Chapter 10: LIFE CYCLE COSTING OF FIRE SUPPRESSION SYSTEMS

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10.1 BACKGROUND

10.1.1 Technical Concept

Aircraft fires impose a significant cost impact on the military. Fire is either the primary cause or a contributing factor in a large portion of mishaps that result in injuries to personnel, material loss of aircraft assets, and loss of mission capability. Methods and technologies to mitigate these costs or "design them out" are a major component in aircraft design, retrofit, and maintenance.

To determine the preferred fire extinguishing medium, system or method for any application, the holistic approach is to compare alternatives based upon on an overall cost of ownership, or “life cycle cost,” either over an aircraft's projected useful life or some fixed period of use. This approach incorporates the various costs associated with procuring, installing and maintaining such equipment, including non-hardware costs such as development and certification, as well as repair and parts replacement. Fire protection equipment that functions successfully will prevent damage to personnel and property, resulting in an offsetting cost savings. The magnitude of these savings depends on the success rate and speed of suppression (thereby minimizing physical damage), and the cost of the protected assets themselves. The net cost or savings of each alternative can then be compared to determine the best choice, in this case as a replacement for the halon 1301 fire extinguishing chemicals.

This process can also serve other purposes:

- Estimation of whether a new fire protection technology is sufficiently superior to the state of the art, in cost effectiveness, to warrant further pursuit.
- Justification of the use of any fire protection system at all for an application of interest. This entails a comparison of the cost savings in terms of assets preserved against the total life cycle cost of the fire protection technology.
- Determination of the economics of an optimal degree of effectiveness of a firefighting system. Historically, fielded fire suppression systems have been less than 100 % effective. There are costs (dollars, mass carried, and volume occupied) that generally increase with an enhanced degree of surety that a firefighting system will protect the aircraft and its occupants.

10.1.2 NGP Tasks

To demonstrate the applications of life cycle costing to aircraft fire extinguishing systems, Bennett, Kolleck and co-workers at Booz Allen & Hamilton:

1. Established a life cycle cost baseline for typical halon 1301 (CF_3Br) fire extinguishing systems that are used on aircraft today, by considering several varied aircraft platform type representatives (both legacy (existing) and future platform types), to establish a life cycle cost equivalence goal for any halon 1301 replacement derived from or considered by the NGP.
2. Performed a similar cost analysis for the same platforms using a different fire suppressant. These systems used the “first generation” halon 1301 replacement, HFC-125, C_2HF_5, (see below) for which extensive data existed. The HFC-125 system was sized to the same level of performance as the existing halon 1301 systems. This established a threshold cost-of-ownership level that any halon 1301 replacement technology must exceed to be preferred over the pre-existing use of HFC-125 and thus maintain further interest for research and implementation.
3. Performed cost of ownership studies by varying the performance levels of such systems, by adjusting the size capacities (with resultant weight and size impacts on life cycle cost), to determine an optimal performance level in terms of life cycle cost by balancing firefighting effectiveness with the size/capacity/cost implications.

4. Evaluated the merits of halon 1301 and HFC-125 systems (and, by extension, or any other fire protection system) in terms of their ability to pay for themselves by determining if the cost savings in terms of assets saved historically actually exceeded the life cycle costs of developing, installing and supporting such systems in the field. This enabled confirming if the systems actually provide a tangible monetary benefit to their aircraft customers, to determine which aircraft configurations (if any) provide such benefits, and to quantify any perceived benefits.

The methodologies developed, modified and demonstrated under the NGP have been documented in References 1, 2, and 3, whose distribution is restricted, and in References 4, 5, 6, 7, and 8, which are available to the public. The methodologies were fashioned to serve as stand-alone products, to provide the framework to build modified models for future halon 1301 replacements, and to serve as analysis tools to identify key indicators of desirable halon 1301 replacement properties to consider in later research on new technologies. Since their formulation, these methodologies have been used to perform trade-off studies and to assist in the selection of the most affordable halon replacement agent and system design for aircraft recently under development.

10.1.3 General Methodology

A methodology was developed to determine the net cost of the fire suppression system. This methodology incorporates the cost of the system, which is a function of system size/weight, and the cost savings provided by the system, which are a function of extinguishant effectiveness and the resultant aircraft saved and their value. The net cost is the cost of the system minus the cost savings.

Fire system characterization was first necessary to understand and appreciate the system cost information fully. This was accomplished for the current halon 1301 systems and estimated for the proposed HFC-125 systems. Information regarding the current systems was available through previous NGP efforts.[9,10] Estimates regarding the proposed systems were made using information generated as a part of the Halon Replacement Program for Aviation.[11] Impact estimates (sensitivity analyses) were also made for the potential increase in bottle size/distribution plumbing.

System cost information was developed utilizing the data contained in the Federal Logistics (FEDLOG) system and various traditional costing factors. The Defense Logistics Agency provided access to this system. It contains part numbers, suppliers, and other logistical information specifically for the Service of interest. It is not releasable to the general public because of the proprietary nature of some of the data.

Cost savings information was obtained by utilizing the Annual Fire Protection Cost Model [1966-1995; 1996-2025][12] and other peacetime incident data.

10.2 AGENT PROPERTIES

Halon 1301 is considered by many to be a nearly perfect compound for fire suppression in challenging and high performance applications, such as aircraft. This compound can be stored compactly as a liquefied gas at room temperature and a 1.61 MPa storage pressure, but quickly flash vaporizes at atmospheric pressure and ambient temperatures. It remains stable for years, which is important for satisfactory storage in fielded use. The electrical conductivity of the gas is low (permitting its use in electrical and electronics areas), it is non-corrosive in its pure state, and it is an effective fire suppressant at concentrations well below levels that pose toxicity concerns to humans.

HFC-125 was the "first generation" halon 1301 alternative chemical recommended for immediate use after intensive research efforts of the U.S. Air Force/Navy/Army/Federal Aviation Administration funded, multiyear Halon Replacement Program for Aviation to identify near-term substitutes for halon 1301 for aircraft platforms needing an immediate replacement.[13] The selection had been made following testing in generic and reconfigurable engine nacelle and dry bay mockups, representing the wide range of aircraft fire zone configurations of interest to the sponsors. Statistical experimental design techniques were used to translate the experiments representing a subset of all the possible combinations of fire zones and scenarios into the determination of the extinguishant with the best firefighting performance i.e., lowest agent mass required to extinguish the fires, for all the applications and conditions of interest. In addition to fire suppression performance results, other data on the extinguishants' storage and discharge characteristics, toxicity and materials compatibility traits were considered in the final decision. Once this decision was made, additional experiments were performed to develop a more precise system sizing model, again using statistical experimental design, for HFC-125 that would facilitate the sizing of extinguishing systems using it for various aircraft engine nacelle and dry bay applications.

HFC-125 has many characteristics similar to halon 1301. It leaves no residue in the event of accidental discharge, and thus requires negligible cleanup support. It is non-reactive with steel, aluminum, or brass, and no adverse effects are expected on plastics. Most importantly, it fills heavily cluttered spaces quickly and easily, even at cold temperatures, and under high ventilation air flow conditions. Its atmospheric lifetime is 26.4 years.[10]

For these two chemicals, Table 10–1 lists the properties that were used in the cost estimates.

10.3 CURRENT SYSTEM DESCRIPTION (HALON 1301) FOR LEGACY AIRCRAFT

10.3.1 Cargo Aircraft

The typical legacy cargo aircraft fire protection system layout is described below. The basic design approach placed emphasis on the prevention and containment of fire. The engine nacelle and APU compartments are designated as fire zones, where combustible fluids (fuel, hydraulic fluid, and engine oil) and ignition sources coexist, and a single failure in the combustible fluid system could result in a fire.[14]

Aircraft Engine Nacelle Fire Protection System Components and Procedures

Provided below are realistic fire protection system configuration data for current (legacy) cargo aircraft currently being procured and operated by the USAF. It was assumed that fire protection systems for future cargo aircraft would be similar to these. Schematic drawings of the engine nacelle systems are shown in Figure 10–1 through Figure 10–3.

Table 10–1. Properties of Halon 1301 and HFC-125 Used in Life Cycle Costing.

Features	Halon 1301	HFC-125
Extinguishant Physical State (ambient)	Gas	Gas
Mechanism of Extinguishment	Chemical, some cooling, inerting	Cooling, inerting
Physical Properties		
Boiling Point (°C) at 101 kPa (1 atm)	-57.8	-48.5
Molecular Weight, g	149	120
Liquid Density, kg/m^3 (lb/ft^3) at 70 EF	97.8	75.7
Vapor Pressure, kPa (psia) at 298 K	249	190
Freezing Point, °C (1 atm)	-168	-103
Critical Temperature, °C	4	72
Critical Pressure, kPa (atm)	39	38
Critical volume, cm^3/mol	200	272
Critical Density, g/cm^3	0.75	0.44
Liquid Density, g/ cm^3	1.5	1.2
Vapor Density, g/L	8.7	4.9
Liquid Specific Heat, cal/g	0.21	0.3
Vapor Specific Heat, cal/g	0.11	0.19
Liquid Heat Capacity, cal/mol-K	30.9	36.1
Vapor Heat Capacity, cal/mol-K	16.5	22.6
Extinguishant Effectiveness		
Cup Burner Value, volume %	3.3	9.1
Weight Impact (ratio to halon systems)	1	2.2
Volume Impact (ratio to halon systems)	1	2.9
Environmental Considerations		
Ozone Depletion Potential (ODP)	10 to 14	0
Global Warming Potential (GWP)	1.9	0.58

Fire extinguishing protection is provided for each engine by a fixed, high discharge rate, halon 1301 fire extinguishing system on each wing. Two engine vaporizing liquid fire extinguishers are located on the front spar of each wing inboard of the outboard pylon. Each extinguisher has two discharge ports, one directed to each engine on that wing. This arrangement allows either engine to receive fire extinguishing agent from either or both extinguishers (as a two-shot system) if needed.

The distribution lines to the engine core and accessory compartments can terminate with discharge nozzles. However, for halon 1301, this is often a simple open pipe. A pylon fire extinguisher check valve, located in the engine distribution lines, isolates the two compartments from each other. The pylon fire extinguisher check valve opening pressure exceeds the differential pressure between the core and accessory compartments.

Each engine's vaporizing liquid fire extinguisher has two engine aircraft fire extinguisher power device cartridges and one agent pressure switch. There are shutoff valves for each engine’s fuel and hydraulic fluid supplies.

When a fire is detected in an engine, the applicable FIRE PULL fire control handle assembly is pulled. Signals are supplied through the handle assembly to close the applicable engine fire fuel and hydraulic shutoff valves, isolating the affected engine.

The agent from the extinguishers is discharged by pulling out the applicable handle assembly. The handle assembly is rotated counterclockwise to discharge the agent from the inboard fire extinguisher and clockwise to discharge the agent from the outboard fire extinguisher. The handle assembly is spring-loaded to the center position. F the use of the first extinguisher does not put out the fire, agent is applied from the second bottle.[14,15,16]

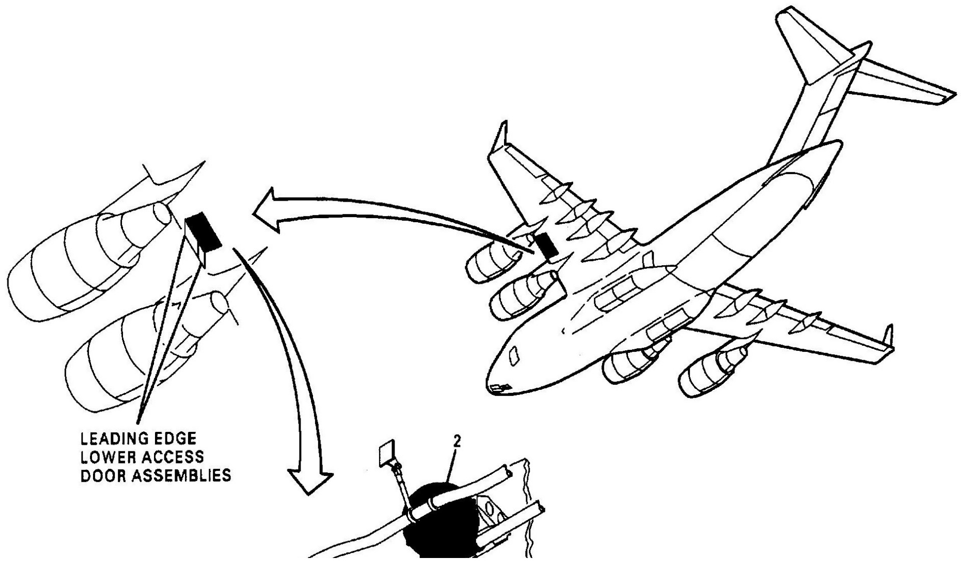

Figure 10–1. Typical Cargo Aircraft Engine Nacelle Fire Protection System Location (Wing Leading Edge).[16]

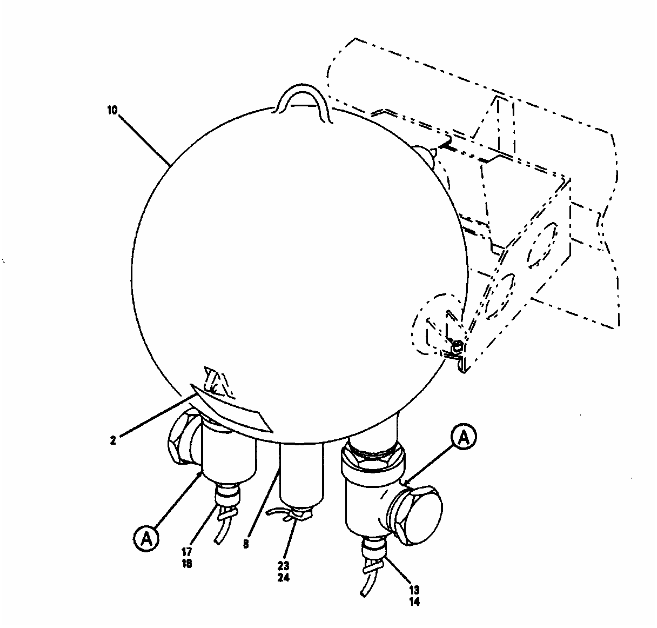

Figure 10–2. Close-up of Typical Engine Nacelle Fire Protection System Bottle.[16] (A: discharge heads)

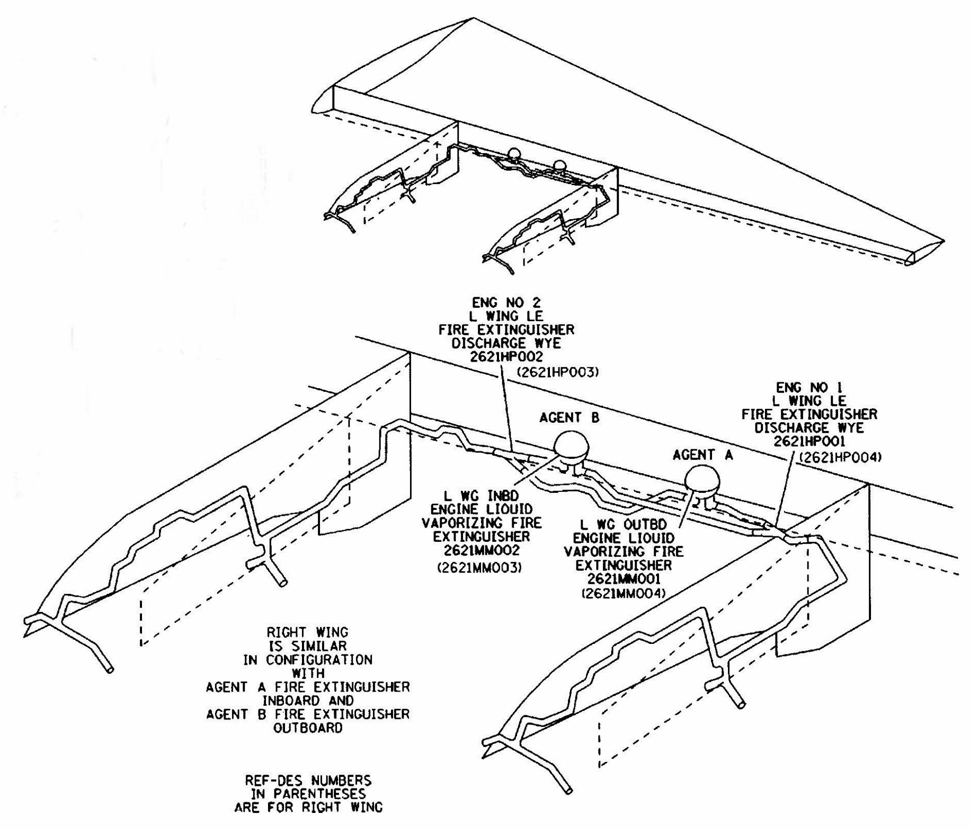

Figure 10–3. Typical Cargo Aircraft Engine Nacelle Fire Suppressant Storage and Distribution System (Wing Leading Edge).[16]

Additional Legacy Cargo Aircraft Fire Protection System Information

Table 10–2 displays additional fire suppression system information (engine nacelle and APU) for a typical legacy cargo aircraft.[1]

Table 10–2. Additional Legacy Cargo Aircraft Fire Protection System Information.

	Engine Nacelle	APU
GENERIC		
Number of aircraft	121	
Fire types	Spray/pool	
FIRE ZONE		
# of fire zones (# of compartments)	2 (4)	1 (1)
Fire zone free volume (net volume), m^3 (ft^3)	7.45 (263)	0.623 (22)
Air ventilation at fire site, kg/s (lb/s)	0.29 (0.64)	0.29 (0.64)
EXTINGUISHANT		
# of halon 1301 systems	2	1
Extinguisher trigger mode	Remote	Remote
Extinguisher volume, cm^3 (in^3)	10,300 (630)	1400 (86)
Diameter of extinguishant container, cm (in)	27.7 (10.9)	14.2 (5.6)

	Engine Nacelle	**APU**
Storage compartment for extinguishant bottle, m^3 (ft^3)		0.42 (15)
Free volume in storage compartment, cm^3 (in^3)		0.43 (260)
Normal charge and pressure of extinguisher container, MPa (psig) @ 21 °C (70 °F) with N_2	5.6 (800)	4.24 (600)
Max extinguisher container pressure (Burst range of safety disc), MPa (psig)	13.2 to 15.6 (1900 to 2300) @ 96 °C (205 °F)	11.96 to 13.3 (1720 to 1920) @ 96 °C (205 °F)
Extinguisher container percent filled, %	67	69
Extinguisher container orientation	Upright with valves at bottom	
Dimensions of bottles with valves, cm x cm (in x in)	6.9 x 3.5	
Dimensions for present access to bottles	20 in x 13 in = $260\ in^2 = 1.81\ ft^2$	
Extinguisher container mass without halon 1301, kg (lb)	5.8 (12.8)	1.5 (3.2)
Halon 1301 mass, kg (lb)	9.5 (21.0)	1.1 (2.5)
Extinguisher container location, inside/outside fire zone	Outside	
STRATEGY FOR USE		
# of shots	2	1
Manual/automatic	Manual	Manual
Procedure for Activation	Fire warning light is activated, pilot initiates firing of pyrotechnic squib which releases the contents of the bottle, the agent travels through the system plumbing to the engine nacelle/APU and is discharged as a gas.	
DISTRIBUTION SYSTEM		
Extinguisher dispersion method, @ 21 °C (70 °F)	5.6 MPa, N_2 @ 800 psig	4.24 MPa N_2 @ 600 psig
Extinguisher discharge rate (95 % in 0.9 s), kg/min (lb/min)	544 (1200)	72 (158)
Distribution system plumbing material	Bottle to pylon stub: 6061ALT6; all else: CRES.	CRES 321
Inner diameter, cm (in)	From bottle to pylon stub, 3.8 (1.5) ID; all else, 3.8 (1.5), 2.5 (1.0), and 1.9 (0.75) ID. Wall thickness, 0.24 (0.095)	1.27 (0.5) ID. Wall thickness, 0.071 (0.028)
Length, cm (in)	99.4 (39.14) from outboard bottle to both outlets in core compartments; 41.7 (16.42); from outboard bottle to inboard pylon	Straight length – 12.7 (5) – 78.7 (31)
Shape, bends, elbows	varies	1 bend, 1.5 radius
Number and nature of nozzles/pipe terminations	Two nozzles	One nozzle
MODIFICATION POTENTIAL		
Restriction on alternative fluids, very/modest/slight	slight	slight

	Engine Nacelle	**APU**
Ease of access of current distribution plumbing for retrofit (0 %-very difficult, 50 %-relatively easy, 100 % easy)	30 % difficult; 70 % easy.	30 % difficult; 70 % easy.
Access & available space for additional distribution plumbing or nozzle modification (0 %-very difficult, 50 %-relatively easy, 100 % easy)	30 % difficult; 70 % easy.	30 % difficult; 70 % easy.
OTHER		
Extinguisher system manufacturer	Walter Kidde	
Evidence of halon 1301 distribution characteristics (from certification tests)	6 % by volume for 0.5 s at cruising condition.	
Range of expected operating temperatures for the bottle and the plumbing, °C (°F)	-60 to 93 (-77 to 200)	
Maximum Air Temperature in the Nacelle, °C (°F)	71 (160)	
MISCELLANEOUS	27.6 kPa (4 psi) is max pressure the protected volume can accept in nacelle. Max pressure in plumbing is 13.8 MPa (2000 psi) allowable. Potential fuels: Jet A and JP-8, Hydraulic Fluid Mil-H-83282, Lube Oil Mil-L-23699.	

Auxiliary Power Unit (APU) Fire Protection System Components and Procedures

Fire extinguishing is provided for the APU by a fixed, high discharge rate, halon 1301 fire extinguishing system in the APU compartment. The APU fire extinguisher consists of the following components:

- APU vaporizing liquid fire extinguisher,
- APU fire extinguisher agent pressure switch, and
- APU fire extinguisher power device cartridge.

The APU extinguisher is externally mounted on the APU compartment forward firewall. The extinguisher has one discharge port. The discharge head, agent pressure switch and power device cartridge are located on the extinguisher.

To extinguish a fire in the APU, the agent is discharged by any of the following switches:

- AGENT DISCH switch on the APU control panel.
- AGENT DISCH toggle switch on the aft loadmaster APU FIRE control panel assembly.
- AGENT DISCH toggle switch on the ground refueling control panel APU FIRE panel.[5]

An APU fire is indicated by at as many as five signals in the aircraft, outside the aircraft, and on the APU itself.[6]

Figure 10–4 shows the typical auxiliary power unit fire protection system location for cargo aircraft.[5, 7]

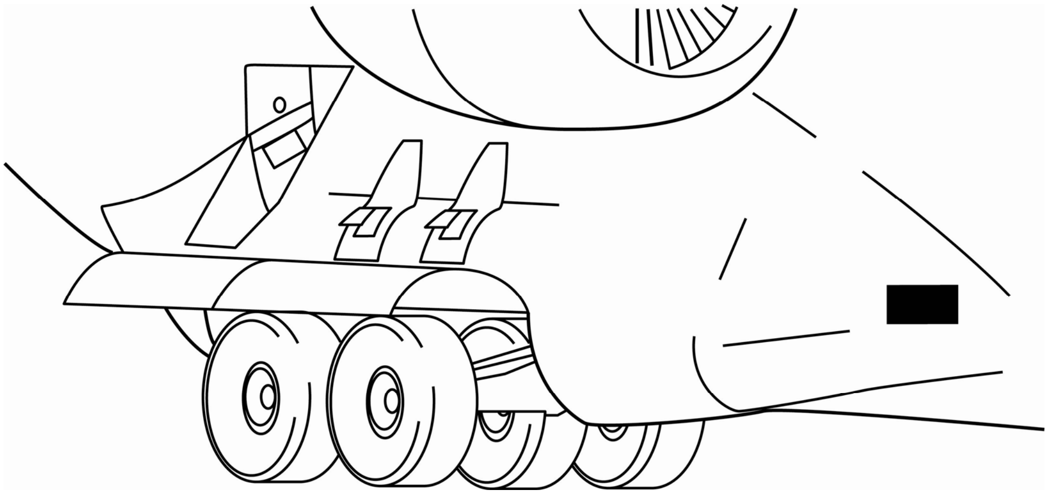

Figure 10–4. Typical Auxiliary Power Unit Fire Protection System Location.[16]

10.3.2 Fighter Aircraft

Fire Protection System Components and Procedures

The location for the representative legacy fighter aircraft fire protection system is in the aft fuselage between the engines, as shown in Figure 10–5 and Figure 10–6.[17] The single-bottle halon 1301 fire suppression system is designed to provide fire protection for the left and right engine nacelles, the left and right airframe mounted accessory drive (AMAD) bays, and the Auxiliary Power Unit (APU) bay.[1] Therefore, the first fire occurrence in either the engine/AMAD or APU bays will utilize all of the agent. The single cylindrical bottle is approximately 46 cm (18 in.) in length with a 11 cm (4.5 in.) diameter.[18] The general system installation is shown in Figure 10–7.[19]

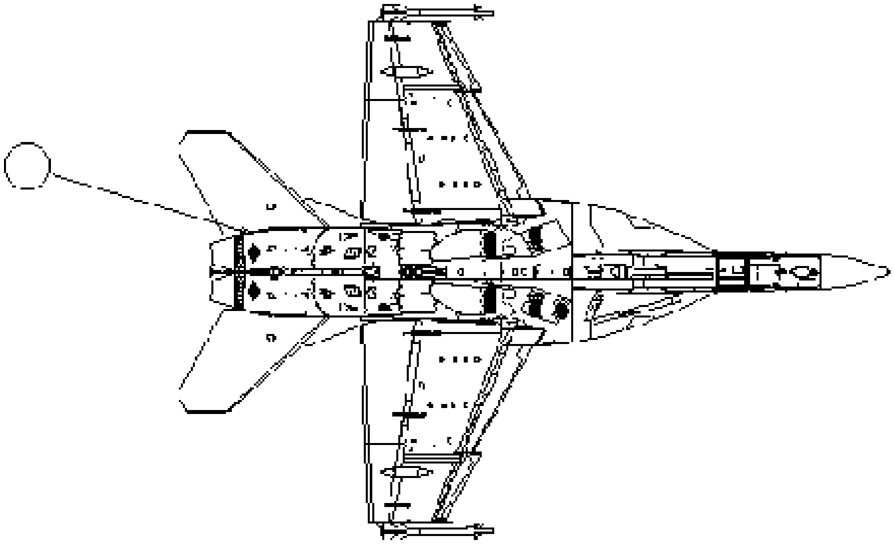

Figure 10–5. Typical General Location of Fighter Aircraft Fire Extinguisher Bottle.[17]

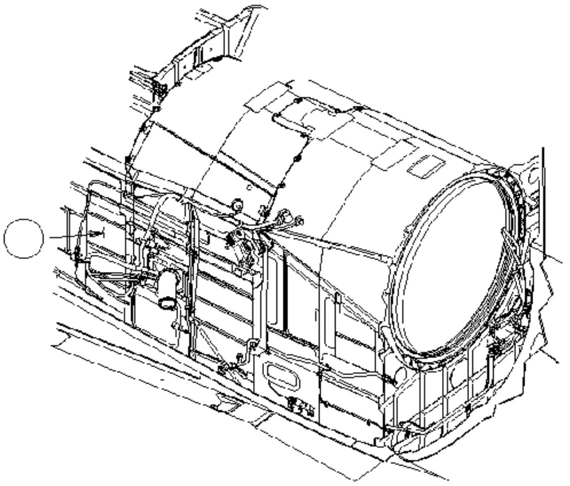

Figure 10–6. Schematic of Typical Fighter Aircraft Engine Bay.[17]

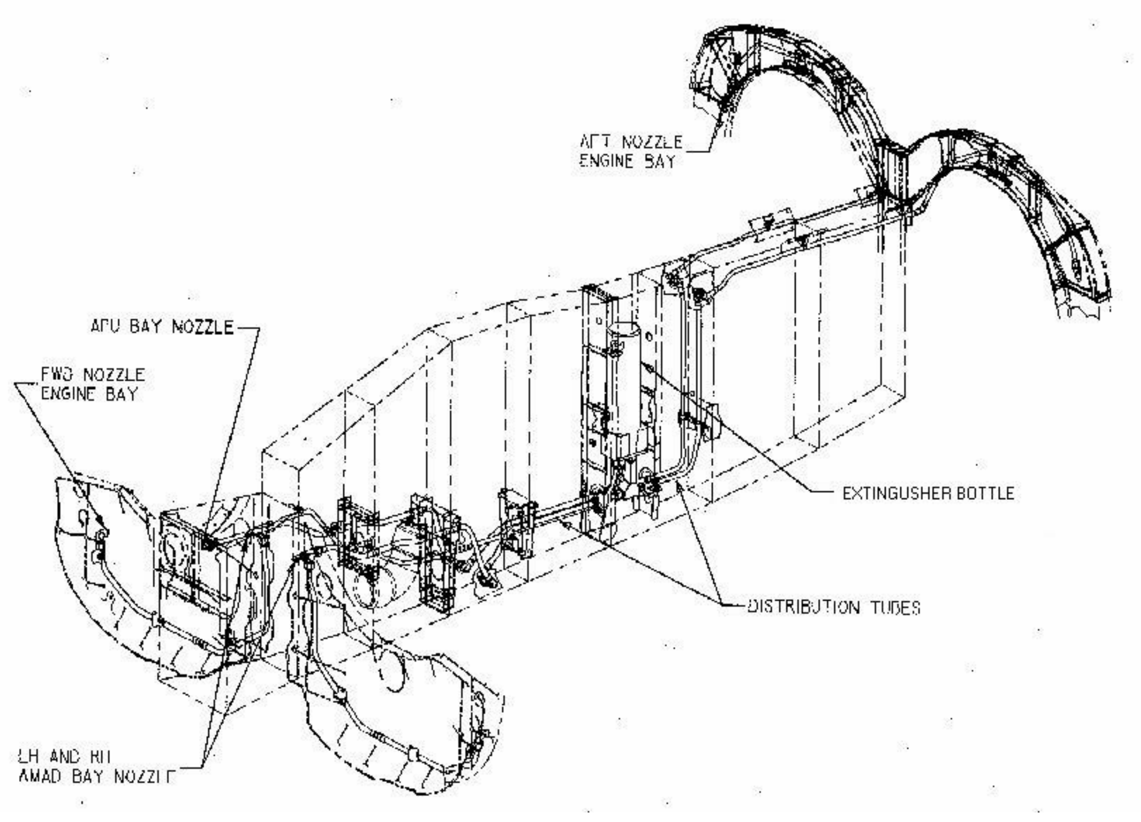

Figure 10–7. Typical Fighter Aircraft Fire Suppression System Installation.[19]

The fire detection and extinguishing system is made up of three fire warning/extinguisher lights, a fire extinguisher pushbutton, one fire extinguisher bottle, a fire test switch and dual-loop fire detection sensors. The extinguisher bottle is in the aft fuselage between the engines. The bottle provides a one-shot extinguishing capability. The system provides engine/AMAD and APU fire warning, emergency shutdown and selective fire extinguishing.[20]

The three fire warning/extinguisher lights are pushbutton switch indicators which come on when a fire condition exists. Two of the fire warning/extinguisher lights are labeled FIRE. One, mounted on the top left corner indicates a fire condition in the left engine bay; the other, mounted on the top right corner of the instrument panel, indicates a fire condition in the right engine bay. The APU FIRE warning/extinguisher light is positioned inboard of the right FIRE light. A voice alert warning is activated anytime a fire warning light comes on. If more than one warning light comes on at the same time, the voice alert warning priority is ENGINE FIRE LEFT, ENGINE FIRE RIGHT, then APU FIRE.[12]

The fire extinguisher pushbutton switch is on the master arm panel and is labeled FIRE EXTGH. The switch has two lights. A yellow light is labeled READY and a green light labeled DISCH (discharge). When READY is on, the fire extinguisher bottle is armed. The READY light comes on when the appropriate fire warning/extinguisher light is pressed. Pressing an engine fire warning/extinguisher light shuts off fuel to the engine at the feed tank. With READY on, pressing the fire extinguisher pushbutton discharges the fire extinguisher bottle and turns on the DISCH light. There is no indication of actual discharge of the fire extinguisher bottle.[12]

The APU fire extinguishing system can be either manually or automatically actuated. To manually actuate the system, the fire extinguisher bottle is first armed and the APU shut down by pressing the APU FIRE warning/extinguisher light. When pressed, the APU FIRE light stays in and a barber pole indicator appears along side the light. The extinguisher bottle is then discharged into the APU bay by pressing the FIRE EXTGH pushbutton with the READY light on. Discharge of the bottle is delayed ten seconds after the light is pressed. This allows the APU time to spool down before the extinguishing agent is introduced. If the aircraft is on the ground, the APU fire extinguishing system is actuated automatically. The result is the same as with manual actuation, with the APU shutting down immediately after a fire is detected and the fire extinguisher discharging into the APU bay ten seconds later. The automatic system is prevented from operating by the action of a relay.[12]

Actuation of the engine/AMAD fire extinguisher can only be performed manually. Lifting the guard and pressing the affected FIRE warning/extinguisher light arms the system. This also shuts off fuel to the engine at the engine feed shutoff valves and closes the cross feed valve. When pressed, the FIRE light stays in, and a barber pole indicator appears in the switch guard. The extinguisher bottle is discharged into the affected engine bay by pressing the FIRE EXTGH pushbutton with the READY light on.[12]

Additional Legacy Fighter Aircraft Fire Suppression System Information

Table 10–3 displays fire suppression system information (engine nacelle and APU) for the typical legacy fighter aircraft.[9]

Table 10–3. Additional Legacy Fighter Aircraft Fire Suppression System Information

Parameter	Engine Bay/APU
FIRE TYPES (pool fires, mist)	Spray/pool
FIRE ZONE	
Number of fire zones	3 (2 engines/AMAD, 1 APU)
Fire zone free volume, m^3 (ft^3)	1.14 (40.3)

Parameter	Engine Bay/APU
EXTINGUISHANT	
Number of halon 1301 systems	1
Extinguisher trigger mode	Pilot activated
Extinguisher volume, cm^3 (in^3)	3031 (185)
Size of cylindrical extinguishant container, cm (in)	11.4 cm (4.5 in) diameter, 46 cm (18 in.) long
Storage compartment for extinguishant bottle, cm (in)	206 x 12.7 x 20.3 (81 x 5 x 8)
Free volume in storage compartment, m^3 (in^3)	0.048 (2953)
Normal charge and pressure of extinguisher container, MPa (psi)	4.3 (625) @ 22.2 °C (72 °F)
Max extinguisher container pressure, MPa (psi)	6.2 (900) @ 16 °C (60 °F)
Extinguisher container percent filled, %	50
Extinguisher container orientation (upright with valves at bottom)	Lateral configuration
Extinguisher container mass without agent, kg (lb)	2.7 (~6)
Halon 1301 mass, kg (lb)	2.5 (5.5)
Extinguisher container location (inside/outside fire zone)	Outside
STRATEGY FOR USE	
Number of shots	1 shot discharges into engine nacelle and AMAD bay or APU.
Manual/automatic	Manual
Procedure for Activation	Fire warning light is activated, pilot initiates firing of pyrotechnic squib which releases the contents of the bottle, the agent travels through the system plumbing to the engine nacelle/APU and is discharged as a gas.
DISTRIBUTION SYSTEM	
Extinguisher dispersion method	Cut-off pipe
Extinguisher discharge rate, kg/s (lb/s)	0.99 (2.2)
Distribution system plumbing	Single pipe discharged into engine and AMAD simultaneously. APU has discharge port, but the first fire occurrence in either the engine/AMAD or APU bays will utilize all halon 1301
Number and nature of nozzles/pipe terminations	Cut-off pipe
Tightness of the bottle space	Only 12.7 cm (5 in) in height available for growth.
Extinguisher Bottle Growth Potential	12.7 cm (5 in) in height
OTHER	
Suppression success fraction	Historical reports show 80% success.
Evidence of halon 1301 distribution characteristics (from certification tests)	Yes
Range of expected operating temperatures for the bottle and the plumbing, °C (°F)	-54 to 316 (-65 to 600)

Typical Legacy Fighter Aircraft Fire Suppression Concentration Tests

The Certification Section of Chapter 2 describes the traditional methodology utilized to certify an aircraft fire suppression system.

Historical Fire Suppression System Effectiveness

As discussed in Chapter 2, data have been compiled on the effectiveness of the F/A-18 fire suppression system.[21] The data show where, when, and why fires occurred from 1982 through 1993, as recorded by the Naval Safety Interactive Retrieval System (NSIRS). During this time period, seven F-18 aircraft were lost or destroyed due to fire.

The engine halon 1301 fire suppression systems were shown to be 80 % successful in extinguishing in-flight fires, and this effectiveness was the same for each engine. Eighty-nine percent of all fires in areas protected by halon 1301 fire suppression (engines and AMAD bays) occurred in flight. Fires in halon 1301-protected areas accounted for 84 % of all in-flight fires. Engine fires accounted for 78 % of all in-flight fires, with 19 occurring in the right engine, 15 occurring in the left engine, three in both engines, and three in unspecified engines.

The preponderance (73 %) of F-18 aircraft fires occurred during a peak period between 1986 and 1989. Seventy-five percent of all engine fires occurred during this time period, and it was reported by Government fire protection engineers that the F-18 afterburner liners were faulty and the cause of at least 25 incidents, not all of which were fire incidents.

The majority (87 %) of F-18 fires were caused by material failures. Common material failures included afterburner liner and spray bar pigtail failures, high-pressure compressor failures, fuel leaks, electrical wire insulation breaches, fuel-filler cap mishaps, failures in the AMAD bay (e.g., hydraulic pump failures), as well as failures of various parts due to fatigue or foreign object debris (FOD).[21]

These aforementioned “real world” effectiveness data were considered when estimating the realistic extinguishing “success rates” to be forecast in future use, and the resultant cost of assets saved, to offset the life cycle costs of developing, acquiring and maintaining a fire extinguishing system for an aircraft platform. This approach was used for all of the platform types studied.

10.3.3 Rotary-wing Aircraft

Fire Protection System Components and Procedures

The general location (between the two engines) of a legacy rotary-wing aircraft fire protection system is shown in Figure 10–8.

The two-bottle halon 1301 fire suppression system is designed to provide dual-shot fire protection for the left and right engine nacelles. Each bottle is cylindrical in shape, and the two bottles are stacked vertically with the long axis of each bottle parallel to the engines themselves.

There are two discharge locations in the engine nacelle, one at the forward firewall, the second at the side. The extinguishing lines truncate with open ended pipes. The inner diameter of the lines is 1.8 cm

(0.69 in. The flame detectors are required to detect a fire within 5 s. Additional time is needed for the pilot to initiate and activate the fire extinguishing system.[22]

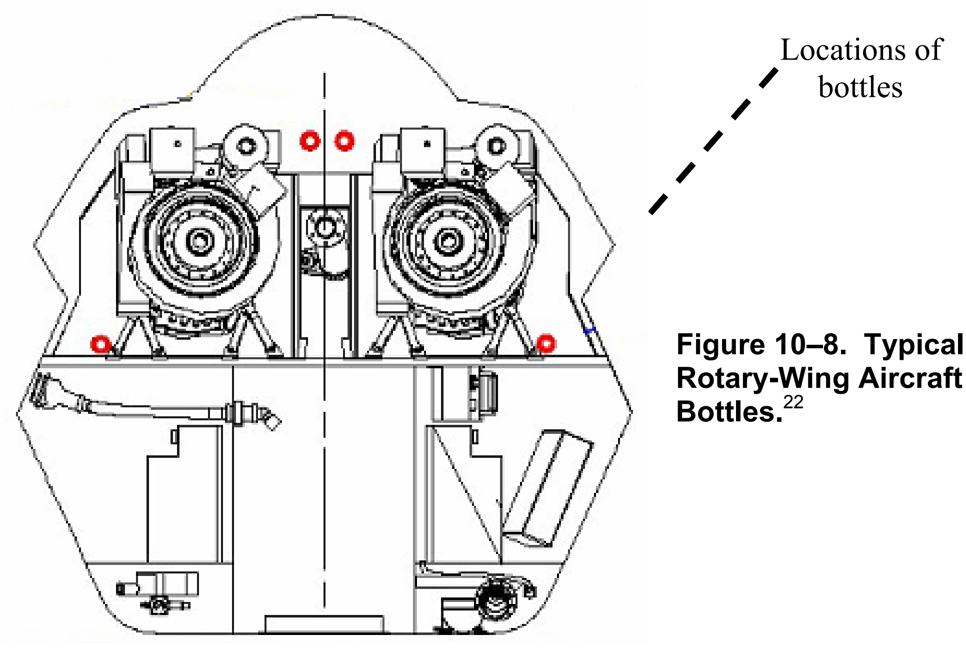

Figure 10–8. Typical General Location of Rotary-Wing Aircraft Fire Extinguisher Bottles.[22]

Each engine nacelle bay has a total volume of approximately 0.85 m^3 (30 ft^3) and houses a single jet turbine engine. Aside from the turbine engine, the bay is fairly cluttered with fuel lines, control systems, etc. The resulting total free volume in each bay is approximately 0.46 m^3 (16.1 ft^3). Each nacelle bay is independently ventilated via four apertures, which provide passive airflow that fluctuates with the helicopter's airspeed and orientation. The airflows inside the nacelle bay range from about 0.54 kg/s to 1.6 kg/s (1.2 lb/s to 3.5 lb/s).

Halon 1301 Design Guide Estimation

The total mass of the current representative rotary-wing system is approximately 6.5 kg (14.3 lb). The total extinguishing agent mass is 0.7 kg (1.5 lb) per platform or 0.3 kg (0.8 lb) for each bottle. The present system requires head space (vapor volume in the bottles above the liquid fill line) to pressurize the fluid to 4.1 MPa (600 psi) with nitrogen, and uses 0.3 cm (1/8 inch) thick 304 stainless steel bottles that weigh 0.8 kg (1.8 lb.) each, or 1.6 kg (3.5 lb) for the two bottles. The mass of the fluid distribution manifold, pyrotechnic valves, mounting hardware, and electrical connectors is about 4.2 kg (9.3 lb), with the estimated mass of electrical cables and mounting hardware of 0.52 kg (1.1 lb) per installation (for a total of 1.0 kg (2.3 lb) per platform).[23]

However, it was unclear whether the current design's halon 1301 mass (0.3 kg (0.8 lb) per bottle, for a total of 0.7 kg (1.5 lb) per platform, used by the rotary-wing representative was sufficient to maintain the necessary concentration of agent of at least 6 % by volume in air in all parts of the affected zone simultaneously for at least 0.5 s at normal cruising condition. Due to this uncertainty, the required halon 1301 amount was calculated using the military specification for sizing systems, MIL-E-22285.[24] This specification applies to the installation of high-rate-discharge type fixed fire extinguishing systems for engine spaces and other potential fire zones in aircraft. As a design guide, the following equations may be used to determine the minimum mass of agent to be discharged into each engine:

1. For "rough" nacelle interior with low air flow, and for a smooth nacelle interior regardless of air flow, using whichever of the following two equations provides the larger value of W:

$$W = 0.05V \tag{10-1}$$

$$W = 0.02V + 0.25WA \tag{10-2}$$

2. For "rough" nacelle interior with high air flow:

$$W = 3(0.02V + 0.25WA) \tag{10-3}$$

3. For a "deep frame" nacelle interior with high airflow:

$$W = 0.16V+0.56WA \tag{10-4}$$

where:

W (lb) = mass of agent
WA (lb/s) = mass flow air passing through the zone at normal cruising condition.
V (ft^3) = net volume of the zone (gross volume of the zone less the volume of major items of equipment.[24])

Figure 10–4 shows the legacy rotary wing aircraft-specific parameters used to estimate the amount of halon 1301 required.

Table 10–4. Legacy Rotary-wing Aircraft Specific Parameters.

Parameter	Value
Airflow	0.54 kg/s to 1.59 kg/s (1.2 lb/s to 3.5 lb/s)
fuel source	MIL-H-83282, MIL-H-5606, JP-8
Maximum air temperature	51.7 °C (125 °F)
free volume	0.46 m^3 (16.1 ft^3)

The resulting halon 1301 system agent capacity per platform ranges from 1.09 kg (2.39 lb.) to 3.26 kg (7.18 lb.), per the guidance of the aforementioned military sizing standards.

Additional Legacy Rotary-Wing Aircraft Fire Suppression System Information

Table 10–5 displays fire suppression system information (engine nacelle and APU) for a typical legacy rotary-wing aircraft.[10]

Table 10–5. Additional Legacy Rotary-wing Aircraft Fire Suppression System Information.

Parameter	Value
FIRE TYPES (pool fires, mist)	Spray/pool
FIRE ZONE	
Number of fire zones	2
Fire zone free volume, m^3 (ft^3)	0.46 m^3 (16.1 ft^3)
EXTINGUISHANT	
Number of halon 1301 systems	2
Extinguisher trigger mode	Pilot activated
Extinguisher volume, cm^3 (in^3)	
Size of extinguishant container, cm, cm, cm (in, in, in)	Cylindrical
Normal charge and pressure of extinguisher container, MPa (psi)	4.14 MPa (600 psi)
Extinguisher container percent filled, %	60
Extinguisher container orientation	Stacked vertically and parallel to engines
Extinguisher container mass without halon 1301, kg (lb)	0.79 kg (1.75 lb.) each or 1.59 kg (3.5 lb.) for the two bottles
Halon 1301 mass, kg (lb)	0.68 kg (1.5 lb.) per platform or 0.34 kg (0.75 lb.) for each bottle
Extinguisher container location (inside/outside fire zone)	Outside
STRATEGY FOR USE	
Number of shots	2
Manual/automatic	Manual
Procedure for Activation	Fire warning light is activated, pilot initiates firing of pyrotechnic squib which releases the contents of the bottle, the agent travels through the system plumbing to the engine nacelle and is discharged as a gas.
DISTRIBUTION SYSTEM	
Extinguisher dispersion method	The extinguishing lines end with open ends.
Distribution system plumbing	There are two discharge locations in the engine nacelle, one at the forward firewall, the second at the side. The inner diameter of the lines is 1.76 cm (0.694 in).
Number and nature of nozzles/pipe terminations	Two; The extinguishing lines end with open ends.

Typical Legacy Rotary-Wing Aircraft Fire Extinguishing Concentration Tests

The protocol for certifying and approving fire suppression systems for rotorcraft via concentration measurements during discharge is the same as previously described for the design of fighter aircraft systems.

Historical Fire Suppression System Effectiveness

Reference 25 provides information on the historical effectiveness of rotary-wing aircraft fire suppression systems. It discusses where, when, and why fires occurred from 1977 through 1993, as recorded by the Naval Safety Interactive Retrieval System (NSIRS). During this period, 146 of 161 rotary aircraft fires (91 %) did not result in "destruction" of the aircraft – the fires were either extinguished by the on-board fire protection systems or ground crew, or self extinguished. The rotary aircraft fire suppression systems were reported as having extinguished 71% of all fire events in which the system was activated to attempt extinguishment. Analysis of the Safety Center data indicates that, when used, the rotary aircraft fire suppression systems were 71 % effective overall in extinguishing fires, and the engine fire suppression systems were 57 % effective.[25]

10.4 PROPOSED SYSTEM DESCRIPTION (HFC-125) FOR FUTURE AIRCRAFT

10.4.1 Design Guide

Since current (legacy) aircraft use halon 1301 (and not HFC-125), a potential system description and sizing for retrofit/future aircraft had to be estimated. The Halon Replacement Program for Aviation developed a Design Guide to assist in sizing systems using HFC-125.[11] These systems are intended to provide extinguishant effectiveness equivalent to halon 1301 systems, which were designed using traditional approaches. This Design Guide was used to size a system for future aircraft platforms under consideration. The legacy aircraft-specific parameters were also used to estimate the mass of HFC-125 required for their platforms. The Design Guide provides a two step design process to be used in sizing systems appropriately.

The five-step approach to determine the required design concentration for certification and estimate the necessary mass of extinguishant to meet certification requirements consists of the following procedure:

1. Calculate the customized design concentration required for the configuration of the platform of interest using Equation 5 in the Design Guide, using relevant operational values of air temperature, air mass flow rate, and fuel type used on the platform in the fire zone.
    a. If the range of air temperature and air mass flow varies considerably in the flight envelope, several combinations of relevant maximum air temperature and corresponding mass flow should be tried to assure the highest concentration calculated to be required over the flight envelope is achieved. In general, the application of the highest air temperature and minimum air mass flow (within acceptable data bounds, as governed by the Design Equation 5) will normally give a conservative worst-case estimate.
    b. For this equation, the values input for maximum air temperature and air mass flow should never be outside the range of the values upon which the equation was developed (37.8 °C to 135.0 °C (100 °F to 275 °F) and 0.4 kg/s to 1.2 kg/s (0.9 to 2.7 lb/s), respectively). If the actual maximum operating condition is outside of these ranges, the closest extreme value should be used. The impact on the accuracy of the results has been shown in experiments to be minimal.
    c. If more than one flammable fluid is present in the engine nacelle or APU (such as hydraulic fluids or oils), use the highest fuel constant (coefficient) value corresponding to

the fluids present. (For example, the fuel constant = 0.4053 for hydraulic fluid would be used if it is present, since it has the highest constant.)

d. If a single system protects one or more engine nacelles and an APU, calculate the required concentration and corresponding mass for either application independently and use the higher of the two mass requirements.

2. Calculate the expected extinguishant mass requirement via Equation 10-6, using the required concentration calculated in Equation 10-5, the volume of the fire zone (nacelle or APU) and the actual air mass flow (even if outside the bounds considered in the previous step).
3. Design the extinguishant container capacity consistent with current design practice and use the mass estimates in Equation 10-6 for use in design trade-study comparisons and as a starting point for certification testing.
4. Perform the certification discharge experiments (using existing Halonyzer or Statham analyzer equipment to measure concentrations real-time, but recalibrated for HFC-125), with the criteria being the attainment of the design concentration calculated in Equation 10-5 at all measurement points in the nacelle simultaneously for at least 0.5 s.
5. If certification is not met, increase the container capacity or modify the distribution system to eventually pass certification.

The concentration calculated using Equation 10-5 will be the concentration used for certification testing of a HFC-125 system designed for engine nacelle or APU protection. Equation 10-5 can give a range of concentration values from 14.5 % by volume to 26 %, by volume,

$$\mathbf{Xe} = 21.10 + 0.0185\ \text{AIRT} - 3.124\ \text{WA} + 5.174\ (\text{FUEL CONSTANT}) + 0.0023\ (\text{AIRT}) \times (\text{FUEL CONSTANT}) + 1.597\ (\text{FUEL CONSTANT})^{11} \quad (10\text{-}5)$$

where:

Xe (% by volume) = Certification Design Concentration

AIRT (°F) = maximum ventilation air temperature in the nacelle or APU during operations

WA (lb/s) = internal air mass flow in the nacelle or APU during operations

FUEL CONSTANT = coefficient to account for presence of JP fuel, hydraulic fluids, or oil

The variable ranges permissible for use in Equation 5 are:

AIRT	37.8 °C to 135.0 °C (100 °F to 75 °F)
$\dot{W}$a	0.4 kg/s to 1.2 kg/s (0.9 lb/s to 2.7 lb/s)

FUEL CONSTANT (Use highest coefficient of fluids present.)

If JP fuel, use	0.3586
If hydraulic fluid, use	0.4053
If oil, use	0
If fire resistant hydraulic fluid (SKYDROL), use	0

Equation 10-6 below is a theoretically derived equation to estimate the minimum mass of extinguishant required for a system to pass the certification process while exhibiting at least the minimum design concentration Xe calculated from Equation 10-5, everywhere in the nacelle simultaneously. The equation was derived using physical flow modeling idealization presumably similar to that used to develop mass sizing formulas used for earlier halon 1301 certification, since the equations are similar in structure. Only one equation now exists for HFC-125, which accounts for the effects of high-speed airflow and compartment obstructions (ribs and other structure), whereas the prior halon 1301 equations had multiple empirical sizing equations for various rib height and clutter classes, since it could exploit a large body of test data with these various configurations. Like its predecessor formula for halon 1301, this theoretical estimation equation assumes optimal distribution and mixing of the extinguishant. It is useful for preliminary sizing of systems for trade studies with other alternatives during the design process and as a starting point to begin certification tests. If a distribution system is not designed to distribute the extinguishant efficiently, certification tests may not be passed initially, and either the distribution system will require modification and improvement or the bottle capacity and extinguishant mass will need to be increased until certification is accomplished. Equation 10-6 will calculate system sizes that will range between 2.3 and 4.3 times the volume of optimally designed halon 1301 systems for identical applications, with a corresponding mass growth ratio only about 80 % of the volume growth ratio compared to a halon 1301 system (due to the lower density of HFC-125 compared to halon 1301). The estimated HFC-125 system size and mass may actually be much closer in size to an existing halon 1301 installation, due to the oversizing of many previous halon 1301 designs.[11]

$$MASS(lb.) = 0.003166XeV + 4.138\frac{Xe}{100 - Xe}\dot{W}_{ACTUAL} \tag{10-6}$$

where:

Xe (% by volume) = engine/APU concentration for certification (Equation 10-5)
V (ft^3) = free volume of nacelle or APU--ft^3
$\dot{W}_{ACTUAL}$ (lb/s) = actual maximum air mass flow (no experimental bounds)

The two-step approach (per the Design Guide) was followed to determine the required design concentration for certification and estimate the necessary mass of extinguishant to meet certification requirements.

The Design Guide[11] is limited to providing a mass estimate that assumes the HFC-125 is optimally distributed (with just the minimal required concentration at all sites simultaneously, and no wasted excess), which may well be too optimistic, based upon experience with fielded systems. The following analysis was performed to provide an alternative method of estimating of the required mass and increased container volume required, by attempting to replicate the amount of inefficiency currently observed with fielded legacy systems, due to simplifications and design limitations of their distribution systems, or even due to simple overdesigns, that result in excess or “wasted” extinguishant discharged that does not directly satisfy the Design Guide criteria. This is accomplished simply by beginning with pre-existing fielded legacy halon 1301 systems in use, and adjusting their size for HFC-125 (with a similar overdesign, presumably), by merely adjusting their capacities and size by the ratios of the design concentrations, liquid densities and molecular weights of HFC-125, compared to halon 1301. This alternative scaling approach (a "scale up" coefficient from halon 1301 to HFC-125, for equivalent protection) for realistic, "inefficient" systems is expressed in Equations 10-7 and 10-8 (illustrated for this application to require an HFC-125 design concentration of 24 %).

$$\frac{MW_{HFC-125}}{MW_{Halon1301}} * \frac{[C]_{HFC-125}}{[C]_{Halon1301}} = \frac{120}{149} * \frac{23.8}{6} = 3.2 = WeightRatio \tag{10-7}$$

$$WeightRatio * \frac{\upsilon_{HFC-125}}{\upsilon_{Halon1301}} = WeightRatio * \frac{\rho_{Halon1301}}{\rho_{HFC-125}} = 3.2 * \frac{97.8}{75.7} = 4.1 = VolumeEstimate \tag{10-8}$$

where:

MW (g) = Molecular Weight

[C] (% by volume) = Concentration determined by the Design Guide

ρ (lb/ft^3) = Liquid Density @ 70 ºF

10.4.2 Cargo Aircraft

Table 10–6 and Table 10–7 show the results of the Design Guide calculations (concentration and mass estimation) for the future cargo aircraft engine nacelle and auxiliary power unit fire systems, respectively.

Table 10–6. Design Guide Estimates of HFC-125 Concentration and Mass for Future Cargo Aircraft Engine Nacelles.

Maximum Temperature	Air Mass Flow kg/s (lb/s)	Fuel Constant	Concentration	Mass Estimate (lb)	Mass Estimate (kg)
71.1 °C (160 °F)	Maximum - 1.22 (2.7)	Jet A (0.359)	17.8	N/A	N/A
71.1 °C (160 °F)	Maximum - 1.22 (2.7)	JP-8 (0.359)	17.8	N/A	N/A
71.1 °C (160 °F)	Maximum - 1.22 (2.7)	MIL-H-83282 (0.405)	18.1	N/A	N/A
71.1 °C (160 °F)	Maximum - 1.22 (2.7)	MIL-L-23699 (0.0)	15.6	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	Jet A (0.359)	23.4	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	JP-8 (0.359)	23.4	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	MIL-H-83282 (0.405)	***23.8***	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	MIL-L-23699 (0.0)	21.3	N/A	N/A
71.1 °C (160 °F)	Actual – 0.29 (0.64)	MIL-H-83282 (0.405)	N/A	***21.3***	***9.7***

Table 10–7. Design Guide Estimates of HFC-125 Concentration and Mass for Future Cargo Aircraft Auxiliary Power Units.

Maximum Temperature	Air Mass Flow kg/s (lb/s)	Fuel Constant	Concentration	Mass Estimate (lb)	Mass Estimate (kg)
71.1 °C (160 °F)	Maximum – 1.22 (2.7)	Jet A (0.359)	17.8	N/A	N/A
71.1 °C (160 °F)	Maximum – 1.22 (2.7)	JP-8 (0.359)	17.8	N/A	N/A
71.1 °C (160 °F)	Maximum – 1.22 (2.7)	MIL-H-83282 (0.405)	18.1	N/A	N/A
71.1 °C (160 °F)	Maximum – 1.22 (2.7)	MIL-L-23699 (0.0)	15.6	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	Jet A (0.359)	23.4	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	JP-8 (0.359)	23.4	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	MIL-H-83282 (0.405)	***23.8***	N/A	N/A
71.1 °C (160 °F)	Minimum – 0.41 (0.9)	MIL-L-23699 (0.0)	21.3	N/A	N/A
71.1 °C (160 °F)	Actual – 0.29 (0.64)	MIL-H-83282 (0.405)	N/A	***2.6***	*1.2*

Note that the concentration estimate is based upon an air mass flow of 0.4 kg/s (0.9 lb/s) (within the bounds relevant for the equation) and the mass estimate is based upon the actual air mass flow of 0.27 kg/s (0.6 lb/s), as directed by the Design Guide. The first eight rows in each table are calculations of the maximum concentration required, evaluated over a range of air flows and fuel types, with the maximum concentration is denoted in bold face. The last row is the calculation of the required mass needed to hold the maximum required concentration, while accounting for airflow dilution at the highest actual operating mass flow, with the mass also being denoted in bold face.

The estimate of the proposed system concentration, mass and volume increase is given in Table 10–8. Table 10–9 shows the current and proposed system extinguishant and bottle masses. This is only an (proportional) estimate because the larger bottles would have to be designed by a fire suppression system manufacturer using factors such as agent density, agent pressure, percent liquid fill, and required container wall thickness.

Table 10–8. Future Cargo Aircraft Proposed System Estimates.

	Aircraft Engine Nacelle					Auxiliary Power Unit					Total Agent Per Platform	
	Conc.	Mass		Volume		Conc.	Mass		Volume			
	% by vol.	lb	kg	in^3	L	% by vol.	lb	kg	in^3	L	lb	kg
Current halon 1301 system	6.0	21.0	9.5	630	10.3	6.0	2.5	1.1	86.0	1.4	86.5	39.2
Estimated HFC-125-optimally distributed	23.8	21.3	9.7	814	13.3	23.8	2.6	1.2	110.9	1.8	87.9	39.9
Estimated HFC-125-non-optimally distributed	23.8	67.2	30.5	2583	42.3	23.8	8.0	3.6	352.6	5.8	277.0	125.6

Table 10–9. Future Cargo Aircraft Extinguisher Container and Agent Mass.

	Current Halon 1301 System				Estimated HFC-125-Optimally Distributed				Estimated HFC-125- Non-Optimally Distributed			
	AEN		APU		AEN		APU		AEN		APU	
	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg
Bottle mass	12.8	5.8	3.2	1.5	13.0	5.9	3.3	1.5	41.0	18.6	10.1	4.6
Agent mass	21.0	9.5	2.5	1.1	21.3	9.7	2.6	1.2	67.2	30.5	8.0	3.6
Total mass	33.8	15.3	5.7	2.6	34.3	15.6	5.9	2.7	108	49.1	18.2	8.3

Potential Airframe Impact

Depending on the legacy cargo aircraft of interest, the potential airframe impact will vary. Issues to consider include: impact to the airframe weight/volume, maintenance, and modification.

Weight/Volume Impact

The weight/volume impact depends on the system optimization. As shown in the previous tables, a system that is optimally distributed can have a significant weight and volume reduction versus a non-optimally distributed system. Increases in weight will cause an increase in the fuel required to haul the additional weight. Increases in volume will cause a reduction in weapon system capability (such as reduced storage for munitions).

Maintenance Impact

During this study, maintenance personnel were contacted for their insight and advice regarding the impact to maintenance procedures. The maintenance personnel provided the following maintenance time estimates and procedures. Two AFSC senior airmen are required to assist in access or removal of the items and to perform retrofit. Access to all five fire bottles requires one man-hour total. The fire bottles require weight checks every 10 years and the explosive actuating squibs are time change items and require time change every five years from date of manufacture or three years from the date of installation. Four man-hours total for all five fire bottles are required to remove the item. Six man-hours total for four fire bottles are required to reinstall and inspect the item.

Current regulation Bottle requires that the bottle mass not exceed 17 kg (37 lb) if it is to be lifted overhead by one person. If the resulting design exceeds this limit, an additional maintenance person would be required and would result in additional operation and support costs.

Any modification to the system must allow access to the fire bottles and distribution system. The areas accessed during normal fire suppression system maintenance include the wing leading edge and engine pylons. The access panels are routinely opened for other maintenance and there are no problems foreseen in removing any of the access panels. Typically, the access panels are the only components that have to be removed to access the fire protection system. The same access panels are typically used to access the distribution system as are the fire bottles. Access panels may need to be made larger if a larger bottle is used.

Modification Impact

An estimate of the modification impact was difficult to ascertain and depends on the modification required. A more accurate assessment of the impact requires input from the airframe manufacturer, which was not available. Modification to the structure may be significant (and may be cost prohibitive).

If the distribution system is optimally designed, HFC-125 may be able to fit in the existing space. However, if the distribution system is not optimally designed it will require a larger and heavier bottle, which may not be feasible in the current configuration. This may require either modification of the existing structure, a relocation of the bottles, or the optimization of the distribution system. It would need to be determined whether enough access/available space for additional distribution plumbing or nozzle modification exists.

A poorly designed distribution system results in an unnecessary increase weight. Therefore, there is a strong incentive to optimize the system. It is recommended that a distribution optimization study (similar to the Navy's program for the F/A-18 E/F) be performed or else extensive aircraft modification will be required.

Due to the current lack of airframer engineering assistance, the significant cost impact of modifying an aircraft (including structure) to accommodate fire system changes could not be estimated accurately. Therefore, those costs were not included in this study (since it requires a detailed, multi-faceted engineering assessment for engineers familiar with a specific platform and its design details and modification labor estimations, and performed on a case-by-case basis), and any estimates of retrofit costs in this study using larger systems that may require moderate or extensive structure modifications should be considered a very conservative underestimate of actual retrofit costs involved.

Prior to the final design of an HFC-125 system, assistance from extinguisher system manufacturers and from the airframe manufacturer needs to be sought.

10.4.3 Fighter Aircraft

General Description

Future fighter aircraft fire suppression systems will utilize a four-nozzle HFC-125 system in addition to the agent outlets in the AMAD and APU bays for enhanced agent distribution. The general location for the future fighter aircraft fire suppression system is similar to the legacy fighter aircraft fire suppression system. The extinguisher bottle is in the aft fuselage between the engines and provides a one-shot extinguishing capability. Future fighter aircraft fire suppression systems utilize a single bottle of HFC-125. The four-nozzle distribution system, shown schematically in Figure 10–9 is designed to swirl the agent into the incoming ventilation air and around the engine nacelle.[26]

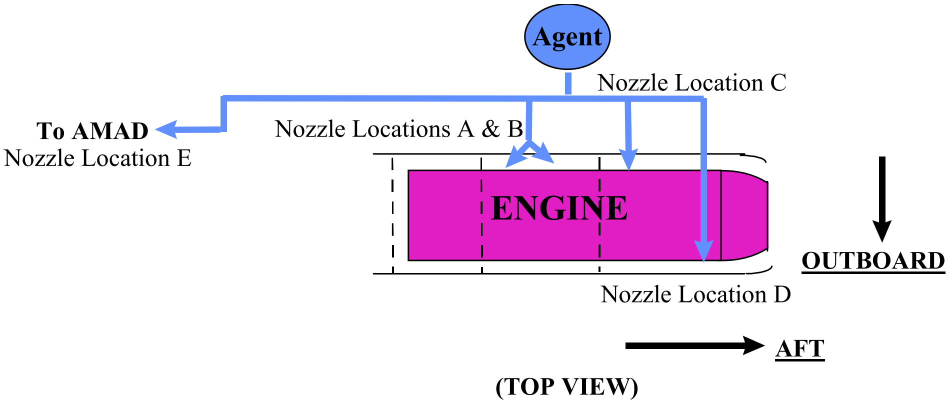

Figure 10–9. Typical Future Fighter Aircraft Agent Distribution System.

The general characteristics of the enhanced plumbing highlight the significance of plumbing modifications. Compared with the much simpler legacy aircraft plumbing scheme, which employs a single discharge nozzle, the future aircraft four-nozzle system prepositions the HFC-125 throughout the nacelle. This pre-positioning, in concert with the prevailing nacelle airflows, optimizes agent presence at any fire in the nacelle. The future fighter aircraft distribution system utilizes the same plumbing diameters as the legacy system.[27]

Fire Protection System Components and Procedures

It was assumed that the procedures for future fighter aircraft fire protection systems are similar to the procedures for the legacy systems as described previously. Table 10-10 displays the components of the future aircraft engine nacelle fire suppression system. [28]

Fire Suppression System Optimization

The Naval Air Systems Team conducted and participated in several varied halon 1301 replacement programs. Each offered data that gave rise to the opportunity of successfully applying HFC-125 to the in-service fleet as an adequate alternative to halon 1301. The particular on-board retrofit applications being promoted are the fixed halon 1301 fire protection systems protecting the engine nacelles aboard aircraft.

Future fighter aircraft will not have the luxury of accepting any system larger than the halon 1301 system currently aboard earlier models. Future fighter aircraft utilized the same bottle compartment dimensions as their legacy fighter aircraft counterparts, which had only minimal growth opportunity for a new agent cylinder.[22] Consequently, the Navy invested in a system optimization program. This program focused on nacelle airflow analyses and plumbing optimization and proved that enhanced distribution of the less effective chemical could, and did, deliver an HFC-125 system design capable of meeting the performance of the halon 1301 system it was replacing. This was extremely beneficial since original estimates predicted up to 200 % to 300 % system growth required.[11]

Due to the early system optimization, the resulting future fighter aircraft Engine/AMAD/APU fire extinguishing mass system mass only grew by 19 %, and the agent mass only grew by 27 %. Table 10–11 shows a comparison of the fire extinguishing system masses.

Table 10–10. Future Fighter Aircraft Engine Nacelle Fire Protection System Components.

Part Number	Description	Units Per Assembly
2-100280-1	Fire Extinguisher Tank (4SQT109) Cartridge, Aircraft (Left Engine Cartridge) (05167) (McDonnell Douglas Corp Spec 74-500054-101) (4SQT109-J1)	1
M25988/1-905	O-Ring (Packing) (81349)	1
33500009	Tank Fire Extinguisher (05167) (McDonnell Douglas Corp Spec 74-500052-111) (4SQT109)	1
M25988/1-906	O-Ring (Packing) (81349)	1
2-100280-3	Cartridge, Aircraft (APU Cartridge) (05167) (McDonnell Douglas Corp Spec 74-500054-103) (4SQT109-J3)	1
M25988/1-905	O-Ring (Packing) (81349)	1
2-100280-5	Squib, Electric (Right Engine Cartridge) (05167) (McDonnell Douglas Corp Spec 74-500054-105) (4SQT109-J2)	1
74A502115-1001	Tube Assembly (76301)	1
74A502116-1003	Tube Assembly (76301)	1
74A330710-2341	Shim (76301)	1
4M36-02020	Washer, Flat (76301)	2
NAS6604-4	Bolt, Shear (80205)	2
AN894J10-8	Adapter, Straight, TU (88044)	1
74A502106-1003	Tube Assembly (76301)	1
74A330710-2339	Shim (76301)	1
74D490106-1001	Dummy Connector, Plug (Shorting Plug) (76301)	3

Table 10–11. Fighter Aircraft Fire Suppression System Mass Comparison.

	Halon 1301 System (1 nozzle)[a]		HFC-125 System (4 nozzles)[a]	
	kg	lb	kg	lb
Bottle Mass	4.2	9.3	5.6	12.2
Agent Mass	2.5	5.5	3.2	7.0
Plumbing Mass	4.3	9.5	4.6	10.1
Total Mass	11.0	24.3	13.4	29.3

[a] in addition to the agent outlets in the AMAD and APU bays

Design Guide Estimation

To show the value of investment in system optimization, estimates were made during this program of the required mass and volume impact and the resulting costs of not utilizing an optimized system. These estimates were made using the referenced report generated as a part of the Halon Replacement Program for Aviation. [11]

The intent of the design guide was to retain an equivalent level of fire fighting performance to the current halon 1301 systems. Like the halon 1301 systems they replace, the new systems incorporating HFC-125 will not extinguish every imaginable fire condition created and if so, it could not be verified via experimentation. Historical data revealed an overall effectiveness of 60 % to 80 % for halon 1301 systems. The HFC-125 design guidance demonstrates a validated 80 % to 100 % effectiveness. Systems designed using HFC-125 will generally require varying degrees of additional quantities per application compared to their halon 1301 counterparts for an identical application, assuming an optimized halon 1301 system was used. Many fielded halon 1301 systems are not optimal in sizing, and the estimate of installing a replacement HFC-125 container has resulted in much smaller size increase impacts than expected.

The design guide presumed optimal mixing. Less efficient distribution systems will require higher masses to achieve the required concentration simultaneously for a half second during certification, with the designer having the option of accepting higher mass requirements or modifying and improving the distribution system.

Table 10–12 shows the future fighter aircraft specific parameters used to estimate the mass of HFC-125 required. The concentration estimate is based upon an air mass flow of 0.4 kg/s (0.9 lb/s) (within the bounds of the equation), and the mass estimate is based upon the actual air mass flow of 0.96 kg/s (2.11 lb/s) as directed by the design guide.

Table 10–12. Future Fighter Aircraft Specific Parameters.

Parameter	Value
Airflow	0.96 kg/s (2.11 lb/s)
Fuel Source	JP-8, hydraulic fluid
Maximum air temperature	104.4 ºC (220 °F)
Free Volume	1.10 m^3 (38.8 ft^3)

Estimates of the HFC-125 system concentration, mass, and volume increase are given in Table 10–13. The resulting concentration and mass estimates were 25 % and 2.70 kg (5.96 lb), respectively, which differed somewhat from the Navy-generated results of 18 % and 2.21 kg (4.87 lb), respectively.

Table 10–13. Estimates of System Parameters for Proposed Future Fighter Aircraft System Description.

	Concentration	Mass		Volume	
	% by volume	kg	lb	L	in^3
Legacy Fighter Aircraft (halon 1301) – (1 nozzle)[b]	6	2.5	5.5	3.0	185
Future Fighter Aircraft (HFC-125) - (4 nozzles)[b]	9	3.2	7	4.0	242
Estimated HFC-125- non-optimally distributed (this study)	25	8.4	18	13	800
Estimated HFC-125- non-optimally distributed (Navy study)	18	6.2	14	10	600

[b] in addition to the agent outlets in the AMAD and APU bays

Table 10–14 shows the current and proposed system extinguishant and bottle masses. This is only an (proportional) estimate because the larger bottles would have to be designed by a fire suppression system manufacturer using factors such as agent density, agent pressure, percent liquid fill, and required container wall thickness.

Table 10–14. Future Fighter Aircraft Extinguisher Container and Agent Mass.

	Legacy Fighter Aircraft (Halon 1301) (1 nozzle)[C]		**Future Fighter Aircraft (HFC-125) (4 nozzles)**[C]		**Future Fighter Aircraft Non-Optimally Distributed**[D]	
	kg	**lb**	**kg**	**lb**	**kg**	**lb**
Bottle Mass	4.2	9.3	5.6	12.2	15.5	34.3
Agent Mass	2.5	5.5	3.2	7.0	8.4	18.4
Plumbing Mass	4.3	9.5	4.6	10.1	6.0	13.3
Total Mass	11.0	24.3	13.2	29.3	29.9	66.0

[C] in addition to the agent outlets in the AMAD and APU bays
[D] Proportionally estimated

As evidenced by the two previous tables, the Navy's investment in distribution system optimization realized a substantial payoff in weight and volume savings.

10.4.4 Rotary-wing Aircraft

System Description

For these calculations, it was assumed that future rotary-wing aircraft would utilize a four-nozzle HFC-125 fire suppression system. The location for the future rotary-wing aircraft fire suppression system is the same as in the legacy rotary-wing aircraft fire suppression system, i.e., between the engines. The single bottle provides a dual-shot extinguishing capability.

Fire Protection System Components and Procedures

It was assumed that the procedures for actuating the future rotary-wing aircraft fire protection systems are the same as the procedures for the legacy systems, as described previously.

HFC-125 Design Guide Estimation

At the time of these calculations, testing was underway to determine the required masses of various halon 1301 alternative fire extinguishing agents for rotary-wing platforms. Thus, the mass of HFC-125 had to be estimated for the current purpose. The following is a description of that process and the resulting design guide.[3]

The intent of the design guide was to retain a level of fire fighting performance equivalent to the current halon 1301 systems. Like the halon 1301 systems they would replace, the new systems incorporating HFC-125 would not extinguish every imaginable fire condition created and if so, it could not be verified via experimentation, since finite (albeit even numerous) repeated successes in tests cannot statistically guarantee 100 % effectiveness in extended field use. Historical data revealed an overall fire suppression effectiveness of 60 % to 80 % for halon 1301 systems. The HFC-125 design guidance provides a validated 80 % to 100 % effectiveness. Systems designed using HFC-125 will generally require additional masses and volumes of agent, compared to their halon 1301 counterparts for an identical application. Fortunately, many fielded halon 1301 systems were overdesigned, so the replacement HFC-125 containers showed much smaller size increases than expected.

The design guide presumes optimal mixing of the agent within the nacelle. Less efficient distribution systems will require higher masses to achieve the required concentration simultaneously for 0.5 s during certification, with the designer having the option of accepting higher mass requirements or modifying and improving the distribution system.

Table 10–15 shows the future rotary-wing aircraft specific parameters used to estimate the amount of HFC-125 required.

Table 10–15. Future Rotary-wing Aircraft Specific Parameters.

Parameter	Value
Air flow	0.5 kg/s to 1.6 kg/s (1.2 lb/s to 3.5 lb/s)
Fuel source	MIL-H-83282, MIL-H-5606, JP-8
Maximum air temperature	52 °C (125 °F)
Free volume	0.5 m^3 (16.1 ft^3)

The design guide yielded a platform HFC-125 mass estimate of kg 3.6 kg (7.9 lb.). However, the design guide assumes the HFC-125 is optimally distributed. The following analysis was performed to provide another estimate of the required mass required using the ratio of the molecular weights. This estimate assumes that the HFC-125 is not optimally distributed. The resulting platform HFC-125 mass estimate was 7.6 kg (16.8 lb.).

Analysis of Increase in Total System Mass

The representative rotary-wing platform provided a breakdown of the various fire suppression system component masses, as shown in Table 10-16; the "Other" includes distribution tubing, brackets, wiring, detectors and other miscellaneous components. However, it was unclear whether the provided bottle mass (M_{agent}) (0.8 kg (1.8 lb)) included the squib. A process to determine the mass of the original bottle is described in detail in Reference 3. Within the representative rotary-wing platform, there is minimal room for an increase in the diameter of the fire suppression system cylinder. However, there is room for an increase in the cylinder length. Another process was used to analyze the increase in total fire suppression system mass and is also described in Reference 3. Table 10–16 shows the results of these analyses.

Table 10–16. Future Rotary-wing Aircraft Analysis of Increase in Total Mass.

Mass per Platform	Current Halon 1301 Design		Redesigned Halon 1301 (optimally distributed)		Redesigned Halon 1301 (not optimally distributed)		HFC-125 (optimally distributed)		HFC-125 (not optimally distributed)	
	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb
Agent	0.7	1.5	1.1	2.4	3.3	7.2	3.6	7.9	7.6	16.8
Bottle	2.6	5.7	4.0	8.9	11.8	26.0	15.9	35.1	33.4	73.7
Other	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3
TOTAL	7.5	16.5	9.3	20.6	19.3	42.5	23.7	52.3	45.4	99.8

10.5 COSTS OF CURRENT AND REPLACEMENT SYSTEMS

The life cycle cost of a system includes the acquisition, operation, and maintenance over the life of the system. Both the HFC-125 systems and halon 1301 systems are reusable and rechargeable. The pressure vessels must be hydrostatically tested periodically, and the explosive initiators used in the design must be changed periodically due to the limited propellant life. Support equipment and facilities required to service these units add to the life cycle cost. Costs associated with actual system utilization are generally low because of the infrequent need to use the system, although the rate of inadvertent discharge in some older aircraft may be significant. The life cycle cost of a system can be heavily impacted by the potential for increased mass that may result from incorporation of a non-ozone depleting fire extinguishing chemical.[29]

The costs estimated in this effort are those that would be incurred in the research, development, test and evaluation (RDT&E), procurement, and operations and maintenance (O&M) phases of an acquisition. RDT&E costs deal with all costs required to develop the fire suppression technology into a deployable system. Procurement (also called initial or nonrecurring) costs are those associated with the purchase of the fire suppression system (and associated hardware) and suppressant. O&M costs are broad and far-reaching. Included in this category are those costs associated with program management support and life cycle sustainment management.

There are some limitations to these cost estimates:

- The significant cost impact of modifying an aircraft (including its structure) to accommodate fire system changes could not be accurately estimated and was thus not included
- Dimensioned drawings of the aircraft were proprietary. As an alternative, technical orders were used.
- Minimal FOS data existed. The data available were used and adapted.

Prior to performing this cost analysis, the ground rules and assumptions (similar for all three platform assessments) were developed to bound this assessment:

- Minimal FOS data existed. The data available were used and adapted.
- This cost analysis was performed for the existing halon 1301 system and the off-the-shelf-alternative (HFC-125) for both legacy and future cargo platforms and developed for a system with equivalent performance of halon 1301.
- Raw Inflation Indices, dated 2001, from the Office of the Secretary of Defense were used to arrive at then-year (inflated) dollars.
- This cost analysis assumes that each platform will be retrofitted for only one agent.
- The maintenance concept assumed was the contractor logistics support (CLS). The average of CLS costs for analogous platforms was used. This estimate is assumed to be funded out of procurement dollars.
- This cost analysis assumes a similar delivery schedule and number of aircraft to existing fielded aircraft.
- Prime mission equipment (PME) unit costs for the legacy aircraft fire suppression system are based on Technical Orders (TOs) and FEDLOG pricing.

- For the legacy aircraft, no RDT&E costs for the halon 1301 option were included since it was assumed that these were sunk costs.
- HFC-125 is available at the time of retrofit.
- The basic research data pertaining to HFC-125 is complete and available. Such information includes its chemical, thermophysical, thermodynamic, and transport properties. Other key items include: pressure, boiling point, molecular weight, liquid density, vapor pressure, critical temperature.
- The following small- to medium-scale effectiveness experiments have been performed on HFC-125 and the data are complete and available:
    - ISO cup burner
    - Laminar opposed-flow diffusion flame (OFDF)
    - Turbulent spray flame
    - Propane inertion testing
    - Baffle-stabilized pool fire testing
- The following small-scale environmental experiments have been performed on HFC-125 and that the data are complete and available:
    - Measurement of ozone depleting potential (ODP).
    - Measurement of global warming potential (GWP).
    - Measurement of acute toxicity (high-exposure, short-duration).
    - Evaluation of the production of acid gases and other hazardous by-products by small-scale R&D fire testing in a reasonably accurate simulation of the fire challenge or application under consideration.
    - Favorable completion of a typical corrosion test such as those conducted in the evaluation of new agents for aircraft engine fire suppression in accordance with ASTM Standard F1110-90, entitled "Standard Test Method for Sandwich Corrosion Test."
- A full-scale testing of the suppressor in a military simulator has been performed and that the data are complete and available.
- The agent meets the following time and concentration requirements as prescribed by the Air Force certification requirements specified in MIL-E-22285. For engine nacelles and APUs in USAF fixed wing aircraft, a certification test series is conducted using the calculated agent mass requirement as a starting point for discharge measurements using the calibrated concentration measurement equipment to insure the attainment of the required concentration for a prescribed time interval, usually 0.5 seconds. During this test series, adjustments in agent mass and/or distribution parameters are made until the system meets the requirement.
- HFC-125 must leave no damaging residue to harm electronic or other components. For many applications, HFC-125 must fill a space to inert flammable or explosive atmospheres. With no damaging residue, HFC-125 cleanup would be with minimal effort.
- HFC-125 is not electrically conductive.
- According to DuPont, HFC-125 has an indefinite shelf life if the material is stored properly in a sealed container that prevents leakage as well as entering moisture. HFC-125 meets NFPA

2001 specifications for clean agents. These specifications are set to ensure product performance over long storage periods (many years).

Additional details are available in References 1, 2, and 3.

10.5.1 Life Cycle Cost Estimate (LCCE) Summary for Legacy Aircraft

The following tables contain the life cycle cost estimate summary for the existing halon 1301 system and the off-the-shelf-alternative (HFC-125) for legacy cargo, fighter, and rotary-wing platforms and developed for a system with equivalent performance of halon 1301.

Cargo Aircraft

Table 10–17 shows the Life Cycle Cost Estimate (LCCE) for the legacy cargo aircraft halon 1301 and HFC-125 systems in FY00 constant dollars and then-year dollars by type of funding.

Table 10–17. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY00 to FY22) Cost Estimates for Legacy Cargo Aircraft ($ M).

		HFC-125 126 kg (280 lb)			HFC-125 40 kg (88 lb)		
Description of Effort	**Halon 1301 Total**	**Container Mod**	**Container and Nozzle Mod**	**Container and Distribution Sys Mod**	**Container Mod**	**Container and Nozzle Mod**	**Container and Distribution Sys Mod**
FY2000 Constant Dollars							
1.0 RDT&E ($M)	0	0.3	0.3	0.4	0.3	0.3	0.3
2.0 PROCUREMENT	10.3	20.1	21.2	21.8	18.3	19.4	19.9
3.0 O&M	14.7	17.2	17.3	18.5	15.8	15.9	17.0
4.0 MILITARY PERSONNEL	0.2	0.2	0.2	0.2	0.2	0.2	0.2
5.0 MILITARY CONSTRUCTION	0	0	0	0	0	0	0
TOTAL	25.2	37.9	39.1	40.8	34.5	35.7	37.5
TOTAL COST PER AIRCRAFT	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Then Year Dollars							
1.0 RDT&E	0	0.3	0.3	0.4	0.2	0.3	0.3
2.0 PROCUREMENT	11.0	22.2	23.5	24.1	20.2	21.4	22.1
3.0 O&M	18.4	21.5	21.6	23.0	19.8	19.9	21.2
4.0 MILITARY PERSONNEL	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5.0 MILITARY CONSTRUCTION	0	0	0	0	0	0	0
TOTAL	29.7	44.4	45.8	47.8	40.5	41.9	44.0

In terms of FY00 (Fiscal Year 2000) constant dollars, the legacy cargo aircraft halon 1301 fire suppression system cost is estimated to be $208 k per aircraft over a 23-year life cycle (FY00 to FY22), based on 121 aircraft. This is approximately 0.11 % of the total flyaway aircraft cost of $183 M. In FY00 constant dollars, the non-optimally distributed HFC-125 system, weighing 126 kg (280 lb) is estimated to range from $313 k to $338 k per aircraft. This is approximately 0.17 % to 0.18 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 40 kg (88 lb) ranges from $285 k to $310 k. This is approximately 0.16 % to 0.17 % of the total flyaway aircraft cost.

Fighter Aircraft

Table 10–18 shows the LCCE for the legacy fighter aircraft halon 1301 and HFC-125 systems in FY00 constant dollars and then-year dollars by type of funding. In terms of FY00 constant dollars, the legacy fighter aircraft halon 1301 fire suppression system cost is estimated to be $20.5 k per aircraft over a 29-year life cycle (FY00 to FY28), based on 549 aircraft. This is approximately 0.04 % of the total flyaway aircraft cost of $51.1 M. In FY00 constant dollars, the non-optimally distributed HFC-125 system, weighing 8.4 kg (18.4 lb) is estimated to be $32.5 k per aircraft. This is approximately 0.06 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 3.2 kg (7.0 lb) is estimated to be $28.6 k. This is approximately 0.05 % of the total flyaway aircraft cost. Using the conservative value of 60 % system effectiveness, the breakpoint between cost and benefit is $282 k per aircraft.

Table 10–18. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY00 to FY28) Cost Estimates for Legacy Fighter Aircraft ($ M).

	Halon 1301	**HFC-125 (optimally distributed)**	**HFC-125 (not optimally distributed)**
Description of Effort	**2.5 kg (5.5 lb)**	**3.2 kg (7lb)**	**8.4 kg (18.4 lb)**
FY2000 Constant Dollars			
1.0 RDT&E ($M)	0	2.0	2.0
2.0 PROCUREMENT	8.1	9.5	9.6
3.0 O&M	3.0	4.0	6.1
4.0 MILITARY PERSONNEL	0.14	0.14	0.14
5.0 MILITARY CONSTRUCTION	0	0	0
TOTAL	11.2	15.7	17.8
TOTAL COST PER AIRCRAFT	0.02	0.03	0.03
Then Year Dollars			
1.0 RDT&E	0	2.0	2.0
2.0 PROCUREMENT	9.1	10.9	11.0
3.0 O&M	3.9	5.4	8.0
4.0 MILITARY PERSONNEL	0.2	0.2	0.2
5.0 MILITARY CONSTRUCTION	0	0	0
TOTAL	13.3	18.5	21.3

Rotary-Wing Aircraft

Table 10–19 shows the LCCE for the legacy rotary-wing aircraft halon 1301 and HFC-125 fire suppression systems in FY03 constant dollars and then-year dollars by type of funding. In terms of FY00 constant dollars, the legacy rotary-wing aircraft non-optimally distributed halon 1301 system, weighing 3.3 kg (7.18 lb) is estimated to be $30.3 k per aircraft over a 33-year life cycle (FY03 to FY35), based on 1213 aircraft. This is approximately 0.18 % of the total flyaway aircraft cost. The optimally distributed halon 1301 system, weighing 1.1 kg (2.4 lb) is estimated to be $28.2 k per aircraft. This is approximately 0.17 % of the total flyaway aircraft cost. In FY03 constant dollars, the non-optimally distributed HFC-125 system, weighing 7.6 kg (16.8 lb) is estimated to be $43.7 k per aircraft. This is approximately 0.26 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 3.6 kg (7.9 lb) is estimated to be $39.5 k per aircraft. This is approximately 0.24 % of the total flyaway aircraft cost. Using the conservative value of 60 % system effectiveness, the breakpoint between cost and benefit is $306.8 k per aircraft.

Table 10–19. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY03 to FY35) Cost Estimates for Legacy Rotary-wing Aircraft ($ M).

	Halon 1301 (optimally distributed)	**Halon 1301 (not optimally distributed)**	**HFC-125 (optimally distributed)**	**HFC-125 (not optimally distributed)**
Description of Effort	**1.1 kg (2.4 lb)**	**3.3 kg (7.2 lb)**	**3.6 kg (7.9 lb)**	**7.6 kg (16.8 lb)**
FY2003 Constant Dollars				
1.0 RDT&E ($M)	0	0	3.2	3.2
2.0 PROCUREMENT	23.7	24.0	30.2	30.4
3.0 O&M	10.3	12.6	14.3	19.2
4.0 MILITARY PERSONNEL	0.19	0.19	0.18	0.18
5.0 MILITARY CONSTRUCTION	0	0	0	0
TOTAL	34.2	36.8	48.0	53.1
TOTAL COST PER AIRCRAFT	0.03	0.03	0.04	0.04
Then Year Dollars				
1.0 RDT&E	0	0	3.3	3.3
2.0 PROCUREMENT	28.3	28.8	37.0	37.3
3.0 O&M	14.1	17.3	19.6	26.4
4.0 MILITARY PERSONNEL	0.32	0.32	0.32	0.32
5.0 MILITARY CONSTRUCTION	0	0	0	0
TOTAL	42.8	46.3	60.2	67.2

10.5.2 Life Cycle Cost Estimate (LCCE) Summary for Future Aircraft

The following tables contain the life cycle cost estimate summary for the existing halon 1301 system and the off-the-shelf-alternative (HFC-125) for future cargo, fighter, and rotary-wing platforms and developed for a system with equivalent performance of halon 1301.

Cargo Aircraft

Table 10–20 shows the LCCE for the future cargo aircraft halon 1301 and HFC-125 systems in FY00 constant dollars and then-year dollars by type of funding. In terms of FY00 constant dollars, the future cargo aircraft halon 1301 fire suppression system cost is estimated to be $301 k per aircraft over a 32-year life cycle (FY00-31), based on 121 aircraft. This is approximately 0.16 % of the total flyaway aircraft cost of $183 M. In FY00 constant dollars, the non-optimally distributed HFC-125 system, weighing 125.6 kg (276.8 lb) is estimated to range from $318 k to $366 k per aircraft. This is approximately 0.17% to 0.20 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 39.9 kg (87.9 lb) ranges from $288 k to $336 k. This is approximately 0.16 % to 0.18 % of the total flyaway aircraft cost.

Table 10–20. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY00 to FY31) Cost Estimates for Future Cargo Aircraft ($ M).

		HFC-125 125.6 kg (276.8 lb)			HFC-125 39.9 kg (87.9 lb)		
Description of Effort	**Halon 1301 Total**	**Container Mod**	**Container and Nozzle Mod**	**Container and Distribution Sys Mod**	**Container Mod**	**Container and Nozzle Mod**	**Container and Distribution Sys Mod**
FY2000 Constant Dollars							
1.0 RDT&E ($M)	0.56	0.61	0.69	0.75	0.54	0.62	0.68
2.0 PROCUREMENT	18.3	17.8	20.2	22.0	15.9	18.2	20.0
3.0 O&M	17.3	19.8	20.0	21.3	18.1	18.3	19.6
4.0 MILITARY PERSONNEL	0.31	0.31	0.31	0.31	0.31	0.31	0.31
5.0 MILITARY CONSTRUCTION	0	0	0	0	0	0	0
TOTAL	36.5	38.5	41.1	44.3	34.9	37.5	40.6
TOTAL COST PER AIRCRAFT	0.30	0.32	0.34	0.37	0.29	0.31	0.34
Then Year Dollars							
1.0 RDT&E	0.57	0.62	0.70	0.77	0.55	0.63	0.70
2.0 PROCUREMENT	22.3	21.7	24.6	26.8	19.4	22.2	24.4
3.0 O&M	25.7	29.2	29.5	31.3	26.8	27.1	29.0
4.0 MILITARY PERSONNEL	0.54	0.54	0.54	0.54	0.54	0.54	0.54
5.0 MILITARY CONSTRUCTION	0	0	0	0	0	0	0
TOTAL	49.1	52.1	55.3	59.4	47.3	50.5	54.6

Fighter Aircraft

Table 10–21 shows the LCCE for the future fighter aircraft halon 1301 and HFC-125 systems in FY00 constant dollars and then-year dollars by type of funding. In terms of FY00 constant dollars, the future fighter aircraft halon 1301 fire suppression system cost is estimated to be $26.3 k per aircraft over a 33-year life cycle (FY00 to FY32), based on 549 aircraft. This is approximately 0.05 % of the total flyaway aircraft cost of $51.1M. In FY00 constant dollars, the non-optimally distributed HFC-125 system, weighing 8.4 kg (18.4 lb) is estimated to be $32.7 k per aircraft. This is approximately 0.06 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 3.2 kg (7.0 lb) is estimated to be $28.7 k. This is approximately 0.05 % of the total flyaway aircraft cost. Using the conservative value of 60 % system effectiveness, the breakpoint between cost and benefit is $285 k per aircraft.

Table 10–21. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY00 to FY32) Cost Estimates for Fighter Cargo Aircraft ($ M).

	Halon 1301	**HFC-125**	**HFC-125**
DESCRIPTION OF EFFORT	**2.5 kg (5.5 lb)**	**3.2 kg (7lb)**	**8.4 kg (18.4 lb)**
FY2000 Constant Dollars			
1.0 RDT&E ($M)	2.0	2.0	2.0
2.0 PROCUREMENT	9.1	10.2	10.3
3.0 O&M	3.2	3.5	5.5
4.0 MILITARY PERSONNEL	0.16	0.16	0.16
5.0 MILITARY CONSTRUCTION	0	0	0
TOTAL	14.4	15.8	18.0
TOTAL COST PER AIRCRAFT	0.03	0.03	0.03
Then Year Dollars			
1.0 RDT&E	2.0	2.0	2.0
2.0 PROCUREMENT	11.0	12.3	12.5
3.0 O&M	4.5	4.8	7.8
4.0 MILITARY PERSONNEL	0.29	0.29	0.29
5.0 MILITARY CONSTRUCTION	0	0	0
TOTAL	17.8	19.4	22.5

Rotary-Wing Aircraft

Table 10–22 shows the LCCE for the future rotary-wing aircraft halon 1301 and HFC-125 fire suppression systems in FY03 constant dollars and then-year dollars by type of funding. In terms of FY03 constant dollars, the future rotary-wing aircraft non-optimally distributed halon 1301 system, weighing 3.3 kg (7.2 lb) is estimated to be $35.9 k per aircraft over a 42-year life cycle of FY03 to FY41, based on 1213 aircraft. This is approximately 0.22 % of the total flyaway aircraft cost. In terms of FY03 constant dollars, the future rotary-wing aircraft optimally distributed halon 1301 system, weighing 1.1 kg (2.4 lb) is estimated to be $33.7 k per aircraft over a 42-year life cycle of FY03 to FY41, based on 1213 aircraft. This is approximately 0.20 % of the total flyaway aircraft cost. In FY03 constant dollars, the non-optimally distributed HFC-125 system, weighing 7.6 kg (16.8 lb) is estimated to be $41.4 k per aircraft. This is approximately 0.25 % of the total flyaway aircraft cost. The optimally distributed HFC-125 system, weighing 3.6 kg (7.9 lb) is estimated to be $37.1 k per aircraft. This is approximately 0.22 % of the total flyaway aircraft cost. Using the conservative value of 60 % system effectiveness, the breakpoint between cost and benefit is $312.2 k per aircraft.

Table 10–22. Comparison of Halon 1301 and HFC-125 System Life Cycle (FY03 to FY41) Cost Estimates for Future Rotary-wing Aircraft ($ M).

	Halon 1301	Halon 1301	HFC-125	HFC-125
DESCRIPTION OF EFFORT	**1.1 kg (2.4 lb)**	**3.3 kg (7.2 lb)**	**3.6 kg (7.90 lb)**	**7.6 kg (16.8 lb)**
FY2003 Constant Dollars				
1.0 RDT&E ($M)	3.2	3.2	3.1	3.1
2.0 PROCUREMENT	26.9	27.3	27.2	27.4
3.0 O&M	10.6	12.9	14.5	19.5
4.0 MILITARY PERSONNEL	0.22	0.22	0.22	0.22
5.0 MILITARY CONSTRUCTION	0	0	0	0
TOTAL	40.9	43.6	45.0	50.3
TOTAL COST PER AIRCRAFT	0.03	0.04	0.04	0.04
Then Year Dollars				
1.0 RDT&E	3.2	3.2	3.2	3.2
2.0 PROCUREMENT	35.4	35.9	35.8	36.1
3.0 O&M	16.2	19.8	22.2	29.9
4.0 MILITARY PERSONNEL	0.43	0.43	0.43	0.43
5.0 MILITARY CONSTRUCTION	0	0	0	0
TOTAL	55.2	59.4	61.6	69.6

10.5.3 Detailed Cost Element Structure (CES)

This fire suppression system's detailed cost element structure (CES) given in Table 10–23 is based on the DoD 5000.4-M and MIL-HDBK-881 CES. It was customized for each system and approach. Due to space limitations and for clarity, only general information about the various cost elements is presented here. Additional details are available in References 1, 2, and 3.

10.5.4 Cost Element Structure Data Development

Cost factors used by government and industry were obtained from the Aeronautical Systems Center (ASC) Cost Library and ESC/FMC. These cost factors were then applied to the subsystem costs (Group A/Group B kits). A Group A Kit is defined as the hardware used to install/mount the fire suppression system while the Group B Kit is actually the fire suppression system itself, including the agent. The following sections are organized according to the Cost Element codes in Table 10–23. When no information was available for a given Element, a cost factor was used (multiplied by the appropriate Group A/Group B kit price) to estimate this element. However, cost factors were not available for every element.

Table 10–23. Detailed Cost Element Structure.

Cost Elements
1.0 RDT&E (3600)
1.1 Concept Exploration
1.2 Prototype Engineering And Manufacturing Development (EMD) Cost Sharing (Fire Suppression System Prototype)
1.2.1 Subsystem
1.2.1.1 Group A Kit (Hardware to install/mount fire suppression system)
1.2.1.2 Group B Kit (Fire suppression system)
1.2.2 Commercial-Off-The-Shelf (COTS)/Government-Off-The Shelf (GOTS) Software – N/A
1.2.3 Development Software – N/A
1.2.4 Integration, Assembly, Test and Checkout
1.3 System/Platform Integration
1.4 System Engineering/Program Management
1.4.1 Systems Engineering
1.4.2 Program Management
1.4.3 Travel
1.5 System Test and Evaluation
1.5.1 Developmental Test and Evaluation (DT&E)
1.5.2 Operational Test and Evaluation (OT&E)
1.6 Data
1.7 Training
1.8 Evolutionary Technology Insertions (ETIs) - N/A
1.8.1 Program Management
1.8.2 Prototype and Test Bed
1.8.3 Market Surveys
1.9 Support Equipment
1.9.1 Common Support Equipment
1.9.2 Peculiar Support Equipment
2.0 PROCUREMENT (3010)
2.1 Prime Mission Product (Fire Suppression System)
2.1.1 Subsystems
2.1.1.1 Group A Kit (Hardware to install/mount fire suppression system)
2.1.1.2 Group B Kit (Fire suppression system)
2.1.2 Non-Recurring Engineering – N/A
2.1.3 Software Integration – N/A
2.1.4 Integration, Assembly, Test and Checkout
2.2 System/Platform Integration and Assembly (Cost of installation)
2.3 Systems Engineering/Program Management
2.3.1 Systems Engineering
2.3.2 Program Management
2.3.3 Logistics Management
2.4 System Test and Evaluation
2.4.1 Operational Test and Evaluation
2.5 Engineering Change Orders (ECOs)
2.6 Initial Cadre Training
2.7 Data
2.8 Operational Fielding/Site Activation
2.9 Depot Setup - N/A
2.10 Support Equipment
2.10.1 Common Support Equipment

Cost Elements
2.10.2 Peculiar Support Equipment
2.11 Initial Spares and Repair Parts
2.12 Warranty
2.13 Evolutionary Technology Insertions (ETIs) - N/A
2.14 Interim Contractor Support (ICS)
2.15 Flexible Sustainment Support (Maintenance Support)
3.0 OPERATIONS AND MAINTENANCE (3400)
3.1 Program Administration
3.1.1 Program Management Support
3.1.1.1 Miscellaneous Contract Services
3.1.1.2 Government Technical Support
3.1.1.3 Travel
3.1.2 Life Cycle Sustainment Management (LCSM)
3.2 Program Operational Support
3.2.1 Recurring Training
3.2.2 Technical Data Revision
3.2.3 Software Maintenance - N/A
3.2.4 Hardware Maintenance
3.2.4.1 Organic Support
3.2.4.2 Contractor Maintenance
3.2.5 Replenishment Spares
3.2.6 Repair Parts and Materials
3.2.7 Transportation, Packaging, and Handling
3.2.8 Storage
3.2.9 Disposal
3.2.10 Facility Projects/Upgrades/Leases
3.2.11 Operational O&M Impacts of ETIs - N/A
3.2.12 Program Operations
3.2.13 Unit Level Support
3.2.13.1 Recurring Training (Unit Travel/TDY Costs)
3.2.13.2 Operating Consumables
3.2.13.3 Unit Level O&M Impacts of ETIs
3.2.14 Depot Level Support
3.2.15 Contractor Logistics Support (CLS)
4.0 MILITARY PERSONNEL (3500)
5.0 MILITARY CONSTRUCTION – N/A

RDT&E (1.0)

No cost information was available for the concept exploration (1.1).

The prototype EMD cost sharing (1.2) is the hardware and software used to accomplish the primary mission and includes all integration, assembly, test and checkout, as well as all technical and management activities associated with individual hardware/software elements. ASC Avionics Support Cost Element Factors were used to estimate costs for systems engineering/program management, system test and evaluation, data, and training.

The data used to derive these cost factors were extracted from Cost Performance Reports (CPR) and Cost/Schedule Status Report (C/SSR) reports. The other cost factors used in this estimate originated from Electronic Systems Center (ESC/FMC). Data used for these factors encompassed thirty-seven CPR and

C/SSR stored in the Automated Cost Estimating Integrated Tool's (ACE-IT) Automated Cost Data Base (ACDB). The data represent ESC production contract efforts occurring between 1974 and 1992.

Technical orders and FEDLOG pricing were used to capture the cost of the Group A (1.2.1.1) and Group B (1.2.1.2) kits for the fire suppression system. The cost factors are applied to the Group A and Group B Kit costs.

The integration, assembly, test and checkout (1.2.4) includes the effort associated with bending metal, mating surfaces, structures, equipment, parts, and materials required to assemble all equipment, components and subsystems into an operational system. Since specific cost information was not available, a multiplicative cost factor was used to estimate this element, as is common practice when such cost data is not available.

System/platform integration (1.3) includes the efforts associated with integrating/installing systems or subsystems into an existing platform/weapon system. No cost information was available for this cost element.

Systems engineering/program management (1.4) involves all associated elements to be reported, including the overall planning, directing, and controlling of the definition, development, and production of a system or program. Since specific cost information was not available, a cost factor was used to estimate this element.

System test and evaluation (1.5) is the use of prototype, production, or specifically fabricated hardware and/or software to obtain or validate engineering data on the performance of the system during the development phase of the program. It includes detailed planning, conduct of, support for, data reduction, and reports from such testing, and all hardware/software items which are consumed or planned to be consumed in the conduct of such testing as well as all effort associated with the design and production of models, specimens, fixtures, and instrumentation in support of the system level test program. Since specific cost information was not available, a cost factor was used to estimate this element.

Data (1.6) includes the effort required to develop technical and managerial data in support of the program. Since specific cost information was not available, a cost factor was used to estimate this element.

Training (1.7) includes all efforts associated with the design, development, and production of deliverable training equipment as well as the execution of training services. Since specific cost information was not available, a cost factor was used to estimate this element.

Support equipment (1.9) includes the effort required to design, develop and produce system peculiar and common support equipment. Since specific cost information was not available, the cost factors were used to estimate these elements.

Procurement (2.0)

The prime mission product (PMP) (2.1) is the hardware and software used to accomplish the primary mission and includes all integration, assembly, test and checkout, as well as all technical and management activities associated with individual hardware/software elements. Technical Orders (TOs) and FEDLOG pricing were used to capture the cost of the Group A/B Kits for the fire suppression system.

The integration, assembly, test and checkout (2.1.4) includes the effort associated with bending metal, mating surfaces, structures, equipment, parts, and materials required to assemble all equipment, components and subsystems into an operational system. Since specific cost information was not available, a cost factor was used to estimate this element.

System/platform integration and assembly (2.2) includes the efforts associated with integrating/installing systems or subsystems into an existing platform/weapon system. Depending on the alternative, labor was estimated for modifications to the container, nozzles, and the distribution system.

Systems engineering/program management (2.3) includes the effort required for system definition; overall system design; design integrity, cost effectiveness, weight, and balance analyses; intra-system and inter-system compatibility; safety, security, and survivability requirements; human engineering; and performance specifications. Program management includes the effort required for configuration, contract, and data management; cost and schedule management; transportation and packaging management; vendor liaison; value engineering; and quality assurance. Logistics management includes the effort required for reliability, maintainability and logistics support integration. Since specific cost information was not available, a cost factor was used to estimate this element.

System test and evaluation (2.4) includes the effort required for: all detailed test planning, support data consolidation and corresponding reports; hardware items consumed in the conduct of testing; and efforts associated with models, specimens, fixtures and instrumentation. No cost information was available for this cost element.

Engineering change orders (2.5) includes the effort required for anticipated "in scope" contract engineering changes to the prime mission product. No cost information was available for this cost element.

Initial cadre training (2.6) includes the effort required for the design, development, and production of training equipment, course material preparation, and travel costs associated with conducting training for an initial cadre of both operational and depot personnel. Since specific cost information was not available, a cost factor was used to estimate this element.

Data (2.7) includes the effort required to develop technical and managerial data in support of the program. Since specific cost information was not available, a cost factor was used to estimate this element.

Operational fielding/site activation (2.8) includes the real estate, construction, conversion, utilities, and equipment to provide all facilities required to house, service, and launch prime mission equipment at the organizational and intermediate level. Since specific cost information was not available, a cost factor was used to estimate this element.

Common support equipment (2.10.1) involves the acquisition of additional support equipment, over and above existing support equipment inventories, required to support the acquisition of a new system or subsystems. Peculiar equipment (2.10.2) generally involves unique or special purpose vehicles, equipment or tools used to transport and hoist; service, repair, overhaul, assemble and disassemble; test and inspect; and to perform other maintenance on the prime mission product. Since specific cost information was not available, cost factors were used to estimate these elements.

Initial spares and repair parts (2.11) includes the effort required to procure modules, spare components and assemblies used for replacement purposes (building logistical pipeline) to support prime mission product. Since specific cost information was not available, a cost factor was used to estimate this element.

The maintenance concept assumed was the contractor logistics support (CLS). Therefore, there are no costs associated with flexible sustainment support (2.15).

Operations and Maintenance (O&M) (3.0)

Program management support (3.1.1) includes the effort required for configuration, contract and data management, cost and schedule management, transportation and packaging management, vendor liaison, value engineering, and quality assurance. Since specific cost information was not available, a cost factor of 0.05 was used to estimate this element for the halon 1301 system and 0.10 for the HFC-125. The cost factor is varied depending on the maturity of the system; therefore, a higher factor was applied to the HFC-125 system since it is in the earliest stages for this platform.

Hardware maintenance organic support (3.2.4.1) includes civilian labor, material, and overhead costs incurred after deployment. This cost element was estimated by taking the number of flying hours for a typical cargo platform (contained in the Air Force Instruction (AFI) 65-503 Attachment 42-1 for Aircraft Endstrengths) and multiplying by the average civilian hourly pay (contained in AFI 65-503 Attachment A28-1) and the average maintenance staff hour per flying hour.

Replenishment spares include the cost of materials consumed in operation, maintenance, and support of the primary system and associated support at the unit level. Since specific cost information was not available, a cost factor in relation to initial spares and repair parts was used to estimate this element.

The maintenance concept assumed was the CLS. The average of CLS costs (3.2.15) for analogous platforms was used.

The tubing and brackets for the fire suppression system are nonrepairable and condemned at the field level, with a local manufacturing capability. The bottles are repaired (recharged) and condemned at the depot and have limited "O" and "I" level repair.[30]

Military Personnel (4.0)

Military personnel support was estimated by taking the number of military personnel endstrengths (contained in the AFI 65-503 Attachment 42-1 for Aircraft Endstrengths) and multiplying by the average officer and enlisted pay (contained in AFI 65-503 Attachment A19-1) and the percentage of the fire suppression system to the total aircraft cost.

10.6 COST SAVINGS

In a previous study (Reference 31), the historical and projected costs to the U.S. Air Force aircraft fleet due to in-flight fires were determined. By combining the components which comprise the costs of peacetime aircraft losses due to fire, a resulting historical cost (over a 30 year period) of approximately \$9.3 billion was determined, measured in 1995 dollars. The costs of combat aircraft losses due to fire were estimated to be approximately $5.9 billion (in 1995 dollars), based primarily on Southeast Asia experience. The costs of utilizing aircraft fire protection were estimated to be approximately $316 million (in 1995 dollars). Thus, the total historical costs of fire to the U.S. Air Force over the 1966 to 1995 time period was estimated to be $15.5 billion (in 1995 dollars). The total projected costs of fire to the U.S. Air Force over the 1996 to 2025 time period was estimated to be $16.0 billion (in 1996 dollars). A net present value of over $119 million was projected to be the benefit of fire suppression systems over the next 30 years, in terms of the reduction in casualty-related losses due to their presence, even with the costs of the protection systems themselves included.

The cost savings for the life of the legacy and future aircraft were estimated by using the traditional extinguishing success rate for existing engine halon systems, the estimated fire costs per flight hour, and the number of flight hours for the legacy cargo aircraft. Field experience of existing engine halon systems on current aircraft, depending on the platform, shows that the systems have a 60 % to 80 % success rate. This study (Reference 31) postulated that future aircraft losses due to fire incidents were a function of the total number of flight hours (FH) for this period. An historical relationship between fire costs and flight hours was established. The resulting average fire cost per flight hour (in 2000 dollars) was $63.[31]

Table 10–24 through Table 10–26 show the estimated cost savings determined, while using on-board fire protection for legacy and future aircraft of the three types.

Table 10–24. Cargo Aircraft Cost Savings Estimation.

Cost Factors	Legacy Aircraft	Future Aircraft
PAA Quantity Cumulative	121	121
Flying Hours Cumulative	3.24 M	3.60 M
Fire Cost Cumulative	$204 M	$226 M
Cost Savings: 60 % effective system	$122 M	$136 M
Cost Savings: 80 % effective	$163 M	$181 M

Table 10–25. Fighter Aircraft Cost Savings Estimation.

Cost Factors	Legacy Aircraft	Future Aircraft
PAA Quantity Cumulative	549	549
Flying Hours Cumulative	4.10 M	4.15 M
Fire Cost Cumulative	$258 M	$261 M
Cost Savings: 60 % effective system	$155 M	$157 M
Cost Savings: 80 % effective	$206 M	$209 M

Table 10–26. Rotary-wing Aircraft Costs Savings Estimation.

Cost Factors	Legacy Aircraft	Future Aircraft
PAA Quantity Cumulative	1,213	1,213
Flying Hours Cumulative	9.9 M	10,0 M
Fire Cost Cumulative	$620 M	$631 M
Cost Savings: 60 % effective system	$372 M	$379 M
Cost Savings: 80 % effective	$496 M	$505 M

10.7 COST ANALYSIS USING ALTERED FIRE SUPPRESSION PERFORMANCE

Analyses discussed up to this stage in the cost analyses for halon 1301 and HFC-125 for legacy and future platforms have assumed a replacement HFC-125 system with an equivalent level of performance to legacy halon 1301 systems. For the next stage of this analysis, a methodology for legacy and future platforms utilizing systems with performance levels from traditional, fielded halon 1301 systems was developed. This allowed examination of whether there was an optimal performance or success rate that balances the costs of the system size (at that performance level) vs. the savings of the assets preserved at that success rate. Such a methodology could determine, for instance, if only a negligible increase in success rate resulted from doubling the size or cost of the system.

To address the issue of a potential fire suppression system with altered performance, data from the Factor of Safety study performed during Phase III of the Halon Replacement Program for Aviation (HRPA) were used.[11] Phase III was conducted in order to develop system sizing design equations for using HFC-125 as a halon replacement. As a final step in Phase III, the resulting design equations were "qualified" by performing Factor of Safety (FOS) tests. FOS testing provided an estimation of the fire protection effectiveness (as a percentage of fires successfully extinguished) of the amount of HFC-125 predicted by the design equation. Additional testing then determined the fire protection effectiveness percentages at agent capacities above and below the design equation amount. FOS data for the F-22 were used and adapted. These suppression system masses and corresponding effectiveness were correlated to the cargo and fighter aircraft platforms. The resulting systems' costs, costs savings, and net costs were calculated. The relationship between varying the system size and system effectiveness (and therefore costs and savings) was determined. More detailed information regarding these cost analyses are available in References 25, 26, and 27.

10.7.1 Factor of Safety Testing

The resulting system sizing design formula from the HRPA was "qualified" by performing FOS tests under conditions similar to those of actual aircraft applications. The goals of FOS testing were twofold:

- Determine the fire protection effectiveness (expressed as the success rate percentage in extinguishing fires) of the amount of HFC-125 predicted by the design equation for a typical aircraft application.
- Compare the level of fire protection provided by the amount of HFC-125 predicted by the design equation with the level of fire protection offered by an aircraft's current halon 1301 system. This comparison not only provided an estimate of how much HFC-125 is needed for equivalent protection to halon 1301 for the particular aircraft, but also provided a guideline for use in similar aircraft engine nacelles.

The FOS testing and the need to estimate the effectiveness of the quantity of HFC-125 predicted by the design equation were driven by the fact that the bracketing technique used to determine the final successful mass in each test run could not consistently check the repeatability of the results. These FOS tests provided the data necessary to estimate the actual effectiveness of varying quantities of HFC-125. These tests were also performed to see if a suitable universal scale-up factor could be identified to estimate the masses of HFC-125 associated with near 100 % effectiveness, or to estimate masses of HFC-125 having the same effectiveness as current halon systems.

Fire suppression engineers for various military aircraft systems were queried about "typical" operating conditions for their respective aircraft. These operating conditions were then translated into level settings for the parameters used in the testing. Information was gathered on three aircraft system engine nacelles in order to obtain a wide range of possible test conditions. The aircraft chosen were the RAH-66, F-22, V-22, and F-15.

In keeping with the overall test strategy, the dependent variable was the observation of whether or not the fire was extinguished at the given agent amount. It was determined that at least ten shots at each agent amount of interest were required to capture the response of the system with sufficient precision of success rate, as measured by the percentage of fires extinguished.[32]

FOS data for the F-22 were used and adapted for this methodology. This methodology is explained in the next section.

10.7.2 System Description

Table 10–27 through Table 10–29 show the resulting system description for the actual cargo, fighter, and rotary-wing aircraft, respectively, selected and used for consideration and replication in the FOS tests.

Table 10–27. Estimated Cargo Aircraft System Description.

	Aircraft Engine Nacelle					**Auxiliary Power Unit**					**Total Agent Per Platform**	
	Conc.	**Mass**		**Volume**		**Conc.**	**Mass**		**Volume**			
	% by vol.	**lb**	**kg**	**in^3**	**L**	**% by vol.**	**lb**	**kg**	**in^3**	**L**	**lb**	**kg**
Current Halon 1301 System	6	21	9.5	630	10	6	2.5	1.1	86	1.4	86	39
Estimated HFC-125-Optimally Distributed	24	21	9.7	810	13	24	2.6	1.2	111	1.8	88	40
Estimated HFC-125-Non-Optimally Distributed	24	67	30	2580	42	24	8	3.6	350	5.8	280	125

Table 10–28. Estimated Fighter Aircraft System Description.

	Legacy Fighter Aircraft (Halon 1301) (1 nozzle)[e]		**Future Fighter Aircraft (HFC-125) (4 nozzles)[e]**	
	kg	**lb**	**kg**	**lb**
Bottle Mass	4.2	9.3	5.6	12.2
Agent Mass	2.5	5.5	3.2	7.0
Plumbing Mass	4.3	9.5	4.6	10.1
Total Mass	11.1	24.4	13.3	29.4

[e] in addition to the agent outlets in the AMAD and APU bays

Table 10–29. Estimated Rotary-wing Aircraft System Description.

Mass per Platform	Current Halon 1301 Design		Redesigned Halon 1301 – small		Redesigned Halon 1301 – large		HFC-125 – small		HFC-125 – large	
	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb
Agent	0.7	1.5	1.1	2.4	3.3	7.2	3.6	7.9	7.6	16.8
Bottle	2.6	5.7	4.0	8.9	11.8	26.0	15.9	35.1	33.4	73.7
Other	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3
TOTAL	7.5	16.5	9.3	20.6	19.3	42.5	23.7	52.3	45.3	99.8

10.7.3 Altered Fire Suppression Performance

FOS data for the F-22 (shown in Figure 10–10) were used and adapted for this methodology.

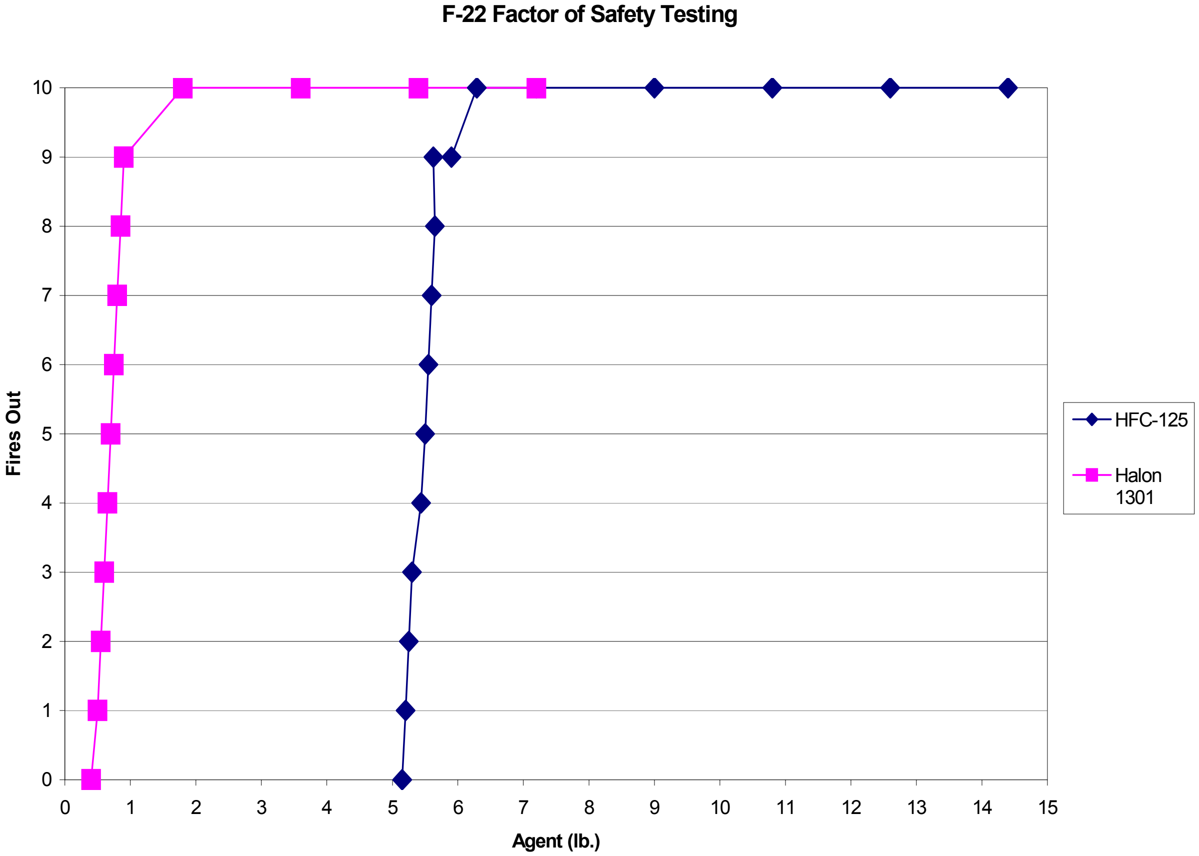

Figure 10–10. F-22 Factor of Safety Data.

These data were scaled from the corresponding Design Guide amount to the required amount of HFC-125 for the cargo, fighter, and rotary-wing aircraft, respectively, yielding an altered system description. For example, the 40 % success rate for HFC-125 resulted in an estimated mass of 2.5 kg (5.4 lb). The 90 % success rate for HFC-125 in the F-22 FOS resulted in an estimated mass of 2.6 kg (5.6 lb). The resulting

Design Guide amount was 6.4 lb. Thus, the ratio for 40 % success rate was 5.4/6.3 (or 0.9) of the Design Guide amount, and the 90 % success rate was 5.6/6.3 (or 0.9) of the Design Guide amount. These ratios were applied to the required amount of HFC-125 for the cargo, fighter, and rotary-wing aircraft, respectively. Table 10–30 through Table 10–32 show the resulting altered system descriptions for the cargo, fighter, and rotary-wing aircraft, respectively. These altered fire suppression system masses were used in the cost analysis for varied performance.

Table 10–30. Cargo Aircraft Altered System Description.

	Aircraft Engine Nacelle					**Auxiliary Power Unit**					**Total Agent Per Platform**	
	Design Conc.	**Mass Estimation**		**Volume Estimation**		**Design Conc.**	**Mass Estimation**		**Volume Estimation**			
	% by vol.	**kg**	**lb**	**L**	**in^3**	**% by vol.**	**kg**	**lb**	**L**	**in^3**	**kg**	**lb**
100 % Laboratory Success Rate												
Current halon 1301 system	6	9.5	21	10	630	6	1.1	2.5	1.4	86	39	86
Estimated HFC-125-optimally distributed	24	9.7	21	13	810	24	1.2	2.6	1.8	110	40	88
Estimated HFC-125- non-optimally distributed	24	30	67	42	2580	24	3.6	8	5.8	350	125	277
90 % Laboratory Success Rate												
Current halon 1301 system	5.4	8.5	19	9	560	5.4	1.0	2.2	1.3	77	35	77
Estimated HFC-125-optimally distributed	21	8.7	19	12	730	21	1.0	2.3	1.6	99	36	79
Estimated HFC-125- non-optimally Distributed	21	27	60	38	2310	21	3.2	7.2	5.2	315	112	248
40 % Laboratory Success Rate												
Current halon 1301 system	5.2	8.2	18	9	540	5.2	1.0	2.2	1.2	74	34	75
Estimated HFC-125-optimally distributed	21	8.4	18	11	700	21	1.0	2.2	1.6	96	34	76
Estimated HFC-125- non-optimally distributed	21	26	58	37	2230	21	3.1	6.9	5.0	300	110	240

Table 10–31. Fighter Aircraft Altered System Description.

	Halon 1301		**HFC-125 Optimally Distributed**		**HFC-125 Non-optimally Distributed**	
	kg	**lb**	**kg**	**lb**	**kg**	**lb**
100% Laboratory Success Rate						
Bottle mass	4.2	9.3	5.6	12.2	15.5	34.3
Agent mass	2.5	5.5	3.2	7	8.4	18.4
Plumbing mass	4.3	9.5	4.6	10.1	6.0	13.3
Total mass	11.1	24.4	13.3	29.4	29.9	65.9
90 % Laboratory Success Rate						
Bottle mass	3.8	8.3	5.0	10.9	13.9	30.7
Agent mass	2.2	4.9	2.8	6.3	7.5	16.5
Plumbing mass	3.9	8.5	4.1	9.1	5.4	11.9
Total mass	9.9	21.8	11.9	26.3	26.7	59
40 % Laboratory Success Rate						
Bottle mass	3.7	8.1	4.8	10.6	13.4	29.6
Agent mass	2.2	4.8	2.7	6.1	7.2	15.9
Plumbing mass	3.7	8.2	4.0	8.8	5.2	11.5
Total mass	9.6	21.1	11.5	25.4	25.9	57.0

Table 10–32. Rotary-wing Aircraft Altered System Description.

Mass per Platform	**Current Halon 1301 Design**		**Redesigned Halon 1301-small**		**Redesigned Halon 1301-large**		**HFC-125-small**		**HFC-125-large**	
	kg	**lb**	**kg**	**lb**	**kg**	**lb**	**kg**	**lb**	**kg**	**lb**
100% Laboratory Success Rate										
Agent	0.7	1.5	1.1	2.4	3.3	7.2	3.6	7.9	7.6	16.8
Bottle	2.6	5.7	4.0	8.9	11.8	26.0	15.9	35.1	33.4	73.7
Other	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3	4.2	9.3
TOTAL	7.5	16.5	9.3	20.6	19.3	42.5	23.7	52.3	45.3	99.8
90 % Laboratory Success Rate										
Agent	0.6	1.3	1.0	2.1	2.9	6.4	3.2	7.1	6.8	15.0
Bottle	2.3	5.1	3.6	7.9	10.6	23.3	14.2	31.4	29.9	65.9
Other	3.8	8.3	3.8	8.3	3.8	8.3	3.8	8.3	3.8	8.3
TOTAL	6.7	14.7	8.3	18.4	17.2	38.0	21.2	46.7	40.5	89.2
40 % Laboratory Success Rate										
Agent	0.6	1.3	0.9	2.1	2.8	6.2	3.1	6.8	6.6	14.5
Bottle	2.2	4.9	3.5	7.7	10.2	22.5	13.7	30.3	28.9	63.7
Other	3.7	8.0	3.7	8.0	3.7	8.0	3.7	8.0	3.7	8.0
TOTAL	6.5	14.2	8.1	17.8	16.7	36.7	20.5	45.2	39.1	86.3

10.7.4 Cost Analysis

These altered suppression system masses and corresponding effectiveness were correlated to the cargo, fighter, and rotary-wing aircraft for the cost studies using the methodology in References 1, 2, and 3. The resulting systems costs (which are a function of system size/mass), costs savings (which are a function of extinguishant effectiveness and the resultant aircraft saved), and net costs (cost of the system minus the cost savings) were calculated. The relationship between varying the system size and system effectiveness (and therefore costs and savings) was determined.

Cargo Aircraft

Table 10–33 and Table 10–34 show the resulting net costs for the legacy and future cargo aircraft, respectively. “Slope” is the net cost ($M) divided by the percent system effectiveness, determined from Figure 10–11, Figure 10–12, and Figure 10–13. The negative cost numbers indicate a net cost savings due to the presence of fire protection on board. Larger negative numbers mean a greater cost savings incurred.

Table 10–33. Legacy Cargo Aircraft Net Costs ($ M).

Effectiveness (%)	Halon 1301	HFC-125 – non-optimized (276.8 lb)			HFC-125 – optimized (87.9 lb)		
		Container Mod	Container and Nozzle Mod	Container and Distribution Sys Mod	Container Mod	Container and Nozzle Mod	Container and Distribution Sys Mod
24	-23.9	-11.9	-10.7	-9.1	-14.1	-12.9	-11.3
32	-40.2	-28.2	-27.0	-25.4	-30.4	-29.2	-27.6
54	-85.0	-72.5	-71.3	-69.7	-75.7	-74.5	-72.9
60	-97.0	-84.4	-83.2	-81.4	-87.7	-86.5	-84.8
72	-121.7	-109.2	-108.0	-106.3	-112.3	-111.2	-109.5
80	-137.8	-125.1	-123.9	-122.2	-128.5	-127.3	-125.6
slope	-2.03	-2.02	-2.02	-2.01	-2.04	-2.04	-2.04

Table 10–34. Future Cargo Aircraft Net Costs ($ M).

Effectiveness (%)	Halon 1301	HFC-125 – non-optimized (276.8 lb)			HFC-125 – optimized (87.9 lb)		
		Mod 1	Mod 2	Mod 3	Mod 4	Mod 5	Mod 6
		Container Mod	Container and Nozzle Mod	Container and Distribution Sys Mod	Container Mod	Container and Nozzle Mod	Container and Distribution Sys Mod
24	-18.0	-16.7	-14.1	-11.1	-19.1	-16.5	-13.5
32	-36.1	-34.8	-32.1	-29.2	-37.2	-34.6	-31.6
54	-85.8	-83.9	-81.3	-78.3	-87.3	-84.7	-81.7
60	-99.1	-97.1	-94.4	-91.3	-100.7	-98.1	-95.0
72	-126.4	-124.6	-121.9	-118.9	-128.0	-125.4	-122.4
80	-144.3	-142.3	-139.6	-136.5	-145.9	-143.3	-140.2
slope	-2.25	-2.24	-2.24	-2.23	-2.27	-2.27	-2.26

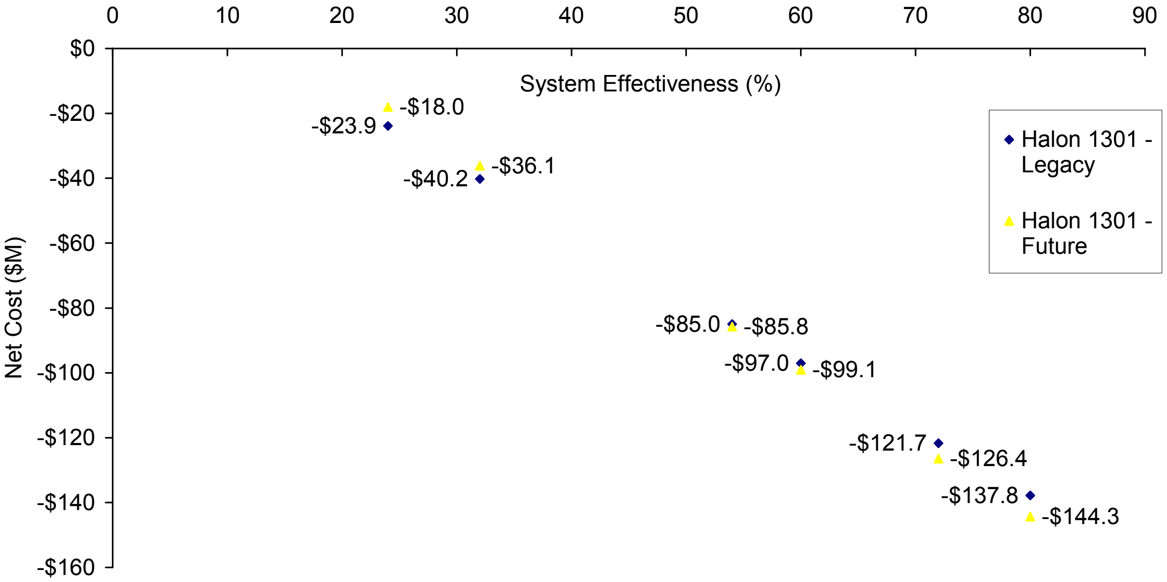

Figure 10–11. Legacy and Future Cargo Aircraft Net Costs vs. System Effectiveness for Halon 1301.

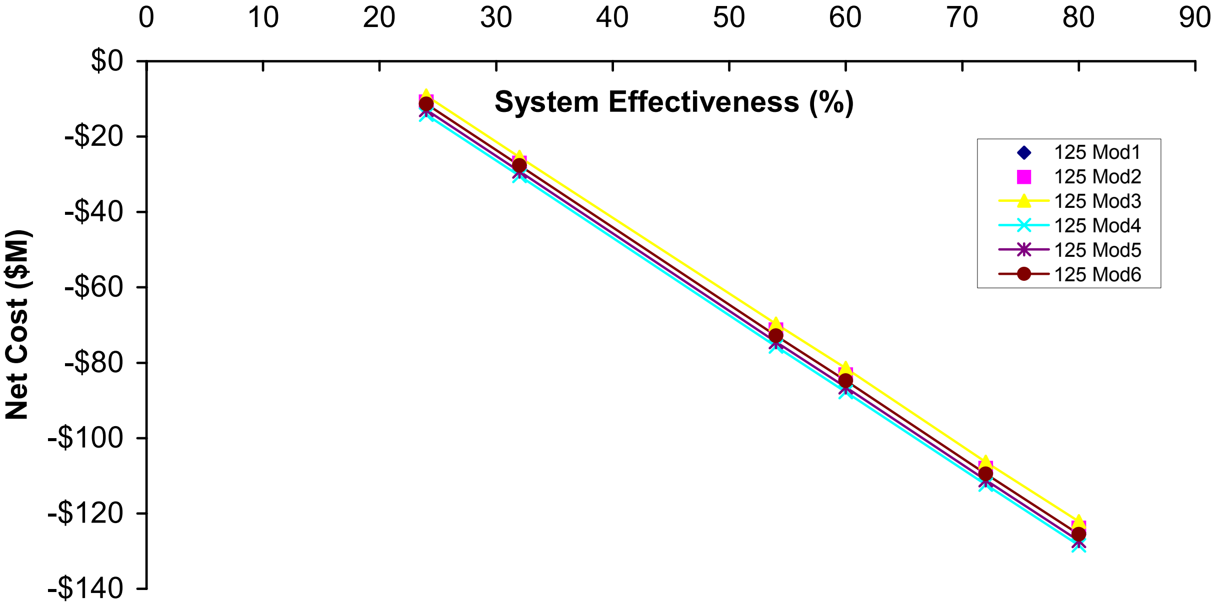

Figure 10–12. Legacy Cargo Aircraft Net Costs vs. System Effectiveness for HFC-125.

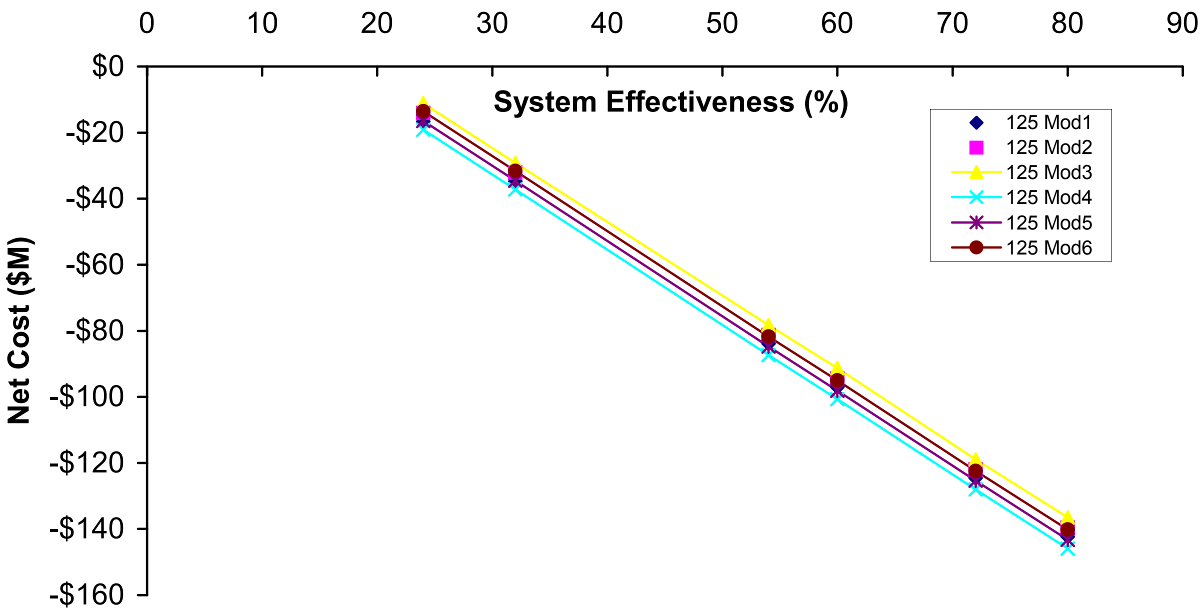

Figure 10–13. Future Cargo Aircraft Net Costs vs. System Effectiveness for HFC-125.

Figure 10–14 shows the legacy and future cargo aircraft cost savings vs. system effectiveness. For cargo aircraft, the net cost change per single percent change in extinguishing of the fire system was approximately -$2.0 M. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets (costs) saved.

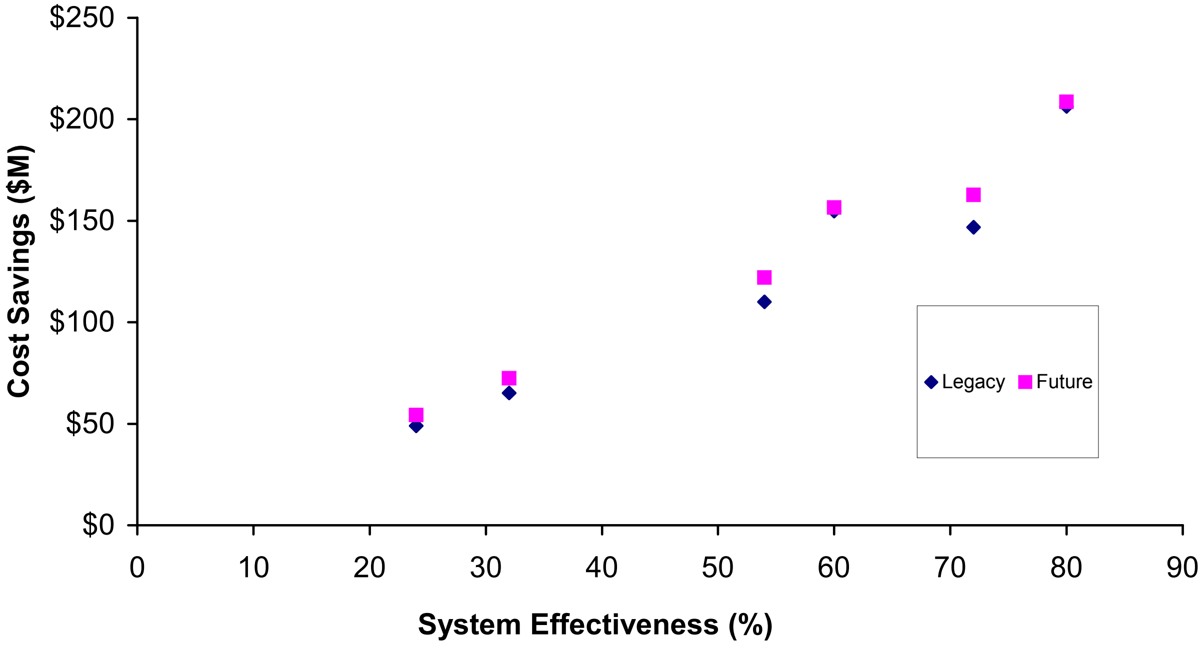

Figure 10–14. Legacy and Future Cargo Aircraft Cost Savings vs. System Effectiveness.

Fighter Aircraft

Table 10–35 and Table 10–36 show the net costs for the legacy and future fighter aircraft, respectively. Figure 10–15 and Figure 10–16 show the legacy and future fighter aircraft net costs vs. system effectiveness for halon 1301 and HFC-125, respectively. Figure 10–17 shows the legacy and future fighter aircraft cost savings vs. system effectiveness.

Table 10–35. Legacy Fighter Aircraft Net Costs ($M).

Effectiveness (%)	Net Costs		
	Halon 1301 (5.5 lb)	**HFC-125 (7 lb)**	**HFC-125 (18.4 lb)**
24	-51	-475	-45
32	-71	-67	-65
54	-128	-124	-122
60	-143	-139	-137
72	-1756	-170	-168
80	-195	-191	-188
slope	-2.57	-2.57	-2.57

Table 10–36. Future Fighter Aircraft Net Costs ($M).

Effectiveness (%)	Net Costs		
	Halon 1301 (5.5 lb)	**HFC-125 (7 lb)**	**HFC-125 (18.4 lb)**
24	-48	-47	-45
32	-69	-68	-66
54	-127	-125	-123
60	-142	-141	-138
72	-174	-172	-170
80	-194	-193	-191
slope	-2.60	-2.60	-2.60

For fighter aircraft, the net cost change per single percent change in extinguishing effectiveness of the fire system was approximately -$2.5 M. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets (costs) saved.

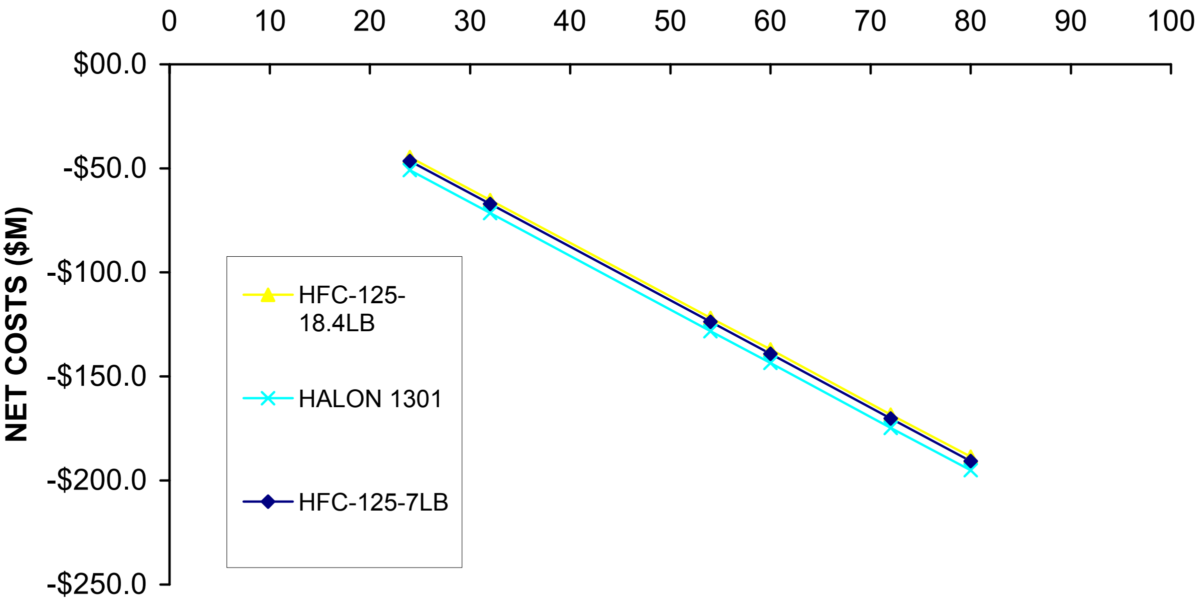

Figure 10–15. Legacy Fighter Aircraft Net costs vs. System Effectiveness.

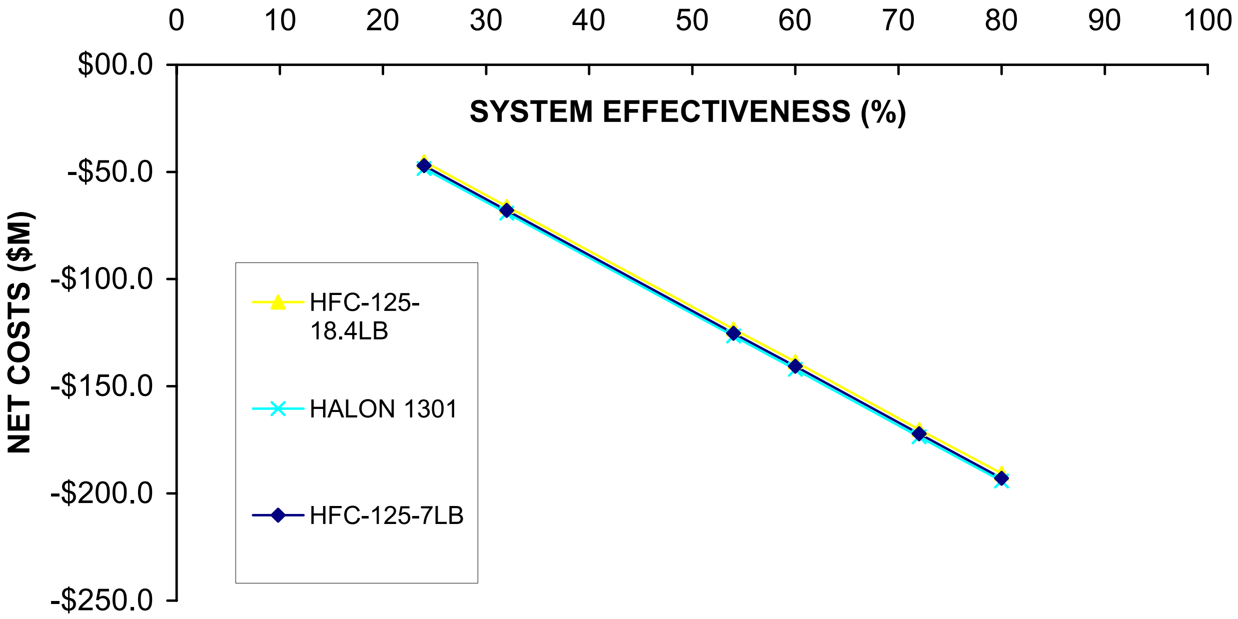

Figure 10–16. Future Fighter Aircraft Net Costs vs. System Effectiveness.

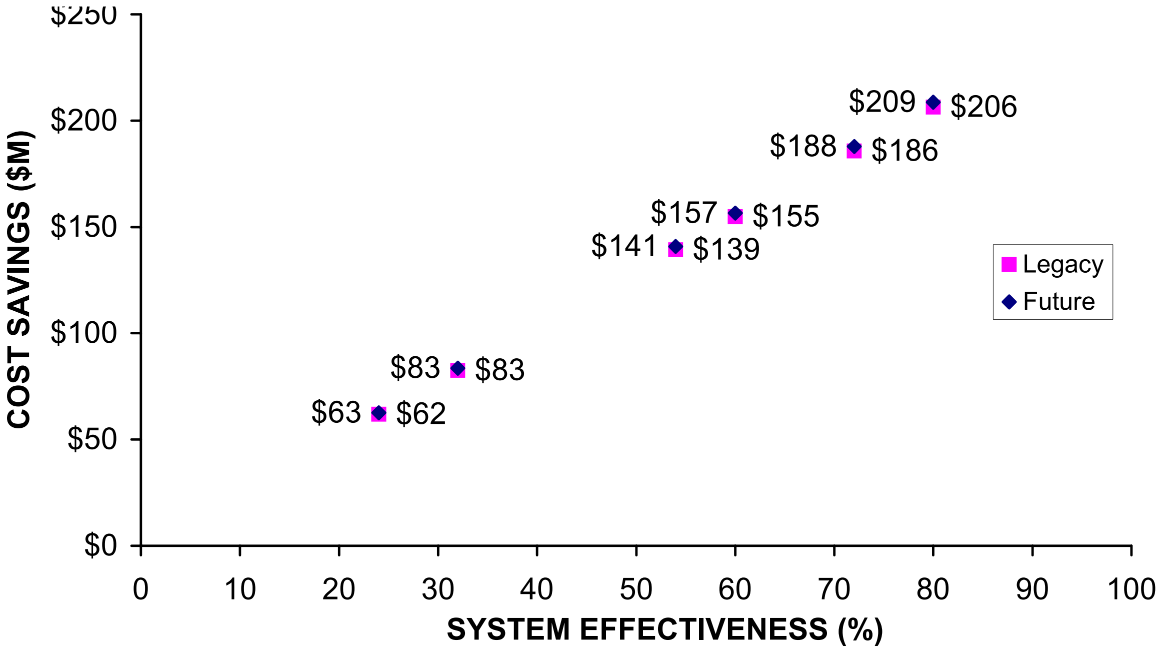

Figure 10–17. Legacy and Future Fighter Aircraft Cost Savings vs. System Effectiveness.

Rotary-Wing Aircraft

Table 10–37 and Table 10–38 show the resulting net costs for the legacy and future rotary-wing aircraft, respectively. Figure 10–18 and Figure 10–19 show the legacy rotary-wing aircraft net costs vs. system effectiveness for halon 1301 and HFC-125, respectively. Figure 10–20 and Figure 10–21 show the future rotary-wing aircraft net costs vs. system effectiveness for halon 1301 and HFC-125, respectively. Figure 10–22 shows the legacy and future rotary-wing aircraft cost savings vs. system effectiveness.

For legacy rotary-wing aircraft, the net cost change per single percent change in extinguishing effectiveness (i.e., 91 % successful vs. 90 % in the field) of the fire system was approximately $-6.2M. For future rotary-wing aircraft, the net cost change per single percent change in extinguishing effectiveness of the fire system is estimated to be -$6.3 M. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets (costs) saved.

Table 10–37. Legacy Rotary-wing Aircraft Net Costs ($M).

	Net Costs			
	Halon 1301		HFC-125	
Effectiveness (%)	1.1 kg (2.4 lb)	3.3 kg (7.2 lb)	3.6 kg (7.9 lb)	7.6 kg (16.8 lb)
24	-115	-113	-102	-97
32	-165	-162	-151	-147
54	-301	-299	-287	-283
60	-338	-335	-324	-319
72	-413	-410	-399	-395
80	-462	-459	-448	-443
slope	-6.19	-6.19	-6.18	-6.17

Table 10–38. Future Rotary-wing Aircraft Net Costs ($M).

Effectiveness %	Net Costs			
	Halon 1301		HFC-125	
	1.1 kg (2.4 lb)	3.3 kg (7.2 lb)	3.6 kg (7.9lb)	7.6 kg (16.8 lb)
24	-111	-109	-107	-103
32	-161	-159	-158	-153
54	-300	-298	-296	-292
60	-338	-335	-334	-328
72	-414	-411	-410	-405
80	-464	-461	-460	-455
Slope	-6.30	-6.30	-6.29	-6.28

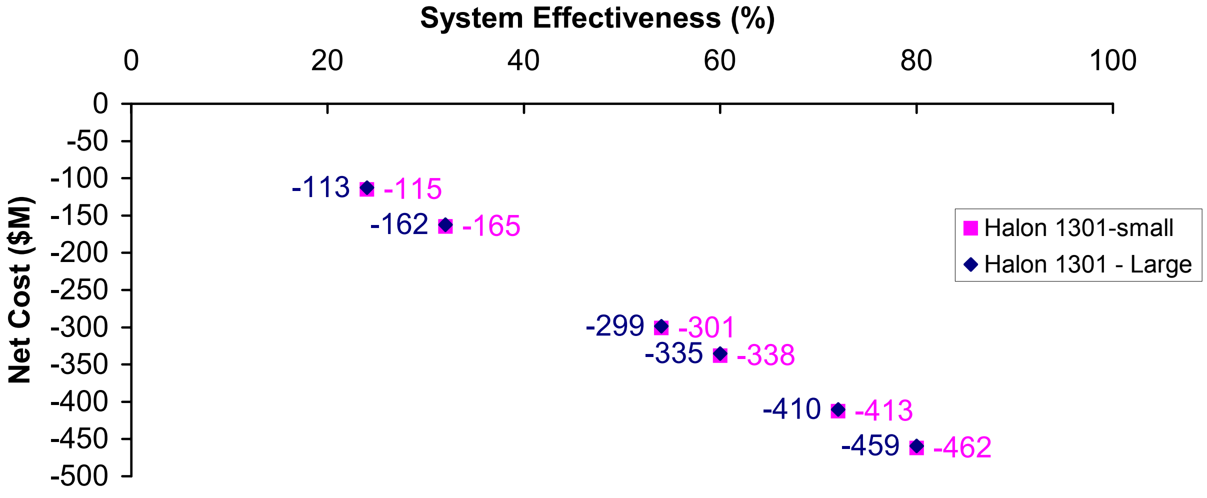

Figure 10–18. Legacy Rotary-wing Aircraft Net Costs vs. System Effectiveness for Halon 1301.

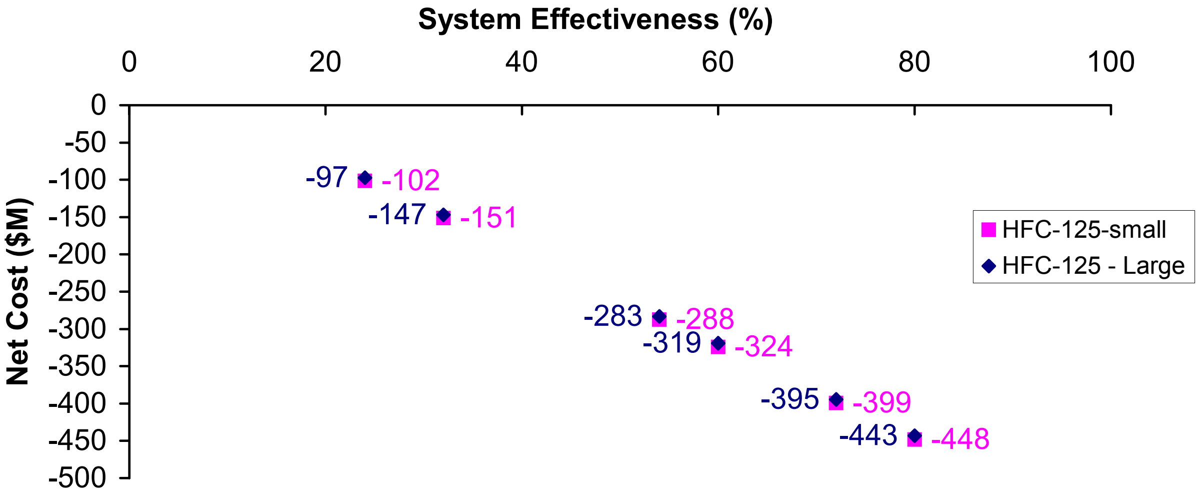

Figure 10–19. Legacy Rotary-Wing Aircraft Net Costs vs. System Effectiveness for HFC-125.

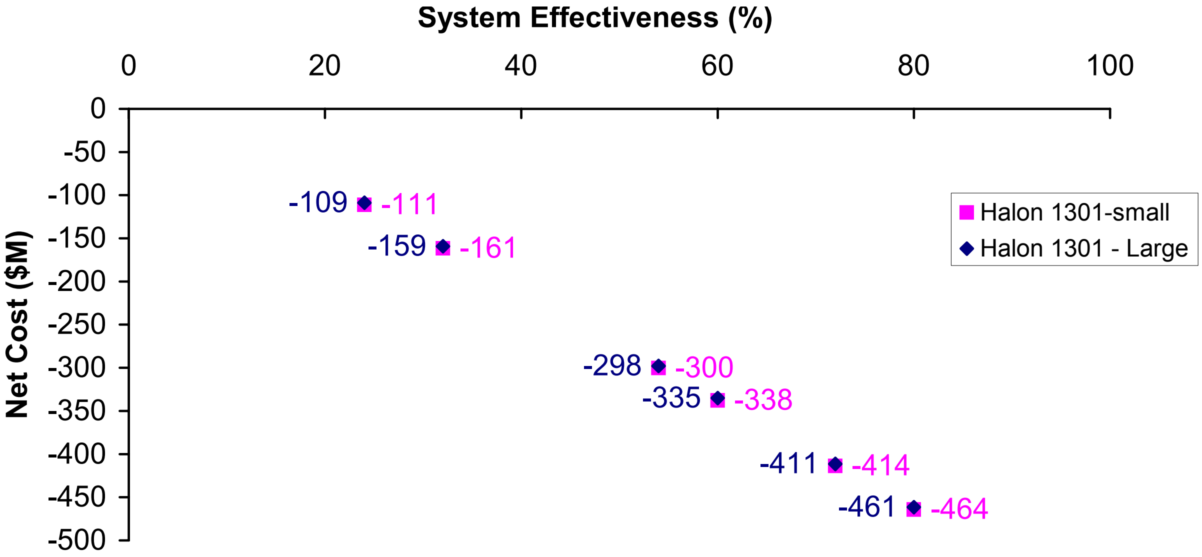

Figure 10–20. Future Rotary-Wing Aircraft Net Costs vs. System Effectiveness for Halon 1301.

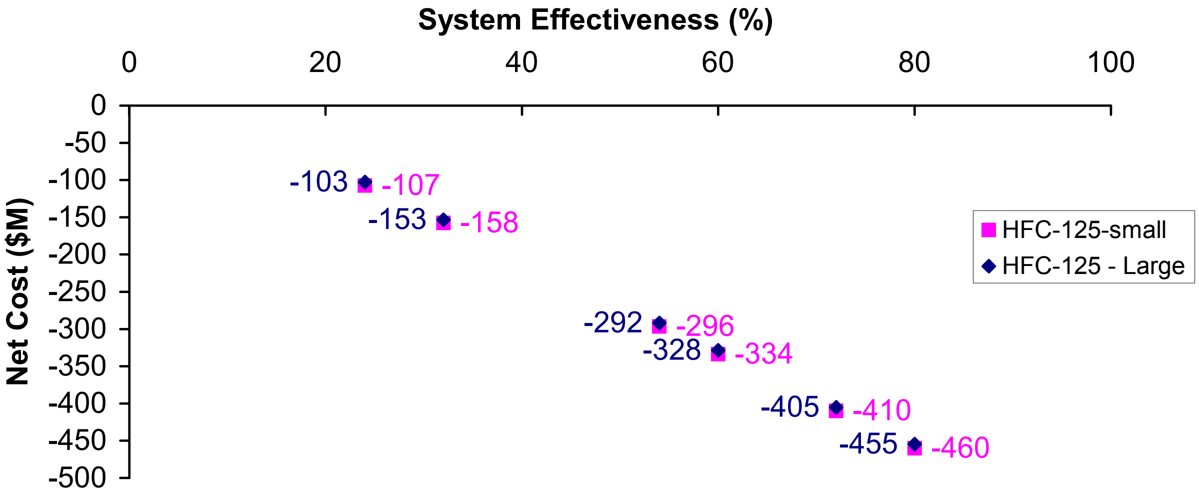

Figure 10–21. Future Rotary-Wing Aircraft Net Costs vs. System Effectiveness for HFC-125.

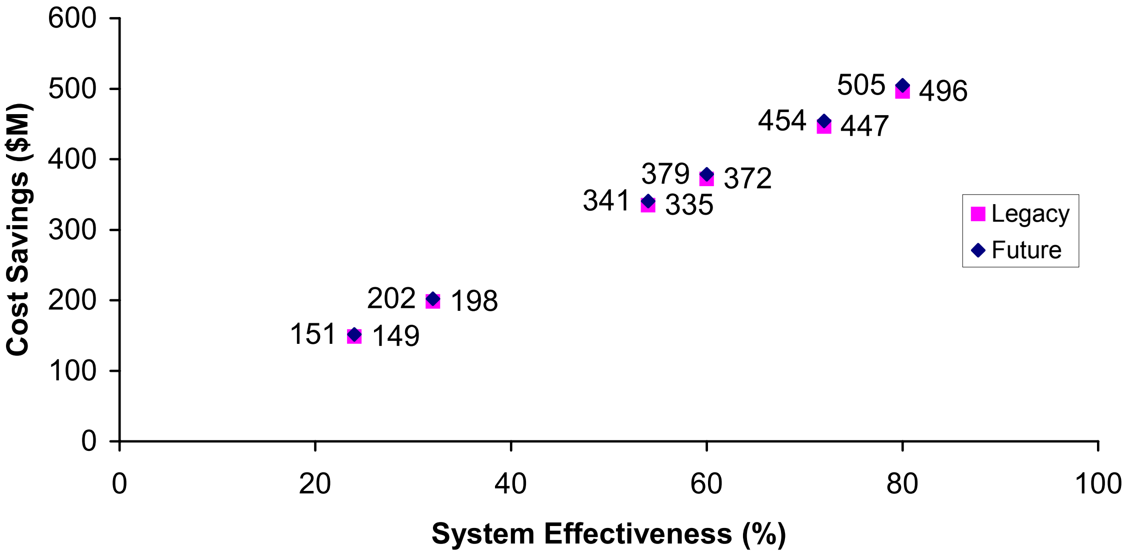

Figure 10–22. Legacy and Future Rotary-Wing Aircraft Cost Savings vs. System Effectiveness.

10.8 CONCLUSIONS

The NGP adapted a life cycle cost model to estimate the cost benefits of carrying fire protection systems for engine nacelles and dry bays on board military aircraft and developed a methodology for estimating the total cost of either retrofitting existing aircraft or configuring future aircraft with new systems based on a non-ozone-depleting fire suppressant. The calculations were performed for cargo, fighter, and rotary wing aircraft. The model replacement agent was HFC-125, since some data were available for such systems. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets saved for all the platforms examined. Specifically:

- It is highly cost effective for aircraft to carry fire protection systems, despite their life cycle costs (about 0.05 % to 0.2 % of the total cost of the aircraft) and the infrequency of their use. This is largely due to the high cost of losing an aircraft. Based on historical data, the return on investment in halon 1301 fire protection systems was estimated to be about 5:1 for cargo aircraft, 15:1 for fighter aircraft, and 12:1 for rotary-wing aircraft.
- It would also have been highly cost effective for HFC-125 systems, of fire suppression effectiveness comparable to these halon 1301 systems, to have been installed on military aircraft. The return on investment would have been at least two-thirds that of the halon 1301 systems.
- For comparable fire suppression effectiveness, the net cost of a system using HFC-125 installed in a future aircraft is approximately the same as the net cost of a conventional halon 1301 system.
- The cost of replacing the halon 1301 system with one of equal effectiveness, using HFC-125, in a legacy cargo aircraft is of the order of \$77 k to \$120 k per aircraft, which amounts to approximately 0.042 % to 0.066 % of the total cost of the aircraft. The estimates for fighter and rotary-wing aircraft are \$8.1 k to \$12.0 k (0.016 % to 0.023 %) and \$9.2 k to \$13.4 k (0.055 % to 0.080 %), respectively.
- Additional investment in a system of fire suppression performance above the historical levels is cost effective. For each 1 % increase in effectiveness (above the historical 60 % to 80 %), there is a net life cycle cost savings of about \$5 k per fighter or rotary-wing aircraft and about \$17 k per cargo aircraft. These estimates would be substantially improved were more extensive experimental data regarding factors of safety developed.

Already, the team overseeing at least one aircraft platform in development has used this methodology for estimating the costs associated with the selection of each alternative fire protection system, for deciding among those alternatives, for selecting the preferable system performance level, and for sizing the capacity of the system. This methodology can be expanded to meet the additional challenges of new aircraft, new fire suppression technologies, and additional applications, such as fuel tank inerting.

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