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16. Abstract

This report contains a summary of available fire suppression agents and their properties. The applicability of various technologies for each major onboard aircraft application is assessed. Classes of agents, with presently available agents listed, are recommended for use in the development of test protocols. The test protocol developed for a class of agents can be used, with minor modifications, to test all agents belonging to that class.

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PREFACE

The International Halon Replacement Working Group (IHRWG) was established by the FAA and cooperating agencies in 1993 to provide input for the FAA's Halon replacement program. This group originally was formed to develop minimum performance standards and test methodologies for non halon aircraft fire protection agents/systems in cargo compartments, engine nacelles, hand held extinguishers, and lavatory trash receptacles. The focus of the IHRWG has since been expanded to include all system fire protection research and development for aircraft. The name of the working group was changed to the International Aircraft System Fire Protection Working Group (IASFPWG). Participants include aviation regulatory authorities, other government agencies involved in research and development, airframe manufacturers, airlines, industry associations, manufacturers and suppliers of fire protection equipment and agents, and researchers.

The first meeting of the IHRWG was held on 13-14 October 1993 at the FAA Technical Center, Atlantic City International Airport, New Jersey, USA. A number of task groups were established at that meeting. Among these were task groups for the four onboard areas of aircraft fire protection: cargo compartment, engine nacelle, passenger cabin (hand helds), and lavatory. Task Group 6, later designated as the Task Group on Halon Options, was assigned to review chemical options to halons. A major goal was to recommend two to three agents for use in developing FAA test protocols for each major area of onboard aircraft use: (1) engine nacelles, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection. A final report was published in 1995, Chemical Options to Halons for Aircraft Use, DOT/FAA/CT-95/9.

At the 19-20 April 1995 meeting of the IHRWG in Rome, Italy, a decision was made to maintain a review of new halon option technologies as they appeared and to continue to update the February 1995 report. All members of the original Task Group were contacted to determine who wished to maintain membership, and an announcement was made to find new members. This group prepared a second updated report, Halon Replacement Options for Use in Aircraft Fire Suppression Systems, DOT/FAA/AR-96/90, 1996.

At an IHRWG meeting in London on 9-10 October 1996, a decision was made to continue the work of the Task Group on Halon Options and to begin preparation of a second update of the initial February 1995 report. A slight change in the mandate was issued to assess the applicability of various technologies for each major onboard aircraft application rather than to recommend agents for development of test protocols. The major areas of onboard aircraft use are (1) engine nacelles and APU (auxiliary power unit), (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection. The third updated report was puplished: Options to the Use of Halons for Aircraft Fire Supression Systems- 2002 Update, DOT/FAA/AR-99/63, 2002.

The ISFPWG agreed to update the report in 2009. Chapter/section leads and assists were selected from the meeting attendees and assistants for each chapter/ section were solicited at that

and subsequent task group meetings. This report reflects significant changes that have occurred in the aircraft fire suppression arena since the last update was published in 2002.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AEL	Acceptable Exposure Limit
AIHA	American Industrial Hygiene Association
ALC	Approximate Lethal Concentration
APU	auxiliary power unit
CAA	chemical action agent
CAA	Civil Aviation Authority
CFC	chlorofluorocarbon
CNS	central nervous system
DARPA	Defense Advanced Research Projects Agency
DNA	deoxyribonucleic acid
DoD	Department of Defense
EC	European Community
ECG	electrocardiographic
EGL	Emergency Guidance Level
EMAA	Encapsulated Micron Aerosol Agent
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guideline
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FC	(per)fluorocarbon
FIC	fluoroiodocarbon
FMRC	Factory Mutual Research Corporation
GWP	Global Warming Potential
HAG	Halon Alternatives Group
HARC	Halon Alternatives Research Corporation
HBFC	hydrobromofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HMIS	Hazardous Materials Identification System
HTOC	Halon Technical Options Committee
IDLH	Immediately Dangerous to Life and Health
IPCC	Intergovernmental Panel on Climate Change
IHRWG	International Halon Replacement Working Group
JAA	Joint Aviation Authorities
LEL	Low Effect Level
LOAEL	Lowest Observed Adverse Effect Level
MOP	Montreal Protocol
MPS	Minimum Performance Standard
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NEAG	New Extinguishants Advisory Group
NEL	No Effect Level
NIOSH	National Institute for Occupational Safety and Health

NIST	National Institute of Standards and Technology
NMERI	New Mexico Engineering Research Institute
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No Observed Adverse Effect Level
NPCA	National Paint and Coatings Association
ODP	Ozone Depletion Potential
OSHA	Occupational Safety and Health Administration
PAA	physical action agent
PBPK	physiologically based pharmacokinetic modeling
PEL	Permissible Exposure Limit
PFC	perfluorocarbon
PGA	pyrotechnically generated aerosol
PVC	polyvinyl chloride
REL	Recommended Exposure Limit
RPU	Rotor Positioning Unit
SCBA	self-contained breathing apparatus
SNAP	Significant New Alternatives Policy
SPGG	solid propellant gas generator
STEL	Short-Term Exposure Limit
TCA	Transport Canada Aviation
TLV	Threshold Limit Value
TOGW	takeoff gross weight
TWA	Time Weighted Average
UDS	unscheduled DNA synthesis
UL	Underwriters Laboratories
UNEP	United Nations Environment Programme
U.S.	United States
WEEL	Workplace Environmental Exposure Limit
WGL	Workplace Guidance Level

EXECUTIVE SUMMARY

This report which is an update of three earlier reports published in February 1995, September 1996 and February 2002[1, 2, 3], summarizes available fire suppression technologies that could be considered as halon substitutes for the four major aircraft onboard applications: (1) engine nacelles, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection. The options are divided into two groups: replacements (halocarbon agents) and alternatives (all other options). The technologies are discussed and the applicability of each is assessed for the four primary applications.

During preparation of this report, draft versions were circulated among task group members and reviewed at meetings of the IASFPWG and the Halon Options Task Group to permit review, comment, and recommendations. In particular, manufacturers were informed of the Internet posting to allow review and comment on discussions of their products.

1. INTRODUCTION.

1.1 OVERVIEW OF FIRE PROTECTION.

The most common fuels in fire and explosion incidents are petroleum products, cellulosic materials (wood, paper), and polymers. Fires of cellulosic materials are termed "Class A" and liquid fuel fires are termed "Class B." Polymeric material fires can exhibit characteristics of either Class A or Class B depending on the extent of melting (if any) during combustion. Class C fires involve energized electrical equipment and Class D fires, flammable metals. Rapid gas phase combustion can result in an explosion or, in the limit as the combustion becomes very rapid, detonation.

There are five general types of fire and explosion protection applications for aircraft: (1) total-flood fire extinguishment, (2) total-flood fire suppression (3) streaming fire extinguishment, (4) explosion suppression, and (5) inertion against explosions and fires. The Fire Protection Handbook and the SFPE Handbook of Fire Protection Engineering are excellent sources of information on all aspects of fire and explosion protection [4 and 5].

In total-flood applications, an extinguishing agent is discharged into an enclosed space to achieve a concentration sufficient to extinguish or suppress an existing fire. The agent concentration that a system/agent combination is designed to produce is termed the "design concentration." Total-flood extinguishment usually uses fixed systems (e.g., nonportable systems attached to a protected structure) with either manual or automatic activation. Automatic systems detect a fire and automatically discharge the extinguishing agent. Total-flood applications include protection of enclosed spaces such as aircraft cargo compartments.

In streaming applications, an agent is applied directly onto a fire or into the region of a fire. This is usually accomplished using manually operated wheeled or portable extinguishers. Hand-held portable extinguishers provide fire protection in aircraft passenger compartments.

Halons are bromine-containing gaseous or volatile liquid chemicals used in fire and explosion protection. Most widely employed are Halon 1301, bromotrifluoromethane ($CBrF_3$), used primarily as a total-flood agent, and Halon 1211, bromochlorodifluoromethane ($CBrClF_2$), used primarily in streaming applications. These clean (residue-free) chemicals are applicable to Class A, B, and C fires. They cannot be used for Class D fires.

1.2 ENVIRONMENTAL OVERVIEW.

Although airworthiness regulations for most applications do not require the use of a particular fire suppression agent (hand extinguisher regulations are the exception), halons have been the agents of choice of airframe manufacturers. In 2010, worldwide production of halons for fire protection uses ended under the provisions of the Montreal Protocol. The primary environmental characteristics to be considered in assessing a new

chemical option to halons are Ozone Depletion Potential (ODP), Global Warming Potential (GWP), and Atmospheric Lifetime. The agent selected should have environmental characteristics in harmony with international laws and agreements, as well as applicable national, state, and local laws. An agent that does not have a zero or near-zero ODP and the lowest practical GWP and Atmospheric Lifetime may have problems of international availability and commercial longevity.

1.3 TOXICOLOGY OVERVIEW.

The toxicological acceptability of a chemical option to halons is dependent on its use pattern. As a general rule, the agent must not pose an unacceptable health risk for workers during installation, maintenance, or operation of the extinguishing system. In areas where passengers or workers are present, or where leakage could cause the agent to enter the passenger compartment, at no time should the cumulative toxicological effect of the agent, its pyrolytic breakdown products, and the byproducts of combustion pose an unacceptable health risk during probable normal and failure conditions.

1.4 OPTIONS.

The following defines some terms used in this report. The term "options" is used for anything that could be used in place of halons. "Replacements" denote halocarbon fire extinguishants, i.e., agents that are chemically similar to the present halons. "Alternatives" are everything else.

"Chemical alternatives" are materials such as carbon dioxide (CO_2), foam, water, and dry chemicals, whose chemistry differs significantly from that of the halons. "Engineering alternatives" (not covered in this report) involve such approaches as rapid response and fire-resistant structures. Note that many alternative technologies are actually "chemical/system" alternatives since the agent and system cannot be separated (e.g., solid propellant gas generators, SPGGs).

Alternatives and replacements have been discussed in a number of papers (recent overviews are given in references 6 and 7).

Any option to the use of halons in the U.S. must be determined acceptable by the U.S. Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) program, which implements section 612 of the amended Clean Air Act of 1990. A current list of SNAP acceptability decisions can be found on the EPA website [8 and 9].

2. HALOCARBON REPLACEMENTS.

At present, halon replacements (e.g., halocarbons) fall into four major categories (see table 1). Note that one category included in the 2002 update report from the Task Group on Chemical Options to Halons [3]—PFCs (perfluorocarbons)—are no longer being commercialized. A new category of replacements – fluoroketones – has been commercialized since the 2002 update.

TABLE 1. CLASSES OF HALON REPLACEMENTS

HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
FICs	Fluoroiodocarbons
FKs	Fluoroketones

There are a number of desirable characteristics for halon replacement agents. They must have acceptable global environmental characteristics (low-zero ODPs and GWPs, and short atmospheric lifetime) and, if applicable, an acceptable low risk of adverse health effects from exposure that is comparable to halons, specifically halon 1301. A continuing debate on acceptable levels for these characteristics is expected. The primary reason for using halocarbons, rather than such alternatives as foams and dry chemicals, is that halocarbons are clean, volatile, and electrically nonconductive. Finally, the agent must be effective. Note, however, that effectiveness does not necessarily mean as effective as the present halons, though this is desirable.

Physical action agents (PAAs) are those that operate primarily by heat absorption. Chemical action agents (CAAs) are those that operate primarily by chemical means — removal of flame-free radicals. The chemical effect contribution to extinguishment by PAAs is only 10 to 25 percent of the physical contribution [10]. In general, CAAs are much more effective extinguishants than are PAAs. Halons 1211 and 1301 and CF_3I are primarily CAAs. Other halocarbon agents are primarily PAAs. It has been shown that Halon 1301 extinguishment of n-heptane in air is approximately 20 percent physical and 80 percent chemical [11]. The analysis also indicates that about 25 percent of the extinguishment is due to the CF_3 group and about 55 percent is due to the bromine. Though CAAs are more effective, they often have higher ODPs because they usually contain bromine. One exception is trifluoroiodomethane (CF_3I).

Most halocarbons now commercialized as halon replacements require significantly higher design concentrations than required for Halons 1301 and 1211 and, in the event of a fire, produce larger amounts of toxic or corrosive byproducts (e.g., hydrogen fluoride and, for chlorine-containing agents, hydrogen chloride) [12]. One halocarbon, CF_3I, produces relatively large amounts of iodine. Byproduct formation is strongly influenced by the mass flux of inhibitor into the flame sheet and the extinguishment time. Slow extinguishment due to the use of lower concentrations of agent produces more byproducts.

2.1 TOXICOLOGY.

2.1.1 Cardiac Sensitization.

Cardiac sensitization is the term used for the phenomenon of the sudden onset of cardiac arrhythmias caused by a sensitization of the heart to epinephrine (adrenaline) in the presence of some concentration of a chemical. Cardiac sensitization (specifically leading to ventricular fibrillation) was first demonstrated in 1912 in cats exposed to chloroform

in the presence of epinephrine, which was nonhazardous without epinephrine [13]. Since then, cardiac sensitization has been demonstrated in humans as well as laboratory animals.

When comparing concentrations necessary to elicit acute toxic responses such as anesthesia, cardiac sensitization, or lethality, cardiac sensitization usually occurs at a lower concentration for halocarbons than other acute toxicity endpoints. Therefore, regulatory and standard-making authorities have used cardiac sensitization thresholds as the criterion for determining acceptability for use in areas where human occupancy may occur. Cardiac sensitization is particularly important in firefighting. Higher levels of epinephrine secreted by the body, under the physiological stress of a fire event, may increase the possibility of sensitization.

For halocarbon agents, the health effect of greatest concern is cardiac sensitization. The use conditions for halocarbon substitutes under the SNAP program are based on the no observed adverse effect level (NOAEL) and lowest observed adverse effect level (LOAEL) for cardiac sensitization. LOAEL and NOAEL concentrations entail measurement of cardiotoxic effects in animals made sensitive to these effects by the administration of epinephrine. The administered epinephrine doses are just below the concentration at which epinephrine alone would cause cardiotoxicity in the experimental animal and are approximately ten times greater than the concentration a human would be likely to secrete under stress. Thus, LOAEL and NOAEL values are conservative even in high-stress situations [14, 15].

2.1.2 Physiologically-based Pharmacokinetic Modeling.

Because the cardiac sensitization potential is measured in dogs, a means of providing human relevance to the concentration at which this cardiosensitization occurs (LOAEL) has been established through the use of physiologically based pharmacokinetic (PBPK) modeling.

The PBPK model, as described in the National Fire Protection Association (NFPA) 2001 gaseous agents standard and the International Standards Organization (ISO) 14520 gaseous agents standard, provides safe human exposure times for various concentrations of halocarbons [16, 17]. A PBPK model is a computerized tool that describes time-related aspects of a chemical's distribution in a biological system. The PBPK model mathematically describes the halocarbon uptake into the body and the subsequent distribution of the halocarbon to the areas of the body where adverse effects can occur. For example, the model describes the breathing rate and uptake of the halocarbon from the exposure atmosphere into the lungs. From there, the model uses the blood flow bathing the lungs to describe the movement of the halocarbon from the lung space into the arterial blood that directly feeds the heart and vital organs of the body.

It is the ability of the model to describe the halocarbon concentration in human arterial blood that provides its primary utility in relating the dog cardiac sensitization test results to a human who is unintentionally exposed to the halocarbon. The concentration of the halocarbon in the dog-arterial blood at the time the cardiac sensitization occurs (5-minute

exposure) is the critical arterial blood concentration (target concentration), and this blood parameter is the link to the human system. Once this critical arterial blood concentration has been measured in dogs, the EPA-approved PBPK model simulates how long it will take the human arterial blood concentration to reach the critical arterial blood concentration (as determined in the dog test) during human inhalation of any particular concentration of the halocarbon agent.

2.1.3 Exposure Limits.

Exposure criteria have been established for the use of halocarbon agents in total flood applications as part of NFPA 2001 and ISO 14520 [16, 17]. Under these international standards, a halocarbon agent may be used at a concentration up to its cardiac sensitization NOAEL value in normally occupied enclosures provided the maximum expected exposure time of personnel is not more than five minutes. A halocarbon agent may be used at a concentration up to its cardiac sensitization LOAEL value in normally occupied and normally unoccupied enclosures provided certain criteria are met that depend on agent toxicity, egress time, and in some cases PBPK model values. In addition, these standards call for avoidance of unnecessary exposure to agents covered in the standard and for suitable safeguards to ensure prompt evacuation. Audible and visual predischarge alarms are required. EPA references the exposure criteria in the current version of the NFPA 2001 standard for agents listed as acceptable under the SNAP program.

2.2 ENVIRONMENTAL CONSIDERATIONS.

2.2.1 Ozone Depletion Potential.

Ozone Depletion Potentials (ODPs) are the calculated ozone depletions per unit mass of material released relative to a standard, normally CFC-11. It should be noted that ODPs are calculated; they cannot be measured. Although calculations of ODPs require time horizons (see section 2.2.3), steady-state calculations have generally been used. Although ODPs vary somewhat, depending on the calculation method, it is believed that relative values for compounds containing the same ozone-depleting element are relatively reliable. Thus, halocarbons that contain only chlorine and fluorine (in addition to carbon and, possibly, hydrogen) can be compared to CFC-11. It is well established that bromine is much more damaging to ozone than is chlorine on a per atom basis. Exactly how much more damaging is not precisely known and lends some uncertainty to the ODPs of bromocarbons. The model calculations used by the U.S. EPA incorporate an effect ratio of 55 chlorine atoms to 1 bromine atom. An excellent nontechnical historical overview is contained in reference 18.

2.2.2 Atmospheric Lifetime.

Atmospheric lifetimes are generally modeled as e-folding lifetimes. The gas concentration decays exponentially following the equation

$$C_t = C_0 e^{-t/L}$$

where C_0 is the initial concentration, C_t is the concentration at any time t, and L is the atmospheric lifetime. After one lifetime, the gas concentration drops to 1/e (approximately 0.369) of its initial value. Note that this equation predicts that the concentration will never reach zero, although it can approach it very closely. For example, after only five lifetimes, the concentration drops to 0.0067 of its initial value.

2.2.3 Global Warming Potential.

The GWP is the change in radiative forcing resulting from the emission of 1 kilogram of a chemical relative to the radiative forcing resulting from the emission of 1 kilogram of a reference gas. In the past, CFC-11 was often used as the reference; however, carbon dioxide (CO_2) is now typically used. The global warming potential depends on three variables: (1) the location of the IR absorption bands, (2) the strength of the IR absorption bands, and (3) the lifetime of the gas. It is important to note that the GWP can vary significantly depending on the time period used for the comparison of the radiative forcing of the chemical relative to that of the reference. The time period used to calculate the GWP is termed the time horizon and is primarily a policy decision. Time horizons of 100 and 500 years are often used in calculated GWP values; however, other time horizons may be more appropriate. GWPs with longer time periods are believed to be more inaccurate than those with shorter times periods [19]. All GWPs in this report are 100-year time horizon values referenced to carbon dioxide from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [19].

2.2.4 Atmospheric Impacts of Blends.

Some replacement agents are blends of more than one component. The atmospheric impacts of blends should be evaluated by looking at the ODP, GWP, and the atmospheric lifetime of each component separately because each component acts independently when released to the atmosphere even if it has been blended with other components. The atmospheric effects of an individual component in a blend have the same impact as if the individual component were released to the atmosphere as a pure substance.

Some manufacturers calculate and report averages of ODP, GWP, and/or atmospheric lifetime for a blend. Other manufacturers do not identify all components and use the environmental characteristics of a principal component to represent the atmospheric impact of a blend. Neither the parties to the Montreal Protocol nor government agencies such as the U.S. Environmental Protection Agency accept such practices as representing an accurate evaluation of the atmospheric impact. Instead, such groups and organizations use the ODP, GWP, and atmospheric lifetime of each component to evaluate the overall atmospheric impact of a blend.

2.3 REGULATORY RESTRICTIONS.

2.3.1 Halons.

Under the Montreal Protocol, global production of halons for use in fire protection applications ended in 2010. In most countries, recycled halons can be used to service

existing equipment and for continuing important uses for which suitable alternatives are not yet available.

The exception is the European Union, which banned all non-critical uses of halons in 2003. Critical uses are listed in the current Annex VI to European Commission Regulation (EC) No. 1005/2009. All current onboard uses of halons in aviation are included on the critical use list under the EC regulation. Annex VI was revised in 2010 and now contains “cut-off dates” for the use of halons in new equipment or facilities and “end dates” when all halon systems or extinguishers in a particular application must be decommissioned.

TABLE 2. HALON PHASE OUT DATES IN EC ANNEX VI

Purpose	**Type of extinguisher**	**Type of halon**	**Cut-off date: Application for new type certification**	**End date: All halons decommissioned**
Normally unoccupied cargo compartments	Fixed system	1301 1211	2018	2040
Cabin and crew compartments	Portable extinguisher	1211 2402	2014	2025
Engine nacelles and APU	Fixed system	1301 1211 2402	2014	2040
Inerting of fuel tanks	Fixed system	1301	2011	2040
Lavatory waste receptacles	Fixed system	1301 1211	2011	2020
Protection of dry bays	Fixed system	1301 1211 2402	2011	2040

In September 2010 a new resolution on halon replacement (A37-9) was adopted at the 37th Session of the International Civil Aviation Organization (ICAO) Assembly. It replaces Resolution A36-12 that was adopted in 2007.

The new resolution directs the ICAO Council to establish a mandate for the replacement of halon:

- in lavatory fire extinguishing systems used in aircraft produced after a specified date in the 2011 timeframe;

- in hand-held fire extinguishers used in aircraft produced after a specified date in the 2016 timeframe; and

- in engine and auxiliary power unit fire extinguishing systems used in aircraft for which application for type certification will be submitted after a specified date in the 2014 timeframe.

The ICAO Air Navigation Commission is moving forward with amendments to Annex 6 – Operation of Aircraft, and Annex 8 – Airworthiness of Aircraft, in order to implement the new resolution.

2.3.2 HCFCs.

Under the Montreal Protocol, production of HCFCs for fire protection uses will be phased out on 1 January 2020 in developed countries and 1 January 2030 in developing countries. HCFCs are restricted from use in fire protection in the European Union under Commission Regulation (EC) No. 1005/2009. This regulation allows EU states to apply for exemptions that would allow HCFCs to be used through 2019.

2.3.3 HFCs.

Due to global warming concerns, amendments were proposed in 2009 and 2010 under the Montreal Protocol to slowly phase down the global production of HFCs used as alternatives for ozone-depleting substances. The proposed HFC amendments were considered but not approved at the 2009 and 2010 Meeting of Parties to the Montreal Protocol (MOP). Similar amendments are likely to be proposed for consideration at the 2011 MOP.

Only a few countries such as Switzerland and Denmark currently have restrictions on the use of HFCs in fire protection. The European Union F-gas regulation (EC No. 842/2006) does not restrict the use of HFCs in fire protection, but instead requires containment, leak inspection, labeling, training, reporting, and recovery in order to reduce emissions. This regulation is up for review in 2011.

None of the current key regulatory initiatives would place restrictions on the use of HFCs in fire protection. Emissions of HFCs from fire protection are estimated at less than 1% of total HFC emissions from all sources.

2.4 COMMERCIALIZED HALOCARBON REPLACEMENTS.

Here, the term commercialized is used to refer to materials now being marketed or are planned to be marketed in the near future. Halocarbons are considered “in-kind” replacements to halons. This means that these compounds are volatile (evaporate leaving no particulates), extinguish fires by reaching a specific vapor concentration in the fire zone, and are electrically non-conductive. Because of their gaseous nature, these agents have a better capability to pass tests that involve hidden fires or heavily obstructed hazards than non-volatile agent options. Specific halocarbon replacements have been approved for lavatory, handhelds, and engine protection. Halocarbon replacements tested against the exploding aerosol can test, required by the minimum performance standard for cargo protection, have been shown to act differently than halon 1301. These specific successes and failures are described in more detail in Chapter 4.

All of the commercialized total-flood agents in table 3 except for Halon 1301 are listed in NFPA 2001 and most in ISO 14520 [16, 17]. Halon 1301 is listed in the NFPA 12A standard [20].

TABLE 3. COMMERCIALIZED TOTAL-FLOOD AGENTS

Agent	Chemical	Formula	Company / Trade Name
Halon 1301	Bromotrifluoromethane	$CBrF_3$	
HCFC Blend A HCFC-123 HCFC-22 HCFC-124	Additive plus Dichlorotrifluoroethane Chlorodifluoromethane Chlorotetrafluoroethane	3.75 wt % $CHCl_2CF_3$ 4.75 wt % $CHClF_2$ 82 wt % $CHClFCF_3$ 9.5 wt %	North American Fire Guardian / NAF S-III
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$	DuPont / FE-241
HFC Blend B	Tetrafluoroethane Pentafluoroethane Carbon dioxide	CH_2FCF_3 86 wt % CHF_2CF_3 9 wt % CO_2 5 wt %	American Pacific / Halotron II
HFC-23	Trifluoromethane	CHF_3	DuPont / FE-13
HFC-125	Pentafluoroethane	CHF_2CF_3	DuPont / FE-25
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3	DuPont / FM-200 or FE-227
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	DuPont / FE-36
FIC-13I1	Trifluoroiodomethane	CF_3I	Ajay/ Iodoguard
FK-5-1-12	Dodecafluoro-2-methylpentan-3-one	$CF_3CF_2(O)CF(CF_3)_2$	3M / Novec 1230

2.4.1 Physical Properties, Design Concentrations, Exposure Limits

The physical properties of commercialized total-flood agents are shown in table 4. The design concentrations for total-flood fire extinguishment for Class A and Class B fires, the inerting concentrations, and the NOAEL and LOAEL exposure limits for commercialized total-flood agents from the ISO 14520 standard are shown in table 5. These design concentrations are, in general, determined as the extinguishment concentration for the specific fuel increased by a safety factor of 30 percent; though the results of other testing may be taken into account. The ISO 14520 standard requires a minimum safety factor of 30 percent for all fuels. Some users are employing some agents at considerably higher concentrations than the minimum recommended values shown in table 5 based on the specific fuel, scenario, and threat.

TABLE 4. PHYSICAL PROPERTIES OF COMMERCIALIZED TOTAL FLOOD AGENTS

Generic Name	**Vapour Pressure @ 20º C, bar**	**k1 m^3/kg**	**k2 m^3/kg/ºC**	**Vapour Density, @ 20ºC & 1 atm, kg/m^3**	**Liquid Density @ 20º C, kg/m^3**
Halon 1301 (a)	14.3	0.14781	0.000567	6.255	1,574
HCFC Blend A	8.25	0.2413	0.00088	3.861	1,200
HCFC-124 (b)	3.30	0.1585	0.0006	5.858	1,373
HFC Blend B (b)	12.57	0.2172	0.0009	4.252	1,190
HFC-23	41.80	0.3164	0.0012	2.933	807
HFC-125	12.05	0.1825	0.0007	5.074	1,218
HFC-227ea (c)	3.89	0.1269	0.0005	7.282	1,408
HFC-236fa	2.30	0.1413	0.0006	6.544	1,377
FIC-13I1	4.65	0.1138	0.0005	8.077	2,096
FK-5-1-12	0.33	0.0664	0.000274	13.908	1,616

Notes: All values from ISO 14520 unless otherwise indicated
(a) NFPA 12A (2009 edition) and Thermodynamic Properties of Freon 13B1 (DuPont T-13B1)
(b) NFPA 2001 (2008)
(c) DuPont

TABLE 5. MINIMUM EXTINGUISHING CONCENTRATIONS AND EXPOSURE LIMITS FOR COMMERCIALIZED TOTAL-FLOOD AGENTS

Generic Name ISO standard reference	**Minimum Design Conc., Class A Fire Vol. % (1)**	**Minimum Design Conc., Class B Fire Vol. % (1)**	**Inerting Conc. Methane/Air, Vol. %**	**NOAEL Vol. % (2)**	**LOAEL Vol. % (2)**
Halon 1301	5.0 (3)	5.0 (3)	4.9	5	7.5
HCFC Blend A ISO 14520-6	(7)	13.0	20.5	10	>10
HCFC-124 (5, 6) (not included in ISO)	(7)	8.6 (4)	-	1	2.5
HFC Blend B (not included in ISO)	(7)	14.7	-	5	7.5
HFC-23 ISO 14520-10	16.3	16.4	22.2	30	>50
HFC-125 ISO 14520-8	11.2	12.1	-	7.5	10
HFC-227ea ISO 14520-9	7.9	9.0	8.8	9	10.5
HFC-236fa ISO 14520-11	8.8	9.8	-	10	15
FIC-13I1 (5) ISO 14520-2	(7)	4.6	-	0.2	0.4
FK-5-1-12 ISO 14520-5	5.3	5.9	-	10	>10

Note 1: Design concentration = Extinguishing concentration x 1.3, the minimum permitted by ISO 14520.

Note 2: A halocarbon agent may be used at a concentration up to its NOAEL value in normally occupied enclosures provided the maximum expected exposure time of personnel is not more than five minutes. A halocarbon agent may be used at a concentration up to the LOAEL value in normally occupied and normally unoccupied enclosures provided certain criteria are met that depend on agent toxicity and egress time. The reader is referred to NFPA 2001-1.5 (2008) and ISO 14520-G.4.3 (2006) for details of the recommended safe exposure guidelines for halocarbon agents.

Note 3: Exceptions, halon 1301 design concentration is taken as the historical employed value of 5%.

Note 4: HCFC-124 data from 1999 revision of this report.

Note 5: Not approved for use in occupied spaces.

Note 6: These agents are not generally supplied in new suppression systems but may be found in legacy systems.

Note 7: Agent manufacturer did not provide Class A extinguishing concentration data.

2.4.2 Weight and Volume Equivalents to Halon 1301

Tables 6 and 7 show weight and storage volume equivalents relative to Halon 1301 for design concentrations for Class A and B fuel applications. The weight equivalent is the weight of agent required divided by the weight of Halon 1301 required. The storage volume equivalent is the storage volume of agent required divided by the storage volume of Halon 1301 required. Three things must be noted. First, the storage volume equivalent is different from the simple ratio of the design concentrations. The storage volume equivalent takes into account the volume occupied by the agent (usually, but not always, a liquid) when contained in a cylinder. Second, this definition results in different values than one would obtain if extinguishing concentrations rather than design concentrations were used because the design concentration for Halon 1301 is more than 130 percent of its extinguishing concentration. In general, this makes the storage volume and weight equivalents lower than would be predicted from the cup burner value or some other measure of extinguishing efficiency. Third, these equivalents are based on the minimum design concentrations contained in table 5. Larger design concentrations may be used for aviation applications based on results from the various minimum performance standards for each system (e.g., engine, handheld, lavatory, cargo). Thus, the values for equivalents in tables 6 and 7 are minimum values.

TABLE 6. HALOCARBON AGENT QUANTITY REQUIREMENTS FOR CLASS A COMBUSTIBLE HAZARD APPLICATIONS (1, 2)

Generic Name	**Agent Mass, kg/m^3 of Protected Volume @ 20 °C**	**Mass Relative to Halon 1301**	**Agent Liquid Volume litre/m^3 of Protected Volume**	**Maximum Cylinder Fill Density, kg/m^3 (3)**	**Cylinder Storage Volume Relative to Halon 1301 (4)**	**Cylinder Pressure @ 20 °C, bar**
Halon 1301 (5)	0.331	1.00	0.210	1,121	1.00	25 or 42
HCFC Blend A (6)	0.577	1.74	0.481	900	2.17	25 or 42
HCFC-124 (6,7)	0.549	1.66	0.400	1,185	1.57	25
HFC Blend B (6,7)	0.733	2.21	0.616	929	2.67	25 or 42
HFC-23	0.571	1.73	0.708	860	2.25	43
HFC-125	0.640	1.93	0.525	929	2.33	25 or 42
HFC-227ea	0.625	1.89	0.444	1,150	1.84	25 or 42
HFC-236fa	0.631	1.91	0.459	1,200	1.78	25 or 42
FIC-13I1 (6)	0.389	1.18	0.186	1,680	0.79	25
FK-5-1-12	0.778	2.35	0.482	1,480	1.78	25 or 42

Note 1: Halon alternative agent quantities based on 1.3 safety factor.
Note 2: Mass and volume ratios based on "Minimum Class A Fire Design Concentrations" from table 5.
Note 3: Fill density based on 25 bar pressurization except for HFC-23.
Note 4: Agent cylinder volume per m^3 protected volume = (Agent Mass, kg/m^3 protected volume)/ (Maximum Fill Density, kg/m^3 cylinder) = ($V_{CYL}/V_{ProtVol}$). For halon 1301 cylinder volume per m^3 hazard = (0.331 kg/m^3 hazard)/ (1082 kg/m^3 cylinder) = 0.0003059 m^3 cylinder /m^3 protected volume.
Note 5: NFPA (12A) [20]; ASTM D5632-08 [21].
Note 6: Agent manufacturer did not supply complete Class A extinguishing data, hence no Class A MDC established; the heptane MDC was employed in this table.
Note 7: NFPA 2001 (2008) [16]

TABLE 7. HALOCARBON AGENT QUANTITY REQUIREMENTS FOR CLASS B FUEL APPLICATIONS (1, 2)

Generic Name	**Agent Mass, kg/m^3 of Protected Volume @ 20 °C**	**Mass Relative to Halon 1301**	**Agent Liquid Volume litre/m^3 of Protected Volume**	**Maximum Cylinder Fill Density, kg/m^3 (3)**	**Cylinder Storage Volume Relative to Halon 1301 (4)**	**Cylinder Pressure @ 20 °C, bar**
Halon 1301	0.331	1.00	0.210	1,121	1.00	25 or 42
HCFC Blend A	0.577	1.74	0.481	900	2.17	25 or 42
HCFC-124	0.549	1.66	0.400	1,185	1.57	25
HFC Blend B	0.733	2.21	0.616	929	2.67	25 or 42
HFC-23	0.575	1.74	0.713	860	2.27	43
HFC-125	0.698	2.11	0.573	929	2.55	25 or 42
HFC-227ea	0.720	2.18	0.512	1,150	2.12	25 or 42
HFC-236fa	0.711	2.15	0.516	1,200	2.01	25 or 42
FIC-13I1	0.389	1.18	0.186	1,680	0.79	25
FK-5-1-12	0.872	2.63	0.540	1,480	2.00	25 or 42

Note 1: Nominal maximum discharge time is 10 seconds in all cases.
Note 2: Mass and volume ratios based on "Minimum Class B Fire Design Concentrations" from Table 11-4.
Note 3: Fill density based on 25 bar pressurization except for HFC-23.
Note 4: Agent cylinder volume per m^3 of protected volume = (Agent Mass, kg/m^3 of protected volume)/(Maximum Fill Density, kg/m^3 cylinder) = ($V_{CYL}/V_{ProtVol}$). For halon 1301 cylinder volume per m^3 of protected volume = (0.331 kg/m^3 hazard)/ (1082 kg/m^3 cylinder) =
0.0003059 m^3 cylinder/m^3 of protected volume.

2.4.3 Environmental Properties

The environmental properties of commercialized total-flood agents are shown in table 8. ODP, GWP, and atmospheric lifetime values shown in the table come from the 2006 Scientific Assessment of Ozone Depletion [22]. All agents other than Halon 1301 listed in table 8 are acceptable under EPA's SNAP program, however, there are limitations on use for certain agents (see table footnotes).

TABLE 8. ENVIRONMENTAL PROPERTIES OF COMMERCIALIZED TOTAL-FLOOD AGENTS

Generic Name	**Ozone Depletion Potential**	**Global Warming Potential, 100 yr. (1)**	**Atmospheric Life Time, yr. (1)**
Halon 1301	12	7,140	65
HCFC Blend A	HCFC-22 – 0.05 HCFC-124 – 0.02 HCFC-123 – 0.0098	HCFC-22 – 1,810 HCFC-124 – 609 HCFC-123 - 77	HCFC-22 – 12 HCFC-124 – 5.8 HCFC-123 – 1.3
HCFC-124	0.02	609	5.8
HFC Blend B	0	HFC-134a – 1,430 HFC-125 – 3,500 CO_2 - 1	HFC-134a – 14 HFC-125 – 29 CO_2 – N/A
HFC-23	0	14,800	270
HFC-125	0	3,500	29
HFC-227ea	0	3,220	34.2
HFC-236fa (2)	0	9,810	240
FIC-13I1	0.0001	1	0.005
FK-5-1-12	0	1	0.01

Note 1: Source: 2006 Scientific Assessment of Ozone Depletion [22] except for FK-5-1-12 for which data was supplied by the manufacturer and HCFC-123 which is from Journal of Environmental Science and Technology [23]].

Note 2: Under EPA SNAP program, HFC-236fa is restricted for use in total flooding fire suppression to applications where other alternatives are not technically feasible.

2.4.4 Commercialized Streaming Agents

Commercialized halocarbon steaming agents are listed in table 9. Note that two categories of streaming agents included in the 2002 update report from the Task Group on Chemical Options to Halons [3]—PFCs (perfluorocarbons) and FICs (fluoroiodocarbons)—are no longer being commercialized. In addition, three HCFC-based streaming agents that were included in the 2002 report – HCFC Blend C, HCFC Blend D, and HCFC Blend E, are no longer being commercialized. The environmental and toxicity properties of commercialized streaming agents are shown in table 10. Additional information on the potential use of halocarbon agents in hand-held extinguishers for aviation is contained in section 4.3 of this report.

TABLE 9. COMMERCIALIZED STREAMING AGENTS

Agent	Chemical	Formula	Company / Trade Name
Halon 1211	Bromochlorodifluoromethane	$CBrClF_2$	
HCFC-123	Dichlorotrifluoroethane	$CHCl_2CF_3$	DuPont / FE-232
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$	DuPont / FE-241
HCFC Blend B PFC-14 HCFC-123 Ar	Proprietary blend of Tetrafluoromethane Dichlorotrifluoroethane Argon	CF_4 $CHCl_2CF_3$ Ar	American Pacific / Halotron I
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3	DuPont / FM-200 or FE-227
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	DuPont / FE-36
FK-5-1-12	Dodecafluoro-2-methylpentan-3-one	$CF_3CF_2(O)CF(CF_3)_2$	3M / Novec 1230

TABLE 10. ENVIRONMENTAL AND TOXICITY PROPERTIES OF COMMERCIALIZED STREAMING AGENTS

Agent	ODP [a]	GWP [a,b] (100 years)	Atmospheric Lifetime, [a] (yrs)	NOAEL (%)	LOAEL (%)
Halon 1211	7.1	1,890	16	0.5[c]	1.0[c]
HCFC-123	0.0098	77	1.3	1.0[d]	2.0[d]
HCFC-124	0.026	609	5.8	1.0[e]	2.5[e]
HCFC Blend B [g] PFC-14 / Ar (<4%) HCFC-123 (>96%)	0.0 0.0098	Ar – N/A PFC-14 - 7,390 HCFC-123 - 77	Ar – N/A PFC-14 - 50,000 HCFC-123 - 1.3	1.0[d]	2.0[d]
HFC-227ea	0.0	3,220	34.2	9.0[e]	10.5[e]
HFC-236fa	0.0	9,810	240	10.0[e]	15.0[e]
FK-5-1-12	0	1	0.01	10[e]	>10[e]

[a] Relative to CFC-11. Reference ,

[b] Based on a time horizon, relative to CO_2.

[c] Reference 24.

[d] Reference 15

[e] Reference 16.

[f] The amount and type of PFC must be considered when assessing the environmental impact (see section 2.2.4). This blend contains a PFC in small proportions.

2.4.5 Combustion Byproducts

All of the halocarbon agents have tradeoffs for total-flood and/or streaming applications. As noted earlier, halon replacements should have four characteristics: a low global environmental impact, acceptable toxicity, cleanliness/volatility, and effectiveness. Though it is very easy to find candidate replacements that meet any three of these criteria, it has been difficult to find agents that meet all four. For most (but not all) applications, significantly more replacement agent is needed to provide the same degree of protection as provided by the present halons.

One potential problem that occurs with many (but not all) of the new halocarbon agents is that they generate four to ten times more hydrogen fluoride (HF) than Halon 1301 does during comparable extinguishment [10 and 25]. Although a large amount of information is available on hydrogen fluoride toxicity [26 and 16], it is difficult to determine what risk is acceptable. A good review of the toxicity of HF as it relates to short exposures of high concentration of HF can be found in the NFPA 2001 Appendix [16]. Some data exists to determine what hydrogen fluoride levels are likely in real fire scenarios. In

general, agent decomposition products and combustion products increase with fire size and extinguishment time [27 and 16]. To minimize decomposition and combustion products, early detection and rapid discharge are recommended.

The effects of HF will occur at the site of contact and will be observed as inflammation (irritation) that can progress to severe, deep-penetrating irritation. At high concentrations of HF (>200 ppm) for an extended duration of time, e.g., 1 hour, fatalities may occur, particularly in the absence of any medical treatment.

At concentrations of <50 ppm for up to 10 minutes, definite irritation of upper respiratory tract, skin, and eyes would be expected to occur. At these low concentrations, escape-impairing effects would not be expected in the healthy individual. As HF concentrations increase to 50 to 100 ppm, an increase in irritation is expected. At 100 ppm for 5 minutes, moderate irritation of all tissue surfaces would be expected, and as the duration of exposure increases to 10 minutes, escape-impairing effects would begin to occur. As the concentration of HF increases, the severity of irritation, including escape-impairing irritation of the eyes and respiratory tract, increases and the potential for delayed systemic effects also increases. At these higher concentrations, humans would be expected to shift to mouth breathing, and deeper lung irritation is expected. At greater concentrations (>200 ppm), respiratory discomfort, pulmonary (deep lung) irritation, and systemic effects are possible. Continued exposure at these concentrations may be lethal in the absence of medical treatment.

The American Industrial Hygiene Association (AIHA) Emergency Response Planning Guideline (ERPG) represents limits established for emergency release of chemicals [28]. These limits are established to also account for sensitive populations, e.g., those with compromised health. The ERPG limits are designed to assist emergency response personnel in planning for catastrophic releases of chemicals. These limits are not to be used as safe limits for routine operations. The ERPG limits consist of three levels for use in emergency planning and are typically 1-hour values; 10-minute values have also been established for HF. For the 1-hour limits, the ERPG 1 (2 ppm) is based on odor perception and is below the concentration at which mild sensory irritation has been reported (3 ppm). ERPG 2 (20 ppm) is the most important guideline value set and is the concentration at which mitigating steps should be taken (such as evacuation, sheltering, donning masks). This level should not impede escape or cause irreversible health effects and is based mainly on the human irritation data in references 29 and 30. ERPG 3 (50 ppm) is based on animal data and is the maximum nonlethal level for nearly all individuals. This level could be lethal to some susceptible people. The 10-minute values established for HF and used in emergency planning in fires where HF vapor is generated are ERPG 3 = 170 ppm, ERPG 2 = 50 ppm, and ERPG 1 = 2 ppm.

The concentration of thermal decomposition products from a halogenated fire suppression agent is dependent upon several factors. The size of the fire at the time of system activation and the discharge time of the suppression agent play major roles in determining the amount of decomposition products formed. The smaller the fire, the less energy (heat) is available to cause thermal decomposition of the suppression agent, and hence the lower the concentration of thermal decomposition products. The size of the

fire at the time of system activation is dependent upon the fire growth rate, the detector sensitivity, and the system discharge delay time. The first factor is primarily a function of the fuel type and geometry, whereas the latter two are adjustable characteristics of the fire protection system. The discharge time affects the production of thermal decomposition products, as it determines the exposure time to the fire of sub-extinguishing concentrations of the fire suppression agent. Suppression systems have traditionally employed a combination of rapid detection and rapid discharge to limit both the production of thermal decomposition products and damage to assets by providing rapid flame extinguishment.

The enclosure volume also affects the concentration of thermal decomposition products, since larger volumes, that is, smaller fire size to room volume ratios, will lead to dilution of decomposition products. Additional factors affecting the concentration of thermal decomposition products include vaporization and mixing of the agent, the pre-burn time, the presence of hot surfaces or deep-seated fires, and the suppression agent concentration.

This decomposition issue is not unique to the new clean halogenated agents. The thermal decomposition products resulting from the extinguishment of fires with Halon 1301 have been investigated by numerous authors (Ford, 1972, and Cholin, 1972, for example), and it is well established that the most important Halon 1301 thermal decomposition products from the standpoint of potential toxicity to humans or potential corrosion of electronic equipment are the halogen acids HF and HBr.

2.5 HALOCARBON REPLACEMENTS IN DEVELOPMENT.

In 1999 the University of New Mexico Research Institute performed initial toxicology tests on several compounds in the brominated alkene family. From this work, as well as additional work performed by the Advanced Agent Working Group, 2-bromo-3,3,3-trifluoropropene (2-BTP) was identified as a promising halon replacement. This agent was of interest especially for cargo protection and performed on a one-to-one weight basis with halon 1301 in small-scale bulk load tests. In FAA cargo tests conducted in 2003, it was determined that this agent added to the intensity of the exploding aerosol can event when used at concentrations lower than required to extinguish the fire. The agent was then evaluated for engine protection and was able to pass the tests, but it was noted that when the reflash of the fuel occurred that there was an additional pressure pulse present that was not seen when the fuel reflashed with halon 1301 present. It was never fully determined whether 2-BTP was acceptable for engine protection, but due to the results of the cargo and initial engine tests, further development of this agent had been put on hold. These results are discussed further in Chapter 4.

Some work using 2-BTP in handheld extinguishers was performed in 2004 and no abnormal results were noted. Based on this data, interest arose again recently for the use of this agent in handhelds as it appeared that this agent might be able to fit into the same cylinder size as is standard equipment on Boeing aircraft. This capability was validated by testing performed at Underwriters Laboratory in 2009 as part of a joint American

Pacific and Boeing program. Based on these results, this agent is being further evaluated for commercialization. While several acute toxicology tests have been completed, there is still an array of additional toxicology tests required before the agent may be approved under the EPA SNAP program. If testing moves forward and is successful, this agent would be commercially available in 2013. Table 11 provides an overview of the properties of 2-BTP. It is noted that this material may react with air and moisture and stabilizing additives were developed to maintain stability under storage conditions. Further discussion of the use of 2-BTP in handheld extinguishers is presented in Chapter 4.

TABLE 11. PROPERTIES OF 2-BROMO-3,3,3-TRIFLUOROPROPENE (2-BTP)

Atmospheric Lifetime (yrs)[a]	0.008
GWP (100 year)[a]	Varies by latitude, 0.007 to 2.3
ODP[a]	Varies by latitude, 0.00006 to 0.02 <0.0005 for US, EU, and Asia (except southeast Asia)
NOAEL (%)[b]	0.5
LOAEL (%)[b]	1.0

[a]Reference 31.
[b]Reference 32.

3. ALTERNATIVE TECHNOLOGIES.

Nonhalocarbon substitutes are increasingly being considered as options to the use of halons. Already, water sprinklers are replacing halon systems in many applications. Dry chemical extinguishants and carbon dioxide (CO_2) are also receiving increased use. Alternatives can be divided into two types: classical alternatives and new alternatives (see table 14). Note that the word “new” does not necessarily imply that a technology was developed recently, but that there is a new or renewed interest in the use of a technology as a replacement for halons. Misting and particulate aerosols require decreased amounts of agent. This may decrease the probability of secondary fire damage. Thus, these technologies may allow protection while minimizing the problems normally associated with water and solids. Recent advances allow the use of inert gases and inert-gas blends in new applications, particularly in occupied areas.

TABLE 14. ALTERNATIVES

Classical	New
Foams	Water Misting
Wetting Agents	Inert Gases
Water Sprinklers	OBIGGS
Dry Chemicals	Particulate Aerosols
Carbon Dioxide	Solid Propellant Gas Generators
Loaded Stream	Combination

3.1 FOAMS AND WETTING AGENTS.

Foams are an alternative to halon systems for a number of hazards, particularly those involving flammable liquids [33]. Foams extinguish fires by establishing a barrier between the fuel and air. Drainage of water from the foam also provides a cooling effect, which is particularly important for flammable liquids with relatively low flash points and for Class A fuels where glowing embers are a problem. The disadvantages of foams are similar to those of water. They can cause secondary damage and cannot be used on fires involving electrical equipment without careful design considerations.

There are four basic classifications for foam fire protection systems:

a. Fixed Foam Systems are complete installations with foam piped from a central location and discharged through fixed nozzles. The concept is similar to a fixed halon system; although the applicability is very different.

b. Semifixed Foam Systems are of two types. In one type, the foam agent is connected to a fixed piping system remote from the fire threat at the time the foam is required. In the second type, foam is delivered from a central station to portable foam makers, which may include hose reels.

c. Mobile systems are vehicle-mounted or vehicle-towed complete foam units.

d. Portable systems are nothing more than hand-carried mobile systems. Portable foam extinguishers are generally intended for use on flammable liquids; although foam extinguishers may also be used for general protection against Class A fires in the same manner as water extinguishers.

3.1.1 Low-Expansion Foam.

Low-expansion foams have the following limitations:

a. Low-expansion foams are suitable only for horizontal or 2-dimensional fires, not 3-dimensional.

b. The correct foam must be used depending on the type of liquid fuel. There are two basic types of low-expansion foams: hydrocarbon fuel foams and polar solvent foams. The polar solvent foams are primarily for alcohol fires, but may also be used on hydrocarbon fires. These are sometimes called universal foams. Hydrocarbon fuel foams are usually lower cost, but the foam blanket degrades in the presence of polar chemicals like alcohols.

c. Different kinds and brands of foam concentrates may be incompatible and should not be mixed during storage.

d. Since low-expansion foams consist of at least 90 percent water, their use is limited to applications where unacceptable water damage or electrical conductivity is not a problem.

e. Foams are generally used as concentrates, which are proportioned with water during delivery. The effectiveness of a foam on a fire is highly dependent on the system designed to proportion and deliver the foam.

3.1.2 High- and Medium-Expansion Foam.

High-expansion foam systems are uncommon but can be used for total flood of a protected space; particularly where a Class A fire may be difficult to access for manual firefighting. Examples of applications include areas between floors, in which a small number of high-expansion foam systems have recently been used in preference to using halon, and marine machinery spaces. A preliminary evaluation of high-expansion foams for U.S. Naval shipboard applications has been performed [34]. Disadvantages of high-expansion foam systems include greater weight and space requirements, the need for a suitable water supply, relatively long extinguishing time, and possible cleanup problems. Also, due to poor visibility, the use of high-expansion foams can be dangerous in large, cluttered, or hazardous enclosures where people might be present. Toxicity and asphyxiation are not considered to be problems with high-expansion foam, total-flood systems.

High- and medium-expansion foams have the following limitations:

a. Since high- and medium-expansion foams have a relatively low water content, they are not as effective as low-expansion foams for most fire scenarios. The hazard must be carefully evaluated and the foam system carefully designed.

b. The use of high- and medium-expansion foams for fires involving flammable liquids and gases must be carefully evaluated in view of the actual situations. These foams are not as forgiving of poor engineering design and application. In particular, high- and medium-expansion foams are often useless against fires involving liquefied natural gas.

c. Although high- and medium-expansion foams contain less water than low-expansion foams, they should not be used with fires of water-reactive materials or on Class C fires without careful evaluation and testing.

3.1.3 Wetting Agents.

UL's Guide Information [35 ~~167~~] provides the following description, "Wetting agents are liquid concentrates which, when added to water in the concentrations specified in the individual Listings, reduce the surface tension and increase the wetting agent solution's ability to penetrate and spread. Wetting agent solutions extend the efficiency of water in protection against fire exposure and the extinguishment of Class A and Class B fires in ordinary combustibles and flammable or combustible liquids that are not soluble in water and ordinarily stored at atmospheric temperatures and pressures. Wetting agents are not intended to be stored at temperatures below 0°C (32°F) or above 49°C (120°F)." Wetting agents have some foaming ability, but unlike foams they provide little capability to protect against burnback. There is some variation to wetting agents and some are more effective on Class B than Class A, and vice-versa.

The disadvantages of wetting agents are similar to those of water. They can cause secondary damage and cannot be used on fires involving electrical equipment without careful design considerations.

There are several UL listed wetting agents available. The listings are limited to fire service and pumper applications applied through handlines with flow rates of 10 gallons per minute or greater. There are no handheld extinguishers which contain wetting agents that have UL listings. There are only a few wetting agents that have applied to the US EPA and been approved under the SNAP program. These are listed below.

3.1.3.1 FlameOut.

FlameOut, is manufactured by Biogenesis Enterprises solely for Summit Environmental Corporation, Inc. [**Error! Bookmark not defined.**]. This extinguishant is a blend of complex alcohols, lipids, and proteins, which is diluted to strengths of 1 to 10 percent in water for use. The surfactants, like all wetting agents, may enhance the rate of heat absorption by water. The blend acts on oil, gasoline, and petroleum-based liquid fires (Class B) by encapsulating the fuel, thus removing the fuel source from the fire. This feature prevents flame propagation and reduces the possibility of reignition. The agent is UL listed as a wetting agent in addition to water for extinguishing Class A and B fires. FlameOut is approved as a replacement for Halon 1211, under the trade name ColdFire 302. This product should not be confused with ColdFire as manufactured by FireFreeze Worldwide. It is an entirely different blend. Summit Environmental Corporation owns the patent and intellectual property rights to ColdFire 302/FlameOut.

3.1.4 ColdFire.

FireFreeze Worldwide, Inc. manufactures ColdFire, a proprietary blend of organic surfactants and water, which is diluted to strengths of 1-10 percent in water. The

surfactants in ColdFire, like all wetting agents, may increase heat absorption by water. ColdFire is UL listed as a wetting agent for Class A and B fires. The agent is said to extinguish Class B fires by fuel encapsulation to separate fuel from fire, reducing possible reignition and preventing flame propagation. ColdFire should not be confused with ColdFire 302/FlameOut, which is an entirely different blend.

3.1.5 Fire-X-Plus.

Fire-X-Plus, a wetting agent produced by Firefox Industries, is SNAP approved as a Halon 1301 replacement under the generic name Foam A (formerly Water Mist/Surfactant Blend A) [9].

3.2 WATER SPRINKLERS.

Water is a very effective extinguishing agent because of its unusually high specific heat and heat of vaporization. Water can be delivered in three ways—from fixed systems, from handlines, and from portable extinguishers. It is primarily a Class A fire extinguishant, cooling the fuel to a temperature below the fire point; however, fine water sprays can be very effective against Class B fires and have the additional benefit of cooling which helps to reduce the chances of reignition. .

As an extinguishing agent, water has a number of disadvantages compared with halons:

a. Secondary damage (damage to facilities and contents due to the agent) may result from discharge.

b. A cleanup requirement may exist after discharge: runoff water may have to be removed and contents of protected areas may require drying.

c. Water is unsuitable for discharge onto live electrical equipment.

d. Water does not penetrate enclosures as well as halons and other gaseous agents.

e. Discharge normally takes longer than that of a gaseous agent.

f. Most water fire protection applications are unsuitable for Class B fires although this may be overcome by misting systems.

g. Water causes problems with storage, discharge, and cleanup at very low temperatures.

h. Of particular importance in aviation is that water may carry a relatively large weight penalty, though this may not be true for zoned systems utilizing water mist (discussed in Section 3.6).

There are several types of fixed water systems for fire protection [36]. Wet pipe sprinkler systems are widely used. These systems have pipes that are constantly

pressurized with water and that are connected to sprinkler heads which are opened by heat activation. They require no electrically activated fire detectors. Dry pipe systems are filled with air or nitrogen under pressure. When the sprinkler heads are opened by fire, the gas is released allowing water to flow to the heads. These systems are a little more costly than wet pipe systems and have a slower response time. Preaction sprinkler systems require a detection system to actuate a valve allowing water to fill pipes to sprinkler heads which are closed until fire activation opens them. These systems are used primarily where inadvertent discharge must be avoided. A detector is required. Water deluge systems have heads that are normally open unlike the wet pipe, dry pipe, and preaction systems which require fire activation of the sprinkler heads. A detector activates a valve allowing water to discharge from all of the heads. This type of system results in widespread water discharge and, therefore, has a higher possibility of water damage. Deluge systems are unlikely to be used for replacement of Halon 1301 total-flood systems. Other, combination and special, systems have been used, including some that shut off the water when a fire has been extinguished.

Automatic sprinkler systems were first developed in the last century and are well proven, highly reliable form of fire protection. This is particularly true in general industrial and commercial premises in which none of the disadvantages listed above are of major practical significance. Automatic sprinklers may be used for protection of many facilities (e.g., computer rooms) for which halon is traditionally used. To avoid damage to the equipment, however, the electrical power must be deactivated before water is discharged. Although most of the new generation of computer equipment is not permanently damaged by water, if it is first powered down, it must be dried out before use. This means that either redundant equipment is needed or the facility must be able to withstand any losses due to down time.

A fixed water sprinkler system may be very cost-effective for protection of an area that already has halon systems if existing piping, valves, and miscellaneous equipment do not require major modifications. However, if protection of a limited area involves installation of a water supply and if a storage tank, pumps, and increased pipe sizing are required, sprinkler protection could be much more expensive than a halon system. Predesign inspections should be a mandatory consideration for all existing halon-protected areas.

The types of traditional water sprinklers discussed in this section would be expected to result in large weight penalties if used onboard aircraft. When water is misted, it can achieve a Class B extinguishing capability, which the water systems discussed in this section cannot achieve. Therefore, if water or water with additives is used in onboard systems, they are envisioned to be part of a water mist system, as described in Section 3.6.

3.3 DRY CHEMICALS.

Certain finely ground powders can be used as extinguishing agents. The extinguishing mechanism is complex and not fully understood. However, the mechanism depends mainly on the presence of a chemically active surface within the reaction zone of the fire. Sodium bicarbonate was one of the first dry chemical extinguishants to be used. Potassium bicarbonate and monoammonium phosphate were developed later in the 1960s. These powders typically have particle sizes of less than 10 μm up to 75 μm with average particle sizes of 20 to 25 μm.

Dry chemicals generally provide very rapid knockdown of flames and are more effective than halons in most applications [37]. The main disadvantages of dry chemical fire extinguishants include:

a. poor penetration behind obstacles,
b. no inhibiting atmosphere after discharge,
c. no direct cooling of surfaces or fuel,[1]
d. secondary damage to electronic, electromechanical, and mechanical equipment,
e. cleanup problems, and
f. temporary loss of visibility if discharged in a confined space, and

g. corrosion of surfaces not cleaned after discharge.

Fixed dry chemical systems are very uncommon; uses are normally limited to localized applications, such as with textile machines or deep-fat fryers, for which halons would not normally be used. However, these systems should be considered for fire suppression in some marine engine spaces and land-based transportation engine compartments.

Dry chemical extinguishers are rated for Class B and C fires, and in some cases, Class A fires depending on the type of powder used. Dry chemical extinguishers are often suitable substitutes for halon with fires of flammable liquids. They are also suitable for situations where a range of different fires can be experienced, e.g., electrical fires, flammable liquid fires, and fires in solids. In this respect, dry chemical extinguishers resemble halon extinguishers.

An aircraft OEM released a Service Letter [38 ~~152~~] in 2005 which states "Dry chemical extinguishers use extinguishing agents such as monoamonium-phosphate, sodium bicarbonate, or potassium bicarbonate (commonly called Purple K). All of these dry chemical agents are corrosive and abrasive, and may cause moderate to severe damage to aluminum alloys and electrical/electronic equipment. Monoamonium-phosphate is used in A-B-C rated fire extinguishers (also called multi-purpose extinguishers) and is especially corrosive to aluminum alloy structures. Monoamonium-phosphate melts from the heat of a fire and flows into cracks, crevices and faying surfaces in structures making it difficult to remove before corrosion starts. … [OEM] recommends that operators and airplane maintenance providers take positive actions to prevent the use of dry chemical fire extinguishes in and around airplanes."

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[1] Cooling of the flame due to thermal decomposition has been proposed as a mechanism for flame suppression by dry chemical agents (Ewing, C. T., Hughes, J. T., and Carhart, H. W., "The Extinction of Hydrocarbon Flames Based on the Heat-Absorption Processes Which Occur in Them," *Fire and Materials*, Vol. 8, No. 3, pp. 148-156, 1984). However, this is somewhat different from the direct cooling of surfaces, fuel, and flames by an agent such as water where cooling occurs in the absence of flame/agent interaction.

3.3.1 Monoammonium Phosphate.

This material is often referred to as "ABC Powder" and is the most common dry chemical extinguishing agent used today. It is an excellent explosion and fire suppressant and is effective on Class A, B, and C fires. It is, however, corrosive on metals. . It is noted that monoammonium phosphate (MAP) content of ABC powders has generally gone down over the years due to the rising MAP costs.

3.3.2 Sodium Bicarbonate.

This is considered to be an excellent explosion suppressant and is effective on Class B and C fires. Sodium bicarbonate does not seal the surface of the combustible material, such as is seen with monoammonium phosphate, and therefore lacks Class A capability. Sodium bicarbonate is recommended for residential stove-top fires as it has a mild saponification effect on hot grease, which forms a smothering soapy foam which helps block re-ignition. Commercial kitchens have transitioned away from sodium bicarbonate to loaded stream, Class K rated, extinguishing agents discussed in Section 3.5.

3.3.3 Potassium Bicarbonate.

Potassium bicarbonate is a widely used dry chemical fire extinguishant suppressant on aircraft rescue fire fighting (ARFF) vehicles due to: 1) being more effective than other dry chemicals on jet fuel, and 2) having better capability for 3-dimensional fires than the foam equipped on ARFF vehicles. Potassium bicarbonate is often referred to as "Purple K" and is effective on Class B and C fires and has been shown to be 2-3 times as effective as sodium bicarbonate on a weight basis when tested under laboratory conditions [39 ~~165~~]. It does not seal the surface of the combustible material, such as is seen with monoammonium phosphate, and therefore lacks Class A capability. There is some indication that the potassium ion has a chemical effect on fires. It is widely recognized that the amount of carbon dioxide released by this agent, and by sodium bicarbonate, in fires is insufficient to explain the fire suppression ability.

3.3.4 Proprietary.

Here, the term proprietary is used to denote a special dry chemical rather than one of those described above which have small amounts of an additive to improve flow and other characteristics. Monnex, a urea and potassium bicarbonate complex, developed by ICI, is an exceedingly effective proprietary dry chemical on Class B fires, but, like sodium and potassium bicarbonate, lacks Class A capability. It is more expensive than the generic agents discussed above and has a somewhat less effective delivery.

3.4 CARBON DIOXIDE.

Carbon dioxide (CO_2) resembles the other inert gases discussed in section 3.9. However, CO_2 can be considered a classical alternative and is the most common inert gas used as a fire extinguishant today. The physiological effects of carbon dioxide, however, differ significantly from those of the other inert gases; CO_2 inhalations result in respiratory and

pulmonary changes and it is not considered a simple asphyxiant as other inert gases. Like Halons 1301 and 1211, CO_2 is a gas at normal ambient temperature and pressure. It is also a clean, electrically nonconductive agent with good penetrating capability. Carbon dioxide is discharged as a gas, though some frozen particulate (dry ice) often forms. The presence of frozen particulate increases the heat absorption capacity. Only through the use of refrigerated systems (see below) can any liquid discharge occur.

At one time, CO_2 systems were used for many of the applications that now use halon. Indeed, fixed CO_2 systems still remain in popular use for a number of applications, particularly in unmanned areas. Carbon dioxide is also a common agent in portable fire extinguishers and in localized fixed systems. Research is under way for using carbon dioxide as a component in twin-fluid water misting systems (section 3.6) and mixed with particulate aerosols (section 3.7). Carbon dioxide is used as a pressurizing agent in some dry chemical extinguishers. . It is also used in the Inergen and HFC Blend B halon alternative agents in a small proportion.

Design concentrations for carbon dioxide total-flood systems for protection against Class B fires involving typical liquid hydrocarbons range from 34 to 43 percent depending on the fuel [40] compared with approximately 5 to 8 percent for Halon 1301 systems [20]. Cup burner data show that a concentration of approximately seven times that of halon is required for *n*-heptane [41]. (Note, however, that this does not imply that seven times as much CO_2 is needed in a streaming or localized application.) Carbon dioxide is less efficient than halons—the time to extinguishment is longer and, in general, storage requirements are greater. Carbon dioxide is, however, more efficient than other inert gases, a characteristic that is due to its greater heat capacity [42 (~~Old 164-Colton~~]. For most total-flood applications, an agent storage volume of approximately eight times that required for halon is required for most CO_2 systems (however, see the next paragraph for a discussion on liquid CO_2 systems where the ratio can be as low as four times). Weight and space considerations are more relevant in retrofitting than in new installations, but they are unlikely to be major obstacles for retrofit into existing industrial and commercial facilities. On the other hand, weight and space requirements are likely to be a barrier for CO_2 retrofit of onboard aircraft applications. Traditionally, CO_2 fixed systems cost two to three times (excluding agent cost) that of halon systems.

Pyrozone Sales Pty. Ltd. in Australia manufactures a range of modular low-pressure CO_2 storage units that use liquid CO_2. Liquid CO_2 requires considerably less volume than the gas phase agent found in most CO_2 systems and, moreover, it is claimed that Pyrozone Systems have the potential to use existing Halon 1301 pipework and detection equipment. The Pyrozone units use refrigeration to maintain the CO_2 as a liquid and have integral contents measuring capability. Pyrozone units are designed to be refilled in situ negating the need to dismantle any part of the system after a discharge.

Concerns exist about the safety hazard to personnel in areas protected with fixed, total-flood CO_2 systems. Unlike the other inert gases, CO_2 is toxic in large amounts (it is a respiratory regulator), and the design concentrations are well above dangerous levels (above 9 percent, loss of consciousness occurs within a short time, with death occurring

around 25 to 30 percent [43]). With most fixed localized systems, on the other hand, the hazard is much less and with portable extinguishers, any hazard is minimal. It is possible to manage the safety hazard with fixed, total-flood CO_2 installations by designing the system to ensure that automatic discharge does not occur while people are present in the protected area or by using manual activation. There are many well developed internationally recognized standards that provide the guidelines for the safe use of CO_2 total-flood systems. However, owing to the toxicity and the reduced efficiency, CO_2 is generally less attractive to fire insurers.

Concerns have been expressed about erasing of magnetic tape and damage from thermal shock due to CO_2. Testing has failed to substantiate the first concern, and thermal shock does not normally occur unless the discharge is directed at objects close to the nozzle. Some specialized installations are designed to pass the CO_2 through a vaporizing unit (converting all of the CO_2 to a gas) to reduce cooling by vaporization and sublimation. Continued use by telecommunications and modern power supply industries support compatibility of CO_2 with risks of this type.

Carbon dioxide portable fire extinguishers have been available for many years and are in common use. They have certain disadvantages compared with Halon 1211: larger size, greater weight, lower efficiency, shorter throw range, and no Class A rating. In many applications, however, these disadvantages do not rule out the use of CO_2 fire extinguishers. Note, however, that complete protection of any facility with CO_2 may leave the facility devoid of sufficient Class A protection, and other types of agents—water, foam, dry chemical—may be needed.

3.5 LOADED STREAM.

The term "loaded stream" is used to indicate any mixture of a salt (usually an acetate, a citrate, and/or a carbonate) with water. This mixture is rated for Class K fires (cooking oil and fats). Most loaded stream agents are used for protection of cooking and restaurant facilities. Kidde manufactures two different types of loaded water extinguishers with sodium acetate, water, and ethylene glycol—one contains a mixture with 50 percent sodium acetate and the other a mixture with 30 percent sodium acetate.

One study has shown that sprays of aqueous solutions containing 60 percent potassium lactate or 60 percent potassium acetate are far superior to neat water sprays in extinguishing JP-8 fuel fires [44].[2] The improved performance is attributed to the release of solid salts upon evaporation of the water droplets. The work also shows that iodide salt solutions are superior to bromide salt solutions. . The disadvantages of the loaded stream agents are potential secondary damage, requirement for cleanup, unsuitability for discharge onto live electrical equipment, and inability to penetrate enclosures as well as halons and other gaseous agents.

[2] JP-8 is a hydrocarbon fuel with a flashpoint typically about 50°C. The fuel in the study cited here had a flashpoint of 50°C.

3.6 Water Misting Systems.

Water misting systems allow the use of fine water sprays to provide fire protection with reduced water requirements and reduced secondary damage. Calculations indicate that on a weight basis, water could provide fire extinguishment capabilities better than those of halons provided that complete or near-complete evaporation of water is achieved. Since small droplets evaporate significantly faster than large droplets, the small droplets achievable through misting systems could approach this capability. The NFPA 750 Standard on water misting systems [45] establishes 1000 microns (micrometers, μm) or less as being the water droplet size for a system to be designated as a water misting system; however, many misting systems have droplet sizes well below this value. Water misting systems extinguish fires by three mechanisms: (1) heat absorption through evaporation and, to a lesser extent, vapor-phase heat capacity, (2) oxygen dilution by the water vapor formed on evaporation, and (3) radiative heat obstruction by the mist.

A detailed review of water misting has been written by the Navy Technology Center for Safety and Survivability and Hughes Associates [46]. More recent reviews are presented in references 47 and 48. Water misting is being evaluated both as a possible replacement for total-flooding Halon 1301 systems [49] and for use in hand-held extinguishers [50].

At the request of the EPA, manufacturers of water misting systems and other industry partners convened a medical panel to address questions concerning the potential physiological effects of inhaling very small water droplets in fire and nonfire scenarios. Disciplines represented on the medical panel included inhalation toxicology, pulmonary medicine, physiology, aerosol physics, fire toxicity, smoke dynamics, and chemistry with members coming from the commercial, university, and military sectors. The executive summary of the final report [51] states the following:

> "The overall conclusion of the Health Panel's review is that water mist systems using pure water do not present a toxicological or physiological hazard and are safe for use in occupied areas. The Panel does not believe that additional studies are necessary to reach this conclusion. The Health Panel recommends that additives be evaluated on a case-by-case basis depending on the toxic properties of the additive and the concentration at which it is used."

As a result of this study, the EPA is listing water mist systems composed of potable water and natural sea water as acceptable without restriction under SNAP. Water mist systems comprised of mixtures in solution must, however, be submitted to EPA for review on a case-by-case basis.

There are two basic types of water mist suppression systems—single fluid and twin fluid. Single-fluid systems utilize water stored or pumped under pressure; twin-fluid systems use air, nitrogen, or another gas to atomize water at a nozzle. The systems can also be classified according to the pressure in the distribution system piping as high pressure

(above 500 psia (34.5 bar)), intermediate pressure (175 to 500 psia (12.1 to 34.5 bar)), and low pressure (175 psia (12.1 bar) or less). Both single- and twin-fluid systems have been shown to be promising for fire suppression. Single-fluid systems have lower space and weight requirements, reduced piping requirements, and easier system design and installation; twin-fluid systems require lower water supply pressure, larger nozzle orifices (greater tolerance to dirt and contaminants and may allow the use of higher viscosity antifreeze mixtures), and increased control of drop size [46].

The performance of a water mist system depends on the ability to generate small droplet sizes and the ability to distribute mist throughout a compartment in concentrations that are effective [46]. Suppression effectiveness depends on five factors: (1) droplet size, (2) droplet velocity, (3) spray pattern, (4) momentum and mixing characteristics of the spray, and (5) geometry and other characteristics of the protected area.

Water mist systems are reasonably weight efficient. The use of small-diameter distribution tubing and the possible use of composite, lightweight, high-pressure storage cylinders would increase this efficiency. It may also be possible to integrate a central storage of water for use in several potential fire locations (for example, cargo and passenger cabin locations). However, this integration may not always be beneficial, it could introduce failure modes, decrease availability, and reduce safety.

The major difficulties with water mist systems are those associated with design and engineering. These problems arise from the need to generate, distribute, and maintain an adequate concentration of the proper size drops throughout a compartment while gravity and agent deposition loss on surfaces deplete the concentration. Water mist systems have problems extinguishing fires located high in a space away from the discharge nozzles. Water mists also have difficulty extinguishing deep-seated Class A fires. Other concerns that need to be addressed are (1) collateral damage due to water deposition, (2) electrical conductivity of the mist, (3) inhalation of products of combustion due to lowering and cooling of the smoke layer and adhesion of the smoke particles to the water drops, (4) egress concerns due to loss of visibility during system activation, (5) lack of third-party approvals for most or all applications, and (6) lack of design standards [52]. Concern has also been expressed about the possibility of clogging of small nozzle orifices used in some systems.

For aircraft use, misting systems are most appropriately considered for cargo bays and, possibly, engine nacelles. Some concern has been expressed that water mists may be inappropriate for cargo bays due to the possibility of deep-seated and hidden fires. The FAA William J. Hughes Technical Center data show that deep-seated fires are probable and have caused several fatal cargo compartment fires. Tests by the FAA and others on deep-seated cargo fires indicate that water mist systems can be effective in combating such fires. Water mist may hold several advantages and should be considered for cargo bay application.

The use of water mists for protection of nacelles may be difficult. First, the low temperatures, around -57°C (-70°F) at altitudes of 36,000 feet, hinder storage, discharge, and evaporation. Second, there is concern about the possible collateral damage due to thermal shock when water contacts hot titanium components. Third, water systems are likely to be bulky. Finally, water is not expected to be distributed as uniformly as halocarbon and other gaseous agents.

Table 15 gives a list of manufacturers for water misting systems. Only the country for the main headquarters is listed; however, most have locations in several countries.

TABLE 15. COMMERCIAL WATER MISTING SYSTEMS

Manufacturer or Distributor	Trade Name	Pressure
Single Fluid		
Baumac International, USA	MicroMist	High
Chemetron Fire Systems, USA	Chemetron	Low
Fike Corporation, USA	Micromist	Medium
FOGTEC Fire Protection, Germany	FOGTEC	High
Ginge-Kerr, Denmark/Kidde-Deugra, Germany	AquaSafe	Low
Grinnell, USA	AquaMist	Medium
GW Sprinkler, Denmark		Low/Medium
Marioff Oy, Finland	Hi-fog	High
Phirex, Australia	[a] Mistex	Low/Medium
Semco Maritime A/S, Denmark	Sem-Safe	High
[b] Spraying Systems Company, USA	FogJet	High
Total Walther, Germany	MicroDrop	Low
Ultra Fog AB, Sweden	Ultra Fog	High
Twin Fluid		
Securiplex, Canada	Fire Scope 2000	Low
International Aero Inc., USA	IAI Water Mist	Low
Life Mist Technologies, USA	Life Mist	Low
Victraulic	Vortex	Low

[a] Both fixed and self-contained portable systems.
[b] Manufactures nozzles only.

3.7 FINE PARTICULATE AEROSOLS.

Fine particulate aerosols are air-suspended dry chemicals with micron-size particles that give some total-flood capabilities. Dry chemical agents are at least as effective as halons in suppressing fires and explosions in many applications; however, such agents can damage electronic and mechanical equipment. Moreover, dry chemical agents, as now used, do not provide explosion inertion or fire suppression for time periods similar to those provided by halon systems due to settling of the particles. The discharge of dry

chemicals also obscures vision. In Geneva, Switzerland, at the 2nd Conference on the Fire Protecting Halons and the Environment, 1-3 October 1990, representatives of the Soviet Union provided information on a solid agent that they claimed provided relatively long-term (20 minutes or more) inertion of an enclosed volume and excellent fire extinguishment [53]. The first detailed technical information on this technology, however, was provided in the 1993 Halon Alternatives Technical Working Conference in Albuquerque, New Mexico [54-56].

Most, but not all, of the commercialized technologies for production of particulate aerosols employ an oxidizing agent and a solid fuel which, when ignited, produces a fine solid particulate aerosol providing extinguishment similar to that provided by dry chemical agents. An alternative process manufactures aerosol-size dry chemical agents by spray drying—spraying aqueous solutions into a heated space [57]. The small particle size appears to increase efficiency, decrease deposits, and increases the space-filling capability (multidimensionality) relative to normal dry chemical agents. Some have termed this type of technology "pyrotechnically generated aerosol (PGA)." Others have suggested that the term "pyrogenic aerosol" is more appropriate. In this report, "pyrotechnically generated aerosol" and "pyrogenic aerosol" are considered synonymous. PGAs are generated from nonpressurized containers. For a review of this area see reference 58.

As particle size decreases, the particulate surface on which heterogeneous recombination of combustion chain propagators can occur increases (e.g., Reactions 1, 2).[3] Moreover, as particulate size decreases, the sublimation rate increases, enhancing homogenous gas phase inhibition mechanisms, examples of which are shown in Reactions 3 through 5 for potassium-containing aerosols (the most common type) [59]. Thus, in addition to improving dispersion, the small particle sizes inherent in particulate aerosols give these materials a greater weight effectiveness than standard dry chemical agents, decreasing problems due to residue. Both heterogeneous (particulate surface) and homogenous (gas-phase) inhibition appear to contribute to flame inhibition by particulate aerosols. Heat absorption by decomposition reactions and phase changes may also contribute.

$$\bullet\bullet O + \bullet H \rightarrow \bullet OH \tag{1}$$

$$\bullet H + \bullet OH + M \rightarrow H_2O + M \tag{2}$$

$$\bullet K + \bullet OH + M \rightarrow KOH + M \tag{3}$$

$$KOH + \bullet H \rightarrow \bullet K + H_2O \tag{4}$$

$$KOH + \bullet OH \rightarrow H_2O + KO\bullet \tag{5}$$

The following presents information on some commercialized materials. NFPA has developed a design standard for aerosol generators, NFPA 2010, *Standard for Fixed Aerosol Fire- Extinguishing Systems* [60 ~~168~~]. Aerosols may extinguish surface-

[3] Here, "•" denotes a free radical.

burning Class A fires, and Class B and C fires. Per NFPA 2010, aerosols should not be used for deep-seated Class A fires unless it can be proven effective to the authority having jurisdiction for that application. All aerosol generators currently approved by the US EPA are limited to either unoccupied areas or areas not normally occupied.

3.7.1 Spectrex/ Ansul Fire-Extinguishing Agent.

The family of Spectrex fire-extinguishing agents (S.F.E.) (also known as EMAA, Encapsulated Micron Aerosol Agent) [55] are contained in generators and in applicators. Ansul is licensed by Spectrex Inc. of New Jersey, USA, to produce the S.F.E. agents under the trade name Micro-K and to market them worldwide. The powdered aerosol agents are produced in an oxidation-reduction combustion process that takes place in a combustion chamber specifically designed to contain various amounts of solid-casted material from 100 grams and up to several kilograms. The combustion chamber is introduced in modular units (generators) that include a cooling means (chemical and physical) as well as discharge outlets that direct the aerosol flow towards the protected volume. The agents provide an air-suspended dry chemical aerosol with micron-size particles that give total-flood capabilities [61].

U.S. Navy and U.S. Air Force tests and evaluation programs [58] indicate that on a weight basis, the agents are three times more efficient than regular dry powders and five times more efficient than halocarbon extinguishing agents. The agents, designated as "powdered aerosol A," have been approved under SNAP for total flooding of unoccupied areas [9]. The S.F.E. agents were also evaluated by the FAA in a test program performed at its test facilities at the William J. Hughes Technical Center. S.F.E. Formulation "D" performance is reported in reference 62 and further in section 4.4.3 of this report.

Before ignition, S.F.E. has a density of 1300 to 1800 kg/m^3. The combustion temperature is 1500 to 2400 K, and the combustion velocity is 0.3 to 1.5 mm/sec. The material, which may be a solid pellet or a gelled paste, has a shelf life of 15 years. Prior to combustion, the S.F.E. solid material is not affected by prolonged exposures to extreme temperatures (from -55°C to +250°C) and remains functional in its original state (does not change phases to liquid or gas). Emissions from S.F.E. contain 40 percent particulate aerosols with a median diameter of 1 to 2 micron [63], comprising salts such as K_2O, KCl, and K_2CO_3. The remaining 60 percent of the emissions are gaseous combustion products such as CO_2, N_2, H_2O, O_2, and traces (ppm) of hydrocarbons. Hazardous gases such as CO and NO_x are not observed in improved formulations recently tested.

The toxicity of S.F.E. agents has been evaluated by the U.S. Navy Medical Research Institute Toxicology Detachment [64- 68]. Two formulations, A1 and A2, were compared. Prolonged exposure of test rats to powdered aerosol S.F.E formulation A1 at concentrations exceeding 80 g/m^3 caused toxic effects that resulted in deaths and have led to the development of formulation A2. Multiple exposures to the byproducts of pyrolyzed formulation A2 at concentrations ranging from 50 g/m^3 to 240 gr/m^3 caused no deaths to Fischer 344 rats and only minimal toxic effects [66]. All the animals recuperated after the exposure ceased. Formulation A2 is commercialized as S.F.E.

The S.F.E. agents are casted solids contained in modular units (generators) of various sizes containing from 100 grams to 5 kilograms net weight S.F.E., some of which include cooling. The approximate design factor is 50 g/m^3 for direct material activation in enclosed areas and 100 to 120 g/m^3 when discharged from cooled generators, where a safety factor of 20 percent is included [69]. Typical system configurations include several modular units connected in a loop to a control box/display panel activated electrically by a signal from a separate detection system or by a self-contained detection element incorporated in the modular unit. The modular units and systems are manufactured and distributed by Spectrex (USA), Grinnell Ansul (USA), Gamesa - I.S.E. (Spain), and other companies. The main applications/installations are Modular Unit Micro-K for electrical board, engine compartments, etc., by Ansul; nuclear power stations and transformer rooms by Gamesa - I.S.E.; and deployable and portable extinguisher by Spectronix Ltd., Israel.

3.7.2 PyroGen and Firepak.

A pyrotechnically generated aerosol manufactured by Pyrogen Corporation has been approved under SNAP as Powdered Aerosol C for total flood of normally unoccupied areas [8, 9]. The agent is marketed in the U.S. by International Aero Inc. under the name Firepak and in most other countries, including Australia, New Zealand, Southeast Asia, and Europe by Pyrogen Corporation under the trade name PyroGen [4].

The self-contained nonpressurized canister contains two solid tablets—an aerosol-producing propellant and a coolant. Upon activation of the canister, either electrical or thermal, the propellant burns to produce a fire-extinguishing aerosol—a mixture of micron-sized chemical powders and inert gases. The aerosol propels itself through the coolant and out of the canister into the enclosure.

The aerosol-producing propellant consists mainly of potassium nitrate and plasticized nitrocellulose. Combustion products of the propellant are finely dispersed potassium carbonates, carbon dioxide gas (1.2 percent), nitrogen gas, and water vapor; the mixture being the actual extinguishing medium. The design concentration—the mass of nonignited solid aerosol-producing propellant required to produce an adequate amount of aerosol to extinguish a specified type of fire per unit of volume—has been established as 100 g/m^3 for Class B fires and surface Class A fires.

Like other PGAs, the use of Firepak in the United States is now limited to normally unoccupied areas, in part because the finely dispersed solid particles of the aerosol decrease visibility in the protected enclosure. Some byproducts of the aerosol generating reaction of the solid propellant (e.g., carbon monoxide and nitrogen oxides) could cause moderate local irritation of the upper respiratory tract and eyes. Elevated temperature of the aerosol at the discharge outlet requires that minimum clearances be observed.

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[4] This agent was originally marketed as FEAS by Bytenet Holdings, Australia.

3.7.3 Soyus.

Dynamit Nobel GmbH Explosivestoff und Systemtechnik, Troisdorf, Germany, produces a number of different sizes of pyrotechnically generated aerosol fire-extinguishing generators. The aerosol generating units, which are marketed under the trade name Soyus, contain an ignition device, the fire-extinguishing composition, a reaction compartment, and a cooling unit in a cylindrical metal housing. The generators produce potassium carbonate, K_2CO_3, of which 99 percent has a particle size of 0.5 to 4 micron. The SO 200 E-E01 unit (height = 118 mm, diameter = 82 mm, weight = 0.88 kg) protects a volume of approximately 2.0 m^3. The SO 300 E-E01 unit (height = 208 mm, diameter = 82 mm, weight = 1.49 kg) protects a volume of approximately 3.0 m^3. Aerosol generation is reported to last 8 seconds for the first unit and 10 seconds for the second unit with a particulate residence time of approximately 1 hour. Ignition can either be electrical or manual.

3.7.4 Stat-X.

FireAway LLC purchased the rights to aerosol generators sold under the Aero-K trademark and now have harmonized products under the Stat-X trademark. There are eight UL listed models of Stat-X generators containing from 0.07 to 5.5 Lb (0.03 to 2.5 kg) of aerosol generant, protecting volumes from 16 to 1,380 ft^3 (0.5 to 37.3 m^3) per generator. The generant consists of alkaline metal nitrates and a combustible organic binder. The combustion products are primarily potassium salts with some ammonium bicarbonate. . This agent has been approved under SNAP as “Powdered Aerosol D” for total flood of normally unoccupied areas.

3.7.5 Kidde-Deugra Aerosol, KD-A-96.

Kidde-Deugra produces a very fine aerosol powder (KD-A 96) using a dry spray technique [57]. The aerosol powder is stored in cylinders together with inert gases as the propellant. This procedure avoids problems of hot gas emissions found for pyrotechnically generated aerosols. This agent has found use in the protection of limousines, and certain high hazard industrial applications.

3.8 SOLID PROPELLANT GAS GENERATORS.

Solid propellant gas generators (SPGG) are similar to fine particulate aerosol generators which are based on a solid propellant. The exception is that SPGGs can produce limited particulates and those particulates generated may be filtered before the discharge, leaving a clean discharge stream of inert gas. Depending on the generator, the discharge gas may be nitrogen, or a mixture of nitrogen, CO_2, and water vapor. There are some SPGG where chemical additives are used to create a limited amount of fine aerosol particulates. These particulates are often potassium salts, which will enhance Class B performance, but do not provide much additional Class A performance. The U.S. Navy has conducted numerous feasibility and design verification tests on several aircraft platforms to assess

and refine SPGG designs. NAVAIR has qualified, installed, and has over 15 years of flight experience with SPGG technology aboard their F/A-18E/F and V-22 aircraft, with a notable success in having successfully extinguished an in-service 3-D pressurized fuel-fed fire in a V-22 mid-wing area. The U.S. Air Force has been evaluating the technology for aircraft dry-bay applications and will be testing SPGGs for protection of F-22 aircraft. The U.S. Army TACOM (Tank Automotive Command) has been performing testing in engine compartments of tracked vehicles and may also evaluate SPGG technology in crew compartments. Several overviews of SPGG technology and the progress of testing conducted to date have been presented [70- 72].

3.8.1 Aerojet (formerly General Dynamics and Primex Aerospace Company).

Aerojet SPGGs are used on the V-22 Osprey and the F/A-18E/F Super Hornet for dry bay fire protection. They use an electrically activated squib to ignite a solid propellant that generates an inert gas mixture of nitrogen, carbon dioxide, and water vapor. The SPGGs are designed to discharge rapidly (on the order of ~100 milliseconds) in order to address explosive fire threats. They have been qualified through series of U.S. Department of Defense (DoD) sponsored test programs [73 , 74, 75 OLD155-157 Colton].

Aerojet has been involved with DoD and commercial vehicle testing and has developed and manufactures generators for this use. These devices were originally considered for use for fire protection of aircraft dry bays [74 ~~old 156~~]. Chemically active propellants and Hybrid Fire Extinguisher (HFE) technology where the generator is used in combination with other extinguishing agents have been developed. The original Aerojet device uses an electrically activated squib to ignite a solid propellant that generates an inert gas mixture consisting of nitrogen, carbon dioxide, and water vapor. More recently, these devices have incorporated a propellant composition that has been modified to generate a fine aerosol particulate composed of potassium carbonate together with the inert gas blend; this aerosol significantly enhances effectiveness in fire suppression, presumably via the chemical means common to other potassium-based suppression (agents). These chemically active generators are cleaner than aerosol gas generators and the small amount of particulates result in a large gain in weight efficiency for Class B fires. Testing has demonstrated a 50 – 70% propellant weight reduction when compared with inert gas generator technology for Class B fires [76 - 77 ~~old 158-159- Colton~~]. Aerojet has a range of chemically active generator sizes, but the most common size has a gross weight of ~2.5 lb (1 kg) and occupies the space of a 2 in. diameter cylinder with a length of 8 in. The protected volume for Class B hazards is approximately 35 ft^3 (1 m^3) depending upon airflow conditions. These devices are used by at least one tactical vehicle manufacture for fire protection in engine compartments.

Aerojet SPGGs installed on the V-22 and F/A-18E/F aircraft utilize the FS 0140 agent, which has been listed as acceptable under the EPA SNAP program as “Inert Gas/Powdered Aerosol Blend” for use as a total-flood agent in unoccupied areas [9]; this limitation is due to levels of CO_2 generated at effective loading concentrations. Aerojet’s chemically active compositions are effective at CO_2 levels within occupied space limitations.

3.8.2 ATK

The ATK OS-10 generator is EPA approved for occupied spaces. The discharge stream is comprised of 34% nitrogen and 66% water vapor, with trace amounts of other combustion by-products within acceptable exposure limits. This exothermic process of gas generators results in large quantities of excess heat. This heat is typically absorbed with external coolant beds (such as residing within the overall system) or radiated outwardly from the exterior of the container. Since water vapor is a significant component of the extinguishing agent generated with the system, some of this water vapor will condense onto the surfaces of the internal cooling bed, leaving within the gaseous effluent a mass proportion of water vapor equal to the saturation humidity ratio at the local temperature (the higher the temperature, the higher the mass proportion).

The ATK quad-generator system can protect 1,360 ft^3 (38.5 m^3) of Class A hazard, or 904 ft^3 (25.6 m^3) of Class B hazard [78 ~~old 153- Colton~~]. This system has a gross weight of 261 Lb (118.4 kg) and occupies a space of 16.4 in. x 16.4 in. x 30.3 in. (41.7 cm x 41.7 cm x 77.0 cm).

3.8.3 N2 Towers

N2 Towers has developed a gas generator that has discharge stream comprised of almost pure nitrogen, with only trace amounts of other combustion by-products within acceptable exposure limits. N2 Towers has two generator concepts: 1) a fast acting generator intended for crew compartments and other hazards that need response times under a second, and 2) a slower burning generator that discharges on the order of seconds, which would be daisy chained together for industrial and commercial applications, such as computer rooms. The fast acting generator was tested in military crew compartment simulations and performed well [79 ~~old169- Colton~~]. This test utilized two 6" long by 6" diameter generators mounted in the opposite left and right corners of a 130 ft^3 (3.68 m^3) lexan test booth. The left generator was activated 40 milliseconds after the explosive fire was detected and the second generator was activated 100 milliseconds later. The fire consisted of a gasoline fuel directed across an electrical arc igniter with the fuel supply valve being left open for 2 seconds and the igniter left on for 3 seconds. The fire was detected in approximately 2 milliseconds, a delay of 40 milliseconds was programmed into the release control box and the fires were extinguished in approximately 55 to 173 milliseconds. The generator extinguished the fire and brought the protected space down to approximately 15.7 % oxygen per volume, at a 2 psi pressure increase and an ambient noise level increase to approximately 138.8 decibels for 150 milliseconds inside the test compartment.

The slower burning generator design utilizes generator assembly that has a 6 in. diameter x 24 in. length (15.2 cm diameter x 61 cm length). Each generator can protect 400 ft^3 (11.3 m^3). An EPA SNAP application has been submitted for the N2 Tower generators

and the EPA has provided a preliminary decision that these generators will be acceptable for occupied areas.

3.9 INERT GASES AND OBIGGS.

Combustion cannot occur when the oxygen content of air at normal pressures is sufficiently reduced (below approximately 15 percent oxygen, many fires cannot be initiated, and at lower concentrations, fires are extinguished). However, 12 percent or below is required to inert aircraft fuel tanks. Thus, inert gases, such as nitrogen and argon, etc., can extinguish fires by diluting the air and decreasing oxygen content. Extinguishment is also facilitated by heat absorption.

Health problems can occur at low concentrations of oxygen. Although asphyxiation is not probable at concentrations required to extinguish a fire, sufficient impairment could occur to prevent safe evacuation or emergency response. OSHA requires that no one enter a space with less than 19.5 percent oxygen without a self-contained breathing apparatus (SCBA). NIOSH gives the following effects at varying oxygen concentrations [80]. Note, however, that health problems that can occur would not happen immediately and would be a problem only for extended stays in an environment with a low oxygen level. Thus, there is some feeling that these predictions are meaningless without specifying a time period [81].

- 16 percent—impaired judgment and breathing
- 14 percent—faulty judgment and rapid fatigue
- 6 percent—difficult breathing, death in minutes

The minimum oxygen concentration where astronauts can still perform the minimum physical and mental activities required to safely pilot a spacecraft, although with great difficulty, has been established by the National Aeronautics and Space Administration (NASA) as 12.3 volume percent [82]. Between 16 and 12.3 volume percent oxygen, performance is increasingly impaired. An expert panel has reported, however, that a 3-minute exposure to an atmosphere containing 10 volume percent oxygen provides an adequate margin of safety considering the variability of a working population, but that lethality occurs quickly at oxygen concentrations below 8 volume percent [83].

One method that can be used is to increase the atmospheric pressure so that the partial pressure of oxygen does not decrease below that required for human respiration while reducing the percent oxygen to the point that extinguishment occurs [84]. The higher heat capacity due to increased atmospheric pressure also helps suppress fires. For example, submarines could use nitrogen flooding to dilute the oxygen while keeping its partial pressure constant to maintain life support [85]. This method can only be applied to completely enclosed areas with high structural strengths and is, therefore, limited to very few applications.

Pure and blended inert gases marketed as alternatives to halons are shown in table 16. All of the agents shown in this table are EPA approved under SNAP. The agent concentrations needed for extinguishment are approximately 34 to 52 percent, depending on the fuel and the fire scenario. The extinguishing properties of argon are similar to those of nitrogen for Class A, B, and C fires; however, unlike nitrogen, argon is suitable for Class D fires involving metals that react with nitrogen (e.g., magnesium and lithium). Effective extinguishment of a series of *n*-heptane, wood crib, and polyvinyl chloride (PVC) cable crib fires has been reported by the UK Loss Prevention Council for IG-541, IG-55, and IG-01 using the recommended design concentration and systems provided by commercial equipment manufacturers [**Error! Bookmark not defined.**]. In general, extinguishment times were longer with the inert gases than found for halocarbon extinguishing agents.

TABLE 16. INERT GASES

Designation	Composition	Extinguishment Concentration[a] (vol %)	Manufacturer
IG-541	Nitrogen 52 ±4% Argon 40 ±4% CO_2 8 ±1%	31	Ansul Incorporated, USA, and Fire Eater A/S, Denmark (INERGEN)
IG-55	Nitrogen 50 ±5% Argon 50 ±5%	35	Ginge-Kerr Denmark A/S (ARGONITE)
IG-01	100% Argon	42	Minimax GmbH (Argotec)
IG-100	100% Nitrogen	31	Koatsu (NN100), Japan

[a] Cup-Burner Extinguishment Concentration with *n*-heptane fuel, NFPA 2001 [16]

NOAEL and LOAEL values, which are normally based on cardiac sensitization for halocarbons, are inappropriate for inert gases. The EPA allows design concentrations to an oxygen level of 10 percent (52-percent agent) if egress can occur within 1 minute, but to an oxygen level of no lower than 12 percent (43-percent agent) if egress requires more than 1 minute [8 and 9]. Designs to oxygen levels of less than 10 percent are allowed only in normally unoccupied areas and only if personnel who could possibly be exposed can egress in less than 30 seconds.

In place of NOAEL and LOAEL values, the 2008 Edition of the NFPA 2001 Standard [16] uses a no effect level (NEL) and a low effect level (LEL) for inert gases. These values are based on physiological effects in humans in hypoxic atmospheres and are the functional equivalents of the NOAEL and LOAEL values given for halocarbons. All inert gas agents listed in the NFPA 2001 have sea level-equivalent[5] NEL and LEL values

[5] The term "sea level-equivalent" means concentrations that have the same oxygen partial pressures as those given by the NEL and LEL values at sea level (respectively, 91.2 Torr and 76 Torr partial pressures at an ambient total pressure of 760 Torr). For example, at an ambient total pressure of 600

of 43 percent (12-percent oxygen) and 52 percent (10-percent oxygen), respectively. Similar to that done for halocarbon agents, the Standard allows the use of an inert gas agent up to the LEL value for Class B hazards in normally occupied areas where a predischarge alarm and time delay are provided. In the absence of a time delay, only design concentrations up to the NEL are allowed. One major difference between the NFPA and EPA approaches is that the allowable design concentrations are not based on specific egress times in the NFPA Standard.

NEAG/HAG recommends [86] that oxygen concentrations in occupied areas protected by inert gas systems not be less than 12 percent unless a room can be evacuated in 1 minute (2 minutes in the case of INERGEN). This oxygen level corresponds to an inert gas concentration of 43 percent. NEAG/HAG also recommends that exposures to oxygen levels less than 10 percent not be allowed for any period of time.

3.10 OBIGGS

The Onboard Inert Gas Generation System (OBIGGS) is a gas separation technology that has been developed that separates oxygen and nitrogen gas from air. These systems are quite similar to inert gas systems that utilize nitrogen as the extinguishing agent. The main difference is that OBIGGS systems generate nitrogen enriched air on an as-needed basis. Therefore, over the length of a flight, the OBIGGS has the capability to generate more nitrogen than would be possible utilizing high pressure nitrogen cylinders. However, the OBIGGS flow rate limits the speed at which the nitrogen enriched air may be supplied to a chamber. A NASA study [87 ~~Old 151- Colton~~] provides the following description concerning how various OBIGGS operate:

"This [gas separation] can be accomplished by application of different technologies such as by the use of a permeable membrane or pressure swing adsorption or by air distillation columns. Gas separation devices can separate an incoming stream of air into two exit streams with the composition of one being nitrogen-enriched air (approximately 95% nitrogen and 5% oxygen) and the other being oxygen-enriched air. These devices are currently in use in commercial trucks and ships to transport fresh fruit and vegetables in a nitrogen gas atmosphere to preserve freshness and for a longer storage life.

There are some military aircraft that employ gas membranes for the generation of nitrogen for fuel tank inerting and dry bays for fire and explosion protection and oxygen for crew breathing. …

There are newer technologies in development that utilize distillation columns and cryogenic coolers to generate and store both liquid nitrogen and oxygen to meet the requirements for inerting and passenger and crew breathing. One such system now in development is called TALON, an acronym for total atmospheric liquefaction of oxygen and nitrogen. This type of system is capable of providing 99% pure oxygen and >96% pure nitrogen."

Torr, the oxygen concentrations would have to be 15.2% and 12.7% to achieve the same oxygen partial pressures. This would correspond to allowable agent concentrations of 27.6% and 39.5%.

The systems described all utilize a bleed air stream as input. Phyre Technologies, Inc. proposed a system that would pull air and fuel vapor directly from the ullage of the fuel tank. This system used a catalytic gas separation system to lower the oxygen and fuel content of the air returned to the ullage.

OBIGGS are becoming common on aircraft due to the 2008 FAA ruling requiring a decrease in the flammability of center fuel tanks. The ruling affects all future fixed-wing aircraft designs (passenger capacity greater than 30) and requires OBIGGS to be retrofit on more than 3,200 Airbus and Boeing aircraft with center wing fuel tanks. Both the new Airbus 380 and Boeing 787 are equipped with OBIGGS. Because of this, there has been interest in whether the nitrogen enriched air available from these systems could be diverted for use in other areas, especially for cargo protection. The drawback has been that the flow rate of nitrogen enriched air is limited, requiring too long of a period before the cargo compartment would be inerted.

The systems currently being installed on aircraft are based on membrane technology that separates the nitrogen and oxygen from a bleed air stream. These membrane separation units are installed in the pack bay within the wings of the aircraft.

There has been significant interest in developing more advanced OBIGGS that would be able to obtain higher flow rates. Additionally, there has been interest in creating combination systems where a secondary agent could be used to inert the space during the time it takes for the OBIGGS to deliver enough nitrogen into the protected space.

3.11 COMBINATION AND NEW FOAM AGENTS.

Mixtures with water or with halocarbon bases have been marketed for many years. One example is the loaded stream type of agents mentioned earlier. In addition, blends of dry chemicals with halons or other halocarbons, sometimes with a gelling agent, have been marketed. With the phaseout of halons, there is an increased interest in and development of such mixtures.

3.11.1 Envirogel.

The SNAP list gives a variety of formulations under the category “gelled halocarbon/dry chemical suspension” (designated as “Powdered Aerosol B” in the first SNAP listing [**Error! Bookmark not defined.**]) developed for particular markets. The materials, which are marketed under the trade name Envirogel by Powsus Inc., have been tested in a number of applications, including tracked vehicles [88 and 89]. Testing to date indicates that at least some formulations have an effectiveness similar to that of Halon 1301 on either a weight basis or a storage volume basis [90]. Each blend contains one or more halocarbons, a dry chemical, and a gel that keeps the powder and gas uniform.

The gelled agents are acceptable under SNAP for use in a streaming application provided that any halocarbon contained has a cardiac sensitization LOAEL of at least 2.0 percent

and that the dry chemical is one that is now widely used (i.e., monoammonium phosphate, potassium bicarbonate, and sodium bicarbonate) or is ammonium polyphosphate [9]. Among the halocarbons included in the SNAP submission were HFC-227ea, HFC-125, HFC-134a, and HFC-125 blended with HFC-134a. Also judged acceptable under SNAP for use as total-flood agents in normally unoccupied areas are formulations containing ammonium polyphosphate and monoammonium phosphate blended with either HFC-125 or HFC-134a [8 and 9].

3.11.2 Cease Fire.

Cease Fire manufactures CF-33, a patented blend of monoammonium phosphate and a polymer that absorbs an extinguishing gas. The automatic overhead Cease Fire units are UL listed for Class A, B, and C fires and are available in four sizes with coverage from 800 to 2700 cubic feet.

3.5.3 Aerojet

Aerojet Hybrid Fire Extinguisher (HFE) technology uses a solid propellant gas generator to pressurize and dispense a tank of fire suppression fluid [91- 92 ~~old 160-161-Colton~~]. Aerojet developed and manufactures a hybrid unit that is used for fire suppression on the Ford Crown Victoria Police Interceptor [93 ~~Old 162- Colton~~]. This system utilizes a gas generator to pressurize and distribute a firefighting foam solution. Aerojet has also developed and tested HFEs for ground vehicle crew compartments [92, 94 ~~Old 161-cross reference-Colton, old 163-Colton~~]. The protected crew volumes are dependent upon the chosen fire suppression agent (both aqueous and halocarbon agents are used) and a range of extinguisher sizes are available. Nominally, this extinguisher has a 5 in. diameter with a length of 12 in. for a protected volume ranging from 90 – 150 ft^3 (2.5 – 4.2 m^3).

3.5.4 ECOLOG Extinguishing System

Airbus teamed with two partners to develop a replacement engine and APU fire-extinguishing system: Siemens subsidiary SAS, which specializes in on-board fire safety; and PyroAlliance, which is a division of France's SNPE. The ECOLOG extinguishing system consists of a gas generator sized to provide the pressurization source for a spherical cylinder containing the FK-5-1-12 extinguishing agent. The FK-5-1-12 agent has a high boiling point, 118.4 °F (48 °C), and therefore the heat from the gas generator also helps to vaporize the agent. Full scale testing was conducted in July, 2007 at the Airbus test facility in Toulouse France. The testing consisted of an engine assembly using a Rolls Royce Trent 500 jet engine, which is typically used on the Airbus A340 aircraft. These test results were indicated to have met the minimum FAA MPS requirements for both the engine and APU compartments [95 Old 166- Colton].

4. APPLICABILITY OF TECHNOLOGIES TO AIRCRAFT APPLICATIONS.

As noted in the introduction, a major goal for the Task Group on Halon Options is an assessment of the applicability of halon substitute technologies to each major area of onboard aircraft use: (1) engine nacelles and APU (auxiliary power unit) compartment, (2) hand-held extinguishers, (3) cargo compartments, and (4) lavatory protection.

In evaluating agents for recommendations, we considered the essential properties/characteristics, the likely fire threat, the present fire detection and suppression practices, applicable regulations, and the current state of the technology. We did not allow the requirements of existing systems to influence our analysis. To allow this would have forced us to just one recommendation: Halon 1301 for total-flood applications and Halon 1211 for streaming agent applications.

4.1 REQUIREMENTS.

The candidate agents must meet the following requirements. The requirements imposed by the specific threat or application are additional to these requirements. A discussion of requirements or possible requirements by application has been published by the FAA [96].

a. The agent must be suitable for the likely Class of fire. It should be recognized by a technical, listing, or approval organization—National Fire Protection Association (NFPA), Underwriters Laboratories (UL), Factory Mutual Research Corporation (FMRC), etc.—as a suitable agent for the intended purpose or such recognition should be anticipated in the near future.

b. It should be compatible with construction materials in the areas where fires may occur and with materials used in the extinguishing systems. There should be, at most, minimal corrosion problems due to extinguishment, either from the neat agent or from likely decomposition products. This is particularly important for aircraft engines and for areas where contact with electronic components could occur.

c. It should comply with the provisions of the Montreal Protocol. It must have a near-zero ozone depleting potential. Low Global Warming Potential (GWP) and atmospheric lifetime are desirable, but presently there are no generally accepted requirements. Nevertheless, GWP and atmospheric lifetimes were considered in these analyses.

4.2 ENGINE AND APU COMPARTMENT.

Title 14 Code of Federal Regulation (CFR) Part 25.1195, 25.1197, 25.1199, 25.1201, 25.1207 [97] identify the requirements for fire extinguishing systems in aircraft power plants.

Related to the objectives and performances of the system

1. A fire extinguishing system is required as identified in the CFR.

2. The extinguishing system must be shown to be effective in quantity of agent, rate of discharge, and distribution by live test during actual or simulated flight conditions.

3. The extinguishing system must provide adequate, simultaneous protection throughout the compartment or compartments (also termed as fire zones).

Related to the extinguishing agent

4. The agent must be capable of extinguishing flames emanating from any burning fluids or other combustible materials in the area protected by the fire extinguishing system.

5. The agent must be stable taking into account storage conditions.

6. The toxicity of the agent must be taken into account to not endanger personnel.

Related to the agent container assuming a typical pressurized container architecture where the agent is fired in the nacelle/compartment using a pyrotechnic cartridge (see Fig 1).

7. The container must be protected against bursting due to excessive pressure.

8. The pressure relief system must not damage the airplane.

9. There must be a mean to identify when the container has been discharged or when the internal pressure is too low to operate.

10. The temperature of the container must be maintained to prevent pressure from becoming too low to operate, and from becoming too high, causing premature discharge, or to cause deterioration of the pyrotechnic device, if used.

Related to the material of the extinguishing system

11. The extinguishing system material must not react chemically with the agent itself.

12. The components of the system in the fire zones (the zones to be protected) must be fireproof.

Compliance to these requirements can be shown by tests and analyses, including full scale fire testing, tests of similar powerplant configurations, tests of components, and/or service experience of similar powerplant configuration or analysis.

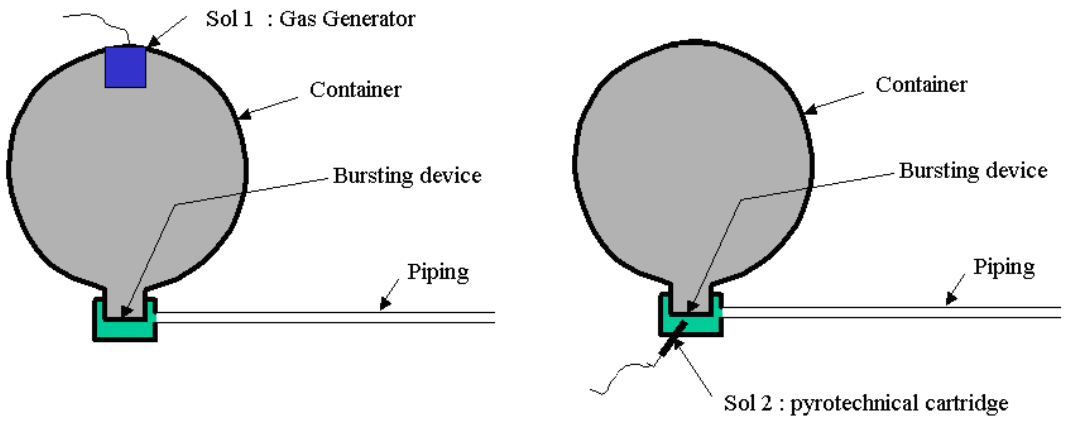

Fig 1. Typical fire extinguisher architecture. The solution on the left illustrates the use of a Gas Generator to pressurize the vessel at the time of discharge. The solution on the right illustrates a normally-pressurized vessel that is discharged by initiation of a pyrotechnic cartridge.

These requirements apply to all designated fire zones except for combustor, turbine, and tail sections of the turbine engine installations that contain lines or components carrying flammable fluids or gases. These areas are exempted because a fire originating in these sections can be controlled.

The fire threat addressed for these compartments is a Class B fire (aviation fuel, hydraulic fluid, and oil lubricant). The compartments are normally ventilated, have complicated air flow pathways, possess excessively heated materials, and are approximately at ambient pressure. Considerations which may adversely impact the system design are the continual presence of ventilation air flow during and after an agent discharge, potential residual fuel after a shutdown, and the presence of heated surfaces. Added to this are the extinguishing agent storage and delivery considerations.

Fires result when a failure allows flammable fluid to contact an ignition source under conditions permitting combustion. A flammable fluid release results from a mechanical failure, a hose, tube or fitting failure or even a maintenance error. This fluid then comes in contact with an ignition source—possibly hot surfaces or gases associated with operating conditions at the time of failure, abnormal conditions posed by friction (heat or sparks), or electrical energy. Any fire that is detected by thermal sensors activates aural and visual fire warnings on the flight deck. The accepted practice to combat an engine compartment fire is to eliminate ignition and fuel sources and then activate the fire extinguishing system. The process is achieved by shutting the engine down, closing local flammable liquid valves that include the fuel and hydraulic system, turning off local electrical power, and then activating the fire extinguishing system.

A gaseous fire extinguishing system is evaluated by an agent discharge test, which confirms the capability of the distribution system to provide the design agent

concentration for the necessary time duration. (Other systems for solid, liquid, aerosol, hybrid agents and possibly other methods shall have their individual test methods and procedures approved by their individual certification authorities). The test requires an engine to be operating at critical conditions when the agent release occurs. For gaseous agents a minimum of 12 sampling probes from a gas analyzer, customarily a Statham or Halonyzer type unit, are located in critical areas of the compartment during this test. The device records the discharge event in the form of a gas concentration vs. time relationship. The record is reviewed for compliance with FAA-accepted criteria for certification. Advisory Circular 20-100 [98] provides a good summation for the aspects of a discharge test.

The basis of AC20-100 means of compliance to 25.1195 requirements consists of showing the agent concentration exceeds the AC20-100 threshold for known gas agents. AC20-100 provides also guidance for gas concentration measurement apparatus. In order to demonstrate compliance to FAR 25 requirements, one must establish the threshold to be met by a replacement candidate. In engine nacelle/APU compartments, it was established that Halon 1301 performance is the reference for minimum extinguishing performance expected from any replacement candidate. Therefore a specification called Minimum Performance Standard for Engines (MPSe) has been put in place based on fire testing to enable this comparison.

A detailed history of the establishment of the Minimum Performance Standard (MPS) for aircraft engine nacelles can be found on FAA Technical Center web page [99]. The MPSe is currently at issue 4, published March 2010. Under the previous MPSe revision 3, three agents were successfully tested and minimum concentrations were established. The minimum concentration thresholds to provide equivalent fire extinguishing performance to Halon 1301 as established under MPSe revision 3 are [100] :

FK-5-1-12	6.1%v/v
CF3I	7.1%v/v
HFC 125	17.6%v/v

The agent 2-BTP was evaluated under MPSe revision 3, however it was rejected in 2005 due to concerns during testing [101].

Successfully testing a replacement candidate through the MPSe process at the FAA Tech Center is not sufficient to ensure the certification of a fire extinguishing system based on a new extinguishing agent. All the requirements discussed above must be met, and detailed discussions between FAA Transport Airplane Directorate and/or EASA with the airframe manufacturer must be conducted to determine the demonstration process for showing compliance. Consideration shall be given to specific aircraft installation requirements, distribution requirements, and operational environment for agent storage and agent performance. These include and are not limited to: agent long term storage environment including corrosion, settling, caking, agent decomposition, changes in physical and chemical properties, compatibility with engine materials including performance in fuel, oil and hydraulic fluid environment, agent delivery impediments

such as funneling, gelling, effects of swirling, loss of driver agent, variations in temperatures during storage and in the fire zones (see.102 for discussion on cold operation), vibration, aircraft speed, ventilation, altitude effects, effects of humidity and precipitation on agent performance.

4.2.1 HCFCs, HFCs, PFCs, and Blends.

These agents are similar in their performance and in their system characteristics. For this reason, they can be treated together when establishing a test protocol. These materials are typical PAAs.

Heptafluoropropane (HFC-227ea) and pentafluoroethane (HFC-125) were on the final list of agents being tested at Wright-Patterson AFB and both are recognized acceptable agents for Class B fires by technical and listing organizations, such as UL or equivalent. Both HFC-227ea and HFC-125 are acceptable under SNAP as a Halon 1301 substitutes [9]; however, under the present NFPA Standard 2001 [16], HFC-125 will be restricted to normally unoccupied areas for most fuels (not a problem in this application). It is also recommended that at least one blend be included in establishing test protocols since there may be differences between blends and pure materials in handling and/or performance.

HFC-125 was the final candidate from the DoD program. The program concluded with a design model for HFC-125 [103] that affords the designer the ability to calculate agent mass requirements for a particular nacelle or APU compartment based on parameters of ventilation air temperature and mass flow rate, anticipated fuel type, and compartment volume. This model is based on many points of fire extinguishment data produced in a test fixture. Guidance for the designer and limitations of the model are incorporated in the report.

A second source for HFC-125 design information can be found within the U.S. Navy. The Navy's F/A-18E/F underwent an evaluation with respect to potential fire extinguishing technologies for its aircraft engine nacelle. Ultimately, a quantity of HFC-125 considerably less than that predicted as necessary by the design equation derived from the earlier DoD program, successfully met the design challenge [104]. This effort is based on fire test results as produced in a complex test fixture representing the aircraft engine nacelle. The result represents a single point, but does offer another perspective on the performance for HFC-125 in the engine nacelle.

HFC-125 has successfully passed the testing protocol of MPSe revision 3 and subsequently must meet or exceed a concentration of 17.6%v/v to demonstrate performance equivalent to Halon 1301.

4.2.2 Trifluoromethyl Iodide (FIC-13I1) and FIC-13I1 Blends.

Testing at Wright-Patterson AFB has demonstrated that the chemically active agent trifluoromethyl iodide (FIC-13I1) is more effective in engine nacelle fire extinguishment than any other replacement halocarbon tested to date. A number of blends of CF_3I with other halocarbons have been reported as candidate extinguishing agents [105- 107]. The material is acceptable under SNAP [8, 9] in both streaming and total-flood applications with some use restrictions. The environmental characteristics are good, and the volume requirements and effectiveness are essentially identical to those of Halon 1301. A paper from NOAA (National Oceanic and Atmospheric Administration) states that

> "...the extremely short lifetime of CF_3I greatly limits its transport to the stratosphere when released at the surface, especially at mid altitudes, and the total anthropogenic surface release of CF_3I is likely to be far less than that of natural iodocarbons such as CH_3I on a global basis. It is highly probable that the steady-state ozone depletion potential (ODP) of CF_3I for surface releases is less than 0.008 and more likely below 0.0001. Measured infrared absorption data are also combined with the lifetime to show that the 20-year global warming potential (GWP) of this gas is likely to be very small, less than 5. Therefore this study suggests that neither the ODP nor the GWP of this gas represent significant obstacles to its use as a replacement for halons." [108]

It should be noted that the likely ODP is actually less than that determined for some of the hydrofluorocarbons (HFCs), which are given a nominal ODP of zero [109]. The cardiotoxicity of CF_3I is greater than that of other halocarbon candidates; however, the relatively low cardiac sensitization NOAEL and LOAEL values may be of little concern for engine nacelle and APU applications where potential for contact with personnel is very limited.

CF_3I has successfully passed the testing protocol of MPSe revision 3 and subsequently must meet or exceed a concentration of 7.1%v/v to demonstrate performance equivalent to Halon 1301.

4.2.3 Novec 1230 (FK-5-1-12)

Novec 1230, $C_6F_{12}O$, (3M Novec 1230) fluid is an acceptable Halon replacement for use as a gaseous fire extinguishing agent. Novec 1230 is manufactured by 3M (ODP=0 ; GWP=1 ; AL=0.014).

Novec 1230 fluid is a high molecular weight material, compared with the first generation halocarbon clean agents. The product has a heat of vaporization of 88.1 kJ/kga and low vapor pressure. Although it is a liquid at room temperature it gasifies immediately after being discharged in a total flooding system.

The product is appropriate for use in total flooding applications, localized flooding systems, directional spray type applications. In addition to the conventional methods of super-pressurization using nitrogen, Novec 1230 fluid also lends itself for use in pump applications because it is a liquid.

Novec 1230 fluid is based on a proprietary chemistry from 3M called C6-fluoroketone; it is also known as dodecafluoro-2-methylpentane-3-one; its ASHRAE nomenclature is FK 5-1-12 — the way it is designated in NFPA 2001 and ISO 14520 clean agent standards.

Novec 1230 has successfully passed the testing protocol of MPSe revision 3 and subsequently must meet or exceed a concentration of 6.1%v/v to demonstrate performance equivalent to Halon 1301.

4.2.4 PhostrEx

An alternative to Halon for engine fire extinguishing was certified by the FAA on the Eclipse EA500 very light jet in 2006 and subsequently approved by EASA in November 2008. The EA500 uses PhostrEx™ which employs phosphorous tribromide (PBr_3) as the fire extinguishing agent. The certification of the Eclipse engine fire extinguishing system was based on intensive fire extinguishing testing for this particular application in lieu of establishing a minimum concentration requirement through MPSe testing. The viability of the use of PhostrEx™ for other aircraft must be studied in more detail, including consideration of material compatibility, toxicity, MPSe test protocol and means for measuring agent concentration.

4.2.5 Gas Generators.

Both inert solid propellant gas generators (SPGGs) and next generation chemically active SPGGs have been tested as options for engine bay fire protection. Test results indicate that an SPGG (either inert or chemically active) used in engine bay fire protection will impose a take off gross weight (TOGW) penalty significantly lower than that expected for a typical halocarbon extinguishing system (HFC-125) [110, 111]. Early testing involved the use of distribution lines, thus negating many of the weight advantages based upon predicted changes in insulation and distribution lines required to protect against the hot gases from an SPGG. Recent work has demonstrated the effectiveness of radial discharge chemically active SPGGs in an AH-64 Apache helicopter nacelle simulator; SPGGs extinguished all fire scenarios and were deemed to be a suitable method for protecting the AH-64 engine nacelle environment [112]. In the U.S. Navy F-18 engine bay [113]; the results of a different SPGG variant; however, were not promising. No SPGG tested provided adequate fire extinguishment [114]. The F-18 testing was conducted in the mid-1990's and the AH-64 simulator tests were conducted in the mid to late 2000's.. Studies indicate that factors other than oxygen starvation or cooling contribute to flame suppression by SPGGs in military aircraft engine bays [115], and that chemically active SPGGs are more effective at preventing re-light than halocarbons and inert SPGGs [116]. One in-service success story is the successful extinguishment of a

real, hydraulic-fluid-fed mid-wing fire involving the rotor positioning unit (RPU) in a Navy V-22 aircraft [117].

Although work to date with aircraft engine bay fire protection using an SPGG technology has been mixed, it should not be ruled out as a direct fire suppression system for use in engine nacelles. The advantages of this technology are most pronounced in situations where the use of distribution lines can be limited or even eliminated altogether.

Rather than using a Gas Generator as the direct source of fire suppression, Gas generators can be used as a pressure generator for the extinguisher container to provide the motive force for an stored agent. Airbus research project [118] demonstrated this means for increasing the viability of a heavy replacement candidate by eliminating the need to store the agent under constant pressure.

4.2.6 Future Candidates

MPSe revision 4, includes provisions for the testing of agents different from the traditional gases studied in the past. Solid aerosols, liquids, non-gases, or mixtures may be accommodated under this test revision protocol.

4.3 HAND-HELD FIRE EXTINGUISHERS.

Federal Aviation Regulations mandate hand-held fire extinguishers be conveniently located in passenger compartments. The number of required extinguishers depends on the passenger capacity of the airplane [119]. The total number of extinguishers required are shown in table 17.

It is required that at least one of the extinguishers on an airplane with a passenger capacity greater than 31 and two of the extinguishers on an airplane with a passenger capacity greater than 61 must contain Halon 1211 (bromochlorodifluoromethane) or equivalent as the extinguishing agent. The minimum performance standard defines the equivalency.

TABLE 17. HAND-HELD EXTINGUISHERS REQUIRED FOR COMMERCIAL AIRCRAFT

Passenger Capacity	Number of Extinguishers
7 through 30	1
31 through 60	2
61 through 200	3
201 through 300	4
301 through 400	5
401 through 500	6
501 through 600	7
601 through 700	8

In addition, at least one hand-held fire extinguisher must be located in the pilot compartment, and at least one extinguisher must be available for use in each Class A[6] or Class B cargo or baggage compartment and in each Class E cargo or baggage compartment that is accessible to crew members during flight.

The FAA Advisory Circular AC 20-42D [120] provides guidance for the fire-fighting effectiveness, selection and safe-use of hand fire extinguishers in airplanes and rotorcraft. It establishes acceptable replacements agents for required Halon extinguishers. In it it is shown how to gain Federal Aviation Administration (FAA) approval of hand fire extinguishers for aircraft. This AC establishes an FAA approved minimum performance standard (MPS) for halon replacement agents which includes a hidden fire test and a seat fire/toxicity test. [121].

Required hand-held fire extinguishers for aviation use must meet the following requirements , specified in detail in the MPS [121].(The MPS applies to extinguishers required by FAA regulation).

a. Any hand-held fire extinguisher adopted for final use shall be listed by a listing organization such as UL or equivalent, be of a specific rating, and be of a size and weight that a typical flight attendant can use. The smallest recommended hand-held extinguisher has a UL 5-B:C rating in accordance with the UL 711 Standard [122]. This corresponds to 2.5 pounds net charge weight for a Halon 1211 extinguisher

b. The extinguisher must be able to extinguish fires in indirectly accessible spaces (hidden fires) as effectively as a Halon 1211 extinguisher with a 2.5 lb net charge weight. It is desirable that the agent be sufficiently volatile to allow expansion and penetration into such spaces. Hand-held extinguishing agents are by nature streaming agents; however, Halon 1211 and most potential replacements have the ability to also function as a flooding agent. To insure no loss of safety, replacement agents must maintain the same level of flooding ability as Halon 1211. A hidden fire test has been developed to assess the firefighting performance of the hand-held extinguisher/agent combination in a flooding scenario. This test [123] was developed by Kidde International-UK, under contract from the UK's Civil Aviation Authority.. The operating procedure has since been refined and standardized at the FAA William J. Hughes Technical Center, USA. The hidden fire test is administered by Underwriters Laboratory. Extinguishers that are filled with acceptable agents (see "c" below) and pass the hidden fire test will receive FAA approval to replace Halon 1211 in aircraft cabins.

[6] To avoid confusion with fire types, the classification of cargo compartments is underlined in this report.

c. The extinguisher must have an acceptable toxicity for use where people are present and must not cause unacceptable visual obscuration or passenger discomfort. In particular, the combined toxicity of the agent and fire products must not be unacceptable for use in an aircraft fire under in-flight conditions. The FAA has determined that the following agents are acceptable from a toxicity viewpoint for use in occupied aircraft cabins: Dupont™ FE-36 (HFC-236fa), , Dupont™ FM-200® (HFC-227ea), POWSUS Envirogel™, Safety Hi-Tech NAF P-IV™ (HCFC Blend E),, and American Pacific Halotron® I (HCFC Blend B). The FAA aircraft seat fire toxicity test was conducted with each of these agents and the toxicity criterion applied to assess acceptability.

As further discussion relating to the hidden fire test, a test fixture was developed that was comprised of arrays of four fires in two of five locations to establish those regions in which an extinguishing concentration was attained. A matrix of ten tests ensured that each fire location was adequately represented. Tests were carried out with several commercially available hand-held extinguishers. Results varied from 45 to 60 percent extinguishment depending on the quantity of halon contained in the extinguisher and the discharge rate (a faster discharge rate creates more turbulence, aiding mixing and dispersion). In addition, tests were carried out using under- and over-filled extinguishers to examine the sensitivity of the test method. With the exception of one hand-held extinguisher, all results could be correlated to the mass of agent and the flow rate used.

The CAA project carried out limited testing with six halon replacements: HFC-227ea, HFC-125, FC-3-1-10, FC-5-1-14, HFC-236fa, and FIC-13I1, using apparatus designed to give a constant discharge time (10 ±1 seconds). The results obtained appeared to be similar to Halon 1211 (50 ±5 percent extinguishment), provided the quantity of agent is scaled according to its *n*-heptane cup burner concentration. The two exceptions were agents whose volatility is markedly different from that of Halon 1211 (boiling point: -4°C (24.8°F), HFC-125 (boiling point: -49°C (-56.2°F), 65-percent extinguishment), and FC-5-1-14 (boiling point: 58°C (136.4°F), 35-percent extinguishment). As the boiling point increases, it is more difficult for the agent to immediately volatize and a portion of the agent falls to the floor and is carried out through ventilation openings in the fixture, resulting in the need for higher agent quantities to achieve the necessary airborne concentrations to extinguish the fires. The testing indicated that use of the physically acting candidate agents (all except FIC-13I1) would give a weight penalty of 1.4 to 2.6 and a volume penalty of 1.9 to 2.9 compared to Halon 1211.

The FAA revised the hidden fire test to have a fire present at all 20 possible locations within the fixture. An average of 9 cups (45% of the cups) is extinguished using an extinguisher containing a 2.5 Lb net charge weight. This 45% extinguishment of the cups is the requirement for any agent that will replace Halon 1211.

In the first report [1], the Task Group recommended establishment of tests for the groups of agents identified in the subsections below. These three groups of agents operate by different mechanisms and/or have large differences in physical properties. They cover the range of testing procedures and apparatuses that should be established. Dry chemical

extinguishing agents are not listed due to (1) the potential for damage to electronic equipment, (2) the possibility of visual obscuration if the agent were to be discharged in the cockpit area, and (3) the clean-up problem that results from their use. Restricting the use of dry chemicals to cabin areas does not prevent an extinguisher from inadvertently being carried to the cockpit and discharged in an emergency.

4.3.1 Halocarbons and Halocarbon Blends.

Of all the three agent groups, this group holds the most promise in being able to successfully replace Halon 1211. Halocarbons are considered "in-kind" replacements to Halon 1211. This means that these compounds are volatile (evaporate leaving no particulates), extinguish fires by reaching a specific vapor concentration in the fire zone, and are electrically non-conductive. Because of their gaseous nature, these agents have a better capability to pass the hidden fire test than other types of agents. There are three commercially available, UL-listed and FAA approved, agent/hardware combinations which could be installed today.

The first two of these approved combinations became available in 2004. However, the airframe manufacturers have not yet endorsed any of these agents. The three available combinations each use a different extinguishing agent: HFC-227ea, HFC-236fa, or HCFC Blend B. A number of HFCs, including these two, were first listed as acceptable by the US EPA in the mid-1990's to replace halons. HFC-125 is not a candidate handheld extinguisher replacement agent because it is not an effective streaming agent. HFCs are considered to have a zero ODP value, and therefore were not part of the Montreal Protocol, which phased out the new production of halons and controls the ongoing phase-out of new production of HCFCs. However, based on global warming concerns, the EU has started to require reporting of HFCs and the US has been involved in proposals to add HFCs to the Montreal Protocol. Potential regulation of HFCs has been discussed in terms of a phase-down versus a complete phase-out of new production.

FIC-13I1 (like some of the other halocarbons) will also face some restrictions based on toxicity. Under SNAP, this agent is not permitted as a total-flood agent in a normally occupied area.

HCFCs have a nonzero ODP and currently face an eventual regulated production phaseout. The phaseout dates in the United States depend on the material (table 6); however, all HCFCs now considered for streaming have the same phaseout schedule. When used in nonresidential applications, portable fire extinguishers containing HCFCs are exempted by the U.S. EPA from bans on HCFC-pressurized dispensers [124]. In the EU, HCFCs are not allowed to be used without securing an exemption. No EU states have applied for exemptions, which would allow use until the end of 2019. HCFC Blend B is a blend, based primarily on HCFC-123. Recent 3-dimensional environmental models have reduced the ODP of this compound to less than half of the original value listed in the Montreal Protocol [149]. The analysis evaluated both global warming and ozone depletion and determined that the use of HCFC Blend B resulted in a lower

environmental impact than use of HFCs. Based on this, potential regulatory lifetime extensions are being proposed.

Besides regulatory issues, there is a concern from airframe manufacturers about the larger size and weight of the HFC and HCFC extinguishers. The increased size and weight will generally require changes to the mounting brackets, location of the extinguisher, and in some cases the structure supporting the extinguisher and bracket. There is an up-front engineering, parts and labor cost associated with the initial design and installation of the handheld extinguisher replacement.

PFCs are accepted by the U.S. EPA [9] (FC-5-1-14 for streaming, FC-218 and FC-4-1-10 for total flooding) for nonresidential use where other alternatives are not technically feasible due to performance or safety requirements: (1) due to physical or chemical properties of the agent, or (2) where human exposure to the extinguishing agent may result in failure to meet applicable use conditions. The principal environmental characteristic of concern for these materials are their extremely high GWPs and long atmospheric lifetimes. Since HFCs and HCFCs meet all requirements, there would be no technical justification to use PFC compounds.

Concerning FICs, the only compound that has been accepted for use by the US EPA is CF_3I. Previously, there was some concern expressed about preliminary mutagenicity assays indicating that CF_3I might be a carcinogen. However, additional testing has been completed and has shown that CF_3I is not considered a carcinogen. In addition, there is some concern that iodine emissions from CF_3I could cause a problem. While no data has yet been collected showing that iodine emissions are any worse with CF_3I than bromine emissions are with Halon 1211, emissions at altitude only happen during fire events and the quantities released by handhelds would be extremely small. CF_3I has a non-zero ODP and falls into a newer category of compounds referred to a Very Short Lived Substances (VSLS). Since the atmospheric lifetime for VSLS are on the order of days, the ODP and GWP values for these compounds are dependent upon where these compounds are emitted. CF_3I has an ODP similar to HCFC-123. Currently, there are no proposed or existing US regulations limiting the production of CF_3I. In the EU, recent regulatory changes now require reporting of CF_3I quantities. Extinguishers containing CF_3I may be a potential solution. There are generally two reasons, however, why CF_3I has not become a commercial product. The first is cost; CF_3I is a difficult compound to manufacture and the cost is several times higher than existing halon replacements. This significantly limits the commercial and industrial markets for wider use outside of aviation. The second reason is the LOAEL value (0.4%vol.) as compared to Halon 1211 (1.0%vol.). Another consideration for the use of CF_3I in streaming applications is that it is fairly gaseous (boiling point: -22°C), which may make it difficult for CF_3I to be used in all streaming applications where Halon 1211 was used.

One fluoroketone, FK-5-1-12 (sold under the 3M trademark Novec 1230), was EPA accepted for both flooding and streaming use in 2003. This compound requires more weight than the HFCs or HCFCs, but it has made some market penetration in the total flooding market due to its low environmental values (zero ODP and GWP of 1). While

this agent has undergone multiple tests for streaming applications over the years, this compound is not commercially available in UL listed handheld extinguishers. While this compound should have the potential to pass the required tests for aviation handhelds, the size and gross weight of the unit is anticipated to be less than satisfactory (~3 times the gross weight of a Halon 1211 extinguisher and similar in size to the HFC-227ea extinguisher) unless some innovation is developed. Testing of this compound against the FAA seat fire/toxicity test is planned.

Based on regulatory and extinguisher relocation concerns, the aviation industry has been evaluating an experimental compound, 2-bromo-3,3,3-trifluoropropene (BTP). This compound is also considered a VSLS with a non-zero ODP. However, in a 2-dimensional analysis, the ODP has been calculated to be <0.0005 based on discharges in latitudes covering the US and EU [150]. The global warming potential is also extremely low. A handheld extinguisher containing BTP was tested at UL in a joint effort between Boeing and American Pacific. The results were an agent/hardware combination that passed the 5B pan test and hidden fire test in a cylinder similar to what is currently being used onboard Boeing aircraft. The extinguisher had a net charge weight of 3.75 Lb. Evaluations are ongoing for this compound and consideration is being given to proceeding with the necessary toxicology tests in order to gain approvals for this compound for use in the US and EU. FAA seat fire/toxicity tests are scheduled. This agent has not yet been submitted to EPA for SNAP review. Table 18 below reflects the size and weights of the BTP extinguisher as well as the commercially available HFC and HCFC extinguisher options.

TABLE 18. SIZE AND WEIGHT MATRIX FOR CANDIDATE HAND-HELDS[1]

Agent	Agent Weight, Lb.	Total Weight, Lb.	Dimensions, in. (H x W x D)
Halon 1211	2.5	3.93	17 x 4.8 x 3.25
BTP (2-bromo-3,3,3-trifluoropropene)	3.75	5.6	15.75 x 5 x 3.5
FE-36® (HFC-236fa)	4.75	7.8	15.9 x 8 x 4.5
Halotron® I (HCFC Blend B)	5.5	9.3[2]	15 x 5 x 4.25
FM-200® (HFC-227ea)	5.75	9.8	18.5 x 6.5 x 5.5

Novec 1230™ (FK-5-1-12)	TBD[3]	TBD[3]	TBD[3]

1. The agent/hardware weights and sizes are based on commercially available hardware or hardware that has passed the UL 5B pan and hidden fire tests. The combinations are sorted from lowest to highest gross weight. The values presented for the Halon 1211 extinguisher are based on the Kidde Technologies model 898052, which is standard equipment for Boeing aircraft.
2. This weight is based on the current carbon steel cylinder. Alteration to an aluminum cylinder has been proposed and would reduce this gross weight to approximately 7.8 Lb. The size of the unit would remain the same.
3. Testing to establish a minimum required weight for a 5B-rated fire extinguisher is currently being conducted by 3M. Successful testing will also result in identifying a total weight and volume.

In summary, three options (two HFC and one HCFC) have been commercially available for several years, but the airframe manufacturers have been reluctant to install these options. The airframe manufacturers have concerns based on the weight and size penalties for these options. Several of the potential agent options currently being evaluated are characterized by non-zero ODPs and there is a risk that future environmental regulatory actions may place limitations on their use. There are three additional potential agent options. CF_3I has been available in small commercial quantities for quite some time. Only limited interest has been shown in this compound due to cost and comparatively low LOAEL values. The fluoroketone option has not gone through many of the required tests, but based on known data points, the unit would be expected to be heavier, and potentially larger in size, than the options shown in Table 18. The BTP agent, which is still in development, will require more agent, but has been shown through testing to fit into a volume similar to what is utilized currently on Boeing and other commercial aircraft. There is additional testing and regulatory approval required before BTP can be confirmed as acceptable for use. Assuming that toxicity tests are funded in 2010 for BTP, it is estimated that the battery of required tests would not be complete until mid-2012. There are no additional halocarbon compounds beyond what is presented here known to be in development that would be available to be considered in the near term.

4.3.2 Carbon Dioxide.

There has been a large amount of experience with hand-held carbon dioxide fire extinguishers. They are known to be safe to use in a streaming application where people are present, and the carbon dioxide should be able to reach into indirectly accessible areas. A major problem exists in the lack of a Class A rating for hand helds in sizes from 5 pounds (5-B:C rating) to 100 pounds (20-B:C). If testing shows that carbon dioxide

extinguishers cannot extinguish Class A fires of the type likely to be found in cabin fire scenarios, this agent would have to be eliminated from consideration. From past testing [DOT/FAA/CT-82/111, reference125], more than 10 lbs of CO2 would be required to match the seat fire extinguishing characteristics of 2.5 lbs of Halon 1211. Additional concerns regarding carbon dioxide are related to its limited throw range and potential thermal shock to sensitive electronics. Due to these issues, as well as gross weight requirement, there has been little interest in the development of CO_2 extinguisher for onboard application.

4.3.3 Combination Agents and Foams.

These agents include Surfactant Blend A, Loaded Stream, and Gelled Halocarbon/Dry Chemical Suspension. Though these are listed together, their properties are sufficiently different, therefore, major differences in test procedures will probably be required. In the absence of test results, it is impossible to rank the fire extinguishment effectiveness in hand helds for aircraft use. They should all prove very effective for Class A fires; however, these agents may very well lack the ability to penetrate in indirectly accessible spaces. A study of hand-held fire extinguishers by FMRC states that "around object capability" for Halon 1301 is good, dry chemical is poor, and water is poor [126]. Most, and possibly all, combination agents may also have problems with penetration and obstacles. Testing with water-based extinguishers have confirmed their inability to pass the hidden fire test. As the water based agents are not gaseous, they have limited ability to penetrate significantly through the baffles of the hidden fire test. A test was conducted at the FAA Tech Center using a sodium bicarbonate extinguisher having a 2.5 Lb net charge weight. The dry chemical primarily fell to the floor upon impact with the first baffle. Additional concerns are that there could be some compatibility problems with electrical equipment and, possibly, structural materials with some of the combination agents. Both the Surfactant Blend A and the Gelled Halocarbon/Dry Chemical Suspension series of agents are acceptable under EPA SNAP.

4.4 CARGO COMPARTMENT.

The recent ruling eliminating Class D as an option for fire safety certification for cargo compartments in certain transport category aircraft will increase the number of compartments requiring fire suppression systems [127]. Such compartments must now meet the standards of Class C and/or Class E compartments. Most Class C compartments are larger than 1000 ft^3; many are larger than 2000 ft^3.

According to the report of Task Group 4 [128], the likely fire by an aircraft-supplied ignition source is a surface fire and will most likely be fueled by Class A material. In some instances, the Class A material may be contaminated by small quantities of Class B material. Human- and cargo-supplied ignition sources can cause a variety of fires (deep seated, flaming, explosive, metallic, fires with their own oxidizer, chemical, etc.). These fires are not easily characterized, but the task group defined, as specified in the Cargo

Compartment Minimum Performance Standard, four different fire test scenarios in order to address the variety of fires.

A cargo compartment fire suppression system must meet the following fire test requirements. (See table 19 to obtain maximum allowable compartment temperatures.)

a. The system must suppress a Class A deep-seated fire (bulk-loaded cargo) for at least 30 minutes.

b. The system must suppress a Class A fire inside a cargo container for at least 30 minutes.

c. The system must extinguish a Class B fire (Jet-A fuel) within 5 minutes.

d. The system must prevent, either by fire control or inerting the compartment, the explosion of an explosive hydrocarbon mixture.

The cargo compartments are normally pressurized with a minimum normal pressure corresponding to an altitude of 8,000 feet. In flight, the temperatures are maintained above freezing by several means, including ventilation. Fire in the cargo compartments is detected by smoke and ionization aerosol detectors or thermal sensors. The fire detection system is required to detect and provide visual indication of the fire to the flight crew within 1 minute after the start of a fire. Also, the system must be capable of detecting a fire at a temperature significantly below that at which the structural integrity of the airplane is substantially decreased (FAR 25.858 [129]). Fire detection systems are certified using an FAA-approved fire simulator.

Systems that provide a warning within 1 minute from the start of smoke generation are considered to be in compliance with FAR 25.858 [129]. The present practice is to control ventilation and drafts within the compartment prior to the activation of the suppression system. However, there is a small infiltration into the compartment through the compartment walls (typically fiberglass liner) and leakage out of the compartment through door seals. The general practice is to divert to the nearest field on detection of a fire. On long-range (across the ocean) aircraft, suppression is required for up to the maximum diversion time which could be in excess of 200 minutes [130].

The agent or system for cargo compartments must meet the following requirements in addition to the essential requirements identified earlier.

The agent/system for cargo compartments must also meet the requirements of FAR 25.795 (b) (3) [131], FAR 25.851, Part B [132], FAR 25.857[133] and FAR 25.1309 [134].

a. The agent/system must be suitable for fires likely to occur. These include Class A and B fires and hazardous materials.

b. The discharge of the agent/system must not cause structural damage.

c. The agent/system must be able to prevent hazardous quantities of extinguishing agent from entering occupied compartments.

d. The agent/system must be able to provide fire suppression over a period of up to the maximum diversion time, which could be in excess of 200 minutes, depending on the aircraft type and route structure.

It is desirable for the agent to have the following attributes.

a. Low toxicity and that it not be an asphyxiant at the concentrations required for extinguishment are desired to ensure the personnel safety in the event of an accidental discharge while the compartment is occupied. This would also be beneficial in the event of a false alarm while animals are carried in the cargo bay. Furthermore, no agent can be allowed that could leak into occupied compartments in toxic concentrations. Federal regulations require that "There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by crew or passenger." Airframe manufacturers meet this by design. Typical cargo compartments contain a fiberglass liner, which is tested with a smoke generator for leakage and with burners for flame penetration. Escape of smoke or extinguishing agent in hazardous quantities from cargo compartments of properly maintained aircraft is unlikely.

b. The agent should not impose additional (in addition to system recharge and check-out) departure delay following a false discharge.

c. The agent should not require extensive clean-up post discharge. Cargo bays have many difficult to reach areas due to structure, cargo handling equipment and other features. Equipment centers such as Electronics bays are often located nearby and could also become contaminated if agents requiring clean-up entered them. This concern is exacerbated if the agent is corrosive or conductive.

d. The agent/system should not be subject to any additional transport restrictions (relative to current Halon 1301 based systems) which would hinder shipping spares components in AOG situations.

The FAA has distributed a survey package to airlines and airframe manufacturers to determine opinions on agents and technologies proposed for cargo compartments in the earlier reports [1 and 2]. The response was poor. A majority (60 percent) of those responding preferred halocarbons, with a small, but significant, number believing that water and particulate aerosols are best [135]. Respondents were unanimous that the high-expansion foams are not appropriate for use in cargo compartments. Due to this negative response and technical considerations, high-expansion foams have been removed from the list of agents proposed in the past by the Task Group on Halon Options for cargo compartments. The remaining agents—water and water-based agents, halocarbons and halocarbon blends, and particulate aerosols—are still recommended for the establishment of test protocols.

The Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems was published September 2000 [136]. This document provides the extinguishing/suppressing performance of Halon 1301 (when subjected to the four fire scenarios mentioned earlier) and the standard test protocols. .The document has since

been updated twice. The current version [137] updated the aerosol can explosion test protocol allows either a “long” or “short” test protocol. The “long” test protocol combines the aerosol can test with the bulk fire test. If temperatures can be maintained below 212 deg F or the fire is extinguished the aerosol can simulator is not required to be discharged/activated to pass the test.

To date several promising agents have failed the aerosol can challenge. HFC-125, 2-BTP and FK 5-1-12 all have failed the aerosol can test by enhancing the overpressure (relative to an unsuppressed event) when agent concentrations fall below design concentration [138] [139]. This is in stark contrast to Halon 1301 which still reduces the pressure pulse (relative to the unsuppressed event) when below inerting concentrations. In addition testing of FK 5-1-12 also failed to fully control the bulk load fire test (as configured).

FAA test data are now available on Halon 1301, HFC-125, HFC-227ea, PGA, 2-BTP, FK 5-1-12 and water mist. The MPS requirements are shown in table 19 for a 2000-ft^3 cargo compartment.

TABLE 19. ACCEPTANCE CRITERIA FOR A 2000-cubic foot CARGO BAY FROM TN05-20 (SECOND UPDATE)

Fire Scenario	Maximum Temperature °F (°C)	Maximum Pressure psi (kPa)	Maximum Temperature-Time Area °F-min (°C-min)	Comments
Bulk Load	720 (382)	[a]	9,940 (5,024)	Temperature limit starting 2 minutes after suppression system activation. Temp.-Time area between 2 and 30 minutes starting with suppression system activation.
Containerized Load	650 (343)	[a]	14,040 (7,302)	Temperature limit starting 2 minutes after suppression system activation. Temp.-Time area between 2 and 30 minutes after with suppression system activation..
Surface Fire	570 (299)	[a]	1,230 (594)	Temperature limit starting 2 minutes after suppression system activation. Temp.-Time area between 2 and 7 minutes after with suppression system activation.
Aerosol Can	212 (100) [b]	0	[a]	There shall be no explosion

[a] Not applicable.
[b] only applicable to "long" aerosol can test

4.4.1 Water and Water-Based Agents.

Water meets almost all of the above requirements including the "long" aerosol can test.. Water is the most common fire-extinguishing agent for ordinary combustibles. The efficiency of the agent depends on the application method (sprinkler, mist, total flood, zoned application, etc.). Several investigators have determined it to be as effective as Halon 1301 for identical fire threats. It can be used in misting or sprinkler applications. In the present application, it is recommended that testing of misting systems be performed; however, sprinkler systems could be considered. Both sprinklers and misting

systems could use a zoned application. It is possible to use surfactant/water or dry chemical/water blends; however, in the absence of test results to the contrary, it is difficult to determine what benefit would ensue from the use of such mixtures. Moreover, such mixtures could cause an increase in cleanup efforts.

The FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey, has carried out a mist system testing program for the FAA TC-10 cargo test compartment. The objective was to design and install a water mist system that would prevent a fire in a luggage container from spreading to an adjacent luggage container and maintain temperatures within the space below 350°C for 90 minutes. The program has shown that one misting system can pass both the loaded luggage container and bulk-loading fire tests for the TC-10 cargo test compartment using 30 gallons of water [140]. These results are encouraging and suggest that an area-coverage water mist system may impose a lower takeoff gross weight (TOGW) penalty for large cargo compartments. Another advantage may be lower sensitivity (compared to gaseous agents) to compartment leakage.

It has been suggested that water-based fire suppression systems may be recharged from the portable water system if the initial capacity fails to adequately suppress a fire. It has also been proposed that it may be possible to recycle water using runoff from discharge to reduce the amount of water needed to provide protection. These proposals would require significant engineering to incorporate and may not be practical. Water-based systems may provide an acceptable environment for animals in the event of a false discharge. In addition, water-based systems may not depend on the integrity of the compartment liner for effective performance. Some concerns have been expressed about the possibility of stored water freezing; however, design solutions are available to prevent such occurrences.

4.4.2 Halocarbons and Halocarbon Blends.

Table 20 gives a rating for various criteria for halocarbons in cargo compartments. Here "1" denotes the highest rating. Arbitrarily, ratings for design concentrations have been assigned as

- 5 percent and below: 1
- 5 to 8 percent: 2
- 8 to 11 percent: 3
- above 11 percent: 4

Ratings for storage volume and weight equivalents are given ratings as follows:

- 1.0 or less: 1
- 1.0 to 1.5: 2
- 1.5 to 2.0: 3
- above 2.0: 4

Note that these effectiveness ratings were derived from data for a Class B fire with *n*-heptane fuel. They may not indicate performance for a deep-seated Class A fire, which is the probable fire in cargo compartments. Agents with NOAEL values of 30 percent or above are rated as 1 for toxicity. Agents with NOAEL values less than 30 percent but which are acceptable (or likely to be acceptable) for total flood in normally occupied areas under NFPA Standard 2001 [16] are given a rating of 2. HFC-125, whose NOAEL value is only slightly less than that which would allow total-flood use in normally occupied areas, is given a rating of 3. HCFC-124 with a NOAEL of 1.0 and FIC-13I1 with a NOAEL of 0.2 are rated as 4 and 5, respectively. Note, however, that cargo compartments are not considered to be normally occupied areas. Due to its high-vapor pressure, the delivery characteristics and system requirements for HFC-23 may differ significantly from those for most other halocarbons.

TABLE 20. RATING MATRIX FOR CANDIDATE HALOCARBONS FOR CARGO COMPARTMENT

Agent	Class B Fire Design Conc., %	Class B Fire Weight Equivalent	Class B Fire Storage Volume Equivalent	Known or Potential Regulatory Restrictions [a]	Cardiac Sensitization NOAEL
HCFC-124	3	3	3	3	4
HCFC Blend A	3	2	2	3	2
HFC-23	4	3	4	2	1
HFC-125	3	3	4	2	3
HFC-227ea	2	3	3	2	2
HFC-236fa	2	2	2	2	2
FC-218	3[b]	4[b]	4	3	1
FC-3-1-10	2	3	3	3	1
FIC-13I1	1	1	1	1	5

[a] Only includes regulatory restrictions based on environmental impact. Does not include restrictions due to toxicity.

[b] The storage volume and weight equivalents used in determining ratings for this agent, which does not appear now in the NFPA Standard, were calculated from the design concentration, molecular weight, and the liquid density. Ratings for the other agents were determined from equivalents calculated using weight requirements and fill densities as reported in the NFPA 2001 Standard [16]. See Table 8 and 9.

There has been some work indicating that misting (and, perhaps, standard discharge) of higher molecular weight (lower-vapor pressure) halocarbons can provide total-flood-like protection of enclosed areas [141]. At present, no manufacturer offers such a system, and the technology must still be considered unproven. However, the possibility that one or more new, lower-vapor pressure compounds will be proposed for total-flood protection must be kept in mind.

Class A fires develop slowly. It is feasible to detect a fire in a cargo compartment within a zone and suppress it by a zoned fire suppression system. In the past, total-flood systems have been used, but the federal regulations do not mandate a total-flood system. The halocarbon agents fall in two categories: liquid agents, which could be applied in a zoned application, and gaseous agents for total-flood applications. It is recommended that test protocols for both types of agents be developed.

4.4.3 Particulate Aerosols.

Some preliminary testing has been performed by the FAA on type S.F.E. formulation "D" particulate aerosols using modular units of 4 kilograms each. The scope of the test was to evaluate the S.F.E. aerosol performance on deep-seated Class A fires, specifically shredded papers. The FAA requirements were to extinguish the fire and inert the protected volume for 30 minutes. The S.F.E. particulate aerosol formulation "D" was tested at an application concentration of 60-100 gr/m^3. The agent partially suppressed a Class A fire in a 2357-ft^3 compartment and inerted the volume for approximately 17 minutes [62].

These preliminary results and consideration of the possible weight/volume cost benefits of the particulate aerosols technology, render its application to aircraft fire protection as potentially viable, and the technology should be further evaluated.

4.5 LAVATORY TRASH RECEPTACLE.

4.5.1 Background

Lavatories are located in the pressurized aircraft cabin with environmental conditions similar to the conditions in other occupied areas. The likely fire threat in the lavatory trash receptacle would involve Class A materials (paper and paper products), with the typical ignition source being burning material discarded into the container, such as a lit cigarette. The trash containers are designed to contain the likely fire. No fire detection system is provided in the container. Rulemaking was implemented on April 29, 1987, that required each lavatory trash container be equipped with a built-in automatic fire extinguisher that discharges automatically into the container upon the occurrence of a fire. In order to accomplish this, the extinguisher bottle incorporates a eutectic device at the end of a tube directed into the container. In the event of a fire, the heat generated will melt the eutectic tip, releasing the agent directly into the receptacle. Historically a small amount of agent (100 grams of 1301) has been effectively used in extinguishing this type of fire. Halon 1211 (0.3Kg (0.66lb), 0.5Kg (1.1lb) & 0.12kg (0.26lb)) has also been used .

The agent for trash containers must meet the following requirements in addition to the essential requirements identified earlier in Section 4.1, Requirements.

a. The agent must extinguish a Class A (paper towel) fire as defined in the Minimum Performance Standard (MPS) [142].

b. The agent must have a toxicity such that, if the same quantity of agent used for the trash container is released into the entire lavatory, the NOAEL is not exceeded.

A survey of 24 airlines showed that 66 percent preferred halocarbons or halocarbon blends for use in aircraft lavatory trash receptacles [143]. The reasons given for this preference were reduced weight, minimum impact on current installation, and effectiveness. Sixteen percent preferred water, giving as reasons, low environmental impact and reduced maintenance. Weight and effectiveness concerns were mentioned as potential drawbacks for water. The IHRWG, and the FAA have established a Minimum Performance Standard for lavatory trash receptacles. The following agent types are most likely to have utility in lavatory trash receptacle applications: HFC-125, HFC-227ea, HFC-236fa, and Envirogel.

4.5.2 Water-Based and Combination Agents.

Water, water/surfactant (e.g., Surfactant Blend A), Dry Chemical/Water Mixtures, and combination agents meet all the above requirements. Water is the most common fire-extinguishing agent (sprinkler, mist). Freeze protection would have to be considered for use on airplanes. Loaded stream or surfactant blends could improve surface wetting of Class A materials. These are all likely to be more effective on Class A materials than halocarbons. Envirogel combined with other agents such as FE-36 have been considered by fire extinguisher manufacturers.

4.5.3 Halocarbons and Halocarbon Blends.

Most halocarbons would provide acceptable extinguishing ability in this application. Moreover, recent work with HFC-227ea suggests that some halocarbons might allow retrofit into existing systems [144]. However, to achieve the required low-temperature performance (5°F), some halocarbons will need to be pressurized with nitrogen. HFC-227ea (FM-200) was extensively tested and proven to be effective. This agent requires superpressurization with nitrogen to achieve low-temperature performance. HFC-236fa (FE-36) was also tested and proven to be effective.

4.5.4 Airbus Status

In 2005, Airbus replaced all Halon 1301 automatic fire extinguishers used in production lavatory trash receptacles with HFC-236fa (FE-36). The FE-36 automatic fire extinguishers were also made available as a drop-in replacement for in-service airplanes.

4.5.5 Boeing Commercial Airplane Status

In 2006, Boeing replaced all Halon 1301 automatic fire extinguishers used in production lavatory trash receptacles with HFC-227ea (FM-200). Boeing is currently working with the FAA to gain approval to allow the use of FM-200 automatic fire extinguishers for all models of in-service airplanes.

4.5.6 Bombardier Aerospace Status

Bombardier is at the initial stages of replacing the Halon automatic fire extinguishers in the lavatory trash receptacles for production aircraft. The CSeries (not yet in production) will not have Halon automatic fire extinguishers in its lavatory trash receptacles.

4.5.7 Embraer Status

Embraer is conducting a final analysis for lavatory trash receptacle extinguishing agent selection, and a solution will be available for implementation by 2011 for series programs including the Embraer Jets.

4.6 SUMMARY.

Fire-extinguishing agent technology is extremely dynamic. A number of new agents and technologies have been evaluated in the laboratories across the nation. The recommendations above are based on the present state of the technology, EPA approvals, and listing by technical organizations.

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APPENDIX A—COMPANIES AND MANUFACTURERS

CATEGORY	COMPANY INFORMATION	AGENT/SYSTEM/PRODUCT
Halocarbon Agent Producers	Ajay North America, LLC 1400 Industry Road Powder Springs, GA 30127 USA Phone: 770-943-6202 Fax: 770-439-0369 Email: sales@ajay-sqm.com URL: http://www.iodeal.com or http://www.ajay-sqm.com	CF3I (Triodide)
Halocarbon Agent Producers	American Pacific Corporation Halotron Division 3883 Howard Hughes Parkway Suite 700 Las Vegas, NV 89169 USA Phone: 702-735-2200 Fax: 702-735-4876 Email: Halotron@apfc.com URL: http://www.halotron.com	(HCFC Blend B) Halotron 1 (HFC Blend B) Halotron II 2-BTP
Halocarbon Agent Producers	3M Company Electronics Markets Materials Division Building 0224-03S-11 St. Paul, MN 55144-1000 USA Phone: 1-800-810-8513 or Outside US: 1-651-575-6888 Fax: 651-732-7735 Email: emmdcustomerservice@mmm.com URL: http:www.3m.com/novec1230fluid	3M™Novec™1230 Fire Protection Fluid
Halocarbon Agent Producers	DuPont Company Chemicals and Fluoroproducts Chestnut Run Plaza, Bldg 711 4417 Lancaster Pike Wilmington, DE 19880 USA Phone: 1-800-473-7790 Fax: 302-999-4727 Email: info@dupont.com URL: http://www.cleanagents/dupont.com	HFC-227ea(FM-200) HFC-23(FE-13) HFC-125(FE-25) HFC-236fa(FE-36) HCFC-123(FE-232) HCFC-124(FE-241)

Halocarbon Agent Producers	Safety Hi-Tech S.r.l. Via Cavour 96 67051 Avezzano (AQ) Italy Phone: 39 863 1940720 Fax : 39 863 1940724 Email : mail@safetyhitech.com URL : http://www.safetyhitech.com	HCFC Blend A (NAF S-III) HCFC Blend D (Blitz) HCFC Blend E (NAF P-IV) HFC-125 plus additive (NAF S 125) HFC-227ea plus additive (NAF S 227) HFC/FIC Blend plus additive (NAF P 5)
Water Misting Systems	SECURIPLEX LLC 3710 Lakeside Court Mobile, AL 36693 USA Phone: 251-602-6111 Fax: 251-661-5340 Email: info@sucuriplexllc.com URL: http://www.securiplexllc.com	Water Mist Fire Suppression Systems
Water Misting Systems	GW Sprinkler A/S Kastanievej 15 DK-5620 Glamsbjerg Denmark Phone: 45 64 72 20 55 Fax: 45 64 72 22 55 Email: ginge@ginge-kerr.dk URL: http://www.ginge-kerr.com	Argonite (IG-55)
Water Misting Systems	Ginge-Kerr Denmark A/S Industriholmen 17-19 DK-2650 Hvidovre Denmark Phone: 45 36 7711 31 Email: ginge@ginge-kerr.dk URL: http://www.ginge-kerr.com	
Water Misting Systems	Chemetron Fire Systems 4801 Southwick Drive, 3rd Floor Matteson, IL 60443-2254 USA Phone: 1-800-878-5631 Fax: 708-748-2847 Email: info@chemetron.com URL: http://www.chemetron.com	
Water Misting Systems	Marioff North America 400 Main Street Asland, MA 01721 USA Phone: 1-800-654-7763 Ext. 2436 Email: John.Harding@marioff.net URL: http://www.marioff.com or http://www.marioff.net	Water Mist

Water Misting Systems	Ultra Fog AB Backa Strandgata 18 SE-422 44 Hisings Backa Sweden Phone: 46 31 979870 Fax: 46 31 982368 Email: info@ultrafog.se URL: http://www.ultrafog.se	High Pressure Water Mist Systems Water Mist System
Water Misting Systems	Kidde-Deugra Brandschutzsysteme GmbH D-40880 Ratingen Germany Phone: 49 2102 405 149 Fax: 49 2102 405 151	
Water Misting Systems	Amerex Corporation Amerex Defense 7595 Gadsden Highway Trussville, AL 35173-0081 USA Phone: 205-655-3271 Fax: 205-655-0976 Email: jmccullough@amarex-fire.com URL: http://www.amarex-fire.com	Potassium Acetate Wet Chemical (K-Ace) Fire Suppression System
Water Misting Systems	FOGTEC Brandschutz GmbH & Co. KG Schanzenstr. 19a D-51063 Cologne Germany Phone: 49 221 96223-0 Fax: 49 221 96223-30 Email: contact@fogtec@com URL: http://www.fogtec.com	High and Low Pressure Water Mist Systems Hybrid Water Mist Systems Water Mist Foam Systems
Particulate Aerosols	Spectrex Inc. Peckman Industrial Park 218 Little Falls Road Cedar Grove, NJ 07009 USA Phone: 973-239-8398 Fax: 973-239-7614 Email: Spectrex@spectrex-inc.com URL: http://www.spectrex-inc.com	Powdered Aerosol A (SFE), Green EX
Particulate Aerosols	Amerex Corporation Amerex Defense 7595 Gadsden Highway Trussville, AL 35173-0081 USA Phone: 205-655-3271 Fax: 205-655-0976 Email: jmccullough@amarex-fire.com URL: http://www.amarex-fire.com	Aerosol Generator (Stat-X®) Systems

Particulate Aerosols	Fireaway LLC 5852 Baker Road Minnetonka, MN 55345 USA Phone: 952-935-9745 Fax: 952-935-9757 Email: mgross@statx.com URL: http://www.statx.com	Stat-X
Particulate Aerosols	Dynamit Nobel Defence GmbH Dynameco Dr. –Hermann-Fleck-Allee 8 57299 Burbach-Wurgendorf Germany Phone: 49 2736 46 2104 Fax: 49 2736 46 2107 Email: info@dynameco.com URL: http://www.dynameco.com	Aerosol Extinguisher
Particulate Aerosols	Kidde-Deugra Brandschutzsysteme GmbH Halskestrasse 30 D-40880 Ratingen Germany Phone: 49 2102 405 149 Fax: 49 2102 405 151	
Inert Gases	FOGTEC Brandschutz GmbH & Co. KG Schanzenstr. 19a D-51063 Cologne Germany Phone: 49 221 96223-0 Fax: 49 221 96223-30 Email: contact@fogtec@com URL: http://www.fogtec.com	High and Low Pressure Water Mist Systems Hybrid Water Mist Systems Water Mist Foam Systems
Inert Gases	Ginge-Kerr Denmark A/S Industriholmen 17-19 DK-2650 Hvidovre Denmark Phone: 45 36 7711 31 Email: ginge@ginge-kerr.dk URL: http://www.ginge-kerr.com	Argonite (IG-55)
Inert Gases	Tyco Fire Suppression & Building Products Ansul 1 Stanton Street Mannette, WI 54143-2542 Phone: 715-735-7411 Fax: 715-732-3479 Email: tcarman@tycoint.com URL: http://www.ansul.com	IG-541 (Inergen)

Gas Generators	Aerojet – General Corporation Force Projection and Protection Safety Products 11650 137th Place NE Redmond, WA 98052 USA Phone: 425-885-5000 Fax: 425-882-5748 Email: Jennifer.mccormick@aerojet.com URL: http://www.aerojet.com/capabilities/fire.php	Solid Propellant Fire Extinguisher (SPFE) Hybrid Fire Extinguisher (HFE)
Hand Fire Extinguishers	Amerex Corporation Amerex Defense 7595 Gadsden Highway Trussville, AL 35173-0081 USA Phone: 205-655-3271 Fax: 205-655-0976 Email: jmccullough@amarex-fire.com URL: http://www.amarex-fire.com	HFC Blend B (Halotron I) Agent Hand Portable & Wheeled FK-5-1-12 (Novec™1230) Agent Hand Portable & Wheeled Water Mist Hand Portable Potassium Acetate (K-Ace) Hand Portable, Wheeled, & Hand-Line Foam AFFF Hand Portable & Wheeled Alcohol Resistant Foam FFFP Hand Portable & Wheeled
Hand Fire Extinguishers	Fire Fighting Enterprises Ltd. 9 Hunting Gate Hitchin, Hertfordshire, SG4 OTJ, United Kingdom Phone: 44 1462 444740 Email: sales@ffeuk.com URL: http://www.ffeuk.com	
Halocarbon Fire Suppression System Hardware	Amerex Corporation Amerex Defense 7595 Gadsden Highway Trussville, AL 35173-0081 USA Phone: 205-655-3271 Fax: 205-655-0976 Email: jmccullough@amarex-fire.com URL: http://www.amarex-fire.com	HFC-227ea(FM200®) Fire Suppression Systems FK-5-1-12 (Novec™1230) Fire Suppression Systems
Halocarbon Fire Suppression System Hardware	Fire Combat; A Division of Sensor Electronics Corporation 2650 Industrial Parkway Marinette, WI 54143 USA Phone: 715-735-9058 Fax: 715-735-7223 Email: shornick@firecombat.com URL: http://www.firecombat.com	Mobile Fire Suppression and Fire Suppression Components

Combination and New Foam Agents	FOGTEC Brandschutz GmbH & Co. KG Schanzenstr. 19a D-51063 Cologne Germany Phone: 49 221 96223-0 Fax: 49 221 96223-30 Email: contact@fogtec@com URL: http://www.fogtec.com	High and Low Pressure Water Mist Systems Hybrid Water Mist Systems Water Mist Foam Systems