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Aviation Engine Test Facilities (AETF) Fire Protection Study

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An analysis is presented of the effectiveness of various types of fire fighting agents in extinguishing the kinds of fires anticipated in Aviation Engine Test Facilities (AETF), otherwise known as Hush Houses. The agents considered include Aqueous Film-Forming Foam, Halon 1301, Halon 1211 and water.

Previous test work has shown the rapidity with which aircraft, especially high performance aircraft, can be damaged by fire. Based on this, tentative criteria for this evaluation included a maximum time of 20 s from fire detection to extinguishment and a period of 30 min in which the agent would prevent reignition. Other issues examined included: toxicity, corrosivity, ease of personnel egress, system reliability, and cost effectiveness. The agents were evaluated for their performance in several fire scenarios, including: under frame fire, major engine

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fire, engine disintegration fire, high-volume pool fire with simultaneous spill fire, internal electrical fire, and runaway engine fire.

Recommendations as a result of this investigation include:

1. Provide fire protection for the hush house through the use of two AFFF systems: one covering the underwing area and a deluge system protecting the entire test bay.

2. The underwing system should be actuated by a flame detection system while the deluge system is actuated by ceiling mounted heat detectors.

3. Determine if past hush house operating experience warrants the cost of a halon total flooding system to extinguish engine and internal electrical fires.

4. Examine other possibilities for providing fixed halon protection to the engine nacelles.

5. Test the flash point of all fuel brought into the hush house, whether in the aircraft tanks or refueling vehicles, with an intent of defueling whenever the flash point falls below 38°C (100°F).

6. Ensure adequate floor drainage for all future hush house designs.

7. Either prohibit hot refueling in the hush house or provide a pantograph system to lower the associated hazard.

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AVIATION ENGINE TEST FACILITIES (AETF) FIRE PROTECTION STUDY

BACKGROUND

The proper maintenance of high performance military aircraft necessitates frequent operational testing of the engines at all power levels, including afterburner settings. In some instances the duration of this testing may be 24 hours or more. In order to minimize aircraft down time much of this testing is performed with the engines in-frame. Environmental concerns for the test personnel and equipment, and the need to reduce the high noise levels produced by the engines, require that the tests be performed inside an acoustically designed structure. This structure is known as an Aviation Engine Test Facility (AETF) or hush house.

Fire protection for the hush house must consider not only the structure and occupants but the aircraft, whose value (approximately $40 million) may be several times the cost of the structure and other contents. Personnel to be protected include, as a minimum, the aircraft driver (located in the pilot's seat with canopy down), an engine trimmer (often located on the hangar floor below the aircraft), and a control room operator.

Major fuel sources include the aircraft fuel tanks and fuel trucks which might be brought into the hush house to perform hot refueling during extended testing. Hot refueling is not performed at the hush house at NATC Patuxent River nor at NAS Jacksonville, although aircraft <u>are</u> refueled inside the NATC hush house. Interior refueling is not apparently a routine practice at Air Force hush houses since standard practice requires that most electrical circuits be de-energized before fueling. (This is because JP-4 may have a flash point as low as -29°C (-20°F) and most electrical circuits in the hush house are not designed to be explosion proof.) Out-of-frame engine tests (which are conducted only in the Air Force hush house) are fueled by a refueler truck located outside the hush house pumping to the engine through a fuel hose.

High energy ignition sources such as the exhaust and hot metal surfaces will obviously be present whenever tests are in progress, and other sources will generally be present between tests. Thus the potential for a fire occurrence is

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fairly high. Given the amount of fuel which could be involved, as well as the cost and damageability of the aircraft involved, the probability of a catastrophic fire is also hi^h unless adequate fire protection is provided. Imping j pool fires are estimated to cause aircraft skin damage (melt-through) in less than 60 s. The time to damage is even less when access panels on the bottom are open, which is often the case in hush house testing since test equipment must be connected in these areas.

There is, as yet, no consensus standard concerning fire protection for hush houses, neither in the military nor in the private sector. The National Fire Protection Association (NFPA) has produced standards addressing hangars (NFPA 409) and engine test cells (NFPA 423) but not the hush house. However, the NFPA 409 committee has just recommended inclusion of a separate hangar category to specifically address hush houses. They have also recommended that AFFF be the primary agent for fixed fire protection systems in hush houses.

The Navy and Air Force, meanwhile, do address standard methods of fire protection in their standard designs for hush houses, but differ on their approaches. The Air Force, placing heavy emphasis on the erection of pre-packaged hush house designs at forward Air Force bases (where water supplies may be inadequate), has selected Halon 1301 as the extinguishing agent. The Navy has utilized aqueous-film-forming-foam (AFFF) as its extinguishing agent, even requiring its installation in Navy facilities protected by halon in accordance with the Air Force standard design.

The Navy originally intended to utilize rate compensated, fixed temperature heat detection systems to actuate its fixed fire extinguishing systems. The heat from a tail pipe after engine shutdown has been hot enough, on one occasion, to actuate the AFFF system at NAS Miramar. This has led the NATC Patuxent River and NAS Jacksonville, and it can be assumed NAS Miramar as well, hush house personnel to switch the AFFF system to the manual actuation only mode during testing.

Other detection schemes which have merit include flame detectors to provide the earliest possible response to a fire. The possible presence of an afterburner flame makes installation of such a system very challenging. The Halon 1301 system in the Air Force hush house is activated manually only. There is no detection system of any kind.

Both the Navy and Air Force fire protection systems have significant built-in time delays to agent application. As the AFFF system is not pre-primed it requires 18-20 s before

AFFF first flows from either the overhead or underwing nozzles. The Halon 1301 system has a built in time delay of 40-45 s to allow all doors to close, including the main hangar door.

In the absence of sufficient technical information on which to base its choice of extinguishing agent, the Naval Facilities Engineering Command (NAVFAC) has tasked the Naval Civil Engineering Laboratory (NCEL) to recommend the optimum fire suppression system for Navy hush houses. NCEL has, in turn, sought the assistance of the Naval Research Laboratory (NRL) in this effort, in recognition of NRL's key role in the development and implementation of Navy fire protection systems.

Agents being considered for the hush house fire protection system are water, AFFF, Halon 1301, and Halon 1211.

OBJECTIVE

This study seeks first to identify the relative strengths and weaknesses of the candidate extinguishing agents with regard to the criteria enumerated below, based on use in the hush house environment. This has been accomplished through a survey of the applicable scientific and engineering literature to identify relevant experiments, tests, and actual fire experience.

Based on this research, recommendations have been made on the optimum extinguishing system design. In addition, testing needed to provide missing data on the effectiveness and/or consequences of use of each of the agents has been identified. Test plans for each item have been developed to detail the scope, materials, instrumentation, and desired output.

Current or pending research by other Defense Department activities or federal agencies, as well as by private industry, has also been identified and evaluated where possible. This information is intended to prevent duplication of effort and encourage cooperation among different agencies and/or corporations to reduce total testing costs.

SYSTEM PARAMETERS

Intent

The fire suppression system for the hush house must provide the required level of protection for personnel, aircraft, and the structure itself. Life safety is of paramount concern, but the high dollar value and strategic importance of the aircraft involved may alone merit unusually high investment in the fire protection systems. The total fire protection program for the hush house, which includes preplanned personnel actions, secondary extinguishing agents and systems, as well as the primary extinguishing system, is intended to severely limit fire related damage to the aircraft after the initiating incident. Damage due to application of the primary extinguishing agent, either in a fire incident or an accidental discharge, must be minimal or non-existent. Personnel safety, either in a fire situation or inadvertent actuation, should not be threatened by the agent nor its by-products. The extinguishing system must be highly reliable and effective. It should also, preferably, be self-contained. This system intent is more completely spelled out in the criteria listed below.

Facility Description

The facility to be protected is the "standard" Navy design hush house, pictured in Fig. 1. The Navy has not developed a design for mass production, as the Air Force has, but this design can be considered a prototype. The test bay is assumed to have dimensions of 26.2 m (86 ft) wide by 25 m (82 ft) long by 6.7 m (22 ft) high, for an approximate volume of at least 4248 m^3 (150,000 ft^3). The primary air intake is 24.4 m (80 ft) by 1.2 m (4 ft) located at the top of the hangar doors. The entrance to the augmenter tube is 4.3 m (14 ft) high by 5.5 m (18 ft) wide. Secondary air is introduced through a stack on top of the augmenter tube, outside the test bay, and can therefore be neglected in the fire protection design for the Navy hush house. Reference will also be made to the standard Air Force hush house design depicted in Fig. 2.

The major difference between the two designs which impacts fire protection is the method of introduction of primary air (for engine operation) and secondary air (for exhaust combustion) into the hush house. The Navy design introduces primary air through an intake above the hangar doors sized as indicated above. Secondary air is introduced into the augmenter tube through a stack at the beginning of the tube. The Air Force design draws both primary and secondary air into the test bay through a series of doors in the sides of the facility, five on each side. Due to this difference, and the smaller test bay volume, the air velocities are much higher in the Air Force hush house.

Another difference between the two designs is the provision of floor drains. Air Force hush houses are regarded as test equipment and are required to be provided only with a foundation and an electrical supply. While the

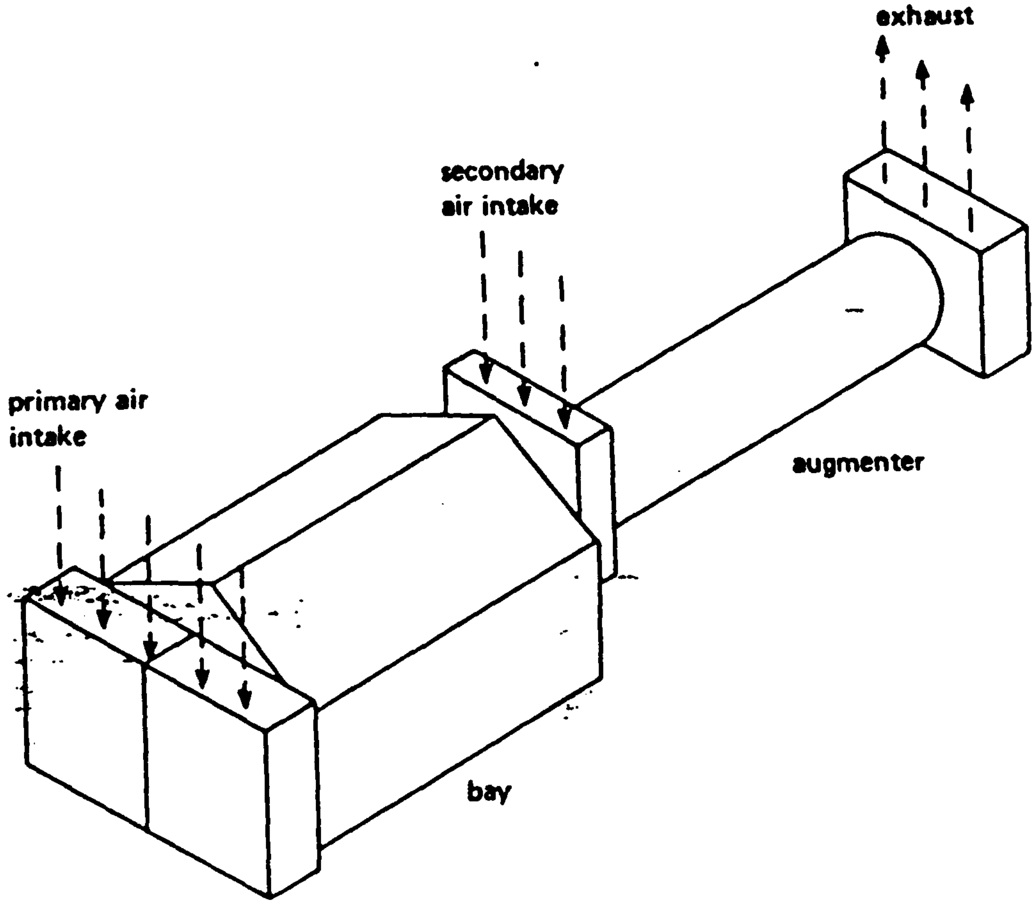


Figure 1 Basic Configuration of Navy Designed Hush House

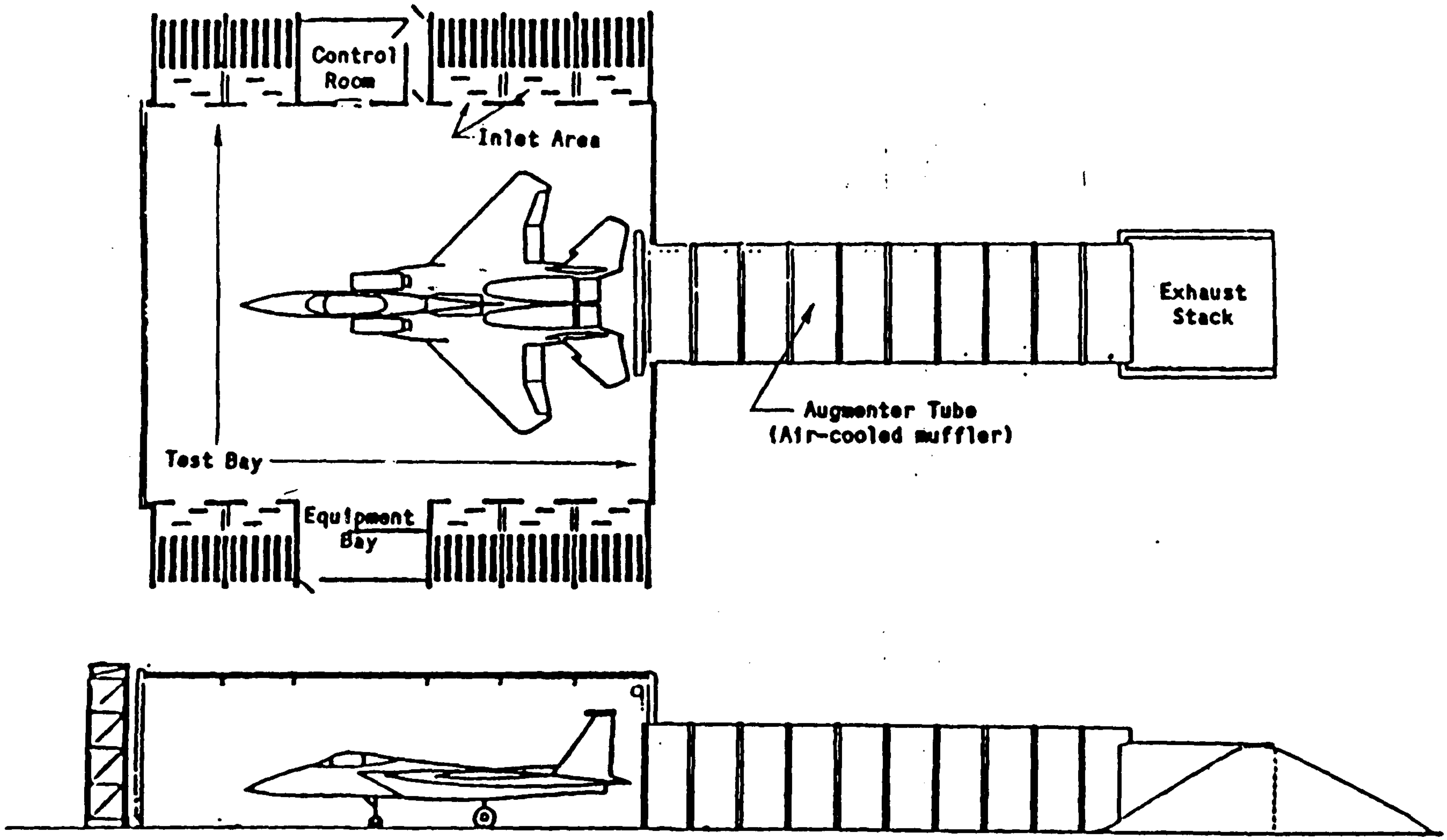


Figure 2 Basic Configuration of Air Force Designed Hush House

hush house observed at Andrews AFB was provided with a single floor drain, it was only 0.9m^2 (10 ft^2) in area, and no obvious floor pitch to this drain was noted. The hush house at NAS Patuxent River is provided with floor drains in accordance with NAVFAC criteria for hangars.

Navy hush houses are currently protected by ceiling height deluge systems discharging AFFF at a rate of 6.5 l/min/m^2 (0.16 gal/min/ft^2) and by floor level oscillating monitors (or fixed nozzles) protecting the underwing areas at a discharge rate of 4.1 l/min/m^2 (0.10 gal/min/ft^2) of AFFF. Air Force installations, on the other hand, are provided with total flooding Halon 1301 systems with a discharge concentration of six percent.

The Navy AFFF systems were intended to be actuated by rate compensated, fixed temperature detectors with a nominal operating temperature of 104°C ± 1°C (220°F ± 1.5°F). These detectors are at ceiling height and are placed on a 6.1 m x 6.1 m (20 ft x 20 ft) spacing pattern. The Air Force Halon 1301 system is a manual system, no detection is provided despite the fact that aircraft are often left unattended in the hush house overnight or on weekends (according to Air Force personnel).

Extinguishing System Criteria

The following criteria have been used as a baseline in this research in order to ensure the proper protection of personnel and equipment at a minimum cost.

Extinguishment Time

The goal for maximum time from detection system actuation (or manual operation) to fire extinguishment is 20 seconds. In the case of an AFFF system, fire control (90% extinguishment) in 20 s has been substituted for the goal due to the observed persistance of small flames around the fuel spill perimeter and other boundary areas during actual fire tests. (This small amount of flame could be extinguished by test personnel or responding fire fighters without significant additional damage to the aircraft.)

Reignition Prevention

A goal of 30 minutes of reignition prevention has been established to allow cooling of hot surfaces and to ensure complete extinguishment. Burnback resistance of an AFFF blanket is fairly limited and the blanket would therefore have to be renewed several times during this period.

Self-Contained System

The optimum system design would incorporate a self-contained unit because of the possibility of positioning installations at forward bases with unreliable utilities. This is not considered an overriding concern for AFFF systems, however, since Naval Air Stations should all have adequate water supply systems. As a concession to this possible problem the Navy standard design could be revised to include a pressure tank, or at least a diesel fire pump, if adequate water supply (volume) can be assumed, to be provided during hush house construction.

Low Risk of Failure

The final system selected/recommended for use in the hush house must have a high certainty of extinguishing the fire(s) which it was designed to combat. In addition, extinguishment must occur with sufficient rapidity to limit damage to acceptable levels. Each candidate system will be analyzed to identify potential failure modes and the probabilities associated with them. The expected goal for the failure rate is a value of less than 0.01. It should be noted that the available statistics on fire protection systems' performance is very limited, therefore an objective value for component/system failure rates may not be available.

Toxicity

Personnel must not be exposed to unacceptable levels of potentially toxic materials. This includes the non-fire (accidental discharge), fire, and post-fire (soak time or overhaul) periods. Each agent must be examined for its toxicity in both its stored form and in its decomposition products when exposed to heat, flame, electric arcs, etc. Potential impact on the surrounding environment (air and water) must also be examined.

Corrosivity

The corrosivity of each agent, both in pure form and any decomposition products, will be examined relative to aircraft components. This includes sensitive electronics, the aircraft skin, and the engines themselves. Corrosivity must be minimized in order to reduce potential costs of overhaul and repair due solely to agent use. Corrosion occuring as a result of inadvertent/accidental extinguishing system actuation must also be considered.

Personnel Egress

Each agent must be evaluated to determine any impediments it might present to rapid egress of personnel within the hush house. Possible adverse effects include slippery floors, visual obscuration, and impaired coordination/mental acuity due to toxicity of agents and their decomposition products.

Cost Effectiveness

Given the life safety threat involved and the high cost of the aircraft at risk, it is understood that a significant investment in fire protection systems will be acceptable. However, some measure of the additional protection provided by a more expensive system, or other additional equipment, must be developed to aid in the decision making process. While the cost of hardware is easily obtainable, an evaluation of the increased level of protection will necessarily involve an objective assessment.

Fire Scenarios

The candidate agents/systems must be evaluated on their ability to extinguish fires in the following scenarios.

Underframe Fire

The aircraft which will be tested in the hush house have an underframe area of up to 56 m^2 (600 ft^2). The candidate extinguishing systems must be capable of extinguishing a pool fire extending beneath this entire area in the previously specified 20 seconds. The system must be effective despite the presence of numerous fixed and moveable test stands under and around the aircraft.

Major Engine Fire

This fire would be caused by the failure of a pressurized fuel or hydraulic line followed instantaneously by ignition on hot metal surfaces. The system should preferably be able to extinguish this type of fire once the aircraft handler has cut off fuel flow and shut down the engine. This is not an overriding concern as portable, large volume Halon 1211 extinguishers are provided in the hush house. In addition, engines on some advanced military aircraft are provided with a one-shot Halon 1301 (or 1211) extinguishing system. While this may be inadequate to ensure fire extinguishment, since the engine will not see the large volume of cool air it would see in flight, the extinguishers located in the hush house will enable test personnel to complete extinguishment of such a fire. (These extinguishers are used successfully to extinguish engine fires occuring on the flight line.)

Engine Disintegration Fire

A catastrophic failure of an engine, e.g. a thrown turbine blade, could result in a more severe fire than the engine fire just described. This is because of the increased total fuel potential since the aircraft handler may be unable to cut off fuel flow due to damaged valves, etc. Damage to the engine nacelle makes it likely that there will be a simultaneous pool fire on the hangar floor along with a running fuel fire. The ability of the fire protection system to extinguish an engine fire, as well as the pool fire, would be highly beneficial. The availability of portable extinguishers, and/or a built-in extinguishing system in the engine, precludes making the ability to extinguish an engine fire an absolute requirement.

High Volume Pool/Spill Fire

A high challenge pool fire with an area of up to 42 m^2 (450 ft^2) and a continued fuel input of 132 l/min (35 gal/min) will present a major test of each candidate extinguishing system. The fuel source could be either an internal aircraft tank or the refueling truck if refueling in the hush house remains an allowable procedure.

One fuel source, the fuel truck, could be eliminated/reduced by providing a pantograph within the hush house and keeping the refueler outside. Inclusion of a dead-man type valve in the fuel line would also prevent the refueler from becoming the source of a running fuel fire after a fuel line rupture.

The system must be capable of suppressing this fire rapidly enough to prevent significant aircraft/structural damage. Suppression must be maintained while actions are taken to shut off the flow of fuel.

Runaway Engine Fire

A runaway engine occurs when the aircraft handler loses the ability to regulate the fuel flow to the engine, e.g. due to a stuck or damaged valve. Although the handler can shut off the master fuel valve, the engine will continue to operate for some time. If this occurs at the same time as a fire, the candidate extinguishing system will operate at the same time as continuing high airflow rates throughout the test bay (including the air intakes) and into the engine. This may impact the halon system's capability to seal the test bay due to a pressure differential across the doors and the damaging effect of the jet exhaust on the augmenter tube door.

Internal Electrical Fire

The ability, or inability, of each agent/system to extinguish internal electrical fires will also be addressed. Although a small first aid extinguisher is provided in the cockpit, and additional large extinguishers will be in the test bay, it would be beneficial for the extinguishing system to have the capacity to extinguish these types of fires. (This is especially true since an external pool fire could spread to the electrical components and manual suppression by test personnel would be impossible since they would have evacuated the building.) The availability of portable extinguishers again precludes requiring the candidate extinguishing system to have the capacity to extinguish an internal electrical fire.

System Effectiveness

In order to ensure the effectiveness of the detection and extinguishing systems the design of the candidate systems should comply with standard engineering practice. The design shall comply with all applicable NFPA codes including NFPA 423, Aircraft Engine Test Facilities, which should be considered as applicable to the hush house. It should be noted that the NFPA 409 committee has recommended inclusion of the hush house as a separate hangar category and this standard would then become more applicable. However, hush houses are still used to test out-of-frame engines on test stands so that certain requirements of NFPA 423 would still apply.

CANDIDATE EXTINGUISHING AGENTS

This study was limited to the agents most commonly used to extinguish hangar fires, namely water and AFFF, as well as Halon (both 1301 and 1211) since this agent is utilized by the Air Force. Use of other agents such as CO_2, dry chemicals, or high expansion foam was ruled out for various reasons such as toxicity and quantity required (CO_2) and potential clean up problems (dry chemicals).

This section of the report will describe the historical use of each agent and its potential application to fire suppression in the hush house environment. Inherent strengths and limitations of each agent will be identified. Finally the anticipated discharge system configuration for a hush house application will be described, including known potential problem areas associated with system operation.

Water

The oldest and most widely used fire extinguishing agent is, of course, water. Water is also the agent used in the most prevalent automatic fire extinguishing system, the sprinkler system. Protection, when provided, in early hangars was open head water deluge systems. (Water deluge systems began to be replaced by protein foam/water deluge systems in the 1950's (and later by AFFF), due to the increased ability of foam to extinguish flammable liquid fires.)

The advent of larger (and hence greater fuel capacity) and more expensive wide body aircraft led to studies of the ability of water deluge systems to protect aircraft (both adjacent and the aircraft of origin) in addition to the structure. The simultaneous significant increase in the cost of advanced military aircraft led to further concern over the ability of water to protect the large investment present in each aircraft.

Water has remained, however, the most widespread extinguishing agent because it is cheap and generally readily available. Application of water through a deluge system requires a reliable source of water supply as well as a reliable means of pressurizing the water for delivery through the piping network. During forward deployment, buildings may be constructed and occupied before an adequate water and power supply system is established. Therefore, an integral water supply might be considered necessary in the hush house standard design. Depending on the design density and duration this could be a major additional expense.

Water extinguishes fire mainly by absorbing heat and cooling surfaces below their ignition temperature. (Steam smothering occurs only in relatively small, confined spaces.) However, a large flammable liquid fire burns so hot and rapidly that water application is largely ineffective as is evidenced by any number of news stories showing fire fighters trying to extinguish storage tank fires. The water from a sprinkler system reaching the seat of a Class A fire cools the burning combustible, or at least wets down adjacent combustibles to prevent their ignition. However, the water reaching the flammable liquid surface of a Class B fire merely slips below that surface where it can have no possible effect on extinguishment (except to wash the flammable liquid toward a drain if the floor pitch is adequate).

As stated before, water was dispensed in aircraft hangars by means of open-head sprinklers connected to deluge valves. Large hangars are divided into several deluge zones by draft curtains in order to limit the number of heads which will be discharging at one time. Water supply requirements are usually quite high and generally result in the provision of dedicated water storage tanks and fire pumps for the hangar area. In a structure as small as the hush house all heads in the test bay would be operated at the same time whenever the system was operated.

NFPA 409 does not permit water sprinkler protection for strategically important aircraft [1]. However, where permitted, it specifies a minimum water density of 6.9 $l/min/m^2$ (0.17 $gal/min/ft^2$) over the entire protected area, in this case the entire test bay. This would require a total flow rate of approximately 5300 l/min (1400 gal/min) in the Navy standard hush house (when including a 10-15% overdesign allowance). An additional 283 '/min (75 gal/min) would be required to supply an underwing foam system, which is still required, by NFPA 409, along with the sprinkler system. To meet NFPA 409 requirements the water supply system must be capable of meeting this flow rate, at a residual pressure of approximately 7.03 kg/cm^2 (100 lb/in^2), for at least 30 minutes. At a site with a poor water supply this would require a 189,000 l (50,000 gal) storage tank and two 2840 l/min (750 gal/min) fire pumps.

The deluge system would be activated by a heat detection system. The standard detection scheme utilizes rate compensated, 104°C (220°F) fixed temperature detectors, installed on a 6.1 m by 6.1 m (20 ft x 20 ft) spacing pattern.

Recent work [2] has also been done utilizing water in a rapidly deployed fine mist to extinguish fires (including flammable liquid fires) in confined spaces. A density of 1.0 $l/min/m^3$ (.0075 $gal/min/ft^3$) is maintained for a one minute period. However, the largest test volume so far has been only 324 m^3 (11,442 ft^3) and required an extensive piping system based on a maximum spacing of 41 cm (16 in) between nozzles, 1.2 m (4 ft) between branch lines, and a maximum height (which can be protected by one set of nozzles) of 3 m (10 ft). Applying this density figure to the hush house results in a water demand of 4248 l (1100 gal); twice that if two-shot protection is required. The minimum nozzle pressure is 17.6 kg/cm^2 (250 lb/in^2).

Aqueous-Film-Forming-Foam (AFFF)

As stated previously, water began to be displaced as the primary extinguishing agent in hangars by protein foam in the 1950's. The development of aqueous-film-forming-foam (AFFF) in the early 1960's, and extensive testing of AFFF extinguishing systems showing its significant increase in extinguishing ability over even protein foam, led to its introduction as a hangar protection agent. The advent of larger (and hence greater fuel capacity) and more expensive wide body aircraft led to studies of the ability of water deluge systems to protect aircraft (both adjacent and the aircraft of origin) in addition to the structure. The simultaneous significant increase in the cost of advanced military aircraft led to further concern over the ability of water to protect the large investment present in each aircraft.

Since the mid-70's AFFF has become the preferred extinguishing agent for aircraft hangars. AFFF was utilized despite its higher cost because it provided a twofold reduction in extinguishing time over protein foam when applied by hand lines or turret nozzles and a 40% decrease when used in deluge systems [3].

AFFF extinguishes a flammable liquid fire by means of two simultaneously operating mechanisms. First, the water in the foam cools the fuel surface to reduce the rate of vapor production. Second, the fluorocarbon surfactants form a vapor sealing layer which advances in front of the foam blanket and prevents fuel vapors from migrating into the combustion zone. The rapid flame knockdown achievable with AFFF is dramatic. However, the rapid drainage characteristics, which permit the development of the leading vapor suppressing layer, also limit the burnback resistance and durability of the blanket. The foam blanket must be renewed every 5-6 minutes (depending on the fuel, nozzle type and application/method, etc.) to maintain a margin of safety during fire overhaul operations.

There are several limitations to the use of AFFF in aircraft hangars. The first has to do with the method of application. Foam, whether protein or AFFF, was originally applied only by the overhead deluge system. The increased wing area of wide body aircraft, which shields the area below from direct foam application, led to significant delays in extinguishment of the fire below the aircraft. This resulted in a high potential for total loss of the aircraft as damage to the airframe at or near the wing root often renders the entire airframe useless. However, placement of supplementary application devices, either oscillating monitors or fixed nozzles, which discharge foam beneath the wings and fuselage, has overcome this problem.

A second limitation of AFFF use is its inability to combat internal aircraft fires, whether in the engines or in the electronics areas. This is because the AFFF system is not designed to reach inside either the aircraft interior or the engine nacelles. While a boom arrangement could be used to permit AFFF discharge into the engine, the relative infrequency of these fires, combined with the excellent ability of portable extinguishers to combat these types of fires, does not warrant this additional expense and potential operational headache.

While standard practice on aircraft carriers, before deployment of high volume halon extinguishers, was to douse a burning engine with AFFF, this required a complete overhaul of the engine [4], regardless of how little fire damage actually occurred. This is because AFFF solution prepared with seawater (as is done onboard all ships) is corrosive, due to the salt water, and unless it is completely removed from all the normally inaccessible engine surfaces it could lead to subsequent engine failure. AFFF prepared with fresh water requires only flushing with fresh water for clean up. While the hush house AFFF system would not be set up to discharge agent into the aircraft engines, engine ingestion could occur if an accidental discharge occurs while the engines are operating.

Obviously, AFFF is also not the agent of choice for extinguishing Class C fires in sensitive electronic equipment. However, such fires are generally very small when detected and can readily be extinguished using the small halon extinguisher in the cockpit. In addition, larger extinguishers would be immediately available inside the hush house. There exists a possibility that a Class C fire could occur within the aircraft as a result of an external pool fire. While the AFFF would extinguish the pool fire it would do nothing about the Class C fire. Since the test personnel would likely have evacuated the building, the Class C fire would not be addressed until the arrival of the station fire department.

AFFF is normally applied in hangars by overhead deluge nozzles with underwing application by oscillating monitors or fixed nozzles. NFPA 409 recommends an overhead system density of 6.5 $l/min/m^2$ (0.16 $gal/min/ft^2$) with the underwing system discharging at 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$). In large hangars the area is divided into multiple deluge zones to limit the number operating simultaneously. However, in the hush house the entire test bay would be discharging at the same time. The underwing area in the hush house can be taken at 56 m^2 (600 ft^2), while the test bay area is 655 m^2 (7050 ft^2).

NFPA 409 [1] requires a discharge duration of 45 minutes for the overhead system and 10 minutes for the underwing system. Allowing for a 10% overdesign factor the total water volume is 201,000 l (53,100 gal). The required amount of 6% AFFF concentrate is 25,660 l (6780 gal), including both primary and reserve supplies for the 45 and 10 minute discharge periods. Positioning of an AFFF protected hush house at a forward site would therefore require provision of a 227,100 l (60,000 gal) water storage tank with a 5678 l/min (1500 gal/min) diesel fire pump (or two pumps of half that size).

AFFF is not generally stored as a pre-mixed solution because of problems with settling. (Most manufacturers recommend a storage time of less than five years for pre-mixed AFFF solution.) Instead, AFFF concentrate is injected into the discharge piping where mixing with the water also flowing in the line occurs within several pipe diameters. The two common injection methods for deluge systems are direct injection via a foam pump and orifice injection from a pressure proportioning tank. If the water supply characteristics are constant and the system demands are also constant, i.e. additional demands from subsequently operating systems or devices will not occur, then the direct injection method will work. This utilizes a foam pump to inject the AFFF concentrate through a carefully sized line to achieve a 6% ratio of concentrate in solution.

The more widely used method, however, is the orifice system featuring a pressure proportioning tank. AFFF concentrate is stored in a bladder tank inside a metal tank. Through a complicated looking piping and valving scheme the tank is connected to the main discharge header. As water flows through this header a small amount of water, directly proportional to the flow rate, is diverted into the metal tank. This influx of water applies pressure to the bladder tank, forcing AFFF concentrate (by displacement) into the discharge header through an orifice. While it appears complicated, this method is considered the simplest and most effective [5]. It has a major advantage in that it maintains the proper foam concentration despite varying water supply conditions and changes in demand (such as additional systems operating or foam hose lines being charged), while having a very low pressure drop across the foam injection point.

The intent of the original Navy hush house design was to use a heat detection system to actuate both the overhead and underwing AFFF systems. In practice, the AFFF system at NATC Patuxent River and NAS Jacksonville (and presumably NAS Miramar) is placed in the manual operation mode whenever a test is in progress. This apparently was in response to an inadvertent actuation of the AFFF system at a hush house at NAS Miramar, which was due to a hot tail pipe generating sufficient heat to activate ceiling level detectors after the engine was shut off. The detector type and spacing is the same as that described for the water deluge system. Manual actuation stations are also provided in the test bay and in the control room.

Halon 1301

Use of halogenated hydrocarbons (halons) as fire extinguishing agents dates back to the use of carbon tetrachloride in the early 1900's. (Use of carbon tetrachloride shows another important concern in the history of halons as its use was discontinued in the 1960's due to toxicity concerns.) Other early halons used in naval and aviation fire protection throughout the world included methyl bromide and bromochloromethane, both of which were highly toxic. A shorthand notation method for referring to the halogenated hydrocarbons, "halon numbers," was developed and is given below.

Chemical Name	Formula	Halon No.
Carbon tetrachloride	CCl_4	104
Methyl bromide	CH_3Br	1001
Bromochloromethane	CH_2ClBr	1011
Dibromodifluoromethane	CBr_2F_2	1202
Bromochlorodifluoromethane	$CBrClF_2$	1211
Bromotrifluoromethane	$CBrF_3$	1301
Dibromotetrafluoroethane	$CBrF_2CBrF_2$	2402

Research was conducted by the U.S. Army after World War II to find an extinguishing agent as effective as those discussed above, but without the high toxicity. The four halons they identified as worthwhile were Halon 1301, Halon 1211, Halon 1202, and Halon 2402. After further experimentation the Army settled on Halon 1301 for use in extinguishers in battle tanks and electronic vans. The Air Force, meanwhile, selected Halon 1202 for use in aircraft engine extinguishing systems. Halon 1211 was selected by the British for use in both military and commercial aircraft. Subsequently, the military and civilian sectors used Halon 2402 in protecting some aircraft engines, and it has also been employed in total flooding systems in some parts of Europe.

In the U.S. use of Halon 1301 in total flooding commercial applications began in the early 1960's. Halon was promoted as a "clean" agent without the toxicity problems associated with carbon dioxide, the traditional clean extinguishant. Typical applications include: computer rooms, magnetic tape storage vaults, electronic control rooms, storage areas for art works and rare objects, and flammable liquid and gas hazards. Computer rooms are far and away the most prevalent hazard protected by total flooding halon systems due to the overwhelming concern of data processing managers with water damage from automatic sprinklers.

Halon extinguishes fires by interfering with the chemical chain reactions necessary for fire propagation. This can be achieved with very low concentrations of halon (6%) when compared to carbon dioxide (40%). Extensive industry testing in the 1960's and 70's identified the minimum halon concentrations necessary to extinguish fires in various combustible materials, whether solid, liquid or gas. These results were then incorporated in the governing consensus standard, NFPA 12A [6], adopted in 1970.

Extinguishment with halon is predicated on achieving and maintaining the prescribed minimum concentration. This requires the shutdown of external ventilation and the sealing of all openings, including doors and ducts, prior to halon discharge. This requires the incorporation of a time delay to allow for fan rundown and closure of the openings. The time delay is also necessary for health reasons. Although Halon 1301 is considered safe for humans (in short exposures) in concentrations up to seven percent [6], the thermal decomposition products (HF, HBr and Br_2) are highly toxic [7]. A time delay of 30 seconds to allow evacuation is fairly standard.

Halon total flooding systems are generally actuated by smoke detection systems. To prevent costly false alarm discharges, the detection system is usually cross-zoned, requiring the operation of at least one detector on both of the detector circuits in the area being protected. Manual actuation stations are also generally provided at the exits from the protected space. As a further protection against spurious discharges, many halon systems are equipped with abort switches. If the abort switch is actuated before the time delay has been completed, the delay is either re-started or is frozen until released. A reserve supply of halon for quick system restoration, and/or second shot application, is usually required.

In the standard Air Force hush house design there is no detection system. Instead, the halon system can only be actuated manually. A brief description of the entire system is provided by Buckley [8]. The Halon 1301 design concentration is six percent. Electrically motor driven doors are provided over the ten air inlets and the entrance to the augmenter tube. The stated time for complete closure of these doors is 20 seconds, however the main hangar door, if open, requires 40-45 seconds to close completely.

In reviewing an Air Force hush house built to the standard design it was seen that the system is provided with time delay of 45 s. A manual abort switch is provided and can also be used, if released once pressed, to actuate the system instantly. This would enable the operator to release the agent once the air inlet doors have closed, in 20 s, rather than waiting the full 45 s. The manual actuation station and abort switch are located in the control room. Positive indication of door closure is not provided, therefore the control room operator will not know if a door hangs up, unless it is one he can see. A reserve supply of halon is not provided.

There are a number of potential problems associated with the use of any total flooding system. These include: toxicity (both from the agent and its thermal decomposition products), sealing of the hazard area to allow agent concentration to be achieved and maintained, inability of halons (in low concentrations) to extinguish deep-seated fires, and the corrosion of sensitive electronic equipment and engine components by the thermal decomposition by-products. In addition, it should be noted that halon has little or no effect on cooling of heated surfaces and does not secure the fuel spill surface to prevent evaporation of flammable vapors.

Toxicity

Pure Halon 1301

Halon 1301 has been found to be free of adverse effects on humans for short term (15 min) exposure in concentrations up to 7% and for brief (1 min) exposure in concentrations up to 10% [6]. The design concentration in the Air Force hush house is only six percent.

Halon 1301 Decomposition Products

Halon 1301 breaks down when exposed to temperatures in excess of 482-538°C (900-1000°F). Major decomposition products include HF, HBr, and Br_2. These compounds can cause significant damage to the respiratory tract and eyes in fairly low concentrations [7]. Fortunately the highly irritating nature should force all personnel to evacuate, if they possibly can, before lethal levels are reached.

Sealing of Hazard Area

Achieving and maintaining the 6% design concentration requires that all ventilation be shut down and all openings into or out of the test bay be sealed. Proper operation of the rolling steel doors which cover the air inlets has proved to be a problem in the civilian sector. In addition, the possibility exists that these doors could be blocked at the time of a fire.

Deep-Seated Fires

Deep-seated (char) combustion can occur in cellulosic materials if the required geometry and pre-burn time are present in a fire situation. Much higher halon concentrations, on the order of 15%, are required to extinguish deep-seated fires. Since Class A materials could be present in the test bay a deep-seated fire is a possibility and presents a re-ignition hazard.

Corrosion

The halogen acids, HF and HBr, will cause corrosion of electronic equipment and even metal surfaces, if the concentration is high enough. It is unknown what concentrations can be expected from extinguishment of a large pool fire with a significant pre-burn period.

Cooling

Halon does not have a significant cooling effect on hot surfaces. If the required concentration is lost before sufficient cooling has occurred the fuel surface will re-ignite. This is especially true for JP-4, or mixtures of JP-4 in JP-5, due to the lower flash point and ignition temperature.

Vapor Securing

Halon does not provide a vapor securing blanket like AFFF. If the halon is removed while an ignition source still exists, e.g. an electric arc, re-ignition could occur.

Halon 1211

As stated previously, Halon 1211 is far more prevalent as an extinguishing agent in Europe than in the U.S. It is utilized in exactly the same manner as 1301 in both total flooding systems and other applications.

Due to a lower vapor pressure Halon 1211 is discharged as a liquid, rather than a gas as is 1301. This results in a longer "throw," i.e. a longer, more coherent discharge stream, for 1211 when discharged from a nozzle. This, in turn, has led to increased use of 1211 in portable extinguishers due to the increased standoff distance which can be employed by extinguisher users when combatting a fire.

The percentage amount of agent required to achieve extinguishment in fires involving various materials is essentially the same for both 1211 and 1301. However, 1211 has a lower specific vapor volume, therefore a greater amount of the agent is required to achieve a given concentration, when compared to 1301. These considerations are all taken into account in the governing consensus standard, NFPA 12B [9].

Toxicity is also more of a concern with Halon 1211, both in its pure form, and when considering its decomposition products. Concentrations up to 4% produce no adverse effects during short (several minute) exposure. At concentrations above 4% adverse effects (dizziness, etc.) begin after approximately one minute. Prolonged exposure presents a risk of unconciousness and possible death [9]. Likewise 1211 produces a greater quantity of toxic by-products when undergoing thermal decomposition [7].

TECHNICAL DATA REVIEW

Water

Water, of course, was the original extinguishing agent utilized to protect aircraft hangars. It should be noted, however, that water deluge systems were intended for just that, protecting the hangar, not protecting the aircraft of origin or even adjacent aircraft. World War II vintage hanger protection was "standardized" by the Bureau of Yards & Docks in August 1941 [10]. Requirements included a minimum density of 7.7 $l/min/m^2$ (0.19 $gal/min/ft^2$) based on 57 l/min (15 gal/min) per head, 7.4 m^2 (80 ft^2) maximum spacing, at a minimum end head pressure of 0.7 kg/cm^2 (10 lb/in^2).

Water fog can be used by an experienced operator to extinguish small (up to 9.3 m^2 (100 ft^2)) flammable liquid fires. However, water discharge from sprinklers has proven ineffective in controlling or extinguishing larger pool fires. (Sprinklers can be effective if the hangar floor is pitched and drained to such a degree to allow rapid washoff and removal of fuel.) Fitzgerald [11] showed that a very large 121 m^2 (1300 ft^2) JP-4 pool fire could cause structural damage to steel beams within minutes, despite a deluge system density of 10.2 $l/min/m^2$ (0.25 $gal/min/ft^2$). (Ceiling temperatures fluctuated between 427°C (800°F) and 816°C (1500°F) at a height of 18m (60 ft) above the floor.) Water deluge systems could prevent structural damage from smaller fires but provide little, if any, protection for the aircraft of origin or adjacent aircraft.

As long as hangar protection remained the primary fire protection goal, and aircraft remained small and relatively inexpensive, water deluge protection was a viable alternative. However, the early 1970's saw the introduction of wide body aircraft with fuel capacities in excess of 57,000 l (15,000 gal) and a much higher cost per aircraft. Advanced military aircraft, although small by comparison, also escalated dramatically in cost to the point where an advanced aircraft has a price tag of approximately $40 million. In a reversal of the historical trend, one aircraft now could have a price tag many times higher than the replacement cost of the hangar. As a germane example the Navy designed hush house installed at NATC Patuxent River cost less than $6 million, and the Air Force design costs $2 million (less required site preparation work).

While the fighter aircraft which will be brought into the hush house environment are significantly smaller than the wide body jumbo jets mentioned above they still have fuel inventories of upwards of 9,463 l (2,500 gal). Add to this the 30,280 l (8,000 gal) inventory of the fuel trucks which could be used to conduct refueling of aircraft within the hush house and the potential for a major spill is evident. Farmer [12] indicates that a spill rate of only 568 l/min (150 gal/min) will result in a pool fire with a radius of 5.5 m (18 ft), or a total area in excess of 93 m^2 (1,000 ft^2). Tests by Fitzgerald [11] showed that water deluge systems were ineffective in controlling large fires, even at discharge densities of 12.2 $l/min/m^2$ (0.30 gal/min/ft).

Current aluminum alloy aircraft skin materials have been shown to be susceptible to fire damage from direct flame impingement in one minute or less [13,14]. Radiative heating to adjacent aircraft may cause damage in less than two minutes depending on fire size, separation, and other factors, although that is not a factor in the hush house scenario. Fitzgerald's data shows that water deluge systems cannot provide rapid flame knockdown, and thus alone cannot meet the initial requirements of a maximum of 20 seconds to extinguishment. Water, as delivered by deluge systems alone, should therefore be eliminated from further consideration as the primary extinguishing agent in hush houses.

NFPA 409, where it permits use of water sprinklers, also requires a foam system for the underwing area. In the interest of cost savings in converting protection for existing hangars, NAVFAC had research performed on the compatibility of overhead water deluge with foam monitor nozzles. Work by Breen [3] showed that water deluge rates of up to 8.2 $l/min/m^2$ (0.20 $gal/min/ft^2$) did not significantly increase the extinguishment time for floor level monitors discharging AFFF at a rate of 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$), on fires up to 9.3 m^2 (100 ft^2) in size. However, there is little cost savings in such an arrangement in a newly constructed facility, and the sole use of AFFF would be beneficial under most foreseeable conditions. Therefore the use of a water deluge system in combination with the AFFF underwing system is not recommended.

The water mist system described in Ref. 1 has been shown to be effective in extinguishing flammable liquid fires in enclosed spaces. However, the fire sizes which were utilized in testing this system were relatively small. In addition, the piping/nozzle spacing rules applied to designing this system would be unworkable in the hush house. Current design criteria allow a single piping grid to protect an area only 3 m (10 ft) high. Areas taller than this require the installation of two (or more) grids. Since the maximum distance between branch lines is only 1.2 m (4 ft), it would be impractical to install a water mist system in a hush house where aircraft and test equipment are taller than 3 m (10 ft) and are moveable.

The water mist concept looks attractive for forward base deployment in that only a 4250 l (1100 gal) self-contained pressure tank is needed for agent storage. However numerous questions remain as to whether this system can extinguish a very large pool fire in a large space. Even if it can, the piping configuration required may not be practical given the operating parameters of the hush house. Therefore while additional work on this concept as applied to hush houses may be beneficial, it is not recommended for consideration under this program as the lead time to a practical system appears too long.

AFFF

The available literature contains numerous reports of fire tests demonstrating the effectiveness of AFFF in extinguishing flammable liquid fires in typical aircraft hangar configurations [3, 14, 15, 16, 17]. However, all of these references cite the inability of overhead AFFF nozzles to control and extinguish fires beneath obstructions (aircraft fuselage and wings) quickly enough to prevent damage to the aircraft of origin.

Ninety percent control times in these tests vary from 1 min 30 s to 2 min 30 s for unobstructed fires being extinguished by overhead deluge systems only. (Fires ranged from 9.3 to 84 m^2 (100 to 900 ft^2).) These tests, however, generally feature a detection delay of at least 10 s, a delay of about 15 s for discharge of water from the open sprinkler heads, and another 10-20 s before foam is discharged from the heads. In addition, Krasner [14] reports a delay of approximately 1 1/2 minutes from deluge system actuation to proper (6%) proportioning of the foam solution.

Thus, in the typical aircraft hangar scenario, properly proportioned foam may not be applied until over two minutes after ignition. Yet, 90% control is accomplished with less than properly proportioned foam, or at worst, within another minute, for these unobstructed fires. Therefore, improvements in the detection system and foam delivery mechanisms can be expected to shorten the extinguishment time by one minute or more.

As stated above, the presence of obstructions can significantly increase the control and extinguishment times of fires being extinguished by overhead sprinklers alone. Tests by Krasner [14] showed that approximately one additional minute was necessary to achieve control over an 84 m^2 (900 ft^2) JP-4 pool and spill fire when a 37 m^2 (400 ft^2) obstruction was introduced. Breen [3], investigating JP-4 spill and pool fires up to 84 m^2 (900 ft^2) in size, was unable to achieve rapid enough extinguishment to prevent damage to the aircraft of origin when using densities of up to 14.2 $l/min/m^2$ (0.35 $gal/min/ft^2$) to combat fires involving the same 37 m^2 (400 ft^2) obstruction. Obviously, damage to the aircraft during this time (a total of 3 min 30 s from ignition) would be significant.

Provision of low-level supplementary foam application devices, either oscillating monitors or fixed nozzles, overcomes this problem. Breen [3] controlled 9.3 m^2 (100 ft^2) JP-4 pan fires in as little as 15 s after foam first entered the pan during sweeps of 946-1893 l/min (250-500 gal/min) oscillating monitors. Obviously, this is even faster than the control time achieved by overhead foam sprinklers on unobstructed pool fires, despite the fact that the density of the overhead nozzles was generally 6.5 $l/min/m^2$ (0.16 $gal/min/ft^2$) as opposed to an average density of only 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$) for the monitor nozzles.

Oscillating monitors achieve significant knockdown of the fire on the first sweep over the fire area. Subsequent applications actually cause momentary increases in the fire intensity as the discharge stream disturbs the existing AFFF film on the fuel surface. In between sweeps the drainage from the additional foam forms a more widespread film over the fuel and the fire size continues to decrease. The disturbance of the fuel/film interface often results in the final portion (1%) of the fire not being extinguished until after the monitor is shut off in these test fires. No directly comparable data was found for low level AFFF application from fixed nozzles.

The ability of low level monitors to obtain much faster control and extinguishment than overhead nozzles, despite an average density only 63% of that applied by the sprinklers, is not surprising. In a summary of work carried out at FMRC, Breen [15] notes maximum (centerline) plume velocities of 9.1 - 23.2 m/sec (30-76 ft/sec) in fires ranging from 9.3 to 83.6 m^2 (100 to 900 ft^2). In an earlier report [16] Breen calculates maximum AFFF particle velocities of only 0.8 - 3.1 m/sec (9-33 ft/sec) when discharging from conventional sprinkler heads. Therefore, it can be seen that droplets from an overhead system would be unable to penetrate the central portions of a large pool fire. This corresponds with actual fire test observations where extinguishment is seen to progress from the periphery inward. But rather than being due to the migration of foam over the fuel surface, Breen contends that it is the progressive reduction of the fire size, and hence plume velocity, which allows the particles from the overhead nozzles to penetrate the plume and land directly on the fuel surface.

The stream from a low level system, being closer to the seat of the fire and in a more coherent form (thus possessing a higher velocity) is able to reach the fuel surface despite the high upward velocity. In addition, the shorter transit time decreases thermal degradation of the foam. The much more rapid extinguishment times noted with monitor nozzles are therefore reasonable and expected despite the lower average density.

The underwing system can be expected to extinguish any pool fire under the aircraft rapidly enough to prevent significant damage to the aircraft, if the detection system is fast enough. This system protects the hangar floor only in the immediate vicinity of the aircraft. Other areas in the test bay where fuel spills may collect are covered by the overhead sprinklers. The increased control/extinguishment time is acceptable, however, because the spatial separation of the fire from the aircraft increases the time required for melting of the skin material.

The high value of the aircraft tested in the hush house, combined with their ease of damageability from fire, causes legitimate concern over the delays in system actuation and proper foam proportioning mentioned earlier. Delays due to detection system actuation can be avoided by utilizing one of the rapid detection devices utilized in explosion suppression systems, provided the system is not placed in the manual mode during testing. (Reliance on manual only actuation during aircraft testing presents the possibility of significant delays in system actuation.) These systems utilize either ultraviolet or infrared detectors sensitive in the wavelength range produced by flames. Other more recent systems employing laser technology are also available. As the most damaging fire would be one located below the aircraft, the low level underwing AFFF system should be actuated by these types of detectors positioned to detect a fire in this area.

As these types of detectors are sensitive to even the smallest of fires, the overhead deluge system should not be actuated by them. This is because AFFF from the overhead system would be ingested into engines which are still operating, necessitating a costly engine overhaul where salt water is used in fire mains [4]. Opening of the canopy, or an already open canopy, could also result in damage to the aircraft's sensitive electronic systems. Operation of the low level underwing system may result in damage to test stand equipment but would not be directed onto any part of the aircraft except the landing gear. Therefore spurious actuation, or operation in response to an insignificant fire, would not cause damage to the aircraft. Applicable detector technologies are discussed in detail below.

The AFFF system configuration used for comparison to the extinguishing system performance criteria (and the one recommended by this report) is as follows. First, an underwing system (that is a system which protects the underwing area, not one which is physically located under the wing) discharging at 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$). This system would be actuated by a flame detection system and is provided to protect the aircraft from direct flame impingement in the event of a fuel spill beneath it. This system should be pre-primed with properly proportioned AFFF solution. Since the geometries of the aircraft and test equipment are fairly well known it would seem advantageous to utilize fixed nozzles rather than oscillating monitors. The use of a multitude of nozzles, rather than a single oscillating monitor should result in fewer areas being shielded from direct AFFF discharge. In addition, possible problems with the oscillating mechanism of the monitor nozzle are avoided. Second, to protect the rest of the test bay, an overhead deluge system should be provided to discharge AFFF at a density of 6.5 $l/min/m^2$ (0.16 $gal/min/ft^2$) over the entire test bay. The deluge valve should be actuated by the heat detection system utilized in the present standard hush house design.

An evaluation of this AFFF system design, with respect to the previously identified system performance criteria, is given below.

Extinguishment Time

Ninety percent control times of 15 s from agent application have been reported for monitor nozzles attacking pool fires of up to 9.3 m^2 (100 ft^2). The use of fixed underwing nozzles can be expected to approximately equal this figure as foam would be applied over the entire fuel surface,

rather than just the portion within the arc of the monitor at any given time.

Use of a pre-primed system and the rapid detection technology described above should reduce the 1 min 30 s delay in proper foam application observed by Krasner [14] to a delay of less than 5 s. Therefore, the extinguishment criteria of 20 s from ignition could be achieved, since the fire size should not be much more than 9.3 m^2 (100 ft^2).

If a rapid (flame) detection system is not utilized the potential for a significant delay in system actuation exists. If manual actuation is precluded for some reason, i.e. the control room operator goes to the aid of personnel in the test bay, the heat detection system would not actuate for at least 10-15 s, and perhaps longer depending on the fire size. Failure to provide a pre-primed system means a delay of 18-20 s in foam discharge after detection. Therefore the 20 s extinguishment (control) criterion would not be met.

The fire size is not expected to exceed 9.3 m^2 (100 ft^2) because even if the fuel spill is larger, the fire size should not exceed this because the spread of flame across a JP-5 pool is not extremely rapid. However, this assumes a fuel tank content of 100% JP-5. (With JP-4, or even a 10% mixture of JP-4 in JP-5, the flame spread rate would be much higher, and more than 9.3 m^2 (100 ft^2) of the fuel surface would be involved, even if the entire surface did not become involved.)

The underwing system, of course, only covers fires under the aircraft and in its immediate vicinity. Fires outside this area would be covered by the overhead deluge system. Even without the use of a pre-primed system one would expect extinguishment within 2 min 15 s of detection system actuation, with the detection system responding within 10 s for large fires, longer for small fires. Although this exceeds the 20 s criteria, it should not result in damage to the aircraft. This is due to the fact that the fire is separated from the aircraft and the intensity of radiation hitting the aircraft falls off with the square of the separation distance. It should be noted that small fires outside the underwing area could be extinguished by test personnel with portable halon extinguishers without any AFFF discharge at all.

Reignition Prevention

AFFF does offer limited reignition prevention for a pool fire as measured by its burnback resistance. However, this is on the order of 5-7 minutes for AFFF as opposed to 15-20 minutes for protein foam [15]. Thus to afford the desired 30 minutes of reignition prevention the foam blanket would have to be renewed 4-5 times. This would require an increase in foam storage capacity above the NFPA 409 mandated 10 minutes.

However, since AFFF does offer significant cooling capacity the probability of reignition is low, unless an energized electrical system is still arcing. Even this may not result in reignition since the flashpoint of JP-5 is on the order of 60°C (140°F) and the fuel pool will have been cooled below this temperature during the 10 minute discharge period. A mixture of 10% JP-4 in JP-5 however, has a flashpoint of 10°C (50°F). In light of this, a sampling of fuel flash point might be recommended for every aircraft and refueler before it is brought into the hush house, with defueling required whenever the flashpoint drops below 38°C (100°F).

Reignition prevention could not be expected in the event of an engine or electrical fire as these would not be extinguished by the AFFF system in the first place. The AFFF blanket would extinguish fuel from an engine fire or fuel tank or fuel line rupture once it has reached the hush house floor.

Self-Contained System

The AFFF system would become self-contained if the standard hush house design incorporated a 227,000 l (60,000 gal) water tank and a 5678 l/min (1500 gal/min) diesel fire pump, in addition to the foam tank and balanced pressure proportioner currently provided. The addition of such a tank would cost about $100,000, while a fire pump installation would cost about $50,000.

While $150,000 is not much compared to the cost of a $40 million aircraft, it is more than 2.5% of the cost of the more expensive hush house constructed at NATC Patuxent River. Such an expenditure would seem unnecessary since water supplies at most air stations should be capable of meeting the demand of the hush house AFFF system. The tank and pump could be added to the standard Navy hush house design as an option to cover the possibility of construction at a forward base or a base with an inadequate water supply.

Low Risk of Failure

As the previously defined extinguishing system criteria state, the AFFF (or any other) fire extinguishing system selected for the hush house must have a low risk of failure. A failure rate of less than .01 percent was selected as the desired level of performance. Unfortunately, little or no detailed data is available on the performance of fire protection systems and their components. While the Navy undoubtedly has extensive data and predictive models for the reliability of similar electronic and electro-mechancial equipment, this is beyond the scope of this study. Instead what specific data is available in the general literature has been presented along with some subjective assessments.

The elements necessary for proper performance of the AFFF extinguishing system include:

1. Adequate water supply
2. Proper flame detection system actuation
3. Operation of the deluge valve supplying the underwing system
4. Proper operation of the bladder tank and proportioner
5. Proper operation of the heat detection system
6. Operation of the deluge valve supplying the overhead sprinklers
7. Piping intact and unobstructed

Known unavailability of any of these components, i.e. a system out-of-service, should generally be cause to preclude testing in the hush house.

Air Station water supplies are routinely tested by the station fire department and any long term degradation should be known in advance of dropping below required levels. If adequate control of valve closing is maintained, and pumps are tested in accordance with the recommended schedule, no sudden impairments should occur, either. The same tests and checks would apply to the pump(s) and tank at a forward base installation so the failure rate should be low, but it is unknown whether it is less than the .01 criterion.

High speed detection systems are made highly reliable for their use in explosion suppression systems since the consequences of failure are so high. The detector heads incorporate self checking circuits that verify they are still operable. Insensitivity of detectors of this type is seldom a problem. Rather they are often too sensitive, responding to spurious sources such as welding or sunlight. Again, the literature contains no reliability data on these systems, and it is unknown whether the .01 criterion can be met.

The NFPA has compiled sprinkler reliability data from sources throughout the world and gives values ranging from a success rate of 95 percent to 98 percent. However the vast majority of failures were due to human errors such as shut valves and improperly designed systems, rather than equipment failure. Therefore the two deluge valves, if properly maintained, can be considered to have a very low failure rate and may meet the .01 criterion.

As explained earlier, the bladder tank and balanced pressure proportioner are considered highly reliable. Once the tank is properly filled and the valves correctly aligned the system is ready to operate instantly. There are no pumps or other moving parts to fail. Although AFFF concentrate, when exposed to air, is somewhat corrosive, use of proper materials in system construction, combined with routine inspections, should prevent any problems which would result in a system failure. Once again, no reliability data is available but it is reasonable to assume a low failure rate.

Although the Navy standard design does not specify a particular heat detector manufacturer, the Fenwal Corporation Detect-A-Fire Unit, Model 27121-20, detector has been utilized for the majority of Navy hush house installations. Data from Fenwal, cited by Buckley [8] reports no known failures despite numerous installations across the country for many years. Therefore an assumed failure rate of less than .01 seems to be readily assignable to this component.

Toxicity

AFFF has virtually no toxicity to humans in the exposures which can be anticipated from a system discharge. Prolonged contact can cause minor skin a ' eye irritation which can be overcome by simply rinsing with clean water.

Toxicity to aquatic organisms is another issue, however. Allowable concentrations when discharging to a waterway vary with the manufacturer of the concentrate. Even if the floor drains in the hush house are connected to the sanitary sewer, as now required by NAVFAC policy, limits are placed on the allowable discharge rate due to foaming problems in the treatment beds at the sewage treatment plant.

In most localities the officials responsible for the sewage treatment plant are willing to accept the possibility of excess AFFF from an actual fire induced system discharge. Discharge from system testing, however, is required to be metered into the sewage flow at an acceptable rate. This requires a shutoff valve and pump pit in the discharge line leading away from the hush house drainage system.

Corrosivity

AFFF solution, when prepared with seawater, is mildly corrosive, due mainly to the seawater, requiring a fair amount of time to cause noticeable corrosion. AFFF concentrate is corrosive when an air/liquid interface exists. This requires careful selection of materials in the proportioner and storage system. Use of a pre-primed system may require that all system piping be corrosion resistant, and special care given to selection of any seals or gaskets.

NAVAIR requires no special steps, other than washdown with fresh water, for equipment which is sprayed with AFFF prepared with fresh water, according to its Corrosion Control Manual [4]. Engines, however, which ingest a significant amount of AFFF prepared with seawater are required to undergo a complete breakdown and cleaning to remove residual AFFF which could otherwise cause long term corrosion problems in the engine possibly resulting in a subsequent, sudden failure. AFFF prepared with seawater could also cause significant corrosion problems in sensitive electronic equipment inadvertently doused during a fire or spurious actuation. This damage is secondary, however, to the immediate shorting effects which would be experienced with energized equipment. Prompt cleaning of wetted parts should prevent subsequent corrosion problems.

Personnel Egress

Egress should not be a problem for any test personnel, except the aircraft handler. Other test personnel will most likely have evacuated before the AFFF deluge system actuates, if the fire is indeed large enough to activate the detectors within the 10-15 s minimum observed in the tests cited above. The aircraft handler, however, must first shut down the engines, open the canopy, climb out of the cockpit, and then traverse the hangar floor. Personnel at NATC Patuxent River estimated that this would require 10-15 seconds.

The aircraft handler may also descend into an underwing system discharging at chest height. This in itself could be somewhat disconcerting especially in view of the anxiety which could understandably accompany the sight of a large fire. However, since the underwing suppression system should preclude the presence of any fire in his immediate area, he should be able to identify a safe escape route.

Discharge of AFFF from the overhead deluge system should not significantly obscure his vision. AFFF on the hangar floor would make the floor slippery. However, by adjusting his gait to a smaller step a person in reasonable physical condition should be able to exit safely. Provision of a non-skid surface on the hangar floor, or wearing of non-skid shoes, would also help to mitigate this potential problem.

Cost Effectiveness

In a recent comparison of the Navy and Air Force hush house designs [8], Buckley provides a breakdown of the estimated costs to duplicate the AFFF extinguishing system installed in the hush house at NATC Patuxent River, MD. With a price tag of $80,740 this system is representative of the one required by the present "standard" design.

Upgrading the detection system to permit use of ultraviolet or infrared flame detectors to actuate the underwing system would cost approximately $20,000. Provision of a water storage tank and diesel fire pump for forward base deployment would cost an additional $150,000.

A total system cost of $101,000 ($251,000 for a forward base) seems reasonable when considering the significant fire threat posed to each of the upwards of $40 million aircraft tested in the hush house. The cost is high relative to the $6 million, or less, structure since fire protection costs are normally estimated at less than 2% of the cost of a building. However, structural protection is not the primary goal of the AFFF system, or any other system selected for the hush house.

Fire Scenarios

Under Frame Fire

The AFFF underwing system is designed specifically to rapidly control and extinguish an under frame fire. A foam blanket would cover the entire area within 15-20 seconds after the detection system was tripped because of the use of a pre-primed system. The traditional delay in detection due to the use of heat detectors at the top of a high bay would be overcome by use of the flame detectors. These detectors respond so rapidly that the foam blanket could be applied before the fire would have spread across the surface of a large JP-5 spill.

Even such a brief fire could still damage test equipment and any sensitive equipment in the aircraft which was exposed by the removal of access panels beneath the aircraft. However the airframe, engines, and all unexposed components should be adequately protected.

Major Engine Fire

The AFFF system would have little or no effect on the progress of an engine fire. The underwing system is not directed upwards at the engines. The overhead system will no doubt be actuated eventually by a sustained engine fire of any size. Some AFFF will be ingested by the engine, if still running, but it would not be sufficient to extinguish the fire. Damage could result in the cockpit if the canopy were open during the overhead system discharge.

Extinguishment of an engine fire is not impossible however. The first expedient, which Buckley [8] reports as being used successfully, is to cut off the flow of pre-heated air to the engine allowing the high flow of air at ambient temperature to cool metal surfaces below the ignition temperature of JP-5. (Obviously this would not work for JP-4, or even 10% JP-4 mixtures.) This works only if the excess fuel is in certain locations, and the fire is not due to a ruptured fuel line.

Secondly, the aircraft handler can cut off the flow of fuel to the engine and then trigger the built-in engine fire suppression (halon) system, if any. Monasko and Hoffman [18] demonstrated the ability of such a system to extinguish a fire in the engine of an F-14A. However, the success of such a system may require continued high airflow rates to cool hot surfaces and prevent reignition as reported by Altman, et al [19]. Indeed, in ground testing conducted as part of the program described in Ref. 18, the engine fire was reignited by an exterior ground fire once the halon concentration had dissipated. Another possible problem is that discharge nozzle placement is predicated on normal airflows through the engine nacelle of an operating aircraft.

A possible solution to the engine fire problem would be to provide a tee in the piping (tubing) supplying the discharge nozzles in the engines, for those engines equipped with a built-in extinguishing system, and connecting an outside source of halon. This outside source could be sized to allow multiple applications of halon of a volume greater than the original storage cylinder on the aircraft. Alternatively a continuous application at a carefully calculated rate could also be used. The controls for the outside discharge system would be located in the control room where the person in charge of the test could apply halon in complete safety while other personnel in the test bay evacuated. Only a few of the Navy aircraft tested in the hush house, however, are provided with such an onboard system.

The cost of providing such a system would have to be balanced against the currently observed frequency and severity of engine fires at hush houses. In the absence of such a system, extinguishment would be by manual application of large volumes of halon as practiced on the flight line and the flight deck. On the flight line, halon is contained in large wheeled extinguishers and several of these should be present in the hush house test bay.

The third, and perhaps most practical solution, is the use of the large, wheeled Halon 1211 fire extinguishers provided in the test bay. These units have been used repeatedly on the flight line and flight deck to extinguish engine fires.

Engine Disintegration Fire

The engine disintegration fire may be impossible to extinguish with halon as described above for built-in engine extinguishing systems because of the possibility of copious quantities of fuel and large rents in the engine nacelle. Such a large fire would probably have to be extinguished with AFFF handlines, and this can be done without regard to cleanup costs, even if the AFFF is prepared with salt water, as the engine is probably already a total loss. A skilled operator may be able to extinguish such a fire with the large, wheeled halon extinguisher.

In the interim between the fire occurrence and the arrival of the station fire department, test personnel may be able to reduce the volume of flame by judicious application of the available quantities of halon (either in an engine extinguishing system and/or the portable halon units). The AFFF underwing and overhead deluge systems will also be tripped and will extinguish any pool fire on the hangar floor and also provide cooling of the airframe. The fireproofing and heat shielding provided in advanced aircraft, as described in Ref. 18, should prevent migration of the fire out of the nacelle before extinguishment by the arriving firefighters, depending on the mechanical damage caused by thrown engine parts.

High Volume Pool Fire

Again, the AFFF system is designed especially for the extinguishment of pool fires, tests having shown an ability to quickly extinguish pool fires up to 83.6 m^2 (900 ft^2) [14-16] with systems not designed as well as the system proposed above. This is especially important since one or more access panels on the bottom of each aircraft are generally open during testing for the connection of test equipment, increasing the speed with which a fire would damage an aircraft.

The AFFF system will not, however, extinguish the continuing running fuel fire if a cascade situation exists. If there is no cascade, just a naked spill, JP-5 will not support flame propagation back up the vertical stream. This is not true for JP-4 or JP-4 mixtures in the 10%, or more, range. In the event of a cascade, or JP-4 fire, AFFF will extinguish the burning fuel once it finds its way to the hangar floor. The cascade fire could be extinguished by the test personnel, if they have not evacuated, or by arriving firefighters. Tests by Carhart, et al [20] have shown tnat a 189 l/min (50 gal/min) JP-5 cascade fire can be easily extinguished in a no-wind situation, barring complex debris configurations (as from an explosion), with a single 360 l/min (95 gal/min) AFFF, or 2.3 kg/s (5 lb/s) halon, handline. JP-4 cascade fires are much more difficult to extinguish.

Runaway Engine

A runaway engine, one which the handler cannot shut off, is virtually identical with the other engine fires already discussed, with respect to the effectiveness of the AFFF system. The AFFF system will not extinguish this fire but will extinguish any fuel spilling to the hangar floor. It will also provide cooling of the fuselage and other exposed equipment. AFFF ingestion into the engine will definitely occur if the overhead system actuates, requiring an engine overhaul even if fire damage is not significant, if the AFFF is prepared with salt water. Again, the halon extinguishers provided in the test bay could be used to extinguish this type of fire.

Electrical Fire

The AFFF system will have no effect whatever on internal electrical fires. Fortunately, such fires are generally quickly identified in the cramped arrangements of a fighter or attack aircraft and easily extinguished by the small extinguisher found in the cockpit. In addition, the aircraft handler also can utilize the numerous larger halon extinguishers located in the test bay.

System Effectiveness

The effectiveness of the AFFF system is predicated on a sound design and a professional installation along with continued inspection and proper maintenance. No major loss has been reported in an aircraft hangar that was protected by an AFFF system properly designed, constructed, and maintained. Of course, very few hangars are utilized as engine test facilities with the consequent significantly increased hazard.

The first step in developing a proper design is adherence to all of the applicable consensus standards published by NFPA. They include:

NFPA 11,	Standard for Low Expansion Foam and Combined Agent Systems
NFPA 13,	Standard for Installation of Sprinkler Systems
NFPA 16,	Standard for Installation of Deluge Foam-Water Sprinkler Systems
NFPA 30,	Flammable and Combustible Liquids Code
NFPA 70,	National Electric Code
NFPA 72D,	Standard for the Installation, Maintenance, and Use of Proprietary Protective Signalling Systems
NFPA 72E,	Standard on Automatic Fire Detectors
NFPA 409,	Standard on Aircraft Hangars
NFPA 423,	Aircraft Engine Test Facility

The system specification must also detail the high level of construction inspection which is required to ensure problems such as improperly installed piping, or presence of debris in the piping, are avoided. System testing, including a final full discharge test, must also be specified. Piping must be adequately pressure tested and the proper proportioning of the foam must also be checked.

The final element in ensuring system effectiveness is inspection and routine maintenance. Elements such as adequacy of the water supply, valve positioning, and quality of the foam concentrate must be checked periodically. Operation of the detectors and deluge valves can be tested without discharge of agent. Finally, a full discharge test equivalent to the system acceptance test should be conducted every three years or so.

Halon 1301

An extensive amount of testing has been conducted to determine the minimum concentration of Halon 1301 necessary to extinguish fires in flammable liquids, solids, and gases. The majority of this work was performed by, or for, the companies which produce or distribute halons for fire extinguishment. Unfortunately many of the test plans and instrumentation schemes are not well documented so it is often difficult, or inappropriate, to compare the results of one test program to another.

There have been hundreds of full scale fire tests run on simulated computer rooms and similar facilities using Halon 1301 as a suppression agent. Fuels included cellulosics (paper, punched cards, etc.), polymeric cable insulation, magnetic tapes, and liquid fuels. Most of these tests sought to define the effectiveness of Halon 1301 fire suppression agents relative to the damage sustained by the protected equipment, the production of corrosive gases and the problem of deep-seated fires. In addition to these tests, hundreds of tests have been conducted on the suppression effectiveness of 1301 on flammable and combustible liquids and flammable gases.

The data on these tests have been largely incorporated in standard design requirements, i.e., NFPA 12A [6] and NFPA 12B [9]. DiNenno and Starchville summarized much of this testing in a literature search conducted as part of a study on fire protection options for critical shipboard electronic spaces [21]. Their summary forms the basis for the following technical review of Halon 1301 and its potential use in the hush house.

The variables which determine the effectiveness of total flooding Halon 1301 on a given fire are similar to those for any other gaseous suppression agents. The most relevant variables are:

1. growth rate of fire
2. size of fire at agent discharge (pre-burn)
3. time to discharge agent
4. fuel type & geometry
5. agent concentration
6. soaking time (time duration for which a design concentration is held)
7. Continuing ventilation and/or agent loss through unsealed openings

The effectiveness of Halons on solid Class A fuels is primarily controlled by the nature of the combustion process. For simple fuel arrays and short pre-burn times, and predominantly fuel-surface fires, the gaseous Halon agents are effective in relatively low (<6%) concentrations. For cellulosic fuels and some other polymers subject to deep-seated fires (smoldering and char oxidation), the agents are only effective in fairly high (>15%) concentrations [21].

Ford [22] summarizes most of the testing of Halon 1301 on Class A fuels, conducted prior to 1974. He cites unpublished UL data which indicates that for wood crib and excelsior fires, an extinguishing concentration of 3-6% for 10 minutes is adequate. Shredded paper required concentrations above 18%, probably due to smoldering combustion, or the development of a "deep-seated" fire. Similar high concentrations are required for a number of other Class A materials, including: plywood, masonite, cardboard, and ceiling tile.

The FAA conducted tests of simulated pressure-tight cargo compartments with cellulosic fuels [23]. The compartment volume was 142 m^3 (5000 ft^3) and the fuel packages consisted of corrugated cardboard boxes filled with excelsior. Halon 1301 concentrations of 3% and 5% were tested. The preburn time was nominally 4 min. At discharge the ventilation of the space was reduced to 2.1 m^3/min (75 ft^3/min). The 1301 was allowed to soak for 120 min. In all tests smoldering combustion continued although the fire was "controlled".

A joint industry program [22] was conducted by DuPont, Fenwal, Cardox and Ansul in the early seventies. Hundreds of tests were run. The specific issues of deep-seated fires and 1301 decomposition products were addressed. The corrosion properties of decomposition products were also evaluated. Table I summarizes the extinguishment data for the cellulosic fuels used in these tests. Table II summarizes the data for polyethylene, polyvinyl chloride and polyester magnetic tape. This test program also included a test series conducted by Cardox in which Halon concentrations below the threshold for extinguishment were used. These tests, summarized in Table III, show the potential generation of large quantities of corrosive decomposition products.

The data presented in Table II for plastic fuels demonstrates that some non-cellulosic fuels, i.e. magnetic tape, in certain geometries (unwound randomly) are not readily extinguished. Other plastics, including polymers widely used in electronic equipment areas (PVC and PE) are easily suppressed with Halon 1301 concentrations on the order of 3% by volume.

This inability of low levels of Halon 1301 to extinguish deep-seated fires, despite extended soak times, could have serious impact on the acceptability of a stand alone halon system for extinguishing fires in a hush house. While Class A combustibles are not generally found in a hush house while a test is in progress, packaging materials such as crates and boxes might be present during test set-up. Since the design concentration is only 6% this system would not be able to extinguish smoldering deep-seated combustion, if it occurred, in any Class A materials which happened to be in the test bay. As Halon 1301 has no vapor securing abilities a re-flash of a fuel spill could occur upon re-opening of the hush house when the halon concentration would rapidly diminish. Although 100% JP-5 has a minimum flash point of 60°C (140°F),

Table I - Summary of Extinguished Data - Cellulosic Fuels
Computer Fire Test Program

Test I.D.	Fuel Package	Enclosure Volume m^3 (ft^3)	Preburn (Sec)	1301 conc. (% Vol)	Soak Time (min)	Results	Post-Extinguishment Atmosphere Peak Value (ppm) HF	HBr
A9	paper tape & shredded paper	49 (1729)	197	5.1	10	not extinguished	11.9	18.2
A10	paper tape & shredded paper		105	5.1	10	not extinguished	12.0	16.2
A11	Stacked printer paper		552	5.1	10	extinguished at 2.0 minutes after discharge	12.0	13.2
A15	Random cellulosics cards, paper, & punch tape, 4 lbs total		361	5.1	30	not extinguished	12.0	26.2
A16	"		199	5.1	30	not extinguished	18.0	26.2
A18	"		114	5.1	30	not extinguished	24	3.5
A24	"		306	5.1	30	not extinguished	33.0	26.3
A25	"		306	11.8	30	extinguished (20 min)	15.4	6.4
A26	"		265	21.0	30	extinguished (1 min)	6.8	1.7
						freeburn	35.0	44.3

Table II - Summary of Extinguishment Data - Non Cellulosic Polymers
Computer Fire Test Program

Test I.D.	Fuel Package	Enclosure Volume m^3 (ft^3)	Preburn (sec)	1301 conc. (% Vol)	Soak Time (min)	Results	Post-extinguished atmosphere peak value (ppm) HF	HBr
F13	Polyester base magnetic tape	43 (1536)	60	2	1	not extinguished	23.7	3.0
F14	Loose basket 732m (2400 ft)	"	60	3	10	not extinguished	23.7	3.0
F15	"	"	60	3	10	not extinguished	22.6	8.9
F16	"	"	30	5	10	extinguished	2.7	4.5
F17	"	"	60	5	30	not extinguished	43.0	11.0
F18	"	"	75	6	30	not extinguished	179.2	18.3
F22	"	"	90	10	10	extinguished	5.9	27.1
F13	Polystyrene tape reels		60	2	1	questionable		
F14	"		60	3	10	extinguished		
F15	"		60	3	10	extinguished		
F16	"		30	5	10	extinguished		
F17	"		90	5	30	extinguished		
F18	"		75	6	30	extinguished		
F19	"		90	3	30	extinguished	40.9	41.8
F20	"		90	3	30	extinguished	26.0	27.1
F21	"		90	3	30	extinguished	18.3	56.5
F23	"		90	3	30	extinguished	71.1	56.5
Kss-7283	5 lbs PVC tubing		120	2.6	1	extinguished		
D2	"		120	5	28	extinguished		
D3	"		300	5	25	extinguished		
D4	"		120	5	28	extinguished		
D5	"		300	5	25	extinguished		

Table III - Corrosive Product Generation Tests
(Intentional Sub-Threshold 1301 Concentration)

Test	Fuel Package Description	Preburn	Halon 1301 (% Vol)	Peak Values (ppm) HF	HBr
7	low density cellulosic fiberboard 0.3 m^2 ($3ft^2$)		10	2407	110
8	"		20	2831	760
9	"		freeburn	43	87
10	"		5	1628	912
11	258 cm^2 (40 in^2)		freeburn	13	13
12	"		(35% CO_2)	10	8
14	"		5	139	94
15	"		10	326	147
3	cardboard 0.3m^2 ($3ft^2$)		10	921	72
4	"		(36% CO_2)	33	107
5	"		10	1416	1229
19	181 cm^2 (28 in^2)		10	1076	276
6	isopropol		2	33	130
17	ethanol 100cc		freeburn	9	42
18	ethanol 300cc alcohol (60cc)		2	3256	372

a 90-10 mixture with JP-4 would have a flash point of approximately 10°C (50°F). This possible problem is further compounded by the fact that heated surfaces could still be present adjacent to the fuel pool since Halon 1301 has little or no cooling effect for heated objects. Thus sufficient vapors for ignition (by the deep-seated fires) could be generated from even 100% JP-5 by metal surfaces with temperatures well above ambient.

Fires involving flammable liquids are not characterized by the problem of deep-seated fires. Although they could cause deep-seated fires in adjacent Class A materials, they are readily extinguished if the proper concentration of Halon 1301 is applied rapidly (10 s or less).

As stated previously hundreds of tests were conducted on various liquid and gaseous fuels in the early seventies and the results incorporated in NFPA 12A. The tests were of two types, static and dynamic. The dynamic tests [24-28] were tests in which the extinguishing agent (Halon 1301, Halon 1211, or CO_2) was added to the airstream which passed by, and supplied oxygen to a flame. (The flame was from burning of the various liquids and gases tested.) The combustion products were not recirculated in any way. The percentage of agent in the air stream was slowly increased until the flame was extinguished. The value obtained was labeled as the threshold extinguishment value for the agent and fuel combination. These values were utilized in the governing NFPA Standards, 12A and 12B, after increasing them by 10% as a safety factor.

Static tests [29-32], on the other hand, did feature recirculation of the exhaust gases, or the absence of any ventilation at all in some of the larger scale tests. These tests were undertaken to validate the dynamic tests which were conducted in far greater quantity (as they were so inexpensive to run by comparison). The static tests were in general agreement with the dynamic tests although the values obtained were slightly lower. This reflects the part the reduced levels of oxygen, due to combustion, would play in speeding extinguishment in these more realistic tests.

Based on the results cited it appears that a rapid (10 s) discharge of Halon 1301, building up to and maintaining a concentration of 6%, would extinguish any fire in the test bay involving flammable liquids or electrical cabling. Flaming combustion in cellulosic materials would also cease, although char burning could continue if the material's geometry and pre-burn time allowed a deep-seated fire to form.

Disregarding the question of deep-seated fires, the ability to achieve and maintain the required halon concentration in the hush house is a major issue. Also of concern is the toxicity of the agent and the lack of available data on the corrosion effects which can be expected in the fire scenarios envisioned in the hush house.

The Navy "standard" hush house, as designed now, cannot incorporate a halon extinguishing system, since there is no provision for sealing every opening to the exterior (as would be required to achieve and hold the required 6% concentration of Halon 1301). The Air Force design does permit sealing of openings through the provision of electric motor driven rolling shutters over each of the ten ventilation openings as well as the entrance to the augmenter tube. Personnel doors are not equipped with automatic closers, but are closed during testing, and are provided with gaskets to ensure an effective seal.

Improper sealing of all openings is one of the major causes of halon system failures, as discussed below. This problem is of even more concern with the Air Force hush house design as the number of openings which must be sealed at the time of agent discharge is much higher than those found in the average computer room. Personnel doors can be damaged or blocked open in the hasty evacuation of the test bay at the time of a major fire. Field inspections by fire protection engineers often identify damage to the tracks of rolling steel fire doors similar to the doors being used to shut off the ventilation openings. The use of electric motors, rather than gravity, to close these doors raises the possibility of a power failure at the same time as a major fire causing a system failure. It is also not known whether these doors would close fully despite a significant pressure differential caused either by a major fire or inability (or failure) to shut down the aircraft engines.

Toxicity of the thermal decomposition products of Halon 1301 is a major concern. The major compounds of concern are HF, HBr, and elemental bromine, all of which can cause significant injury to the human respiratory system in relatively low concentrations. As discussed in detail below, the levels of these toxins produced is very low if the fire is extinguished early (while it is still small) and the agent is applied quickly, in the required concentration. However if the pre-burn is extensive and the fire size is large, or deep-seated burning has been established, then the amount of these materials produced could be quite large. It is unknown what levels of these materials would be produced by engine ingestion of Halon 1301.

The potential for the development of lethal, or at least debilitating, concentrations of HF, HBr, and Br_2, in any halon protected space necessitate evacuation before the agent is discharged. This generally results in the inclusion of a time delay of at least 30 s above the delay in system actuation by either manual or automatic means. This means that the 20 s extinguishment criterion would not be met and the fire could become quite large. The threshold of aircraft damage will therefore be approached, if not exceeded, depending on the exact scenario.

Another concern in relying on a halon only protection scheme is the ability of the aircraft handler to escape. If the initiating event is a fuel spill, from whatever source, under the aircraft, the handler is likely to be trapped in the aircraft. Once the halon system was discharged the handler would be exposed to the potentially high levels of toxic gases. If the extinguishing system were to fail he would have no means of escape at all.

While extensive corrosion data is available, as reported by Jensen [33], most of it is not applicable to the fire scenarios developed for this evaluation. None of the test fires that were extinguished were of the magnitude of the pool fire which could develop in the hush house. In addition, no corrosion studies have been identified regarding the impact of halon agent ingestion into an aircraft engine.

More detail on all these concerns is presented in the analysis below. This analysis is based on the sole use of Halon 1301 to protect the test bay in the same manner as the standard Air Force hush house. The design concentration is assumed to be six percent. The system can only be activated manually, in the control room. There is no automatic actuation, and the building has no detection system. A time delay of 40-45 s is incorporated to allow for evacuation and damper closure however the system can be manually actuated at any time. Electric motor driven doors (dampers) are provided for the ventilation openings and augmenter tube. Personnel doors are not equipped with automatic closers. Soak time is assumed to be 30 minutes.

Extinguishment Time

Numerous large scale fire tests involving mainly computer rooms, but also some flammable liquid hazards, have shown that all flaming combustion will cease after completion of the normal 10 s agent discharge period. However, unless the concentration significantly exceeds the anticipated 6% level, smoldering combustion may continue if a deep-seated fire is established before agent discharge. Tests by the FAA

[23] show that this smoldering combustion could continue despite a soak time of 120 min.

When the 40-45 s time delay, plus an approximate 5 second delay for manual actuation, is added to the 10 s discharge time, the time from ignition to suppression is approximately 60 s. This is beyond the specified 20 s maximum from detection to extinguishment. This is also dangerously close to the time required for aircraft skin damage if the initial fire is fairly large and is located beneath the aircraft. Damage will also almost certainly occur if access panels on the aircraft are open.

Reignition Prevention

The maintenance of the concentration of Halon 1301 at six percent for 30 min will prevent reignition for this same time period. This applies, however, only to flaming combustion. Smoldering combustion could continue throughout this period.

Halon does not have any appreciable cooling effects therefore heated surfaces could remain hot throughout most, if not all, the soak period. As the surface of a fuel spill is not secured in any way, reignition could occur after halon dissipation due to heated surfaces or electric arcs. While floor drains would remove a majority of the fuel spilled, residual fuel could remain and could be augmented by a continuing fuel spill.

Self-Contained System

A halon extinguishing system is essentially self-contained in the sense necessary for forward base deployment. While the detection and actuation systems require an electrical input, they would be equipped with battery back-up. These batteries would be sufficient to power the systems during brief (24 hr or less) power outages. The power to close the ventilation opening doors would not be supplied by these same batteries and unless some other source, such as a standby generator, were provided, the system would not function properly during a power outage.

Low Risk of Failure

Very limited data is available on the reliability of installed Halon 1301 total flooding systems. A qualitative sense of the reliability of such systems can be obtained through an examination of pre-acceptance discharge test results. Ford [34] reports on 307 Halon concentration tests performed by Dupont in support of system designers and installers. Of these 307 concentration tests over the period

1973 - 1975, a total of 57 (18.6%) failures were reported. The primary reason for these failures was faulty installation; e.g., generally mechanical installation deficiencies, including:

- faulty pipe threading-resulting in pipes being separated by discharge, and

- pipes obstructed with construction debris.

One would also expect some failures to result from faults in detection systems, ventilation system interlocks, and system actuation mechanisms. No such failures are apparent in the very brief report cited above.

Another class of reliability problems associated with Halon systems is that of accidental agent discharge. The Department of Energy [35] reports 8 accidental discharges in the period 1966 to 1983 and a total of 3 fires extinguished with Halon 1301 systems. As of 1982 the Department of Energy had a total of 101 systems installed. Most of these systems were in trailer installations. Sixty percent of these systems incorporate cross-zoned smoke detection systems, with the balance actuated by heat detectors. The 8 accidental discharges are due to three reasons. Four of the accidents were due to detectors sensing smoke not due to a fire (overheated motors, dust on coils, welding vapors, etc). The corresponding problem for heat detectors would be a response to a sudden change in the temperature of the protected area, e.g. the doors of an air conditioned hangar are suddenly opened on a summer day. Two were due to faults in the control panel circuits, and one caused by improper maintenance of a manual actuating device.

A compilation of data from unknown sources, provided by DOE [35] indicates a failure rate of 62% in the acceptance tests of total flooding Halon 1301 systems.

Presumably, installation errors found during system checkout and acceptance testing can be corrected, improving the "on demand" reliability of an accepted system. This cannot be confirmed from the available experience data.

A review of the National Fire Protection Association (NFPA) Fire Incident Data Organization (FIDO) between 1971 and 1983 by the NFPA Fire Analysis Division identified 29 incidents involving halon systems [36]. FIDO is not a comprehensive national fire incident data base, hence these results are by no means comprehensive. The results are illustrative in that several major trends, previously suspected, are consistently illustrated.

Six of the 19 fires reported were successfully extinguished. Four incidents occurred outside the area protected causing extensive losses to the spaces protected by Halon systems. Six incidents were outright failures of the halon system to operate, two of which were due to explosions which initiated the fires, the other four due to operational and maintenance problems.

There are two unique incidents which illustrate additional problems. One was a shipyard fire, where manual actuation of the 1301 system caused the firefighting team to back out, interfering with firefighting efforts. It is not clear from the report what exactly was the cause of interference. The second unusual incident reported was a short circuit induced fire at an electronics equipment facility, the fire was reported to be too small to actuate a detector and thus the installed Halon 1301 system was not discharged. This small fire resulted in a loss of a particularly valuable memory board ($100,000).

These widespread, diverse and incomplete data indicate that the reliability of even properly designed Halon 1301 systems is inadequate. The primary reasons for system failures are improper maintenance and operation. A second important conclusion is that a major source of fire-induced damage to Halon protected spaces is from fires started <u>outside</u> of a protected area and subsequently exposing the space. This is of concern in the hush house for areas such as the control room. A third observation is that systems actuated by smoke detection systems will result in a fairly large number of accidental discharges; however use of heat detectors for actuation in the hush house eliminates or vastly reduces the likelihood of this potential problem, but slows detection time significantly.

While the problems associated with poor installation and false detection system actuation can presumably be overcome there still remains significant potential problems with regard to sealing of all openings in the test bay. As stated before field inspections of rolling steel fire doors more often than not reveal problems with these installations. Tracks are often bent or otherwise damaged by mechanical impact or are fouled with dirt and other debris. As these doors are installed in ventilation openings a buildup of dirt, lint, etc. is only to be expected.

Frequent inspection could head off some of these problems, but one or more of these doors could be blocked open at any time simply because a piece of equipment is inadvertently placed in the opening. While this problem could also probably be reduced by a pre-test inspection, the loss of power to any of the motors closing these doors would likely reduce the halon concentration below the level required to provide successful extinguishment. Whether through loss of normal power or through damage from a catastrophic engine failure, this possibility is not too remote.

Another scenario involves opening of the hangar doors. These doors must be opened to admit a fuel truck or fuel hoses when hot refuelling of an aircraft undergoing testing is required. Although this is not now normally done, it is still permitted by current procedure. A fire could occur when the fuel truck or hose is blocking open the hangar door, thus negating the protection provided by the halon system. Obviously using a pantograph, supplied by a fueler outside the building, would eliminate this problem.

Finally, it is unknown whether these types of doors would experience any difficulty in closing if a pressure differential were to exist between the inside and outside of the hush house. Such a pressure differential could occur either as a result of the fire itself or from inability, or failure, to shut off the aircraft engines. Also, in the event of a runaway engine and simultaneous fire, it is unlikely the augmenter tube door (damper) could survive the effects of the direct impingement of the engine exhaust, especially in the afterburner mode, for any length of time.

Personnel doors are also a common cause of concentration test failures. Improperly latched doors can blow open under the halon discharge pressure. Missing or ill-fitted gasket materials can permit significant leakage past the doors since the protected area is at a higher pressure relative to the exterior. Finally, in an actual emergency evacuation it is not difficult to envision these doors, typically not equipped with closers, being left open in the hush house. If one of these doors is open during the discharge period, enough agent could be lost to prevent achieving the design concentration even if it is closed immediately afterward.

Toxicity

Table IV summarizes the approximate lethal concentration data for 15 minute exposures to typical Halon 1301 decomposition products. The most hazardous material is phosgene, or carbonyl chloride. It is questionable, however, whether lethal concentrations of this material would be generated by Halon 1301 discharged into a fire area.

Table IV - Approximate Lethal Concentrations for Predominant Halon 1301 and Halon 1211 Decomposition Products

Compound	ALC for 15 min Exposure, ppm by Volume in Air	Dangerous concentrations, ppm by Volume in Air*
Hydrogen Fluoride, HF	2500	50-350
Hydrogen Bromide, HBr	4750	-
Hydrogen Chloride, HCl	-	-
Bromine, Br_2	550	-
Chlorine, Cl_2	-	50
Carbonyl Fluoride, COF_2	1500	-
Carbonyl Chloride, $COCl_2$	100-150	-
Carbonyl Bromide, $COBr_2$	-	-

*Source: Sax, N. Irving: Dangerous Properties of Industrial Materials.

Hill [37] summarizes the effects of hydrogen fluoride on humans at various concentrations. At concentrations as low as 32 ppm, irritation of the eyes and nose occurs. At 60 ppm irritation of the respiratory tract occurs after 60 seconds. At concentrations of HF of 120 ppm, irritation of the conjunctival and respiratory tracts is tolerable for only 60 seconds. Concentrations between 50 and 100 ppm are considered dangerous to life after a several minute exposure. The highly irritant nature of the halogen acids is somewhat of a positive feature. Generally, atmospheres containing HF are so irritating that personnel are forced to evacuate, if possible, before serious health risk is incurred.

Decomposition product data clearly indicate that life threatening concentrations of HF are possible, and in fact, likely. HF concentrations of 300 ppm are typically measured in full scale tests [38,39].

HF and HBr are not the only decomposition products of Halon 1301. Table V summarizes the major products. It appears that for design and analysis purposes, however, the toxic threat of decomposed 1301 is well characterized by the halogen acids produced, particularly HF. While it is possible that some very toxic and insensible (non-irritating) product of decomposition may be formed in certain situations posing a much more hazardous situation, none of the literature indicates the likelihood of such a situation.

Table V - Typical Decomposition Products of Various Halons

Decomposition Products	Halon 1301	Halon 1211	Halon 2402
*halogen acids	(HF)	(HF)	(HF)
		(HBr)	
	(HBr)	(HCl)	(HBr)
**free halogens	(Br_2)	(Br_2)	(Br_2)
		(Cl_2)	
***carbonyl halides	($COBr_2$)	(COBr)	($COBr_2$)
		(COF_2)	
	(COF_2)	($COCl_2$)	(COF_2)

*(HF) Hydrogen Fluoride
*(HBr) Hydrogen Bromide
*(HCl) Hydrogen Chloride
*(Br_2) Bromine
**(Cl_2) Chlorine
***(COF_2) Carbonyl Fluoride
***($COCl_2$) Carbonyl Chloride
***($COBr_2$) Carbonyl Bromide

The major finding relative to the toxicity of decomposed Halon 1301 is that unprotected personnel must be evacuated from the space prior to agent discharge, and that in order for personnel to remain in the space, full protective equipment must be worn. This includes full-face respiratory protection, as well as exposed skin protection. Another toxicity concern is the concentration of these products in the discharge from the augmenter tube exhaust stack. No data is available on ingestion of halon by an operating engine on which to base an estimate of relative concentration in the exhaust. These numbers are needed in order to calculate the levels back at ground level exposing adjacent buildings, which in some cases includes military housing.

Corrosivity

The rate of production, and total quantity of, corrosive and toxic by-products produced during extinction of flames, or surface oxidation, by induced Halon 1301 concentrations is affected by many variables. Any variable which alters the behavior of either flames or surface oxidation fires will in general affect the rate of decomposition of 1301. In addition, the time at which the agent is discharged, the rate at which it is discharged and the concentration of halon gas will all have important effects on the production. Test results indicate the following trends:

1. larger fires produce higher temperatures and thus larger quantities of decomposition products,

2. long discharge durations increase quantities of decomposition products, and

3. lower 1301 concentrations (above threshold for extinguishment) produce larger quantities of decomposition products.

Little can be said relative to the yield of decomposition products. That is, the quantity produced vs. the size of the fire, although this is a typical way to assess the production of gases due to the combustion of materials.

Tests conducted by NRL [40] on full scale simulated machinery space fires are particularly notable due to the large concentrations of HF and HBr recorded. The fuel source was Marine Diesel Fuel (DFM) in a bilge type of situation. The space tested was 9.1 m x 10.7 m (30 ft x 35 ft) in area with a 6.7 m (22 ft) high ceiling. The bilge then represented a pool fire of DFM with a maximum size of 97.5 m^2 (1050 ft^2). The design concentration of 5% Halon 1301 was discharged within 10 seconds following a 50 second pre-burn. All of these parameters are well within normal design ranges. Exceptional care was taken in the gas sampling and analysis procedures which is typically not the case for full scale "demonstration" fires using Halon 1301.

Peak HF concentrations varied between 2400 - 6400 ppm. The HBr concentrations were much lower than the HF values, whereas the authors believe the values should be comparable. One partial explanation is offered for the greater than factor of 10 differences noted. As high as the HF values were, the authors state them to be minimum values, due to depletion of HF and HBr by reaction with sampling line materials. Therefore the HBr could have reacted more vigorously with the sampling line materials.

Another interesting facet of these tests was the effect of ventilation. In one test series natural ventilation was provided through hatches and portholes. These tests resulted in more intense fires and HF concentrations 10 times those measured when the hatches and portholes were secured. The openings, while allowing a more intense fire, simultaneously reduce the concentration of 1301. No Halon 1301 measurements were reported. Carhart [41], in correspondence to NAVSEA in

1979, reports that measured concentrations of Halon during the fire tests were slightly higher than the 5.9% design concentration, due to the elevated space temperature. Since the fires were extinguished on the order of 8 seconds, and the peak concentrations of HF were measured 20 seconds after ignition, it is not clear that 1301 depletion due to vent openings explains the high HF concentration measured. It has been shown in other tests that reductions in 1301 concentration near the threshold extinguishment value will result in increased HF concentration [22].

A series of 15 cm x 25 cm (6 in x 10 in) pan fires in a 1.7 m ($60 ft^3$) chamber were run using an infrared absorption measurement technique for HF and HBr to test the postulate that HF and HBr concentrations should be approximately the same [42]. For three fuels reported, the largest difference in peak values was for methanol where an HF concentration of 1200 ppm was measured against an HBr concentration of 600 ppm. Perhaps more importantly, the authors noted an order of magnitude decrease in measured HF concentration when the HF was sampled through a "short" metal tube as opposed to a Teflon tube. This confirms suspicions that the gas sampling techniques used for most of the full scale tests reported in the literature are suspect.

Ford [43] has presented data on Heptane fuel fires in a fixed enclosure volume of 48 m^3 (1695 ft^3) and varying pool fire sizes. These data are summarized in Table VI. Two

Table VI - Halon 1301 Decomposition Produced by n-Heptane Fires
Enclosure Volume: 48 m^3 (1695 ft^3)
Halon 1301 concentration: 4% by volume

Fuel Surface Area Per Unit Enclosure Volume ft^2 Per ft^3	Flame Extinction Time, Seconds	Total Decomposition Products, ppm
0.06	11.5-15.4	4.5-5.6
0.06	7.1-7.6	2.8-4.2
0.06	4.0-4.8	3.3-4.5
0.6	20-37	94-289
0.6	11.5-13.5	64-284
0.6	4.7-6.7	11.5-169
6.0	20-22	2252-2304
6.0	13.0-16.3	1292-1590
6.0	5.2-10.0	358-778

trends are obvious. As the size of the Heptane pool increases, the total production of decomposition products increases and extended extinguishing times result in a greater concentration of decomposition products. The value of the correlation is questionable, as they would seem intuitive. For example, for a fixed fire size, one expects a higher concentration of products if the volume of the space is reduced.

Sheehan [44] reports on the results of 6 tests done for the Coast Guard on shipboard machinery space fires. Of relevance is the low concentration of HF and HBr measured, even under long pre-burns of the Class B fuels (10-20 min). In all tests except one, HF concentrations remained below 13 ppm, and HBr less than 3 ppm. The last test which required a longer agent discharge time resulted in a measured HF concentration of 230 ppm. All of the Class B machinery space fires were extinguished with Halon 1301 concentrations of 3.4 to 6% by volume.

McDaniel [45] conducted fire tests in the machinery spaces of a surface ship. Experimental fires involved diesel fuel in a 2832 m^3 (100,000 ft^3) space, with Halon 1301 concentrations and discharge times being variables. All discharge times below 28 seconds produced HF and HBr concentrations of 12 ppm and 3 ppm respectively. A discharge time of 28 seconds produced HF and HBr concentrations of 230 ppm and 68 ppm respectively.

These data indicate that even for surface burning fires, the production of corrosive gases increases with pre-burn time. The data for test F18, show a 179 ppm HF concentration for a fire that was successfully extinguished under typical NFPA 12A design guidelines. This is a relatively high exposure; 5 to 6 times higher than most of the other data. This provides at least cause for concern relative to the sample gathering and analysis techniques. The HF and HBr concentration data also indicate that even with relatively small fires that are quickly extinguished, it is necessary to evacuate a space prior to the discharge of the agent.

The highest production rates of HF and HBr were measured during liquid pool fire tests when the pool area was a large fraction of the room floor area.

In tests where electronic and electrical components were exposed to the post fire extinguishing atmosphere containing HF and HBr, no deleterious effects on the equipment were noted. However in most of these tests, the post fire environment of HF and HBr usually did not exceed 10 ppm. Data is needed for exposure of electronic equipment to higher levels of HF and HBr before the corrosive effects of halon decomposition products can be fully quantified/understood.

No data has been located which reports the corrosive effects, if any, on aircraft engines which ingest halon, either in a fire situation or in normal operation. These data are essential to a proper evaluation of the use of Halon 1301 (or 1211) in the hush house. Musick and Williams [46] report on a test by Grotsky where a diesel engine ingested an atmosphere containing 5% Halon 1301. "A bright orange smoke 'which could have been bromine gas' appeared in the exhaust." No damage was apparent on the engine parts and the halogen acids appeared to have removed most of the normal carbon buildup. Acidity of the lube oil did increase, however, during the test, and this could cause a problem in aircraft engines.

<u>Personnel Egress</u>

As discussed above under the heading of toxicity, Halon 1301 at concentrations less than eight percent does not cause adverse effects in humans in brief exposures. Therefore the agent would not normally present a hazard to personnel exiting the area after an inadvertent discharge. However, if the aircraft being tested is operating, the engine(s) will ingest the halon and cause it to break down into its toxic by-products, HF, HBr and Br_2. While the majority of the tainted engine exhaust would exit into the augmenter tube, eddy currents may carry some of the toxins into the test bay. Even low levels of these compounds could cause severe respiratory irritation and possibly affect the judgement of exposed personnel. This entire scenario is fortunately highly unlikely as it would require the sudden release of the agent, without the initial evacuation period. If the system were inadvertently actuated any other way, e.g. detector malfunction, test personnel would be able to manually abort the halon system discharge and reset the control panel.

Personnel egress should not be affected by the halon system in the event of a fire because the 40-45 s time delay would allow all personnel (who are able) to exit the building before agent is discharged. The aircraft handler, located in the cockpit, may be unable to leave if the initial fire is large and located under the aircraft fuselage. Without the presence of an underwing AFFF system, or large semi-portable AFFF extinguishers, other test personnel have no way of opening and maintaining an evacuation path. Use of the large semi-portable AFFF extinguisher to rescue the handler would necessarily delay actuation of the halon system as all personnel not equipped with proper protective clothing and respiratory protection must be evacuated before the halon is discharged. This very necessary delay would almost certainly increase the extinguishment time, already calculated as approximately 60 s, beyond the point where the aircraft can be expected to emerge unscathed.

It is also appropriate to discuss the hazards facing fire fighters who enter the hush house at the end of the 30 min soak time. As explained above, halon does not secure the fuel surface and reflash could conceivably occur immediately upon loss of the required 6% halon concentration. While the fire fighters would be equipped with AFFF hose lines and should therefore be able to avoid injury, this second fire could damage, or further damage, the aircraft. AFFF overspray into the engines becomes a possibility for the first time and could result in the need for costly engine overhaul despite the absence of other damage.

Cost Effectiveness

Buckley [8] cites a total cost of about $65,000 for installation of a halon system in the Air Force hush house design. This does not include the cost of the 11 sliding doors to shut off the ventilation openings, which would not be required if halon protection were not utilized. These 11 doors were estimated to cost a total of $45,450. It should be noted that the standard Navy design is not set up to permit sealing off of the test bay by doors such as these.

If, as recommended below, an AFFF *underwing system* is added, to allow the aircraft handler to escape, the cost would be about $30,000 for fixed AFFF nozzles and piping, an AFFF storage tank, and the proportioner. Flame detection would cost $20,000. (Provision of an overhead AFFF deluge system would cost an additional $50,000.)

Fire Scenarios

Under Frame Fire

The Halon 1301 would extinguish this fire by the end of the 10 s discharge period. As calculated before, this could be as much as 50 s after fire ignition (10 s for detection, 30 s for evacuation, plus 10 s for discharge). This is very close to the point of aircraft damage as calculated by Geyer [13] and Krasner [14]. This is probably past the point of damage when access panels are open during testing, as is often the case. The under frame fire presents a case where an even greater delay is likely. This is because the aircraft handler may be trapped in the cockpit, requiring other test personnel to cut a rescue path to him with the semi-portable AFFF extinguisher which is located in the test bay. This will delay agent application since discharge should not begin until all personnel have evacuated the protected area.

Major Engine Fire

Once the specified 6% concentration of Halon 1301 has been achieved (and maintained) the engine fire will be extinguished. However, if the 6% concentration is lost before the heated surfaces in the nacelle have cooled, reignition will occur immediately. As discussed previously in the analysis of the AFFF system, the aircraft handler will have attempted numerous strategies for extinguishing an engine fire, assuming he has control over fuel flow to the engine. These steps include actuation of the built-in halon extinguishing system for the engine nacelle, when provided.

The recommendation regarding connection of an auxiliary halon supply to the engine fire suppression system which was previously detailed (under the AFFF system analysis) would still have merit when considering total flooding halon as the primary fire protection system. Rather than discharging the entire halon volume to achieve a 6% concentration throughout the test bay, a much smaller quantity could be discharged repeatedly (or continuously) into the engine nacelle until the heated surfaces had cooled sufficiently to prevent reignition. Obviously the total halon volume would have to be increased to allow for attempted extinguishment of an engine fire while still retaining enough agent to achieve a total flooding concentration of 6%, should this be necessary.

Engine Disintegration Fire

This fire is virtually no different from the major engine fire just discussed, with respect to the performance of a Halon 1301 total flooding system. The ability to connect the hush house halon supply to the nacelle extinguishing system through an external pipe or tube would again have merit, although the ability to extinguish an engine fire may be reduced due to mechanical damage to the nacelle by thrown engine parts. For this reason the full complement of halon required for total flooding must be maintained in reserve so that the entire test bay could be flooded, if necessary, to extinguish the engine fire.

High Volume Pool Fire

Tests conducted by Sheehan [44] and Kay [47] show the ability of a Halon 1301 total flooding system to extinguish flammable liquid pool fires. Some of these tests featured extensive (10-20 min) pre-burn periods as well as continuing running fuel (spill) fires in addition to the pool fires.

Early loss of the required concentration could result in immediate reignition since halon does not cool hot surfaces during discharge. Since halon also has no vapor securing ability, reignition could also occur upon loss of halon concentration if ignition sources, such as electric arcs or smoldering combustion in cellulosic materials, are still present.

Runaway Engine

The runaway engine scenario presents potential difficulties in terms of achieving sealing of the test bay prior to halon discharge. Continued operation of the engine will result in significant pressure differentials across the ventilation openings. This differential could slow or stop the movement of the rolling steel doors as they approach the fully closed position. Failure of any of the doors to close before discharge would result in loss of a significant amount of halon, possibly preventing even momentary fire extinguishment. Even if the fire is small, the operating engine will break down large quantities of the agent, until the engine's flames are extinguished, producing high levels of toxic and corrosive compounds. It is also possible that a runaway engine could break down sufficient quantities of the halon to prevent extinguishment.

Electrical Fire

The total flooding halon system will extinguish any internal electrical fires which occur independently, or as a result of, a simultaneous pool fire below the aircraft. Test work cited above shows that grouped electrical cables do not produce deep-seated fires, even with long pre-burn periods.

<u>System Effectiveness</u>

The halon total flooding system would appear to be much more subject to human failures, as well as equipment failures, which could result in non-performance of the system in a fire situation, than the AFFF system. Utmost care must be taken in the design, construction, testing, and maintenance of the system to ensure it will operate properly. The construction drawings and specifications must be very detailed in order to ensure the contractor has no room for having to make judgement calls as to what is intended.

Follow-up inspection, testing, and maintenance is even more important for the halon system than the AFFF system. Failure of even one small item could prevent the system from achieving and/or maintaining the required 6% concentration. Failure of some portion of the AFFF system would only prevent one of the two systems (overhead and underwing) from working or would result in a discharge of water instead of AFFF, therefore providing at least some level of protection.

The first element in ensuring the halon system design is effective is to follow the applicable consensus fire codes published by NFPA. These include:

NFPA 12A, Standard on Halogenated Extinguishing Agent Systems - Halon 1301
NFPA 30, Flammable and Combustible Liquids Code
NFPA 70, National Electric Code
NFPA 72D, Standard for the Installation, Maintenance, and Use of Proprietary Protective Signalling Systems
NFPA 72E, Standard on Automatic Fire Detectors
NFPA 409, Standard on Aircraft Hangar
NFPA 423, Aircraft Engine Test Facility

Halon 1211

The technical data review just presented for halon 1301 is equally applicable to Halon 1211 total flooding systems. The only appreciable difference between the two is the fact that 1211 is more toxic than 1301, in both its pure form and its decomposition products. Required threshold concentrations of 1211 for extinguishment are slightly higher than those for 1301 but the 6% design concentration is more than adequate for either agent for application in the hush house, assuming minimal loss of agent.

Essentially the two agents are equally suited for the hush house total flooding system. Cylinders of the two agents would be interchangeable except for the fact that 1211's density is slightly lower and therefore more agent would be required to achieve the same 6% concentration. No different hardware is required for the use of 1211 instead of 1301.

Halon 1301 is far and away the more common agent used for total flooding systems in the U.S. and our military bases. Therefore, its use should be specified for all hush houses located in the U.S and the Pacific. In Europe, however, 1211 is the predominant agent in total flooding system and specification of its use there may lessen potential supply and refilling problems.

Detection Systems

In the event of a fire in the hush house, the in-place fire protection system must protect personnel, the aircraft and the test facility. Large scale fire testing results indicate that the fire growth rate and severity associated with pool fires can readily result in extremely hazardous conditions [48]. When the fire is beneath the aircraft, damage to the aircraft will occur very rapidly.

To prevent catastrophic impact from fire, the fire protection system must be capable of rapid agent discharge and effective suppression of the incipient fire. A critical element in a fire protection system designed to accomplish this is the fire detection system.

The current detection system featured in the Navy hush house design utilizes heat detectors. While these types of systems have been found to be highly reliable, they have also been found to have significant time delays. These delays are important when considering the rapidity with which military aircraft can be damaged and the potential cost of this damage. This report therefore recommends that rapid response flame detectors be utilized to actuate the underwing AFFF system. These flame detectors are generally designed to operate in either the infrared and/or ultraviolet range of electromagnetic radiation. These three detection schemes; heat, ultraviolet, and infrared, are discussed below.

Critical Detection Requirements

Test results indicate that a hush house fire detection system must meet very rigorous requirements. The system must:

(1) be capable of detecting incipient fires within 3 seconds of ignition,
(2) be capable of distinguishing/discriminating between actual fires and sources of heat energy (e.g. jet exhaust), and
(3) have a relatively low probability of failure ($P(f) < .01$).

Environmental Factors

In identifying candidate methods for fire detection, selected environmental factors require consideration. For example, fuel spill fires result in very rapid fire growth and energy release rates. The direct result of this rapid fire growth rate is exposure of the personnel and aircraft to high energy release rates in a very short time period. In addition, exposure of the aircraft and its fuel tanks enhances the likelihood of a catastrophic event - further jeopardizing the personnel, as well as the facility. Finally, fuel spill fires under the aircraft may be shielded by the aircraft from overhead detection (and suppression) systems.

Hardware/Device Factors

The primary device factors which directly influence the ability of a particular system to meet or exceed the performance requirements are (1) sensitivity, (2) reliability (3) maintainability, and (4) stability [49].

The sensitivity of a particular detection device is generally dependent on its design and the detection mechanism (e.g. heat, flame, smoke, etc.). For example, ionization smoke detectors respond to smoke/aerosol particle sizes in the 0.05-1.0 micrometer diameter range. This particle size is common to many burning fuels, but is particularly prevalent in flaming plastics and Class B fuel oil fires. Flame detectors respond to radiant energy; infrared devices are typically designed to respond in the 0.7-1.4 micrometer light band wavelength, and ultraviolet devices respond in the 0.001-0.4 micrometer band. All burning materials exhibit radiation in these light bands. However, flame detectors (IR and UV) are quicker to respond to flammable liquids and plastics fires, but not as proficient on smoldering cellulosics as other conventional detector modes.

Reliability relates to the ability of the system and its components to remain in proper working condition. The estimate of reliability requires consideration of the design of the device, its application, and environmental influences. Historically (though not quantitatively documented), fixed temperature and rate compensated heat detectors have had the highest reliability, primarily due to simplicity and ruggedness of design. Rate of rise heat detection devices have had slightly lower reliability - attributed to the more delicate nature of the sensing surface and possible failure of the rate of rise function. Products of combustion (smoke) detectors and flame detectors inherently have lower reliability due to the incorporation of electronic components which historically have higher individual failure rates than mechanical devices.

Maintainability varies with design complexity. Thermal devices have no periodic maintenance requirements. Flame and products of combustion detectors require periodic maintenance to assure that the sensing element is in proper working order.

Stability relates to the device's ability to sense fires over extended periods of time with no change in sensitivity. A problem with stability is most common in devices incorporating electronic components.

Fire Signatures

From the instant a fire is initiated, it produces a variety of changes in the environment. These changes can be used for detection provided the signature(s) produce measurable changes in ambient conditions significantly different than normal background variations.

Signatures common to a wide range of burning materials include:

(1) suspended aerosols (solid and liquid particles) in the $5x10^{-4}$ to 10 micrometer range.
(2) combustion gases (e.g. CO and CO_2) which are always generated in combustion processes. Other combustion gases include HCL, HCN, HF, H_2S, NH_3 and nitrogen oxides, but these are all fuel specific and may not always be present in a fire. Oxygen concentrations can also be used as a fire signature since oxygen concentrations are depleted under fire conditions.
(3) Ambient temperature, which increases proportionally to energy release rate, and
(4) Radiant energy; the most common signatures being infrared (IR) and ultraviolet (UV).

It is unlikely that conventional heat, aerosol or combustion gas technology can respond quickly enough to initiate suppression of an underframe pool fire in three seconds. The signature generation rates, and transport times to reach the detector devices can typically result in delays of minutes from ignition to detection. While such delays are acceptable for a wide range of fire scenarios, they are unacceptable in providing very rapid detection of incipient fires.

However, flame detectors respond to both visible and invisible radiant energy - a signature that is released in detectable quantities throughout the course of a fire. The most prevalent signatures are infrared (IR) and ultraviolet (UV), and detection devices are available which respond to these two radiant energy signatures. Typically, state-of-the-art IR or UV detectors can respond within 50 to 100 milliseconds to a 0.1 m^2 (1 ft^2) flame at a distance of 7.6 m (25 ft); this response characteristic is within the range needed to meet the performance requirements for underframe protection.

<u>Heat Detectors</u>

The current hush house designs utilize heat detection systems to actuate the fire extinguishing system. The detectors specified are rate-compensated, fixed temperature detectors. Fenwal Model 27121-20, or equivalent, set to operate at 104°C \ 1°C (220°F \ 1.5°F). The detectors are placed on the 6.7m (22 ft) ceiling on a 6.1 m by 6.1 m (20 ft by 20 ft) spacing pattern. Previously cited data from Fenwal show no reported detector failures despite several years of operation at facilities around the world. False alarms have also never been cited as a common problem in hangars such as the hush house where the interior bay is not provided with HVAC equipment.

Fire test data reported by Breen [3] and others show a time delay of 10-20 s for heat detector operation, even in JP-4 fires ranging from 46 to 84 m^2 (500 to 900 ft^2) in size. While it can be argued that test personnel would actuate the suppression system manually before this time, they may be too busy trying to save their lives, or those of co-workers, to hit the manual actuation station.

Based on a detector response model developed by Alpert [50] and pool burning equations presented by Babrauskas [51] the detectors in the hush house can be calculated to be insensitive, i.e. they will not respond, to JP-5 pool fires smaller than 2 m^2 (21.5 ft^2). A fire this size occurring beneath the aircraft will eventually cause considerable damage if it continues to burn undetected. Use of a more sensitive heat detector (lower temperature rating), or closer detector spacing, would appear to increase the probability of false alarms beyond an acceptable level. The threat of false (unnecessary) actuation has already prompted the staff at more than one hush house to bypass the heat detection system during testing. A high potential for false alarms would be a critical problem with AFFF systems, where there is no built in time delay and abort capability.

These long detection time delays are especially unacceptable in the under frame fire scenario where damage will occur most quickly due to open access panels. This is compounded in the case of the halon system where additional delays of at least 30 s for evacuation and 10 s for agent discharge are unavoidable.

A faster detection system technology must therefore be considered. It is recommended that this fast response system be utilized for actuation of the AFFF underwing system while the existing heat detection system be used to actuate the ceiling level AFFF deluge system. In the case of a halon total flooding system this report still recommends that an AFFF underwing system be provided and that it be actuated by the rapid detection system. The halon system would be activated by the heat detectors. If the halon system were selected for use without the underwing AFFF system then the halon system should be actuated by flame detectors. This would allow immediate evacuation and increase the probability that the halon system could be discharged before the aircraft is damaged by the fire. There is also an inherent risk of false actuation not experienced with the current Air Force manually operated system. This risk, however, has been accepted in the case of the Hardened Aircraft Shelter [48].

Infrared Type Flame Detectors

Infrared (IR) detectors basically consist of a filter and lens system to screen out unwanted wavelengths and focus the incoming radiant energy on a photovoltaic or photoresistive cell that is sensitive to the infrared spectrum. Generally, IR detectors can be designed to respond to the entire IR component of a flame, a specific wavelength within the IR spectrum, or to a flame energy modulation due to inherent "flickering" of the flame itself [52].

While infrared detectors give a significantly faster response than conventional heat or aerosol detectors (e.g. 50-100 milliseconds) their performance can be adversely affected by atmospheric conditions. For example, a broad spectrum infrared detector responds to sunlight, hot surfaces (e.g. engines), reflections, and so forth.

Devices which focus on intense IR radiation spikes associated with flames (e.g. 4.3 micrometer wavelength) due to the production of hot CO_2 have been developed to reduce this problem. Unfortunately, the 4.3 micrometer spike can also be duplicated by extraneous atmospheric influences. Therefore, recent developments in infrared detection have led to dual-range sensing systems, with one sensor designed to detect the 4.3 micrometer spike and the other to detect IR radiation at a different point in the spectrum.

Dual-range infrared detectors are now available which utilize a secondary sensor which responds to higher wavelengths (on the order of 5 to 7 micrometers) than the 4.3 micrometer spike. However, in this range water vapor may actually absorb the signal, resulting in a false alarm. An alternative design has been to select a secondary sensor to respond to IR radiation in the 3.8 micrometer range, which is not characteristic of other, extraneous IR emitters. While such devices can result in substantial reduction in false alarms, they inherently require more time to respond to an incipient fire. The acceptability of this inherent delay must be determined if such devices are to be employed for underframe fire detection in hush house facilities.

A similar concept employs a dual sensor network specifically to screen out solar interference. One sensor is sensitive to solar radiation in the 0.6 to 1.0 micrometer range and is filtered to respond to wavelengths between 2 and

5 micrometers. A signal from the solar sensor can be used to block the output from the fire sensor, giving the device the ability to discriminate against false alarms from solar sources [53].

For many applications, a flame flicker sensor has been employed in infrared detectors to improve reliability. These devices respond to the flicker or flame modulation characteristic of fires. Such devices use frequency-sensitive amplifiers with inputs tuned to respond to an alternating current signal in the flame flicker range of 1.5 to 15 Hz [54]. Flame flicker detectors are typically designed for volume supervision and may use either a fixed or scanning mode. The fixed units continuously observe a conical volume limited by the viewing angle of the lens system and the alarm threshold. The viewing angles normally range from 15° to 170°, and have prescribed viewing distances.

Ultraviolet Type Flame Detector

The ultraviolet component of flame radiation is also used for fire detection. The sensing elements may be solid state (e.g. silicon carbide), or gas-filled tubes in which the gas is ionized by UV radiation and becomes conductive, activating the alarm [55,56]. The operating range of UV detectors is in the 0.17 to 0.30 micrometer range - in this range the devices are relatively insensitive to sunlight, lightning and artificial light. The UV sensors generally are focused to detect radiation in the 1,820 to 2,450 angstrom band which is well below the ultraviolet band for these sources. They are also volume detectors, similar to IR devices, and have viewing angles from 90° or less to 180° [57].

UV detectors are susceptible to spurious signals from non-fire sources other than sunlight or artificial light. Major false alarm problems come from gamma radiation, X-rays and arc welders. To overcome false alarm problems from gamma rays, they are treated as background noise by the UV sensor. While X-rays probably don't represent a significant problem for hush house applications, arc welding could readily be a nuisance. Screens or barriers can be used with some effect to temporarily shield a detector. However, UV radiation is reflected off enclosure surfaces. Therefore, screens would have to be positioned to close off the entire work area.

In addition, UV detectors can penetrate some aerosols such as water vapor, but are screened by oil mists and heavy smoke.

Combined UV/IR Type Flame Detectors

In applications where very rapid detection and very low false alarm rates are desired, UV and IR sensors have been successfully coupled. The combined detector can be used in areas where one or the other sensors would be inappropriate if used alone.

These combined devices behave as a system. That is, they both must sense a fire before responding. Failure of either sensor effectively negates the protection. So, to guard against an unknown failure of one sensor, some systems have self-checking features.

Candidate Underframe Detection Subsystem

The factors considered in selecting the detection subsystem for underframe detection in the hush house facility include:

1. type of fire expected (e.g. visible flame, smoldering)
2. routine activities in the facility
3. air flow, ventilation, facility geometry
4. acceptable delay times
5. general performance requirements

A qualitative assessment of these factors leads to the recommendation that the detection subsystem incorporate flame detection for underframe fire detection. The typical response time for flame detectors (in the millisecond range) when detecting flammable liquid pool fires is far superior to that expected from state-of-the-art heat, smoke and particles of combustion devices. It is unlikely that any of these devices could meet the three second detection criterion.

The advantages to utilizing flame detection include:

1. radiation signature is always present in a fire
2. sensors respond to an incipient fire in fractions of a second
3. the detectors can be installed to monitor specific volumes (e.g. quadrant protection of aircraft underframe) thus hopefully avoiding the afterburner flame as a false alarm source.
4. the detectors can be positioned to overcome the shielding problem associated with overhead heat and smoke detection.
5. reliability can be improved through selection of sensing devices.

There are two important disadvantages in using flame detection. First, false alarms due to spurious signals from the environment or from activities within the facility pose a serious problem. Indiscriminate initiation of the suppression system due to sunlight, lightning, welding or other factors cannot be tolerated. In addition, a flame detector can be shielded from its detection volume due to the aircraft's configuration, or activities where obstructions are placed in the sensor's viewing path. These factors give rise to the possibility of false alarms, and system failure. For underframe detection, it is desirable to achieve a low probability of system failure (on the order of $P(f) < .01$). However, a careful analysis of readily available detectors, and placement of a sufficient number of detectors should overcome both problems. Indeed, recent work by the Air Force [48] has shown that combined UV/IR flame detection can provide both the required sensitivity and the protection required from false alarms (with the exception of afterburner mode engine operations).

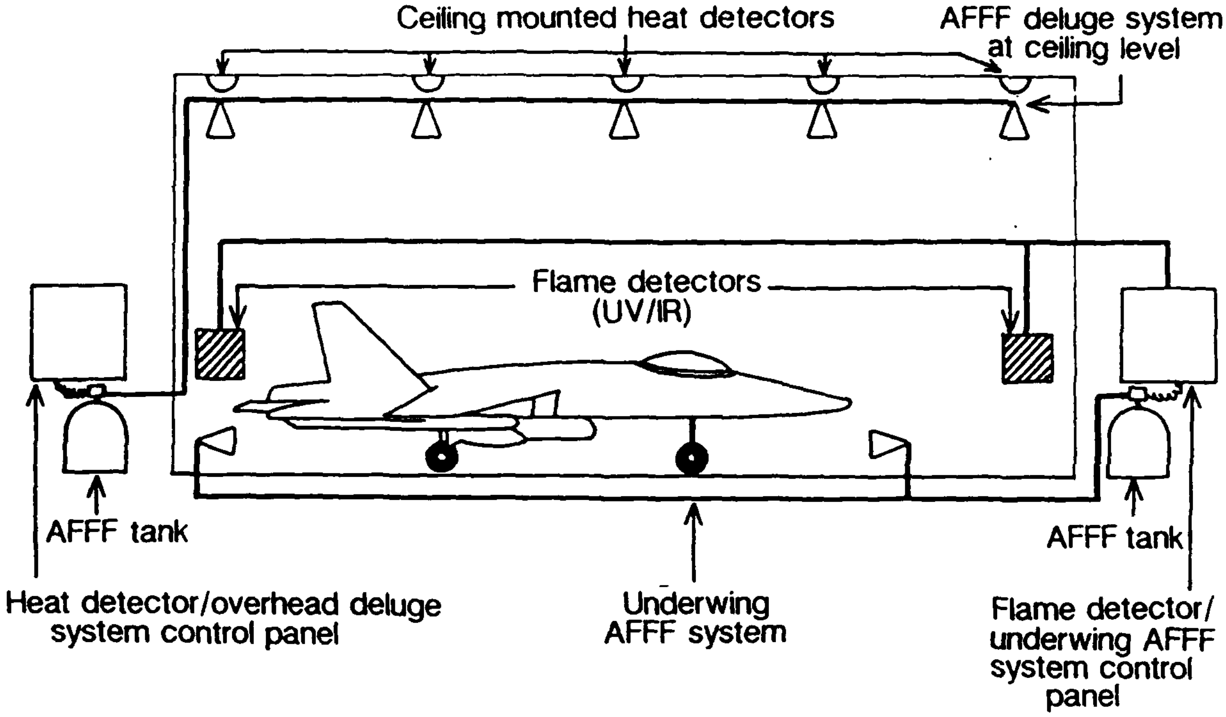
RECOMMENDED CANDIDATE EXTINGUISHING SYSTEMS

AFFF System

Based on the technical data review presented above the most effective extinguishing system is the AFFF system featuring fixed underwing nozzles (nozzles protecting the underwing area, not in the underwing area) activated by flame detectors and an overhead deluge system activated by heat detectors (see Fig. 3). This choice is based on the evaluation criteria as summarized below:

Extinguishment Time - The pre-primed fixed nozzle underwing system should extinguish a pool fire beneath the aircraft within the 20 s criterion. (This is predicted on rapid (35) fire detection, as provided by flame detectors viewing the underwing area.) This is essential in preventing/limiting aircraft damage when access panels are open. Pool fires outside this zone should be extinguished within 1 1/2 to 2 1/2 min by the deluge system. Aircraft engine and electrical fires would not be extinguished, but the AFFF system would cool the airframe. (Engine and electrical fires could be extinguished by use of portable extinguishers in the test bay.)

Reignition Prevention - Reignition prevention will be provided by the foam blanket for 5-7 min after the end of foam application. Additional foam would have to be applied several times to secure the fuel surface for the full 30 min required. The water in the AFFF, however, provides significant cooling of all hot surfaces, as well as penetrating to deep-seated fires in Class A combustibles,



Potential Advantages

- Lowest cost
- Prevents reignition of any pool fires
- Provides airframe cooling
- Best protection for aircraft handler in cockpit

Potential Disadvantages

- Does not extinguish engine/electrical fires
- Possible engine ingestion of AFFF could cause corrossion effects (if AFFF prepared with sea, or brackish, water)

Fig. 3 - AFFF system (both overhead and underwing)

thus significantly decreasing the likelihood of reignition sources being present.

Self-Contained System - The AFFF system could be made self contained by the provision of water tanks and pumps in the hush house design. This additional equipment would cost approximately $150,000, on top of the basic AFFF system cost of $80,000. The Navy, however, is unlikely to construct a new hush house at a facility which does not have an adequate water supply, therefore this additional cost would not be anticipated at most air stations.

Low Risk of Failure - Properly designed and maintained deluge systems have a very low rate of failure as reported in the available literature. The data are very limited in that, generally, only system failures are reported as compared with an unknown number of installations which are functionally without any problem. The proportioning system is also highly reliable and should failure occur, the water-only system would at least provide adequate cooling of the aircraft for small to moderately sized fires. The heat detection system has demonstrated a very low risk of failure. One incident, however, has been reported at NAS Miramar where actuation occurred when test personnel did not feel it was justified. Flame detection systems, however, may experience a significant false alarm problem. This could be partially overcome by switching them to an alarm only mode whenever an actual test is not in progress. Careful selection of flame detector technology is critical to satisfactory performance.

Toxicity - AFFF poses no toxic threat to humans. It can harm marine life if it flows into a waterway in sufficient concentration. It can also damage a biological sewage treatment plant due to its foamability. Both problems can be solved, for the case of a planned discharge (for system testing), by the installation of a metering pit or valve in the floor drain discharge line. (The adverse effects from an emergency (fire) discharge are generally considered acceptable.)

Corrosivity - AFFF prepared with fresh water, as would be the case in most hush house locations, presents no corrosion problems. However, AFFF prepared with salt water is corrosive, primarily because it contains 94% salt water. The possibility of long term corrosion has led NAVAIR to require a complete overhaul of any engine which ingests AFFF which was prepared with salt water [4].

Personnel Egress - AFFF's only effect on personnel egress is to make the floor slippery. By using a shuffling step any able bodied individual should be able to evacuate the test bay without mishap.

Cost Effectiveness - The estimated cost of the recommended AFFF system, including the heat detection system, is $80,000. The flame detection system for the underwing AFFF system has a cost of approximately $20,000. (An additional $150,000 would be required for self-contained systems at locations with an inadequate water supply.)

Fire Scenarios - The AFFF system will extinguish any pool fire scenario. It will not extinguish engine fires or electrical fires. (Such fires could, however, be extinguished with the large volume halon extinguishers provided in the test bay.) The system will cool the fuselage in the event of an engine fire.

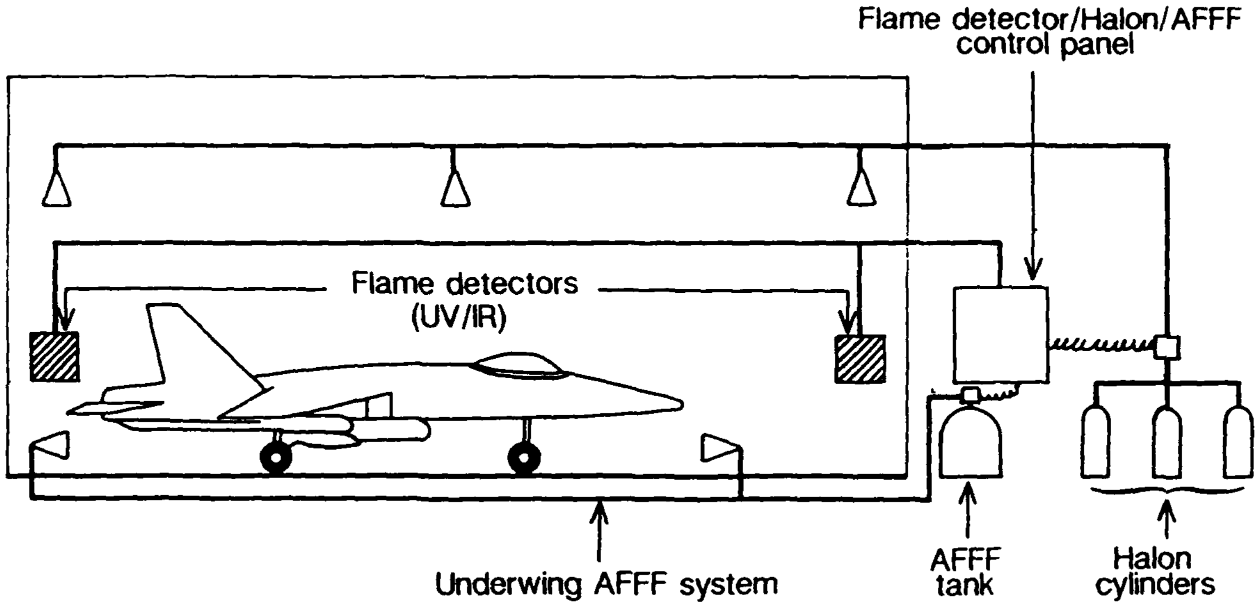
System Effectiveness - The technology behind the heat detection system, deluge system and AFFF proportioner is well understood and highly reliable if properly designed, constructed and maintained.

In summary, the AFFF system provides for immediate (20 sec) extinguishment of the potentially most damaging fire, the underwing pool/spill fire. This system provides protection for the most easily threatened member of the test team, the aircraft handler located in the cockpit. The AFFF system also does not threaten the aircraft handler, or any other occupant of the hush house, with the possible creation of a lethal atmosphere. While the AFFF system will not extinguish an engine fire, and it must be remembered that these fires are more easily (and cheaply) extinguished by operator action or portable extinguishers, it will cool the fuselage.

Halon System With Underwing AFFF System

If remote extinguishment of an engine fire is a driving concern, and the connection of the built-in nacelle extinguishing system to an external agent source is impractical, then total flooding halon (either 1301 or 1211) has a place in the hush house fire protection system package. Use of a halon system, however, does not eliminate the need for AFFF. As a minimum, the underwing AFFF system, with flame detector actuation, must be retained (see Fig. 4). An evaluation of this system, total flooding halon plus underwing AFFF, is given as follows:

Extinguishment Time - The underwing system will extinguish a pool fire below the aircraft in 20 s or less. The halon system will extinguish an engine fire, except a runaway engine, or remote pool fire within 10 s of discharge. However, discharge cannot occur until the hush house has been sealed. If proper sealing does not occur, the fire will



Potential Advantages	Potential Disadvantages
Will extinguish engine/electrical fires	Higher cost
Aircraft handler should be able to exit	Toxicity of Halon
	Corrossivity of Halon
	No cooling of airframe
	Potential reignition of pool fires outside range of underwing AFFF system

Fig. 4 - Halon system with underwing AFFF system

continue to burn, eventually damaging the aircraft as no cooling of the airframe is provided.

Reignition Prevention - The AFFF system will seal the fuel surfaces below the aircraft. The halon system has no cooling nor sealing properties, so that if the halon concentration is lost while ignition sources are present, re-ignition may be instantaneous.

Self-Contained System - The halon system is self-contained. The AFFF system would require a water tank and pump.

Low Risk of Failure - The probability of failure of one of the rolling steel doors would appear to be significantly higher than the specified 0.01 level. In addition, the augmenter tube door could not be expected to function properly in the event of a runaway engine and fire.

Toxicity - Thermal degradation of halon, whether from a fire or engine ingestion, poses a toxic threat to both personnel in the hush house and those down wind of the augmenter tube stack. The magnitude of the threat is unknown since meaningful test data (for this hush house scenario) is not available.

Corrosivity - The halon decomposition products are also corrosive to metals and electronics. It is unknown whether the levels produced would do significant harm to aircraft and/or aircraft engines in the hush house.

Personnel Egress - Provision of the underwing AFFF system will allow all personnel to evacuate before halon discharge.

Cost Effectiveness - This system is not particularly cost effective. The AFFF underwing system is estimated to cost $30,000, plus $20,000 for the flame detection system. (Installation of the remainder of the AFFF system (the deluge system) would only cost an additional $50,000.) The halon total flooding system would cost $110,000. (The $110,000 figure includes the cost of the ventilation closers (doors) in the Air Force design.) This cost figure does not address the difficulty, if not impossibility, of retrofitting a halon system in the Navy hush house design where it will be very difficult to seal the ventilation openings in hush houses of this design. Thus the total cost is a minimum of $160,000.

Fire Scenarios - The provision of a halon total flooding system allows the extinguishment of the engine disintegration fire, major engine fire, and electrical fire scenario, described above, which could not be extinguished by the AFFF system. The deletion of the AFFF deluge system, combined with the reliability problems with the halon system, present the possibility of a pool/spill fire remote from the aircraft continuing to burn with eventual damage to the aircraft.

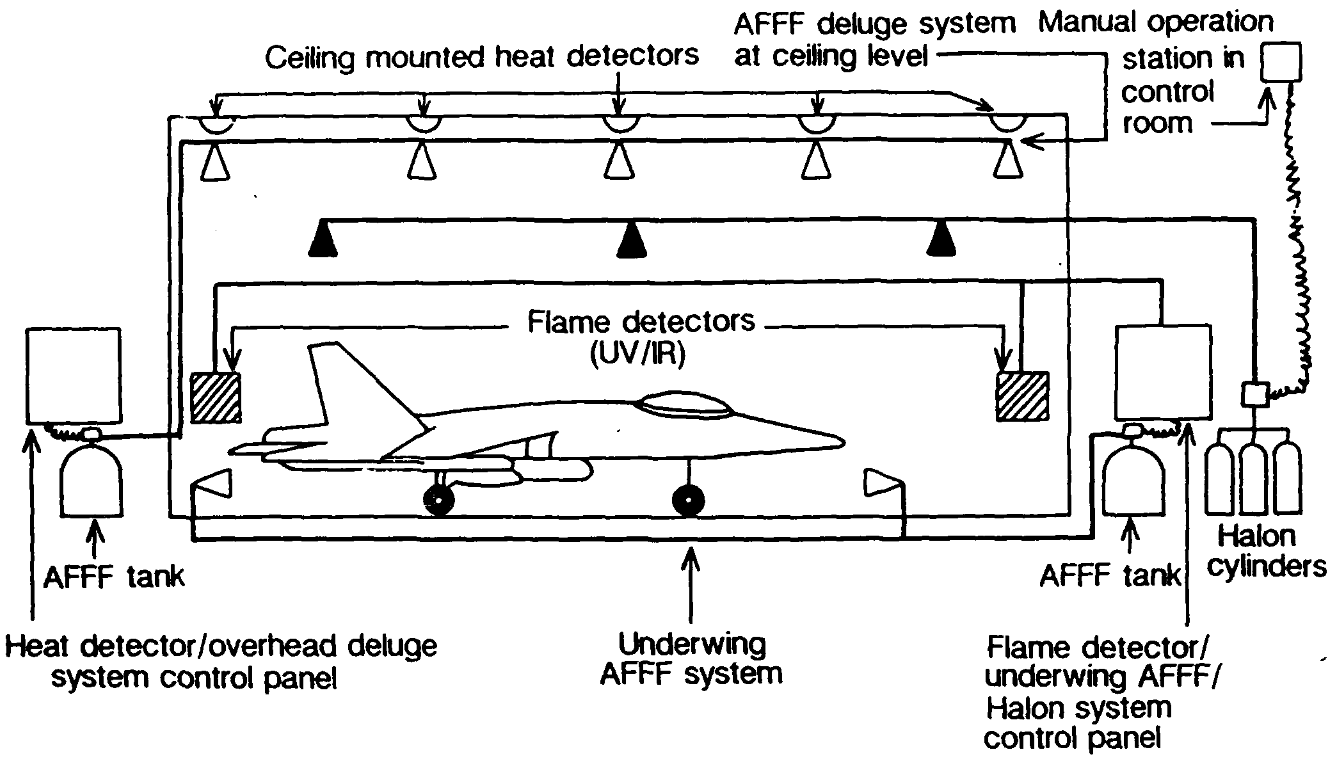
The halon system might successfully extinguish the fire, on a momentary basis, despite an incomplete seal of the test bay, as shown by the Air Force's tests on hardened aircraft shelters (HAS) [48]. (The HAS tests, however, were predicated on immediate (3 s) detection and instantaneous discharge to prevent an incipient fire from growing to full involvement.) The Air Force hush house design has a built-in time delay of at least 40-45 s from visual detection and manual operation to allow the doors (dampers) to close. Therefore, heated surfaces could exist and re-ignition upon loss of halon concentration becomes a very real possibility.

System Effectiveness - The system can be designed, constructed, and maintained to the highest levels but still have its effectiveness threatened by the inherent unreliability of certain components. The potential failure rate of the rolling steel doors remains a major concern.

Complete AFFF System With Halon Backup

The provision of a halon system as a manual-only backup to the overhead and underwing AFFF systems provides the best possible protection (see Fig. 5). The halon system can be manually activated to extinguish the engine and electrical fires which the AFFF system cannot possibly extinguish. Meanwhile the operation of the AFFF system provides superior (more rapid) protection for the aircraft, safe egress for the aircraft handler, cooling of hot surfaces, and securing of the fuel pool surface. The halon system also provides a second means of extinguishment for pool fires if the AFFF system fails to operate properly.

Possible drawbacks to including the halon system as a backup to the AFFF systems include the unknown corrosion risk to the engines and electronic equipment, and the adverse environmental impact of the halon decomposition products exiting the augmenter tube stack. The largest potential obstacle is, of course, cost. The $190,000 (plus $20,000 for the flame detection system) cost of a combined AFFF/halon system is more than double the $80,000 (plus $20,000 for flame detection) cost of the AFFF system alone. This is without the retrofit costs for existing hush houses which could not be readily sealed for halon discharge. NAVFAC must make the determination of whether this additional cost is justified in light of the incidence rate and severity of fires in hush houses.



Advantages	Disadvantages
Extinguishes all fires, except runaway engine	Highest cost

Fig. 5 - Halon system with complete AFFF system

EXTINGUISHING AGENT APPRAISAL

The three candidate systems will have their performance evaluated in this section under a number of varying scenarios.

Accidental Discharge - Engine Off

In this scenario there is a spurious system actuation, without warning, when there is no fire and the aircraft engine(s) are secured.

AFFF

AFFF will not damage the aircraft skin materials and should not project a significant amount into the engines since they are not operating. If the cockpit is open, water damage could result to electronic equipment. The underwing AFFF system could damage electronic test stand equipment located in the discharge path of the nozzles. The AFFF systems could be shut off quickly (in less than one minute) by closing the valves below the deluge valves. Refilling of the AFFF concentrate bladder tank requires at least half a day as the water in the tank would have to be drained before the tank could be filled. (Refilling would not be necessary if the system(s) were shut off quickly.)

Halon With Underwing AFFF

Again the test stands are subject to water damage from the underwing system. No engine or cockpit damage will occur. The halon is not toxic in the short term, in the 6% concentration used, however, the hush house should be evacuated until the halon is exhausted by forced ventilation. The time necessary to locate, purchase, and take delivery of a replacement halon supply would vary significantly with the location of the base. As no reserve supply is included in the design, there would be no protection provided for engine fires and remote pool fires until the halon cylinders were refilled.

AFFF With Halon Backup

The AFFF system could cause the damage described above. Again, the halon system would cause no damage but personnel should be evacuated until the halon is removed. (Accidential activation of the halon system should be a very low probability event since it would be a manually activated backup.)

Accidental Discharge - Engine Operating

In this scenario the extinguishing agent is again discharged without warning, however, the aircraft engine(s) are operating.

AFFF

In addition to the potential damage described above, although the cockpit canopy will almost certainly be closed, AFFF will be ingested into the engine(s). NAVAIR policy currently requires that, if the AFFF was prepared with salt water, the engines then be overhauled.

Halon With AFFF Underwing

In addition to the AFFF damage described above, the halon will be broken down by the hot engine surfaces and exhaust. The generation of corrosive and toxic products has not been quantified by test. Corrosive damage would probably be limited to the engines themselves, if any occurs at all. Toxic products would threaten not only test personnel but also those downwind of the exhaust stack.

AFFF With Halon Backup

The potential effects are identical to the sum of those described above for AFFF and halon.

Pool Fire - Engine Winding Down

A pool fire 42 m^2 (450 ft^2) occurs, either below the aircraft or remote from it, while the engine is winding down.

AFFF

The AFFF system will extinguish a pool fire regardless of where it occurs. The fire beneath the aircraft will be extinguished within 20 s, while one occurring remote from the aircraft would be extinguished within 2 min 30 s. AFFF ingestion into the engine will occur and electronic equipment could be wetted with AFFF with the consequences described above.

Halon With Underwing AFFF

The underwing system will extinguish any pool fire in the immediate vicinity of the aircraft, thus allowing the handler to escape. A pool fire occurring elsewhere will continue to burn until the area has been sealed so that the halon system can be discharged. If the area cannot be sealed, the halon system probably could still be used to extinguish the pool fire, depending on the engine power level (and hence air movement rate). However, since halon provides no cooling of hot surfaces, nor securing of the fuel surface, re-ignition is a very real possibility.

If the engine continues to operate at high power levels (a runaway engine), then sufficient agent could be ingested and broken down to prevent even momentary suppression of a pool fire. The toxic and corrosive effects of the halon decomposition products are as discussed above under the inadvertent discharge-engine operating scenario.

AFFF with Halon Backup

Again, this presents the best of both worlds. The AFFF system will extinguish any pool fire as described above, while the halon system provides a backup should the AFFF system fail to operate properly. The halon system also provides the ability to extinguish an engine fire, if the engine does wind down, as well as an internal electrical fire. Of course, both of these fires could be extinguished with portable extinguishers by test personnel or responding fire fighters.

Pool Fire - Engine Secured and the Doors Open

The 42 m^2 (450 ft^2) pool fire occurs when the aircraft engines are shut down and the hangar doors are open.

AFFF

Having the hangar doors open has absolutely no affect on the performance of the AFFF system. The flame detection system, for the underwing AFFF, may be placed in the Alarm Only mode whenever testing is not in progress. Therefore, the underwing system will have to be activated manually resulting in a delay of at least several seconds in agent application. As long as this delay does not exceed 30 s, no damage to the aircraft should occur.

Halon with Underwing AFFF

The underwing system will extinguish any pool fire below the aircraft. Having the doors open means that the halon system probably cannot achieve even momentary extinguishment of fire in other locations, if the hangar doors are blocked open. (While extinguishment was achieved in the Air Force hardened aircraft shelter tests [48] with the doors open, this occurred with a 3 s detection and discharge time.) The continued burning of a fire remote from the aircraft will eventually damage the aircraft. This would be prevented only by the timely arrival of a crash truck, since responding structural fire vehicles would require too long to set up an AFFF handline.

AFFF with Halon Backup

The AFFF system will function as described above. The (blocked) open hangar doors mean that the backup capability,

and engine fire extinguishment ability, provided by the halon would be lost.

Pool Fire - Engine Secured and Doors Closed

The 42 m^2 (450 ft^2) pool fire occurs when the engines are secured and the hangar doors closed.

AFFF

The AFFF system will perform as described above under the two pool fire scenarios.

Halon with Underwing AFFF

With the doors closed the halon system can perform as designed, assuming the sealing of all openings can be accomplished, in the manner described above. With the engine secured the level of toxic and corrosive products produced will be lower. The underwing AFFF system will perform as previously described.

AFFF with Halon Backup

Securing the hangar doors restores the backup capabilities provided by the halon system. Again, with the engine secured the amount of corrosive and toxic by-products produced by halon decomposition will be reduced.

Engine Compartment Fire

A fire in an engine compartment can be a simple matter of excess fuel spilled, could involve engine disintegration, or a runaway engine and fire.

AFFF

The AFFF system will have absolutely no effect on any of the engine compartment fires. It will, however, provide cooling of the fuselage. It will also extinguish burning fuel spilling to the hangar floor.

Halon with Underwing AFFF

The halon system can extinguish the first two types of engine fires, assuming the engine winds down and proper sealing of the test bay is achieved. However, the exhaust of a runaway engine would destroy the augmenter tube door and prevent extinguishment of the engine fire. The underwing AFFF system would extinguish burning fuel which drops to the hangar floor in the vicinity of the aircraft.

AFFF with Halon Backup

The halon system could extinguish an engine fire under the circumstances described above. The AFFF system will extinguish burning fuel dropping to the hangar floor and provide cooling of the fuselage.

CONCLUSIONS

Water Based Fire Protection Systems

Water deluge systems, even at very high application densities, do not provide adequate protection for either the aircraft or the hush house structure for fires of any magnitude [11]. The water mist system concept is not sufficiently developed to provide a short term solution to the unique fire problems inherent in the hush house.

AFFF Fire Protection Systems

Combined overhead and underwing AFFF systems have proven to be very effective in the rapid control and extinguishment of flammable liquid pool fires once discharge of agent begins [3,14-17]. However, current system configuration cannot begin to meet the 20 s detection to extinguishment criterion due to the time required to flood the normally dry system piping. The time required for the current heat detection system to be activated by a moderately sized fire is also unacceptably long, assuming manual actuation of the AFFF is also delayed for some reason.

Use of a pre-primed fixed nozzle underwing system (a system which protects the underwing area but is not located beneath the aircraft) will overcome the first problem. Provision of a flame detection system to actuate the underwing system will eliminate the second problem. A practical flame detection system has already been identified by the Air Force for use in a similar application [48].

The use of AFFF for the fire protection system in the hush house is clearly superior to a halon total flooding system in the following areas:

Extinguishment Time - The underwing AFFF system can meet the 20 s criterion for a fire below the aircraft, if a pre-primed underwing system is used along with flame detection. (The discharge of the halon system will be delayed at least this long due to the time required to close the ventilation openings.) Fires outside this area will be extinguished by the overhead system in less than two minutes. Damage to the aircraft should not occur due to the spatial separation of the fire.

Reignition Prevention - By cooling the fuel and hot metal surfaces the AFFF discharge removes the most likely causes of reignition. (Halon does not provide any appreciable cooling and therefore reignition could occur if the required concentration was lost quickly.) In addition, AFFF seals the fuel surface to prevent reignition from some other source, such as an electric arc, for a fairly long period of time. (Since halon does not secure the fuel vapors, reignition could occur from such a source as soon as the required halon concentration was lost.)

Low Risk of Failure - The only moving parts in the AFFF systems are the deluge valves themselves, and these have historically been highly reliable if properly maintained. (While the halon actuation valves are also highly reliable, proper operation of the halon system requires the closing of 11 rolling steel doors, a technology which has proven historically unreliable.) The detection and actuation systems would be built of solid state electronics and supervised circuits. (The same equipment would be used for a halon system.) Flame detectors for the underwing system could have a false alarm problem, however recent work by the Air Force [48] shows this problem can be overcome. Activation of the low level system, should it occur, would not damage the aircraft.

Toxicity - AFFF presents no toxic threat to test personnel or passersby. (Halon decomposition products present an unquantified threat to all personnel, especially the aircraft handler who could be trapped in the cockpit, as well as those downwind of the exhaust stack.) AFFF can damage water ecosystems and/or sewage treatment plants if the concentration is high enough. These consequences, along with the fuel runoff, are generally accepted during an emergency (fire) situation. Floor drain runoff can be collected and processed for routine system tests. (Much recent attention has been focused on the possible threat halons pose to the environment due to destruction of the ozone layer; the possibility exists that the production and/or test discharge of halon systems may be restricted in the near future.)

Corrosivity - AFFF prepared with fresh water presents no corrosion hazard. AFFF prepared with salt water can cause corrosion and NAVAIR therefore requires an engine overhaul for any engine which ingests saltwater AFFF. (Halon's thermal decomposition products are very corrosive. The level of these products which would be produced in a hush house fire is unknown and therefore it is not known whether damage to aircraft components would occur.)

Personnel Egress - The rapid actuation of the underwing AFFF system would permit all test personnel, including the aircraft handler, to evacuate the facility. (A fire below the cockpit would preclude the escape of the handler until the halon system is discharged. This would expose this individual to the toxic by-products discussed above, possibly incapacitating him/her.)

Fire Scenarios - The AFFF systems provide superior performance (faster extinguishment) for all pool fire scenarios, especially when considering a spill beneath the aircraft. (The delays inherent in actuation of the halon system could result in aircraft damage before extinguishment occurs, especially for the fire beneath the aircraft.)

Total Flooding Halon Fire Protection System

A halon-only fire protection system is considered unacceptable for three reasons: the threat to the aircraft handler, the inherent delay in system actuation, and the potential unreliability of related hardware such as door closers.

In the event of a spill fire beneath the cockpit the aircraft handler will be trapped. He cannot escape until other personnel utilize AFFF to cut a rescue path to him, thus delaying halon system actuation, or the halon system is activated. Since the handler is not equipped with breathing apparatus he will be exposed to the thermal decomposition products of halon. The quantities of such products in the post-fire hush house atmosphere is unknown, but would likely be incapacitating, if not fatal.

The time delay necessary for closure of the hush house ventilation openings ranges from a minimum of 20 s, to a maximum of 45 s if the main hangar door must be closed. This allows a significant pre-burn, in addition to any delay before the system is actuated, either manually or by a detection system. Fire tests conducted by the Air Force in a hardened aircraft shelter [48] show the difficulty in extinguishing such a fire with halon after a short (less than 30 s) pre-burn, if the halon concentration cannot be maintained. In one such test, the fire was successfully extinguished after a 17 s pre-burn, but then re-flashed immediately. In addition, during this test the temperature (at one thermocouple) exceeded 538 °C (1000 °F), less than 5 s after ignition.

Rolling steel fire doors have historically been highly unreliable. Observed problems include: mechanical damage to tracks, build-up of dirt in mechanism, and presence of obstructions in the opening. In addition, each Air Force hush house ventilation door operating mechanism is powered by an electric motor which could be damaged or de-energized in a fire situation. Failure of any of these doors, combined with the long pre-burn period, could prevent successful extinguishment of the fire or result in a rapid reignition.

While the halon system provides the only small self-contained fire extinguishing system, this does not appear to be a sufficient justification for use of a halon-only system. Only in time of war, when a forward base may have to be constructed rapidly in an area with an insufficient water supply, would the specification of a halon-only system seem justified on this basis. On any other base, construction can easily include the required utilities since these are provided for other hangars.

Total Flooding Halon With Underwing AFFF Fire Protection

Inclusion of the underwing AFFF system with a total flooding halon system solves the personnel egress and rapid aircraft damage problems identified in the halon-only discussion above. It does not correct the potential unreliability problem with the air inlet doors. Therefore a fire remote from the aircraft would continue to burn, in the event of a halon system failure, eventually resulting in damage to the aircraft.

A total flooding halon system provides the ability to remotely extinguish both internal electrical fires and engine fires. The need for this capability is low in light of the availability of large volume portable extinguishers in the hush house. These can be used to extinguish even fairly large engine fires.

The cost of such a combined system, however, is considerably greater than for the AFFF system alone.

RECOMMENDATIONS

1. The Navy hush house should be protected by two separate AFFF extinguishing systems, a pre-primed underwing system with fixed nozzles (which protect the underwing area but are not located below the aircraft) and an overhead deluge

system. The underwing system should operate at a density of 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$) and the overhead deluge system should operate at a density of 6.5 $l/min/m^2$ (0.16 $gal/min/ft^2$). A pre-primed system eliminates the 18-20 s delay in agent application after system activation.

2. The underwing system should be activated by a flame detection system and the deluge system by an overhead heat detection system. The rapid response (3 s) provided by flame detectors is critical in the rapid extinguishment necessary to prevent aircraft damage.

3. NAVFAC should determine, based on actual hush house fire frequency, severity, and type, whether installation of a backup halon system is justified for extinguishment of engine compartment and electrical fires. (This is in view of the fact that the available large halon extinguishers provide ample capability to extinguish these types of fires.)

4. Investigate, as an alternative, the feasibility of connecting the engine nacelle fire extinguishing systems, of aircraft so equipped, to an offboard agent reservoir. This will permit repeated, or continuous, discharge of halon into the engine nacelle without flooding the entire hush house volume. Also examine the possibility of installing a quick connect fitting and halon discharge nozzle on one or more engine access panels for aircraft not equipped with a halon extinguishing system.

5. Institute flash point testing of the fuel in each aircraft before bringing it into the hush house for testing. Whenever the flashpoint is below 38°C (100°F) the aircraft should be defueled and filled with JP-5 to decrease the hazard level in the hush house. These tests should also be performed on the contents of the refueler.

6. Incorporate adequate floor drainage in any future Navy purchases of Air Force hush houses.

7. Discontinue the practice and/or permissibility of conducting hot refueling in the hush house. If this is an absolute operational requirement, provide a pantograph system for refueling in order to decrease the hazard associated with hot refueling.

8. Conduct the testing outlined below to ensure the proper performance of the AFFF and detection systems and to determine the suitability of total flooding halon, in conjunction with AFFF, in the hush house environment.

9. Based on the work performed recently by the Air Force [48] the use of combined UV/IR detectors for the flame detection system is recommended.

RECOMMENDED TEST AND EVALUATION

A number of full scale fire tests in an actual, or simulated, hush house are necessary to ensure the proper performance of the recommended flame detection system and the AFFF system. Fire tests are also required to accurately assess the level of toxicity and corrosivity which can be expected in the hush house environment following extinguishment of a major fire by a halon total flooding system. This information, along with tests on ingestion of halon in an operating aircraft engine, is required to identify the threat to equipment and personnel posed by a halon system. The reliability of the door closers must also be examined to assess the expected performance of the halon system.

Detection System Tests

The detection systems proposed for the hush house, both the existing heat detection scheme and the new IR/UV system must be tested. Tests will be designed to determine their response to both real fires and possible false actuations due to conditions such as hot tail pipes, minor engine fires, and afterburner flames. These tests would be conducted with the detection systems placed in an operating hush house to observe their response to routine testing. As discussed in the next section, the Air Force Engineering and Services Center (AFESC), has already performed similar detection system tests for an IR/UV flame detection scheme proposed for use in hardened aircraft shelters (HAS). While AFESC's tests for the HAS duplicate some of the conditions in the hush house they do not feature the continuous engine operations observed in the hush house. Therefore a separate set of tests in an operating hush house is still recommended. (The HAS tests should be comparable to conditions in a repair or storage hangar, locations where NAVFAC is in sore need of a reliable, false alarm free flame detection system.)

20 Second AFFF Extinguishment Tests

The pre-primed fixed nozzle underwing AFFF system will be tested against the pool/spill fire described above. The ability of this system to achieve extinguishment in 20 s or less will be assessed. The fire will be beneath an aircraft mockup including test stand interferences. The thermal insult to the building and aircraft mockup will be measured along with the extinguishment times.

Burnback Resistance of AFFF

Either separately, or in conjunction with the AFFF tests above, the burnback resistance of the AFFF blanket developed by the underwing system will be evaluated. After a predetermined pre-burn period the fire will be extinguished by the underwing nozzles and foam will continue to be applied for a five minute period. The burnback resistance will be checked both by a flaming source, to simulate a burning tire, and a sparking source, to simulate an electric arc above the fuel surface.

Toxicity Levels In A Halon Protected Hush House

This test series involves extinguishment of large scale, 42 m^2 (450 ft^2) fires with a 132 l/min (35 gal/min) running fuel source. Fuels will be JP-5 and a mixture of 10% JP-4 in JP-5. Tests will be conducted at 6%, 5%, 4%, and 3% concentrations of Halon 1301 and Halon 1211 (only one test at 6% for comparison). The lower concentration tests are meant to assess the effect of agent loss due to incomplete sealing of the test area. A pre-burn time of 45 seconds after ignition will be used.

Measurements will include the thermal impact on the building and a simulated aircraft, the concentration of the agent (1301 or 1211), and concentrations of HF, HBr, Br_2 and other halon decomposition products over the duration of the trial. A remotely activated ignition source will also be used to assess the reflash potential after a sudden loss of agent.

Corrosive Effects During the 30 Minute Halon Soak Time

Samples of aircraft engine materials and electronic components will be subjected to concentrations of HF, HBr, and Br_2 as identified in the test above. These atmospheres will be maintained for 30 min and then replaced by fresh air. The performance/condition of the test specimens will be examined then and at later intervals to determine the effect of these corrosive materials.

Halon Decomposition in an Operating Engine

An operable aircraft engine representative of the types tested in the hush house should be used to determine the concentration of toxic/corrosive compounds produced by the ingestion of varying concentrations of Halon 1301 and 1211. Corrosion of the engine would also be monitored.

Ground Level Halogen Acid Concentrations Following an Inadvertent Operation

This involves a theoretical analysis, rather than actual physical testing. Based on existing airflow data in the Air Force hush house, and on the data for engine ingestion of halon generated above, the concentration of toxic products in the hush house exhaust will be determined. Dispersion of these materials in the area downwind of the stack will be modelled mathematically for a range of wind and adjacent facility proximity conditions.

1000 Cycle Testing of Automatic Door Closers

The reliability of the automatic door closers used to seal off the ventilation openings in an Air Force hush house is suspect. In order to provide some meaningful data a sample door will be subjected to 1000 cycles of operation. This will simulate a pre-test check of the doors in each hush house over a 3-4 year period. The door will also be subjected to temperature extremes during the course of the 1000 cycle test.

Tests of Automatic Door Closers Against High Pressure Differentials

The continued operation of a jet engine can be expected to cause significant pressure differentials between the inside and outside of the hush house as the ventilation doors begin to close. These differentials will be simulated across a sample rolling steel door to assess their effect on the ability of the door to close.

CURRENT OR PROPOSED INVESTIGATIONS

The authors have been unable to identify any current or pending research efforts in the private sector which have any direct potential impact on the design of fire protection systems for the hush house. Some work in the private sector involving improvement of AFFF, either in the agent itself or in development of "super-concentrated" concentrates (1% or less), may have an indirect impact on the effectiveness of an AFFF extinguishing system in the hush house.

Two research efforts having a direct impact on potential hush house extinguishing systems were identified in the government sector. Both projects are being undertaken by the New Mexico Engineering Research Institute (NMERI) under funding provided by the Air Force Engineering and Services Command (AFESC) located at Tyndall AFB, Florida. One project involves the development of a fire extinguishing system for the hardened aircraft shelter (HAS) and the other related project involves development of a small emergency escape mask for use in the HAS.

The work already performed by NMERI [48] involved the testing of six candidate flame detection devices under a host of potential false alarm conditions, including:

Vehicle Head Lamps (Day)
Vehicle Head Lamps (Night)
Frosted Incandescent (Day)
Rough-Service Incandescent
Fluorescent Light
Electric Arc
Vehicle Infrared Light
Sunlight
Ambient Light Extremes
Brightly Colored Clothing
Electronic Flash
Movie Light
Red Beacon Light
Blue-green Dome Light
Flashlight with Red Lens
Flashlight
Reflected Light (Gloss Colors)
Reflected Light (Fluorescent Colors)
Reflected Light (Glass Mirror)
Chopped Light
Arc Welding
Acetylene Flame
Security Personnel Weapons
Flashbulb
Radiation Heater (Operating at 1,000 watts)
Cigarette (Lighted)
Book Match (Flare-Up)
Quartz Light
Black Light
Mercury Vapor Light
Lightning
Black Powder Cartridge Start
APU/-60
HF Radio Tail/HF Radio Wing
Attack Radar Normal/Pencil Beam
Attack Radar (5-Second Increment) TF/Situation
TF/BU Through Attac. ECM (IR Jamming)
Engine Exhaust.

Detection schemes investigated included UV, IR, UV/IR, and UV/UV. NMERI's work indicated that the optimum system featured gated UV/IR detectors arranged in a "voting" (cross-zoned) scheme. Use of such a scheme resulted in a response time of approximately 3 s to an actual fire and eliminated response to all of the false alarm sources listed above except afterburner mode engine operation. This false alarm source was eliminated by use of a sound measuring device which electrically isolated the detection system whenever the sound level approached that produced during afterburner operations. This work has progressed sufficiently that first article procurement and testing of a detection system for the HAS is scheduled for the end of FY 87.

While this test work has direct and immediate application to aircraft repair/storage hangars, an area where NAVFAC is sorely in need of a reliable flame detection system, it is not clear that the work has progressed sufficiently far for inclusion of these detectors in a hush house (without further testing). The frequent and continuous engine operations routine in a hush house may present a significant challenge to AFESC's proposed detection scheme. Therefore the successfully tested AFESC system, along with any newer systems proposed by flame detector manufacturers, should be tested in actual hush house conditions as proposed before and described below. NAVFAC should also consider procurement of the first article detection scheme for testing in a repair/storage hangar where an existing flame detection system has been de-activated because of a high false alarm rate.

The development of a 5 min oxygen producing escape mask for use in the HAS also has immediate applicability in the current generation of Air Force hush house. The prototype device is small enough to clip unobtrusively on the belt and would be issued to all personnel entering the HAS (or hush house). This would be especially important for the aircraft handler who, as described before, could be trapped in the aircraft by a fire and be subjected to the post halon discharge environment. Provision of such an escape mask would protect the handler's respiratory system during the time necessary to exit the aircraft and the hush house. This item has been developed as a prototype but no first article procurement has been scheduled as yet.

A third area of research (again involving AFESC, NMERI and the HAS) which is applicable to the hush house concerns development of a new concept in auditory and visual identification of escape routes. This work involves use of wafer thin electro-luminescent lighting strips to create a traveling light "arrow" along the floor to the exit, combined with a sonar-type auditory device at the exit. This has potential application in the hush house to overcome the possible disorienting effects of either an AFFF or halon discharge. NAVFAC should examine the final report on this new system and evaluate it for use in Navy hush houses and hangars.

DETAILED TEST PLANS

Detection Tests

Intent

The intent of this testing is to identify the performance characteristics and adequacy of candidate rapid detection systems for the hush house underwing AFFF system.

Test Layout

All tests would be performed in existing, high usage rate hush houses, both Navy and Air Force. Candidate detection systems would be installed and their false alarm rate recorded and compared with the hush house log to determine what was the triggering event.

Test Scenarios

Manufacturers of flame detection systems, including the first article detection system purchased by AFESC, would be solicited for the type of equipment and configuration of their design which would be appropriate for a hush house. Each manufacturer would be invited to install his system, or systems, in a hush house in a manner which he feels will provide detection of an underframe fire without false alarms from normal testing. he configurati/n, however, must intertere with regular hush house operations.

The alarm output of each system would be monitored for a one week period. The manufacturers would then be requested to make any adjustments in equipment location which they felt would reduce any apparent false alarm problems. A one month test period would then follow.

Candidate systems which appeared acceptable from their low frequency of false alarms would then be subjected to further testing. Small ignition sources would be placed in numerous locations under operating aircraft to ensure these systems could distinguish a real fire during test operations.

Candidate systems would also be evaluated as to their response to simulated engine fires and fires remote from the underframe protection zone.

Instrumentation

No instrumentation is required except to record the alarms, including date and time, of each system installed in a hush house.

20 Second AFFF Extinguishment Tests

Intent

Previous fire tests with low level oscillating monitor nozzles have shown the rapidity with which they can extinguish flammable liquid pool fires below an aircraft mock-up. No directly comparable data shows the speed of extinguishment which can be achieved with fixed nozzles discharging over the same area. This fire test program will provide that data for both immediate and delayed application of AFFF.

Test Layout

The test facility should be an actual hush house or a near copy as described under the halon fire test plan. An AFFF system must be provided to supply fixed low level nozzles covering the area beneath the aircraft, or aircraft mock-up. The system must be designed to cover the entire 56 m^2 (600 ft^2) anticipated underwing area at an application density of 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$). The entire 42 m^2 (450 ft^2) spill fire area should be within the area protected by the AFFF system. The AFFF system should be pre-primed.

In order to simulate the worst case condition, a representative configuration of test equipment (test stands) which might be located around the aircraft should be in place. This will create the maximum amount of "shaded" areas.

Remote fueling and ignition should be provided as described under the halon fire test program.

Test Scenarios

This test program will include three fuels; JP-5, JP-4, and 10% JP-4 in JP-5, and two pre-burn times; a fixed time of 2 s and a variable time based on 100% involvement of the fuel surface. This will provide data on the relative hazard of the three fuels when combatted with this type of extinguishing system. The different pre-burn periods will show the added degree of protection provided by a rapid detection system, which can be expected to respond to a fire within a maximum of 2 s from the ignition event. Two final tests will be run with an additional pre-burn of 20 s to reflect the use of an unprimed AFFF system actuated by flame detectors and manually.

Test No.	Fuel	Pre-burn Time
1	100% JP-5	2 seconds
1R	100% JP-5	2 seconds
2	100% JP-5	Time to full involvement
2R	100% JP-5	Time to full involvement
3	100% JP-4	2 seconds
3R	100% JP-4	2 seconds
4	100% JP-4	Time to full involvement
4R	100% JP-4	Time to full involvement
5	10% JP-4	2 seconds
5R	10% JP-4	2 seconds
6	10% JP-4	Time to full involvement
6R	10% JP-4	Time to full involvement
7	100% JP-5	22 seconds
8	100% JP-5	Time for test 2 plus 20 seconds

Instrumentation

Temperature and radiative flux measurements should be made in the same way described in the halon fire test plan. Two video cameras should be used to record the tests. Gas samples should be collected from several points in the test bay at periodic intervals for later analysis for the level of toxins and corrosive materials in the fire atmosphere.

Safety

The safety precautions outlined under the halon fire test plan will also be applicable to these tests.

Schedule

Set up of piping, instrumentation, etc. will require two or three days assuming prefabrication of all required piping. Five fire tests could be run each day so testing will require an additional three days.

Burnback Resistance of AFFF

Intent

One of the desired performance characteristics of the fire suppression system utilized for the hush house is the ability to prevent reignition for 30 minutes. The main reason for that criterion, the need to allow heated surfaces to cool, may not particularly apply to AFFF systems extinguishing JP-5 fires due to the excellent cooling capacity of the water in the foam if the foam is applied for an extended period (not shut off immediately after extinguishment). However, the burnback resistance of the AFFF blanket applied by the fixed nozzle system is important in the case of JP-4 and JP-4 mixtures since the fuel surface will be above its flashpoint regardless of the cooling provided by the AFFF.

Provision of this data will permit NAVFAC to make a decision on the desirability of increasing the AFFF discharge period above the 10 minutes mandated by NFPA 409.

Test Layout

These tests can be conducted at the same time as the 20 s AFFF extinguishment tests described above by simply continuing the AFFF discharge period for a full 10 minutes rather than by terminating the discharge at extinguishment or soon after. Since these tests do not require an aircraft (or mock-up) they could be conducted at any convenient test facility, rather than requiring the use of a hush house or similarly sized facility.

Test Scenarios

Once again the fuel pool size will be 42 m^2 (450 ft^2). AFFF will be applied to this area at a rate of 4.1 $l/min/m^2$ (0.10 $gal/min/ft^2$) for a period of 10 minutes. (This can be done either as a part of the 20 s extinguishment tests or separately at another test site.) Reignition will be provided by one of two sources, an electric spark or a burning fuel pan.

The electric spark represents a continuing electric arc ignition source, but this will not be used for tests on 100% JP-5 because its flash point is so high as to make reignition by this source improbable. The burning fuel pan represents the continued burning of an aircraft tire which Alger [17] identified as a lingering spot fire in tests simulating a carrier hangar deck fire.

The time required for the resulting burnback fire to reach 1 m^2 (10 ft^2) and 9 m^2 (100 ft^2) will be recorded for use in evaluating the burnback resistance of AFFF from this type of system. The proposed fire tests are:

Test No.	Fuel	Reignition Source
1	JP-5	Burning fuel pan
1R	JP-5	Burning fuel pan
2	JP-4	Electric spark
2R	JP-4	Electric spark
3	JP-4	Burning fuel pan
3R	JP-4	Burning fuel pan
4	10% JP-4	Electric Spark
4R	10% JP-4	Electric spark
5	10% JP-4	Burning fuel pan
5R	10% JP-4	Burning fuel pan

Instrumentation

The burnback area will be judged by experienced fire test personnel. Their judgement will be confirmed by a video recording of each test. In addition, radiant flux measurements will be taken with radiometers.

Safety

Fueling operations will be hazardous because of the possible spread of flammable vapors. The test area will be adequately ventilated at all times fuel is present. An additional AFFF supply, beyond the 10 min discharge required, will be maintained so that the burnback fire may be extinguished at any time personnel or test equipment are threatened. The test runoff, which will include fuel and AFFF, will have to be collected for processing and/or disposal in an environmentally safe manner.

Schedule

These tests, if run separately from the 20 s extinguishment tests, can easily be set up in one day. The 10 tests can be conducted in less than two days.

Toxicity Levels in a Halon Protected Hush House

Intent

The large scale fire testing found in the literature is concerned mostly with the computer room fire scenario. A few test programs do address flammable liquid hazards [42,44,45, 47,48], however they do not generally reflect the fire size, room size, and pre-burn conditions anticipated in the worst case hush house fire. In those tests which appear to be similar to the hush house case [44,47,48], either toxic by-products were not measured or the sampling method is suspect. This test series is designed to provide the missing data on the level of toxic decomposition products produced when a large flammable liquid fire is extinguished by a halon total flooding system in a hush house scenario.

Since the major toxic by-products of halon decomposition (HF, HBr, and Br_2) are also the corrosive by-products of note, this test series will also determine the concentrations of corrosion agents in the post-fire atmosphere.

The loss of agent through openings which have not been properly sealed is a major concern in the hush house, as in any other total flooding application. Previously cited data also indicates that the lower the level of halon used to extinguish a fire, the higher the concentration of toxic (and corrosive) by-products produced [22]. To obtain data on this effect, the test series will include tests at lower levels of halon concentration than the design level of 6%.

Test Layout

The test series is designed to determine the post-fire conditions in a hush house. Therefore, the tests should be conducted in a facility which duplicates as close as possible the geometry of the hush house. The ideal situation would be to conduct these tests in an actual hush house. If this is not possible, the test facility should be a building approximately 6.7 m (22 ft) high with a total volume of about 4,248 m^3 (150,000 ft^3).

Although this test series is primarily designed to collect information on levels of toxic (and corrosive) byproducts produced by halon decomposition, these large scale fire tests should also be used to collect as much additional information as is possible, such as the ability of lower halon concentrations to extinguish pool fires. Therefore, the test layout should include an aircraft, or aircraft mock-up, set in the geometry anticipated for hush house operations. The aircraft should be centered on the 42 m^2 (450 ft^2) fuel spill area. A 2.5 cm (1 in.) steel fuel line will be run from the exterior of the building to the aircraft (or aircraft mock-up) where it will discharge, at atmospheric pressure, at a rate of 132 l/min (35 gal/min). Another fuel line will be run at floor level to allow remote application of an accelerant to the fuel surface for the ignition of JP-5 fires. A remotely operated ignition source, e.g. electric sparker, will also be provided.

A low level AFFF application system will be provided and be charged in a standby mode for all tests. This will allow rapid fire suppression should fire conditions threaten the test facility or any personnel.

Halon will be discharge by fixed nozzles located so as to closely approximate the standard installation in the Air Force hush house. The agent quantity will be calculated in the same manner as that used for the Air Force design, providing the test design concentration throughout the test bay to a height of 3.7 m (12 ft). Discharge will be accomplished within 10 s of initiation. Discharge actuation will be by remote manual means.

The test building should be equipped with floor drainage to permit more rapid turnaround between tests. (Fuel can then be washed into the floor drains rather than outside.) Provision must be made, however, for the collection and/or impoundment of the floor drain discharge because of the significant quantities of fuels involved. This material must be collected and shipped off for special processing and/or disposal.

Test Scenarios

A total of 20 fire tests are anticipated, 10 different scenarios and a repeat of each test to ensure validity of the data. The 10 scenarios incorporate: different fuels, JP-5, JP-4 and 10% JP-4 in JP-5; different halon agents, Halon 1301 and Halon 1211; and different agent concentrations, 6%, 5%, 4%, and 3% to simulate loss of agent through unsealed openings. The tests focus on extinguishment of JP-5 fires by varying concentrations of Halon 1301. The other tests are added to measure the impact of different fuels and the use of Halon 1211.

The 20 tests planned for this series are:

Test No.	Agent	Agent Concentration	Fuel
1	Halon 1301	6%	100% JP-5
1R	Halon 1301	6%	100% JP-5
2	Halon 1301	5%	100% JP-5
2R	Halon 1301	5%	100% JP-5
3	Halon 1301	4%	100% JP-5
3R	Halon 1301	4%	100% JP-5
4	Halon 1301	3%	100% JP-5
4R	Halon 1301	3%	100% JP-5
5	Halon 1301	6%	10% JP-4
5R	Halon 1301	6%	10% JP-4
6	Halon 1301	3%	10% JP-4
6R	Halon 1301	3%	10% JP-4
7	Halon 1301	6%	100% JP-4
7R	Halon 1301	6%	100% JP-4

Test No. Continued	Agent	Agent Concentration	Fuel
8	Halon 1301	3%	100% JP-4
8R	Halon 1301	3%	100% JP-4
9	Halon 1211	6%	100% JP-5
9R	Halon 1211	6%	100% JP-5
10	Halon 1211	3%	100% JP-5
10R	Halon 1211	3%	100% JP-5

The fuel spill area, as detailed previously, is 42 m^2 (450 ft^2). Assuming a fuel burning rate of 0.5 cm/min (0.2 in/min) a fuel depth of 1 cm (0.4 in.) will support a two minute burn period. (This allows for sufficient fuel to prevent fuel consumption before fire extinguishment under all anticipated conditions.) This translates to a fuel quantity of 426 l (113 gal) per test. An additional 76 l (20 gal) of mogas would be added as an accelerant for each test where 100% JP-5 is the fuel.

The pre-burn for each test will be 45 s to simulate the time required for the main hangar doors in the hush house to close (and the built-in time delay in the halon system). The doors to the test bay will not be completely closed until 43 s after ignition in order to prevent significant oxygen depletion during the pre-burn period.

The fire will be initiated remotely by an electric spark, or other means, (from outside the test bay). The 132 l/min (35 gal/min) spill source will also be activated at this time. The fuel spill will continue for five minutes. The test will be terminated at 15 min after ignition, unless the threat of personnel injury or facility damage requires the actuation of the AFFF system.

Instrumentation

Instrumentation will be required to measure temperature, radiant heating, agent concentration, concentration of various halon decomposition products, and oxygen depletion. Electronic data processing capability will have to be provided to rapidly scan and record all digital and analog output on a real-time basis for later retrieval and manipulation. Sensor locations for the various measurements include:

Temperature (Thermocouples)

1. Floor to ceiling trees around the aircraft
2. Floor to ceiling trees at one side and the rear wall
3. Along the aircraft fuselage
4. Along the aircraft wings
5. Cockpit
6. Inside one or more open access panels under the aircraft
7. In the fuel layer
8. On heavy metal angles located both in and above the fuel surface (to assess the reflash potential)

Radiant Flux (Radiometers)

1. Aircraft fuselage
2. Aircraft wings
3. Cockpit
4. Building walls
5. Building ceiling

Agent Concentration (Halon Analyzer)

1. Three floor to ceiling trees located in widely separated areas of the test bay.

Decomposition Product Concentration

The halon decomposition products will be measured both on a real time basis, by analyzers specifically designed to determine the concentrations of HR, HBr, and Br_2, and by subsequent analysis of samples collected at various points during the test, in order to check for the presence of other possible decomposition products such as COCl and COBr. The samples will be taken on the same three trees used to sample the halon concentration. An additional sampling line will be placed in the cockpit. All sampling lines will be teflon, or teflon coated, to prevent sampling line reaction with the substances being measured.

Oxygen Depletion

An oxygen analysis meter will be used to determine the oxygen depletion occurring in several locations in the test bay as a result of the fire's consumption of the available oxygen. The test bay, however, will not be completely sealed until just prior to agent application in order to simulate anticipated hush house conditions.

Video

All tests will be recorded on at least two video recorders set up to view opposite sides of the aircraft, or aircraft mock-up.

Safety

The proper conduct of a fire test program requires a great deal of attention to safety. An independent safety officer should be present for all testing to ensure all possible steps are taken to mitigate the hazards inherent in a large-scale fire test.

At the time the facility and instrumentation, etc. is declared ready for the next test, no smoking regulations will go into effect. The test bay will be cleared of all non-essential personnel before fueling operations are conducted. All fueling will be controlled from outside the test bay. Fueling of the spill area will be through the floor level fueling line. For JP-5 tests the JP-5 will be discharged into the spill area first, and afterwards the 76 l (20 gal) of accelerant.

Ignition will also be done remotely. Neither fueling nor ignition will take place until the temporary low level AFFF system is charged in a standby mode.

After the 15 min test period, the doors to the facility will be opened to allow dissipation of the post-fire atmosphere. All personnel will be cleared from the area downwind of the test facility. Personnel assigned to open the doors will wear breathing apparatus and protective clothing. No personnel will re-enter the test bay until the instrumentation shows a normal oxygen atmosphere and that the area is free of the toxic halon by-products.

Schedule

It is estimated that 4-5 tests can be conducted per day. Thus testing will require 4-5 days. At least two days will be required for instrumentation set-up and one day for dismantling. This does not include the time necessary to fabricate an aircraft mock-up, if an actual aircraft is not available.

Corrosive Effects During the 30 Minute Halon Soak Time

Intent

The available literature does not contain any applicable data as to corrosive by-products produced by extinguishment of a fire, of the type anticipated in the hush house, by a total flooding halon system. The previous test series will provide this missing data. Now this data must be used to determine the impact of these by-products on the materials and components of advanced military aircraft.

The Air Force hush house halon extinguishing system is expected to prevent reignition for at least 30 minutes. Therefore all the components of an aircraft will be exposed to the corrosives, identified in the post-fire atmospheres of the previous test series, for at least 30 minutes. After this period the hush house would be ventilated and the atmospheric contaminants removed. Unless all aircraft surfaces are properly cleaned, however, the corrosives deposited on the surfaces of the aircraft (and its components) will remain and the corrosion process will continue.

To determine the effects of these corrosives this test series will subject samples of selected aircraft components to the range of post-fire atmospheres determined in the previous test program. The performance of electronic components and corrosion of metal parts will be evaluated periodically to determine if additional corrosion has occurred.

Test Layout

The test layout is not a significant factor since this is a small-scale, non-fire test. The items to be tested should include a representative sample of the materials and components (which would be expected to be most affected by corrosion) installed in a modern tactical aircraft. A minimum of two samples of each of these items will be placed into each of three closed containers. One container will be filled with a mixture of gases including HF, HBr, and Br_2 based on the worst case atmosphere developed during the previous test program. The temperature during the test will be maintained in accordance with the temperature of the aircraft as determined by those fire tests. (A single, constant, elevated temperature will probably have to be selected to assure repeatability. A variable temperature exposure (which is more likely) is difficult to replicate with any accuracy.) The other two test chambers will be subjected to a medium and best (least) case atmosphere. The parts/components will be maintained in these post-fire atmospheres for 30 minutes. The test chambers will then be vented to remove all of the corrosive gases so that normal atmospheric conditions are again achieved. During the extended test period the composition of the atmosphere in the test chamber shall remain normal (an 80-20 N_2-O_2 mixture) but the temperature and humidity shall be fixed to simulate the worst case (with regard to corrosion) exterior climatic conditions.

Test Scenarios

As stated above the three test chambers will be filled with corrosive atmospheres, as determined by the fire test program, in accordance with the best, worst, and median observed corrosion conditions. This will provide the data needed to determine if an aircraft overhaul is needed after a halon system actuation in the hush house environment.

A 30 minute exposure is used to simulate the specified reignition prevention period, which permits cooling of all heated surfaces. "Post-fire" checks of 24 hours, 1 week, 1 month, 3 months, and 6 months, as well as the immediate examination, will provide evidence, if any, that corrosion is continuing due to failure to clean all exposed surfaces. A wide range of temperature/humidity conditions will be used to simulate worldwide weather conditions which might promote corrosion by compounds remaining on the surfaces of the components.

Instrumentation

The majority of the instrumentation necessary for this test program will be required to monitor the atmospheres of the three test chambers. The 30 minute exposure atmospheres will be mixed and heated to duplicate observed fire induced conditions. After venting the corrosive atmospheres the test chambers must be monitored to ensure the chambers' temperature and humidity represents climatic conditions which might worsen corrosion rates.

Corrosion of metal surfaces will be determined by the presence, and depth, of any pitting. Electronic components will have their performance evaluated by connecting them to appropriate equipment and performing diagnostic tests.

Safety

Safety is not a significant problem in this test program as a corrosive/toxic atmosphere will be present for only a 30 minute period. Proper laboratory safeguards must be utilized in the preparation, application, and venting of the corrosive gas mixtures. The laboratory exhaust system must be equipped with the necessary filters and scrubbers to prevent discharge of hazardous quantities of these materials to the atmosphere.

Schedule

The original 30 minute exposures should only require one day to set up and perform. Controlled post-test atmospheres (temperature, humidity) in the test chambers must be maintained for 6 months, however, to identify any long-term corrosion effects.

Halon Decomposition in an Operating Engine

Intent

The available literature does not cite any test work showing the effects of halon ingestion in an operating aircraft engine. For typical halon applications on the flight deck, or on the flight line, however, only a limited quantity of halon is available so that the duration of the exposure will be short. However, in a hush house installation the quantity of halon which will be discharged, either intentionally or in a false actuation, is relatively high and the exposure will be considerably longer. Data on adverse effects, if any, is necessary to properly assess the desirability of a halon extinguishing system in a hush house. These tests will also provide data on the halon decomposition products produced by halon ingestion in an aircraft engine.

Test Layout

These tests should be conducted with an actual engine of a type similar to those used on the aircraft which are tested in the hush house. It should be a functional, but excessed, engine since it could be damaged in these tests. The engine should be mounted on a test stand for these tests in either a hush house or an engine test facility. Inlet air to the engine must be supplied through some type of tubing so that the required amount of halon can be injected far enough upstream to allow adequate mixing before entering the engine. The engine exhaust must be continuously sampled to measure the level of toxic/corrosive by-products from halon decomposition.

Test Scenario

The percentage of halon in the inlet air to the engine can vary significantly depending on the hush house situation envisioned. Therefore the halon concentration will be tested at 3 levels, namely 10%, 6%, and 3%. Halon 1301 will be used for all tests except one comparison test. Five engine power levels will provide the required spread of data: engine idle, 50% military power, 75%, 100%, and afterburner. This requires the following eighteen tests:

Test No.	Agent	Agent Concentration	Engine Power Level
1A	Halon 1301	10%	Idle
1B	Halon 1301	6%	Idle
1C	Halon 1301	3%	Idle
2A	Halon 1301	10%	50% military power
2B	Halon 1301	6%	50% military power
2C	Halon 1301	3%	50% military power
3A	Halon 1301	10%	75% military power
3b	Halon 1301	6%	75% military power
3C	Halon 1301	3%	75% military power
4A	Halon 1301	10%	100% military power
4B	Halon 1301	6%	100% military power
4C	Halon 1301	3%	100% military power
5A	Halon 1301	10%	Afterburner
5B	Halon 1301	6%	Afterburner
5C	Halon 1301	3%	Afterburner
6A	Halon 1211	10%	100% military power
6B	Halon 1211	6%	100% military power
6C	Halon 1211	3%	100% military power

All tests will have a duration of two minutes. After each test the accessible engine components will be examined for evidence of visible corrosion. Sample swipes will be taken from accessible surfaces for analysis for the presence of corrosive compounds. After completion of the last test the engine will be disassembled and examined in detail for evidence of corrosion.

Instrumentation

The inlet air will be continuously sampled and analyzed for the concentration of agent during the duration of the test. Likewise, the engine exhaust will be sampled for the major toxic/corrosive compounds: HF, HBr, and Br_2. All tests will be videotaped.

Safety

This testing will be conducted in either a hush house or aircraft engine tests cell so the engine exhaust will be directed into an augmenter tube for catalytic combustion of unburnt fuels. This exhaust will be directed upwards for dispersion into the atmosphere. Tests should be conducted on windy days to allow maximum dissipation of the toxic gases.

Schedule

Instrumentation set-up will require only one day. Testing may require upwards of a week depending on the requirements for engine maintenance between tests.

Ground Level Halogen Acid Concentration

Standard analytical methods will be employed to evaluate the ground level discharge of Halon decomposition products outside the hush house facility. Using the exhaust gas concentrations measured in the engine halon ingestion tests above, the concentration in the dispersing gases exiting the augmenter tube stack will be calculated for a range of outside wind conditions. This will estimate the exposure to adjacent facilities following an inadvertent halon discharge.

1000 Cycle Testing of Doors

Intent

The reliability of the doors used to seal off the air inlets of the Air Force hush house is in question. This cyclic testing should provide accurate information on the failure rate of these doors.

Test Layout

Two representatives rolling steel doors complete with electronic motors and track systems will each be set up on a steel framework. Each door will be opened and closed 1000 times with the speed of that opening and closing recorded. a controlled weather chamber will be required for low and high temperature tests.

Test Scenarios

The doors will each be subjected to 1000 cycles of operation. 100 cycles will be conducted at a temperature of -34°C (-30°F) to represent worst case winter conditions. 100 cycles will be conducted at a temperature of 46°C (115°F) to represent worst case summer weather. The remaining 800 cycles will be conducted at prevailing ambient conditions.

Instrumentation

No special instrumentation is required for these tests.

Safety

No special safety conditions, other than cold weather protection for the "winter" tests, is required.

Schedule

At an estimated cycle rate of 5 min per test, these tests will require over 166 hours to complete. These hours will have to be spread, however, over at least a two month period, and scheduling of tests at the controlled weather facility could lengthen the required time.

Tests of Automatic Door Closers

Intent

When aircraft are undergoing testing in the Air Force hush house there is a significant pressure differential, up to 0.82 m (2.7 ft) of water for the F-111 with one engine in military power and the other at 75% [58], between the exterior and the interior of the hush house. If the engine(s) have runaway at the time of a fire, activation of the halon system would initiate closing of the ventilation opening doors (e.g. intake & exhaust) in the face of this pressure differential. Only the ventilation doors will be simulated, not the main hangar door as this would always be closed during testing.

No data has been located on the ability of the rolling steel doors, which close off the ventilation openings, to close, even at a reduced speed, when subjected to this type of pressure differential. The pressure differential will further increase as the doors begin to close. The ability of the doors to perform their function under these conditions must be known in order to properly evaluate the performance of a halon system.

Test Layout

Any attempt to test the operability of these doors under aircraft test conditions could result in damage to all these doors. To avoid this, only two doors would be tested, one at a time, in a facility capable of producing the required pressure differential across the door opening.

Test Scenario

The scenario being tested is one, or two, runaway engines which continue to operate at high power levels at the time of a fire. Activation of the halon system will result in the doors over the ventilation openings starting to close in the face of a significant pressure differential. This pressure differential will increase further as the doors begin to close and the available ventilation openings decrease in size. A range of pressure differential profiles for a 20 s door closing period will be calculated and used in the test facility. Any slowing or stopping of the doors will be noted.

Instrumentation

No special instrumentation is required except that necessary to measure and control the pressure differential across the door opening. Each test will be video taped.

Safety

The only safety problem inherent in this test is the high air flow velocities through the door opening(s). This can be mitigated by removal of all personnel from the test bay to a safe area before running each test.

Schedule

Fabrication of a door opening should not involve more than a few days at the selected test site. Actual testing should require no more than one or two days.

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