STATUS OF RESEARCH & TESTING TO REPLACE HALON EXTINGUISHING AGENTS IN CIVIL AVIATION

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ABSTRACT

The Federal Aviation Administration (FAA), working with the civil aviation community through the FAA-sponsored International Aircraft Systems Fire Protection Working Group, has developed Minimum Performance Standards (MPS) for halon replacement agents that primarily describe full-scale fire tests to demonstrate equivalent fire-extinguishing effectiveness with the halon fire-extinguishing agents currently used in lavatories, hand-held extinguishers, engines/auxiliary power units and cargo compartments. This paper reviews the status of this effort with emphasis placed on the following recent accomplishments. A revision to an existing Advisory Circular was developed that prescribes the quantities of halon replacement agents that can be safely discharged from a hand-held extinguisher to extinguish an in-flight fire in any civil aircraft, with due consideration given to volume, ventilation rate, and cabin pressure. In accordance with the draft MPS for Engines and Auxiliary Power Units, the equivalent concentration of three halon replacement agents ─ HFC-125, CF_3I and FK-5-1-12 ─ was determined by conducting full-scale fire extinguishing tests in the FAA's Engine Fire Simulator.

BACKGROUND

For over 45 years, halogenated hydrocarbons (halons) have been practically the only fire extinguishing agents used in civil transport aircraft. However, halon is an ozone depleting and global warming chemical and its production has been banned by international agreement. Although halon usage has been banned in some parts of the world, aviation has been granted an exemption because of its unique operational and fire safety requirements. Under Federal Aviation Administration (FAA) sponsorship, the International Aircraft Systems Fire Protection Working Group (IASFPWG) has developed Minimum Performance Standards (MPS) that describe the full-scale fire tests, which the FAA will accept to demonstrate that an environmentally acceptable replacement agent is equivalent to halon in fire-extinguishing effectiveness.

Halon has been the fire-extinguishing agent of choice in civil aviation because it is extremely effective on a per unit weight basis over a wide range of aircraft environmental conditions, is a clean agent (no residue), is electrically nonconducting, and has relatively low toxicity. Two types of halons are employed in aviation: Halon 1301, $CBrF_3$, a total flooding agent and Halon 1211, $CBrClF_2$, a streaming agent.

Halon 1211 is used in hand-held extinguishers, and Halon 1301 is used in fixed extinguishing systems for protection of lavatories, engine nacelles/Auxiliary Power Units (APU), and cargo compartments. On a weight basis, the largest application by far is in cargo compartments, followed by engine/APUs, hand-held extinguishers and lavatories (minimal quantity). As an example, the relative quantities of halon in the B777 are as follows: lavatories - 1.5-3.0 lb, hand-held extinguishers - 10-17.5 lb, engines/APU – 58 lb, and cargo compartments – 377 lb.

With the signing of the Montreal Protocol on Substances that Deplete the Ozone Layer, the production of halons ceased in developed countries on January 1, 1994, although the use of halons was not prohibited for aviation uses. At that time the FAA convened an informal working group, the International Halon Replacement Working Group (now called the International Aircraft Systems Fire Protection Working Group) to develop MPSs for each of the four aircraft applications. The IASFPWG is international in scope, with active participation by the aviation industry, agent suppliers, extinguishing system companies, the international regulatory authorities, and other interested parties. It is chaired and administered by the FAA's Fire Safety Team, located at the William J. Hughes Technical Center at Atlantic City International Airport, N.J. The main purpose of each MPSs is to define full-scale fire tests to demonstrate that a replacement agent is equivalent to halon in terms of fire extinguishment/suppression effectiveness. Moreover, the full-scale fire tests can be used to derive certification criteria to allow for the approval of new agents/extinguishers/systems by the regulatory authorities. All of the fire tests defined in the four MPS are set up at the Technical Center and have been made available to the aircraft manufacturers and others for cooperative testing with the FAA.

LAVATORIES

The MPS for lavatory trash receptacles was the first to be completed and published because of the relative simplicity of this application [1]. In late 2000, an FAA/Boeing team conducted tests in accordance with the MPS at the Technical Center. Two environmentally acceptable halon replacement agents, HFC-236fa and HFC-227ea, passed the MPS tests. Boeing has reported that it is currently offering lavatory extinguishers containing these agents to its customers. In addition, Airbus has reported that they selected HFC-236fa, and that lavatory extinguishers charged with HFC-236fa are available for installation on new production aircraft and in-service aircraft as well.

HAND-HELD EXTINGUISHERS

Minimum Performance Standard

The purpose of the MPS is to ensure that extinguishers using halon replacement agents pose no reduction in safety, both in terms of effectiveness in fighting onboard fires and toxicity to the passengers and crew. The MPS specifies two extinguisher tests that replacement agents must pass: a hidden fire and a gasoline-drenched seat fire [2]. Halon replacement agents found to be compliant include the halocarbons HCFC Blend B, HFC-227ea, and HFC-236fa. Although it has been reported that several business jets have installed halon replacement hand-held extinguishers, this apparently is not the case in commercial transport aircraft because of greater weight and volume considerations.

The hidden fire test evaluates the flooding characteristics of the agent against a hidden in-flight fire. This test determines the ability of a streaming agent to function as a flooding agent. [2,3]. The test is comprised of 20 n-Heptane cup fires in a three-dimensional array separated by perforated baffles in an enclosure. The cup fires are allowed to burn for 30 seconds before the extinguisher is discharged. The number of fires extinguished is compared to the number extinguished using a Halon 1211 extinguisher. It was determined that the effectiveness of the agent was affected by the hardware used to deliver it. Therefore, approval is granted on an agent/hardware unit basis.

The seat fire/toxicity full-scale fire test measures the agent's ability to extinguish a triple-seat fire in an aircraft cabin and assesses the toxicity of the decomposition products [2]. An experienced firefighter extinguishes the fire as efficiently as possible, following the prescribed 30 second pre-burn. Agent concentration and agent decomposition gas concentrations are measured. Of concern is that crew members operating the extinguisher or passengers near the discharge location are not subjected to harmful levels of the virgin agent or its decomposition products. Unlike the hidden fire test, this test examines the safety of an agent, not an agent/extinguisher combination.

FAA Advisory Circular AC 20-42D

Working with experts in the IASFPWG, the FAA developed extensive guidance material on the selection and use of hand extinguishers in aircraft. This includes safe human halocarbon exposure criteria. A draft FAA Advisory Circular (AC) has been developed which provides Halon 1211 equivalency guidance by referring to the MPS. When used, it will replace the existing AC 20-42C and establishes the halocarbons HCFC Blend B, HFC-227ea, and HFC-236fa as FAA-approved replacement agents to Halon 1211. Existing installations can continue to follow the cancelled AC 20-42C.

Toxicity Guidance. This safe-use guidance was developed to minimize the risk of adverse health effects (cardiac sensitization and anesthetic effects) from potential exposure of compartment occupants to an extinguishing agent. The tables and plots developed indicate the maximum extinguisher charge weights that could be safely used. Additional guidance is provided for minimizing exposures to low-oxygen concentrations resulting from displacement of oxygen when the agent is discharged into small compartments. Guidance for each aircraft installation is based on the maximum certificated pressure altitude of that aircraft. Perfect mixing is assumed.

Nonventilated Spaces. Environmental Protection Agency (EPA) approved and peer-reviewed, 5-minute safe human exposure concentrations were used when available. These safe human exposure concentrations were derived from physiologically based pharmacokinetic (PBPK) modeling [4,5,6,7] of canine "Lowest Observed Adverse Effect Level" (LOAEL) halocarbon exposure data. PBPK modeling relates the arterial blood halocarbons concentration histories to the inhaled halocarbon concentration histories. The safe human exposure concentrations are based on the critical arterial concentration being common for both human and dog. The safe-use guidance is sufficiently conservative to ensure safe use of this agent. Cardiac sensitization occurs before anesthetic effects are observed for the halocarbons Halon 1211, Halon 1301, HCFC Blend B, HFC-227ea, and HFC-236fa. If the PBPK-derived maximum safe human concentration is not available, the 5-minute "No Observable Adverse Effect Level" is used. A table of maximum safe weight/volume ratios is provided in the AC for various maximum certificated aircraft altitudes.

To better access the relative toxicity of halocarbon extinguishers, a table of minimum safe volumes of 5 B:C fire extinguishers are provided in the appendix of the AC. The smaller the volume, the less toxic the agent. Table 1 shows the relative toxicity of various 5 B:C extinguishers in terms of the minimum safe volume. HCFC Blend B is based on the "No Observed Adverse Effect Level" (NOAEL) concentration, as PBPK data is not yet available for this agent.

Table 1. Minimum safe volumes for one 5B:C extinguisher in a nonventilated compartment

Agent	Agent Weight[a] (lbs)	Minimum Safe Volume For One 5B:C Extinguisher (ft^3)[b, c, d,e]				
		Sea Level (for info only)	8,000 ft P Alt (Pressurized Cabin)	14,000 ft P Alt	18,000 ft P Alt	25,000 ft P Alt
HCFC Blend B	5.2	1337	1799	2276	2678	3586
HFC-227ea	5.5	99	135	170	200	269
HFC-236fa	4.75	80	107	128	159	214
Halon 1211	2.5	556	749	947	1111	1497
Halon 1301	5.0	192	259	327	385	517

a *The weight of agent for a 5B:C extinguisher is extinguisher dependent. Nozzle design, pressurization differences, and other factors can result in different agent weights for extinguishers using the same agent.*

b *Use this table if the air change time is unknown or exceeds 6 minutes.*

c *Multiply this number by the number of extinguishers in the aircraft compartment.*

d *The weight of agent for all extinguishers in a compartment should not exceed the minimum safe volume. If it does, select an agent that provides an acceptable minimum safe volume.*

e. *If all agents exceed the minimum safe volume, select the extinguisher with the proper rating which has the lowest minimum safe volume*

Ventilated Compartments. A technique was developed to determine safe-use charge weights of halocarbon extinguishers in ventilated compartments [8]. First order kinetic modeling of agent gaseous dissipation perfect mixing data provides a simple mathematical solution for human arterial concentration histories, as shown in figure 1. PBPK-derived arterial concentration histories for exposures to a constant halocarbon concentration [4,5,6,7] are used to obtain the rate constants k_1 and k_2. "τ" is the air change time.

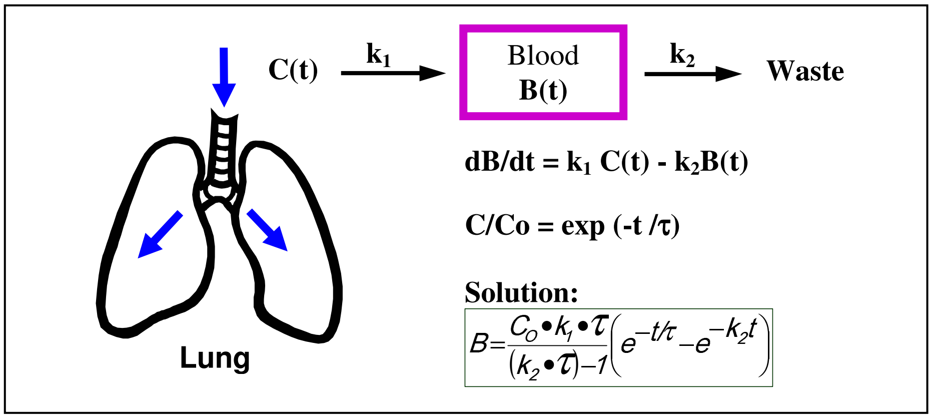

Figure 1. First-order kinetic approach to solve for human arterial concentration histories of halocarbons discharged into a ventilated compartment.

Figure 2 illustrates the calculated arterial concentration histories for various air change times for human exposures to 1.0% Halon 1211. The maximum safe initial discharge concentration for any air change time in figure 2 is the initial discharge concentration multiplied by the ratio of the critical arterial concentration to the peak arterial concentration.

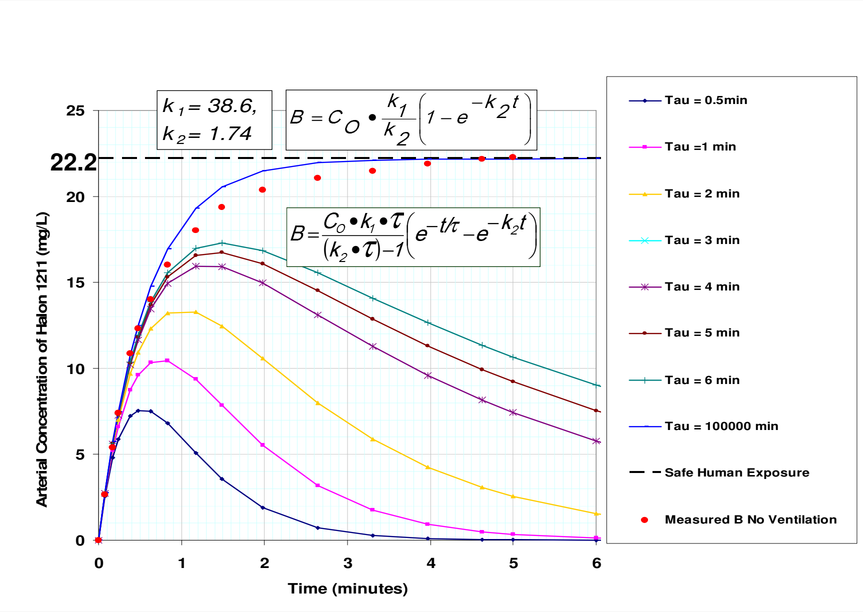

Figure 2. Human arterial blood concentration histories for exposure to 1.0 % halon 1211 for various air change times.

The AC is now in internal FAA review. It is expected to be published in the Federal Register for public comment in 2008.

ENGINES AND APU'S

Aircraft engine nacelles and auxiliary power unit (APU) compartments come in a wide array of configurations. These compartments result from encasing structure surrounding the aircraft's engine or the APU. These voids contain features necessary for the operation and control of the power plant or unit. They are forcibly ventilated and contain complex structure, plumbing networks with different fuel types, and various ignition sources. Aircraft engine nacelles and APU compartments are susceptible to fire given a failure.

Fires in nacelles typically develop into one of two forms: either spray- or pool-diffusion type combustion. A fuel leak issues a high-pressure spray or runs to gravitational low points and collects as a pool. Several confoundable difficulties exist in a nacelle fire. Two primary factors are the complex structure that can provide flame attachment locations and the continual presence of hot surfaces that can act as perpetual ignition sources. Halon 1301s ability to aptly diffuse over a wide range of environmental conditions and effectively interrupt the undesirable combustion process has allowed it to evolve over the previous decades into the current level of safety for these applications.

The Minimum Performance Standards for Aircraft Engine and APU Compartment Fire Extinguishing Agents/Systems (MPSe) provides a methodology to replace Halon 1301 for these applications [9]. This process represents the effort of the civil aviation community for this issue, specifically a task group within the IASFPWG. The tangible work has been completed at the Technical Center. To date, HFC-125, CF_3I, and FK-5-1-12 have been quantified for use in these applications. Cooperative FAA and industry activity is continuing in earnest to evaluate other promising agents.

The MPSe describes the conditions an aviation entity must satisfy to acceptably use an alternate material to replace Halon 1301. A test process evaluating the fire extinguishment performance of a replacement candidate as compared to Halon 1301 is the essence of the MPSe. The task group identified multiple needs the test process must address.

1. Representation of the salient aspects of these applications to challenge Halon 1301 and its potential replacements.
2. Provide multiple conditions on which to assess the comparative behaviors.
3. Replication within the test process of the FAA's certification criteria regarding the delivery of Halon 1301 to these applications.

Additional requirements are written into the MPSe to review other issues not directly related to assessing a replacement candidate's fire extinguishment performance. All requirements must be acceptably satisfied. Such issues are shelf life, material compatibility, assessments regarding interactions with living beings, environmental impact, and performance consistent with the operational envelope of the airframe for which it is intended.

The test process within the MPSe uses a full-scale fixture capable of providing ventilation flows, fire threats, and fire-extinguishing agent storage and delivery. Currently, the complex, full-scale engine nacelle fire simulator only exists at the Technical Center. Evaluations occur in the test section, which has an annular cross section of 0.88 m^2 based on an inside diameter of 0.6 m and an outside of 1.2 m. The test section's annular volume is 2.83 m^3, excluding the inlet and outlet transitions. The fixture is primarily made of 6.4-mm-thick mild steel. The fire threats are located 1.8 m downstream from the front, constant cross-sectional plane of the test section. A spray fire threat resides at 12:00 and a pool fire at 06:00. The fire extinguishing agent is injected near the mouth of the test section. Its external delivery plumbing penetrates the inlet transition to permit internal injection.

Evaluating a replacement candidate for parity with Halon 1301 requires testing in at least four configurations. These configurations result from combining two ventilation flows and two fire threats. The fire threat is either pool- or spray-based. Additionally, the quantity of Halon 1301 delivered to the test environment meets the intent of the FAA certification criteria, which is 6%v/v Halon 1301 for a duration of 0.5 second. This intent is met for a volume of 0.53 m^3, centered on the upstream end of the fire threats, and is measured by a modified Statham-derivative analyzer at 12 points dispersed along 3 rings of 4 points. The possible air-based ventilation flows are 1.2 kg/s at $T_{BULK} \approx 38°C$ or 0.45 kg/s at $T_{BULK} \approx 127°C$. The spray fire threat can be based upon an aviation turbine fuel (JP-8), lubricating oil, or hydraulic fluid. Two nozzles deliver the fuel in 60° hollow cones producing a total fuel rate of 0.95 liters/min. The spray fire is electrically ignited and interacts persistently with the electrical ignition source while simultaneously heating a collection of stainless steel tubes, which pose a hot-surface ignition threat by the time of agent interaction. Aviation turbine fuel fires the pool fire threat. The pool is 51 cm long x 27 cm wide x 1.27 cm deep. The pool fire is electrically ignited and interacts persistently with the electrical ignition source. The bulk fuel temperature is 63°-68°C when ignited for any fire test.

For comparisons, the MPSe uses measurements that are made during fire extinguishment and agent distribution tests. The performance comparison for fire extinguishment between a replacement candidate and Halon 1301 is accomplished using the reignition time delay (RTD). The RTD is the duration of flame extinction the fire threat experiences, resulting from an agent pulse as it transits through the test section in the ventilation flow. The RTD is determined visually by reviewing the video record for each test. The RTD is the arithmetic difference of the times observed for the fire extinction and re-ignition events.

As shown in figure 3, the RTD is a function of the injected agent mass given a constant fire threat and ventilation flow. The MPSe requires minimizing other fire extinction mechanisms besides that of the agent. In the Technical Center fixture, this is accomplished by requiring the agent to be injected counter flow or perpendicular to the ventilation flow. Typically, the distance from the agent injection plane to the fire threat is more than 1.8 m. Thus, any transit effects imparted on the test environment that are associated with agent injection are allowed to diminish by the time of interaction with the fire threat.

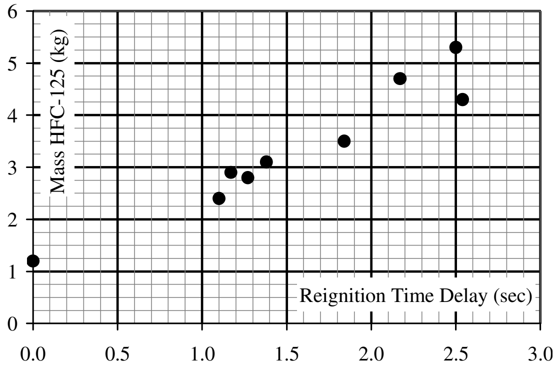

Figure 3. Effect of Mass of HFC-125 on Reignition Time Delay

Halon 1301 performance is characterized by an average of five repeated RTDs, otherwise known as a halon benchmark. As seen in figure 4, the halon benchmarks are reasonably similar between 2003 and 2006 to ensure this comparative process is viable. The halon benchmark is the sought goal for the replacement candidate to replicate or exceed. To establish a condition where the replacement candidate represents the halon performance is an iterative process.

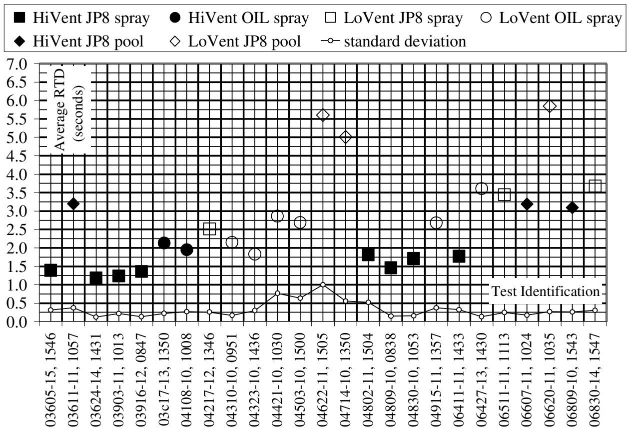

Figure 4. Three Year Variation of Ignition Time Delays

Once the replacement candidate satisfactorily represents the halon performance, also based on an average of five repeated fire tests, fire testing stops and the candidate's distribution within the ventilation flow is measured. The behavior at the flame front of the fire threats is the focus of attention. Three tests are repeated to capture the dispersion of the agent at the flame front in the test section. Two sample points are used at the flame front.

The next step in the process requires altering the distribution data, typically described by exponential growth and decay functions, and representing the dispersion of the candidate agent in the ventilation flow. This transformation results in a data pool based on six histories. The data pool compares concentration against the durations for which the candidate equaled or exceeded a given concentration. Appropriately discretizing the six concentration histories allows creating a data pool sizable enough to permit representation by a best-fit polynomial. An equivalent concentration results when the best-fit polynomial model, durations versus concentrations, is solved by using the average RTD resulting from the fire testing. Recall, the distribution model represents the dispersion of the candidate in the test environment that produced the desired fire extinction behavior, which was comparable to Halon 1301.

A candidate run through the MPSe typically produces four equivalent concentrations. The recommended value the FAA is expected to require for certification would be the largest equivalent concentration resulting from the MPSe. The recommendations for certification values of HFC-125, CF_3I, and FK-5-1-12 are found in figure 5, indicated by enclosure within a dashed rectangle. One must note the absence of pool fire work with CF_3I at low ventilation. Instability observed in the test environment during work with HFC-125 suggested the effort with CF3I would be fruitless, given the expense to acquire additional agent for the work.

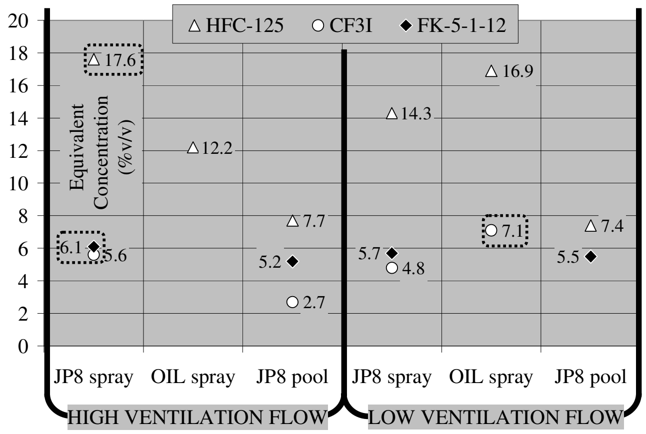

Figure 5. Equivalent Concentration of HFC-125, CF3I, and FK-5-1-12 at Different Fire Scenarios

To further validate whether the test process produces acceptable outcome, comparisons are made between the recommendations for certification and reported inerting and cup burner test results per the National Fire Protection Association (NFPA) cited in NFPA 2001 (revision 2004) tables A.5.4.2 and A.5.4.3. As seen in figure 6, the comparisons are favorable.

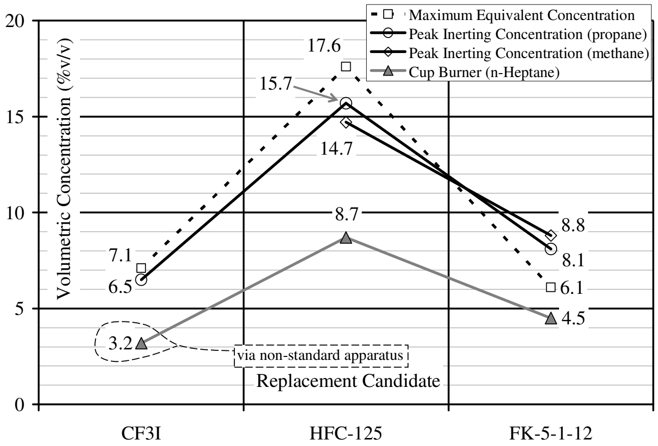

Figure 6. Comparison of Maximum Equivalent Concentrations of CF31 HFC-125, and FK-5-1-12 with NFPA 2001 Inerting and Cup Burner Data

CARGO COMPARTMENTS

The published MPS for cargo compartments describes full-scale fire tests and criteria to demonstrate equivalent performance to Halon 1301 for four separate fire scenarios: bulk-loaded cargo, containerized cargo, surface burning fire, and exploding aerosol scenario [10]. The FAA has teamed with airframe manufacturers, extinguisher companies, and agent suppliers to evaluate a number of halon replacement agents, including commercially available agents approved by the EPA as well as developmental systems and concepts. Generally, each approach had one or more shortcomings compared to Halon 1301. Tests with EPA-approved HFC-125 and HFC-227ea produced excessively high levels of hydrogen fluoride and a significant agent weight penalty. During the fire suppression phase, the smoke layer ignited unexpectedly, producing a “rollover” and temperature spikes, a phenomenon never seen with Halon 1301. Unrealistic quantities of agent would be required to meet the MPS criteria without the rollover effect. Some cargo fire-extinguishing tests were conducted with triodide, CF_3I, once touted as a drop-in replacement for Halon 1301, but were discontinued because of toxicity concerns. An agent that seemed promising to one major airframe manufacturer, 2-BTP, produced unexpected results not previously documented during experiments to determine the capability to prevent aerosol can explosions. It was discovered that at agent concentrations below the value required to prevent an explosion, there was an enhanced overpressure compared to the results measured in air alone. Thus, when present at subinerting concentrations, 2-BTP, actually made the explosive overpressure more severe, by as much as a factor of three. Similar results were obtained with HFC-125. Another promising EPA-approved agent, FK-5-1-12, also experienced two major failure modes - enhanced overpressures during aerosol can tests and a sudden flare-up during the suppression of bulk-loaded cargo fire. Finally, although water mist showed some promise, by itself it cannot prevent an aerosol can explosion.

The only approach that passed the cargo compartment MPS fire test criteria was a water mist/nitrogen gas hybrid system concept. The concept would use water mist to initially extinguish open flames and nitrogen gas, perhaps available from a fuel tank inerting system, to suppress any deep-seated fires for the duration of the flight. Even though the weight of water was comparable to halon, the concept is very different from current systems and would require significant development. Moreover, although the most likely approach to satisfy a proposed FAA regulation for fuel tank flammability reduction, inerting systems are currently not used in commercial transport aircraft. From the MPS testing completed, it is evident that the development of a suitable halon replacement agent/system for cargo compartments is the most difficult application in civil aviation.

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