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Cargo Compartment Fire Protection in Large commercial Transport Aircraft

David Blake
Timothy Marker
Richard Hill
John Reinhardt
Constantine Sarkos

U.S. Department of Transportation
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NOTICE

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16. Abstract

This report describes recent research by the Federal Aviation Administration (FAA) related to cargo compartment fire protection in large transport aircraft. A gaseous hydrofluorocarbon, HFC-125, was compared to Halon 1301 in terms of fire suppression effectiveness and agent decomposition levels in the cargo compartment and passenger cabin during full-scale tests involving a bulk-loaded cargo fire. Also, a zoned water mist system was designed and evaluated against a bulk-loaded cargo fire. An exploding aerosol can simulator is being developed to provide a repeatable fire threat for evaluation of new halon replacement agents. The potential severity of an exploding aerosol can inside a cargo compartment and the effectiveness of Halon 1301 inerting was demonstrated. Tests were also conducted to determine the effectiveness of Halon 1301 against a cargo fire involving oxygen canisters. Finally, HFC-125 was evaluated for use as a simulant for Halon 1301 during cargo compartment approval testing to demonstrate compliance with applicable FAA regulations.

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EXECUTIVE SUMMARY

This report describes recent research by the Federal Aviation Administration (FAA) related to fire protection in cargo compartments of large commercial transports. A background section includes a discussion of the rarity of cargo compartment fires, examples of fatal fires (Saudia, 1980 and ValuJet, 1996), and current and proposed Federal Aviation Regulations for cargo compartment fire protection. The International Halon Replacement Working Group (IHRWG) provides a forum for participation and input by the aviation industry, foreign regulatory authorities, and other government agencies in the FAA's research to evaluate and develop standards for new extinguishing agents. A working draft minimum performance standard for replacement agents in cargo compartments, developed by the IHRWG, identifies four cargo fire threats for agent evaluation: bulk-loaded cargo, cargo containers, surface burning, and exploding aerosol cans.

Recent FAA tests have evaluated HFC-125, a gaseous hydrofluorocarbon, and a water mist against bulk-loaded fires of 90-minute duration which is representative of a long emergency landing time during a transoceanic flight. A baseline test with Halon 1301, which is currently used by the airlines, effectively suppressed a bulk-loaded fire for 90 minutes by employing a metered concentration of 3% (cup burner value). A similar test with HFC-125 used a concentration of 8.8% (cup burner value), almost a factor of three greater than the volumetric concentration of Halon 1301 needed for fire suppression. During the fire suppression phase of the test with HFC-125, an unexpected flashover occurred, raising the ceiling temperature in the cargo compartment to 900°F. By comparison, there was no flashover in the test with Halon 1301, or in numerous previous Halon 1301 tests, and the ceiling temperature was maintained below 420°F. The water mist system consisted of high-pressure, fine water mist nozzles installed in four zones within the cargo compartment. Water discharge in each zone was independently controlled and based on zone temperature measurements. The water mist system effectively controlled the bulk-loaded fire for 90 minutes, preventing ceiling temperatures from exceeding 300°F. Approximately 10-12 gallons of water were consumed.

Of the four previously indicated cargo fire threats, the most difficult to simulate in a repeatable and controllable manner is the exploding aerosol can fire. Previous fire tests with toiletry aerosol cans have shown a large variation in the time and intensity of the aerosol can failures. Because of this variability, an exploding aerosol can simulator was developed that provides a repeatable fire threat for evaluation of new agents. Basically, the simulator consists of a high-pressure, high-temperature, quick-opening valve which discharges and ignites a measured quantity of hydrocarbon propellant. The current test conditions simulate a worst-case aerosol can failure. It was shown that inerting a cargo compartment or cargo container with Halon 1301 prevented the intense, simulated aerosol can explosions. This finding provides further evidence of the effectiveness of the current Halon 1301 fire suppression systems against severe cargo fire threats.

Although not a proposed cargo fire design requirement, cargo fire tests involving oxygen canisters similar to those that are believed to have been the cause of the ValuJet accident, were conducted to evaluate Halon 1301. The test results were mixed. In one test the ceiling liner was penetrated and the test was terminated. However, several tests demonstrated a benefit from Halon 1301, which was highly dependent upon the detection time and cargo compartment

geometry. When the fire was detected early, Halon 1301 limited the number of activated oxygen generators to a few by suppressing the burning of packaging materials and preventing the destructive high-temperature (3300°F) fire plume associated with the progressive activation of a large number of canisters. Even when all the generators were activated in a large cargo compartment fire test, the presence of Halon 1301 prevented the extremely high ceiling temperatures that were previously measured in an uncontrolled fire plume. This finding appears to be related to the distance from the cargo to the ceiling and the ability to sustain minimal concentrations of Halon 1301 in the upper part of the compartment.

Finally, HFC-125 was evaluated for use as a simulant for Halon 1301 during cargo compartment approval testing. A simulant is desirable to reduce the discharge of ozone-depleting halons into the atmosphere. Concentration histories for the two agents were compared in a small cargo compartment test article at various sampling locations and various air leakage rates. The results indicated that HFC-125 was a suitable simulant. Moreover, it was determined the agreement in measured concentrations improved at higher leakage rates.

INTRODUCTION

Cargo compartments in large transport aircraft present a potentially severe fire problem because of the large quantity and great variety of combustible materials carried in passenger luggage, mail, and cargo, including hazardous materials. In large transport aircraft, the cargo compartments are located in the belly of the aircraft beneath the floor of the passenger cabin, requiring built-in design features such as burnthrough-resistant ceiling and wall liners and fire detection and suppression systems. The purposes of these design features are to contain the fire within the cargo compartment, protect flight critical systems, and prevent passengers and crew from being subjected to hazardous quantities of smoke and toxic gases so the aircraft can be landed safely.

FEDERAL AVIATION REGULATIONS.

The Federal Aviation Regulations (FAR's) [1] describe the aviation safety certification requirements issued by the Federal Aviation Administration (FAA). The sections applicable to cargo compartment fire protection in transport aircraft are FAR's 25.855, 25.857, and 25.858. FAR 25.855 contains the requirements for burnthrough-resistant cargo liners specified for under floor cargo compartments, elimination or protection of any items whose damage or failure would effect safe operation, and flight tests to demonstrate (1) the exclusion of hazardous quantities of smoke, toxic gases, or extinguishing agents into occupied compartments and (2) the attainment of extinguishment or inerting agent levels as well as other safety features. FAR 25.857 defines cargo compartment classifications dictated primarily by crew proximity, accessibility, and size consideration. Finally, FAR 25.858 contains the broad requirements for cargo compartment fire detection systems. An important requirement contained in FAR 25.858 (a) is that detection must occur within 1 minute after the start of a fire.

Currently, cargo compartments in large transport aircraft satisfy the provisions of either Class C or Class D compartments. Both compartment classes require burnthrough-resistant cargo liners. The primary distinction lies in whether a detection and suppression system is also required. Basically, a Class C cargo compartment is in excess of 1000 cubic feet in volume and requires a built-in detection and extinguishing system with the agent discharge being controlled from the flight deck. Class D cargo compartments are less than 1000 cubic feet in volume, with prescribed allowable air leakage rates, and contain a fire by oxygen starvation. For the most part, Class D compartments are found in older, narrow (standard) -body aircraft. As discussed later, the FAA has proposed the elimination of Class D compartments.

HISTORY OF CARGO FIRES.

Cargo compartment fires are rare events. Over the 20-year period ending in 1996, a compilation of cargo fire incidents and accidents indicates an annual average of approximately 4 events, ranging from a high of 11 in 1990 to a low of 1 in 1982. [2] The data are based on FAA service difficulty reports, FAA accident and incident reports, information from the FAA Hazardous Materials Program Office, aircraft manufacturers databases, and National Transportation Safety Board (NTSB) accident reports. The majority of the events occurred while the aircraft was on the ground during the loading, unloading, or sorting of baggage, cargo, and mail. In these cases,

there was little or no aircraft damage and no injuries. Recurrent ignition sources include spilled chemicals, matches, electrical short circuits, incendiary devices, oxygen canisters, and heat exposure to sources within the cargo compartment, including lighting, drain heaters, heated blankets, and heat ducts or shrouds.

The occurrence of cargo fires in flight is far smaller than the ground events. In a separate study, there were 19 in-flight accidents/incidents involving Class C and Class D compartments for the same 20-year period. [3] Based on the number of departures during this period, the event rate for in-flight cargo compartment fires is approximately 0.085 per million departures, or one event for about every 12 million flights. Three of these events were fatal fires (table 1) resulting in 523 fatalities, as summarized below:

a.   Saudia L-1011. The fire started in the aft Class D compartment, which was specially equipped with a ventilation system and smoke detectors to provide for the transport of animals. [4] The airplane was returned to Riyadh after the crew became aware of a fire from the cargo smoke detectors and smoke in the aft cabin. Unfortunately, because of the long delays in the crew action at many opportunities throughout the flight, including not ordering an evacuation immediately after landing, all 301 occupants died when a flash fire engulfed the cabin before any emergency exits could be opened.

b.   Gulf Air B737. All 172 occupants perished when this aircraft crashed in the desert. Evidence was gathered during the investigation that indicated an incendiary device caused an in-flight fire.

c.   ValuJet DC-9. Shortly after leaving Miami International Airport, Flight 592 crashed into the Florida Everglades, killing all 110 occupants. The NTSB investigation of the accident determined that an in-flight fire in the forward cargo compartment burned into the passenger cabin. A large number of chemical oxygen generators were improperly packed in cardboard boxes. Extensive burn damage and melting of the steel housings of the recovered canisters indicated that the canisters were the probable cause of the fire. [5] At the request of the NTSB, subsequent tests by the FAA demonstrated that the accidental activation of a single canister inside a cardboard box could ignite plastic packing materials, resulting in the progressive activation of the remaining canisters. The resultant fire plume impinging on the ceiling during the test was unusually severe, with the measured temperature exceeding 3300°F.

TABLE 1. FATAL IN-FLIGHT CARGO COMPARTMENT FIRES IN ALL-PASSENGER TRANSPORT AIRCRAFT

Date	Location	Operator	Airplane Model	Fatalities
8/19/80	Riyadh, Saudi Arabia	Saudia	L-1011	301
9/23/83	Abu Dhabi, UAR	Gulf Air	B737	112
5/11/96	Florida Everglades	ValuJet	DC-9	110

PROPOSED RULEMAKING.

On June 9, 1997, the FAA issued a Notice of Proposed Rulemaking (NPRM) to upgrade the fire safety standards for cargo compartments in certain transport aircraft by eliminating Class D compartments, i.e., the smaller compartments that depend upon oxygen starvation for fire control. [6] Compartments that could no longer be designated as Class D would require the installation of fire detection and suppression systems and would have to meet the standards of Class C compartments. A 3-year implementation period was proposed after the effective date of the final rule or by a projected date of early 2001. The FAA estimates that 2994 passenger airplanes would be affected by the proposed rule.

A primary consideration in the rulemaking proposal is the hazards associated with an exploding aerosol can. In order to contain an in-flight fire, a Class D cargo compartment depends on a relatively small amount of oxygen being available and the integrity and burnthrough resistance of the cargo liners to control a fire by oxygen starvation. However, if the fire should involve aerosol cans, which are most likely present in each piece of passenger luggage, the cargo liners may be damaged by an exploding aerosol can. The explosive nature of an aerosol can failure in a fire is caused by the hydrocarbon propellants such as propane, butane, and isobutane used in the aerosol. Full-scale fire tests showed that an aerosol can explosion could seriously damage or dislodge the cargo liners, rendering them ineffective in limiting the supply of oxygen to the fire. [7] Once the integrity of the liners is compromised, the unlimited supply of oxygen may allow a cargo fire to spread into other areas of the aircraft. Conversely, if the cargo compartment atmosphere is inerted with Halon 1301, the cloud of hydrocarbon gases released by the aerosol can failure will not ignite, posing no additional hazard. [7] Early detection will assure the discharge of halon into the compartment before any serious damage occurs due to failure of any aerosol cans placed in passenger luggage.

Airlines and aircraft manufacturers have indicated that they will continue to use Halon 1301 in fire suppression systems installed in retrofitted and new aircraft impacted by the pending rule. The preference to continue using halon is based on approximately 40 years of experience and familiarity with the agent and various drawbacks associated with available replacement agents such as increased weight, space requirements, and toxicity. The Environmental Protection Agency (EPA) has advised the aviation industry that it will not ban the use of halon used in complying with the pending rule over the lifetime of any current aircraft. At the same time, the EPA urged the industry and the FAA to continue research and testing of alternate agents until a suitable agent is found to replace halon.

INTERNATIONAL HALON REPLACEMENT WORKING GROUP

The FAA has a major program to evaluate and develop performance standards for halon replacement agents used in civil transport aircraft. [8] Impacted and interested organizations participate in the program by membership in the International Halon Replacement Working Group (IHRWG), chaired and administered by the FAA. [9] IHRWG membership is comprised of representatives from the aircraft manufacturers, regulatory authorities, airlines, agent suppliers, extinguishing system manufacturers, research organizations, other government agencies, and the military.

An important function of the IHRWG is the creation of task groups to address various issues or concerns related to the evaluation and use of halon replacement agents. A task group of 27 individuals, including regulators and members of the aviation industry, is currently working to finalize a minimum performance standard for cargo compartment replacement agents. The basic fire scenarios, as listed below, and the pass/fail criteria for these scenarios have been agreed upon by the task group:

- Bulk-loaded fire
- Cargo container fire
- Surface burning fire
- Exploding aerosol can fire

Three main areas are yet to be resolved. The first of these is all the detailed specifications that should be included in the test requirements. The second area still under discussion is how to treat the toxicity associated with the tests. The final unresolved area is the exploding aerosol can fire scenario. It is not yet known if an exploding aerosol can be realistically simulated or if actual cans need to be used. However, as discussed later, the FAA has made progress in the development of an exploding aerosol can simulator.

BULK-LOADED FIRE TEST RESULTS

HFC-125 (pentafluoroethane), a gaseous total flooding replacement agent, and a zoned water mist system were evaluated during full-scale cargo compartment fire tests against a bulk-loaded fire for a 90-minute test duration. The 90 minutes represents the worst-case landing time following the detection of a fire at the midpoint of a transoceanic flight.

HFC-125.

Two tests were conducted that compared HFC-125 and Halon 1301. The bulk-loaded fire consisted of cardboard boxes filled with shredded newspaper. This fire load comprised approximately 30% of the empty volume of the 2357-cubic foot cargo compartment of a DC-10 test article. In-flight airflow conditions were created to determine if the fire suppression system prevented passage of hazardous quantities of toxic gases into the passenger cabin. [7]

The fire was ignited by energizing a coil of nichrome wire that was placed inside a box on the bottom outside row of the stacked boxes. The fire load and ignition location were selected after a series of experiments were conducted to attempt to produce a fire scenario that would be suppressed but not extinguished by a typical Halon 1301 system. This type of scenario will yield the maximum information about the effectiveness of both halon and halon replacement agents because the smoldering suppressed fire has the potential to reignite if the agent concentration is not sufficient, and it will produce relatively large quantities of decomposition products from each agent tested. A surface burning fire that is readily extinguished would not provide that data.

A photoelectric aircraft smoke detection system, set at an alarm point of 94% light transmission per foot, was installed in the cargo compartment. The suppression system was activated 30 seconds after the smoke detector went off.

The suppression system consisted of an initial discharge of a fixed quantity of agent followed by a metered system that added agent to maintain a minimum concentration. The quantities for the initial discharge and the subsequent minimum design concentration that were maintained were based on the current industry practice of 5% initial concentration of Halon 1301 in an empty cargo compartment volume and a 3% concentration for the duration of the flight. The same ratio of initial concentration followed by maintaining the approximate cup burner concentration used with current Halon 1301 systems was used for the test with HFC-125. This ratio resulted in an initial concentration of 14.2% HFC-125 and a maintained concentration of 8.8%.

The quantity of agent needed for the initial concentrations was 46 lbs. of Halon 1301 and 104 lbs. of HFC-125. The quantity of agent needed to maintain the minimum design concentration for the 90-minute tests was not measured directly. However, based on the measured leakage rate of the compartment of approximately 60 cubic feet per minute, the quantity can be estimated. Using this approach, the approximate quantities needed to maintain design concentration for the duration of the 90-minute tests were 54 lbs. of Halon 1301 and 115 lbs. of HFC-125. The total quantities of each agent for both the initial discharge and the metered system were approximately 100 lbs. of Halon 1301 and 219 lbs. of HFC-125.

The results of these 90-minute tests were generally similar to previous shorter duration tests conducted with these agents. [8] The cargo compartment ceiling temperatures ranged from 300 to 450°F while the fires were suppressed and the oxygen concentrations were reduced to 10% to 15%. The depletion of oxygen was caused both by smoldering fires and the displacement of air by suppression agents. Figures 1 and 2 show the ceiling temperatures, oxygen concentrations, and agent concentrations measured in the cargo compartment for the tests with Halon 1301 and HFC-125, respectively. One anomaly was observed during the test with HFC-125. Shortly after the concentration from the initial discharge had decayed down to the cup burner value of 8.8% and the metering system had started, there was an ignition of combustible gases in the smoke layer above the cardboard boxes. The flame front progressed along the entire length of the compartment at the ceiling level. This caused a sharp rise in ceiling temperature and a drop in oxygen concentration. The fire was suppressed for the duration of the test after this event. A similar event had previously been observed in a test using HFC-125 with a containerized fire load. This type of behavior had not been observed with Halon 1301 or other gaseous candidate replacement agents. Further testing is planned in an attempt to understand this anomaly.

Of particular interest for these longer duration tests was the generation and accumulation of agent decomposition products in both the cargo compartment and in the normally occupied passenger cabin area above it. Figure 3 shows the hydrogen fluoride (HF) concentrations in the cargo compartment for the two tests. The values in the graph are the average concentrations of HF over each 10-minute interval. The higher concentrations of HF between 20 and 40 minutes with HFC-125 are due mainly to the open flame that was present when the combustible gases along the ceiling ignited. This open flame produced significantly more decomposition products than the smoldering suppressed fire. Previous testing showed higher concentrations of HF even where there was no ignition of combustible gases when HFC-125 was used as the suppression agent rather than Halon 1301. This result is expected because not only does HFC-125 contain more fluorine per molecule than Halon 1301, but higher concentrations of HFC-125 are also
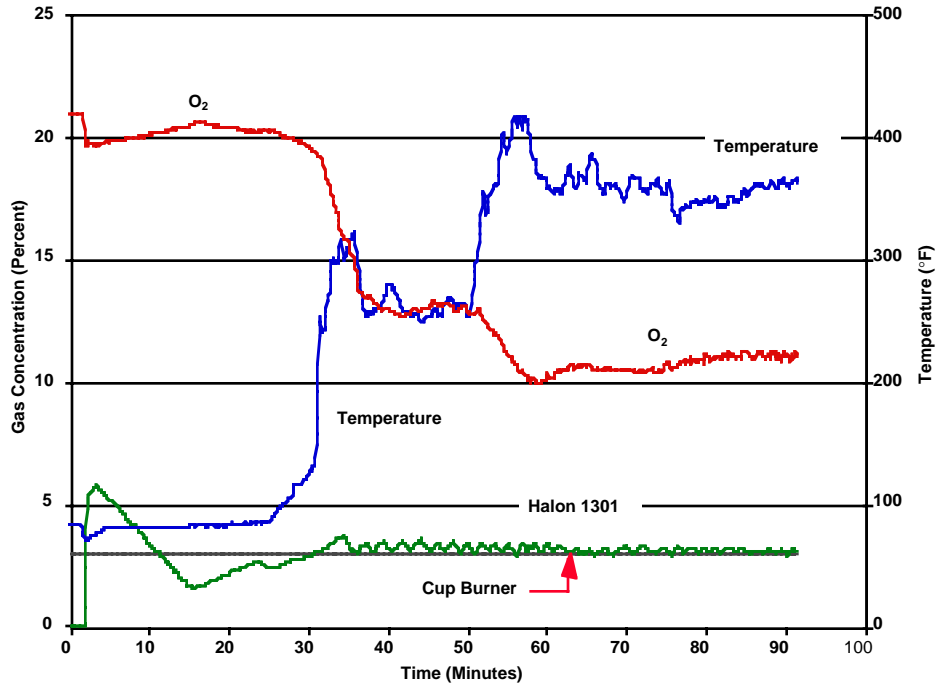
FIGURE 1. GAS AND TEMPERATURE PROFILES IN CARGO COMPARTMENT DURING BULK-LOADED FIRE SUPPRESSION TEST WITH HALON 1301
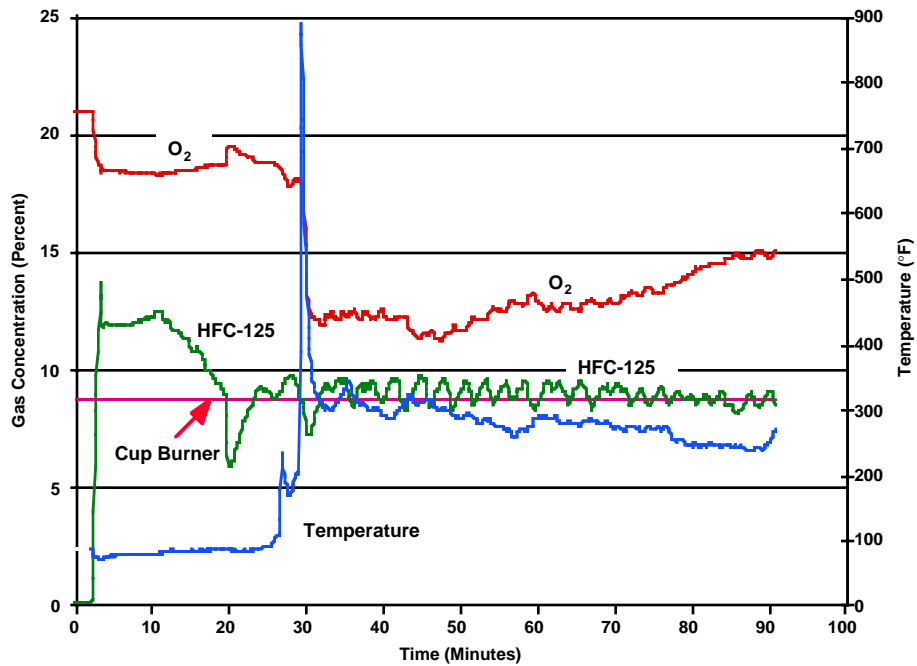

FIGURE 2. GAS AND TEMPERATURE PROFILES IN CARGO COMPARTMENT DURING BULK-LOADED FIRE SUPPRESSION TEST WITH HFC-125
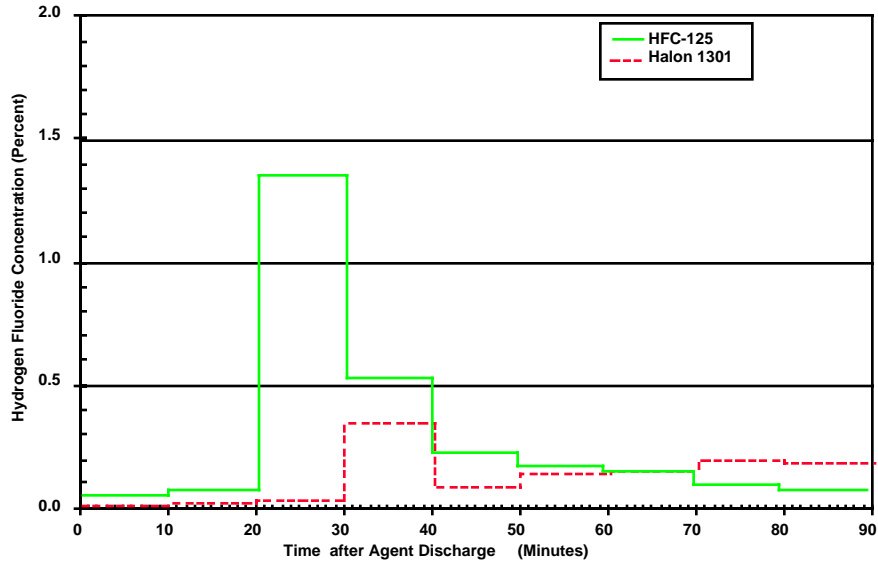
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FIGURE 3. HYDROGEN FLUORIDE PROFILES IN CARGO COMPARTMENT DURING
BULK-LOADED FIRE SUPPRESSION TESTS WITH HALON 1301 AND HFC-125

required compared to Halon 1301. Figure 4 shows the HF concentrations in the passenger cabin
above the cargo compartment. HF concentrations are again higher in the test with HFC-125 for
the same reasons as stated above. However, the data show that there is not a significant
accumulation of HF in the cabin area. The fuselage ventilation system exhausts the
decomposition products out of the cabin at a rate similar to the inflow rate of these products.
The measured levels for both tests were well below the maximum Occupational Safety and
Health Administration (OSHA) 15-minute exposure limit of 6 parts per million (ppm) and the
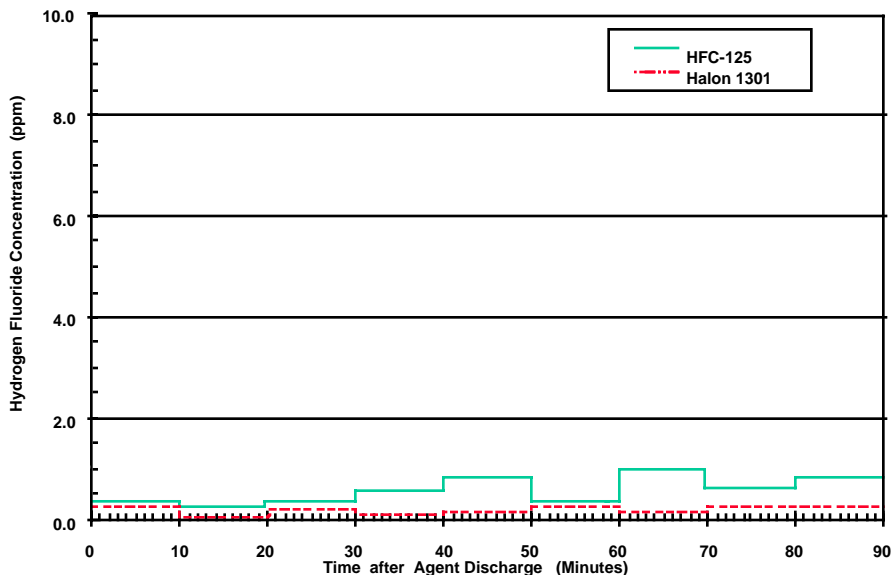Immediately Dangerous to Life and Health (IDLH) limit of 30 ppm.

FIGURE 4. HYDROGEN FLUORIDE PROFILES IN PASSENGER CABIN DURING BULK-
LOADED FIRE SUPPRESSION TESTS WITH HALON 1301 AND HFC-125

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A B727 aft cargo compartment test article was used to evaluate a high-pressure water mist system. The test article measured approximately 120 inches wide by 200 inches long at the ceiling (the floor of the compartment covered significantly less area due to the curvature of the fuselage). The compartment volume was approximately 550 cubic feet. The ceiling and sidewall were constructed of the original fiberglass cargo liners; the forward and aft bulkheads were made of aluminum. Two thermocouples trees were installed along the compartment centerline with three probes each located at 1-, 2-, and 3-foot levels. Video and photographic equipment were placed in the aft bulkhead to monitor test progress.

The water mist system was supplied by Environmental Engineering Concepts (EEC). These systems are commercially available under the trade names Microcool® and Enviromist® Fog Systems and are primarily used for environmental cooling and vegetable hothouse humidification. The system used for the cargo compartment testing was co-designed by the FAA and EEC and consisted of a high-pressure pump, four zone control valves, and the basic piping and nozzles. The water mist system, designed to minimize the amount of waste water by applying the mist to the areas of the fire, was divided into four zones that could be individually activated *(*see figure 5). Each zone contained 19 nozzles and covered an area of approximately 4 by 10 feet. The nozzles were oriented to spray mist both horizontally and vertically (down) to maximize mixing and coverage. The mist was automatically controlled by two thermocouples mounted in the ceiling of each zone. The control of the spray activation could be adjusted prior to each test. During the test, when either of the zone thermocouples exceeded the preset value, a signal was sent to open the zone control valve, discharging the mist in that zone. The water mist pressure was adjustable from 800 to 1200 psi, as supplied by an electrically driven pump.
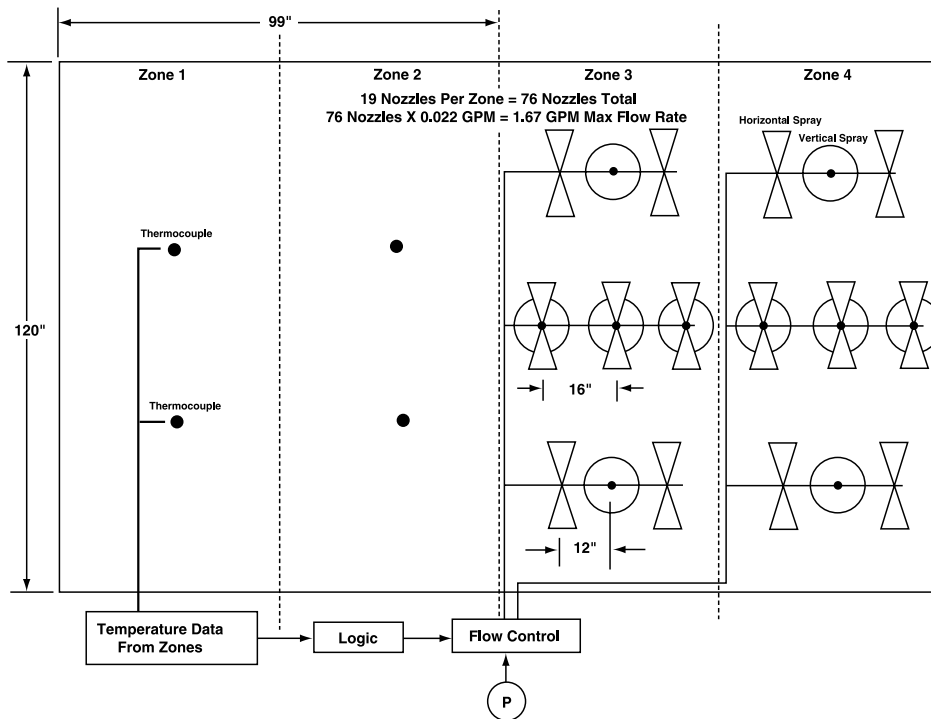

FIGURE 5. WATER MIST SYSTEM SCHEMATIC

After the initial shakedown tests were conducted to observe the operations of the system, a bulk-loaded test was configured. During the test, ten 18- by 18- by 18-inch boxes filled with shredded paper were loaded onto the floor of the compartment and a centrally located box was ignited. The system control parameters were preset to activate mist when the temperature exceeded 200°F and to deactivate when the temperature fell below 180°F. The fire was allowed to burn without intervention for 90 minutes, during which several of the zones cycled on and off dozens of times. At no time did any of the measured ceiling temperatures exceed 300°F. Approximately 10-12 gallons of water were discharged, which is only 7%-8% of the total quantity of water available if all nozzles were discharging throughout the 90-minute test.

EXPLODING AEROSOL CAN FIRE TEST RESULTS

In 1979, due to the ozone depletion potential of chlorfluorocarbons (CFCs), the manufacturers of aerosol cans began to replace the CFC propellants used in aerosol cans with hydrocarbons, including propane, butane, and isobutane, or combinations thereof. Although these flammable gases are not normally permitted on passenger flights, Title 49 of the Code of Federal Regulation provides an exception by allowing each passenger to carry up to 75 ounces of medicinal items, toilet items, and aerosols in checked luggage. It is now believed that the vast majority of checked passenger luggage will contain an aerosol can (hairspray, deodorant, shaving cream) using a hydrocarbon propellant. Previous FAA fire tests showed that aerosol cans subjected to a fire may explode violently [7, 10] and damage and/or dislodge the cargo liner. [7] The dual consequences of the loss in cargo liner integrity—an unlimited supply of air to feed the fire and a pathway for smoke and toxic gases to accumulate in the passenger cabin—are dangerous and totally unacceptable. Fortunately, it was shown that when the contents of a ruptured aerosol can are released into an atmosphere inerted with Halon 1301, an explosion will be prevented. Thus, the IHRWG specified that any replacement or alternative agents have an equivalent performance to Halon 1301 against an exploding aerosol can fire threat.

Two other approaches may be taken to negate the dangers of an exploding aerosol can. First, the exception for flammable hydrocarbons in passenger luggage could be lifted; however, this would appear to be impractical and impossible to enforce. The second approach is to improve the can design. Hydrocarbon propellants could be replaced with ozone-friendly hydrofluorocarbons or the aerosol can itself could be redesigned. An improved aerosol can design was developed under a Small Business Innovative Research (SBIR) study by Materials Engineering, Inc. (MEI) [11, 12]. The improved can design employed welded seams to double the burst strength and venting to provide the controlled release of the can's contents. FAA fire tests showed that the MEI can failed significantly later than a typical can and did not explode. [9] Any improved aerosol can design concepts would likely be costly due to the large number of aerosol cans manufactured each year for toiletries, approximately one billion cans in the United States.

DEVELOPMENT OF AN AEROSOL CAN SIMULATOR.

It is difficult to conduct fire tests using actual aerosol cans due to inconsistencies in the catastrophic failure sequence. In some tests, the metal can container did not completely fail, but slowly released the contents and produced a blowtorch effect. In other tests, the contents were released in a vapor cloud which produced the most explosive force. Combinations of the

blowtorch and vapor cloud explosion also occurred, as the flame front is dependent upon the ignition source as well as the rate of release of the flammable propellant. Moreover, it is often difficult to reliably predict when the rupture sequence will occur as the fire growth can differ from test to test which directly impacts the degree of heat transfer to the metal can surface. For these reasons, a simulation device was constructed which can replicate the worst-case exploding aerosol can fire scenario. A device was developed that was capable of storing and quickly releasing and igniting a specific quantity of hydrocarbon propellant and base product at any desired point in time.

The initial simulator design was a steel pipe pressure vessel mated to a high-rate discharge (HRD) electrically actuated solenoid valve (see figure 6). The vessel contained ports and valves to transfer the base product (initially isopropyl alcohol) and hydrocarbon propellant (typically propane). The contents are heated by blowing a hot-air gun against the surface of the steel vessel, effectively raising the pressure of the contents. When the pressure was sufficient to burst a standard strength can, approximately 210 psig, the contents were released over a set of direct current (dc) spark igniters. A high-voltage transformer produced the electric spark to bridge the 1.2-cm gap between the pair of electrodes.
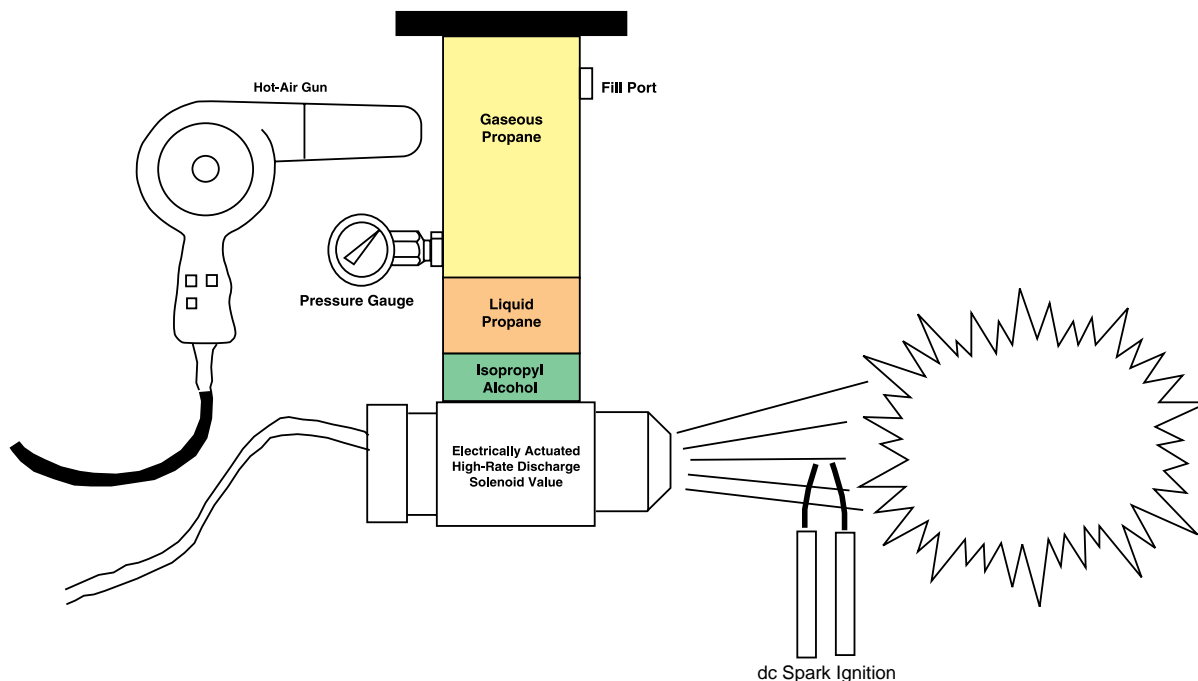
FIGURE 6. EXPLODING AEROSOL CAN SIMULATOR

OPEN AIR TESTS.

Initial tests were performed in a unconfined area to observe the flame propagation and explosion pattern and to test the general operation of the simulator. The early tests used a mix of constituents representative of a large hairspray can (16 ounces) consisting of 3.5 ounces (weight) of liquid propane and 2.5 ounces (weight) of isopropyl alcohol. Several trials were conducted at various pressures, but the HRD valve failed to perform above 200 psig. At this pressure, a large

fireball about 12 feet in diameter could be produced repeatedly. This test condition was compared to the results of a test using an actual hairspray can situated above a small burning pan of heptane. During this event, the aerosol can burst after several minutes of exposure, creating a fireball approximately 8 feet in diameter. Since the initial test condition using the simulator appeared reasonable, further tests in a confined space were conducted.

B727 CARGO COMPARTMENT TESTS.

The initial simulator setup was mounted externally on the forward bulkhead of a B727 cargo compartment. The discharge port of the HRD valve was installed through a cutout in the compartment bulkhead such that a majority of the simulator was situated external to the compartment. The pressure vessel was again filled with the 3.5 ounces of propane and 2.5 ounces of isopropyl alcohol as in the initial tests. After heating the vessel to increase the internal pressure to 200 psig, the mix was released into the compartment over the spark igniters. The ensuing explosion caused severe damage to the entire compartment, including the collapse of the forward and aft bulkheads. The cabin floor above the compartment ceiling liner was blown out of place and landed several yards away from the test article. There was also evidence of severe overpressure inside the structure as several rivet heads on the exterior skin surface failed under tension.

At this point, a test was arranged to measure the effectiveness of Halon 1301 to mitigate this event. The damaged compartment was reconfigured and the simulator was filled with the same mix of propane and isopropyl alcohol. The entire compartment was first inerted with Halon 1301 to a concentration of 6.5%. This concentration was measured using a continuous gas analyzer that drew samples from the center of the compartment at a height of 2 feet. The hydrocarbon mixture in the simulator was heated to 200 psig and released into the inerted compartment over the spark igniters. There was no explosion.

LD-3 CARGO CONTAINER TESTS.

Several additional proof-of-concept tests using the aerosol simulator were conduct using LD-3 cargo containers as the confining space. First, an actual hairspray aerosol can was placed in the LD-3 container over a small pan of burning heptane fuel for comparison. The hairspray can explosion overpressurized the LD-3 container enough to disengage and partially swing open the bi-fold door. The test was repeated using the aerosol simulator containing the mixture previously used in the B727 test. Upon release, the mixture exploded with violent force, blowing the bi-fold door off its hinges and catapulting it several yards into a wall. The container sustained heavy damage in the form of long cracks due to overpressure. A pressure rise of 8 psig was measured in the container using an omega pressure transducer; a high-speed data acquisition system monitored and recorded the input signal from the transducer. A cursory review of these and prior tests indicated the simulator produced a more severe explosion than an actual exploding aerosol can. A major reason for the consistent potency of the simulator lies in the ability to release the entire combustible mixture contents as a vapor cloud, promoting complete combustion upon ignition. When an actual can explodes, the overpressure often causes an incomplete failure of the container, releasing the flammable mix in a smaller cloud or other shape that is less conducive to complete combustion.

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The effectiveness of Halon 1301 at preventing explosions was tested by inerting the LD-3 container with a Halon 1301 concentration of 6%. The heated contents of the simulator were released into the container with no resulting event. The test was repeated with a Halon 1301 concentration of 4% with no resultant explosion. Additional tests using 3%, 2%, and 1% Halon 1301 concentrations were conducted with identical results, illustrating the effectiveness of halon against this type of threat. The results found here conflict with previously published inerting concentration data. [13] Thus, further testing and analyses must be done before any final conclusions can be made on the effectiveness of low concentrations of halon against this type of threat.

OXYGEN CANISTER FIRE TEST RESULTS

Most commercial transport aircraft use oxygen canisters to supplement or replace cabin air for passenger breathing in the event of a cabin depressurization. Figure 7 shows the design of a common oxygen canister. The main components are the chemical core composed of sodium chlorate and iron particles, a stainless steel housing, a means of initiating the chemical reaction (such as a spring-loaded hammer striking a percussion cap), and outlets for the gaseous oxygen generated. Because the oxygen-producing reaction is exothermic, the steel housing is insulated from the chemical core to maintain the temperature of the housing below 500°F. As discussed earlier, the activation of improperly packaged and shipped oxygen canisters in the forward cargo compartment was the probable cause of the fatal ValuJet in-flight fire. [5]

Cargo compartment inerting concentrations for Halon 1301 (3%) are based on the suppression of a deep-seated fire involving common Class A materials. At a 3% concentration, Halon 1301 cannot extinguish a fire involving hazardous oxidizing materials such as oxygen canister chemicals. Although not a cargo fire design requirement, cargo fire tests involving oxygen canisters were conducted to determine what benefit, if any, might exist from the discharge of Halon 1301. The tests were conducted in both the DC-10 and B727 cargo compartment test articles.
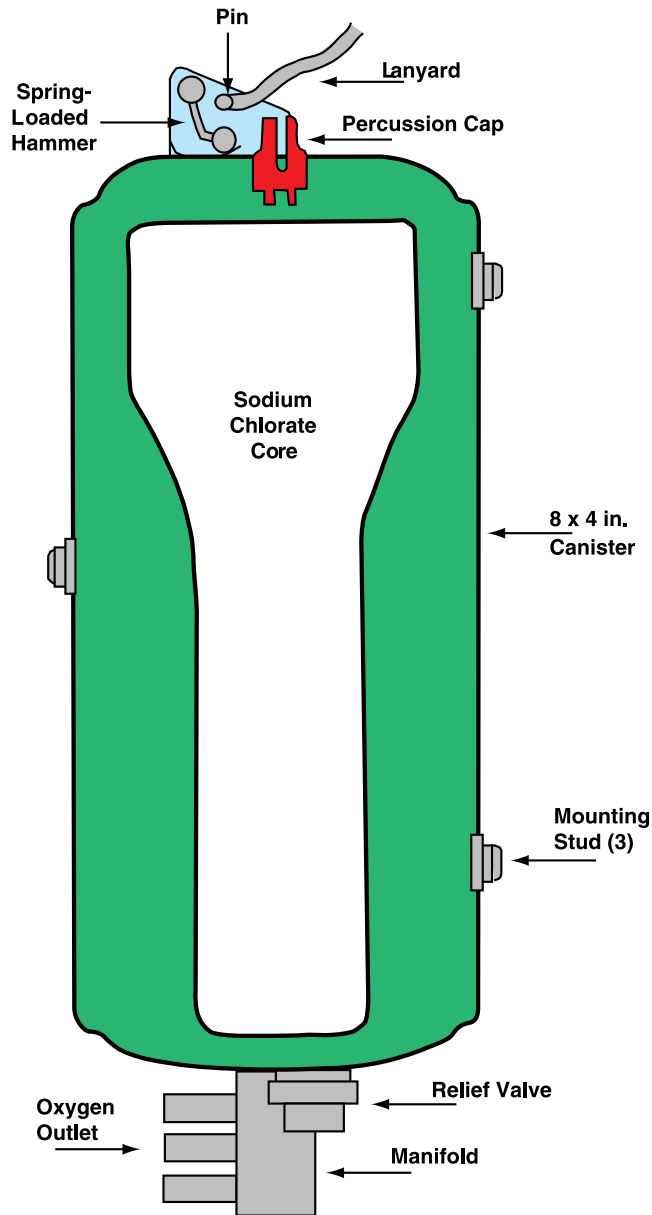
FIGURE 7. CHEMICAL OXYGEN GENERATOR

DC-10 CARGO COMPARTMENT TEST.

The fire load for this test consisted of two cardboard boxes, each containing 15 generators with bubble plastic covering the top row of generators, and two cardboard boxes filled with shredded newspaper. All four boxes were placed adjacent to each other in a steel pan that was on top of an insulating material. The lanyard for one of the generators that was in contact with the bubble plastic was pulled to initiate the test. Flames were first observed 6.5 minutes later. The aircraft smoke detection system went off 8 minutes 15 seconds later and the Halon suppression system was discharged 30 seconds after that. The 30-second delay was meant to simulate flight crew reaction time after the smoke detector alarm. Forty-six pounds of Halon 1301 were used. This

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quantity was sufficient to achieve a concentration of 5% in the empty volume of the cargo compartment. Prior to the discharge of halon, the maximum measured ceiling temperature was approximately 300°F. Immediately after the discharge, the ceiling temperature dropped to approximately 100°F and then started to rise again. The highest ceiling temperature was approximately 800°F and occurred 13 minutes after the test began. The temperature then quickly dropped back below 400°F within a minute. Temperatures continued to subside for the duration of the test. When the compartment was opened following the test, all of the cardboard and shredded newspaper had been consumed by fire, and most of the oxygen generators had been activated by the heat. In this test scenario, the halon system did not prevent the consumption of all combustible materials around the generators but it did keep temperatures sufficiently low so that it is likely that this type of fire would have been contained within a cargo compartment.

B727 CARGO COMPARTMENT TESTS.

Three tests were conducted in the 550-cubic foot B727 cargo compartment to evaluate the effectiveness of Halon 1301 against an oxygen generator initiated fire. In the first test, approximately 120 generators were loosely packed in four cardboard boxes and covered with bubble wrap. These boxes were placed in the compartment, and cardboard boxes filled with shredded newspaper were placed around them. In addition, a second layer of boxes with shredded paper was placed over the entire first layer. The test was initiated by activating a single generator located adjacent to the bubble wrap in one of the boxes. Once the bubble plastic and cellulosic materials ignited, the fire developed very rapidly. Initially, very little smoke was produced. Temperatures measured near the cargo compartment ceiling liner above the fire load reached in excess of 1000°F before the smoke detector activated. The halon system was then immediately discharged. The system was designed to give an initial 5% concentration in an empty compartment. The visible flaming was immediately extinguished. Temperatures at the ceiling fell to below 300°F and the fire was controlled within the next 3 minutes. However, at approximately 3 minutes after agent discharge, rapid flaming combustion reoccurred. The ceiling liner was penetrated and the test terminated. The fire was kept under control through the use of large quantities of both CO_2 and water spray. When the fire was finally extinguished all of the oxygen generators had activated.

The second test was similar to the first with the following exceptions. Only 12 generators were used; all were stored in one cardboard box. Only a single layer of boxes filled with shredded paper was used. In this test the fire was detected much faster than in the first test (see figure 8). Temperatures at the ceiling never exceeded 500°F. As in the first test, upon discharge of Halon 1301 the visible flaming was immediately extinguished. However, in this test the ceiling temperature was maintained at about 400°F for approximately 10 minutes and decreased to approximately 200°F for the next 30 minutes. After the fire was extinguished, it was discovered that only 2 of the 12 generators had activated.

The third test was a repeat of test two without using any suppression agent. Temperatures at the ceiling rapidly reached the point where the liner would be breached and the test was immediately terminated (see figure 8).
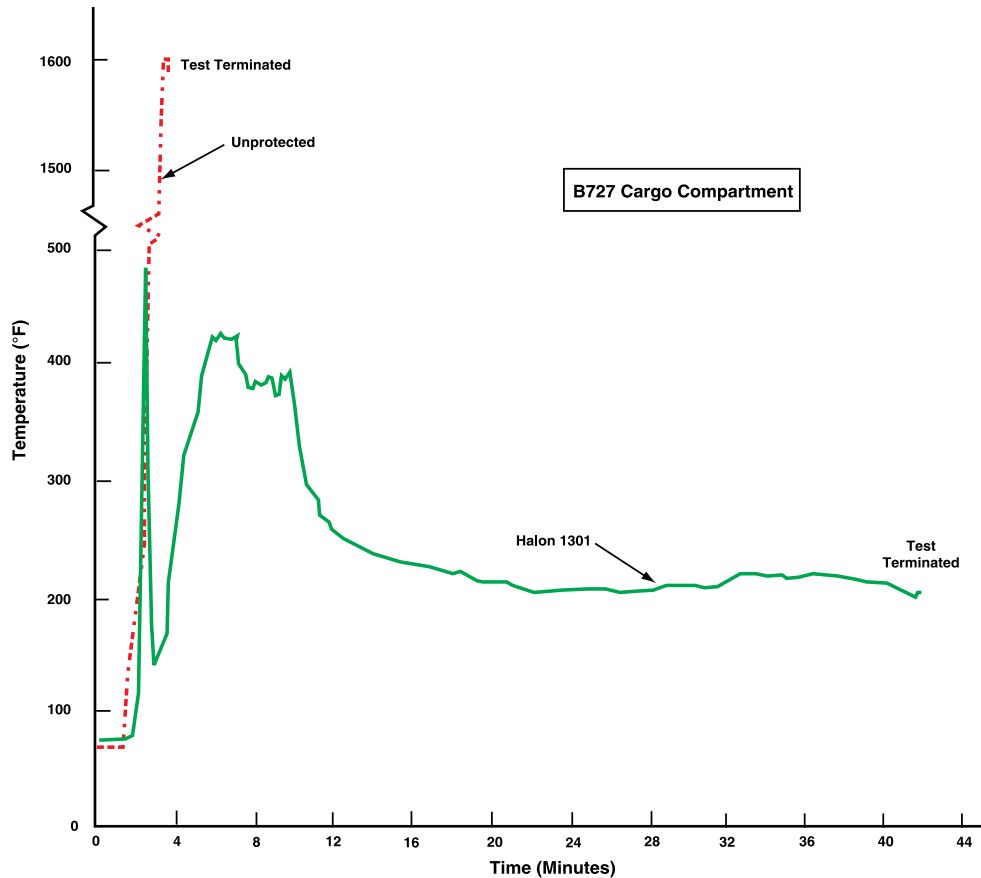
FIGURE 8. COMPARISON OF CEILING TEMPERATURES DURING A CARGO FIRE INVOLVING 12 OXYGEN CANISTERS WITH HALON 1301 SUPPRESSION AND UNPROTECTED

HALON 1301 SIMULANT FOR CERTIFICATION TESTING

The FAA requires, under FAR 25.855, certification tests of fire suppression systems to ensure proper operation of the system and an adequate concentration of extinguishing agent. Because Halon 1301 will continue to be the agent of choice in new fire suppression systems installed to meet the pending cargo compartment rule, [6] quantities of halon will be discharged into the atmosphere during certification testing. To reduce atmospheric ozone depletion from future certification test discharge of Halon 1301, the IHRWG formed a task group to evaluate HFC-125 (zero ozone depletion potential) as a simulant for Halon 1301. The choice of the simulant was based on previous work that showed HFC-125 was an excellent simulant for Halon 1301 in aircraft engine fire suppression systems. [14] Of concern was whether HFC-125 could simulate or predict decay rate and stratification over relatively long periods of time compared to an engine nacelle environment where extinguishing concentrations are maintained for a fraction of a second.

Discharge tests with HFC-125 and Halon 1301 were conducted and compared in a 300-cubic foot cargo compartment. The air leakage rate in the test article could be set at 0.5, 10.5, or 21.1 cubic feet per minute (CFM). The main instrument was a Heat Technology Laboratory (HTL)

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Halonyzer, a 12-channel continuous gas analyzer calibrated for HFC-125 in air and Halon 1301 in air. Gas samples were taken from six sampling tree elevations at two locations. To obtain similar storage bottle discharge characteristics for both agents, the bottle was filled with the equivalent liquid fraction, as used previously, [14] and pressurized with nitrogen to 375 pounds per square inch absolute (psia).

A comparison of the HFC-125 and Halon 1301 concentration histories at the three leakage rates for the sampling tree nearest the leak duct is shown in figure 9. The data represents the average concentration measured at the six sampling heights and from replicate tests at each leakage rate. The higher peak concentrations of Halon 1301 were expected due to the difference in charged weight; 5.8 pounds and 4.45 pounds for Halon 1301 and HFC-125, respectively. Also, the Halon 1301 decays faster than HFC-125 due to its higher vapor density; however, the difference in decay rate lessens as the leakage rate increases. It appears that HFC-125 can be used as a simulant for Halon 1301 provided that suitable conversion equations are used to correlate the concentrations of Halon 1301 and HFC-125.
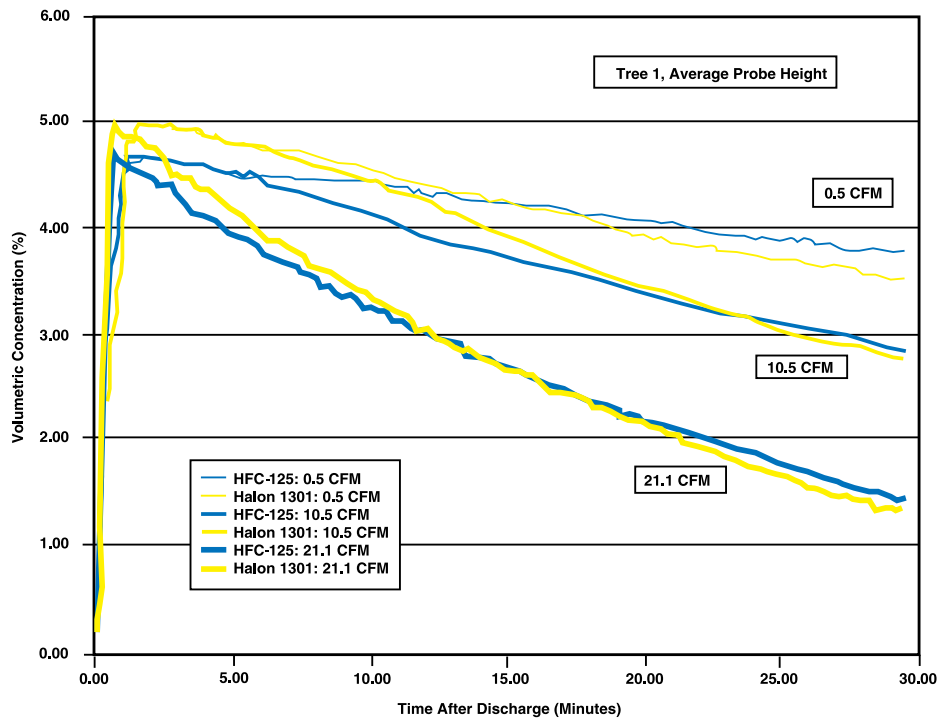
FIGURE 9. AGENT CONCENTRATION HISTORY AT DIFFERENT LEAK RATES

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