{F}$) in commercial aviation to $38\text{ }^{\circ}\text{C}$ ($100\text{ }^{\circ}\text{F}$) in DoD aviation.⁷⁰ A subsequent review of nacelle compartment airflow temperature data for a variety of aircraft platforms, including a commercial transport aircraft, indicated temperatures ranging from $-18.5\text{ }^{\circ}\text{C}$ ($-1.3\text{ }^{\circ}\text{F}$) to $274\text{ }^{\circ}\text{C}$ ($525\text{ }^{\circ}\text{F}$).^{71,72,73,74,75} Though this data may not address every operating environment, they suggest that even at low outside air temperatures (OAT) it is probable that the typical operational engine nacelle compartment temperature will be greater than $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$).

For decades, high T_b suppressants have been used in military aircraft nacelle fire suppression systems. In addition to halon 1011 on C-130 aircraft, this also includes halon 1202 on C-5 and previously on F-111 aircraft, which are now retired.⁷⁶ Since the signing of the Montreal Protocol, at least two high T_b halon alternative agents have been fielded outside the DoD.^{xix,77,78} Successful implementation and history of high T_b suppressants is likely attributable to several factors such as (1) the fact they are brominated halogens, (2) elevated nacelle operating temperatures, (3) applications that may benefit from the high T_b characteristic, e.g., single-phase flow in long distribution runs, (4) freezing points well below temperatures likely to be experienced on ground and at altitude, and (5) distribution system design that ensures adequate distribution throughout the nacelle. This last factor was also emphasized and applied in the development of the F/A-18E/F HFC-125 nacelle fire suppression system.⁷⁹ HFC-125 is a low boiling point fire suppressant. The obvious conclusion is that both low- and high-boiling-point suppressants are likely to realize higher probability of success when distribution is optimized. Chapter 8 discusses additional factors identified during NGP CFD experiments and modeling that need to be considered relating to suppressant delivery and evaporation.

Analysis of military aircraft experience regarding release of nacelle fire suppressants was conducted during the TDP, the purpose of which was to quantify halon discharges at altitude and for evaluating discharge frequency and quantity of agent discharged below and within the ozone layer.⁸⁰ Combining both fixed-wing and rotary aircraft discharges that analysis indicates:

- Approximately 77 % occurred between 0 km and 3 km (0 ft and 10,000 ft), and about 92 % occurred between 0 km and 6 km (0 ft and 20,000 ft).
- Over 60 % of all discharged suppressant was accounted for by only three of the 30 military aircraft platforms covered by the study. These three platforms (C-130, F-15, and P-3) have altitude ceilings that extend above 6 km (20,000 ft) but were contributors to the frequency of discharges below 3 km (10,000 ft).^{xx}
- Over 25 % of all suppressant discharged was high-boiling point suppressant (i.e., halons 1011 and 1202).

Prior to the NGP, an operational context that had not been investigated was whether temperature conditions at the time of agent release correlated with the typical boiling point temperature requirement. These include OATs, nacelle operating temperatures, cold-soak temperature conditions and cold climatic extremes. Based on review of nacelle compartment airflow temperature data for a variety of aircraft platforms, it was reasonable to assume that nacelle compartment temperatures are well above boiling points of fielded nacelle fire suppression agents. When considering that historic release of nacelle fire suppression agents has typically occurred below 6 km (20,000 ft), with over 75 % occurring below 3 km

^{xix} These agents are phosphorous tribromide (PBr_3), which has a T_b of 173 °C, and trifluoroiodomethane (CF_3I), which has a T_b of -22.5 °C. PBr_3 is installed for nacelle fire protection on Eclipse 500 commercial aircraft, which are small commercial jet transport aircraft, and CF_3I is installed for nacelle and APU fire protection on Royal Australian Navy SH-2G rotary aircraft. The CF_3I system is similar to a halon 1301 system in its implementation in that the suppressant is distributed throughout the nacelle by means of remotely-contained storage bottles and plumbing. The PBr_3 system implementation is different: suppressant discharge is targeted to the flame holding regions within the nacelle, which were identified through analysis and test, per Reference 77. Considering nacelle operating temperature environments, which are described later, and boiling points of each suppressant, CF_3I will likely be vaporized where as for PBr_3 the heat from a fire will effect vaporization.

^{xx} The aircraft platforms in the TDP study, Reference 80, that each accounted for at least 5 % of discharged suppressant were the P-3, C-130, F-15, F-111, C-5, C-141, and A-10 platforms, all fixed-wing aircraft. Review of the data utilized for the reference [44] study found similarly that the aircraft platforms each accounting for at least 5 % of discharged suppressant were the P-3, C-130, C-5, A-10, F-15, F/A-18, and F-111, and in general that fixed-wing aircraft accounted for 85% of all suppressant discharged.

(10,000 ft), and that the likely occurrence of fire while either cold soaked or while in cold climatic extremes is likely a low probability event, the likelihood of not extinguishing a nacelle fire after suppressant release and realizing a catastrophic event under such conditions suggests strongly that the combination of these events has a low probability. The implication of the preceding is that selection of a fire suppressant whose boiling point is compatible with cold soaking or a cold climatic extreme results in a protection capability against events whose likelihood of occurrence has a very low probability, and that halon alternative suppressants with higher boiling points are not likely to appreciably increase risk under such conditions. These preceding assertions provided the NGP with the impetus to perform the following efforts:

- Obtain and review aviation Safety Center fire incident data to extract, if possible, altitude and/or outside air temperature (OAT) information that would permit characterization of OAT conditions during which suppressant release has historically taken place. Based on this data, it may be possible to assess probability of suppressant release under conditions that are likely to be well above a suppressant's boiling point.
- Construct and validate an in-flight nacelle air temperature model to estimate likely nacelle compartment air temperature for given altitude, outside air temperature, general engine surface temperatures, and aircraft airspeed conditions. Such a model would be useful in allowing system designers to assess compartment temperatures at altitude relative to a suppressant's boiling point.
- Evaluate implications of aircraft cold-soak conditions, particularly during aircraft takeoff.
- Assess safety risk, considering the findings in the preceding elements, of utilizing a fire suppressant whose boiling point is much higher than of those agents commonly fielded today in military aircraft (i.e., halon 1301).

DoD Safety Centers Fire Incident/Mishap Data

A review conducted within U.S. Army aviation of rotary aircraft fires between 1985 and 1995 had found that the lowest outside air temperature (OAT) reported was 0 °C (32 °F) and the highest reported was 35 °C (95 °F).⁸¹ This review concluded that the only time a -50 degree temperature would remotely be encountered is at extremely high altitude or in extremely remote northern/southern areas of the earth.^{xxi} The use of the term “remotely” has significance in that within DoD it relates to the rate of hazard occurrence. During the time period of the U.S. Army study, the aggregate rate of occurrence of in-flight rotary aircraft fires was 4.9 per million flight hours, a remote rate of occurrence. Thus the likelihood of a nacelle fire occurring at lower outside air temperatures or in an extremely cold environment and resulting in loss of aircraft would likely be even lower (improbable).^{xxii}

Aviation fire incident data was obtained for the years 1980 through 2002 from the U.S. Army, Navy and Air Force Safety Centers. Table 2-3 summarizes the number of mishaps and incidents provided by the Safety Centers. (Note: the counts in Table 2-3 reflect incidents categorized by the DoD services as mishaps as well as lesser severity events or incidents.) The data was reviewed to determine whether

^{xxi} The final memorandum did not indicate whether the temperature threshold considered was -50 °C or -50 °F.

^{xxii} The terms remote and improbable are categories of hazard probability as described in DoD specification MIL-STD-882D, Standard Practice for System Safety. These terms may be described either qualitatively or quantitatively. Assigning a hazard probability category based on aircraft flight hours is one method per MIL-STD-882D of describing a probability quantitatively.

suppressant release occurred and to identify the altitude and OAT associated with each release. Only suppressant releases associated with discharge of systems protecting nacelle and APU compartments were considered. Combat-related events, or direct-enemy action events, are typically not provided by the DoD Safety Centers, and if they are provided they only contain limited information. For mishaps and incidents that provided altitude data but did not include temperature data, the International Civil Aviation Organization (ICAO) standard atmosphere model was applied to estimate OAT. For mishaps and incidents without altitude and temperature information, the methodology applied was that used during the TDP for assuming flight altitude based on aircraft flight phase from the previously-described discharge-at-altitude analysis.

Table 2-3. Number of Mishaps and Incidents.

Aircraft Type	Service		
	Army	Navy	Air Force
Fixed Wing	88	1,212	3,932
Rotary	465	834	98

Mishap and incident data was first reviewed for the geographic locations where fires and suppressant releases occurred. Table 2-4 summarizes the results of this review, which was performed to assess occurrence of fire in the cold or severe-cold land environments of Figure 2-33, for incidents occurring on the ground, and to assess occurrence of fire for incidents occurring in flight or characterized as in-flight for aircraft operating nearest to locations in those cold or severe-cold environments.

Table 2-4. Percentage of Fire Mishaps and Incidents Occurring in Geographic Cold or Severe-Cold Environments.

Event Phase	Service		
	Army	Navy	Air Force
Ground	0	1.5 %	1.1 % (a)
In-Flight	< 1 %	< 1 %	2.7 % (b)

- (a) From data categorized as ground fire mishaps and incidents only.
- (b) From data categorized as in-flight fires only but also includes mishaps and incidents on the ground characterized as flight fire mishaps and incidents (i.e., intent for flight existed).

Generally, the fire mishap and incident data provided by the Safety Centers included altitude information in terms of mean sea level (MSL), above ground level (AGL), or flight level (FL). Altitude expressed in these terms in the Safety Center data is typically in terms of pressure altitude, while the Standard Atmosphere is based on geopotential altitude. Figure 2-34 illustrates the variation of ambient pressure vs. pressure altitude and geopotential altitude on standard-day and non-standard-day temperature conditions. The implication with regards to estimating OAT using the ICAO Standard Atmosphere Model is that cold temperature conditions may be lower than estimated on non-standard-days or if altitude is based on pressure altitude. However, the percentages indicated previously in Table 2-4 suggested strongly that applying the MIL-HDBK-310 cold WWAEs or the JAR-1 Arctic Climate profile as the basis for estimating temperature conditions would not reflect operational experience.

An additional consideration for using the ICAO Standard Atmosphere Model for estimating OATs during suppressant release is fuel flammability limits. Figure 2-35 depicts flammability limits of Jet-A and Jet-B aviation fuels vs. altitude and standard atmospheres, including a subarctic profile (JP-8 limits are similar to limits for Jet A, and JP-5 limits are slightly higher than those depicted for Jet-A.). Though ignition depends on many variables, Figure 2-35 suggests that for military aircraft using JP-8 and JP-5 fuels, attaining the flammability limits is more likely at atmospheres above the Standard Atmosphere.

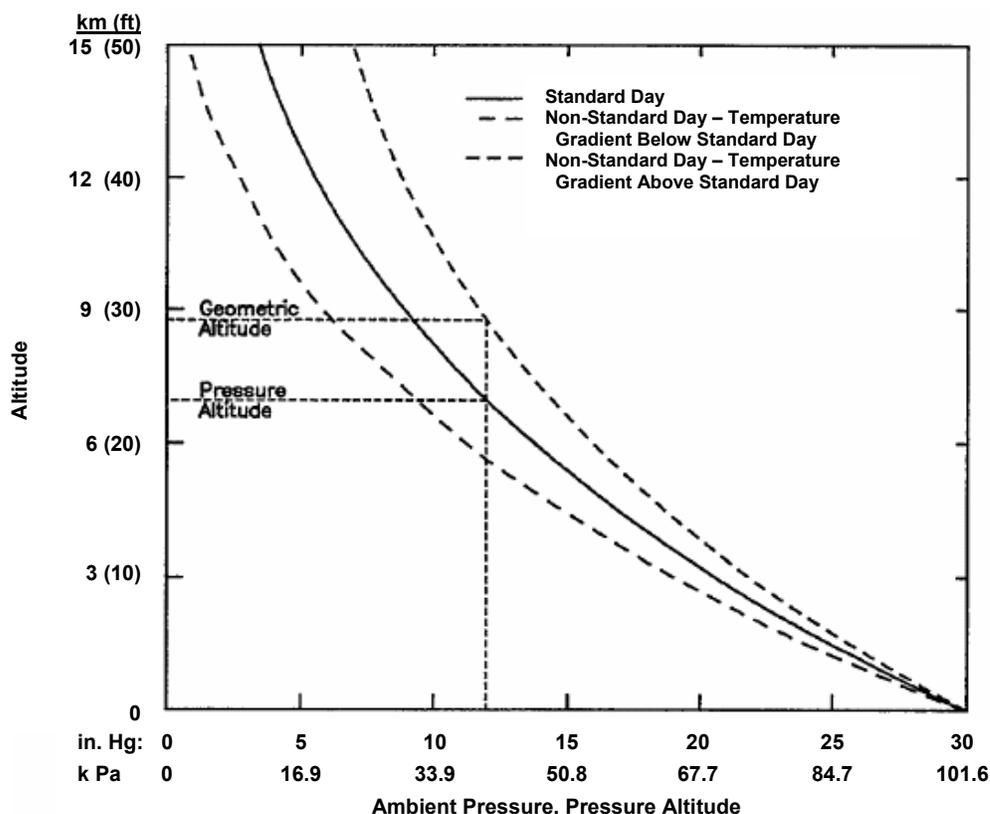


Figure 2-34 Variation of Ambient Pressure vs. Pressure and Geopotential Altitudes on Standard-Day and Non-Standard-Day Temperature Conditions.⁸²

Figure 2-36 plots the safety center data for nacelle and APU fires in which suppressant release occurred and for which suppressant release did not occur. In addition, the figure also plots fire events that were not nacelle or APU fires. *This is done to plot all aircraft fire mishaps and incidents for which Safety Center data included both altitude and OAT.* It is interesting to note in Figure 2-36 that there are just two data points indicating a fire occurrence above 10.7 km (35,000 ft), three data points indicating fire above 9 km (30,000 ft), and only four data points indicating fire above 7.6 km (25,000 ft). In combustion experiments that established the spectral criteria for optical fire detection, it was established that flames could be maintained up to 10.7 km (35,000 ft); however, at higher altitudes, the flames would self extinguish.⁵⁹ Distribution of Safety Center data that included both altitude and OAT for which suppressant release occurred indicated that suppressant releases occurred generally about or above the Standard Atmosphere profile. The lowest OAT below the profile for which suppressant release occurred on the ground was indicated as -3.3 °C (26 °F). The highest altitude below the profile for which suppressant release was indicated to have occurred was 1.65 km (5,400 ft), and the lowest OAT was indicated as 2 °C (36 °F).

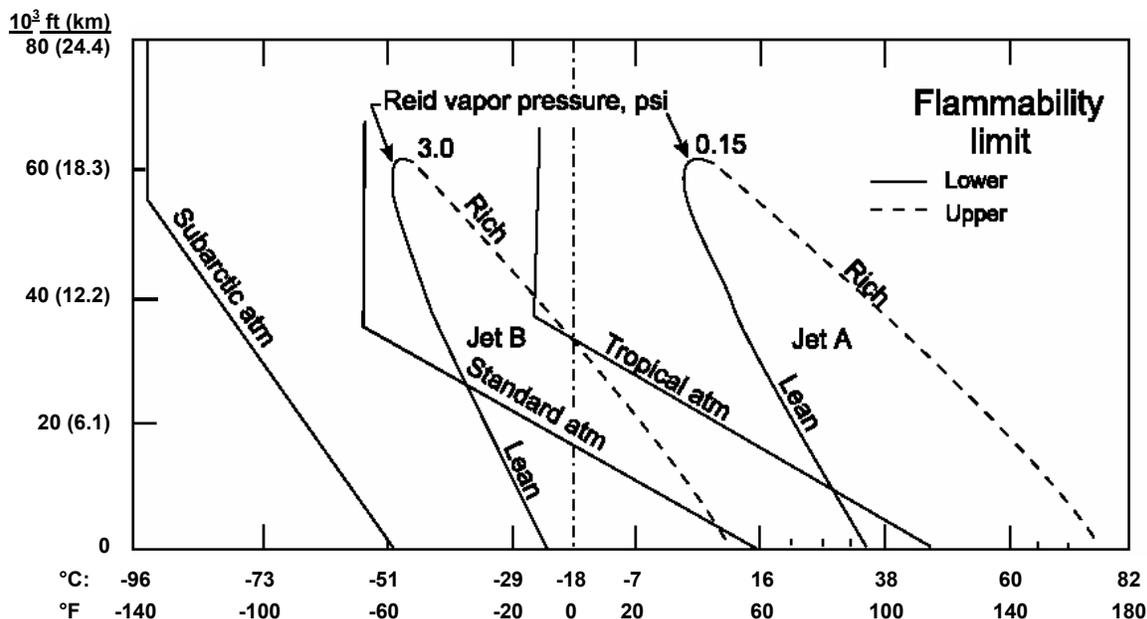


Figure 2-35. Flammability Limits of Jet-A and Jet-B Fuels vs. Altitude and Standard Atmospheres.^{76, 83, 84, xxiii}

(JP-8 limits are similar to limits for Jet A; JP-5 limits are slightly higher than limits for Jet-A.)

For other fire incidents for which Safety Center data included both altitude and OAT but in which there may have been no engine or APU fire, or for which there was an engine or APU fire but *no* agent release, the majority of the incidents at altitude occurred above the Standard Atmosphere profile and below 6 km (20,000 ft). Only one incident is indicated that is beyond the profile at altitude and below -18 °C (0 °F), which occurred at 12 km (40,000 ft), -61 °C (-78 °F). This was the only incident for which *both altitude and OAT* were provided and that occurred below -40 °C (-40 °F). The highest altitude below the profile and above -18 °C (0 °F) occurred at 1.95 km (6,400 ft) with an OAT indicated as -10 °C (14 °F). There are three incidents indicated at zero altitude (on the ground) and below -18 °C (0 °F). These occurred with OATs at -25 °C (-13 °F), -28 °C (-18 °F), and -33 °C (-27 °F).

Commercial aircraft data was also reviewed from the National Transportation Safety Board (NTSB) aviation accident database for occurrence of fire at altitude vs. temperature. Data then obtained spanned the years 1988 through 2000. The distribution of fire events in which both altitude and OAT were provided is shown in Figure 2-37. The lowest temperature indicated in the Figure is -28 °C at zero altitude. There were several events at this condition. (Whether any were nacelle or APU fires was not further researched.) One event was identified in the data at -32 °C, but no corresponding altitude was provided so it is not shown in the figure. Additional fire occurrences at low temperature that were identified with no corresponding altitude and are not indicated in the figure occurred at -27 °C and -26 °C (one each) and at -22 °C (two events).

^{xxiii} Reid vapor pressure (RVP) is a measure of fuel volatility. The higher the RVP, the more volatile the fuel is and the more readily it evaporates. RVP is measured at 37.8 °C (100 °F).

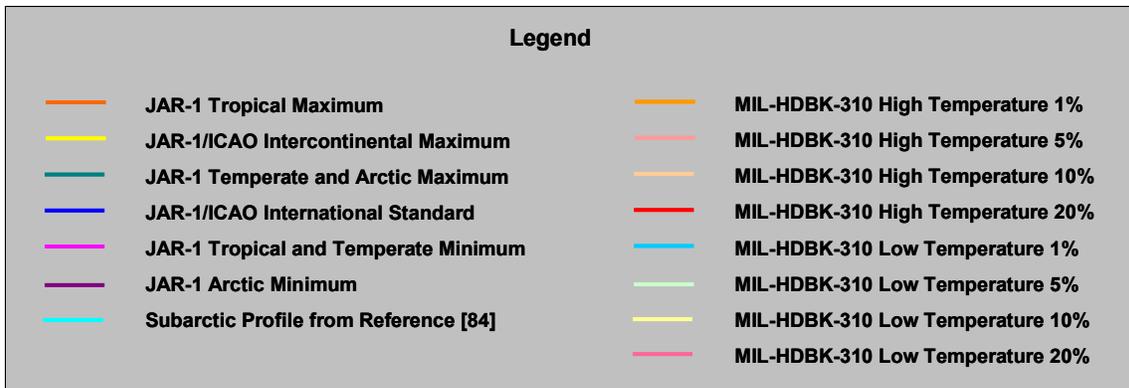
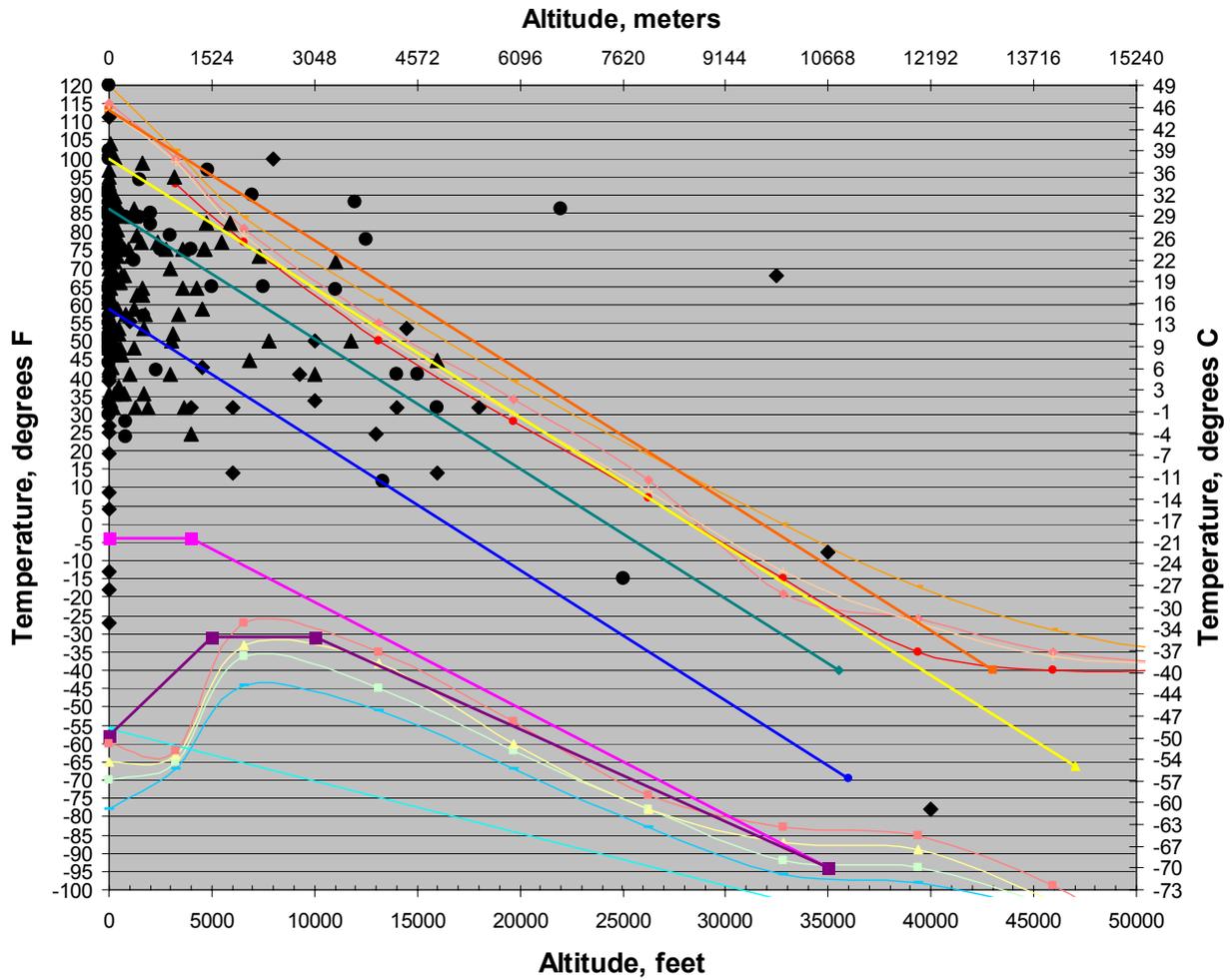


Figure 2-36. Plot of Standard Climate Profiles and WWAEs vs. All DoD Aircraft Fire Events and Suppressant Releases where Both Altitude and OAT Were Provided.

Given the preceding, it was concluded that the Standard Atmosphere Model could be used to provide a reasonable estimate for OATs at which suppressant releases at altitude have occurred. This model was applied to fire incidents for which there were no OAT data, which were then combined with incidents that had included OAT data. The results are summarized in Figures 2-38 through 2-41, with the data from Reference 44.

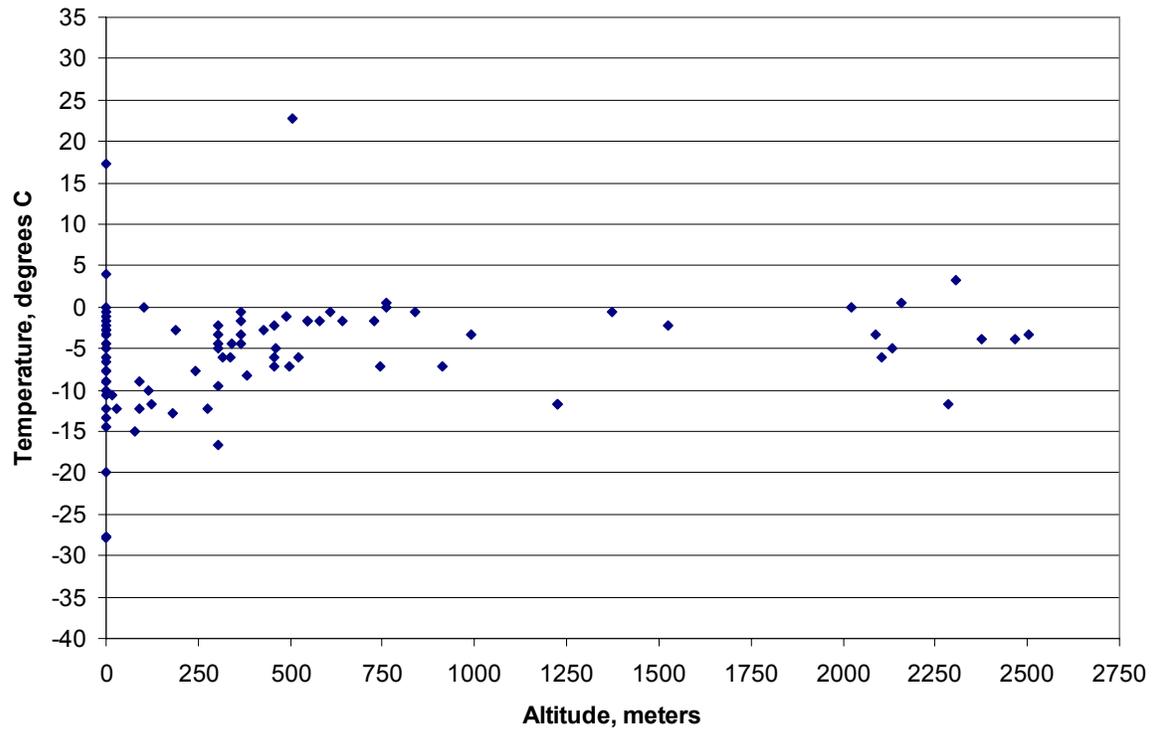


Figure 2-37. Plot of 1988-2000 Commercial Aircraft Fire Events vs. Altitude and OAT, Events for which NTSB Database Provided Both Altitude and OAT.

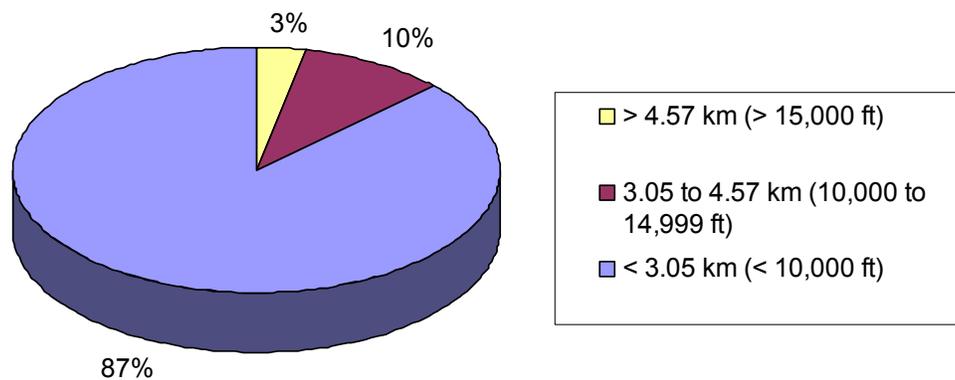


Figure 2-38. Rotary Aircraft Nacelle/APU Compartment Fire Suppressant Releases by Altitude.

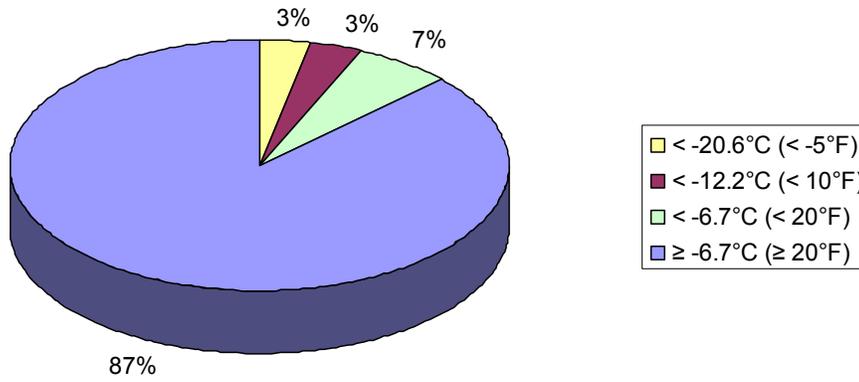


Figure 2-39. Rotary Aircraft Nacelle/APU Compartment Fire Suppressant Releases by OAT.

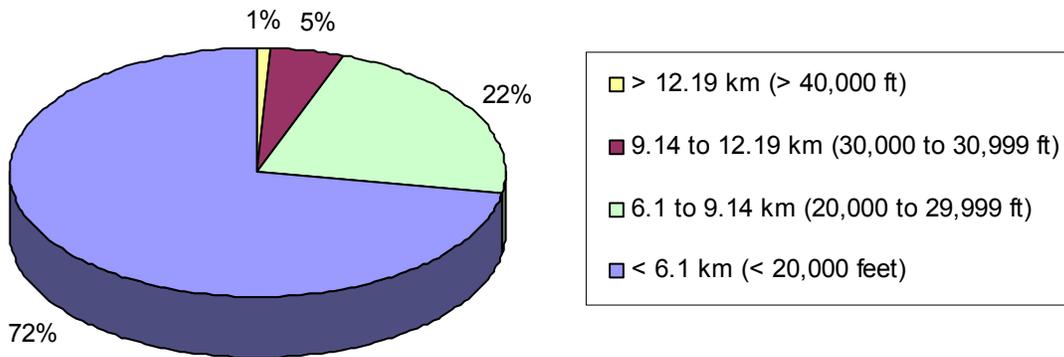


Figure 2-40. Fixed-wing Aircraft Nacelle/APU Compartment Fire Suppressant Releases by Altitude.

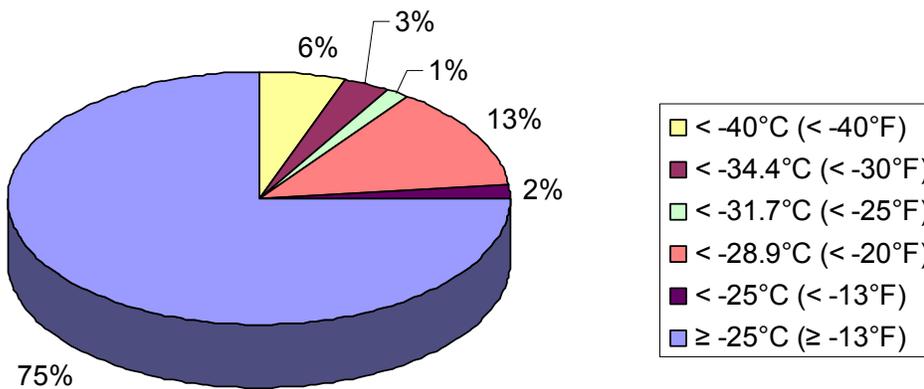


Figure 2-41. Fixed-wing Aircraft Nacelle/APU Compartment Fire Suppressant Releases by OAT.

Nacelle Air Temperature Modeling

An in-flight nacelle air temperature model was constructed to estimate nacelle air temperature during flight conditions. The model uses the U.S. Standard Atmosphere 1976 data on pressure-altitude, temperature, and viscosity.⁸⁵ The model treats the nacelle as an air heat exchanger, and it computes the terminal temperature difference based on average, bulk values. The inlet conditions at the ram scoop are computed to be the stagnation properties for the given flight conditions, and these are taken to be the same as those inside the nacelle, close to the inlet. The effect of conduction and radiation heat transfer is assumed negligible; i.e., heat losses from air through the nacelle wall to the ambient outside by convection and conduction. The model is described in detail in Reference 44.

To evaluate in-flight conditions generally representative of likely flight and nacelle operating conditions, the model was evaluated for over 1,000 cases against the high and low operational parameter settings utilized during the TDP for nacelle configuration (length), clearance (net volume), nacelle mass airflow, and engine hot surface temperature. Conditions were evaluated for altitudes up to 9 km (30,000 ft). Model runs were limited to this altitude for two reasons: (1) only 6 % of all fixed-wing aircraft fire suppressant releases (Figure 2-40) were indicated to have occurred above 9 km (30,000 ft), and (2) though the Standard Atmosphere Model for the tropopause has a ceiling of 11 km (36,152 ft), only 1.7 % of all fixed-wing aircraft fire suppressant releases were indicated to have occurred above this ceiling. The OAT ranged from -45 °C (-48 °F) to 15 °C (58.7 °F) based on the model. The results are indicated in Figures 2-42 and 2-43, which depict peak nacelle temperature vs. altitude for the two airspeed conditions modeled: 50 knots and 400 knots.

Review of the model output showed that 88 % of the cases indicated nacelle air temperatures greater than -18 °C (0 °F). The remaining 12 % of the cases (those less than -18 °C) were for input conditions at 6 km (20,000 ft) or greater, and 89 % of these cases (89 % of the 12 %) were noted for airspeeds of 50 knots.

This group of calculated cases was considered to be artificial since military rotorcraft typically have operational ceilings less than 6 km, and 50 knots is below the stall speed for typical military fixed-wing aircraft that have nacelle fire suppression capability (e.g., fighter/attack aircraft, cargo transports, maritime patrol aircraft). The remaining 11 % (i.e., 11 % of the 12 %), or 1.5 % of all the cases modeled, were for input conditions at 9 km (30,000 ft) and 400 knots and indicated nacelle air temperatures ranging between -23 °C (-10 °F) and -24 °C (-12 °F). If the artificial cases were removed from consideration, the actual percentage of total cases indicating nacelle air temperatures greater than -18 °C became greater than 88 %. So modeling additional cases up to the ceiling of the Standard Atmosphere Model for the tropopause was likely to result in additional nacelle air temperatures less than -18 °C, but it was not likely to dramatically impact the percentages described.

The results of the modeling appeared counterintuitive, in that at higher airspeed the results would be expected to indicate lower compartment air temperature. This is due to the assumption in the model that the temperature at the nacelle inlet is based on the stagnation properties for the airspeeds chosen. This is an assumption that had been applied in previous work, with the rationale that the ventilation airflow temperature through the nacelle is influenced by the stagnation temperature at the nacelle air inlets as well as by heat rejected by the engine.⁶³ Thus, at the higher airspeed, the inlet temperature is greater. To investigate this further, results from the model were compared to data obtained previously during in-flight measurement of nacelle air temperatures for several different aircraft platforms.

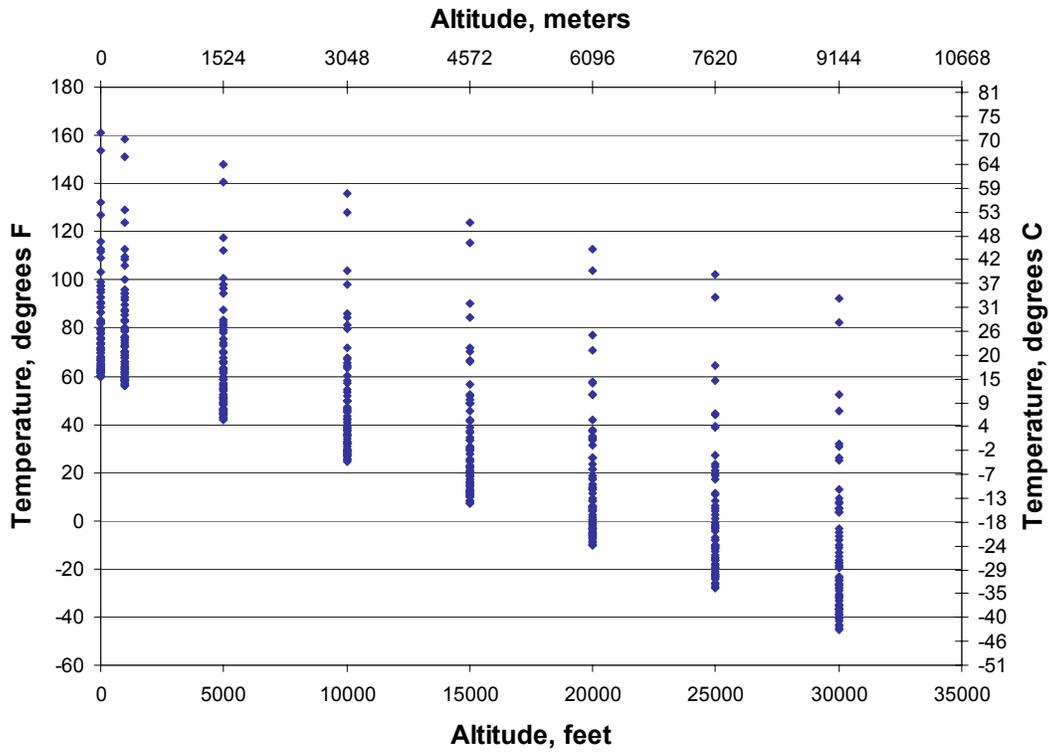


Figure 2-42. Peak Nacelle Temperature at 50 knots Airspeed vs. Altitude.

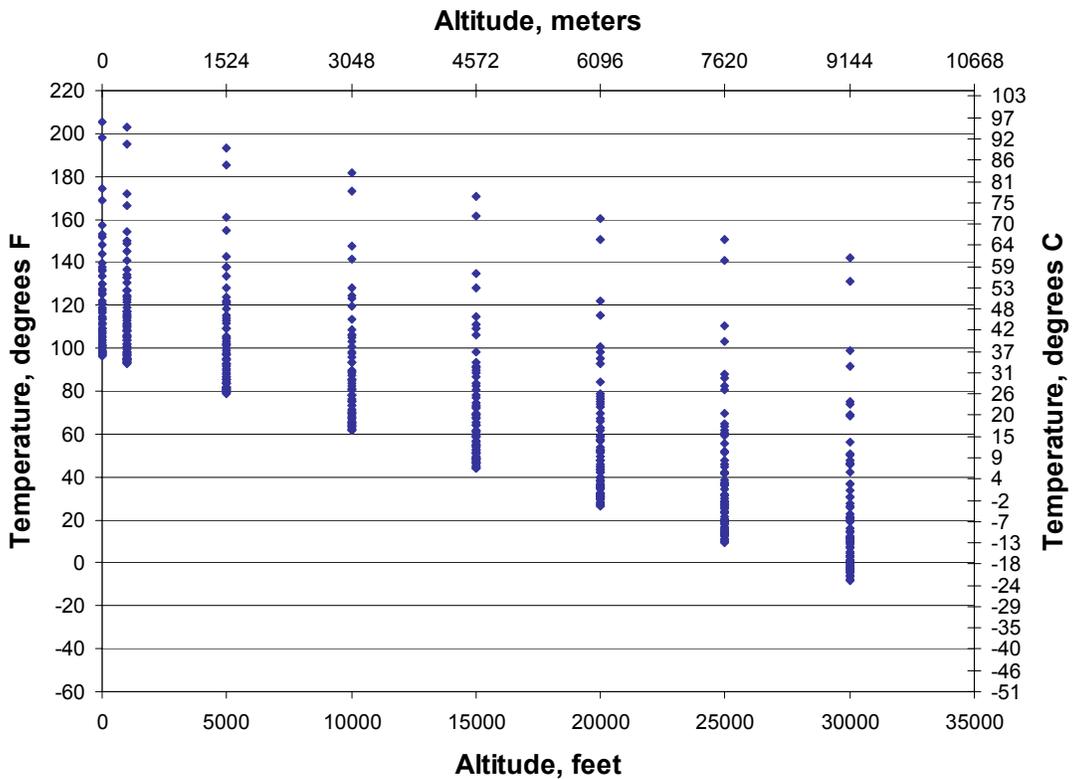


Figure 2-43. Peak Nacelle Temperature at 400 knots Airspeed vs. Altitude.

Additionally, nacelle air temperature data were obtained from current in-flight rotary aircraft propulsion temperature survey testing. The results of the comparison are summarized in Table 2-5. When the model was applied for the purposes of making comparisons, several of the inputs were varied to accommodate differing nacelle characteristics. For example, the clearance between the engine and the nacelle structure is not uniform, thus for each case this parameter was varied between the low and high values that had been utilized during the TDP, unless specific nacelle clearance information was obtained. In general, the model tended to predict (conservatively) lower temperature ranges as compared to measured temperature ranges.

Table 2-5. Comparison of Modeled vs. Measured Nacelle Air Temperatures.

Altitude (km)	OAT (°C)	Engine Surface Temperature Range (°C)	Measured Nacelle Air Temperature Range (°C)	Predicted Nacelle Air Temperature Range (°C)
Sea level	29	Not indicated	33 to 83	Not modeled since engine surface temperature range not indicated
>5	-21	Not indicated	-18 to 30	
0.4	28	102 to 392	33 to 82	23 to 33
0.6	Not indicated	176 to <260	≈ 90 to 160	20 to 115
0.6 to 14	Not indicated	Not indicated	≈ 100 at 0.6 km to ≈ 10 at 14 km	Not modeled since engine surface temperature range not indicated
3	-3	74 to 588	22 to 93	-3 to 28
Sea level	-3	60 to 467	19 to 55	16 to 39
3	1	81 to 587	27 to 94	-3 to 28
3	Not indicated	Up to 260	10 to 93	6 to 12
3	Not indicated	Up to 750	< 110 to < 275	7 to 23
Sea Level	Not indicated	Not indicated	210 ^{xxiv}	Not modeled since engine surface temperature range not indicated

Cold Soak Conditions

The NGP also examined the effect of fire suppression effectiveness under cold-soak conditions, i.e., cases in which the aircraft had been on the ground in a cold climate. Of issue was the relationship between the OAT, the boiling point of a fire suppressant, and suppressant discharge under such conditions, especially during takeoff. Such conditions have been used to support the need for a suppressant with a boiling point of -40 °C (-40 °F) or lower.

Bein performed a literature review to identify existing work related to evaluation of aircraft cold soak conditions.⁴⁴ Work performed by Transport Canada was identified that characterized aircraft wing

^{xxiv} Though the engine surface temperature data was not available for use in during modeling, this temperature data point from Reference 13 is listed as it was the highest nacelle airflow temperature found in the literature during the nacelle air temperature modeling effort.

surface temperatures during ground operations during Canadian winter and aircraft cold soak conditions after flights at altitude.^{86,87} For flights in Canada and Alaska, a general conclusion was that wing temperature surveys of aircraft returning from flights at altitude failed to find evidence of significantly cold-soaked wing conditions. Their surveys generated data that indicate the following relative to non-deiced spot wing temperatures for aircraft on the ground:

- Below 0 °C (32 °F) OAT, wing temperatures were generally higher than OAT. The temperature difference generally ranged from 2 °C at 0 °C OAT to slightly greater than 6 °C at -25 °C OAT.
- Above 0 °C (32 °F) OAT, wing temperatures were generally lower than OAT.
- Radiative cooling on the ground (i.e., aircraft parked overnight in cold weather) is more likely than in-flight conditions to result in cold-soak conditions. Possible wing-to-OAT differential due to radiative cooling may range from -6 °C at 0 °C OAT and reducing to -2 °C at -25 °C OAT.⁸⁸
- The lowest OAT for which cold-soak data was recorded was -13 °F (-25 °C), suggesting that aircraft operations on the ground in cold or extreme cold climates is infrequent. (Note that this correlates well with the operational fire experience indicated in Figures 2-36 and 2-37.)

The data generated during the Transport Canada surveys includes a flight profile for a flight at altitude in Alaska during which wing surface temperatures were recorded. The cruise altitude is not specified but is likely to be approximately 9 km (30,000 ft) based on the aircraft type that was instrumented and flown. At the time liftoff from the ground occurred, measured wing temperatures were higher than both OAT and the initial wing temperatures. During takeoff climb, there was a test point indication of a temperature increase of approximately 3 °C over the first 5 min before that test location temperature began to decrease, whereas all other measurement locations were noted to begin to decrease immediately. At 15 min after takeoff, wing temperatures were generally -20 °C (-5 °F). At 60 min after takeoff, wing temperatures were generally -23 °C (-10 °F). Wing temperatures were found to warm to approximately 7 °C (20 °F) in 15 min during descent to final landing. Except for the radiative cooling condition, these data indicated that temperature conditions of an operational aircraft are likely to be higher than the cold soak temperature conditions, suggesting that aircraft component temperatures are also likely to be higher. To analyze the concern of over too low fire suppressant and system component temperatures under cold or extreme cold temperature conditions during takeoff, a model was constructed to estimate stagnation temperature conditions during takeoff. The premise was that for suppressant bottle(s), distribution lines and components not located near/within heated compartments but adjacent to exterior surfaces, the stagnation temperature should provide a reasonable estimate of likely temperature conditions of components adjacent to the exterior surfaces. Figures 2-44 and 2-45 depict graphically the results of the minimum and maximum temperature profiles for cases modeled for a jet transport aircraft, fighter aircraft, and a turboprop transport aircraft.

- In Figure 2-44, an initial OAT for cold/severe-cold environments was based on the JAR-1 Arctic Standard Climate profile, and then the profile was applied during takeoff climb. This scenario was assumed to estimate a lower bound profile. The modeling estimated that during takeoff climb within a standard arctic profile that the stagnation temperatures can increase to greater than -25 °C (-13 °F) for a period of time, taking into consideration the likelihood that aircraft surface temperature will be greater than OAT at takeoff. The relevance of this is that fire suppression system components adjacent to these surfaces are likely to be similar in temperature. (The resultant temperature profiles indicate a period above -32 °C (-25 °F) for

as few as 3.7 min and as long as 14.2 min. The time to reach this threshold was estimated to occur approximately within 1.25 min or within 3.8 min.)

- In Figure 2-45, an initial OAT of -40 °C (-40 °F) was assumed but also applies a temperature bias condition based on difference of wing skin temperature to OAT described in the Transport Canada work. The JAR-1 Arctic Standard Climate profile is then applied during takeoff climb with the bias condition continuously applied to estimate a potential upper bound profile. The resultant temperature profiles indicated a period above -26 °C (-15 °F), for as few as 3 min and as long as 14.8 min. The time to reach this threshold was indicated to occur approximately within 1.25 min or within 3.6 min. Because of the duration of the climb for the jet transport aircraft, temperature was indicated to increase for a period of time to approximately -15 °C (4.5 °F) before beginning to decrease.

In each of the scenarios modeled it was clear that fire suppressant and system component temperatures could increase above -40 °C (-40 °F) during takeoff profiles for some period of time but continued ascent through the JAR-1 Arctic Standard Climate profile would effect temperature decrease. Thus it became necessary to review the DoD Safety Center data and the studies conducted during the TDP for establishing halon 1301 system effectivity to gage the DoD's historical engine nacelle fire risk during takeoff.

Risk

Within DoD System Safety, organizations assess risk associated with hazards identified during development as well as during fielded operations of weapon systems, including aircraft systems and subsystems. Analytical processes are applied to assess worst-credible and most-probable severity and likely occurrence of identified hazards. Likely occurrence may be expressed as a rate of occurrence, typically per flight hour, or as a probability. The resulting assessment of severity and probability is then categorized as to the level of risk it presents (e.g., high, medium, low, unacceptable, etc.). Generally, assessment of fire hazards results in an assignment of a "Catastrophic" severity.^{xxv} The issue becomes whether the rate of occurrence or probability of a fire hazard results in a risk that is deemed not low.

For example, when the total number of engine nacelle fires evaluated during the TDP for establishing halon 1301 system effectivity are considered, the aggregate rate of occurrence for a nacelle fire event during the period evaluated is approximately 8 per 10⁶ flight hours. Those same data were reviewed during the NGP to estimate the potential hazard frequency of a catastrophic event due an unsuppressed engine nacelle fire hazard, as summarized in Tables 2-6 and 2-7. Note that in each case, the hazard frequency would be assessed as improbable. A catastrophic-improbable hazard is categorized as low risk, which is typically accepted by military aviation program managers. If the same rate of occurrence is considered in conjunction with operating in a low (or high) temperature climatic extreme, the hazard frequency would also be assessed as improbable as indicated in Tables 2-8 and 2-9.

^{xxv} A Catastrophic hazard severity is defined in DoD specification MIL-STD-882D, Standard Practice for System Safety, as a hazard that can result in death, permanent total disability, loss exceeding \$1M, or irreversible severe environmental damage that violates law or regulation. The risk from fire in an aircraft would be presented to an aircraft program manager as the potential consequences of the different categories of possible fires and the likelihood of fire occurring for each category.

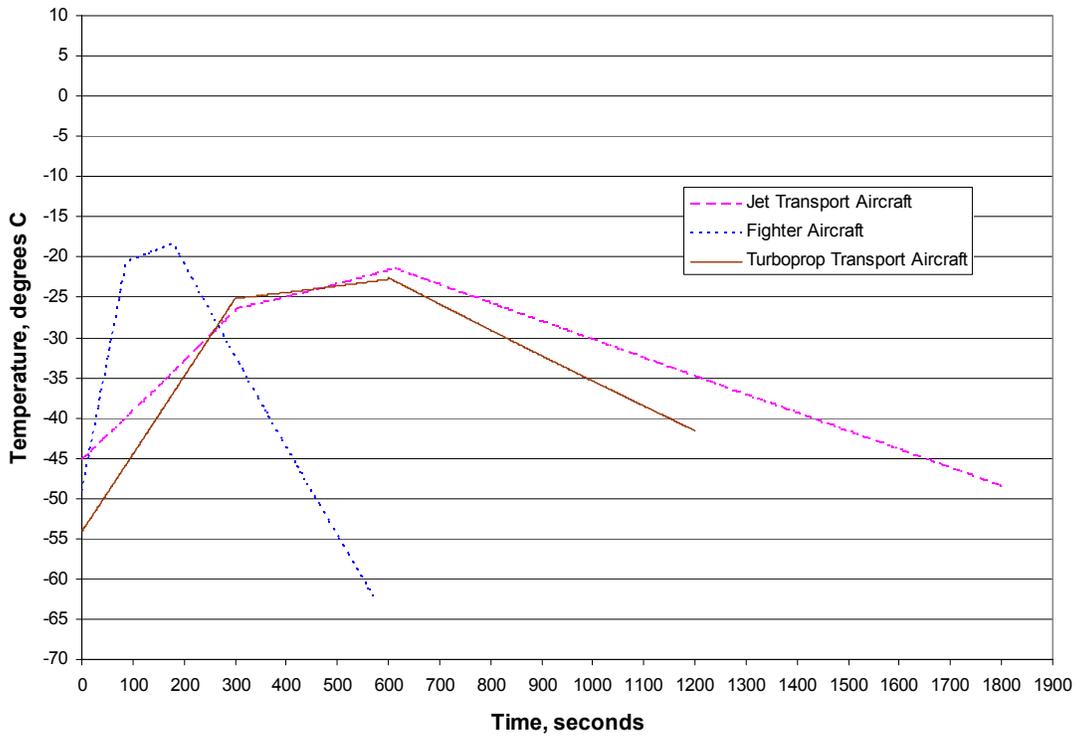


Figure 2-44. Initial OAT per JAR-1 Arctic Standard Climate.
(OAT at Takeoff is -50 °C (-58 °F).)

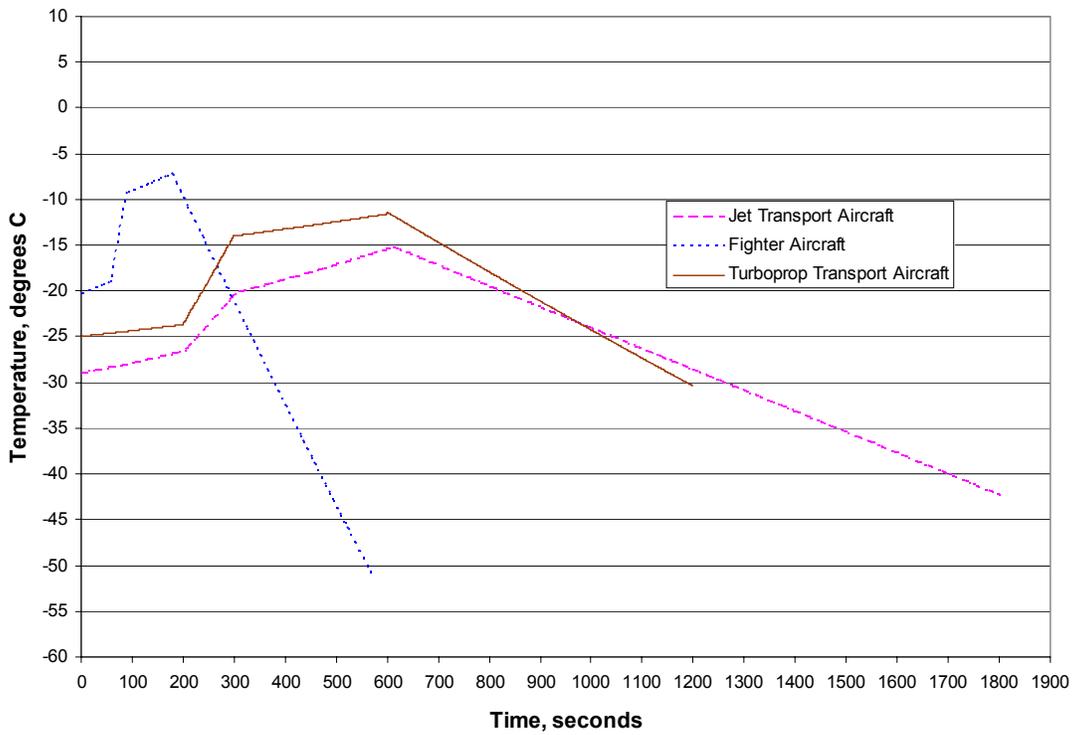


Figure 2-45. OAT at Takeoff is -40 °C (-40 °F) with Bias Applied to OAT.

Table 2-6. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire, Any Time (Does not Consider Multiple Engines).^{xxvi}

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence At Any Given Time	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	1	0.24	0.09	9.84E-08	Improbable (E)
Rotary	0.35	1	0.53	0.27	4.15E-07	Improbable (E)
Aircraft Category	Probability Occurrence On Ground	Probability Occurrence At Any Given Time	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.45	1	0.38	0.03	4.25E-08	Improbable (E)
Rotary	0.65	1	0.36	0.01	1.94E-08	Improbable (E)

Table 2-7. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire, Any Time (Assumes Two Engines per Aircraft).^{xxvi}

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence At Any Given Time	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	1	0.24	0.09	4.92E-08	Improbable (E)
Rotary	0.35	1	0.53	0.27	2.08E-07	Improbable (E)
Aircraft Category	Probability Occurrence On Ground	Probability Occurrence At Any Given Time	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.45	1	0.38	0.03	2.13E-08	Improbable (E)
Rotary	0.65	1	0.36	0.01	9.70E-09	Improbable (E)

^{xxvi} Probabilities in Tables 2-6 and 2-7 are derived from References 45 and 46. End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period and aircraft evaluated in those references and is higher than the rate of $4.9/10^6$ flight hours indicated in an evaluation of Army rotary aircraft fires per Reference 81. No rotary aircraft were indicated lost in ground fire events in Reference 46, but a 1 % probability is assumed for discussion purposes.

Table 2-8. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire in a Climatic Extreme (Does not Consider Multiple Engines).^{xxvii}

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence In Climatic Extreme	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	0.2	0.24	0.09	1.97E-08	Improbable (E)
Rotary	0.35	0.2	0.53	0.27	8.30E-08	Improbable (E)
Aircraft Category	Probability Occurrence On Ground	Probability Occurrence In Climatic Extreme	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.45	0.2	0.38	0.03	8.50E-09	Improbable (E)
Rotary	0.65	0.2	0.36	0.01	3.88E-09	Improbable (E)

Table 2-9. Estimate of Rate of Occurrence of Aircraft Lost Due to Failure to Extinguish a Nacelle Fire in a Climatic Extreme (Assumes 2 Engines per Aircraft).^{xxvii}

Aircraft Category	Probability Occurrence In Flight	Probability Occurrence In Climatic Extreme	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.55	0.2	0.24	0.09	9.84E-09	Improbable (E)
Rotary	0.35	0.2	0.53	0.27	4.15E-08	Improbable (E)
Aircraft Category	Probability Occurrence On Ground	Probability Occurrence In Climatic Extreme	Probability Occurrence Fire Not Extinguished	Probability Occurrence Aircraft Lost	End Event Rate of Occurrence Per Flight Hour	MIL-STD-882 Hazard Frequency
Fixed-wing	0.45	0.2	0.38	0.03	4.25E-09	Improbable (E)
Rotary	0.65	0.2	0.36	0.01	1.94E-09	Improbable (E)

The implication of the preceding is that when considering the risk of a catastrophic end event, the likelihood is driven primarily by whether fire occurs, and this likelihood is reduced by the likelihood of operating in a climatic extreme (e.g., cold temperature conditions). For example, Figure 2-46 summarizes fixed-wing fire mishaps and incidents by phase of operation. The takeoff-related categories total to 18.7 % of all events, and approximately 16 % of suppressant releases occurred during the takeoff phases. However, only 4 % of the takeoff-related releases (and thus fewer than 1 % of all releases) occurred in land environments categorized as cold or severe cold. This strongly suggests that risk is low (i.e., an

^{xxvii} Probabilities in Tables 2-8 and 2-9 derived from References 45 and 46. End event rate of occurrences determined by multiplying $8/10^6$ flight hours by probabilities indicated. This frequency is based on the aggregate number of nacelle fires over all flight hours for the period and aircraft evaluated in those references and is higher than the rate of $4.9/10^6$ flight hours indicated in an evaluation of Army rotary aircraft fires per Reference 81. No rotary aircraft were indicated lost in ground fire events in Reference 46 but a 1 % probability is assumed for discussion purposes. Probability of operation in climatic extreme assumes exposure to either MIL-HDBK-310 20% low or high temperature WWAE.

improbable hazard frequency) for an engine nacelle fire during takeoff on a cold-soaked aircraft and in which the fire suppression system fails to extinguish the fire and a catastrophic event occurs.

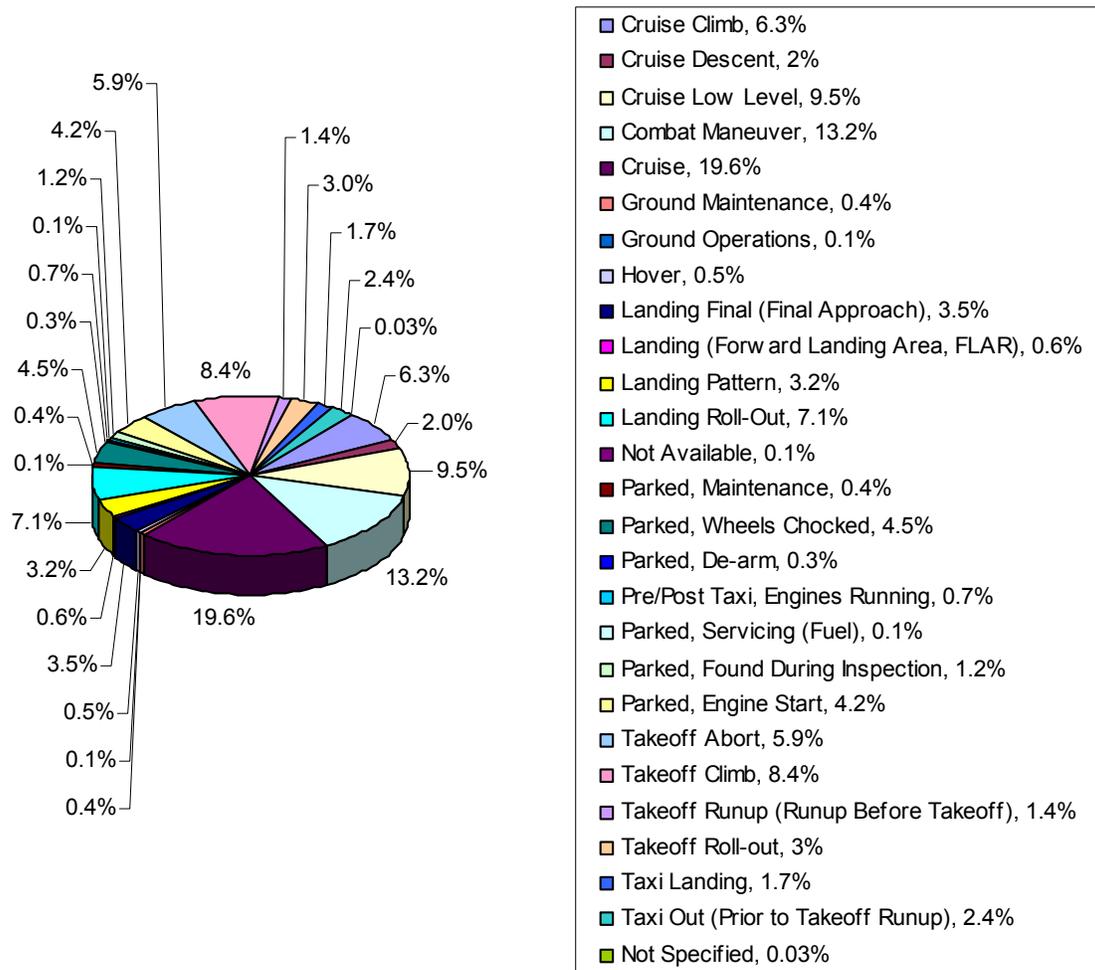


Figure 2-46. Fixed-Wing Aircraft Fire Mishaps and Incidents by Phase of Operation.

Summary – Severity of Aircraft Temperature Environment Criterion

The conservatism of the $-40\text{ }^{\circ}\text{C}$ criterion can be seen when the historical data is plotted against the DoD climatic land environment design guidance and previously published aviation fuel flammability limit profiles in conjunction with various atmospheric profiles. Figures 2-47 and 2-48 plot the geographic locations of ground fire events for rotary aircraft and fixed-wing aircraft, respectively, vs. the DoD climatic land environment design guidance. In these figures, it can be seen that the clear majority of ground fire events occurred in geographic locations associated with the basic land environment category. Figures 2-49 and 2-50 plot the nearest-to geographic locations of in-flight fire events for rotary aircraft and fixed-wing aircraft, respectively, to depict where these events occurred relative to the climatic land environments.

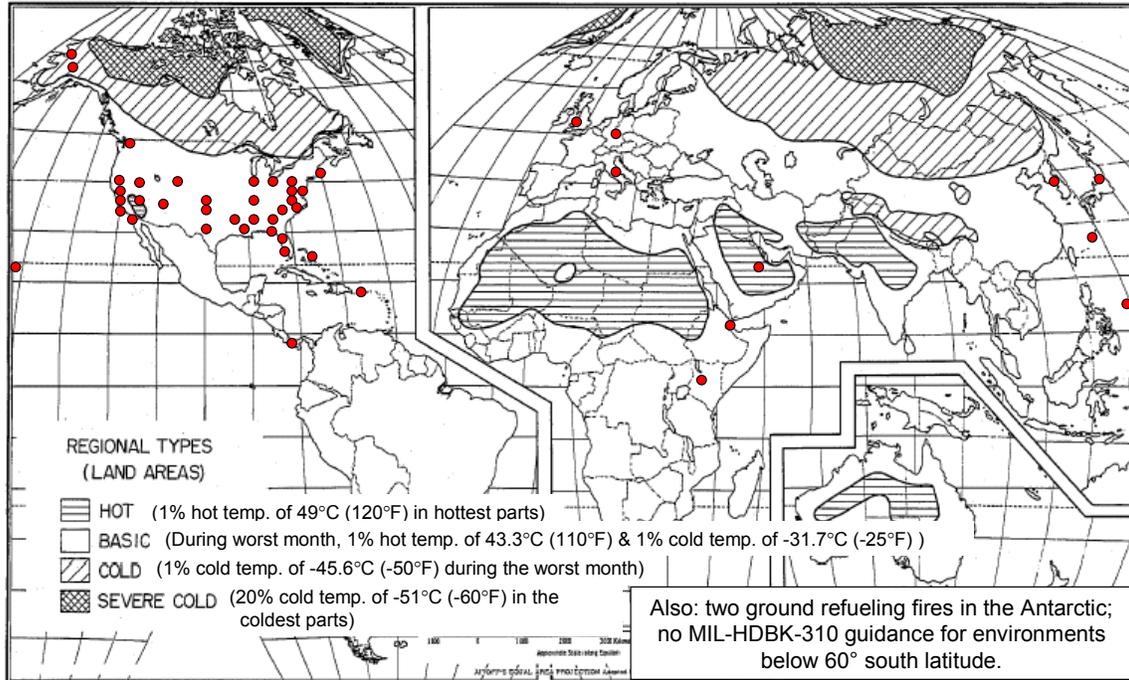


Figure 2-47. Distribution of DoD Rotary Aircraft Ground Fire Locations.⁸⁹

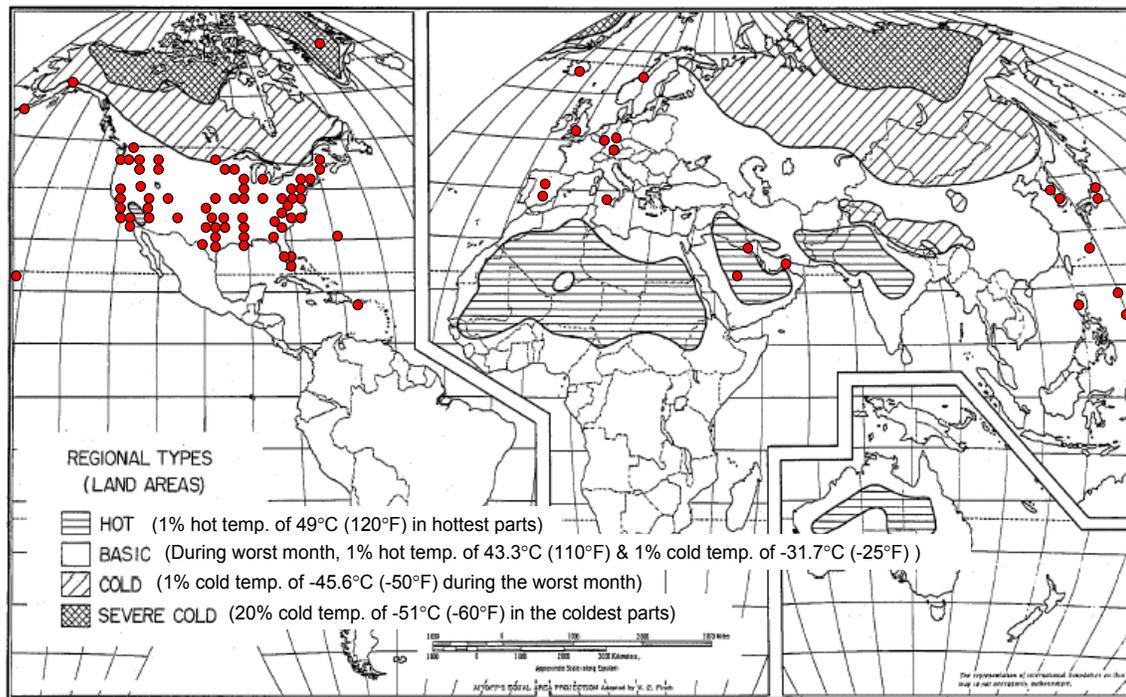


Figure 2-48. Distribution of DoD Fixed-Wing Aircraft Ground Fire Locations.⁸⁹

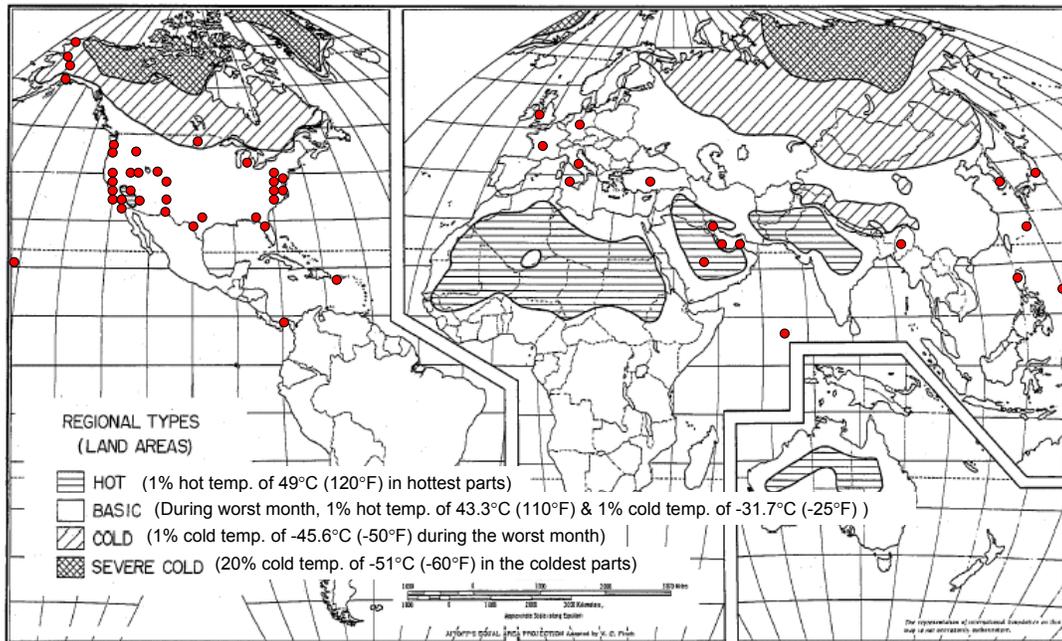


Figure 2-49. Distribution of DoD In-Flight Rotary Aircraft Fire Locations (Nearest-to Locations).⁸⁹

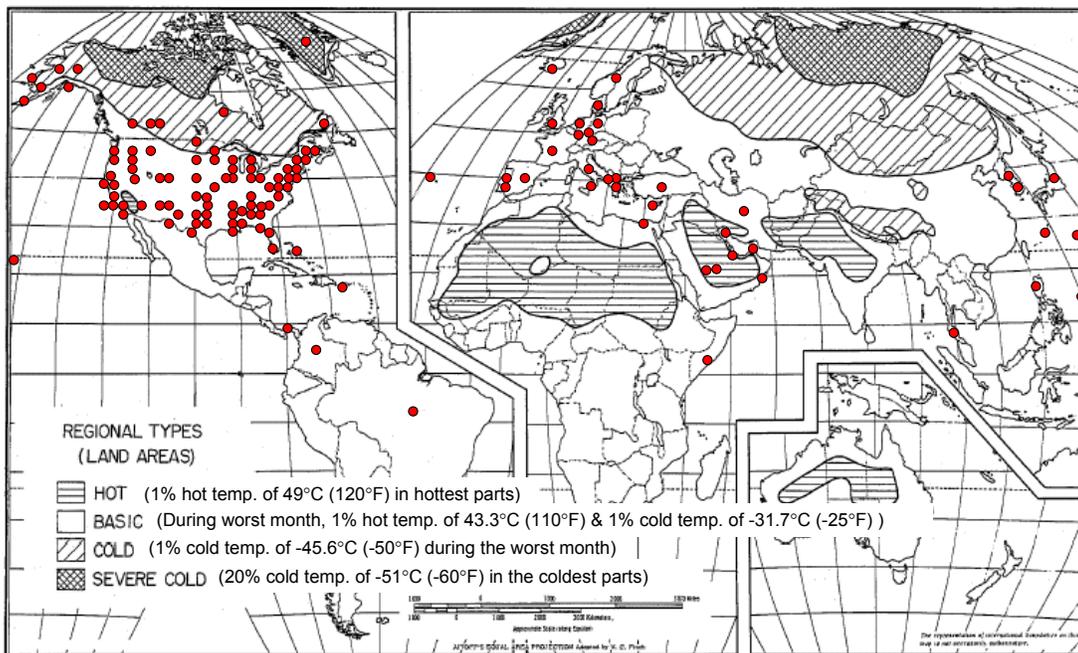


Figure 2-50. Distribution of DoD In-Flight Fixed-Wing Aircraft Fire Locations (Nearest-to Locations).⁸⁹

In Figure 2-51, the DoD rotary aircraft fire data are plotted vs. the standard atmosphere (blue line) and tropical atmosphere profiles (orange line) and Jet A (right) and Jet B (left) flammability limit profiles. Also indicated is the typical rotorcraft operational ceiling and the majority (97 %) suppressant release envelope derived from Figures 2-38 and 2-39. Also shown for reference purposes is an artifact from previous fire testing, described previously in Section 2.3.5, to determine the flame spectral characteristics for optical fire detection at altitude: that testing at pressure conditions representative of altitude of 11.5 km (35,000 ft) resulted in inability to maintain sustained combustion. The preponderance of fire events and suppressant releases on rotorcraft is shown to occur well below the typical operational ceiling for rotorcraft and well above the $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$) NGP boiling point criterion, with 97 % of all rotorcraft suppressant releases occurring above $-12.2\text{ }^{\circ}\text{C}$ ($10\text{ }^{\circ}\text{F}$).

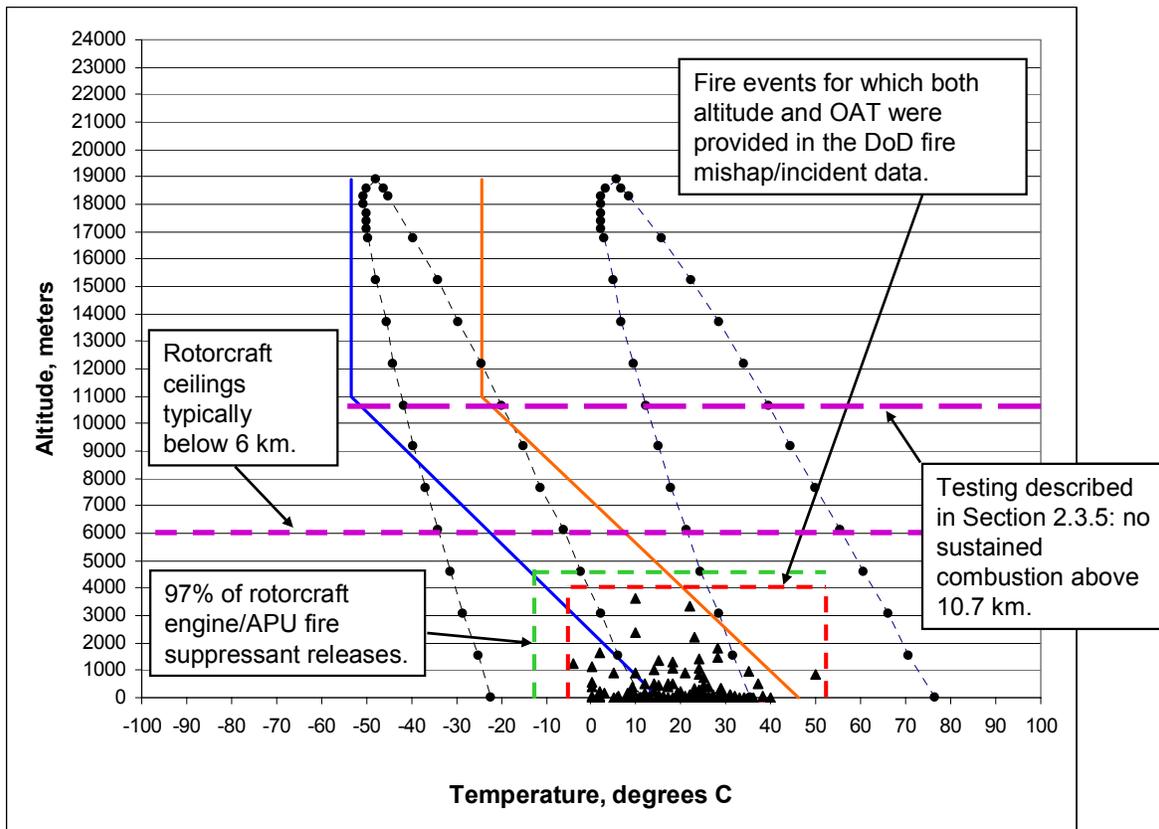


Figure 2-51. DoD Rotary Aircraft Fire Data vs. Atmospheric Profiles, Flammability Limit Profiles, Operational Ceiling, and Suppressant Release.⁸⁹

Figure 2-52 plots the fixed-wing aircraft fire data in similar fashion. The overwhelming majority of fire events from the data is indicated below 7 km (23,000 ft), with 94 % of all suppressant releases occurring at an altitude just above 9 km (29,500 ft). Qualitatively, this latter altitude as a ceiling correlates well with the results of the conclusions drawn from previously described nacelle air temperature modeling and the testing described previously in Section 2.3.5. Additionally, the overwhelming majority of relevant nacelle air temperature modeling cases occurred for OAT conditions at or above $-25\text{ }^{\circ}\text{C}$ ($-13\text{ }^{\circ}\text{F}$), which also correlates well with that very few fire events are indicated below this OAT as well as with the distribution of fire events depicted previously in Figures 2-48 and 2-50. In the basic land environment depicted in those figures, the worst cold temperature exposure is 1% at $-31.7\text{ }^{\circ}\text{C}$ ($-25\text{ }^{\circ}\text{F}$), which also correlates well with the temperature boundary for 94 % all suppressant releases in Figure 2-52.

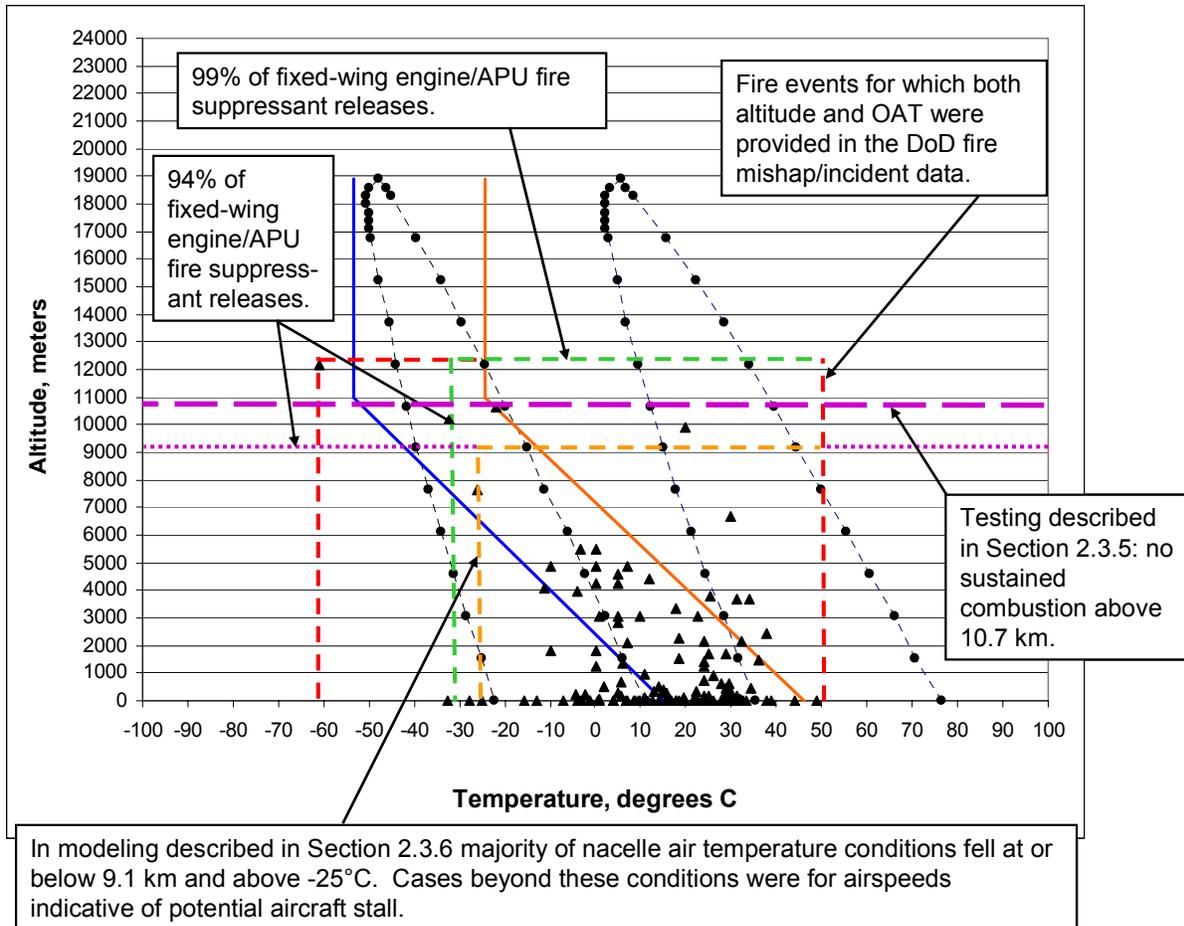


Figure 2-52 DoD Fixed-Wing Aircraft Fire Data vs. Atmospheric Profiles, Flammability Limit Profiles, Potential Stall Condition and Suppressant Release.⁸⁹

In summary, the preceding figures indicate:

- As altitude increases, the number of fire events decreases.
- As altitude increases, occurrence of fire events trends above the standard atmosphere profile.
- Rotorcraft fire events occurred below 4 km (13,000 ft), below the typical operational ceiling for those aircraft, with 97 % of all suppressant releases occurring for OAT above -12.2°C (10°F).
- A clear majority of fixed-wing aircraft fire events occurred below 6.1 km (20,000 ft).
- Similar to publicly-available data for commercial aviation shown in Figure 2-37, the vast majority of fixed-wing aircraft fire events, ground and in flight, occurred with OAT above -20°C (-4°F).
- In-flight rotary and fixed-wing aircraft fire events occurred predominantly near geographic locations associated with the basic land environments, for which DoD design guidance indicates the worst cold temperature exposure as 1 % at -31.7°C (-25°F).

The -40°C criterion used by the NGP is likely conservative. The plots of the DoD fire mishap and incident data in the preceding figures suggest that qualification of nacelle fire suppression systems at an

OAT of 0 °C (32 °F) would respond to over 90 % of the expected fires, based on past experience. The qualification requirements are generally a DoD safety policy matter that rests ultimately with the DoD aircraft programs. This means that the safety and survivability risks associated with qualifying a system with a suppressant that has a boiling point greater than criterion of -40 °C would need to be assessed to determine whether the risk level is acceptable by the aircraft program manager, and the specific performance requirements for the fire suppression system would be reflected in the aircraft specification.

2.3.7 Reignition

Reignition within an engine nacelle or dry bay compartment is always a threat so long as fuel vapor and air can come in contact with sufficiently hot surfaces or if there is some other type of ignition source present, such as arcing from an electrical harness or sparks generated from a rotating component unintentionally in contact with another component. Within an engine nacelle, hot surfaces are the primary ignition threat, as engine case temperatures can easily exceed 538 °C (1000 °F). After suppressant discharge within a nacelle or APU compartment, hot fuel vapor may exist at levels which are flammable, leading to the possibility of reignition. A puddle of hydraulic fluid or jet fuel leaking from a cracked or failed line can vaporize as heat is transferred from a nearby hot metal surface. In addition, hot metal surfaces may occur due to heating by the fire itself, which could occur within a nacelle or APU compartment or even a dry bay compartment. Reignition may then arise from contact of the reactive fuel/air mixture with the hot metal surface.⁴³ In full-scale nacelle fire suppression testing during the TDP, it was observed that when hot operating engine case temperatures were simulated, reignition could occur due to residual fuel adhering to the surface or fuel continuing to be sprayed before being shut off. This was seen typically at surface temperatures at or above 538 °C.⁹⁰ That testing also indicated that when a hot metal surface at 704 °C (1300 °F) was present, greater quantities of fire suppressant were required when compared to no hot surface reignition condition. The NGP has also investigated how induction and convection may control the reignition process. This investigation found that reignition is controlled by cooling and mass transport towards the hot surface. A “worst-case” scenario for reignition was characterized by maximizing the fuel mass transfer while keeping the characteristic time for cooling of the surface shorter than the time to attain a flammable mixture.⁹¹

Reignition suppression requirements within a dynamic environment on an aircraft are very dependent on the specific scenario. Currently, there is no reliable method to predict the optimal agent requirements to prevent it, other than conduct of full-scale testing for the unique aircraft configuration for *all* possible reignition conditions. Strategies to prevent reignition include removing fuel vapor, reducing surface temperatures, either through design or active cooling, and inerting the fuel/air mixture with a suppressant. Fuel vapors can be removed intentionally by design or unintentionally as an affect of the ventilation airflow required by a compartment for cooling. Leaking flammable fluids can be removed by drain holes and systems or sump ejectors. Typically, before activation of the engine nacelle fire suppression system, the jet fuel to the particular engine and hydraulic fluid flow to engine compartment accessories is shut down. This limits the amount of fuel in the nacelle, but it could take a relatively long time to remove the combustibles from the nacelle, especially low vapor pressure liquids.

In considering the issue of reignition, it is important to distinguish between the temperature at which autoignition occurs vs. hot surface ignition. The autoignition temperature (AIT) is also referred to as the spontaneous ignition temperature, self-ignition temperature or autogenous ignition temperature. It is the lowest temperature at which the substance will produce a hot-flame ignition in air without the aid of an

external spark or flame.⁹² This temperature is determined by heating a sample of a fluid in air in a laboratory flask. The AITs for JP-type military aviation fuels range between 204 °C (400 °F) and 232 °C (450 °F). For MIL-H-83282-type hydraulic fluid, the AIT is approximately 354 °C (670 °F). Aircraft manufacturers will typically self-impose a safe design temperature (SDT) practice that is usually 10 °C (50 °F) lower than the AIT of a fluid that may come in contact with a hot surface. This cannot be accomplished for engine nacelles or APU compartments due to their case temperatures.

Reignition on a hot surface within a dynamic environment such as within an aircraft engine nacelle is distinct from autoignition. Extensive lab-scale and full-scale testing has been conducted over the past several decades that demonstrates, generally, hot surface ignition of aviation JP-type fuels and hydraulic fluids used in military aircraft occurs at surface temperatures greater than the AIT for those fuels and fluids. Minimum hot metal surface ignition temperatures for JP-8 (or kerosene) for ambient temperatures and pressures and low air flows have been found to vary from 360 °C to 650 °C, depending on test conditions. Hot surface ignition temperatures will generally decrease as the size or surface area increases or as fuel contact time increases, and they will generally increase with increasing air velocity.⁹³ An exception is MIL-H-83282 hydraulic fluid, which during testing conducted in a nacelle simulator with a portion of a simulated F-16 engine was found to have the potential to ignite when exposed to a hot surface below the fluid's AIT and when ambient air temperature was heated to at least 150 °C (300 °F). At a ventilation air temperature of 316 °C (600 °F) the fluid would ignite without the hot surface.^{94,xxviii}

From work conducted during the TDP it was asserted that a reasonable target concentration for suppressant in the fire zone (not the free stream) is the concentration which ensures that the most flammable fuel/air ratio cannot occur. Such a suppressant concentration should ensure both flame suppression and prevention of re-ignition for a period of time on the order of the suppressant injection (discharge) duration. After this period, however, it is likely that re-ignition would still be possible.¹³

2.4 FIRE SUPPRESSANTS USED ON AIRCRAFT

As early as 1922, there is reference to implementation of engine compartment fire suppression, which consisted of a fire extinguisher within that compartment that was controlled from the pilot's seat. Additionally, shutters were installed to eliminate external airflow into the compartment.⁹⁵ No specific reference is provided as to the fire suppressant in this case, but one could speculate. The Naval Studies Board reported that in the 1920s, non-fluorinated halon agents were tried experimentally in engine nacelle extinguishers, but their use was abandoned by the U.S. military in favor of the non-corrosive CO₂.⁸ Even as aircraft fire suppression matured, there are instances in which researchers and aircraft designers ponder the rationale for a specific requirement. An example of this is the unpublished technical data and various published statements supporting the certification requirement for engine nacelle halon 1301 fire suppression systems. Regardless, since the identification of stratospheric ozone depletion and subsequent efforts to identify alternatives to the halons for aircraft fire suppression, there have been numerous compilations of the history of fire suppressants used on aircraft.

^{xxviii} Previous research indicated in Reference 149 also indicated for MIL-H-83282 an AIT of 354°C and a stream hot manifold ignition temperature of 322°C. The later was determined by Federal Test Method Standard (FTMS) 7916, Method 6053. In hot surface ignition studies surveyed in Reference 150, some of the studies showed MIL-H-5606 was more ignitable than MIL-H-83282, whereas other studies surveyed, which used different test configurations, indicated diametrically opposite results.

Perhaps the most comprehensive compilations are those in reports generated by the National Institute of Standards and Technology (NIST) under the TDP, by the Federal Aviation Administration (FAA) as part of work it has been performing related to development of minimum performance standards for halon alternative nacelle fire suppression systems, and by Kidde Aerospace and Defense, PLC, one of the primary suppliers of aircraft fire suppression system components today.^{13,96,97} Additional historical references are contained within the investigation performed by the NGP to document active suppression technologies for ullage fire/explosion protection and work done by Boeing to document options for dry bay fire protection.^{31,98}

The following provides a brief summary of fire suppressants that have been used on DoD aircraft for powerplant and dry bay fire protection, excluding halon alternative suppressants identified during the TDP or developed under the NGP. The reader is referred back to Section 2.2.6 for discussion of suppressants that have been utilized for ullage fire suppression. Fielding of halon alternative suppressants subsequent to the TDP is discussed briefly in the next section. Throughout this section, the phrase “powerplant” may refer to an engine or APU compartment or other type of powerplant described earlier in this chapter.

2.4.1 Powerplant Compartments

The requirements for and implementation of aircraft fire suppression for powerplant compartments have evolved for a variety of reasons, primary among them being powerplant design and the fire suppressant. For example, powerplant fire suppression system design guidance published by the CAA in 1943 for use of methyl bromide (halon 1001) and CO₂ was relative to mass airflow in the compartment and the number of cylinders in a radial cylinder engine installation. For potential fire zones with high airflow, agent quantity was to be based on 20 % of the mass airflow through the zone in two seconds.^{99, xxix} Agent distribution was to be accomplished using spray nozzles or perforated tubes providing approximate equal distribution and a “sheet of agent spray” across the cross section of the protected zone orthogonal to the airflow. These systems were to become known as conventional distribution systems. Figure 2-53 illustrates an example of this type of installation. The aircraft engine compartment fire suppression systems for the B-36 and XR60-1 aircraft employed halon 1001. Some of the first aircraft to deploy fixed CO₂ fire suppression systems for engine compartment protection included the C-46, C-47, B-17, B-26, and the B-45 aircraft.

During World War II the German Navy sponsored efforts by I.G. Farbonindustrie to develop an alternative to halon 1001 due to its toxicity, which resulted in the development of chlorobromomethane (CB or halon 1011) in the 1939 to 1940 time period. Halon 1011 was determined to be as effective as halon 1001 and less toxic. Testing in 1942 by then Junkers/Dessau for the German Luftwaffe focused on developing a powerplant fire suppression system using Dachlaurin (D-L), a mixture of 65 % halon 1011 and 35 % CO₂. In early 1945 the Luftwaffe approved the principle of the D-L system and ordered its installation on all German military aircraft, subject to then not-yet-established priorities. It was planned that the D-L system was to be installed on the Messerschmitt ME 262, the first operational jet-powered fighter.¹⁰⁰ Given the time the directive was issued, it is likely D-L did not come into widespread use before the end of the war. After the war extensive evaluation of halon 1011 was conducted within the U.S. and by 1950, the USAF required use of halon 1011 systems instead of CO₂ systems in new aircraft

^{xxix} As of the writing of this book, CAA reports are available from the Department of Transportation’s Online Digital Special Collections at <http://dotlibrary.specialcollection.net/>.

and subsequently issued a specification for such systems.^{101,102,103} Design guidance for use of halon 1011 in powerplant fire suppression system evolved as jet propulsion became more widespread and was provided relative to compartment airflow and free volume. However, the conventional distribution system approach was still employed for halon-1011-based fire suppression systems. Examples of these arrangements are shown in Figures 2-54 and 2-55. Some aircraft known to have utilized halon 1011 for powerplant fire suppression include the C-97, C-119F, C-123, C-130 and B-57 aircraft.

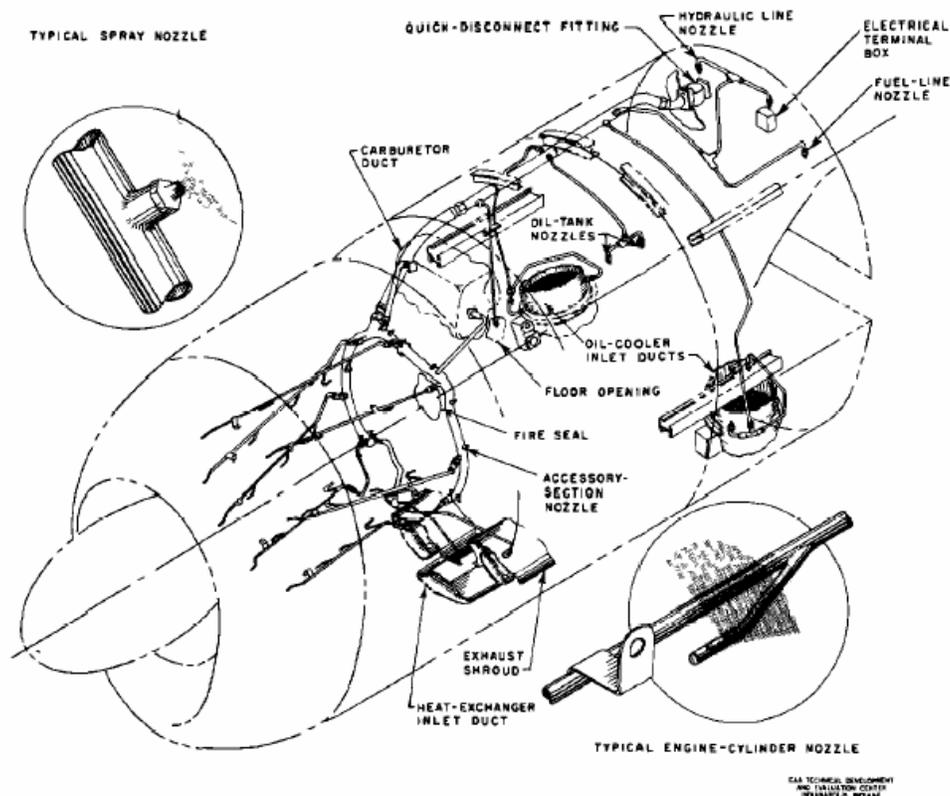


Figure 2-53. Example Conventional Halon 1001 Powerplant Fire Suppression System Distribution Installation, USN Turboprop Powerplant.¹⁰⁴

Techniques for assessing adequate distribution, which are described later in this section, changed along with the evolution to jet propulsion powerplants. During testing conducted by the CAA, it was observed during filming and time recording of discharge duration from a conventional distribution system that the apparent full-strength discharge time was 1 s.¹⁰⁴ (The certification requirement that had been established for the conventional fire suppression systems was, and still is, a required concentration level maintained at all measured locations throughout the compartment for a minimum of 2 s.) During these same tests, comparisons were made of fire suppression performance of conventional systems vs. open-ended systems, which later became known as high-rate-discharge (HRD) systems. The HRD systems presented a simplified distribution approach in that perforated distribution lines were replaced with few open tubes out of which the fire suppressant would discharge at a much higher rate. Rather than relying on plumbing to disperse the suppressant, dispersion would be effected by the turbulent mixing of the suppressant discharge jet and the nacelle mass air flow. Further testing by the CAA demonstrated that the HRD design required less halogenated fire suppression agent to suppress nacelle fires and simplified

distribution system design. Testing conducted later by the Wright Air Development Center (WADC) promoted the conclusion that the efficiency of a fire suppression system would be improved with increasing suppressant discharge velocity, and that a “critical saturation value,” in percent by volume, occurred between 15 m/s (50 ft/s) and 30 m/s (100 ft/s) for the suppressants evaluated (halon 1011, halon 1301, and dibromodifluoromethane or halon 1202).¹⁰⁵ The example fire suppression system installation shown earlier in Figure 2-8 is a representative halon 1301 HRD system installation.

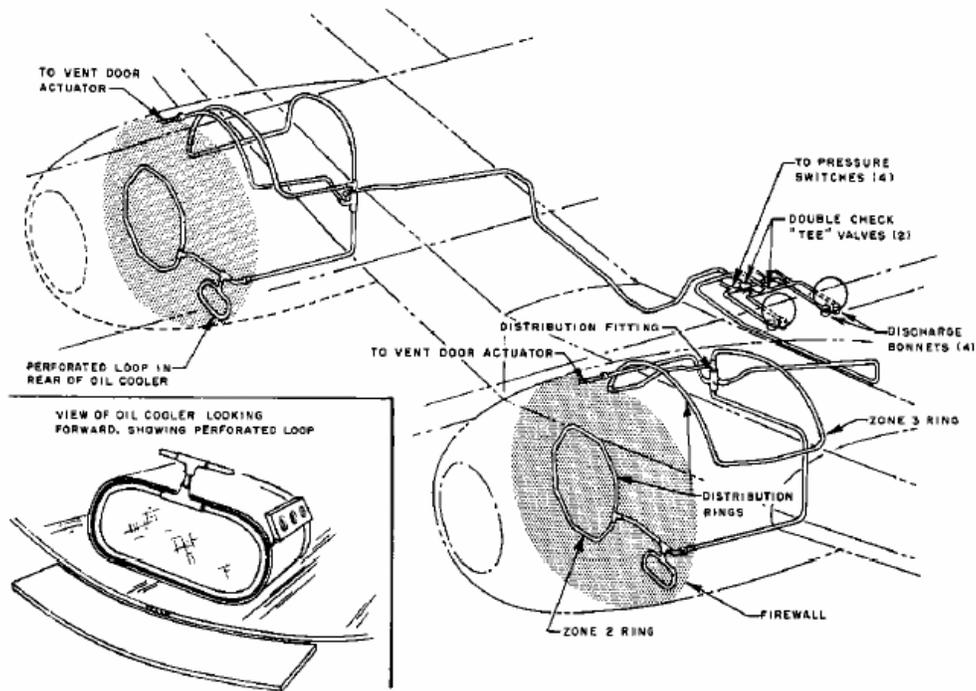


Figure 2-54. Example Conventional Halon 1011 Fire Extinguishing System Distribution Installation, Turboprop Powerplant.¹⁰⁶

Halon 1301, which had been determined to be superior to halons 104 and 1001 in hand portable extinguishers during testing conducted by the Purdue Research Foundation (PRF),¹⁰⁷ was also found to be well-suited for use in powerplant HRD systems. During CAA tests that were performed that resulted in the design guidance for halon 1301, in which a minimum discharge duration of 0.5 s is required, discharge durations varied between 0.5 s and 0.9 s.^{108,109,110} It is interesting to note that technical intelligence gathered after the end of World War II suggested that design policy for engine compartment CO₂ fire suppression systems followed by the Imperial Japanese Navy required discharge within 1 s.⁵² A timeline of the evolution of the 0.5 s duration requirement for HRD systems can be hypothesized based on year of publication of the reports and specifications as follows:

- 1948: As mentioned previously in Chapter 1, the U.S. Army commissioned the PRF to search for a suppressant of high fire suppression efficiency but low toxicity. During flammability limit testing a halon 1301 inerting concentration was determined as 6 % volumetric concentration. This testing was not related to engine nacelle fire suppression.

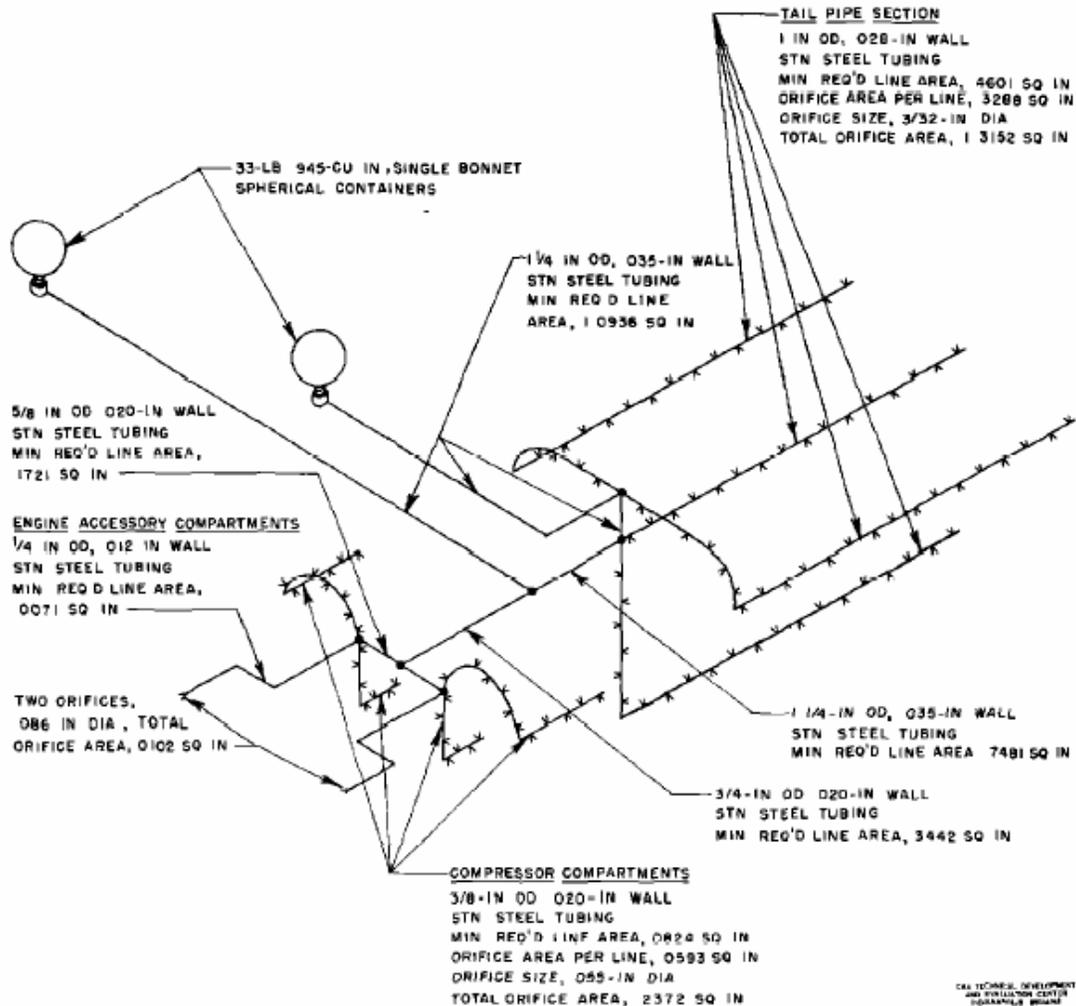


Figure 2-55. Example Conventional Halon 1011 Fire Extinguishing System Distribution Installation, USAF Turbojet Powerplant.¹¹¹

- 1953: Fire testing is conducted by the CAA to determine the minimum amounts of suppressant required for varying airflows using CO₂ and halons 1001, 1011, and 1202.¹¹² Statham Laboratories began manufacturing the Model GA-1 Gas Analyzer for the USAF for use in measuring suppressant concentrations based on an experimental gas analyzer developed by the USAF.¹¹³ This device is to later become known throughout the aviation fire suppression field as the Statham Analyzer.
- 1955: Fire and suppressant concentration testing was conducted by the CAA using halon 1011. A recommendation was developed that halon 1011 systems provide a minimum 15 % volumetric concentration for 1 s.¹⁰⁶
- 1956: Fire testing of HRD systems was conducted by the CAA using CO₂ and halons 1001, 1011, 1202, and 1301, and design formulae for suppressant quantity are published. In successful fire extinguishment tests using the halons, discharge durations are indicated to have varied between 0.5 s and 0.9 s.¹⁰⁸ For CO₂ the duration was indicated to have varied between 1.25 s and 1.35 s.

- 1958: Fire testing of conventional and HRD systems was conducted by the CAA for the Northrop F-89 Scorpion using halons 1011, 1202 and, to a lesser extent, halon 1301.¹¹⁴ This effort included specific tests to evaluate discharge duration and distribution using halon 1011. An overlapping time period of 0.44 s was noted for the two compartment sections evaluated, as indicated in Figure 2-56. (In Figure 2-56 the time axis is in 0.125 increments, thus 0.44 occurs between three and four increments.) Though the report indicates that by the time halon 1301 had been evaluated in the HRD system for fire testing some degradation in the test article had occurred, there is no indication in the report that this was a factor in the halon 1011 discharge duration and distribution tests (i.e., they may have been completed prior to conduct of halon 1301 fire testing).
- 1959: Fire and concentration measurement testing (using a then Statham Laboratories concentration analyzer) at WADC concluded for halon 1301 that roughly a 5.8 % “critical saturation value,” in percent concentration by volume, is required for fire extinguishment.¹⁰⁵ Later during the year, the required minimum relative concentration for halon 1301 was published as 15 %, which was specified to be maintained in all parts of the affected zone and persist in each part of the zone for at least 0.5 s at normal cruising condition. The relative value is that indicated by the Statham measurement device corresponding to a halon 1301 6 % volumetric concentration. At the end of the year, the military specification for installation and test of HRD aircraft fire suppression systems, MIL-E-22285, was issued.¹⁰⁹ The specification includes the previously published halon 1301 design formulae for suppressant quantity.
- 1960: The military specification for installation and test of HRD aircraft fire suppression systems was reissued, revising the concentration requirement from 15 % relative to 6 % volumetric.

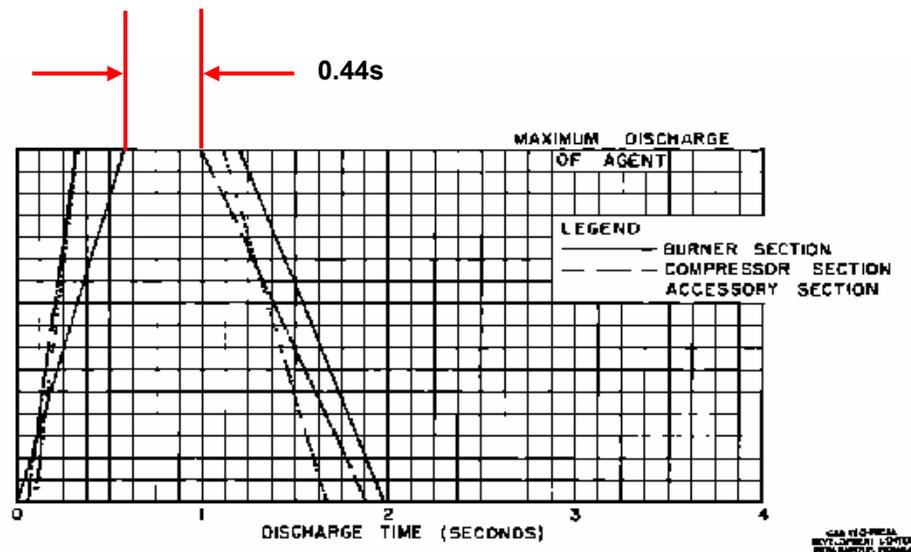


Figure 2-56. Minimum Discharge Duration from an HRD System Using Halon 1011.¹¹⁴

The HRD design formulae that have since been applied for sizing halon-1301-based systems in DoD aircraft applications have essentially remained unchanged since they were first published and were based on testing conducted on a single piston-engine powerplant and one jet power plant. Like the design

guidance for conventional halon 1011 systems, HRD system design guidance is also relative to compartment airflow and free volume. Additionally, a review of the CAA reports indicates that the number of tests conducted using halon 1301 preceding the issuance of MIL-E-22285 was limited. The CAA report that issued the design formulae indicates very few data had been obtained for halon 1301 but that it appeared equal to halons 1001 and 1202 on a weight basis. Given that the HRD design formulae published by the CAA were identical for halons 1001, 1202, and 1301, it is possible that in the case of halon 1301 the design guidance for it was asserted *qualitatively* at that time. It is also possible that this is the case for the 0.5 s discharge duration requirement, as discharge duration testing conducted by the CAA prior to the issuance of MIL-E-22285 was conducted using halons 1011 and 1202.

As indicated in Table 2-10, halon 1301 is today by far the most widely implemented of the halon suppressants for powerplant fire protection (nacelles and APU compartments) on DoD aircraft. Although Table 2-10 is not necessarily meant to be totally comprehensive, it depicts the magnitude of halon 1301 implementation across the DoD. The distribution systems are predominantly HRD designs. For reference, the table also lists other fire suppressants used today excluding halon-alternative fire suppressants installed on DoD aircraft since the Montreal Protocol. These are various forms of nitrogen-based fire protection and aluminum oxide, which is used on some aircraft in powder panels for passive dry bay protection.

2.4.2 Dry Bay Compartments

As discussed earlier in this chapter there are no active halon fire suppression systems installed currently on DoD aircraft for the specific purpose of ballistic dry bay fire protection, though there are compartments for which halon fire suppression is provided to protect against safety fire threats and for which such compartments are also vulnerable to ballistically-induced fire. The C-5 nitrogen fire suppression system provides protection for various dry bay compartments as indicated in Figure 2-57. System discharge is automatic for fires detected in the wing and pylon leading edge dry bays. Aluminum oxide powder (Al_2O_3) has also been fielded on several DoD aircraft. The powder is contained within a parasitic honeycomb panel to prevent ballistically-induced fires in dry bays adjacent to fuel cells and was first developed by the Royal Aircraft Establishment in England.¹¹⁵ If ruptured by a ballistic projectile, the panel releases a powder suppressant to quench incendiaries released by the projectile. The powder panel indicated in the example wing leading edge dry bay shown earlier in Figure 2-18 is an example of a parasitic powder panel installation. Chapter 9 describes NGP work to develop advanced powder panel design techniques.

2.4.3 Certification

The current requirement to certify other than dry-bay fire-suppression systems on aircraft that use halon 1301 requires demonstrating a minimum suppressant concentration for at least 0.5 s at all measurement locations simultaneously. Minimum suppressant concentration requirements for CO_2 , and halons 1001, 1011, 1202, and 1301 are indicated in FAA Advisory Circular 20-100.¹¹⁶ (Military specification MIL-E-22285 provides these requirements for halon 1301 only.) By today's method for certifying halon 1301 powerplant fire suppression systems, previous methods would seem somewhat subjective. One previous method was to discharge water through the distribution system, capture the discharge by large aerology balloons, and determine the quantity discharged as being equal to the difference between the total quantity and quantity captured, assuming a 10 % system loss.

Table 2–10. Fire Suppressants on DoD Aircraft.^{xxx}

Halon 1011 (CH₂ClBr)	Halon 1202 (CF₂Br₂)	Halon 1211 (CF₂ClBr)	Halon 1301 (CF₃Br)	Nitrogen (N₂)	Aluminum Oxide (Al₂O₃)
USAF: C-130 USN: DC-130A LC-130F/R TC-130G	USAF: C-5, C-141 Note: halon 1202 is an alternate for halon 1011 on USAF and USN C-130 aircraft, except for C/KC-130J aircraft.	USAF: C-130J USN: KC-130J	USAF: MH-53, HH-60 A/OA-10, B-2 B-1B (overwing fairing) C-5 (cargo, avionics, and center wing) C-9, KC-10, C-12 C-17, C-20, C-22B C-32A, C-40 C-135, VC-25A C-141, E-3A E-4A, E-8C F-16 (ullage) F-15, F-117 T-34A, T-39, T-43 USN: AH/UH-1, SH-2 HH/SH/UH-3 CH/HH-46 CH/MH-53 HH/SH-60 C-2A, C-9 C-12, C-20 E-2C, E-6A EA-6B, F-14 F/A-18C/D P-3, S-3 T-39, T-44A C-130 (excluding C-130s with halon 1011, 1202 or 1211) US Army: AH-64, CH/MH-47 EH/MH/UH-60 C-7, C/RC-12, C-20	USAF - LN₂ (ullage and dry bay): C-5 USAF – OBIGGS NEA (ullage): F-22 C-17 USN - OBIGGS NEA (ullage): V-22 AH-1Z UH-1Y US Army – OBIGGS NEA (ullage): AH-64 MH-47E MH-60	USAF (dry bay): CV-22 USN (dry bay): MV-22 AH-1W/Z UH-1N/Y

^{xxx} Table 2-10 excludes halon alternative fire suppressants installed on DoD aircraft since the Montreal Protocol. These aircraft are the MV/CV-22, F-22, and AH-1Z/UH-1Y, each of which utilizes HFC-125 for nacelle fire suppression and OBIGGS NEA for fuel tank inerting. Also, the F/A-18E/F utilizes HFC-125 for nacelle fire suppression, except for EMD and LRIP 1 aircraft, which utilize halon 1301. The F/A-18E/F and MV/CV-22 use inert gas generators for dry bay fire suppression. The gas discharge is a gaseous mixture of carbon dioxide, nitrogen, and water vapor. Gas generator technology is also being evaluated for dry bay fire suppression on the Joint Strike Fighter (JSF) aircraft.

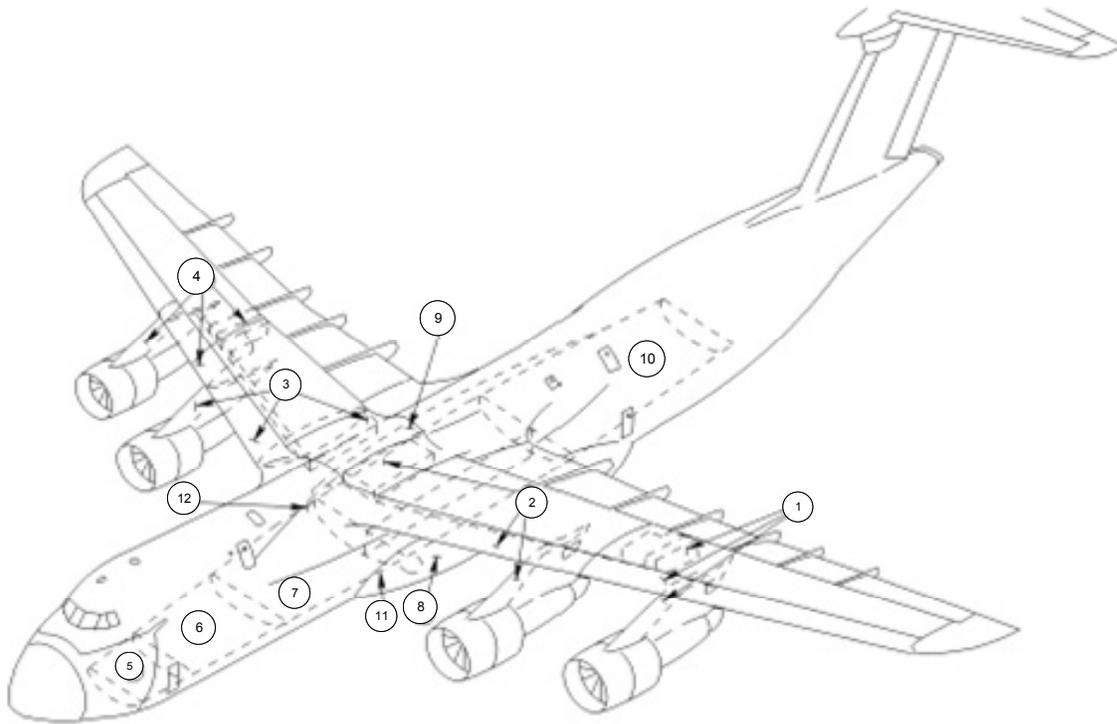
Distribution ratios were determined for each zone protected by the system, thus the required quantity of suppressant for each zone could be determined prior to testing. Another previous method was to measure discharge duration by means of motion pictures taken at the rate of 32 frames per second. Neither of these previous methods could be accomplished in flight.

The Statham-type suppressant concentration analyzer device mentioned in the previous section permits in-flight measurement of fire suppressant concentration.^{xxxi,117} This type of analyzer operates based on a linearized viscosity mixing theory using the weighted viscosities of a binary gas mixture, i.e., air and the fire suppressant. Since the viscosity of pure air differs from that of pure fire suppressants, readings will show that a mixture of gases is present and the “relative” concentration of the suppressant will be indicated by the differential pressure reading obtained. An algorithm converts relative concentration values to volumetric concentration values based on the unique calibration of the analyzer and the fire suppressant. A vacuum pump draws the gas mixture samples through twelve sampling probes (copper tubes) into sensor assemblies. Sampling probe ends are oriented perpendicular to compartment airflow and are located throughout the compartment (Figure 2-58). In each sensor assembly, the gas passes through filter screens, a heat exchanger, a capillary tube differential pressure sensor section, and finally through a sonic flow orifice. The heat exchanger section ensures uniformity of monitoring conditions, and tests are performed only after thermal equilibrium is achieved. The sonic flow orifice ensures a constant flow while the capillary tubes create the pressure drop measured by a transducer. The transducer transmits the pressure signal to a processor unit which performs the necessary calculations and then records and displays relative concentrations.¹¹⁸ The relative concentrations are then converted to volumetric concentrations for evaluation as to whether the fire suppression system meets a certification requirement (Figure 2-59).

Until recently, non-dry-bay fire suppression systems qualification has been normally accomplished by concentration measurement. There are unique cases where a system such as a nacelle fire suppression system will be qualified by fire testing. In this case, performance requirements will be specified and agreed to by the acquisition or certifying agency and the aircraft manufacturer. Nacelle fire suppression systems that have been qualified through fire testing are those on the USN F/A-18E/F, which uses HFC-125 as the fire suppressant, and the commercial Eclipse 500 aircraft, which uses PBr₃.

The certification requirement to demonstrate compliance with survivability and vulnerability requirements is Congressionally legislated in Title X, Section 2366 of the United States Code of Federal Regulations, which was passed in 1987. This live fire test legislation requires that realistic testing be done on new systems before they reach the field. The vast majority of DoD aircraft fielded today had initial operating capability prior to enactment of this legislation. Thus it is probable that compartments on aircraft for which halon fire suppression is provided to protect against safety fire threats and for which such compartments are also vulnerable to ballistically induced fire, no live fire testing had been performed, and that such halon systems were certified solely by suppressant concentration measurement.

^{xxxi} There are several versions of this type of analyzer that are certified by the FAA for use in performing fire suppression system concentration measurement for the purpose of qualifying or certifying aircraft fire suppression systems. One is the Statham Analyzer, owned and operated by Walter Kidde Aerospace. This is a modified version of the original Statham analyzer described earlier. Another analyzer is the Halonyzer, of which there are currently two versions, Halonyzer 2 and Halonyzer 3. One Halonyzer 3 analyzer is owned and operated by its manufacturer, Pacific Scientific/HTL Kin-Tech. One Halonyzer 3 analyzer is also owned and operated each by Boeing commercial and by the USAF at WPAFB. One Halonyzer 2 analyzer is owned and operated by Airbus Industries in France. Finally, a ‘modified’ Halonyzer 2 analyzer is owned and operated by the FAA Hughes Technical Center Fire Safety Branch.



Nitrogen Fire Suppression Zones and Controls

Zone	Spaces Included in Zone	Flight Engineer's Panel Discharge Pushbutton	Nose Wheel Well Panel Discharge Pushbutton
1	Left wing dry bay, left outboard leading edge, left outboard pylon leading edge	Left outboard wing	Left wing
2	Left wing root dry bay, left inboard leading edge, left inboard pylon leading edge	Left inboard wing	Left wing
3	Right wing root dry bay, right inboard leading edge, right inboard pylon leading edge	Right inboard wing	Right wing
4	Right wing dry bay, right outboard leading edge, right outboard pylon leading edge	Right outboard wing	Right wing
5	Nose wheel well	Nose wheel well	–
6	Cargo under floor, forward	Under floor, forward	Under floor, forward
7	Cargo under floor, middle	Under floor, forward	Under floor, forward
8	Left main wheel well	Left main wheel well	–
9	Right main wheel well	Right main wheel well	–
10	Cargo under floor, aft	Under floor, aft	Under floor, aft
11	Left power turbine unit (PTU) compartment	Left PTU	Under floor, forward
12	Right power turbine unit (PTU) compartment	Right PTU	Under floor, forward

Figure 2-57. Zones Protected by the Nitrogen Fire Suppression System on C-5 Aircraft.¹¹⁹
 (Reprinted with permission by the USAF Warner Robbins Air Logistics Center)

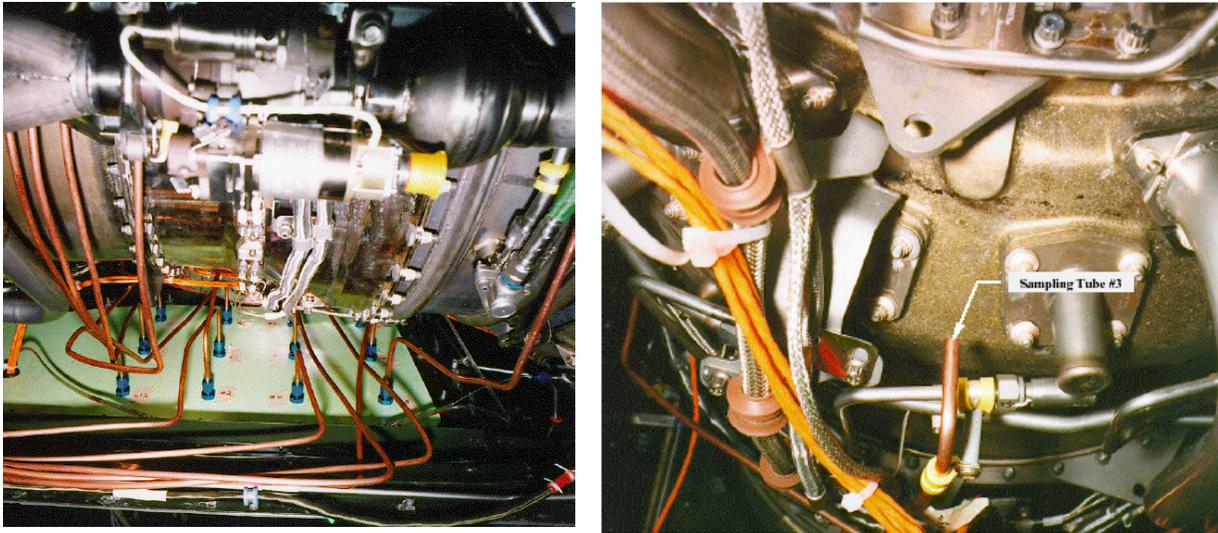


Figure 2-58. Fire Suppressant Concentration Analyzer Sampling Probe Installation.
(Printed with permission of the Naval Air Systems Command.)

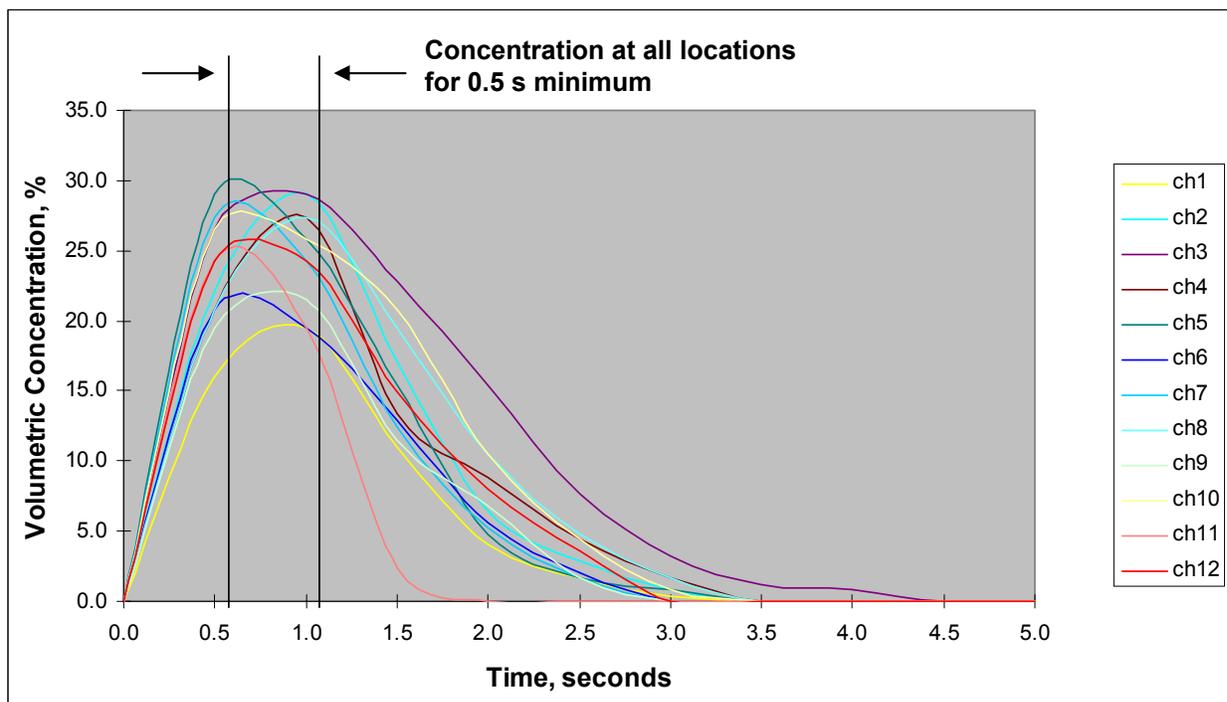


Figure 2-59. Example Fire Suppression System Suppressant Concentration Measurement.

Previous testing with halon 1301 for suppression of dry bay compartment fires with ventilation induced by damage from a ballistic projectile indicated that halon 1301 would suppress fires if discharged very fast, on the order of 10 ms, from a fire bottle type used on the United Kingdom CH-47 Chinook helicopters, or if a comparable halon 1301 quantity was discharged from a bottle design typically used for nacelle or APU fire suppression, from which the suppressant will discharge in approximately 1 s. Even though this testing showed that both types of bottle configurations provided halon 1301 concentrations well above 6 % for greater than 0.5 s,²¹ no concentration-based dry bay fire suppression system certification requirement was ever established by the DoD. Likewise, even though there is historical reference to the fielding of reactive ullage fire suppression systems, there is no DoD concentration-based qualification requirement for these systems as well. It should be noted that the fast discharge capability of the fire bottle type United Kingdom CH-47 Chinook helicopters is consistent with the design guidance indicated in Figure 2-60 for a confined space (i.e., constant volume), which has existed since 1965.

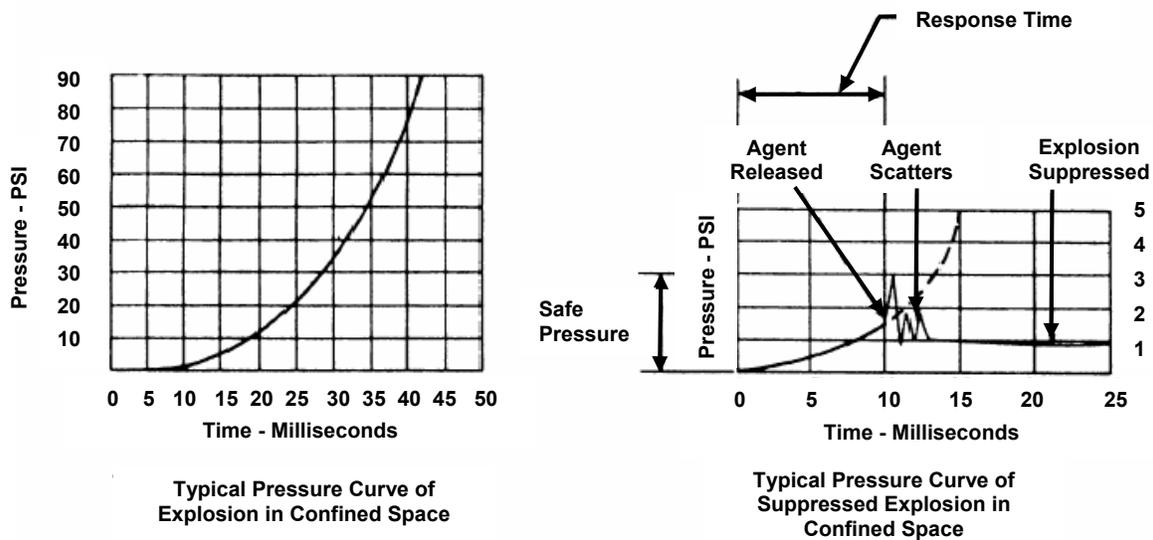


Figure 2-60. MIL-HDBK-221 Design Guidance for Explosion Suppression.¹²⁰

In the case of the C-5 nitrogen fire suppression system, which is an extension of the fuel tank LN₂ inerting system and provides dry bay fire protection, the system is required to reduce the oxygen level within the compartment into which it is discharged, ullage or dry bay, to 10 % or less “in the time duration necessary to cope with the particular fire hazard.” (Typically, the DoD will require that ullage inerting systems reduce oxygen concentrations to 9 % or less.). The USN A-6E ullage inerting system was designed to maintain a halon 1301 volumetric concentration of 20 % upon activation.¹²¹

OBIGGS installations on currently-fielded DoD aircraft were typically certified by measuring the oxygen concentration with a single oxygen sensor installed at the fuel vent interface in one or more fuel tanks or by installing an oxygen sensor on a fill port, as indicated in Figure 2-61. Today, as work continues towards developing OBIGGS for commercial transport aircraft, an oxygen-gas sampling system has been developed by the FAA that is utilized and operates in a manner similar to the concentration measurement analyzers utilized for certifying nacelle fire suppression systems.

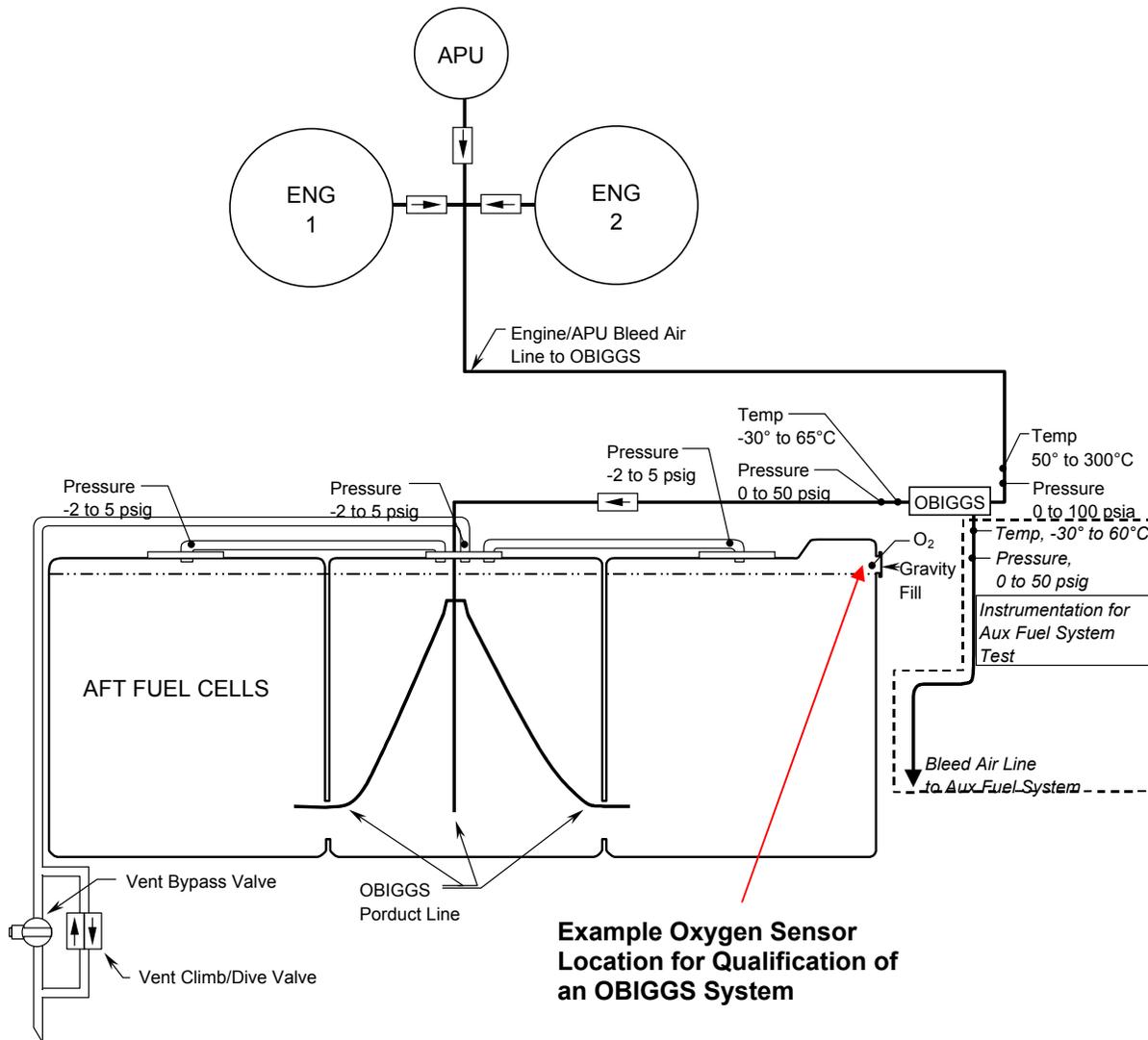


Figure 2-61. Typical Legacy OBIGGS Qualification Test Oxygen Concentration Measurement Location.

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2.5 HALON ALTERNATIVE TECHNOLOGY DEVELOPMENT PROGRAM (TDP)

Chapter 1 discussed why the DoD initiated the TDP and its goal for identifying near-term, environmentally friendly, and user-safe alternatives to halon for aircraft engine nacelle and dry bay applications, and why the limitations of what had been identified along with new/emerging environmental constraints required continued research and development for these applications. However, the breadth and technical approach of the TDP is historically significant. Like previous efforts related to aircraft fire suppression, the TDP spanned several years and was a collaborative effort involving participants from government agencies, industry, and academia.

Following the DoD's 1989 delineation of its policy on halon replacement research, over 600 potential halon replacement chemicals were assessed.^{57,122} This was followed by the USAF initiating the Halon Replacement Program for Aviation in 1992 to develop a non-ozone depleting solution for on-board fire suppression within a timeline to support the F-22 aircraft acquisition program. In addition to the F-22, the V-22 and F/A-18E/F acquisition programs also implemented requirements for fire suppression systems having non-ozone depleting fire suppression agents. Thus, the scope of program was subsequently expanded to address requirements of all DoD and civilian aircraft engine nacelle and dry bay applications and was jointly-sponsored by the USAF, USN, U.S. Army, and the FAA as the TDP. Additionally, an oversight group, the Halon Alternatives Steering Group (HASG), was established to coordinate efforts within the TDP as well as other government research and development (R&D) programs related to fire suppression. This included coordination with related efforts under the EPA's SNAP program, which addressed both environmental acceptability and personnel safety, e.g., toxicity, of candidate halon alternative suppressants. The TDP was a three-phase program, each of which is discussed briefly below. The reader is encouraged to refer the publications referenced in this section for more detailed discussion.

2.5.1 Phase 1 – Operational Parameters Study

Phase 1 determined parameters in aircraft engine nacelles and dry bays that have the greatest influence on the quantity of fire suppressant required to extinguish fire in those types of compartments.^{123,124} Characteristics of each of these compartment types on then-fielded aircraft were acquired to support development of a test matrix used during this portion of the TDP. A statistical design of experiments (DOX) methodology was employed to reduce the number of possible test configurations to 32 using a Plackett-Burman two-level fractional factorial design to permit study of the effects of 14 parameters related to dry bay compartments and 16 parameters related to engine nacelle compartments along with interactions of factors with only 32 test runs for each compartment. Evaluating two¹⁴ combinations of dry bay compartment factors and two¹⁶ combinations of engine compartment factors was not feasible. The DOX methodology permitted evaluating effects of the parameters for each compartment type within the physical and economic resources available to the TDP as well as to permit concurrent acquisition programs to meet schedule requirements for implementing non-ODS-based fire suppression systems. Table 2-11 lists, in order of significance, the factors found during Phase 1 testing at Wright-Patterson Air Force Base (WPAFB) to influence fire suppression the most in each compartment type. Concurrent studies and testing of candidate halon alternative chemicals were conducted by NIST to evaluate materials compatibility, thermodynamic properties, fluid dynamics associated with discharge, flame suppression effectiveness, flame inhibition chemistry, agent stability under storage, and affects to personnel and the environment.¹²⁵ The combined outcome from the WPAFB and NIST efforts resulted in the recommendation that the chemicals listed in Table 2-12 be evaluated during Phase 2.

Table 2–11. Most Significant Fire Suppression Parameters Identified During Phase 1.

Engine Nacelle ^{xxxii}	Dry Bay
Surface Temperature (34 %)	Compartment Volume (48 %)
Fire Suppression Agent (14 %)	Fire Suppression Agent (28 %)
Clearance, or Nacelle Free Volume (12 %)	External Airflow Rate (13 %)

^{xxxii} Two additional non-confounded parameters identified were nacelle airflow temperature and fuel temperature. Testing during Phase 1 also highlighted the significance of hot surface reignition.

Table 2–12. Halon Alternative Fire Suppressants Identified for Phase 2 Evaluation.

Engine Nacelle	Dry Bay
Pentafluoroethane (HFC-125)	Octafluoropropane (FC-218)
Chlorotetrafluoroethane (HCFC-124)	Pentafluoroethane (HFC-125)
Trifluoroiodomethane (CF ₃ I)	Heptafluoropropane (HFC-227ea)
Heptafluoropropane (HFC-227ea)	Trifluoroiodomethane (CF ₃ I)

2.5.2 Phase 2 – Operational Comparison of Selected Extinguishants

The fire suppressants identified during Phase 1 as the most promising halon alternatives for engine nacelle and dry bay fire suppression applications were subjected to additional testing during Phase 2.^{126,127} The DOX methodology was again employed to further evaluate effects of the most significant parameters identified during Phase 1 for each compartment type. Additional factors were also included based on discussion with aviation fire suppression experts. For dry bay fire testing, two additional factors evaluated were fire suppression agent container temperature and clutter (obstructions in the dry bay that inhibit suppressant distribution). For nacelle fire testing, four additional factors were evaluated: fire location in the nacelle, fuel type, nacelle mass airflow rate, and fire suppression agent container temperature. Table 2-13 lists, in order of significance, the factors found during Phase 2 testing at WPAFB to influence fire suppression the most in each compartment type. Additional testing was conducted by NIST to further evaluate fire suppression efficiency, stability during storage, safety following discharge, agent discharge behavior and performance, and interaction with metal fires. Techniques for real-time concentration measurement were also developed along with guidance for engine nacelle fire suppression design and certification.^{128,13} The combined outcome from the WPAFB and NIST efforts resulted in the down-selection to pentafluoroethane (HFC-125) as the optimal near-term halon alternative fire suppression agent for both engine nacelle and dry bay applications. This chemical was taken into Phase 3 for detailed evaluation.

Table 2–13. Most Significant Fire Suppression Parameters Identified During Phase 2.

Engine Nacelle	Dry Bay
Surface Temperature (39 %)	Compartment Volume (45.3 %)
Fire Suppression Agent (15 %)	Fire Suppression Agent (23.6 %)
Nacelle Airflow Temperature (10 %)	Compartment Volume and Location Interaction (14.3 %)
Surface Temperature and Nacelle Airflow Temperature Interaction (6 %)	Fire Suppressant Bottle Location (5.5 %)
Fire Location (4 %)	

2.5.3 Phase 3 – Establishment of Design Criteria Methodologies

During Phase 3, extensive engine nacelle and dry bay fire testing was conducted using HFC-125. The DOX methodology was again employed to evaluate effects of the most significant parameters identified during Phase 2 for each compartment. Extensive statistical analysis of the test data was conducted to develop design models (equations) for aircraft engine nacelle, APU and dry bay applications.⁹⁰ The

equations were developed to assist designers in sizing nacelle and dry fire suppression systems using HFC-125. Table 2-14 summarizes the variables that are to be taken into consideration when applying each of the equations.

Table 2–14. Fire Suppression Parameters in Design Guidance Developed from Phase 3.

Engine Nacelle	Dry Bay
Surface Temperature (Set at 454.5 °C)	Location – Impact Angle of Ballistic Projectile Relative to the Horizon
Nacelle Airflow Temperature	Dry Bay Free Volume
Nacelle Mass Airflow Rate	External Airflow Rate
Fuel Type	

Evaluation of data from engine nacelle fire testing highlighted the significance of engine surface temperature. Various models were developed to converge on one that would provide a best fit to the experimental data. Curve fits from test data in which the surface temperature was 454.4 °C (850 °F) and lower better modeled the overall test results than curve fits that included test data in which the surface temperature exceeded 454.4 °C. This was attributed to the variability induced from hot surface reignition.

Applying the HFC-125 engine nacelle fire suppression design model is a two-step process. The first step is to calculate the HFC-125 concentration required to certify the system. The equation bounds the resultant concentration to either a minimum of 14.6 % and a maximum of 26 %. Embedded within the concentration equation is a factor for a nacelle hot surface temperature of 454.5 °C. The calculated concentration is then used as an input variable in a sizing equation to estimate the quantity of HFC-125 needed to provide the needed concentration for certification. Though the sizing equation is similar in structure to the current design guidance for halon 1301 in that it contains nacelle mass airflow and nacelle free volume as variables, the testing performed under Phase 3 resulted in this two-step design guidance that includes concentration based on values of nacelle-specific parameters. Previous analyses of the current halon 1301 design guidance had indicated that the concentration variable may have been considered, but it may have been embedded with the concentration value fixed at the halon 1301 flammability limit of 6 %.^{63,129}

During dry bay testing, all ballistic shots were initially horizontal with the projectile entering the dry bay compartment from the side. However, additional consideration was given to the fact that some aircraft have belly dry bay compartments. This resulted in testing of vertical shots entering from the bottom of a dry bay. This testing and subsequent data analysis proved that shot angle was an important variable and is one of the variables that must be taken into consideration when applying the HFC-125 dry bay model. During design of an HFC-125 dry bay fire suppression system, the dry bay design model provides an estimate of suppressant quantity needed to suppress a dry bay fire. Prior to the development of this model there had been no design guidance for the sizing of halon 1301 dry bay fire suppression systems, though analysis of results from a previous test effort indicated a halon concentration range between 3 % and 9 % for a protection system incorporating a non-discriminating fire detection sensor, and a range between 6 % and 12 % for a system incorporating a discriminating sensor.¹⁷

2.5.4 Impact of Halon Alternative Fire Suppression to the Aircraft

Nacelle/APU Fire Suppression Applications

As the DoD has relied heavily on halon 1301 for aircraft fire suppression applications, the impact of what was learned during the TDP as well as from subsequent aircraft-specific development and testing efforts has become clear. Application of the outcomes from the TDP would result in halon alternative fire suppression systems that, relative to halon 1301 systems, would:

- Weigh more, due to both the increased mass of suppressant and the increased size of the bottle required to store the suppressant;
- Be more costly to optimize via enhanced distribution, which itself may lead to an incremental weight increase; or
- Cost more to support over the lifetime of an aircraft, e.g., increased weight translates to increased materials required for fabrication as well as increased fuel consumption and thus increased cost.

For example, on the V-22 fire door, actuators will close off two of three air inlets prior to discharge of the nacelle fire suppression system, which substantially reduces airflow through the nacelle. It was estimated that approximately 1.07 kg (2.35 lb) of halon 1301 would be required to protect each V-22 engine nacelle under this reduced airflow condition, whereas a fire bottle containing 2.72 kg (6 lb) of HFC-125 is installed for each nacelle for this same condition (2.55 times the estimated halon 1301 quantity).¹³⁰ At the time of design and qualification of the V-22 nacelle fire suppression system, the TDP design equations had not yet been developed. However, the then-available mass equivalence ratio for HFC-125 mass quantity relative to halon 1301 and a flame suppression number (FSN) were applied in the design analysis for the V-22 system.

Legacy AH-1W/UH-1N aircraft have two fire bottles, primary and reserve, each containing 0.9 kg (2 lb) of halon 1301 for engine nacelle fire protection. The upgraded versions of these aircraft, the AH-1Z/UH-1Y, include exhaust suppression systems. Simply adding such systems can require requalification of a nacelle fire suppression system as nacelle airflow, compartment temperature and suppressant distribution can be impacted. However, these aircraft were also required to implement HFC-125 as the halon-alternative fire suppressant. Examination of the analysis approach to determine the needed HFC-125 mass quantity, which was similar to that used for the V-22, suggested that 1.36 kg (3 lb) of halon 1301 would have been required to protect the nacelles, but these aircraft now have a single fire bottle containing 3.72 kg (8.2 lb) of HFC-125, a single discharge system.¹³¹ This was the mass quantity determined to be necessary to meet a concentration requirement based on application of the TDP concentration equation. Thus relative to a need to only discharge a single fire bottle on the legacy aircraft, the upgrade aircraft HFC-125 suppressant quantity represents an increase of over 2.7 times the potential halon 1301 quantity required and 4 times the halon 1301 installed on legacy aircraft.

For halon 1301, peak flammability limit is indicated by the FAA as the rationale for the 6 % volumetric concentration certification requirement. What the preceding discussion of halon alternative implementation indicates, and what Figure 2-62 illustrates, is that implementing a chemical halon alternative for nacelle fire suppression, in this case HFC-125, is likely to require well over twice the mass quantity of suppressant relative to halon 1301, if typical nacelle fire suppression system design practices are followed. (Figure 2-62 provides a graphical comparison of the current halon 1301 certification

requirements, the minimum and maximum HFC-125 design equation concentrations and the FAA HFC-125 minimum performance standard vs. various published peak flammability limits for both halon 1301 and HFC-125.)

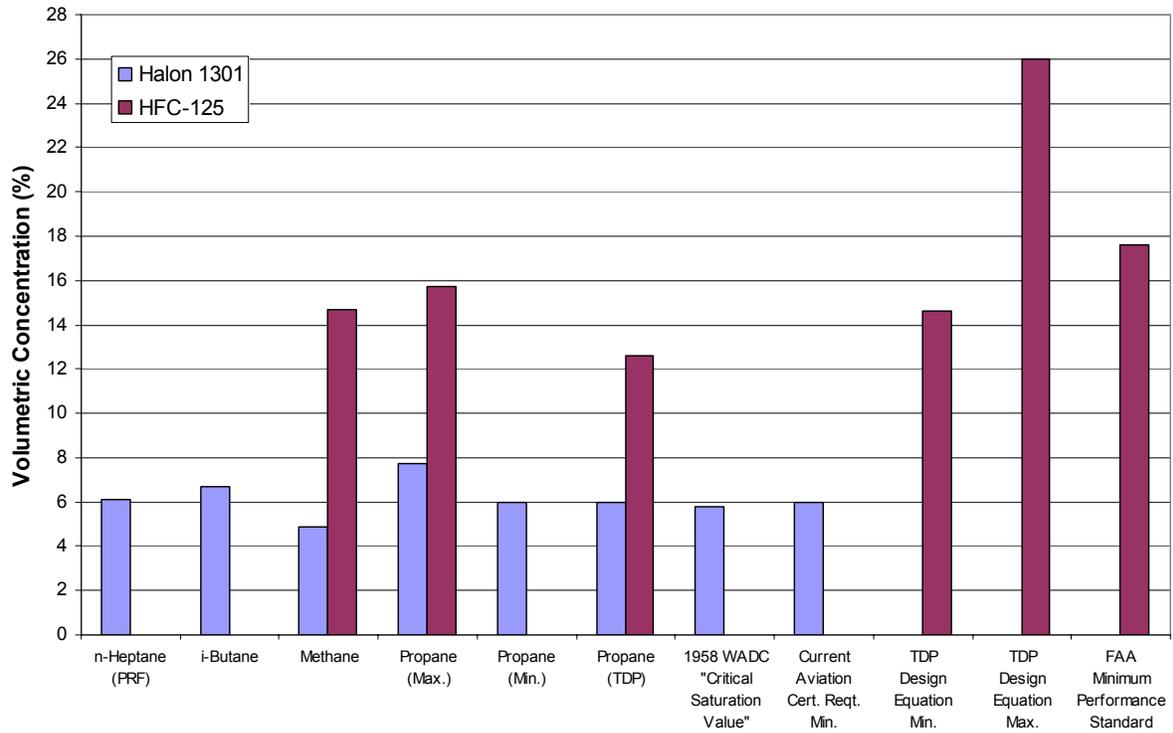


Figure 2-62. Comparison of Halon 1301 Certification Requirement and HFC-125 Design Equation Limits vs. Published Flammability Limits.^{xxxiii}

Typical design practices usually entail using design guidance (i.e., equations) to estimate suppressant mass quantity needed, conducting analysis of nacelle airflow characteristics for the purposes of designing the suppressant distribution system and discharge location or locations within the nacelle, and then performing qualification tests and, if necessary, adjusting the discharge locations in order to pass qualification; i.e., try different nozzles on the ends of the distribution tubing or changing the orientation of the discharge locations. Though the systems may then meet certification requirements, the entire process can result in non-optimized suppressant distribution, which is illustrated in Figures 2-63 and 2-64.

^{xxxiii} In Figure 2-62, the n-heptane flammability limit is from Reference 65. i-Butane, Methane, Propane (max) and Propane (min) flammability limits are from Standard for Clean Agent Fire Extinguishing Systems, NFPA 2001, 2000 Edition. Propane (TDP) flammability limit is from Reference 13. The WADC Critical Saturation Value is from Reference 105. TDP Design Equation Min and Max values are from Reference 90. It is interesting to note that the same halon 1301 volumetric concentration determined by the WADC in 1959 was also indicated in later work described in Dyer, J.H., Marjoram, M.J., and Simmons, R.F., "The Extinction of Fires in Aircraft Jet Engines – Part III, Extinction of Fires at Low Airflows," Fire Technology, 13, 126-138 (1977).

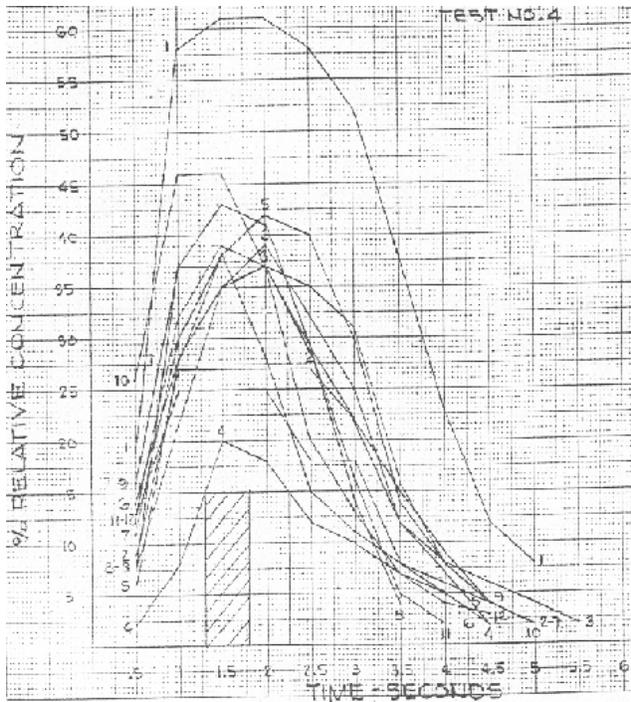


Figure 2-63. Example of Non-Optimized Halon 1301 Nacelle Concentration Distribution.

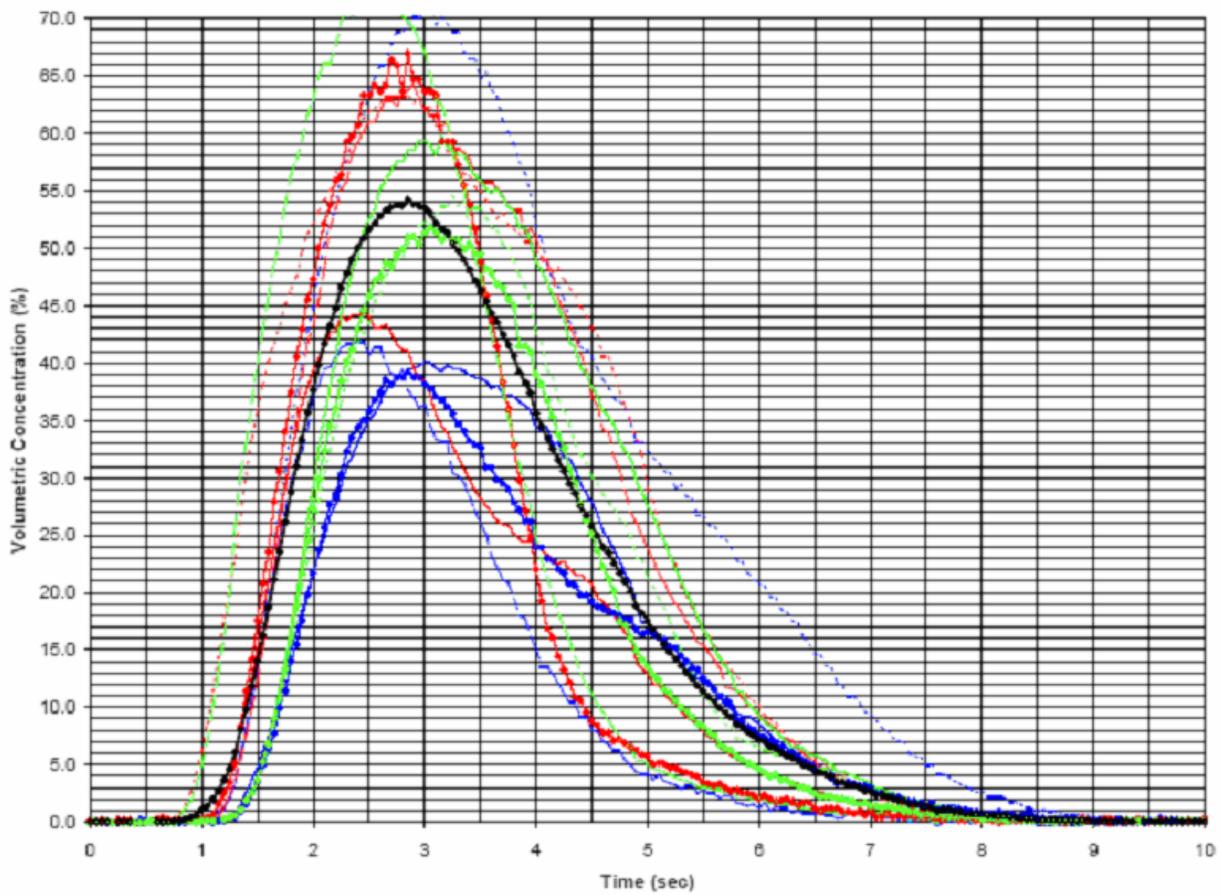
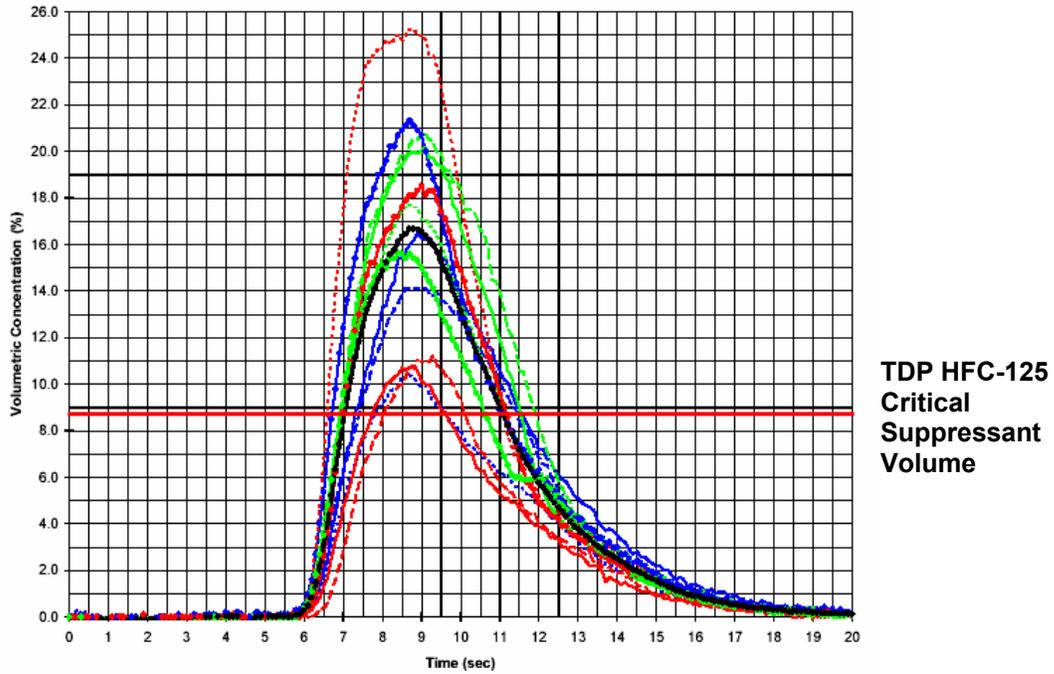


Figure 2-64. Example of Non-Optimized HFC-125 Nacelle Concentration Distribution.

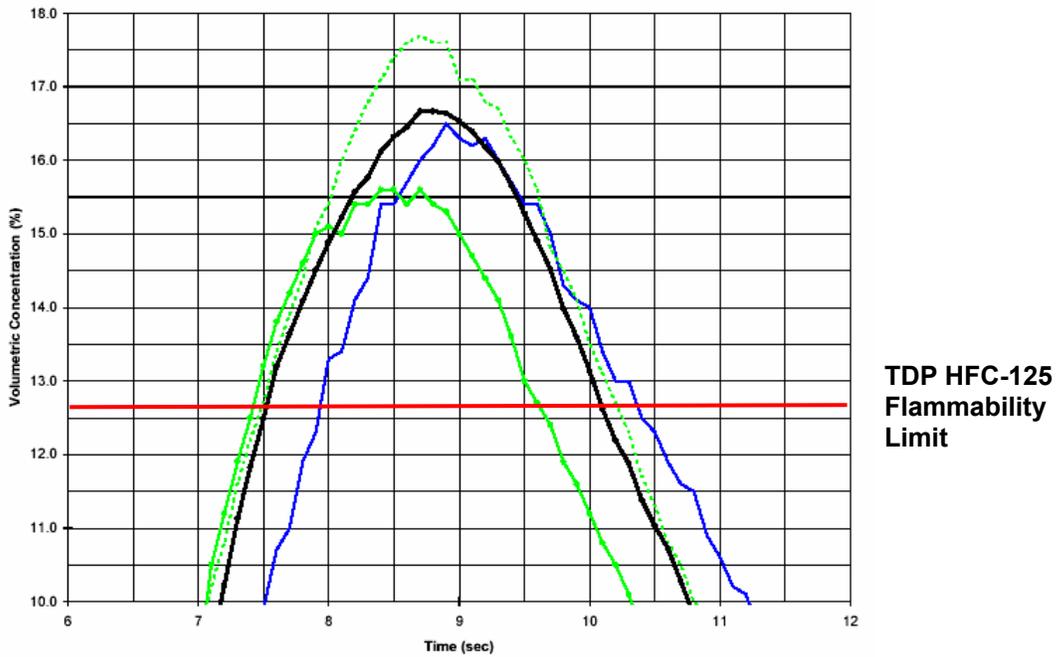
In the case of the F/A-18E/F aircraft, optimizing the nacelle fire suppression system distribution resulted in the fielding of a nacelle fire suppression system with an HFC-125 mass quantity (3.17 kg, 7.0 lb) only 1.27 times that required for the halon 1301 system (2.49 kg, 5.5 lb) on legacy F/A-18 aircraft. While it has been long promoted that the distribution system itself is probably the most important single factor in system design,¹³² the distribution system design on the F/A-18E/F resurrects the concept of increased dwell time within the nacelle after discharge. This implementation parallels a recommendation following detailed review of the F-22 full-scale engine nacelle fire test program to maintain suppressant inerting concentrations for an appropriate duration by optimizing delivery and distribution.¹³³ The F-22 is discussed later in this section. Though the F/A-18E/F system is an HRD system, the suppressant dwell time throughout the entire nacelle is similar to the duration requirement for historical conventional system designs in that the dwell at or above the HFC-125 critical suppressant volume fraction (8.7 %) is maintained for at least 2 s. However, in the portion of the nacelle for which there is a hot-surface ignition threat the suppressant concentration was at or above the flammability limit for at least 0.5 s. An example of this concept is shown in Figure 2-65. Strict application of the HFC-125 concentration equation for the F/A-18E/F would have imposed a certification requirement of 18.5 % volumetric concentration throughout the nacelle for 0.5 s minimum.⁴⁷ In the case of the F/A-18E/F aircraft, it was necessary to optimize suppressant distribution to utilize the physical location of the fire bottle, which was to remain unchanged from the legacy F/A-18C/D design unless significant and costly aircraft structural modifications were pursued. It is interesting to note that even if an 18.5 % volumetric concentration requirement were imposed, the design guidance for the HFC-125 equations indicates that they are intended to provide protection for fire events not subject to hot surface reignition.⁹⁰

The F/A-18E/F experience is an example of aircraft program managers trading the impacts associated with various design options. These trades also take into consideration the amount of resources available to evaluate trade options adequately. Thus, limitation of such resources for another aircraft program manager may only permit traditional design practices to be applied. However, either scenario necessitates that the fire suppression system design be optimized to the greatest extent practicable. Chapter 8 provides detailed discussion of the CFD analysis tool developed under the NGP, which is intended for use by aircraft nacelle fire suppression system designers to optimize suppressant distribution.

Another issue that was investigated during the F/A-18E/F testing efforts relates to the use of the Statham and Halonyzer suppressant concentration gas analyzers used currently to certify nacelle fire suppression systems. The issue of response time of such equipment was investigated during the TDP, and during the F/A-18E/F efforts, testing was conducted to show that such equipment may miss the concentration levels that actually result in fire suppression.¹³⁴ That this could occur had been noted in early application of the Statham analyzer, for which it was concluded that as the suppressant-air mixture was drawn into a sampling tube, normal gas diffusion would tend to level peak concentrations if the peak is preceded and proceeded by lower concentrations.¹⁰⁵ A qualitative conclusion derived from the F/A-18E/F evaluation was that such equipment may be a good technique for suppressants that chemically interact with the combustion process, such as halon 1301, but may be limited in use with suppressants such as HFC-125, which physically interact with the combustion process. Thus following traditional design practices, HFC-125-based nacelle fire suppression systems may then be designed to accommodate more mass than is actually required. The NGP has transferred to the DoD test and evaluation community detailed information for the development and use of a Differential Infrared Rapid Agent Concentration Sensor (DIRRACS-2), which is described further in Chapter 5. Application of CFD modeling and DIRRACS-2 can be used to resolve these issues in nacelle fire suppression system design.



(a) Concentration throughout the Entire Nacelle



(b) Concentration at Locations of Hot Surface Reignition

Figure 2-65. Examples of HFC-125 Nacelle Concentrations.

Another fire suppression methodology that was developed concurrent with the TDP and subject to HASG oversight was the solid propellant gas generator (SPGG), which disperses an inert gas mixture of nitrogen, carbon dioxide, and water vapor. Similar to gas generators developed for automobile airbags, these devices rapidly generate large quantities of this inert gas mixture, which results from internal combustion of multiple pellets (or grains) of the propellant. The mixture is very hot upon exit from the device but cools rapidly as it expands within the compartment into which it is discharged. Full-scale engine nacelle fire suppression testing for the USAF F-22 evaluated HFC-125 along with inert and chemically-active gas generator technology.⁵⁶ The USN had previously evaluated the inert gas generator technology for nacelle fire suppression for the F/A-18E/F and demonstrated that similar mass quantities of halon 1301 and the inert solid propellant would suppress fire and prevent reignition.¹³⁵ During testing on the F-22 program, distribution lines from the generators to the nacelle would become white hot during discharge and for a brief period thereafter. In testing performed by the USN using a “single grain” inert gas generator, the same effect of heating of the distribution line during discharge was also noted. Placing inert gas generators within a nacelle and thus eliminating the need for distribution lines had been previously considered impractical due to the potential degrading effect of the nacelle operating temperature environment on the life of the solid propellant. Inconel distribution lines were demonstrated to not melt but would still become white hot. The NGP subsequently developed and performed evaluations of solid propellant formulations that generate cooler effluent that is also more efficient at fire suppression (Chapter 9).

It was during the F-22 nacelle fire suppression evaluations that these newer, chemically-active gas generator propellant formulations were tested in a full-scale application for the first time. In general at least 25 % to 50 % less chemically-active propellant mass was required to suppress nacelle fires relative to the amount of inert propellant mass. For one formulation over 70 % less mass relative to the inert propellant provided successful fire suppression. However, the biggest surprise from the F-22 evaluations was that the same mass quantity of halon 1301 and HFC-125, 6.4 kg (14.1 lb) each, suppressed the worst-case hot-surface reignition fire threat condition in the F-22 nacelle.¹³³ Though the suppressant mass was similar, in-depth analysis of the suppressant concentrations at the fire zone revealed that the inerting concentration (flammability limit) of halon 1301 was approximately a factor of two smaller than that of HFC-125. It was also noted that 8 s after suppressant discharge, the concentrations in this zone remained above the flammability limit. This 8 s dwell correlated with the criterion established for successful fire suppression, which was no occurrence of reignition within 8 s after suppression.¹³³ Based on this testing, the USAF implemented nacelle fire suppression for the F-22 aircraft using 14 lb of HFC-125.

The U.S. Army had also conducted an extensive halon alternative test and evaluation effort for the Comanche aircraft program. That effort was still in progress when the Comanche program was cancelled by the DoD. Extensive work had been done to replicate the nacelle conditions during flight modes, create the nacelle fires for those conditions, evaluate the potential hot-surface-reignition threat, and determine the agent quantity necessary to ensure suppression. Requirements for the system included reserve fire suppression capability. HFC-125 and, to a lesser extent, inert gas generators were evaluated. Since the majority of the testing had been conducted using HFC-125, it was selected as the agent for use in system optimization testing that was to be performed. At the time of program cancellation, no HFC-125 mass quantity had been established that would suppress fire under all test conditions, and the program had begun to evaluate trades related to retaining the reserve fire suppression capability, certification metrics and testing, and “fire-out” success criteria in testing.¹³⁶ Currently, the Halon Replacement Program of the

U.S. Army Program Executive Office, Aviation, is evaluating use of HFC-125 as the halon replacement on CH-47 Chinook helicopters.

As of the writing of this book, halon alternative testing by the Fire Safety Branch at the FAA Hughes Technical Center had recently been completed. That testing evaluated HFC-125, CF₃I and, more recently, FK-5-1-12 or dodecafluoro-2-methylpentan-3-one (CF₃CF₂C(O)CF(CF₃)₂) for nacelle fire suppression applications in commercial aircraft. Findings to date of notable interest for DoD consideration are concentrations required to suppress spray and pool fires and an overpressure phenomenon. Contrasting results from previous testing, higher HFC-125 and CF₃I concentrations have been required for suppression of nacelle spray fires than pool fires. Also, HFC-125 and another halon alternative tested, bromotrifluoropropene (2-BTP), were observed to produce overpressure phenomena subsequent to reignition within the test fixture flow path. Initial conclusions were that each suppressant appeared to act as a fuel in some instances, and that the phenomenon was not 100 % reliable.¹³⁷ The overpressure phenomenon had also been observed with HFC-125 and 2-BTP in cargo compartment fire suppression testing. During simulated aerosol can explosion tests conducted to evaluate explosion suppression performance for aircraft cargo compartments, tests were conducted to provide 2-BTP volumetric concentrations of 3 %, 4 %, 5 %, and 6 %. An overpressure occurred in each test – the associated overpressures were 530 kPa (63 psig), 530 kPa (63 psig), 780 KPa (100 psig), and 7.3 kPa (93 psig), respectively. 2-BTP enhanced the explosion event with as much as 4 times greater pressures than the un-suppressed event and 23 times greater than the halon 1301 benchmark concentration (2.5 %). HFC-125 was also observed to enhance the explosion event when its concentration was below 11.0 %. It doubled the blast pressure pulse peak, and it produced explosion overpressures of 4460 kPa (53 psig) in tests that provided concentrations of 8.9 % and 11 % by volume. No explosion event was observed when the concentration of HFC-125 was 13.5 % by volume.¹³⁸ Bromotrifluoropropene evaluation was discontinued in the nacelle fire test program. The FAA minimum performance standard (MPS) for certifying use of HFC-125, CF₃I or, FK-5-1-12 in nacelle fire suppression applications is now being developed. The reader is referred to the Fire Safety Branch at the FAA Hughes Technical Center to learn more, particularly in regard to flame attachment behavior observed during testing with CF₃I and FK-5-1-12.^{xxxiv}

Dry Bay Fire Suppression Applications

Both the USAF F-22 and C-130J LFT programs evaluated HFC-125 and gas generator technology for use in dry bay fire suppression. Both programs evaluated inert and chemically-active gas generators. The F-22 testing also evaluated a pyrotechnically-augmented liquid agent system (PALAS) that utilized HFC-227ea. The F-22 testing was specific to the F-22 main landing gear dry bay whereas the C-130J testing evaluated wing dry bays. Figure 2-66 shows a summary of results from the C-130J testing. Results from the F-22 testing are summarized in Table 2-15. These test programs provided the first full-scale comparisons of gas generator fire suppression effectiveness relative to near-term chemical halon alternatives identified during the TDP (HFC-125, HFC-227ea). Both of these test programs clearly showed that on a mass basis, less solid propellant was required to suppress a dry bay fire relative to the chemical alternatives tested, particularly when a chemically-active propellant was used. During the F-22 testing it was found that less than half of the chemically-active propellant was required to effect suppression as compared to the inert propellant.

^{xxxiv} <http://www.fire.tc.faa.gov/>

	Replica Test Article		Production Test Article	
	# API Shots	Weight Selected (lbs)	# API Shots	Demonstrated Weight (lbs)
Wing Leading Edge				
HFC-125	28	2.16	5	2.16
★ SPGG	10	0.93	4	0.93
Wing Engine Area				
HFC-125	17	2.80	2	2.80
SPGG	8	0.93	2	0.93
Wing Trailing Edge				
HFC-125	16	—	0	—
SPGG	8	1.38	2	1.86

★ Wing Leading Edge SPGG testing included FS01-40 and PAC-3302 agents

Figure 2-66. Summary of HFC-125 and SPGG Fire Suppression Results from C-130J Live Fire Testing.¹³⁹

Table 2-15. Minimum Fire Suppressant Quantities from F-22 Main Landing Gear Dry Bay Live Fire Testing, 150-grain Fragment Threat and Jet Fuel Except Where Noted.¹⁴⁰

Suppressant (a)	Delivery System	5 ms Delay	5 ms and 105 ms Delay	400 ms Delay	400 ms and 480 ms Delay	500 ms Delay
HFC-125	Nitrogen Pressurized Bottle	0.68 kg (b)	N/A	N/A	N/A	N/A
HFC-125	Nitrogen Pressurized Bottle	0.91kg	N/A	N/A	N/A	1.5 lb
HFC-125	Nitrogen Pressurized Bottle	N/A	N/A	N/A	N/A	1.13 kg (c)
HFC-227ea	PALAS	1.11kg Fan Nozzle	N/A	N/A	N/A	N/A
HFC-227ea	PALAS	0.89 kg Radial Nozzle	N/A	N/A	N/A	N/A
FS01-40	Inert SPGG	N/A	2 x 0.52 kg (1.03 kg)	N/A	2 x 0.21 kg (0.42 kg)	N/A
FS01-40	Inert SPGG	N/A	N/A	N/A	2 x 0.35 kg (0.70 kg) (c)	N/A
PAC-3302	Chemically Active SPGG	N/A	2 x 0.19 kg (0.38 kg)	0.19 lb	N/A	N/A

(a) A total of 24 tests were conducted using HFC-125, 21 tests were conducted using HFC-227ea, 19 tests were conducted using inert SPGGs, and 10 tests were conducted using chemically-active SPGGs.

(b) Flammable fluid tested was hydraulic fluid.

(c) Ballistic threat was 23 mm HEI. Only HFC-125 and inert SPGGs were evaluated against this threat.

Figure 2-67 illustrates the rapidity with which fire suppression is achieved using gas generators for suppression of ballistically-induced fires within an aircraft dry bay compartment.



Figure 2-67. Time Sequence of Dry Bay Compartment Fire Suppression by Inert Gas Generators, Complete Suppression within 600 ms.¹³⁹

The inert gas generator technology has been implemented for dry bay fire suppression on the USN F/A-18E/F and MV-22 and on the USAF CV-22; the chemically-active technology was not mature at the time that these systems were required to be developed. Figure 2-68 provides an illustration of the system implementation on the MV-22, without auxiliary wing fuel tanks. On the V-22, this system is referred to as the wing fire protection system (WFPS). The gas generators provide ballistic dry bay fire protection for the various wing dry bays and both ballistic and safety fire protection in the mid-wing compartment, which contains an APU, gearbox, shaft driven compressor, hot air ducting, electrical generators, and other equipment. Discharge of the generators in the mid-wing compartment is sequenced to preclude overpressurization of the compartment. During qualification testing of the WFPS for the mid-wing compartment it was observed that, even though the fires were quickly extinguished, it was noted upon review of the test videotapes from each of the tests that the fire location shifted position around the compartment, i.e., the fire would be pushed to different locations within the compartment as each of the gas generators would discharge until combustion could no longer be sustained.¹⁴¹

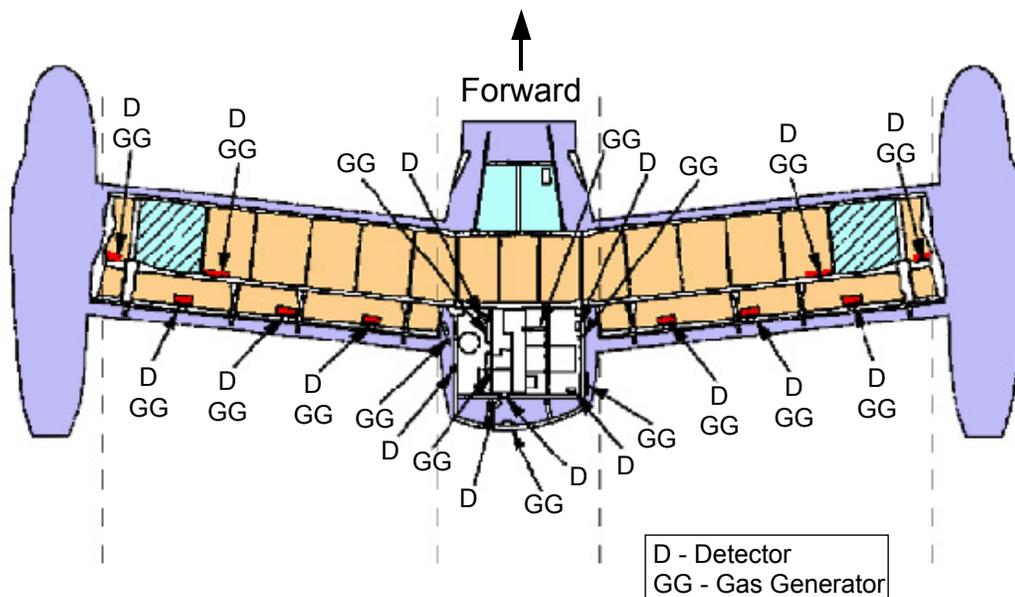


Figure 2-68. V-22 Inert Gas Generator Fire Suppression System.¹²

The V-22 WFPS development effort included a requirement for the capability to measure gas concentration levels within the midwing compartment to demonstrate adequate distribution of the inert gases within the compartment, though no specific gas concentration levels and duration time were set as pass-fail criteria. A gas sampling system was assembled using fast-response CO₂ and oxygen sensors, and gases were drawn from the compartment through 5 m long, 1 mm inside-diameter Tygon tubing. Response time of the concentration measurement sensors was on the order of 120 ms for the CO₂ sensors and 50 ms for the oxygen sensors. In general, lower CO₂ was measured at locations closest to airflow inlets and was greatest at locations near the inert gas generators and where air was drawn out of the compartment, though peak CO₂ concentrations between 13 % and 26 % were recorded.¹⁴¹ This concentration measurement technique was also utilized during the F-22 engine nacelle test series in an attempt to correlate fire suppression with oxygen and CO₂ concentrations within the nacelle. Analysis of the data could not support any correlation.⁵⁶ Detailed analysis of these measurements suggested that the instrumentation could have been contaminated by particulates, water vapor, condensed water vapor, or hydrocarbon vapor. The need to better characterize the mechanisms by which gas generator as well as other fire suppression technology provides fire suppression in a real-world environment such as an engine nacelle led to NGP efforts to develop the Transient Application, Recirculating Pool Fire (TARPF), agent effectiveness screen, which is described in Chapter 6.

Inert gas generators have thus far been proven to be effective though they currently require replacement every five years. On the V-22 there are 17 generators. Given that similarly sized or even larger aircraft could require similar or even larger numbers of these devices, if implemented for dry bay fire protection, the weight and logistics impact (i.e., unit costs, spares provisioning) over the lifetime of an aircraft becomes magnified. As shown in Figure 2-69, fire suppression testing of newer chemically-active solid propellant formulations under the NGP has demonstrated at least a 50 % reduction in propellant mass.

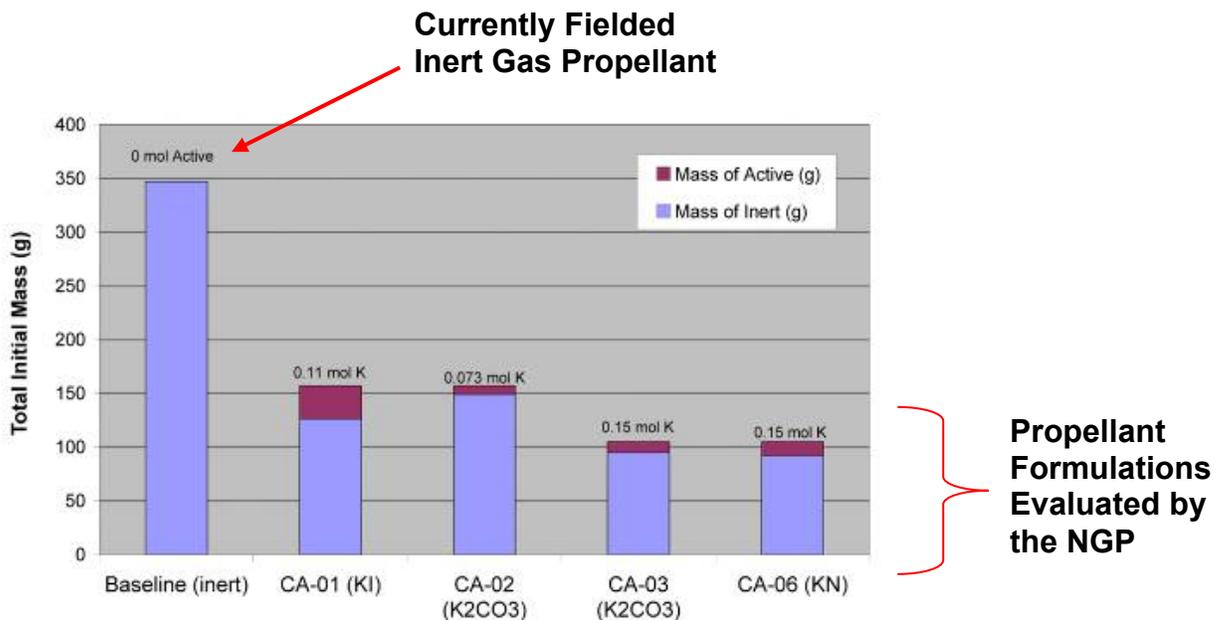


Figure 2-69 NGP Testing Results Comparing Solid Propellant Inert Gas Generator Propellant Mass vs. Chemically Active Gas Generator Propellant Mass.¹⁴²

Aircraft dry bay fire testing conducted by the USN using one of the newer propellant formulations has demonstrated on-aircraft fire suppression with such reduction in propellant mass.^{143,144} However, application of single passive extinguisher (SPEX) concepts has received increased attention. SPEX concepts focus on system simplification, eliminating the subsystems normally associated with active fire suppression systems (i.e., no fire detection system, no crew alerting and controls, and no system health monitoring). These concepts are a recent emergence within the DoD and testing of several concepts has been sponsored by the Joint Aircraft Survivability Program Office (JASPO). Concepts evaluated to date have been for dry bay fire suppression,¹⁴⁵ and one concept using a plastic, heat sensing tube connected to a low pressure container with monnex dry chemical extinguishant is planned for implementation on the V-22 for wheel well dry bay fire protection. Initially, chemically-active gas generators were one of several options being considered for dry bay fire suppression on the USN P-8 MMA,³⁴ but SPEX approaches are also being investigated. Chapter 9 describes the inert gas generator technology and the technologies and techniques developed under the NGP related to improving their performance.

Ullage^{xxxv}

Explosion suppression experiments were conducted to determine the ability of the SCS and LFE reactive ullage protection technologies to suppress ballistically-induced ullage fire/explosion events, with FC-218, HFC-227ea, HFC-125, and pentane tested using the LFE and just pentane using the SCS. Ballistic threats tested were single 110-grain fragment, 12.7 mm API, and 23 mm HEI. Detection systems were not integral to the tests and thus the results do not take into consideration detector-related delays. The tests were sponsored by the Joint Technical Coordinating Group for Aircraft Survivability (JCTG/AS), now known as the Joint Aircraft Survivability Program (JASPO), and were conducted by the USN.

SCSs filled with pentane to provide a 47 % concentration (approximately 0.54 mass fraction) suppressed explosions in a 0.85 m³ (30 ft³) volatile ullage simulator when initiated by both a single 110-grain fragment and a 12.7 mm API. Partial suppression only was realized against the 23 mm HEI. In the same ullage simulator partial suppression only was realized against the 12.7 mm API in all tests of FC-218, HFC-227ea, HFC-125, and pentane using the LFE. The greatest concentrations of each were as follows: FC-218, 38.8 % (0.67 mass fraction); HFC-227ea, 42 %, (0.67 mass fraction); HFC-125, 52.5 % (0.64 mass fraction); and pentane, 37.5 % (0.48 mass fraction). Testing of varying amounts of each suppressant allowed definition of the effect of agent concentration and mass fraction on peak pressure in the simulator, as shown in Figure 2-70.

Examination of the concentration data revealed that, of the suppressants tested, pentane edged out FC-218 as having the best suppression efficiency, followed by HFC-227ea, and then by HFC-125. Comparison of peak explosive pressure as a function of suppressant mass fraction revealed that the amount of pentane required to achieve the suppression level of FC-218, HFC-227ea, and HFC-125 was 70 % of the amount needed for those three suppressants (i.e., 30 % less pentane was required).

As of the writing of this book, none of the DoD services has pursued additional evaluation of the reactive suppression technologies using halon alternative suppressants in aircraft fire suppression applications.

^{xxxv} This section is based on Reference 33. Summary and Conclusions from that report are presented with minor editing for presentation within this chapter.

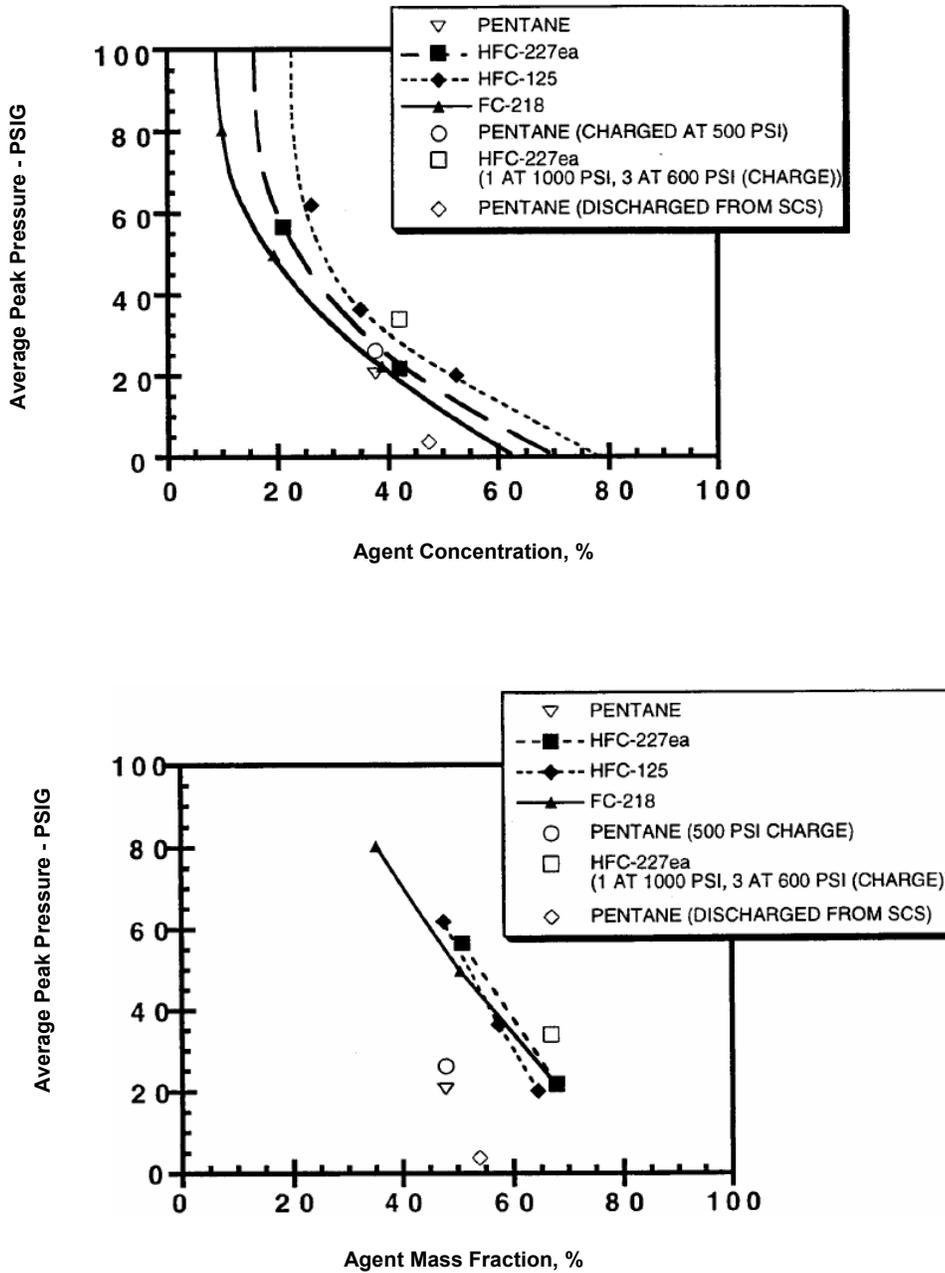


Figure 2-70. Effect of Suppressant Concentration and Mass Fraction on Peak Explosive Pressure for LFEs Pressurized to 1,000 psi, 12.7 mm API Threat and 3 % JP-4S.³³

Forward-Looking Considerations

Major aircraft acquisition programs today include those for unmanned air vehicles (UAV), the USN P-8 MMA program, the USAF-USN-USMC F-35 Joint Strike Fighter (JSF), and the joint USN and U.S. Army Blackhawk/Seahawk Program. UAVs are being utilized with greater frequency during military conflicts. A review of potential cost effective survivability enhancements identified that passive fire suppression for large category UAVs and active fire suppression for Unmanned Combat Aerial Vehicles

(UCAV) are potential cost-effective survivability enhancements for these aircraft.¹⁴⁶ Dry bay fire suppression is planned for the JSF. However, it is a single-engine aircraft, which typically is not provided with nacelle fire suppression. This is because that the typical approach for nacelle fire suppression first involves isolating the nacelle compartment, meaning the pilot shuts off fuel flow, and that the fuel for a nacelle fire is likely that provided to the engine to generate propulsion power for flight. Reduction in or loss of that flow itself can or will lead to loss of thrust and thus lift and flight control. However, given the lessons learned from the Southeast Asia conflict and that a few extra minutes of flight may reduce likelihood of pilot fatality or enemy capture, the DoD's JASPO is currently sponsoring investigation and testing of automatic nacelle fire suppression concepts as a survivability enhancement, particularly for single engine aircraft applications.¹⁴⁷

As long as the DoD components (Army, Navy, and Air Force) operate current and procure new manned multi-engine aircraft, there will be a requirement for engine nacelle fire suppression. Likewise, for new aircraft procurements, the Live Fire Test law will drive requirements for prevention and suppression of ballistically-induced fires. Aircraft fire suppression systems are categorized as mission critical applications, for which continued use of halon by the DoD has been permitted by law. New production aircraft are required to implement a non-ODS alternative or have had executed an ODS waiver certifying that no viable alternative exists for the application presented by that aircraft. While currently-fielded aircraft would most certainly continue to operate using the fire suppressant (or suppressants) installed currently, there are potential uncertainties (e.g., global warming, depletion or destruction of halon banks) that could impact the type of suppressant implemented in fire suppression systems on these aircraft. With respect to global warming, parties to the Kyoto Protocol, of which the U.S. is currently not a signatory, have developed amendments to reduce emissions of fielded HFC systems that are to become effective in 2007.^{148, xxxvi} As of the writing of this book, these requirements would not apply to currently-fielded HFC-based fire suppression systems on DoD aircraft, but DoD environmental activities are likely to monitor the effect of these requirements and whether it is beneficial for DoD to implement similar requirements. The commercial aviation sector is more sensitive to such influences, and it is conceivable that a commercial-derivative aircraft procurement could include a non-halon non-HFC based fire suppression system.

Regardless of potential external regulatory influences, the aircraft program manager is constantly managing risks (i.e., weight, performance, cost, safety and survivability, to name a few). As for any subsystem on an aircraft, there are weight, performance, and cost trades associated with implementing a fire suppression system, and the program manager desires to implement the lightest weight, best performing, lowest cost system. He is concerned with ensuring that aircraft key performance parameters (KPPs) are met. These parameters include weight, performance (range, drag), reliability, and probability of kill (Pk). When weight and/or cost are considered too high, the program manager will trade risk associated with various options, including safety and survivability risks. Such trades receive increased attention and scrutiny when resources (funds) are constrained. For example, if a specific aircraft maneuver drives a worst-case nacelle airflow condition, which in turn drives high the suppressant

^{xxxvi} The Kyoto Protocol is an agreement made under the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases, or engage in emissions trading if they maintain or increase emissions of these gases. The five other gases are methane, nitrous oxide, sulfur hexafluoride, hydrofluorocarbons or HFCs, and perfluorocarbons or PFCs. The USAF CV-22 and F-22, the USMC MV-22, and the USN F/A-18E/F use HFC-125 in their nacelle fire suppression systems. HFC-125 is also approved for use by DoD, as well as by the FAA, as a halon 1301 simulant for certification testing of halon 1301 nacelle fire suppression systems.

quantity for a fire suppression system, yet performing such a maneuver is a small exposure over the projected lifetime of the aircraft, the program manager may accept the safety risk associated with fire occurrence during that exposure in order to proceed with a lighter weight fire suppression system. Likewise, from a survivability perspective, the program manager may trade passive protection techniques against active techniques for dry bay fire protection. He may find that the aircraft vulnerable area requirement can be met by implementing passive protection techniques at the risk of not protecting another compartment that requires an active system and yet still meet the aircraft Pk KPP. That the NGP has developed tools such as CFD modeling for design, development and optimization of nacelle fire suppression systems and cost modeling for assessing the life cycle cost benefit of providing nacelle and dry bay fire suppression systems should benefit the program in conducting risk trades. Better performing enhanced powder panels, chemically-active gas generators, and hybrid fire suppression techniques should provide the program manager options previously unavailable in making such trades.

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