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Halon Replacement Options for Use in Aircraft Fire Suppression Systems

September 1996

Final Report

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16. Abstract

This report contains a summary of available fire suppression agents, their properties, and applicability in the various aircraft applications. 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 first meeting of the International Halon Replacement Working Group (IHRWG) was held on 13-14 October 1993 at the Federal Aviation Administration (FAA) Technical Center, Atlantic City International Airport, New Jersey, USA. At that meeting a number of task groups were established. One of the task groups, Task Group 6, was assigned a review of "Chemical Options to Halons." A major goal for this task group 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) handheld extinguishers, (3) cargo compartments, and (4) lavatory protection. The final report of Task Group 6 was published in February 1995 (Brown, J. A., Jacobson, E., Dvorak, L. E., Gibson, J., Gupta, A., Metchis, K., Mossel, J. W., Simpson, T., Speitel, L. C., Tapscott, R. E., and Tetla, R. A., *Chemical Options to Halons for Aircraft Use*, DOT/FAA/CT-95/9, Final Report, Task Group 6, International Halon Replacement Working Group, U.S. Department of Transportation, Federal Aviation Administration, February 1995).

At the 19-20 April 1995 meeting of the IHRWG in Rome, Italy, a decision was made to maintain a review of new chemical technologies as they appeared and to continue to update the report of February 1995. 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. An overview of this report, Report 2 of the Task Group on Halon Options, was presented at the IHRWG meeting of 18 July 1995 in Albuquerque, New Mexico, USA; at the 26-27 March 1996 meeting in Hamburg, Germany; and at the 16-17 July 1996 meeting at the FAA Technical Center, Atlantic City International Airport, New Jersey, USA. To better reflect the orientation of the report, the title has been changed to *Halon Replacement Options for Use in Aircraft Fire Suppression Systems*.

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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
DoD	Department of Defense
EC	European Community
ECG	electrocardiographic
EGL	Emergency Guidance Level
EMAA	Encapsulated Micron Aerosol Agent
FAA	Federal Aviation Administration
FAATC	Federal Aviation Administration Technical Center
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
LEL	Low Effect Level
LOAEL	Lowest Observed Adverse Effect Level
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
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No Observed Adverse Effect Level
NMERI	New Mexico Engineering Research Institute
NPCA	National Paint and Coatings Association
ODP	Ozone Depletion Potential
OSHA	Occupational Safety and Health Administration
PAA	physical action agent
PEL	Permissible Exposure Limit
PFC	perfluorocarbon
PGA	pyrotechnically generated aerosol
REL	Recommended Exposure Limit
SCBA	self-contained breathing apparatus
SNAP	Significant New Alternatives Policy
STEL	Short-Term Exposure Limit
TLV	Threshold Limit Value
TWA	Time Weighted Average
UDS	unscheduled DNA synthesis
UL	Underwriters Laboratories
UNEP	United Nations Environment Programme
WEEL	Workplace Environmental Exposure Limit
WGL	Workplace Guidance Level

EXECUTIVE SUMMARY

This report is an update of an earlier report published in February 1995 (Brown, J. A., Jacobson, E., Dvorak, L. E., Gibson, J., Gupta, A., Metchis, K., Mossel, J. W., Simpson, T., Speitel, L. C., Tapscott, R. E., and Tetla, R. A., *Chemical Options to Halons for Aircraft Use*, DOT/FAA/CT-95/9, Final Report, Task Group 6, International Halon Replacement Working Group, U.S. Department of Transportation, Federal Aviation Administration, February 1995). The title, however, has been changed to *Halon Replacement Options for Use in Aircraft Fire Suppression Systems*.

This report summarizes available fire suppression technologies with an emphasis on agents, their properties, and applicability in the various aircraft applications—(1) engine nacelles, (2) handheld extinguishers, (3) cargo compartments, and (4) lavatory protection. Specific classes of agents, with agents now available, 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.

1. INTRODUCTION.

1.1 ENVIRONMENTAL OVERVIEW.

Existing fire protection measures, required by Airworthiness Regulations, are largely based on the use of halons. For all practical purposes, production of halons has ceased 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 local laws. It also should be borne in mind that 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.

1.2 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 hazard for workers during installation and maintenance of the extinguishing system. At no time should the agent concentration present an unacceptable health hazard in areas where passengers or workers are present or where leakage could cause the agent to enter the passenger compartment. The cumulative toxicological effect of the agent, its pyrolytic breakdown products, and the byproducts of combustion must not pose an unacceptable health hazard.

1.3 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, foam, water, and a dry chemical 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.

Alternatives and replacements have been discussed in a number of papers (relatively recent overviews are given in references 1 and 2).

Any option to halons must be approved under the EPA's Significant New Alternatives Policy (SNAP) program, which implements section 612 of the amended Clean Air Act of 1990. The proposed plan for the SNAP program and an initial proposed list of decisions on acceptable and unacceptable halon substitutes were published on 12 May 1993 [3]. The final plan and the first list were promulgated on 18 March 1994 [4]. This initial list was prepared from an EPA background document for halon replacements and alternatives [5]. Additional lists or proposed lists of acceptability decisions have since been published [6-13]. Substances which are prohibited, acceptable only under certain conditions or for certain uses, or were removed from a list of prohibited or acceptable substitutes are subject to public comment. Other substances for which there are no limitations are listed as acceptable with no public comment required.

2. REPLACEMENTS.

At present, halon replacements (e.g., halocarbons) fall into four major categories (table 1). Note that two categories noted in the first report from the Task Group on Chemical Options to Halons [14]—CFCs (chlorofluorocarbons) and HBFCs (hydrobromofluorocarbons)—are no longer being commercialized.

TABLE 1. CLASSES OF HALON REPLACEMENTS

HCFCs	Hydrochlorofluorocarbons
FCs (PFCs)	Perfluorocarbons
HFCs	Hydrofluorocarbons
FICs	Fluoroiodocarbons

There are a number of desirable characteristics for replacement agents. That they must have acceptable global environmental characteristics (low Ozone Depletion Potentials, ODPs, and low Global Warming Potentials, GWPs) is obvious. The toxicity must also be acceptable, though there may be some debate about what is an acceptable level. 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 [15]. In general, CAAs are much more effective extinguishants than are PAAs. Halons 1211 and 1301 are primarily CAAs. Work at the Naval Research Laboratory (NRL) indicates that Halon 1301 extinguishment of *n*-heptane in air is approximately 20 percent physical and 80 percent chemical [16]. 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 often contain bromine. One exception is trifluoroiodomethane, CF_3I [17], which is the only CAA being commercialized today.

2.1 TOXICOLOGY OF HALOCARBONS.

2.1.1 Acute Toxicological Indices.

Table 2 contains a summary of acute toxicological indices. These are discussed in more detail in the following text.

TABLE 2. ACUTE TOXICOLOGICAL INDICES

Exposure Limit		Definition
ALC	Approximate Lethal Concentration	The approximate concentration considered to cause death, similar to LC_{LO} but often used in place of LC_{50} when making assessments.
LC_{50}	Lethal Concentration-50%	Concentration causing death in 50% of an animal test population
LC_{LO}	Lethal Concentration-Low	The lowest observed lethal concentration
AD_{50}	Anesthetic Dose-50%	Concentration causing anesthesia in 50% of an animal test population
LOAEL	Lowest Observed Adverse Effect Level	The lowest exposure level that has been observed to cause an adverse effect. For inhalation of halocarbons, the effect is usually cardiac sensitization.
NOAEL	No Observed Adverse Effect Level	The highest exposure level that has been observed to cause no adverse effect. For inhalation of halocarbons, the effect looked for is usually cardiac sensitization.

2.1.1.1 Lethality.

The LC_{50} is defined as the concentration required to cause death in 50 percent of an animal test population. The ALC value, first established by DuPont but now used by other chemical manufacturers, is the Approximate Lethal Concentration. The ALC approximates the lowest concentration that causes death (LC_{LO}). Thus, it is lower than the LC_{50} value. The ALC value is often used in place of the LC_{50} in assessing safety.

2.1.1.2 Anesthesia.

Anesthesia is the condition of loss of consciousness, usually coupled with the loss of response to pain and other stimuli. General anesthesia results from a depression of the central nervous system (CNS) which can be exerted by a wide range of chemicals. Some anesthetic agents elicit CNS depression through specific receptor sites, whereas others have more generalized actions on other cellular sites such as the cell membrane. Anesthetic potency of chemicals is tested in animals by observing decreases in righting reflex (ability to stand up after being knocked over) or diminished response to foot or tail shock. The AD_{50} is the calculated value corresponding to the concentration at which 50 percent of the test animals experience anesthesia. In AD_{50} experiments, anesthesia is defined as loss of the righting reflex or lack of response to shock. Anesthetic potency or mild CNS depression can also be observed in humans using performance decrement studies.

2.1.1.3 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 [18]. 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. In addition, the phenomenon of cardiac sensitization is particularly important in fire fighting because under the stress of the fire event, higher levels of epinephrine are secreted by the body which increases the possibility of sensitization.

The experimental procedure used to investigate the cardiac sensitization potential of a chemical involves outfitting dogs with electrocardiographic (ECG) measurement devices and exposing the animals to a sequence of agent and epinephrine [19]. Healthy male beagle dogs (generally six or more animals per exposure concentration), between the ages of 1 and 2 years, are trained to stand in a cloth sling and to wear a snout mask. The dogs learn to accept venipuncture and ECG monitoring. Thus, they are minimally stressed during the experiment.

The usual sequence of exposure is that the animal is monitored in a baseline condition without any intervention for 2 minutes (table 3). Epinephrine is then intravenously infused to determine the effect of this catecholamine on the cardiac system. The dose and time period for infusion varies slightly between laboratories; however, the levels of epinephrine given are always in the pharmacological rather than the physiological range. After approximately 5 minutes from the initial epinephrine administration, the agent is given as a continuous inhalation exposure either through a mask fitting over the dog's snout or in an exposure chamber. After a 5-minute agent exposure, epinephrine is administered intravenously ("epinephrine challenge") along with the continuous agent exposure. The animals are monitored for another 5 minutes to determine the effect of epinephrine and agent. This protocol is performed at increasingly higher doses until a "marked adverse response" occurs.

A "marked adverse response" is considered as the appearance of five or more multifocal ventricular ectopic beats or ventricular fibrillation [20]. A "mild response" is described as an increase in the number of isolated abnormal beats (less than five consecutive beats) following the epinephrine challenge (second epinephrine administration). The threshold level is the lowest concentration at which cardiac sensitization occurs. No definitive rule exists indicating the number of animals that must experience a marked response to determine the threshold value. In most cases, even one animal experiencing a marked response constitutes establishment of a

TABLE 3. PROTOCOL FOR TESTING CARDIAC SENSITIZATION IN DOGS

Time, minutes	Procedure
0	Start ECG Recording
2	Administer Epinephrine Dose
7	Start Inhalation of Test Gas or Air
12	Administer Epinephrine Challenge Dose
17	Stop Test Gas Inhalation; Stop ECG Recording

threshold value. This level is also called the Lowest Observed Adverse Effect Level (LOAEL). The highest concentration at which no marked responses occur is called the No Observed Adverse Effect Level (NOAEL). For halocarbons, these values are used when determining safe exposure levels for humans. While it is not known with certainty whether the LOAEL and NOAEL in dogs accurately represent these values in humans, the dog is the preferred animal model for determining cardiac physiology.

It should be noted that the cardiac sensitization LOAEL and NOAEL concentrations are conservative [5]. They 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.

2.1.2 Subchronic and Chronic Tests.

2.1.2.1 90-Day Subchronic Toxicity Test.

The 90-day subchronic toxicity test is an assay that determines pathological changes due to repeated and prolonged chemical exposure. Subchronic toxicity testing provides the basis for developing industrial exposure standards.

2.1.2.2 Chronic Toxicity Testing.

Chronic toxicity tests are conducted over the greater part of the animals life span (1.5 to 2 years in mice and 2 or more years in rats), starting at weaning. Daily exposure to the test agent occurs. The principal endpoint is tumor formation, as determined by histological exam.

2.1.2.3 Carcinogenicity Screening.

Chemical carcinogenesis is usually the result of long-term exposure to a chemical that may occur generally during industrial processing and handling. To determine the potential carcinogenicity of an agent, genotoxicity (mutagenicity) screening tests are often performed. Positive mutagenicity results alert toxicologists to the possibility of carcinogenesis and indicate the need for subchronic exposure testing to develop industrial exposure standards. The following genotoxicity tests are most commonly used.

2.1.2.4 Ames Test.

The Ames test, an *in vitro* test for mutagenicity and by implication, carcinogenicity, uses mutant strains of bacterium *Salmonella typhimurium* as a preliminary screen for carcinogenic potential [21]. A number of assays comprise the Ames test, and positives indicate that a mutation in the genetic material has occurred. Mutagenic and presumed carcinogenic materials cause genetic mutations that allow the bacterial strains to grow in a histidine-free medium.

2.1.2.5 Mouse Lymphoma Test.

The mouse lymphoma test, also an *in vitro* screening test, uses cell cultures of mouse lymphoma cells. The mutagenic potential of a material is tested by observing the ability to confer resistance within this cell line to normally toxic agents. Mutations in the genetic material allow the cells to grow in the presence of other known toxic materials (purines, pyrimidines, or ouabain). Promutagens (mutagenic agents that require metabolic activation) can also be identified.

2.1.2.6 Mouse Micronucleus Test.

The mouse micronucleus test, an *in vivo* test, determines the potential of a chemical to cause chromosome breakage or interference with normal cell division. The test entails exposing live mice to the test material, then removing premature red blood cells from the bone marrow, and observing the cells for the presence of chromosome fragments or the lack of signs of normal cell division. This test is not considered the most sensitive test for chromosomal aberrations.

2.1.2.7 Other Screening Tests.

Other *in vitro* tests that yield information on the carcinogenic potential of an agent include the unscheduled DNA synthesis test, the sex-linked recessive mutation test, and the sister chromatid exchange test. The unscheduled DNA synthesis (UDS) test involves the exposure of cultured hepatocytes (liver cells) to the test chemical and monitors the repair of DNA following DNA damage by a mutagen. The sex-linked recessive mutation test for mutagenicity utilizes *Drosophila melanogaster* (fruit fly) males with a marker (yellow body) on the X chromosome. The sister chromatid exchange test, which can also be an *in vivo* test, detects DNA alkylating agents in Chinese hamster ovary cells.

The *in vivo* dominant lethal (rodent) test assesses the ability of a suspected mutagen, which has shown positive in an *in vitro* screen, to cause dominant lethal mutations in rats, mice, or hamsters. Male rodents are treated with the test substance and are then mated to groups of females over several weeks to test for effects occurring at all stages of sperm formation. Following sacrifice, the females are evaluated for a number of fertility indices.

2.1.2.8 Interpretation of Carcinogenicity Results.

For years the predictive value of short-term *in vitro* mutagenicity tests for potential carcinogenicity has been questioned [22]. The degree to which the results of these short-term assays correlate with carcinogenicity in whole animals resulting in actual tumor formation largely depends on chemical class. For fluorinated hydrocarbons, the correlation has not proved to be exact.

2.1.3 Exposure Limits.

Four major noncommercial organizations establish or recommend occupational exposure limits. The National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) are governmental organizations. Standards established under OSHA are enforceable; however, NIOSH only sets recommended occupational exposure limits. Non-governmental organizations establishing exposure limits are the American Conference of Governmental Industrial Hygienists (ACGIH) and the American Industrial Hygiene Association (AIHA). Table 4 gives the various exposure limits that have been established. Note that most of these levels are not used and are not well developed. The only ones actually used by industrial hygienists are the PEL, the WEEL, and the TLV, which are the appropriate upper exposure limit for safe handling over a lifetime of occupational exposure (e.g., industrial processing, rather than fire fighting). The Acceptable Exposure Limit (AEL), which is widely cited, was originally used by DuPont; however, it is now given by a number of other commercial organizations.

Of greater importance in fire protection are the limits established for exposure during agent discharge. Two somewhat differing sets of criteria have been established for total-flood protection.

The 1996 National Fire Protection Association (NFPA) 2001 Standard [23] requires that the design concentration for total flooding of a normally occupied area by halocarbons not exceed the cardiac sensitization NOAEL. As an exception a halocarbon agent may be used up to the LOAEL value for Class B hazards in normally occupied areas where a predischarge alarm and time delay are provided. The time delay must be set to ensure that occupants have time to evacuate prior to the time of discharge. In addition, halocarbon agent concentrations above 24 percent are not allowed in normally occupied areas. The 2001 Standard calls for avoidance of unnecessary exposure to agents covered and for suitable safeguards to ensure prompt evacuation; however, no specific evacuation time is required. Audible and visual predischarge alarms are required.

The EPA SNAP program uses the cardiotoxic LOAEL value to assess use of an agent in normally occupied areas [4]. Furthermore, the EPA uses OSHA Standard 1910.162 [24] for Halon 1301 as a basis for EPA's fire suppression use conditions. The EPA has applied the following [25]: (1) Where egress from an area cannot be accomplished within one minute, the employer shall not use this agent in a concentration exceeding its NOAEL. (2) Where egress takes longer than 30 seconds but less than 1 minute, the employer shall not use the agent in a

TABLE 4. EXPOSURE LIMIT DEFINITIONS

Exposure Limit		Establishing Organization	Definition
		Long-Term Exposures	
AEL	Acceptable Exposure Limit	Commercial	
PEL	Permissible Exposure Limit	OSHA	Enforceable 8-hour time-weighted average (TWA) exposure limit for airborne substances intended to reduce a significant risk of health or functional capacity impairment
REL	Recommended Exposure Limit	NIOSH	Similar to TLV values
TLV	Threshold Limit Value	ACGIH	TWA exposure limits similar to PEL values.
WEEL	Workplace Environmental Exposure Limit Guide	AIHA	Similar to TLV values.
WGL	Workplace Guidance Level	EPA	Eight-hour per day TWA value analogous to PEL values.
		Short-Term Exposures	
CL	Ceiling Level	OSHA	Enforceable exposure level that cannot be exceeded for any time period.
STEL	Short-Term Exposure Limit	OSHA	Enforceable 15-minute TWA exposure that should not be exceeded at any time during a work day.
IDLH	Immediately Dangerous to Life and Health	NIOSH	Maximum concentrations from which one could escape within 30 minutes without experiencing escape-impairing or irreversible health effects.
EGL	Emergency Guidance Level	EPA	Applies to a short-term exposure of 15 or 30 minutes and is similar to the IDLH.

concentration greater than its LOAEL. (3) Agent concentrations greater than the LOAEL are only permitted in areas not normally occupied by employees provided that any employee in the area can escape within 30 seconds. Thus, unlike the NFPA, the EPA applies specific time limits for evacuation from areas where a total-flooding discharge is used.

The New Extinguishants Advisory Group NEAG, a subgroup of the Halon Alternatives Group (HAG) in the United Kingdom, has attempted to base allowable design concentrations for automatic systems in occupied areas on six endpoints: LC_{50}, CNS effects, cardiac sensitization, respiratory sensitization, genotoxicity, and developmental toxicity [26]. For the three halocarbon agents that they evaluated, NEAG found that cardiac sensitization or, in the case of very low-toxicity agents, hypoxia are the critical endpoints.

2.2 HALOCARBON ENVIRONMENTAL IMPACTS.

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 para. 2.2.3 Global Warming Potential), 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, however, is not precisely known and lends some uncertainty to the ODPs of bromocarbons. An excellent nontechnical historical overview is contained in reference 27.

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 is now typically used. The global warming potential depends on three variables: (1) the integrated infrared radiation absorption spectrum band strength, (2) the location 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 that those with shorter times periods [28]. All GWPs in this report are based on a 100-year time horizon values referenced to CO_2.

2.2.4 Regulatory Restrictions.

Due to concern about stratospheric ozone depletion, production of halons ceased on 1 January 1994 under both the Montreal Protocol (for industrialized nations, table 5) and the U.S. Clean Air Act (for the United States, table 6, reference 29). Under the Protocol, "consumption" is defined as the amount produced by a country minus exports plus imports. Thus, consumption is essentially the same as production.

TABLE 5. CONSUMPTION CUTS UNDER MONTREAL PROTOCOL AS AMENDED IN 1995

Year[a]	CFCs	Halons	Methyl Chloroform	Carbon Tetrachloride	Methyl Bromide	HCFCs	HBFCs
1994	75%	100%	50%				
1995				85%	Cap		
1996	100%		100%	100%		Cap	100%
2001					25%		
2004						35%	
2005					50%		
2010					100%	65%	
2015						90%	
2020						99.5%	
2030						100%	

[a] Beginning January 1 of year cited, the annual consumption amounts must meet the proscribed cuts. The base years are CFCs in original Protocol, 1986; CFCs in 1990 amendment, 1989; halons, 1986; methyl chloroform and carbon tetrachloride, 1989; methyl bromide, 1991. Base for HCFCs is 1989 ODP-weighted HCFC consumption plus 2.8% of 1989 ODP-weighted CFC consumption.

TABLE 6. CONTROLS UNDER CLEAN AIR ACT AMENDMENTS OF 1990

Ozone Depleting Chemicals	Baseline Year	Allowed Production	
		January	% of Base Year[a]
Class I Substances			
Group I: CFC-11, 12, 113, 114, 115	1986	1994 1995 1996	25 25 0
Group II: Halon 1211, 1301, 2402	1986	1994	0
Group III: CFC-13, 111, 112, 211, 212, 213, 214, 215, 216, 217	1989	1994 1995 1996	25 25 0
Group IV Carbon Tetrachloride	1989	1994 1995 1996	50 15 0
Group V Methyl Chloroform	1989	1994 1995 1996	50 30 0
Group VI Methyl Bromide	1991	1994 1995 1996 1997 1998 1999 2000 2001	100 100 100 100 100 100 100 0
Group VII HBFCs	1991	1994 1995 1996	100 100 0
Class II Substances[b]			
HCFC-141b	c	2003	0
HCFC-22, -142b	c	2010 2020	100 0
HCFC-123, -124, remaining HCFCs	c	2015 2030	100 0

[a] 100% denotes a freeze in production to the base year.

[b] HCFC-22 and -1412b can be produced between 2010 and 2020 only to service equipment manufactured prior to 1 January 2010. HCFC-23, -124, and remaining HCFCs can be produced between 2015 and 2030 only to service appliances manufactured prior to 1 January 2020. The HCFC controls do not apply to used or recycled HCFCs, HCFCs used as feedstocks, or HCFCs for use in a process that transforms or destroys the chemical.

[c] The baseline year has not yet been established for HCFCs.

2.3 COMMERCIALIZED HALON REPLACEMENTS.

Here we use the term "commercialized" to refer to materials now being marketed or which are planned to be marketed in the near future. Most of the commercialized agents PAAs—hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), or perfluorocarbons (FCs or PFCs). The only CAA now being commercialized is CF_3I.

HCFCs will eventually be phased out of production due to their non-zero ODP, and some restrictions are already in place in parts of Europe (and to a limited extent in the USA). The European Community (EC) regulation 3093/94, which came into force on 1 June 1995, does not allow the use of HCFCs for fire protection.

Under the SNAP program, the Environmental Protection Agency (EPA) has applied narrowed use limits to the perfluorocarbons. PFCs are fully fluorinated compounds, unlike HCFCs or HFCs, and have several attractive features. They are nonflammable, have low toxicity, are exempt from federal Volatile Organic Compound (VOC) regulations, and do not contribute to stratospheric ozone depletion. The environmental characteristics of concern, however, are their high global warming potentials (approximately 5,000 times that of carbon dioxide) and their long atmospheric lifetimes (around 3,000 years). Although the actual contributions to global warming depend upon the quantities emitted, the long lifetimes make the warming effects of PFCs virtually irreversible. The EPA is allowing the use of PFCs for only selected applications where no other substitute would meet performance or safety requirements.

HFCs are receiving increased prominence as replacements for ozone depleting substances for three reasons: (1) they are usually volatile and many have low toxicities, (2) because they are not ozone depleting as are the HCFCs and because they have lower atmospheric lifetimes than PFCs, they are likely to receive less regulatory action than HCFCs or PFCs, and (3) they have properties similar to those of halocarbons that have been used in the past. This does not, however, mean that HFCs are not receiving attention from environmental organizations. A recent study by the National Institute of Public Health and Environmental Protection, The Netherlands, has projected a significant increase in greenhouse gas emissions due to use of HFCs to replace CFCs and HCFCs [30]. Moreover, the 1994 report of the United Nations Environment Programme (UNEP) Halon Technical Options Committee (HTOC) states that "...several governments have already restricted or banned the use of HFCs and PFCs" [31].

Of particular interest is that halocarbons other than Halons 1211 and 1301 are banned from all fire protection equipment in Denmark other than that used by the Fire Brigade [32].*

A large number of candidate replacement agents have been announced for commercialization, and even more chemicals are under serious consideration. A number of halocarbon replacements

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* The original decree mistakenly listed three allowed bromocarbons, none of which were Halon 1211 or 1301. These were "diflourmonobrommetan, diflourdibrommetan eller triflourmonometan" (difluoromonobromomethane, difluorodibromomethane or trifluoromonomethane [sic]). A later amendment corrected this list to Halons 1211 and 1301, the only halocarbons whose use was requested by fire equipment manufacturers in Denmark.

have been announced for total-flooding applications (table 7). Most (but not all) of these agents are contained in the NFPA 2001 Standard [23].

TABLE 7. COMMERCIALIZED TOTAL FLOOD AGENTS

Agent	Chemical	Formula	Trade Name
Halon 1301	Bromotrifluoromethane	$CBrF_3$	
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$	DuPont "FE-241"
HCFC Blend A	Additive plus		North American Fire Guardian "NAF S-III"
HCFC-123	Dichlorotrifluoroethane	$CHCl_2CF_3$	
HCFC-22	Chlorodifluoromethane	$CHClF_2$	
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$	
HFC-23	Trifluoromethane	CHF_3	DuPont "FE-13"
HFC-125	Pentafluoroethane	CHF_2CF_3	DuPont "FE-25"
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3	Great Lakes "FM-200"
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	DuPont "FE-36"
FC-218	Perfluoropropane	$CF_3CF_2CF_3$	3M "CEA-308"
FC-3-1-10	Perfluorobutane	$CF_3CF_2CF_2CF_3$	3M Company "CEA 410"
FIC-13I1	Trifluoroiodomethane	CF_3I	Pacific Scientific "Triodide"; West Florida Ordnance "Iodoguard"

The design concentrations for fire extinguishment are shown in table 8 The information for this table was compiled from (1) information from manufacturers, (2) the SNAP listing of 26 August 1994 [6] taken, in part, from a document on design concentrations prepared by the Halon Alternatives Research Corporation (HARC) [33], and (3) NFPA Standards. These design concentrations are minimum manufacturer-recommended values for extinguishment of Class B fires with *n*-heptane fuel and are determined as 120 percent of the cup burner value for *n*-heptane.

Design concentrations may differ for other fuels and will be higher for inertion of an area. Some users are planning to employ or are employing some agents at considerably higher concentrations than the minimum recommended values based on the specific fuel, scenario, and threat. U.S. Navy researchers feel that realistic design concentrations must be determined by tests at realistic scale [34]. Such tests have shown that although design concentrations at 20 percent above cup burner can extinguish large turbulent pool fires, these minimum concentrations increase the time required to effect extinguishment and generate extensive decomposition products [35]. In fact,

TABLE 8. DESIGN CONCENTRATIONS OF COMMERCIALIZED TOTAL FLOOD AGENTS

Agent	Minimum Design Concentration for *n*-Heptane, %	Maximum Fill Density, lb/ft^3	Storage Pressure at 70°F, psi
Halon 1301	5[a]	70[b]	360[b]
HCFC-124	8.5[c]	71.0[d]	195[d,e]
HCFC Blend A[c]	11.9[f]	56.2[d]	360[d]
HFC-23	16[c]	54.0[d]	608.9[d,e]
HFC-125	10.9[c]	58.0[d]	166.4[d,e]
HFC-227ea	7[c]	72.0[d]	360[d]
HFC-236fa	6.4[g]	78[g]	18.4[g,e]
FC-218	8.8[g]	80[g]	360[g]
FC-3-1-10	6.0[h]	80.0[d]	360[d]
FIC-13I1	3.6[i]	104.7[g]	360[g]

[a] The design concentration for Halon 1301 is that set by the NFPA 12A Standard [36] and is higher than the value of approximately 3.6% determined by 120% of the cup burner value.

[b] Reference 36.

[c] Reference 6.

[d] Reference 23.

[e] This is the actual equilibrium pressure within the container due to the vapor pressure of the agent alone (i.e., without nitrogen pressurization).

[f] This value is calculated as 120% of the 9.9% cup burner value reported for this material.

[g] Information provided by manufacturer.

[h] Reference 37.

[i] The design concentration of 3.6% for FIC-13I1 has been set by one of the CF_3I manufacturers for new equipment in accordance with the NFPA 2001 Standard [23]. A design concentration of 5% is suggested for retrofit to maintain the 70% safety margin of Halon 1301 in existing equipment.

based on the inclusion of safety and other factors [38], the U.S. Navy plans to employ design concentrations from 50 to 70 percent above the value shown for one agent in table 8 in at least some applications [34]. Work at the Federal Aviation Administration Technical Center indicates that required concentrations of Halon 1301 in aircraft exceed 120 percent of the cup burner concentrations, that even the required concentrations may not be adequate for all fires, and that the same level or greater of protection must be demonstrated to determine the acceptable concentration of a replacement agent. All of this indicates that required concentrations of halocarbon replacement agents will often exceed the concentrations shown in table 8.

Table 9 gives weight and storage volume equivalents relative to Halon 1301. 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 120 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 manufacturer-recommended design concentrations for an *n*-heptane fire and larger design concentrations may be used in some applications based on fuel, scenario, and threat. Thus, the values for equivalents in table 9 are minimum values.

The weight and storage volume equivalents in table 9 have been calculated in two ways. The first set were calculated from the total flooding quantities at 70°F given in NFPA 2001 and 12A Standards [23 and 36] for the *n*-heptane design concentrations and maximum fill densities given in table 8. In this case, the weight equivalent = (W_a/W_{1301}), where W_a and W_{1301} are the total flooding quantities for the agent of interest and Halon 1301 (0.0206 lb/ft^3 at a design concentration of 5 percent at 70°F, [36], respectively. The storage volume equivalent is then the product of the weight equivalent and the ratio (D_{1301}/D_a), where D_a and D_{1301} are the maximum fill densities for the agent of interest and Halon 1301.

The second set of weight and volume equivalents were calculated directly from the design concentrations, the molecular weights, and the liquid densities. The weight equivalent = $(C_a/C_{1301})(MW_a/MW_{1301})$ where C_a and C_{1301} are the design concentrations of the agent of interest and Halon 1301 and MW_a and MW_{1301} are the molecular weights. The storage volume equivalent is then the product of the weight equivalent and (d_{1301}/d_a), where d is the density. In general, the liquid densities were obtained from the manufacturers or from a recent National Institute of Standards and Technology (NIST) report [39].

The first set of weight and volume equivalents, based on NFPA Standards, is probably more meaningful than the second set, directly calculated from chemical properties. Note that in all cases, the equivalents are based on a Class B *n*-heptane fire and may be different for Class A fires and for Class B fuels other than *n*-heptane.

Another method for determining the weight and storage volume equivalents is to directly calculate the values from the laboratory-determined properties. This method does not use the specified design concentration or the fill densities; however, it does more closely compare the actual agent performance to that of Halon 1301. The results are shown in table 10 [40]. The densities and molecular weights used in these calculations have been taken from table 9 and the extinguishment concentrations are cup-burner values taken from a single source [41].

TABLE 9. WEIGHT AND STORAGE VOLUME EQUIVALENTS FOR TOTAL-FLOOD AGENT FOR *N*-HEPTANE FIRES

	Calculated from Weight Requirements and Fill Densities				Calculated from Molecular Weights and Liquid Densities	
Agent	Wt. Equiv.[a]	Storage Vol. Equiv.[a]	Molecular Weight	Liq. Density, g/mL	Wt. Equiv.	Storage Vol. Equiv.
Halon 1301	1.00	1.00	148.93	[b]1.54	1.00	1.00
HCFC-124	1.64 (1.6)	1.62 (1.6)	136.48	[b]1.364	1.56	1.76
HCFC Blend A	1.59 (1.1)	1.98 (1.4)	92.90	1.20	1.48	1.91
HFC-23	1.69 (1.7)	2.19 (2.2)	70.01	[c]1.20	1.50	1.92
HFC-125	1.88 (1.9)	2.26 (2.3)	120.02	[b]1.190	1.76	2.28
HFC-227ea	1.66 (1.7)	1.61 (1.6)	170.03	[b]1.39	1.60	1.77
HFC-236fa	1.35	1.22	152.04	[b]1.37	1.31	1.47
FC-218	[e]	[e]	188.02	[b]1.35	2.22	2.53
FC-3-1-10	1.91 (1.9)	1.67 (1.7)	238.03	[b]1.52	1.92	1.94
FIC-13I1	0.91	0.61	195.91	[f]2.096	0.95	0.70

[a] Calculated from data in NFPA 2001 and 12A Standards [23 and 36] and table 8. Values in parentheses were taken from SNAP Listing [6].

[b] At 25°C

[c] "Genetron Products Brochure," Allied Signal, Morristown, New Jersey, 1993. The temperature of 86°F for this reported value is above the critical temperature! Use caution in interpreting the result.

[d] At 20°C

[e] Agent does not appear in the NFPA 2001 Standard; therefore, data needed for these calculations are not available.

[f] 20 to 25°C

The environmental and toxicity properties of commercialized total-flood agents are shown in table 11. The data for this table were collected from the 1994 IPCC report [42], SNAP listings, NFPA 2001 Standard, and manufacturers. Since SNAP approvals change rapidly, SNAP acceptability is not included in this table. All agents listed are acceptable or anticipated to be acceptable under SNAP; however, there are or will be limitations on use for certain agents (see table 11 footnotes).

TABLE 10. COMPARATIVE PERFORMANCE OF TOTAL-FLOOD REPLACEMENTS (*N*-HEPTANE FUEL)

Agent	Extinguishment Concentration, % by volume	Weight Equivalent	Storage Volume Equivalent
Halon 1301	2.9	1.0	1.0
HCFC-124	6.7	2.12	2.39
HCFC Blend A	9.9	2.13	2.73
HFC-23	12.6	2.04	2.62
HFC-125	9.4	2.61	3.38
HFC-227ea	6.3	2.48	2.75
HFC-236fa	5.6	1.97	2.22
FC-218	6.1	2.66	3.03
FC-3-1-10	5.0	2.76	2.79
FIC-13I1	3.0	1.36	1.00

Until recently, the number of agents announced for streaming applications was small. The number has, however, increased markedly (table 12). Some environmental and toxicological data for these streaming agents are given in table 13. The information sources for this table are, for the most part, the same as those for table 11. An inspection of table 13 indicates that none of the streaming agent candidates appear likely to exceed the cardiac NOAEL under normal usage in a streaming application. SNAP acceptability is not included in table 13, since SNAP approvals change rapidly. All agents listed are acceptable or anticipated to be acceptable under SNAP with use limitations for some (see table 13 footnotes).

All of the halocarbon agents have tradeoffs for total-flood and/or streaming applications. As noted earlier, halon replacements have four desirable 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. The exception is FIC-13I1, which has total-flood use limitations owing to toxicity.

TABLE 11. ENVIRONMENTAL AND TOXICITY PROPERTIES OF COMMERCIALIZED TOTAL-FLOOD AGENTS

Agent	ODP[a]	GWP[b]	Atmospheric Lifetime, Yrs	NOAEL %	LOAEL %
Halon 1301	12-16	5600	65	5[c]	7.5[c]
[d]HCFC-124	0.022	480	6	1.0	2.5
HCFC Blend A	0.044[e]	1450[e]	12[e]	10.0	>10.0
HCFC-123	0.02	93	1.4	1.0	2.0
HCFC-22	0.05	1700	13	2.5	5.0
HCFC-124	0.022	480	6	1.0	2.5
HFC-23	0.0	12100	250	30[f]	>50
[d]HFC-125	0.0	3200	36	7.5	10.0
HFC-227ea	0.0	3300	41	9.0	10.5
HFC-236fa	0.0	8000	250	10.0[g]	15.0[g]
[h]FC-218	0.0	6100	3200	30	40
[h]FC-3-1-10	0.0	5500	2600	40	>40
[i]FIC-13I1	0.0001	<5	<1 day	0.2	0.4

[a] Relative to CFC-11.

[b] Based on a 100-year horizon, relative to CO_2.

[c] References 23 and 43. Note that EPA accepts NOAEL and LOAEL values of 7.5% and 10% based on other sources [44].

[d] Cannot be used as total-flood agent in occupied areas under NFPA Standard 2001 criteria [23], with the exception of Class B fires with a predischarge alarm and a time delay.

[e] Calculated by the manufacturer from a weighted average for the blend components.

[f] Without added oxygen. At least 50% with added oxygen.

[g] Reference 45.

[h] PFCs are acceptable under SNAP for nonresidential use only when other alternatives are not technically feasible due to performance or safety requirements [9].

[i] Acceptable under SNAP for protection of nonoccupied areas only [9].

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 than Halon 1301 does during comparable extinguishment [15, 46]. Although a large amount of information is available on hydrogen fluoride toxicity [47], it is difficult to determine what risk is acceptable. Moreover, insufficient data exist to determine what hydrogen fluoride levels are likely in real fire scenarios. In general,

TABLE 12. COMMERCIALIZED STREAMING AGENTS

Agent	Chemical	Formula	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 HCFC-123	Primarily Dichlorotrifluoroethane	 $CHCl_2CF_3$	American Pacific “Halotron I”
HCFC Blend C HCFC-123 HCFC-124 HFC-134a	Proprietary additive plus Dichlorotrifluoroethane Chlorotetrafluoroethane 1,1,1,2-Tetrafluoroethane	 $CHCl_2CF_3$ $CHClFCF_3$ CH_2FCF_3	North American Fire Guardian “NAF P-III”
HCFC Blend D HCFC-123	Proprietary additive plus Dichlorotrifluoroethane	 $CHCl_2CF_3$	North American Fire Guardian “BLITZ”
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3	Great Lakes “FM-200”
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	DuPont “FE-36”
FC-5-1-14	Perfluorohexane	$CF_3(CF_2)_4CF_3$	3M Company “CEA 614”
FIC-13I1	Trifluoroiodomethane	CF_3I	Pacific Scientific “Triodide”; West Florida Ordnance “Iodoguard”

agent decomposition products and combustion products increase with fire size and extinguishment time [48]. To minimize decomposition and combustion products, rapid detection and rapid discharges are recommended.

TABLE 13. ENVIRONMENTAL AND TOXICITY PROPERTIES OF COMMERCIALIZED STREAMING AGENTS

Agent	ODP[a]	GWP[b]	Atmospheric Lifetime, yrs	NOAEL, %	LOAEL, %
Halon 1211	3		15	0.5[c]	1.0[c]
[d]HCFC-123	0.02	93	1.4	1.0	2.0
[d]HCFC-124	0.02	480	6	1.0	2.5
[d]HCFC Blend B					
HCFC-123	0.02	93	1.4	1.0	2.0
[d]HCFC Blend C					
HCFC-123	0.02	93	1.4	1.0	2.0
HCFC-124	0.02	480	6	1.0	2.5
HFC-134a	0.0	1300	15	4.0	8.0
[d]HCFC Blend D					
HCFC-123	0.02	93	1.4	1.0	2.0
HFC-227ea	0.0	3300	41	9.0	10.5
HFC-236fa	0.0	8000	250	10.0[e]	15.0[e]
[f]FC-5-1-14	0.0	6800	3200	40	>40
[g]FIC-13I1	0.0001	<5	<1 day	0.2	0.4

[a] Relative to CFC-11.

[b] Based on a 100-year horizon, relative to CO_2.

[c] Reference 49

[d] Under SNAP, HCFCs cannot be used in residential extinguishers. In addition, HCFCs can only be used in portable fire extinguishers where other commercially available agents are not as effective for the fire hazard. Since fire hazards vary significantly in commercial settings (including industrial and commercial sectors), the latter restriction has been interpreted as generally allowing commercial, watercraft, and aircraft use in portables.

[e] Reference 45.

[f] PFCs are acceptable under SNAP for nonresidential use only when other alternatives are not technically feasible due to performance or safety requirements.

[g] Proposed acceptable under SNAP for nonresidential use subject to public comment [11].

3. ALTERNATIVES.

Non-halocarbon substitutes are increasingly being considered for replacement of halons. Already, water sprinklers are replacing halon systems in many applications. Dry chemical extinguishants and carbon dioxide are also receiving increased use. Alternatives can be divided into two types: "Classical" alternatives and "New" alternatives (table 14). Note that the word "New" does not necessarily imply that the technology was developed recently, but that there is a new or renewed interest in the use of the 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 in inert gases may allow the use of inert gas blends in new applications, particularly in occupied areas.

TABLE 14. ALTERNATIVES

Classical	New
Foams	Water Misting
Water Sprinklers	Particulate Aerosols
Dry Chemicals	Inert Gases
Carbon Dioxide	Gas Generators
Loaded Stream	Combination

3.1 FOAMS.

Foams are an alternative to halon systems for a number of hazards, particularly those involving flammable liquids [50]. 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. Semi-fixed 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 that 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 flooding” of a protected space, particularly where a Class A fire may be difficult to access for manual fire fighting. 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. Disadvantages of such 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 problem 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.

3.2 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 to prevent reignition. The quantity of water required is, in some installations, less than the amount of halon needed for the same degree of protection.

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 clean-up 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 clean-up 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.

There are several types of fixed water systems for fire protection [51]. 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 below 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. Pre-design inspections should be a mandatory consideration for all existing halon protected areas.

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 and 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 [52]. The main disadvantages of dry chemical fire extinguishants include:

- Poor penetration behind obstacles.
- No inhibiting atmosphere after discharge.

- No direct cooling of surfaces or fuel.*
- Secondary damage to electronic, electromechanical, and mechanical equipment.
- Cleanup problems.
- Temporary loss of visibility if discharged in a confined space.

Fixed dry chemical systems are very uncommon; uses are normally limited to "localized applications," such as with textile machines or deep fat fryers, where 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 suitable for Class A, B, and, in some cases, C fires depending on the type of powder used. Powder 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, powder extinguishers resemble halon extinguishers.

3.3.1 Monoammonium Phosphate.

This is an excellent explosion and fire suppressant and is effective on Class A, B, and C fires. It is, however, corrosive on metals. This material is often referred to as "ABC Powder."

3.3.2 Sodium Bicarbonate.

This, along with monoammonium phosphate, is considered to be an excellent explosion suppressant. It has been used in stove-top fire extinguishers. It is the largest selling dry chemical, primarily because of its low cost and its use in training.

3.3.3 Potassium Bicarbonate.

Potassium bicarbonate is a widely used dry chemical fire extinguishant. 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 with small amounts of additive to improve flow and other characteristics. "Monex," urea potassium carbonate, developed by ICI, is an exceedingly effective proprietary

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* 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.

dry chemical; however, it is more expensive than the generic agents shown above and has a somewhat less effective delivery.

3.4 CARBON DIOXIDE.

In some ways, carbon dioxide resembles the other inert gases discussed further on; however, carbon dioxide can be considered a "classical" alternative and is the most common inert gas used as a fire extinguishant today. Moreover, the physiological effects of carbon dioxide are significantly different from the other inert gases. Like Halons 1301 and 1211, carbon dioxide is a gas at normal ambient temperature and pressure. It is also a clean, nonconducting agent with good penetrating capability.

At one time, CO_2 systems were used for many of the applications that now use halon. Fixed CO_2 systems remain in popular use for a number of applications, particularly in unmanned rooms. Carbon dioxide is also a common agent in portable fire extinguishers and in localized fixed systems.

Carbon dioxide requires a gas-phase concentration approximately ten times that of halon to provide extinguishment in a total-flood environment. (Note, however, that this does not imply that ten times as much CO_2 is needed in a streaming or localized application.) Since CO_2 is less efficient than halons, the time to extinguishment is greater with CO_2 than with halons and greater storage requirements are needed. For total flooding, an agent storage volume of approximately 8 times that required for halon is required for CO_2 systems. On existing industrial and commercial premises, weight and space considerations are more relevant in retrofitting than with new installations, but they still may not be major obstacles. Moreover, excluding agent costs (which are changing rapidly today), a fixed CO_2 system could cost two to three times as much as a fixed halon system.

There are concerns about the safety hazard to personnel in areas protected with fixed total-flood CO_2 systems. CO_2 is a major respiratory regulator. Unlike the other inert gases, CO_2 is toxic in large amounts and the concentration required to extinguish a fire (around 30 percent) is well above the IDLH (Immediately Dangerous to Life and Health) level. With most fixed localized systems, on the other hand, the hazard is much less; and with portable extinguishers, any hazard is usually minimal. It is possible to limit the safety hazards with fixed total-flood CO_2 systems 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. However, owing to the toxicity and the reduced efficiency, CO_2 is generally less attractive to fire insurers.

Of greater concern to a significant number of users is damage from discharge. One form of damage is "thermal shock," where the rapid reduction in temperature could cause damage to electronic equipment. There is, however, a shortage of conclusive information to support this concern. Users are also concerned about the possibility of erasure of recorded material on magnetic tape from CO_2 discharge; however, tests indicate that CO_2 discharge does not harm tapes.

Carbon dioxide portable fire extinguishers have been available for many years and are in common usage. 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 agent—water, foam, dry chemical, halon—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. Most loaded stream agents are used for protection of cooking and restaurant facilities. Kidde puts out 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.

Recent work shows 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 [53].* 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.

3.6 WATER MISTING.

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. A draft NFPA standard [54] has established a criterion of 1000 microns or less for a definition of 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 thorough review of water misting has been written by the Navy Technology Center for Safety and Survivability and Hughes Associates [55]. Concepts and some studies have been described at the Water Mist Fire Suppression Workshop, at the National Institute of Standards and Technology on 1-2 March 1993. Work has been performed by the Fire Research Station in England on non-total-flood applications, primarily aircraft crash/rescue, the Channel Tunnel, and streaming. Water misting has been found to be effective in suppressing flammable liquid fires [56], and it has been considered for use in spacecraft [57]. The Naval Research Laboratory is examining water misting nozzles to simulate Halon 1211 for firefighter training [58]. A recently

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* 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.

completed program evaluated water mists for residential applications [59]. At the request of the EPA, the Halon Alternatives Research Corporation has convened a peer review panel of the potential effects of water mist. This study is nearing completion.

There are two basic types of water mist suppression systems: single-fluid (which may be a high-, medium-, or low-pressure system) and dual-fluid. Single-fluid systems utilize water stored under pressure and spray nozzles that deliver drop sizes in the 10 to 100 μm diameter range. Single-fluid units can be arbitrarily divided into high-pressure (above 750 psi), medium-pressure (175 to 750 psi), and low-pressure (less than 175 psi) systems.* Dual systems use air, nitrogen, or another gas to atomize water at a nozzle. Both types of systems have been shown to be promising fire suppression systems. It is more difficult to develop single-phase systems with the proper drop size distribution, spray geometry, and momentum characteristics. In addition, dual-fluid systems have a higher spray energy for a given water pressure; are a comparatively low pressure system with a maximum air and water pressure in the lines of about 100 psi (many single-fluid systems use pressures of 1000 psi or larger depending on the nozzle design); and have larger nozzle orifices, which may have greater tolerance to dirt and contaminants and which may allow the use of higher viscosity antifreeze mixtures. On the other hand, single-fluid systems require only storage of water, whereas dual-fluid systems require storage of both water and atomizer gas.

The performance of a water mist system depends on two factors: (1) the ability to generate small droplet sizes and (2) the ability to distribute mist throughout a compartment in concentrations that are effective [55]. Five factors are important in determining success or failure of a misting system to protect an area: (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. At this time, the effect of these factors on system effectiveness is not well known. 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 agent for use in several potential fire locations (for example, cargo and passenger cabin locations). This would further increase the benefit.

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

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* The pressures given for high-, medium-, and low-pressure systems are approximate; others may use different values.

(6) lack of design standards [60]. 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. Although Task Group 4 of the International Halon Replacement Working Group has concluded that deep-seated fires are not typical, the Group could not conclude that any fire is typical. Subsequent data produced by the FAA Technical Center show that deep-seated fires do occur and have been the cause in a majority of the fatal aircraft cargo fires. Moreover, recent testing on deep-seated cargo fire indicates 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.

Table 15 gives a list of manufacturers for water misting systems. Not all of these may be commercializing or planning to commercialize fire suppression systems at this time.

TABLE 15. COMMERCIAL AND NEAR-COMMERCIAL MISTING SYSTEMS

Dual-Fluid	Single-Fluid
ADA Technologies, USA	Bete Fog, USA
GEC-Marconi Avionics, UK	Grinnell AquaMist, USA (low pressure)
Ginge-Kerr, U.K., Denmark, Norway	GW Sprinkler, Denmark
Kidde International, UK, USA	Marioff Hi-fog, Finland
Secuirplex, Canada	Microguard-Unifog, Germany
	Reliable Automatic Sprinkler Co. (Baumac), USA
Technology Unknown.	Semco Marine, USA/Denmark
DAR CHEM, UK	Spraying Systems, USA
HTC, Sweden	Total Walther/Wormald MicroDrop (low pressure)
	Unitor, Germany

3.7 PARTICULATE AEROSOLS.

Dry chemicals agents are at least as effective as halons in suppressing fires and explosions in many applications; however, such agents can damage electronic equipment. Moreover, dry chemical agents, as now used, do not provide the extended inertion (explosion or fire) provided by halon systems. The discharge of dry chemicals also obscures vision. In Geneva, Switzerland, at the 1-3 October 1990, 2nd Conference on the Fire Protecting Halons and the Environment, representatives of the Soviet Union provided information on a solid agent that they claimed provides relatively long-term (20 minutes or more) inertion of an enclosed volume and excellent fire extinguishment [61]. They have continued to keep the agent and the generation system secret; however, the small amount of information provided indicates that the Soviet material was a very fine particulate generated by combustion. Some have termed this type of technology "pyrotechnically generated aerosol," PGA.

At the International Symposium on Halon Replacement in Aviation held in Reston, Virginia, on 9-10 February 1993, extreme interest in the PGA technology was expressed. This Technology was also discussed at the 11-13 May 1993 NMERI Halon Alternatives Technical Working Conference, in Albuquerque, NM, where three papers on particulate aerosols were presented [62-64]. A recent paper has reviewed much of this area [65].

One of the problems encountered with particulate aerosols is that the technologies are often proprietary or ill-defined. For example, it is not at all obvious that the term "PGA" applies to all of the agents. The following presents some information on some commercialized materials. The NFPA is establishing a Technical Committee on Fine Aerosol Technology.

3.7.1 Spectrex Extinguishing Agents.

The "S.F.E." family of extinguishing agents (also known as EMAA Encapsulated Micron Aerosol Agent) are produced by Spectrex. The agents provide an air-suspended dry chemical aerosol with micron-size particles that give total flood capabilities [66]. U.S. Navy and U.S. Air Force studies 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 [4]. Approval is pending for occupied areas [6].

In its various forms, the "S.F.E." compound, upon activation, ignites and creates an aerosol that contains about 40 percent solid particles (size of particle less than 1 μm) of salts like KCl, K_2CO_3, etc. 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.

The aerosol solid particles, as a result of the high temperature of combustion, create a large surface area for capturing active species of the fire chain, such as hydroxyl free radicals (OH), which are considered to be the fire chain carriers. The smaller particle size provides for better dispersion and a more effective aerosol. As the particle size decreases, the extinguishing surface of the aerosol, on which heterogeneous recombination of the chain propagators takes place, increases. Moreover, as the size of the particles diminishes, the rate of sublimation increases, and the extinguishing effect is augmented by homogenous gas phase inhibition of the fire/flame through the interference of gaseous products forming from the condensed part of the Aerosol. It appears that both heterogeneous inhibition (on the surface of the solid particles) as well as homogenous inhibition (in the gaseous phase) take place in the extinguishing process. Physical characteristics of the solid compound include:

Specific Density	1600 to 1800 kg/m^3
Combustion Temperature	1500 to 2400 K
Combustion Velocity	0.3 to 1.5 mm/sec
Shelf Life	15 years
Appearance	Solid fine powdered mixture or gelled paste.

Significant toxicity testing has been performed on emissions from two formulations [67-71]. Deaths observed in tests on rats using an earlier formulation, A1, at concentrations exceeding

80 g/m^3 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 up to 240 g/m^3 caused no deaths to Fischer 344 rats and only minimal toxic effects [69]. All the animals recuperated after the exposure ceased. Formulation A2 is now being commercialized as "S.F.E."

The approximate extinguishing concentration 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 was included.

3.7.2 Powdered Aerosol C.

A product marketed as "FEAS" by Bytenet Holdings in Australia has been approved under SNAP as Powdered Aerosol C for total flooding of normally unoccupied areas [12].

3.7.3 "Soyus" PGA Extinguishers.

Dynamit Nobel GmbH Explosivestoff und Systemtechnik, Troisdorf, Germany, produces a number of different sizes of PGA 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 μm. 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. SNAP approval has not yet been sought.

3.8 INERT GASES.

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

Unfortunately, health problems can occur at low concentrations of oxygen. Although asphyxiation is not as 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 [72]. 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" [73].

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

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 [74]. 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 [75]. This method can only be applied to completely enclosed areas with high structural strengths and is, therefore, limited to very few applications.

A number of pure and blended inert gases are being marketed as alternatives to halons (table 16). The 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).

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 [11]. 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 1996 NFPA 2001 Standard [23] 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 1996 Standard (IG-01, IG-541, and IG-55) have sea-level-equivalent* NEL and LEL values of 43 percent (12 percent oxygen) and 52 percent (10 percent oxygen), respectively. Similar to that done for halocarbon agents, the NFPA 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 [26] 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.

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* 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 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 percent.

TABLE 16. INERT GASES

Designation	Composition	Manufacturer
IG-541	Nitrogen 52 ± 4% Argon 40 ± 4% Carbon Dioxide 8 ± 1%	Tyco International, Ltd., USA, and Fire Eater A/S, Denmark ("INERGEN")
IG-55	Nitrogen 50 ± 5% Argon 50 ± 5%	Unitor Denmark A/S ("ARGONITE")
IG-01	100% Argon	Minimax GmbH ("Argotec")
IG-1	100% Nitrogen	Cyberus; Koatsu ("NN100")

3.9 GAS GENERATORS.

Gas generator technology utilizes ignition of solid propellants to generate large quantities of gases. This gaseous effluent can either be used as is to create an inert environment or can be enhanced with various active agents to more aggressively attack the fire. The U.S. Navy has conducted numerous feasibility and design verification tests on several aircraft platforms to assess and refine gas generator designs and has applied gas generator technology to the F/A-18E/F and V-22 aircraft. The U.S. Air Force has been evaluating the technology for aircraft dry bay applications and will be testing gas generators 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 gas generator technology in crew compartments. Several overviews of gas generator technology and the progress of testing conducted to date have been presented [76-78].

3.9.1 Olin Aerospace Inert Gas/Powdered Aerosol Blend.

Olin Aerospace Company, which has been supporting U.S. Department of Defense (DoD) testing, has announced that initial engineering, manufacturing, and development contracts have been received from two airframe manufacturers to protect aircraft dry bays [79]. The Olin Aerospace device uses an electrically activated squib to ignite a solid propellant that generates an inert mixture of nitrogen, carbon dioxide, and water vapor.

Olin Aerospace markets FS 0140, which has been approved under SNAP as Inert Gas/Powdered Aerosol Blend for use as a total-flood agent in unoccupied areas [9].

3.9.2 Walter Kidde Aerospace/Atlantic Research Corporation Consortium.

Walter Kidde Aerospace has teamed with Atlantic Research Corporation to develop gas generator technology for aviation and defense applications. The Walter Kidde Aerospace/ Atlantic Research Corporation Consortium is being funded by the DoD under a Defense Advanced Research Projects Agency "Technology Reinvestment Program." This program will develop gas generator/vaporizing liquid agent hybrid extinguishers and gas generators that expel chemically active flame inhibiting species for the F-22 dry bay and other military applications. The chemically active gas generators have been shown to be more efficient on a weight basis than inert gas generators [80]. In addition, the Walter Kidde Aerospace/Atlantic Research Corporation Consortium is being funded by Batelle Labs to provide chemically active gas generator hardware for the F-22 engine nacelle fire protection test program.

3.10 COMBINATION.

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.

3.10.1 Gelled Halocarbon/Dry Chemical Suspension.

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 [4]) 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 [81 and 82]. Testing to date indicate that at least some formulations have an effectiveness similar to that of Halon 1301 on either a weight basis or a storage volume basis [83]. 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 [6]. 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 [9].

3.10.2 Surfactant Blend A.

This product, marketed as Coldfire 302, is a mixture of organic surfactants and water. In use, this concentrated mixture is diluted to strengths of 1 to 10 percent in water. 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. It can also be used on Class A fires. The agent is UL listed as a wetting agent for addition to water for extinguishing Class A and B fires. The material is claimed to be applicable to Class D fires; however, water-based agents have not been found to be acceptable for this application in the past. The extinguishant is a blend of complex alcohols, lipids, and proteins. Each substance is biodegradable and the material has been assigned a hazardous materials identification system (HMIS) rating, developed by National Paint and Coatings Association

(NPCA) of 0-0-0 for health hazard, reactivity, and flammability. It is approved by US EPA as a substitute for Halon 1211 and for use with water mists in total flooding of normally unoccupied areas [10].

4. AGENTS RECOMMENDED FOR DEVELOPMENT OF TEST PROTOCOLS.

As noted in the introduction, the major goal for Task Group 6 is the recommendation of two to three agents for use in developing FAA test protocols for each major area of onboard aircraft use: (1) engine nacelles and APU (auxiliary power unit) compartment, (2) handheld 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. Remember that these agents are recommended for development of test protocols. They are not necessarily the recommended agents for the application itself.

4.1 REQUIREMENTS.

We believe the candidate agents must meet the following requirements. The requirements imposed by the threat or application are additional to these requirements. A discussion of requirements or possible requirements by application has been published by the FAA [84].

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 no or 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 our analyses.

4.2 ENGINE AND APU COMPARTMENT.

The fire threat in these compartments is a Class B fire (aviation fuel, hydraulic fluid, lubricant). The compartments are normally ventilated, are at a high temperature, and are at ambient pressure.

Fires generally occur when fuel comes in contact with hot surfaces due to a failure. Any fire is detected by thermal sensors that activate aural and visual fire warnings. The industry practice is to throttle back (shut off fuel) and discharge the fire suppression agent in the compartment at the first opportunity. The compartment remains ventilated during and following agent discharge and flammable fluid drainage from fluid lines may continue following engine shut down.

We recommend establishment of tests for the following groups of agents. Note that these two groups cover a range of properties and, therefore, cover the range of testing procedures and apparatuses that should be established.

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) are the agents of first choice within this group. Both were on the final list of agents being tested at Wright-Patterson AFB. HFC-227ea is acceptable as Halon 1301 substitute [4]. It is recognized as an acceptable agent for Class B fires by technical and listing organizations. HFC-125 is acceptable as a total-flood agent for areas that are not normally occupied (not a problem in this application). It is being commercialized and is listed in the NFPA 2001 Standard [23]. HFC-125 has been selected for Phase III testing in the Wright-Patterson program. 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.

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

Testing at Wright-Patterson AFB has demonstrated that this chemically active agent is more effective in engine nacelle fire extinguishment than any other replacement halocarbon tested to date. The material is proposed for approval by the U.S. EPA [7]. 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 midlatitudes, 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." [85]

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 [86]. The cardiotoxicity of

CF_3I is greater than that of other halocarbon candidates; however, the relatively low cardiac sensitization NOAEL and LOAEL values are probably of little concern for engine nacelle and APU applications where potential for contact is extremely limited.

Note: Agent concentrations required for the engine and APU compartment may differ from the design concentrations as determined from heptane flame extinguishing concentrations (table 8) because (a) fuel is shut off prior to the initiation of suppression, (b) compartments are ventilated, and (c) the fuel is different. Also the discharge time influences agent quantity. The heptane flame extinguishing concentrations (and design concentrations) presented in table 8 are intended to provide a basis of comparison. Required concentrations and their duration must be determined by test. The performance of CF_3I at very low temperatures in engine nacelle applications has been questioned [87]. In particular, it has been suggested that equipment modification may be needed to ensure good agent distribution in the F-15 aircraft.

4.3 HAND-HELD FIRE EXTINGUISHER.

Federal Aviation Regulations mandate handheld fire extinguishers be conveniently located in passenger compartments. The number of required extinguishers depends on the passenger capacity of the airplane [88]. The total number of extinguishers required are shown in table 17.

It is required that at least one of the extinguishers on an airplane of passenger capacity greater than 31 and two on an airplane with passenger capacity greater than 61 must contain Halon 1211 (bromochlorodifluoromethane) or equivalent as the extinguishing agent. What is implied by "equivalent" is presently not known, and the methods to demonstrate equivalency are undefined.

TABLE 17. NUMBER OF HAND-HELD FIRE 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 handheld fire extinguisher must be located in the pilot compartment, and at least one extinguisher must be available for use in each Class A or Class B cargo or baggage compartment and in each Class E cargo or baggage compartment that is accessible to crew members in flight.

The agent for handheld fire extinguisher should meet the following requirements in addition to the essential requirements identified earlier.

a. The agent must be suitable for Class A, B, and C fires.

b. The agent must have an acceptable toxicity for use where people are present. Moreover, the agent must not cause unacceptable visual obscuration or passenger discomfort.

c. The agent must have the ability to extinguish two types of fires: (1) Fires in indirectly accessible spaces, "hidden" fires (it is desirable that the agent be gaseous in order to allow expansion and penetration into such spaces.) and (2) Class A and B seat-cushion fires ignited with burning gasoline [89].

d. Any handheld fire extinguisher adopted for final use should 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 Halon 1211 extinguisher is 2.5 pounds, and this achieves a UL 5-B:C rating in accordance with the UL 711 Standard [90] or a BS 3A:34B rating in accordance with British standards [91]. It is expected that this UL 5-B:C or BS 3A:34B fire extinguishing ability along with a demonstrated ability to extinguish a hidden fire and seat cushion fires will be the required minimums for the agent to be acceptable in this application.

In the first report [14], the task group recommended establishment of tests for the following groups of agents. Note that these three groups of agents operate by different mechanisms and/or have large differences in physical properties. They, therefore, 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.

The Civil Aviation Authority (CAA) in the United Kingdom has sponsored research establishing a test for onboard handheld fire extinguishers [92]. A text 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 handheld extinguishers. Results varied from 45 percent extinguishment to 60 percent, 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 handheld extinguisher, all results could be correlated to the mass and mass of agent 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 an apparatus designed to give a constant discharge time (10 seconds ± 1). The results obtained appeared to be similar to Halon

1211 (50 percent extinguishment ± 5), 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): FE-25 (boiling point: -49°C, -56.2°F; 65 percent extinguishment) and CEA-614 (boiling point: 58°C, 136.4°F; 35 percent extinguishment). 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. FIC-13I1 would have a weight penalty of 1.06 and no volume penalty. Note, however, that any hand extinguisher, before it is evaluated against hidden fires, must have passed the traditional ratings (see above) to be approved for aviation use.

4.3.1 Halocarbons and Halocarbon Blends.

Of all of the halocarbon agents, FICs and, possibly to a lesser extent, HFCs are likely to have the lowest restrictions imposed owing to environmental impacts. Nevertheless, even HFCs could face regulatory restrictions. FIC-13I1 (like some of the other halocarbons) will also face some restrictions based on toxicity. This agent will not be permitted as a total-flood agent in a normally occupied area.

HCFCs have a nonzero ODP and 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. At least one HCFC-based agent should be considered in this application because of their gaseous consistencies and their demonstrated abilities on Class A, B, and C fires.

PFCs are approved by the US EPA [4] for nonresidential use where other alternatives are not technically feasible due to performance or safety requirements: (a) due to physical or chemical properties of the agent or (b) where human exposure to the extinguishing agent may approach cardiosensitization levels or result in other unacceptable health effects under normal operating conditions. The principal environmental characteristic of concern for these materials are their high GWPs and long atmospheric lifetimes. Nevertheless, PFCs should be considered in this application because of their extremely low toxicity.

Some concern has been expressed about preliminary mutagenicity assays indicating that CF_3I might be a carcinogen. Certainly this question may need to be resolved; however, some other halon replacement candidates or components also exhibit positive results in at least one genetic toxicity screening test. In addition, there is some concern that iodine emissions from CF_3I could cause a problem. No data have yet been collected showing that iodine emissions are any worse with CF_3I than bromine emissions are with Halon 1211. Nevertheless, the potential for toxic breakdown products must be fully evaluated.

It is difficult to rank the various halocarbon agents against one another since any ranking requires that dissimilar criteria be compared (e.g., toxicity versus effectiveness). Table 18, nevertheless, gives ratings for two criteria (Halon 1211 is also listed for comparison). Here "1" denotes the highest rating. Note that this is qualitative, and undoubtedly, different groups could arrive at different ratings. It is impossible to reliably evaluate the effectiveness of a streaming agent from

TABLE 18. RATING MATRIX FOR CANDIDATE HALOCARBONS FOR HAND HELDS

Agent	Cup Burner Extinguishment Concentration, %	Known or Potential Environmental Regulatory Restrictions[a]	Toxicity Based on Cardiac Sensitization NOAEL
Halon 1211	2.22[b]	3	3
HCFC-123	7.5[c]	3	3
HCFC-124	7.0[d]	3	3
HCFC Blend B HCFC-123	6-7[e]	3	3
HCFC Blend C HCFC-123 HCFC-124 HFC-134a	[f]	3	3
HCFC Blend D HCFC-123	[f]	3	3
HFC-227ea	5.8[d]	2	2
HFC-236fa	5.29[g]	2	2
FC-5-1-14	4.4[d]	3	1
FIC-13I1	3.05[h]	1	3

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

[b] Reference 93

[c] Reference 94.

[d] Reference 4.

[e] Estimated [95]. Testing indicates that HCFC Blend B has an equivalency rating of 1.5 pounds to 1 pound of Halon 1211 in airport fire protection streaming applications [96].

[f] Cup burner data have not been published for this agent.

[g] Reference 97

[h] Reference 98

only cup burner extinguishment concentrations, particularly when the cup burner measures only Class B effectiveness. Nevertheless, the cup burner values, where known, have been included. These can be used as deemed appropriate. The ability of an agent to suppress a fire in a streaming application depends as much on the physical properties and delivery hardware as on the inherent flame suppressing ability. (Note that this is definitely not true for total-flood applications. The cup burner has proven to be highly reliable for predicting the effectiveness of total-flood agents for Class B fires, at least for those containing a single component.) CF_3I and the HFCs are the agents least likely to face serious regulatory restrictions based on environmental impacts. All of the PFCs are essentially nontoxic, and therefore, FC-5-1-14 has been given a rating of 1 for toxicity. HFC-227ea has been given a rating of 2 because it is allowed as a total-flood agent in a normally occupied area, and this may reflect on its toxicity characteristics in a streaming application as well. Likewise, the NOAEL value and extinguishment concentration for HFC-236fa indicates that it should be acceptable for total flooding in occupied areas. Note, however, that acceptabiiity for total-flood use in normally occupied areas is not a criteria for use of an agent for streaming. The remaining agents, all of which have NOAEL values or contain as principal components materials with NOAEL values of 1.0 or below, have been given a toxicity rating of 3. It should be noted that for streaming applications, most, possibly all, of these agents could be used in a normally occupied area. Extensive full-scale testing of both HCFC Blend B and FC-5-1-14 for flight line fire protection has been conducted by both the FAA and the U.S. Air Force. The U.S. Air Force has also conducted significant field testing on several other agents listed in table 18.

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 handhelds 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.

4.3.3 Combination Agents.

These agents include Surfactant Blend A, Loaded Stream, and Gelled Halocarbon/Dry Chemical Suspension. Though these are listed together, their properties are sufficiently different that major differences in test procedures will probably be required. In the absence of test results, it is impossible to rank the fire extinguishment effectiveness of handhelds 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, for dry chemical is poor, and for water is poor [99]. Most, possibly all, combination agents may also have problems with penetration and obstacles. Moreover, 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 EPA approved.

4.4 CARGO COMPARTMENT.

According to the report of Task Group 4 [100], 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. The cargo compartments are normally pressurized with a maximum 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 systems are required to detect fire in its early stage and provide a warning before the fire

- develops into an uncontrollable or uncontainable condition, or
- damages liners, wiring, equipment, structure, or essential or critical equipment.

Systems that provide a warning within one minute from the start of smoke generation are considered to be in compliance with Federal Aviation Regulation, FAR 25.858 [101]. The present practice is to control ventilation and drafts within the compartment prior to the activation of the suppression system. However, there is little 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 ocean) aircraft, suppression is required for 180 minutes. Cargo compartments often contain animal cargo.

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

a. The agent must be suitable for Class A fires.

b. Because cargo compartments can be used for transportation of animals, it is desirable that the agent have a low toxicity and that it not be an asphyxiant at the concentrations required for extinguishment. (Note, however, that the conservative approach of using the NOAEL cardiotoxicity level to determine allowable agents and concentrations may not be required where only animal exposure is likely. The dog, which is used in determining cardiotoxicity NOAEL/LOAEL values, and presumably other animals are considered less susceptible to cardiotoxicity.) In addition, no agent can be allowed that could leak into occupied compartments in toxic concentrations. Such leakage is an unlikely event. 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.

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

d. The agent/system must be able to provide fire suppression over a period of 180 minutes.

We recommend the establishment of test protocols for the following agents.

4.4.1 Water and Water-Based Agents.

Water meets all the above requirements. It 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 an identical fire threat. 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 increase in cleanup effort.

The FAA Technical Center at Atlantic City International Airport, New Jersey, has carried out a mist system testing program for the FAA TC-10 cargo test compartment. The object was to design and install a water mist system that would prevent a fire in a container from spreading to an adjacent container and that would maintain temperatures within the space below 350°C for 90 minutes. The program has shown that one misting system can pass both the loaded cargo container and bulk loading fire tests for the TC-10 cargo test compartment using 30 gallons of water [102]. It is still uncertain how this compares with gaseous agents with respect to weight and space requirements and fire protection performance; however, it is obvious that water misting has potential in this application.

It has been suggested that water-based fire suppression systems may be recharged from the potable 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 19 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 percent to 8 percent: 2; 8 percent to 11 percent: 3; and 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; and 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 the NFPA 2001 Standard [23] 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 and FIC-13I1, which have NOAEL values of 1.0 or less are rated as 4. 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.

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 [103]. At present, no manufacturer offers such a system, and the technology must still be considered unproved. However, the possibility that one or more new, lower vapor pressure compounds will be proposed for total-flood protection must be kept in mind.

4.4.3 Particulate Aerosols.

Some preliminary testing has already been performed by the FAA on particulate aerosols. The agent partially suppressed a Class A fire in a 2357-ft^3 compartment for approximately 17 minutes [104]; however, it has not yet been tested versus an established Halon 1301 baseline. The applicability to cargo compartments is still uncertain; however, this technology should be evaluated.

TABLE 19. 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	4

[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 now appear in an NFPA standard, were calculated from the design concentration, molecular weight, and 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 [23]. See tables 8 and 9.

4.4.4 High-Expansion Foam.

We know of no high-expansion foam system designed for cargo bays; however, such a system might provide extended protection without the constant discharge of a gaseous agent. We recommend that testing of this concept be performed.

Note: 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 agents suggested above 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.

4.5 LAVATORY TRASH CONTAINER.

Lavatories are located in the pressurized shell and the environmental conditions are similar to the conditions in the occupied areas. The fire threat in the lavatory trash container is Class A (paper and paper products). The likely ignition source is burning material discarded into the container. In summary, the fire threat exists only when the temperatures in the lavatory are at a temperature acceptable for passenger comfort, passengers are on board, and the lavatories are in use. The trash containers are designed to contain the likely fire. No fire detection system is provided in the container. However, a smoke detector (visible or invisible aerosol type) is located in the lavatory. The container fire suppression system (commonly referred to as a “potty bottle”) incorporates an eutectic, which, at a preselected temperature, automatically discharges the agent into the container.

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

- The agent must be suitable for Class A fire in general and paper fire in particular.
- The agent must have an acceptable toxicity, in small concentrations.

We recommend establishing a test procedure for the following.

4.5.1 Water-Based Agents.

Water, water/surfactant (e.g., Surfactant Blend A), and dry chemical/water mixtures meet all the above requirements. Water is the most common fire extinguishing agent for paper products. The efficiency of the agent depends on the application method (sprinkler, mist). 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.

4.5.2 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 [105]. However, to achieve the required low temperature performance (5°F), some halocarbons will need to be pressurized with nitrogen. Since the system may be as important as the agent, it is difficult or impossible to rank agents for this application. This will be primarily a system test.

Note: The International Halon Working Group, Task Group 7 has established a standard test procedure for screening agents for trash container applications. The test procedure is presently under review by the FAA.

4.6 SUMMARY.

Fire extinguishing agent technology is extremely dynamic. A number of new agents and technologies are being 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. These recommendations are intended to guide the FAA in the development of the test protocols. It must be recognized that a test protocol developed for a class (liquid, gaseous, solid) of agents may, with minor modifications, be used to test all agents belonging to the class.

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