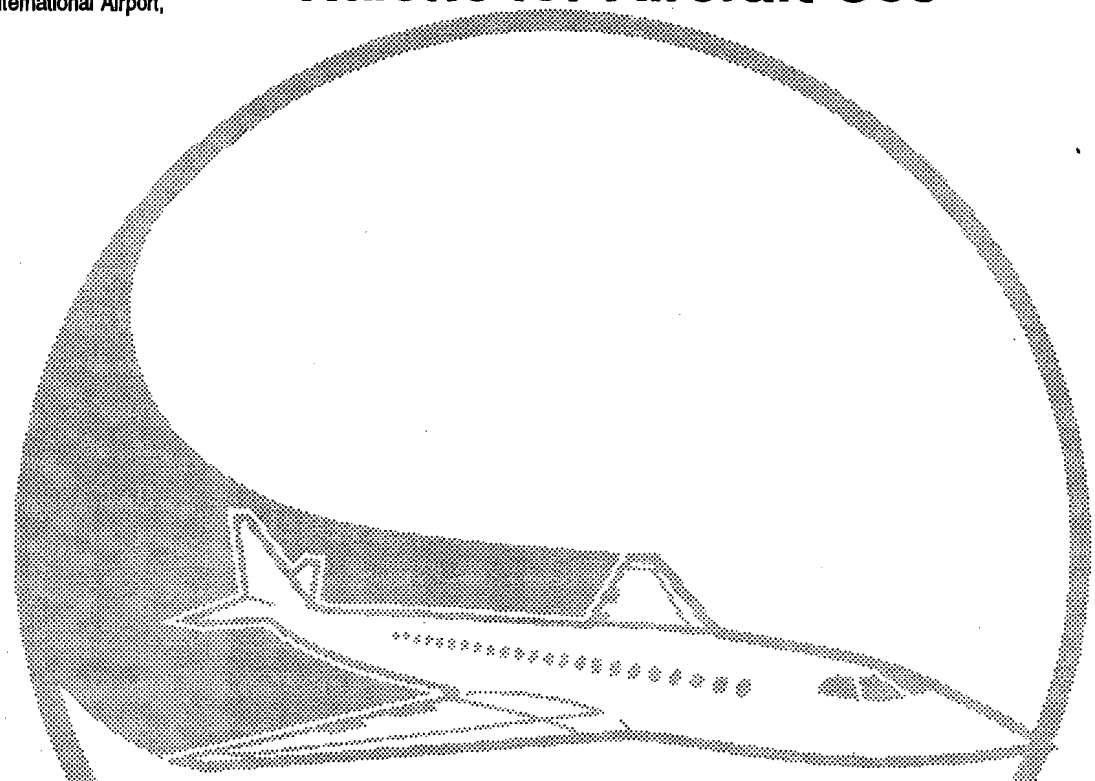
DOT/FAA/CT-95/9

FAA Technical Center
Atlantic City International Airport,
N.J. 08405

Chemical Options to Halons for Aircraft Use



February 1995

Final Report of Task Group 6 of the International Halon Replacement Working Group

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Technical Report Documentation Page

1. Report No. DOT/FAA/CT-95/9	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Chemical Options to Halon for Aircraft Use		5. Report Date February 1995
		6. Performing Organization Code
7. Author(s) Robert Tapscott, et al		8. Performing Organization Report No. DOT/FAA/CT-95/9
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Technical Center Atlantic City International Airport, NJ 08405		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code ACD-240

15. Supplementary Notes

Task Group 6 of the International Halon Replacement Working Group

16. Abstract

This report contains 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.

17. Key Words Fire Extinguishing Aircraft Fire Halon Extinguishing Agent	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 62	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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. Task Group 6 was assigned a review of "Chemical Options to Halons." A major goal for this Task Group is to recommend two to three agents for use in developing FAA test protocols for each major area of on-board aircraft use: (1) engine nacelles, (2) handheld extinguishers, (3) cargo compartments, and (4) lavatory protection.

The first draft of this report was presented at the second meeting of the IHRWG at the Fire Service College in Gloucestershire, England. At that meeting, it was decided to include "classical" alternative agents such as standard foams, dry chemicals, and water sprays. Based on these and other comments received, the report was modified and expanded, and a second draft report was presented at the 3rd meeting of the IHRWG held on 26, 27 July 1994 at the Red Lion Hotel, Seattle, Washington. This report represents the final report from Task Group 6 and was presented at the 4th IHRWG meeting, 15-16 November in Atlantic City, New Jersey, USA. It was distributed in the minutes of the meeting and public input was accepted until 19 December. Throughout that time, members of Task Group 6 were consulted for their comments. The report was then sent to members of Task Group 6 for final review.

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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
CFC	chlorofluorocarbon
CNS	central nervous system
ECG	electrocardiographic
EGL	Emergency Guidance Level
EMAA	Encapsulated Micron Aerosol Agent
FAA	Federal Aviation Administration
FC	(per)fluorocarbon
FIC	fluoroiodocarbon
FMRC	Factory Mutual Research Corporation
GWP	Global Warming Potential
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
IHRWG	International Halon Replacement Working Group
LOAEL	Lowest Observed Adverse Effect Level
NFPA	National Fire Protection Association
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 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.

I. INTRODUCTION

Before discussing chemical options to halons, we need some definitions to ensure that we are all talking about the same thing.

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. "Advanced agents" are non-halocarbon agents that have a high effectiveness. "Alternatives," are everything else. Moreover, replacements are divided into two types — first-generation and second-generation. These are defined in this report.

'Chemical alternatives" are materials such as carbon dioxide, foam, water, and dry chemical whose chemistries differ from those 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 (References 1, 2, 3, 4, 5, 6, 7).

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 plan for the SNAP program and an initial list of decisions on acceptable and unacceptable halon substitutes were promulgated on 18 March 1994 (Reference 8). This was prepared from an EPA background document for halon replacements and alternatives (Reference 9). Additional lists or proposed lists of acceptability decisions were published 26 August 1994 (Reference 10), 26 September (Reference 11), and 13 January 1995 (Reference 12). Substances prohibited, acceptable only under certain conditions or for certain uses, or 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.

II. REPLACEMENTS

At present, halon replacements (e.g., halocarbons) fall into six major categories (Table 1).

Table 1. Classes of Halon Replacements

CFCs	Chlorofluorocarbons
HBFCs	Hydrobromofluorocarbons
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 non-conductive. Finally, the agent must be effective. Note, however, that effectiveness does not necessarily mean as effective as the present halons, though this is desirable.

The terms 'first-generation" and "second-generation" were introduced at the first Halon Alternatives Technical Working Conference held in Albuquerque in 1991. The refrigeration industry has now adopted these terms for refrigerant replacements, though that sector uses three categories: first-generation refrigerant replacements (primarily hydrochlorofluorocarbons, HCFCs), second-generation (hydrofluorocarbons, HFCs), and third-generation (carbon dioxide, air, sulfur dioxide, ammonia, etc.).

Before defining first- and second-generation halon replacements, we need to consider two different types of agents. 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. 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 (Reference 13). 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.

First-generation replacements refer to the halocarbon agents or candidates that were developed during the initial years of halon replacement research and development. Many of those candidates have global environmental, toxicological, or effectiveness drawbacks. They are either (1) CAAs that have high or relatively high ODPs (the hydrobromofluorocarbon HBFC-22B1 being the only example) or (2) PAAs. The chemical effect contribution to extinguishment by selected first-generation PAAs is only 10 to 25 percent of the physical contribution (Reference 14). Second-generation replacement agents are candidate halocarbons that are designed to equal the halons in effectiveness, but have low tropospheric half lives giving them low global environmental impacts (Reference 15). Thus, second-generation halon replacements are CAAs with low ODPs and GWPs. Many families of chemicals are known with these attributes; however, toxicities and other issues are relatively unknown. Many of the second-generation halon replacements are still under investigation and may never be fielded; however, commercialization is proceeding for one second-generation agent, trifluoroiodomethane, CF_3I (Reference 16).

A. TOXICOLOGY OF HALOCARBONS

1. Acute Toxicological Indices

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

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.

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.

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.

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 (Reference 17). 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 firefighting 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 (Reference 18). Healthy male beagle dogs (generally 6 or more animals per exposure concentration), between the age 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.

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

A "marked adverse response" is considered as the appearance of 5 or more multifocal ventricular ectopic beats or ventricular fibrillation (Reference 19). A "mild response" is described as an increase in the number of isolated abnormal beats (less than 5 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 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 three preferred animal model for determining cardiac physiology.

It should be noted that the cardiac sensitization LOAEL and NOAEL concentrations are conservative (Reference 9). 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. Subchronic and Chronic Tests

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.

Chronic Toxicity Testing

Chronic toxicity tests are conducted over the greater part of the animals lifespan (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.

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

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 (Reference 20). 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.

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.

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.

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.

Interpretation of Carcinogenicity Results

For years the predictive value of short-term *in vitro* mutagenicity tests for potential carcinogenicity has been questioned (Reference 21). 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.

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).

Table 4. Exposure Limit Definitions

	Exposure Limit	Establishing Organization	Definition
	Long-Term Exposures		
AEL	Acceptable Exposure Limit	DuPont	
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	8-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.

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 present National Fire Protection Association (NFPA) 2001 Standard on "Clean Agent Fire Extinguishing Systems" requires that the design concentration for total flooding of a normally occupied area not exceed the NOAEL level (Reference 22). For halocarbons, the NOAEL value is based on cardiac sensitization. In addition, halocarbon agent concentrations above 24 percent are not allowed in normally occupied areas. For the only inert gas agent contained in the present standard, a NOAEL level based on other criteria is used. It is likely that future editions of the NFPA 2001 Standard will give NOAEL and LOAEL levels only for halocarbon agents. In this case, exposure limits for inert gases would be specified without reference to a NOAEL or LOAEL value. Such changes are in a new proposed Standard 2001 (Reference 23); however, this still awaits approval. The present 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 pre-discharge alarms are required.

The EPA SNAP program uses the cardiotoxic LOAEL (rather than the NOAEL) value to assess use of an agent in normally occupied areas (Reference 8). Furthermore, the EPA uses OSHA Standard 1910.162 (Reference 24) for Halon 1301 as a basis for EPA's fire suppression use conditions. The EPA has applied the following (Reference 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. Where egress takes longer than 30 seconds but less than one minute, the employer shall not use the agent in a 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, the EPA applies rigorous time limits for evacuation from areas where a total-flooding discharge is used.

B. HALOCARBON ENVIRONMENTAL IMPACTS

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 **3. Global Warming Potential** below), 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 26.

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 is 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.

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 (Reference 27). All GWPs in this report are based on a 100-year time horizon values referenced to CO_2.

4. Regulatory Restrictions

Due to concern about stratospheric ozone depletion, production of CFCs and methyl chloroform will cease by 1 January 1996 under both the Montreal Protocol (for industrialized nations, Table 5) and the U.S. Clean Air Act (for the United States, Table 6). 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 1992

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%
2004						35%	
2010						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 3.1% 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	25
		1995	25
		1996	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	25
		1995	25
		1996	0
Group IV Carbon Tetrachloride	1989	1994	50
		1995	15
		1996	0
Group V Methyl Chloroform	1989	1994	50
		1995	30
		1996	0
Methyl Bromide	1991	1994	100
		1995	100
		1996	100
		1997	100
		1998	100
		1999	100
		2000	100
		2001	0
Class II Substances[b]			
HCFC-141b		2003	0
HCFC-22, -142b		2010	100
		2020	0
HCFC-123, -124, remaining HCFCs		2015	100
		2030	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. 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 are first-generation, and most of these are PAAs — hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), or perfluorocarbons (FCs or PFCs). The only first-generation CAAs that have been announced are hydrobromofluorocarbons (HBFCs), which have high or relatively high ODPs, and which will be phased out by 1 January 1996 under the Copenhagen amendment to the Montreal Protocol. CF_3I, a second-generation agent, is now being commercialized.

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).

Under the SNAP program, the EPA has applied narrowed use limits to the use of perfluorocarbons. PFCs are fully fluorinated compounds, unlike CFCs, HCFCs, or HFCs, and have several attractive features. They are nonflammable, have low toxicity, are exempt from federal VOC regulations, and do not contribute to stratospheric ozone depletion. The environmental characteristics of concern, however, is 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 (Reference 28). Moreover, the 1994 report of the UNEP (United Nations Environment Programme) Halon Technical Options Committee (HTOC) states that "...several governments have already restricted or banned the use of HFCs and PFCs" (Reference 29).

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 have been announced for total-flooding applications (Table 7). Most (but not all) of these agents are contained in the NFPA 2001 Standard (Reference 22).

Table 7. Commercialized Total Flood Agents

Agent	Chemical	Formula	Trade Name
HBFC-22B1	Bromodifluoromethane	CHF_2Br	Great Lakes "FM-100"
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 and are those recommended by manufacturers for extinguishment of Class B fires with *n*-heptane fuel. With the exceptions noted, design concentrations have been determined as 120 percent of the cup burner value for *n*-heptane. For several agents, the design concentration has been verified by listing/approval tests. Design concentrations may differ for other fuels and will be higher for inertion of an area. The information for this table was compiled from (1) information from manufacturers, (2) the SNAP listing of 26 August (Reference 10) prepared, in part, from a document on design concentrations prepared by the Halon Alternatives Research Corporation (HARC, Reference 30), and (3) NFPA Standards.

Table 8. Design Concentrations of Commercialized Total Flood Agents

Agent	Design Conc., %	Maximum Fill Density, lb/ft^3	Storage Pressure at 70°F, psi
Halon 1301	5[a]	70[b]	360[b]
HBFC-22B1	4.9[c]	102.0[d]	360[d]
HCFC-124	8.5[e]	71.0[d]	195[d]
HCFC Blend A[c]	8.6[e,f]	56.2[d]	360[d]
HFC-23	16[e]	54.0[d]	608.9[d]
HFC-125	10.9[e]	58.0[d]	166.4[d]
HFC-227ea	7[e]	72.0[d]	360[d]
HFC-236fa	6.4[c]		
FC-218	8.8[c]	80[c]	360[c]
FC-3-1-10	6[e]	80.0[d]	360[d]
FIC-13I1	3.6[g]	107[c]	360[c]

[a]The design concentration for Halon 1301 is that set by NFPA Standard 12A (Reference 31) and is higher than the value of approximately 3.6 percent determined by 120% of the cup burner value.

[b]Reference 31.

[c]Information provided by manufacturer.

[d]Reference 22.

[e]Reference 10.

[f]This value is based on listing/approval tests rather than cup burner testing.

[g]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. A design concentration of 5% is suggested for retrofit to maintain the 70% safety margin of Halon 1301 in existing equipment.

Table 9 gives Weight and Storage Volume Equivalents relative to Halon 1301. The Weight Equivalent is weight of agent required divided by 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. Two 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.

The Weight and Storage Volume Equivalents have been calculated in two ways. The first set were calculated from the total flooding quantities at 70°F given in NFPA Standards 2001 and 12A (References 22 and 31) 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, Reference 31), 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.

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.

Table 9. Weight and Storage Volume Equivalents for Total-Flood Agents

Agent	Calculated from Weight Requirements and Fill Densities		Molecular Weight	Liq Density, g/mL	Calculated from Molecular Weights and Liquid Densities	
	Wt. Equiv.[a]	Storage Vol. Equiv.[a]			Wt. Equiv.	Storage Vol. Equiv.
Halon 1301	1.00	1.00	148.93	1.54[b]	1.0	1.0
HBFC-22B1	0.86	0.59	130.92	1.80[c]	0.86	0.74
HCFC-124	1.64 (1.6)	1.62 (1.6)	136.48	1.364[b]	1.56	1.76
HCFC Blend A	1.10 (1.1)	1.37 (1.4)	92.90	1.20	1.07	1.38
HFC-23	1.68 (1.7)	2.10 (2.2)	70.01	[d]	1.50	[d]
HFC-125	1.88 (1.9)	2.44 (2.3)	120.02	1.25[c]	1.76	2.16
HFC-227ea	1.66 (1.7)	1.61 (1.6)	170.03	1.39[b]	1.60	1.77
HFC-236fa	[e]	[e]	152.04	1.37[b]	1.31	1.47
FC-218	[e]	[e]	188.02	1.35[b]	2.22	2.53
FC-3-1-10	1.91 (1.9)	1.67 (1.7)	238.03	1.52[b]	1.92	1.94
FIC-13I1	[e]	[e]	195.91	2.096[f]	0.95	0.70

[a]Calculated from data in NFPA Standards 2001 and 12A (References 22 and 31) and Table 8. Values in parentheses were taken from SNAP Listing (Reference 10).

[b]At 25°C

[c]At 20°C

[d]The liquid density of HFC-23 is not well defined since the critical temperature is above room temperature. For this reason, the Storage Volume Equivalent has not been calculated from the physical properties.

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

[f]20-25°C

The environmental and toxicity properties of commercialized total-flood agents are shown in Table 10. The data for this table were collected from the SNAP listings, NFPA Standard 2001, and manufacturers.

Table 10. Environmental and Toxicity Properties of Commercialized Total-Flood Agents

Agent	ODP[a]	GWP[b]	Atmospheric Lifetime, yrs	NOAEL %	LOAEL %	SNAP
Halon 1301	12-16	5800	100	5[c]	7.5[c]	
HBFC-22B1	0.74	N/A	9	0.3	1.0	Acceptable[d]
HCFC-124	0.022	440	7	1.0	2.5	Acceptable[d]
HCFC Blend A				10.0	>10.0	Acceptable
HCFC-123	0.02	90	2	1.0	2.0	
HCFC-22	0.05	1600	16	2.5	5.0	
HCFC-124	0.022	440	7	1.0	2.5	
HFC-23	0.0	9000	280	30[e]	>50	Acceptable
HFC-125	0.0	3400	41	7.5	10.0	Acceptable[d]
HFC-227ea	0.0	2050	31	9.0	10.5	Acceptable
HFC-236fa	0.0			10.0[f]	15.0[f]	
FC-218	0.0	6100	3200	30	40	Acceptable[g,h]
FC-3-1-10	0.0	5500	2600	40	>40	Acceptable[g]
FIC-13I1	0.0001	<5	<1 day	0.2	0.4	Acceptable[i]

[a]Relative to CFC-11.

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

[c]References 22, 32. Note that EPA accepts NOAEL and LOAEL values of 7.5% and 10% based on other sources (Reference 33)

[d]Cannot be used as total-flood agent in occupied areas under NFPA Standard 2001 criteria (Reference 22).

[e]Without added oxygen. At least 50 percent with added oxygen.

[f]Reference 34.

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

[h]Listed under SNAP in a proposed rulemaking, subject to public comment.

[i]Proposed acceptable for protection of non-occupied areas subject to public comment.

Until recently, the number of agents announced for streaming applications was small. The number has, however, increased markedly (Table 11). Some environmental and toxicological data for these streaming agents are given in Table 12. The information sources for this table are, for the most part, the same as those for Table 10. An inspection of Table 12 indicates that none of the

streaming agent candidates appear likely to exceed the cardiac NOAEL under normal usage in a streaming application.

Table 11. Commercialized Streaming Agents

Agent	Chemical	Formula	Trade Name
HBFC-22B1	Bromodifluoromethane	CHF_2Br	Great Lakes "FM-100"
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"

Table 12. Environmental and Toxicity Properties of Commercialized Streaming Agents

Agent	ODP[a]	GWP[b]	Atmospheric Lifetime, yrs	NOAEL, %	LOAEL, %	SNAP Acceptability as Halon 1211 Replacement
HBFC-22B1	0.74	N/A	9	0.3	1.0	Acceptable[c]
HCFC-123	0.02	90	2	1.0	2.0	Acceptable[d]
HCFC-124	0.02	440	7	1.0	2.5	Acceptable[d]
HCFC Blend B						Acceptable[d]
HCFC-123	0.02	90	2	1.0	2.0	
HCFC Blend C						Acceptable[d]
HCFC-123	0.02	90	2	1.0	2.0	
HCFC-124	0.02	440	7	1.0	2.5	
HFC-134a	0.0	1200	16	4.0	8.0	
HCFC Blend D						Acceptable[d]
HCFC-123	0.02	90	2	1.0	2.0	
HFC-227ea	0.0	2050	31	9.0	10.5	
HFC-236fa	0.0			10.0[e]	15.0[e]	
FC-5-1-14	0.0	5200	3100	40		Acceptable[f]
FIC-13I1	0.0001	<5	<1 day	0.2	0.4	Acceptable[g]

[a]Relative to CFC-11.

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

[c]Nonresidential use only; phaseout by 1 January 1996.

[d]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 34.

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

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

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 two exceptions are HBFC-22B1, which will be phased out by 1 January 1996, and FIC-13I1, which has total-flood use limitations owing to toxicity.

One additional potential problem that occurs with many of the agents is the relatively large amount of hydrogen fluoride that is generated during extinguishment. Hydrogen fluoride concentrations are typically five to ten times greater for HFCs and PFCs than for the halons (Reference 14). In general, the decomposition products increase with fire size and agent discharge time (Reference 35).

III. 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 "Second-Generation" Alternatives (Table 13). 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 13. Alternatives

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

A. FOAMS

Foams are an alternative to halon systems for a number of hazards, particularly those involving flammable liquids (Reference 36). 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:

1. 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.

2. 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 a portable foam makers, which may include hose reels.

3. Mobile Systems are vehicle-mounted or vehicle-towed complete foam units.

4. 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.

1. Low-Expansion Foam

Low-expansion foams have the following limitations:

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

2. 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 fire. 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.

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

4. 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.

5. 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.

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

1. 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.

2. 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.

3. 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.

B. 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:

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

2. A clean-up requirement may exist after discharge: runoff water may have to be removed and contents of protected areas may require drying.

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

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

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

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

7. Water causes problems with storage, discharge, and clean-up at very low temperatures.

8. 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 (Reference 37). 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.

C. 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 that 10 microns up to 75 microns with average particle sizes of 20 to 25 microns.

Dry chemicals generally provide very rapid knockdown of flames and are more effective than halons in most applications (Reference 38). The main disadvantages of dry chemical fire extinguishants include:

1. Poor penetration behind obstacles,

2. No inhibiting atmosphere after discharge,

3. No cooling effect,

4. Often, severe secondary damage to electronic, electromechanical, and mechanical equipment

5. Cleanup problems, and

6. 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, for which halons would not normally be used. However, these systems should be considered for fire suppression in some marine engine spaces and land-based transportation engine compartments.

Dry chemical extinguishers are 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.

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."

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. 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.

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

D. 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, non-conducting 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.

E. 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.

F. 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 provide this capability. No criteria have yet been established on the dividing line between mists and sprays; however, droplet sizes of 100 microns or less are often used as a criterion.

Work on misting systems in the U.S. has been scattered. A thorough review has been written by the Navy Technology Center for Safety and Survivability and Hughes Associates (Reference 39). 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 (Reference 40), and it has been considered for use in spacecraft (Reference 41). The Naval Research Laboratory is examining water misting nozzles to simulate Halon 1211 for firefighter training (Reference 42). A recently completed program evaluated water mists for residential applications (Reference 43). At the request of 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 (high-pressure) and dual-fluid systems. Single-fluid systems utilize water stored at high pressure (40-200 bar) and spray nozzles that deliver drop sizes in the 10 to 100 μm diameter range. Dual systems use air, nitrous oxide, or other 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 (single-fluid systems require about 1000 to 3000 psi 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 (high-pressure) 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 (Reference 39). 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 (6) lack of design standards (Reference 44).

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. Experience, however, indicates that such fires are not likely to occur under realistic conditions. This conclusion was reached by Task Group 4 of the International Halon Replacement Working Group. Water mist may hold several advantages and should be considered for cargo bay application.

Table 14 gives a list of manufacturers for water misting systems.

Table 14. Commercial and Near-Commercial Misting Systems

Dual-Fluid
ADA Technologies, USA
Kidde International, UK, USA
Ginge Kerr, U.K., Denmark, Norway
Secuirplex, Canada
GEC-Marconi Avionics, UK
High-Pressure
Baumac International, USA
Semco, USA/Denmark
Marioff Hi-fog, Finland
Microguard-Unifog, Germany
Spraying Systems, USA
Bete Fog, USA

G. 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 2nd Conference on the Fire Protecting Halons and the Environment, 1-3 October 1990, representatives of the Soviet Union provided information on a solid agent that they claimed provides relatively long-term (20 minutes or more) inertion of an enclosed volume and excellent fire extinguishment (Reference 45). 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. An agent designated as "Powdered Aerosol A" has been approved under SNAP for total flooding of unoccupied areas (Reference 8). An approval is pending for occupied areas (Reference 10).

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 1993 NMERI Halon Alternatives Technical Working Conference, 11-13 May 1993 in Albuquerque, where three papers on particulate aerosols were presented (References 46, 47, 48). A recent paper has reviewed much of this area (Reference 49).

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 one series of materials.

1. S.F.E. Extinguishing Agents

The S.F.E. family of extinguishing agents is produced by Spectrex. Their system was recently tested (Reference 50). This new class of fire extinguishing agents known as S.F.E. or EMAA (Encapsulated Micron Aerosol Agent) offer an air suspended dry chemical aerosol with micron size particles, that provide total flood capabilities. Some 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 S.F.E. compound in its various forms, upon activation ignites and creates an aerosol that contains about 40 percent solid particles (size of particle less than 1μ) 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 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	$1.6 - 1.8 \times 10^3$ kg/m^3
Combustion Temp (°K)	1500 - 2400 K
Combustion Velocity (mm/sec)	0.3 - 1.5 mm/sec
Shelf Life	15 years
Texture	Solid fine powdered mixture or gelled paste.

H. INERT GASES

Combustion cannot occur when the oxygen content of air at normal pressures is reduced below approximately 15 percent. Thus, addition of a sufficient amount of an inert gas such as carbon dioxide, nitrogen, argon, etc., can extinguish a fire by diluting the air such that the oxygen concentration is below that required to sustain a fire.

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 (Reference 51). 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" (Reference 52).

1. 16 percent — impaired judgment and breathing
2. 14 percent — faulty judgment and rapid fatigue
3. 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 (Reference 53). 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 (Reference 54). This method can only be applied to completely enclosed areas with high structural strengths and is, therefore, limited to very few applications.

It is becoming increasingly apparent that inert gases may not pose the risks to health that they were once thought to, and there is considerable indication that inert gases could prove to be valuable for total flooding applications. A number of pure and blended inert gases are now

undergoing consideration as alternatives to halons (Table 15). 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). In place of NOAEL and LOAEL values, which are inappropriate for inert gases, the EPA, under SNAP, is proposing to define "no effect levels" levels and "low effect levels" of 12 percent oxygen and 10 percent oxygen, corresponding to agent concentrations of 52 percent and 43 percent, for inert gases (Reference 55). The EPA would then propose design of total-flood systems to give an oxygen level of no less than 10 percent for egress within one minute and no less than 12 percent if egress requires more than one minute. The proposed new NFPA 2001 standard requires that inert gas design concentrations will be no higher than 43 percent, corresponding to an oxygen concentration of 12 percent for normally occupied areas (Reference 23). Note that this is a proposal; this standard has not been approved.

Table 15. Inert Gases

Designation	Composition	Manufacturer	Use Concentration
IG-541(Inergen)	Nitrogen 52% ± 4% Argon 40% ± 4% CO_2 8% ± 1	Ansul	35-50%
IG-55(Argonite)	Nitrogen 50% ± 5 Argon 50% ± 5	Securiplex/Ginge Kerr	35-50%
Argon	100% Argon	MiniMax	35-50%
Nitrogen	100% Nitrogen	Cerberus	

I. GAS GENERATORS

Gas generators are still in the developmental stage, and their potential application in aviation is still uncertain. Such technologies use a variety of means to rapidly produce and expel gases, sometimes mixed with various agents, to extinguish fires. Much of the developmental work and assessment of commercial devices is being performed at Wright-Patterson AFB. A recent presentation gave a thorough overview of gas generator technology (Reference 56).

J. 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.

1. Gelled Halocarbon/Dry Chemical Suspension

The SNAP list gives variety of formulations under the category "gelled halocarbon/dry chemical suspension" (designated as "Powdered Aerosol B" in the first SNAP listing, Reference 8) developed for particular markets. 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 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. Among the halocarbons included in the SNAP submission are HFC-227ea, HFC-125, HFC-134a, and HFC-125 blended with HFC-134a.

One series of agents that has received increased attention is being developed by Powsus. The materials have been tested in a number of applications, including tracked vehicles (References 57 and 58).

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 appear to enhance the heat absorbing capacity of 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 re-ignition. 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 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.

IV. 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 on-board 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.

A. 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 (Reference 59).

1. 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.

2. 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.

3. It should comply with the provisions of the Montreal Protocol. It must have a near-zero ozone depleting potential. HBFC-22B1 does not fit this criterion, and production will be phased out in the near future. For these reasons, HBFC-22B1 is not considered as a candidate for testing . 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.

B. 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.

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 first-generation 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 (Reference 8). 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 NFPA Standard 2001 (Reference 22). 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.

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 (Reference 11). The environmental characteristics are good, and the volume requirements and effectiveness are essentially identical to those of Halon 1301. A recent 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." (Reference 60)

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 (Reference 61). The cardiotoxicity of CF_3I is higher 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.

C. HANDHELD 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 (Reference 62). The total number of extinguishers required are shown in Table 16.

Table 16. Number of Handheld 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

It is required that at least one of the extinguisher 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 methods to demonstrate equivalency are undefined.

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.

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

2. 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.

3. The agent must have the ability to extinguish two types of fires (Reference 63: (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. (2) Class A and B seat-cushion fires ignited with burning gasoline.

4. 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 (Reference 64). It is expected that this 5-B:C UL fire extinguishing ability along with a demonstrated ability to extinguish an as yet undetermined "hidden fire" and seat cushion fires will be required minimums for the agent to be acceptable in this application.

We recommend 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 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.

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 U.S. 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 (Reference 8) for non-residential 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 17, nevertheless, gives ratings for two criteria. 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 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 acceptability 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 flightline 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 17.

Table 17. Rating Matrix for Candidate Halocarbons for Handhelds

Agent	Cup Burner Extinguishment Concentration, %	Known or Potential Environmental Regulatory Restrictions[a]	Toxicity Based on Cardiac Sensitization NOAEL
HCFC-123	7.5[b]	3	3
HCFC-124	7.0[c]	3	3
HCFC Blend B HCFC-123	6-7[d]	3	3
HCFC Blend C HCFC-123 HCFC-124 HFC-134a	[e] Not available at this time.	3	3
HCFC Blend D HCFC-123	[e] Not available at this time.	3	3
HFC-227ea	5.8[c]	2	2
HFC-236fa	5.29[f]	2	2
FC-5-1-14	4.4[c]	3	1
FIC-1311	3.05[g]	1	3

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

[b]Reference 65.

[c]Reference 8.

[d]Estimated (Reference 66). 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 (Reference 67).

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

[f]Reference 68

[g]Reference 69

2. Carbon Dioxide

There has been a large amount of experience with handheld 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.

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 in 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 handheld fire extinguishers by FMRC states that "Around Object Capability" for Halon 1301 is good, for dry chemical is poor, and for water is poor (Reference 70). 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.

D. CARGO COMPARTMENT

According to the report of Task Group 4 (Reference 71), 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

1. Develops into an uncontrollable or uncontainable condition, or

2. Damages liners, wiring, equipment, structure, essential equipment, or critical equipment.

Systems that provide a warning withing one minute from the start of smoke generation are considered to be in compliance with Federal Aviation Regulation, FAR 25.858 (see Reference 72). The present practice is to control ventilation and drafts within the compartment prior to the activation of the suppression system. However, there is small infiltration into the compartment through the compartment walls (typically fiberglass liner) and leakage out of the compartment through door seals. The general practice is to divert to the nearest field on detection of a fire. On

long range (across 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.

1. The agent must be suitable for Class A fire.

2. 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. We note that 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.

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

4. 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.

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 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.

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 occurances.

2. Halocarbons and Halocarbon Blends

Table 18 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 NFPA Standard 2001 (Reference 22) 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 (Reference 73). 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.

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 (Reference 74); 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.

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.

Table 18. 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 Environmental Regulatory Restrictions[a]	Toxicity Based on 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[b]	2[b]	2	2	2
FC-218	3[b]	4[b]	4	3	1
FC-3-1-10	2	3	3	3	1
FIC-13I1	1[b]	1[b]	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 these agents, which do 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 (Reference 22). See Table 8 and Table 9.

E. 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.

1. The agent must be suitable for Class A fire in general and paper fire in particular.

2. The agent must have an acceptable toxicity, in small concentrations.

We recommend establishing a test procedure for the following.

1. Water-Based Agents

Water, water/surfactant (e.g., Surfactant Blend A), and Dry Chemical/Water Mixtures meet all 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.

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 (Reference 75). 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.

F. SUMMARY

The fire extinguishing agent technology is extremely dynamic. We are aware that 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. They are our present recommendations. They 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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☆U.S. GOVERNMENT PRINTING OFFICE: 1995 - 604-081/20012