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THE F-16 HALON TANK INERTING SYSTEM

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Abstract

The F-16 multimission fighter employs a new lightweight approach towards providing fuel tank inerting. The F-16 inerting system stores and effectively distributes Halon 1301 (bromotrifluoromethane) to the air space above the fuel level to provide a nonexplosive atmosphere within the fuel tanks when activated. Background information includes a trades study with alternate inerting concepts. Resolution of component and system development problems is discussed and engine and airframe compatibility testing as well as system level tests are detailed. The results of initial F-16 operating experience is highlighted and a projection is made towards future applications. It is concluded that halon fuel tank inerting is a viable candidate for tactical and strategic aircraft weapon systems.

Introduction

The United States Air Force has actively pursued lightweight aircraft fuel tank inerting concepts as a means of improving flight safety and reducing aircraft vulnerability during combat operations. A number of concepts including vapor enrichers, dry ice inerting, active extinguishing systems, exhaust gas inerting and chemical reactor systems have been explored in the past. A comparatively simple gaseous nitrogen system was applied to the F-86 and F-100 aircraft; neither system was used operationally. The F-86 system weighed 116 pounds and provided 8.8 minutes of purging at 35,000 feet for both fuel tanks and fuel tank cavities. The F-100 system weighed 42 pounds and provided 35 minutes of purging at 20,000 - 30,000 feet for fuel tanks only. Requirements for fuel tank inerting became firmly established as a result of the staggering aircraft losses in the Southeast Asia (SEA) conflict. Thousands of fixed and rotary wing aircraft were lost due to enemy groundfire ranging from .30 caliber small arms fire to large anti-aircraft artillery (AAA) to surface-to-air missiles. Analysis indicates that fuel system fire and explosion was the major cause of aircraft losses due to ballistic impacts.

In 1968 an expedited effort to modify various aircraft with a reticulated polyurethane foam filler material was pursued by the Air Force. The foam is installed within the fuel tanks and prevents an explosion by removal of energy from the combustion process through absorption of heat and mechanical interference. Large numbers of several types of aircraft including the F-105, C-130, and F-4 were modified. However, the majority of these aircraft did not reach service in SEA until near the end of the conflict.

Present day attitudes towards aircraft survivability are that the fuel system design, (fuel tanks) must be protected. The latest technology in defense concepts for fuel tank inerting encompass several types of reticulated foam fillers, liquid nitrogen inerting systems such as deployed on the C-5A and halon tank inerting. Halon tank inerting is a relatively new technique for explosion protection of aircraft tankage, although halons have been used as fire extinguisher agents for some time. This concept has been fully developed by the USAF and the General Dynamics Corporation, Fort Worth, Texas, and deployed on the F-16 airplane. The purpose of this paper is to describe the developmental history and initial operating experience of the F-16 system.

Background

Properties of Halon 1301. Halon 1301 (bromotrifluoromethane) is a colorless, odorless gas with a chemical formula of $CBrF_3$. The military specification is MIL-B-12218. It is a highly effective fire extinguishing agent with widespread commercial and military application for protection of electrical hazards, engines, ordinary combustibles and liquid and gaseous flammable materials. Normally, Halon 1301 is compressed for convenient storage and shipped as a liquefied gas. The liquid density is 13.1 lbs/gallon at 70°F. It is a low-boiling substance with a freezing point of -270°F and a boiling point of -72°F at 1 atmosphere pressure. The variation of vapor pressure with temperature is shown in Figure 1. The mechanism by which Halon 1301 acts as a fire suppressant is not fully established. One theory is that CF_3Br chemically interferes with the combustion process.[1] As a chemical change to the hydrocarbon/air mixture occurs with the introduction of an ignition source, complex transient combustion products are formed. The Bromine (Br) radical that is freed during thermal decomposition of Halon 1301 is considered to react with these transient products and interfere with the intermediate combustion process to halt the development of an explosion. A relatively small amount of Halon 1301 is needed to produce this effect.

Halon 1301 is the safest extinguishing agent currently available with an Underwriters' Laboratory (UL) rating of 6 (least toxic group classification). Numerous animal tests and actual human exposures have demonstrated this low exposure and inhalation toxicity. Because of the low toxicity, Halon 1301 has found widespread application for protection of inhabited areas.

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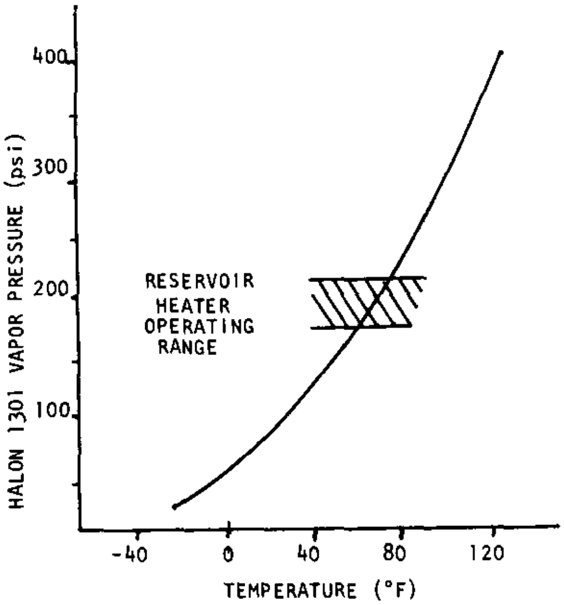


FIGURE 1. VAPOR PRESSURE VARIATION

<u>F-16 Trade Studies</u>. In 1974, the Air Combat Fighter Transition Program accomplished a study to determine the desirability of fuel system survivability improvements in the F-16 and F-17 with emphasis on preventing a fuel tank explosion if any tank were to be hit by enemy gunfire during air-to-air or air-to-surface combat. As the study progressed, the combat effectiveness improvement desirability was determined for each airplane. Four inerting techniques were evaluated by the F-16 contractor, General Dynamics, for the F-16: foam filler materials, a chemical extinguishing system and liquid and gaseous nitrogen inerting.[2] Following this study a follow-on trades study involving two foam configurations, nitrogen inerting and halon inerting were evaluated.

The initial study assumed that the tanks would be filled with type III (red color) polyurethane foam per MIL-B-83054 at a 70% fill ratio. The follow-on studies considered a 100% fill ratio as well. Recognized advantages of the foam technique included:

a. No servicing required.
b. Full-time protection--(take-off to landing).
c. No components to fail.
d. Air Force experience with foam in many aircraft applications.

Disadvantages listed were:

a. Significant penalty to aircraft performance.
b. The increased maintenance task of removing foam pieces for access when changing items located in fuel tanks.
c. The foam had to be replaced every two to five years when it began to deteriorate.

The chemical extinguishing system that was considered was an active explosion suppression system comprised of an infra-red detector unit, a chemical container and a self test electronic device. The detector senses the incendiary projectile or the initial explosive flash and activates a squib to release a chemical (Halon 2402) to suppress the fire. This system was proposed for the F-16 fuselage tanks only. The reticulated foam was to be installed in the internal wing tanks because of the dense structure and lack of access. Approximately ten sensors and fifteen chemical containers were considered necessary to provide adequate tank coverage. Concerns with this type of system are the anticipated frequent maintenance, the possibility of false firings and the unproven capabilities of the system in terms of reaction times against incendiary threats.

FIGURE 2

F-16 TANK EXPLOSION SUPPRESSION TRADES STUDY

CONCEPT	FULLY PACK FOAM	70% PACK FOAM	CHEMICAL EXTINGUISHER AND FOAM	LIQUID NITROGEN	GASEOUS NITROGEN	HALON 1301
Factor						
Weight increase	166#	116#	84#	55#	93#	25#
Usable Fuel Decrease	341#	238#	51#	0	25#	0
*Performance Ranking	6	5	4	2	3	1
Cost Ranking	3	2	6	5	4	1
Effectiveness Ranking	1	5	6	3	2	4

*Aircraft Performance Penalties (Least Impact to Most Impact)

The proposed liquid nitrogen system provided a service connection to mate with a hose coupling from a ground servicing unit. After servicing, a regulator allowed nitrogen to flow to an auxiliary heat exchanger until the dewar pressure was raised to a pressure of 200 psig. When the fuel tank inerting selector switch was placed to "ON" by the pilot, the high dewar pressure forced liquid nitrogen to the fuel/nitrogen heat exchanger where the nitrogen was vaporized. Gaseous nitrogen would then flow to the internal tank pressure vent and control valve so that the tanks could be pressurized to operating pressure with the nitrogen gas and an effective inert atmosphere obtained. The disadvantages of this system were (1) the large number of active components, (2) the investment required for LN_2 servicing trailers, (3) the need for periodic reservicing of airplanes on alert for several days, and (4) a decision to inert must be made by the pilot prior to take-off. The gaseous nitrogen system included four 450 in^3 reservoirs charged to 3000 psi and isolated from each other by check valves. A pressure gauge was provided for each reservoir near a single service connection. A two stage regulator was proposed to reduce the line pressure and allow the plumbing to be designed for a lower pressure.

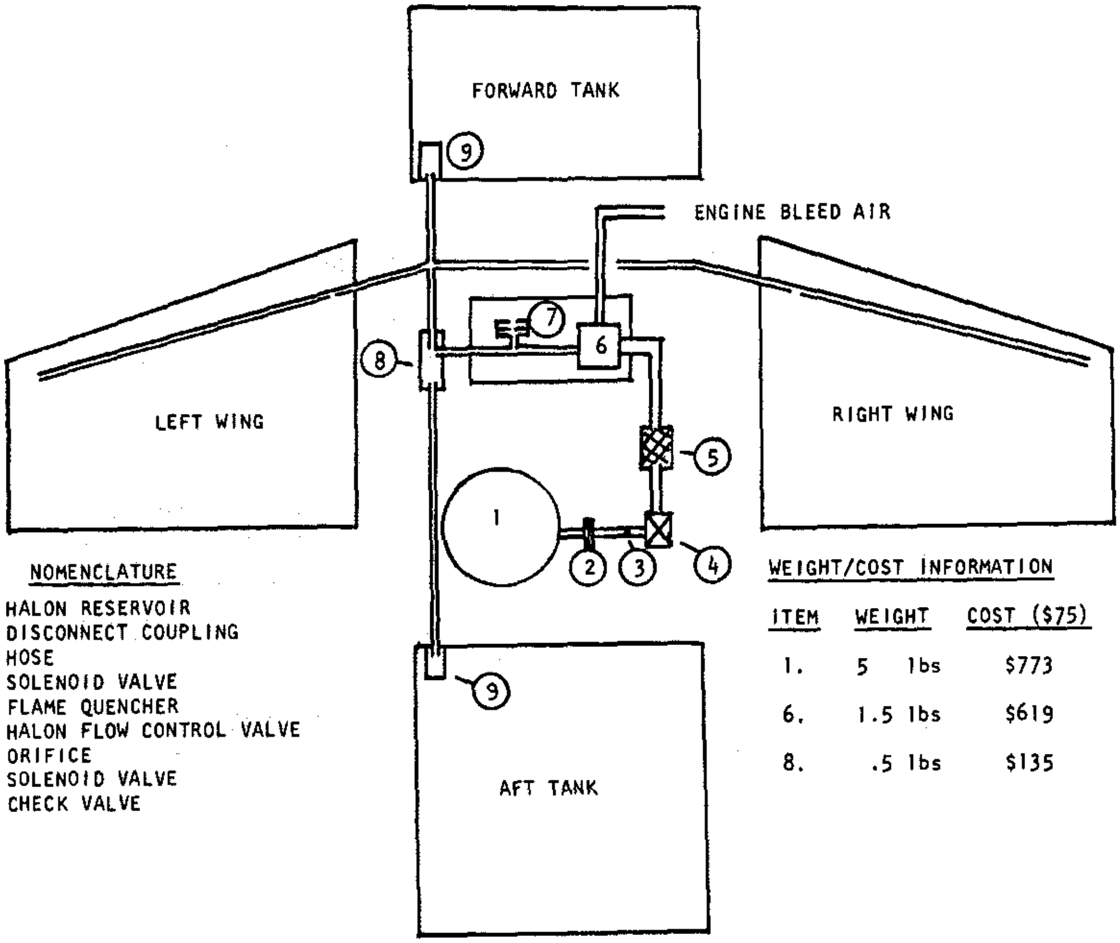
The proposed Halon 1301 inerting system included a 300 in^3 reservoir enabled by a fuel tank inerting selector switch in the cockpit. Based on the predicted low weight and performance penalties, this system was eventually chosen for development and is described below. A comparison of these studies is shown by Figure 2.

System Development

Description of the F-16 Inerting System. The F-16 aircraft is currently being delivered with a Halon 1301 fuel tank inerting system. This system is shown schematically by Figure 3. The system consists of a halon tank reservoir, a halon flow control valve, solenoid operated shutoff valves and associated plumbing, electrical wiring and switches. The halon reservoir is located in the wheel well area for easy access and rapid turnaround. The volume of the halon reservoir is specified at a maximum of 340 cubic inches and the reservoir is pressurized by the vapor pressure of the halon which varies from 560 psi at 150°F to 17 psi at -40°F. A 400-watt heater is installed to maintain reservoir pressures, (refer to vapor pressure diagram, (Figure 1). A window with a ball float is incorporated into the

FIGURE 3.

F-16 INERTING SYSTEM SCHEMATIC



NOMENCLATURE

1. HALON RESERVOIR
2. DISCONNECT COUPLING
3. HOSE
4. SOLENOID VALVE
5. FLAME QUENCHER
6. HALON FLOW CONTROL VALVE
7. ORIFICE
8. SOLENOID VALVE
9. CHECK VALVE

WEIGHT/COST INFORMATION

ITEM	WEIGHT	COST ($75)
1.	5 lbs	$773
6.	1.5 lbs	$619
8.	.5 lbs	$135

reservoir tank to provide a liquid level indication at 235 cubic inches volume without the need for aircraft or ground electrical power. The reservoir also contains an integral pressure relief valve to relieve reservoir pressure at 600 psig, a threaded refill port with a zero leak valve for servicing and a quick disconnect at the outlet port. The halon reservoir is mounted in the aircraft with locator pins and can be readily removed during the combat turnaround and replaced with a fully serviced unit. This can be accomplished simultaneously with the aircraft fueling.

Upon selection of "Tank Inerting" on the fuel control panel in the cockpit, the halon system is activated. Electrical signals are provided to the halon shutoff valve located in the vent tank to allow halon to flow to the fuel tanks, to the initial inert solenoid valve to open and to the internal tank vent and pressure control valve to reduce internal aircraft pressure. An airflow within the tanks is produced as the internal tank pressure is reduced from roughly 5.5 psig to 2.0 psig and air is vented overboard. This assists in the distribution of halon gas throughout the vapor space above the fuel. The initial inert valve opens for 20 seconds to permit a quick dump of halon into the forward, aft and internal wing tanks on the F-16. An inert atmosphere is quickly obtained. The halon flow control valve then mixes pressurization air from the environmental control system with Halon 1301 to maintain an inert atmosphere at proper regulated values as fuel is consumed or the aircraft changes altitude. Some of the halon supplied to the tanks is absorbed by the fuel. This is replaced by a continuous bleed of halon through an orifice in the vent tank plumbing.

In the unlikely event that fuel or fumes should leak backwards into the reservoir and be ignited by the heater, it was theorized that a fire could propagate to the aircraft fuel tanks. In order to protect against this possibility, a flame arrestor is installed in the reservoir outlet line. A weight and cost description of major items of the F-16 system is included in Figure 3.

Development Tests and Analyses. A comprehensive test and analysis program was conducted to develop the F-16 halon system. Material compatibility tests, gunfire tests and F-100 engine component tests were performed as well as environmental and safety analyses.

The compatibility of F-16 fuel tank materials with Halon 1301 was determined by testing at the General Dynamics Corporation.[3] The results of these tests showed no effect or very minimal effect as a result of halon exposures. Fuel tank sealants per MIL-S-83430 were exposed to 10% and 100% concentrations for a period of 100 hours with no reduction in peel strength or adhesion. The MIL-C-27725 polyurethane fuel tank coating was evaluated by salt spray after exposures to the 10% and 100% halon concentrations, and there was no corrosion evidenced. An increase in fluorosilicone O-ring volume from .5 to .7 percent was realized when exposed to the 100% concentration; volume increase at the 10% concentration averaged .14% and decreased with time. There was no change to the dielectric constant of JP-4 or JP-8 fuels and no effect on refuel shutoff valve float materials, viton seals, and fuel quantity cable assemblies.

The engine component tests were performed at Pratt & Whitney Aircraft Company, Government Products Division, West Palm Beach, Florida and at vendor facilities.[4] Except for an increase in flash point and an increase in vapor pressure from 2.4 to 3.9 psi, the properties of the JP-4 fuel were not significantly affected. There was no effect on the thermal stability of the fuel. Main burner ignition tests were performed using JP-4 and JP-5 with no halon and a 1% Halon 1301 concentration. The lean lighting limits were unaffected. F-100 engine augmentor ignition rig tests were also performed at simulated sea level, .8 Mach Number/20,000 feet altitude, .8 Mach Number/40,000 feet altitude and .8 Mach Number/54,000 feet altitude test conditions. Neither the rich nor lean light-off limits were affected and the augmentor steady state ignition bucket width was not significantly affected. Tests were also conducted in an erosion rig to determine the effect, if any, of burning fuel containing 1% Halon 1301 on hot section parts and materials. Samples of materials were slowly rotated in a 2100° gas stream, then allowed to cool for 5 minutes. This exposure was repeated 100 times. No differences were noted between samples exposed to JP-4 without halon and the 1% JP-4/halon mixture. Specific component evaluations were conducted on the F-100 main fuel pump and the F-100 Unified Fuel Control. These parts were selected because of their sensitivity to fuel properties. In both cases, there was a negligible effect on both hardware materials and component operation. Pump performance during calibration and acceptance tests remained unchanged when Halon 1301 was added to the fuel. Vapor to liquid (V/L) tests on the pump showed that the rate of cavitation was not increased by the addition of halon and that the V/L performance was comparable to normal JP-4 even with the increase in vapor pressure.

Solubility characteristics of Halon 1301 in JP-4 and JP-8 fuels were evaluated by General Dynamics.[5] A simulated fuel tank system was constructed and tests were conducted to determine the amount of Halon 1301 absorption into fuel where the halon is injected into the vapor space above the fuel. The exposed liquid surface was varied according to the aircraft fuel tank sequencing and halon concentrations of 8%, 15% and 22% by volume were examined at 0°F and at 78°F. Higher concentration levels were reached at the 0°F temperature. For a one-hour exposure at 0°F, the maximum amount of halon absorbed into JP-8 was .03% by weight and .17% by weight for JP-4. Thus Halon 1301 is more soluble in JP-4 than in JP-8, and for a 60-minute exposure, concentrations are 7% or less of the saturation levels.

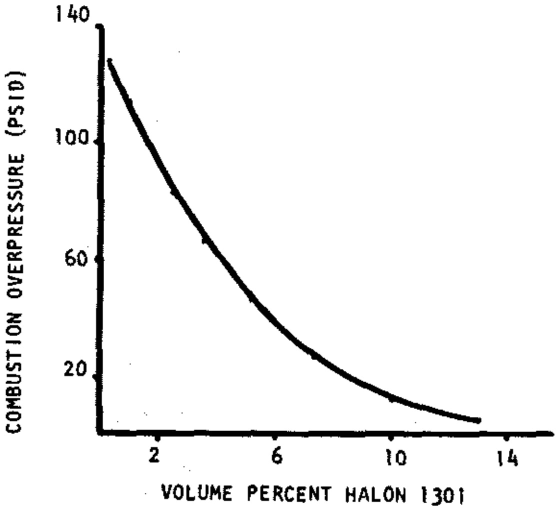
Ballistic testing for the F-16 was conducted by the Aeronautical Systems Division and the Air Force Aero Propulsion Laboratory at Wright-

Patterson Air Force Base. Test parameters included 4-5 volume percent propane in air and Halon 1301 concentrations of 6 to 13 percent by volume. The test fixture was a rectangular, metal tank with a volume of approximately 105 gallons. The tests were conducted using .50 caliber armor piercing incendiary (API) gunfire at tank pressure levels corresponding to the F-16 inerting system pressure levels. The test data is graphically represented by Figure 4. Subsequent testing at the Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio indicates that a 20% by volume concentration of Halon 1301 is required to prevent significant combustion overpressures caused by 23 mm high explosive incendiary threats.

Several environmental studies have been prepared. The effects on stratospheric ozone, toxic exposure to ground personnel and pilot, and exhaust smoke visibility were considered. Stratopheric ozone plays an important environmental role as a filter against harmful solar ultraviolet radiation. It also is a major contributor to climatic conditions on the earth's surface. CF_3Br will react with ultraviolet light to split off a bromine (Br) atom which is recognized as an efficient destroyer of ozone. However, the chemistry indicates that of 12 potential bromine reactions, only 2 involve "active bromine." The predominant reaction in the atmosphere is undetermined. And it has been estimated that only 10% of the CF_3Br released at the surface will reach the stratosphere because the troposphere tends to cleanse itself of bromine. HBr is known to be water soluble and will be washed out of the troposphere. For these reasons, it is not possible to make an accurate quantitative assessment of the environmental impact of the F-16 system. However, a qualitative assessment was performed by the Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts.[6] The study assumed a peacetime F-16 emission rate of 1×10^6 pounds per year. This represents 2000 aircraft worldwide, with a system activation of 3 times per month per aircraft. Using this base, the ratio of bromine atoms released from F-16 CF_3Br to those released from natural sources is calculated to be 5.8×10^{-4} or about .058% of the natural bromine source. This is confidently considered to be too small a contribution to have any measurable environmental impact. Since the F-16 system is used only for actual combat, test operations and landing gear emergency landings, the usage rate assumed in the referenced study is quite conservative. There were about 40 system activations in the first six months of 1980.

Halon Reservoir Qualification. The halon reservoir is designed to meet the general requirements of MIL-R-8573 (nonshatterable steel reservoir). The qualification of the heater contained within the reservoir included a limit on heater surface temperature and outside reservoir temperature for personnel handling reasons. These temperatures were exceeded with the first reservoir design and changes to the heater and thermal switch arrangement were made to resolve the problem. The reservoir also developed cracks at the discharge port weld joint and main mounting bracket during vibration testing. Successive design changes were implemented in the support backets and pivot legs to strengthen these failure points. A gunfire test was required to verify that the halon reservoir will not shatter if hit by enemy gunfire. Two units were tested. The first reservoir was filled with Halon 1301 and tested at normal reservoir pressures. The projectile was tumbled to produce an entry hole at least 1/2 inch wide by 1 inch long. This unit remained intact when tested. A second specimen tested at the reservoir relief pressure for information was torn in several pieces.

FIGURE 4. GUNFIRE PERFORMANCE



System Tests. An F-100 engine endurance test was conducted using a fuel with Halon 1301 at Patt & Whitney Aircraft Company.[4] There were no functional problems observed during the test and no wear or lubricity-oriented problems noted upon post test teardown of the main fuel pump, controls, and sensors. The test consisted of a series of high Mach number cycles with an acceleration from Mach number 1.6/35,000 feet altitude to Mach number 2.3/40,000 feet altitude. The fuel was heated to 200°F for a portion of the test to determine the possible cavitation effects on the main engine fuel pump. The test was completed with the following:

Total run time	75.6 hours
Intermediate Power	32.7 hours
Mach number 1.6	10.2 hours
Mach number 2.0	5.2 hours
Mach number 2.3	1.0 hours
Hot fuel	43.0 hours
Augmentor	10.7 hours

A static functional test was accomplished on F-16B SN0751 to determine the normal system operating characteristics. The airspace above the fuel level (tank ullage) was sampled periodically with evacuated 4-oz. bottles. Each sample was taken by opening a pinch clamp on the sample bottle for approximately 3 seconds and analyzed for Halon 1301 content using a Perkin-Elmer Model 800 gas chromatograph with a differential flame ionization detector. The test was arranged so that the initial inert time could be varied to provide a 20-second and a 40-second exposure, and a simulated mission profile could be performed. These results indicated that the halon concentrations were below target during the initial inert sequence and during a portion of the simulated combat mission. The halon flow control valve was subsequently modified to raise the halon to air mixture ratio and another series of tests was performed on F-16A SN 0750. This testing demonstrated that the halon inerting system generally provided the required concentrations and with the exception of the aft tank, target concentrations were met or exceeded.[7] All inerting system tests were conducted at sea level atmospheric pressures as a worst case condition. At altitude, the partial pressure of the air in the fuel tanks will be reduced whereas the partial pressure of the halon gas would remain approximately the same. Thus, an increase in halon gas concentration with altitude can be anticipated. Results of a combat mission simulation on F-16A SN 0750 with high engine fuel flows is provided in Figure 5. Halon concentrations in the fuel at the engine inlet varied during the simulation to a maximum of .30 pounds of halon per 100 pounds of fuel. Following these tests, the aft tank distribution line was modified to improve the halon concentration in the aft tank.

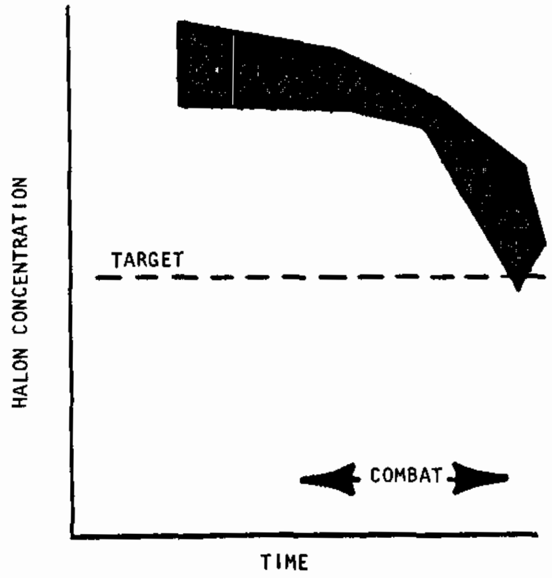
OPERATIONAL EVALUATIONS

Operational Evaluation. Since the F-16 fuel tank inerting system is to be used only during actual combat conditions and emergencies, experience with the system is not obtained through normal service usage. In order to verify operation, function, and system reliability in the operational environment, a limited flight evaluation was accomplished. Twenty-two effective sorties were flown on several airplanes. These flights were conducted to duplicate air combat manuevers and the halon system was activated at the "forward edge of battle area" (FEBA) to simulate combat conditions. The average time that halon was used per sortie was 30.0 minutes. The system was verified during aerial refueling and with and without external tanks installed. The average time to remove, service and reinstall the reservoir was placed at 15 minutes. F-16 fuel system operation was unaffected and the pilot interface and human factors were deemed satisfactory.

One minor but interesting problem was encountered during an airplane acceptance flight. The forward tank check valve stuck open and allowed fuel to flow to the aft tank. This created a fuel inbalance on the airplane. The rate of imbalance was constant until the fuel level in the forward tank dropped below the level of the check valve. The stuck check valve was discovered only after a considerable troubleshooting effort. The only significant operational problem experienced to date with the system is a severe rusting of the sight glass ring. An engineering change to the metal plating has been processed.

FIGURE 5

HALON TANK INERTING SYSTEM
FUNCTIONAL TESTS



FUTURE APPLICATIONS

The primary design considerations for any fuel tank inerting system are the type of mission, duration of coverage, level of protection, and effect on the fuel system. For cargo, tanker and passenger applications where the need for a full-time halon inerting system may be important, the environmental issues should be further examined. Bromine chemistry needs to be studied in detail and perhaps some tests accomplished before a full-time, operational, peacetime system is adopted. For a fighter application where weight is of prime importance and the need for full-time inerting during peacetime is not a necessary requirement, then a halon inerting system similar to that installed on the F-16 aircraft is a very likely candidate. The F-16 program has demonstrated that a lightweight halon inerting system can be produced for combat that is compatible with fuel system and engine operation. The concept is also considered practical for a strategic bomber application. Consider as an example, a new bomber with 75,000 pounds fuel capacity and a mission that includes a 30,000 foot altitude outbound cruise, a 4,000 foot altitude penetration and bombing run, and a return leg again at 30,000 foot altitude. A weight estimate for a halon inerting system for this hypothetical airplane has been calculated and is shown below assuming 25,000 pounds of JP-4 fuel is consumed during each mission segment. The estimate shows that the inerting system weighs 1.9 pounds for every 100 gallons of fuel. This compares to 2.8 pounds per 100 gallons for the F-16 fighter. The smaller number of altitude changes projected for the bomber in the combat arena is responsible for the lower weight ratio.

FIGURE 6

WEIGHT ESTIMATE FOR STRATEGIC BOMBER

● Initial Inert	22 lbs. Halon
● Make-up Requirements & Bombing Run	104 lbs. Halon
● Reserves	7 lbs. Halon
● 3 Reservoir Tanks	45 lbs.
● Plumbing/System	42 lbs.
TOTAL WEIGHT ESTIMATE	220 lbs.

In conclusion, the F-16 development has shown that a halon inerting system for aircraft fuel tanks is practical for most combat aircraft applications and can be deployed with a minimal effect on engine and aircraft performance. The size and weight of a halon inerting system will be determined by mission variables and the anticipated threats, but generally an effective and lightweight system can be designed.

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