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ADVANCED AGENT PROGRAM: RISK ASSESSMENT

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13. ABSTRACT *(Maximum 200 words)*

Halon 1211 has been widely used throughout the United States Air Force (USAF) as a streaming agent to extinguish fires. Because it is a depleter of stratospheric ozone, however, its production has been halted. The USAF has been performing research to identify potential replacements. Most "first-generation" candidates, those chemicals that were readily available and had significant toxicological information, are not as effective as Halon 1211, and many have environmental and toxicological drawbacks. Consequently, the USAF has initiated a search for advanced streaming agents. Thechnology review have identified promising chemical families. This report provides a description of the National Academy of Science (NAS) risk assessment paradigm and its use in assessing specific chemicals and families of chemicals identified as having potential to replace Halon 1211 for streaming applications.

14. SUBJECT TERMS
Halon 1211, halon replacement, streaming agent, risk analysis, risk assessment

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PREFACE

This report was prepared by the Center for Global Environmental Technologies, New Mexico Engineering Research Institute (NMERI), The University of New Mexico, Albuquerque, New Mexico 87131, for the Infrastructure Technology Section of Wright Laboratory (WL/FIVC), Tyndall Air Force Base, Florida 32403-5319 under Contract F08635-93-C-0073, NMERI Number 8-31882. This report documents the risk assessment performed on streaming agent candidates.

The project Start Date was 5 December 1994, and the End Date was 30 November 1995. The WL/FIVCF Project Officer was Juan Vitali, and the NMERI Principal Investigators were Stephanie R. Skaggs and Robert E. Tapscott.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of the overall advanced agent program is to develop new, highly effective chemicals to replace Halon 1211 in military streaming applications. The portion of the work discussed in this document provides a risk assessment methodology for evaluating streaming agent candidates.

B. BACKGROUND

The production of Halon 1211, widely used throughout the United States Air Force (USAF) as a streaming fire extinguishing, has been halted due to its potential to deplete stratospheric ozone. The USAF has been conducting research to identify potential replacements. Most "first-generation" agents, those chemicals that are readily available and have significant toxicological information, are not as effective as Halon 1211. Moreover, many have environmental and/or toxicological drawbacks. Consequently, the USAF initiated a search for advanced streaming agents. Technology reviews have identified promising chemical agents and chemical families; however, toxicological indices indicate that some of these may be more toxic than Halon 1211. The question "how toxic is too toxic?", however, remains to be answered. This assessment of likely replacements relative to their likely use scenario provides information to aid in assessing the applicability and risk of candidate agents.

A companion report entitled *Advanced Streaming Agents: Toxicological Assessment* describes the methods used in the toxicological screening of candidate chemical families being considered as Halon 1211 replacements.* The companion report, which also summarizes toxicological indices and their definitions, serves as a useful compendium of toxicological information.

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*Skaggs, S. R., and Tapscott, R. E., *Advanced Agent Program: Toxicological Screening Methods*, WL-TR-95-XX, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, December 1995.

C. SCOPE

Work to develop advanced halon replacements was initiated in September 1993 under the "Advanced Streaming Agent Testing Program." The objective of this program, which is now being continued as the "Advanced Agent Program," is to develop new advanced chemical replacements for Halon 1211 in streaming applications. This report surveys the limited available literature risk assessment studies and other reports, papers, etc., that are applicable to halon streaming replacement agents. It also reviews the National Academy of Science (NAS) risk assessment paradigm and uses it to assess chemicals and chemical families identified as candidates for replacing Halon 1211 in USAF streaming applications.

D. RESULTS

The toxicological effects of exposure to specific candidate agents or chemical families have been discussed. A methodology has been developed to assess the risk associated with using halons and their replacements in a variety of applications applicable to USAF mission requirements. The method indicates that there is a beneficial advantage (reduction in risk) for continuing the advanced streaming agent development program.

E. CONCLUSIONS

In 1983, the National Academy of Science (NAS) released its risk assessment/risk management paradigm to define a scheme for assessing the risk of hazards. This paradigm is the basis for this study. According to the NAS paradigm, the risk assessment process is broken down into four steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization.

The hazard identification step reviewed relevant information on the hazards posed by potential halon replacement streaming agents. Information on health effects caused by exposure to Halon 1211 and several potential replacements has been provided. Toxicological effects of specific candidates were discussed when information was available; otherwise, general information on the chemical family as a whole has been presented. In most cases there is very

little of the required toxicological data (dose-response) and exposure concentration measurements available on most of the specific advanced streaming agent being investigated under this present USAF project. These limited data have also limited the completeness of this risk assessment.

The most likely exposure pathway has been determined to be inhalation. Contact exposure to the skin and eyes could conceivably occur depending on the chemical properties of the replacements, i.e., if the agents are liquids, contact exposure is more likely than if the agents are gases. Oral exposure is highly unlikely, unless the replacement agent is a liquid at room temperature and ground water contamination has occurred. Accidental ingestion could conceivably occur, but is not likely. Generally, two types of exposures were found to occur with streaming agents (e.g., uncontrollable and controllable): firefighting (high concentration, short duration), and service or maintenance (low to moderate concentration, minutes to 8-hr duration).

Several tests have been conducted to assess the exposure concentrations encountered while using halons and their replacements in streaming (portable) applications. Exposure concentrations depend upon the halon replacement chemical and physical properties. Exposures to the neat agent and decomposition products are of concern. Most typical exposure concentrations for the neat agents range from a few hundred ppm to near 10,000 ppm. Seldom do the agent concentrations exceed 3000 to 6000 ppm (0.3 to 0.6 vol.%). Highest concentrations have been measured in downwind plumes and inside enclosed spaces when large extinguisher were used. Because these agents are heavier than air, concentrations are also highest near the ground surface.

The final step in risk assessment is risk characterization, which involves predicting the frequency and/or severity of effects due to chemical exposure in the likely exposed population. In this step, information from the dose-response evaluation (what effects are caused by exposure to a certain dose?) is compared to information from the exposure assessment (what dose is the person receiving?) to produce an estimate of the likelihood of observing adverse effects. Most risk assessments for regulatory purposes, especially for cancer, produce a single number estimating the increased incidence of disease. However, for the purposes of this effort, a quantitative risk assessment is impossible for all candidates because (1) not all candidates have

been identified, and (2) information on most of the candidates is insufficient to allow a quantitative assessment. Therefore, where possible, a quantitative assessment was performed; however, in general a qualitative assessment was emphasized to determine whether a chemical or class of chemicals would pose a lesser or greater health threat than Halon 1211.

Several projects have been completed in which a variety of exposure concentrations have either been measured or calculated using computer models. Typical maximum recommended exposure concentrations for 15 to 20 min of the replacement streaming agents range from a few ppm to 3000 ppm depending upon the specific streaming agents and use scenario (application). These concentrations provide a Hazard Index (HI) less than 1.0 compared to Halon 1211 with a HI equal to 0.3. The lower the HI the less the expected health risk. Based on the analysis presented herein, a HI equal to or greater than 1.0 would indicate an unacceptable agent for the considered application.

F. RECOMMENDATIONS

The developed risk assessment methodology shows that careful consideration can and should be given when applying (specifying) the current and future halon replacements. The Air Force fire suppression design engineers need a risk-based tool for assessing halon and replacement usage. It is not appropriate to recommend these agents without proper consideration of all the factors: GWP, ODP, Atmospheric Lifetime, Toxicity, etc. Therefore, the following projects are submitted for continued development of an user friendly risk-based computer model for assessing new and existing USAF halon-like installations.

- Collect exposure data during all large-(field-)scale testing of halon replacements, compile additional literature data into exposure assessment dataset;
- Develop Hazard Quotients (HQ) for all dose-response data on desirable compounds;
- Investigate the Reference Concentration (RfC) and Reference Dose (RfD) derivation algorithms, refine as required;

- Develop HQs for the various fire suppression applications, GWP, lifetime, ODP, and other critical risk elements associated with each available compounds;
- Use the HQs and determine a HI for each chemical that is being considered as a replacement, initially look at HFC-227ea, -236fa, -236ea, and 1-bromopropane blends, include information on advanced agents as it becomes available;
- Use the developed model and assess an existing USAF installation; and
- Refine risk-based model as required while assessing initial installation.

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LIST OF ABBREVIATIONS

AAWG	Advanced Agent Working Group
AD_{50}	concentration at which 50 percent of test animals experience anesthesia
ALC	Approximate Lethal Concentration
APT	Advanced Protection Technologies
CAS	Chemical Abstracts Service (American Chemical Society)
CFC	Chlorofluorocarbon
CNS	central nervous system
EPA	Environmental Protection Agency
FC	(per)fluorocarbon
GWP	Global Warming Potential
HBFC	hydrobromofluorocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HI	Hazard Index
HR	SAX Hazard Rating
HQ	Hazard Quotient
HTOC	Halon Technical Options Committee
LOAEL	Lowest Observed Adverse Effect Level
NAS	National Academy of Sciences
NFPA	National Fire Protection Association
NMERI	New Mexico Engineering Research Institute
NOAEL	No Observed Adverse Effect Level
ODP	Ozone Depletion Potential
OEL	Occupational Exposure Limit
PEL	Permissible Exposure Limit
PFC	perfluorocarbon
RfC	Reference Concentration
RfD	Reference Dose
RTECS	Registry of Toxic Effects of Chemical Substances
SNAP	Significant New Alternatives Policy

LIST OF ABBREVIATIONS (concluded)

UL	Underwriters Laboratory
UNEP	United Nations Environment Programme
USAF	United States Air Force
VOC	volatile organic compound

LIST OF UNITS AND SYMBOLS

C	concentration at a specific toxicity endpoint
g	gram
hr	hour
k_1, k_2	constants specific to the agent being used
LC_{Lo}	lowest concentration causing death
LC_{50}	concentration required to cause death in 50 percent of an animal test population
LD_{Lo}	lowest dose causing death
LD_{50}	dose required to cause death in 50 percent of an animal test population
m	meter
mg	milligram
min	minute
ppm	parts per million
S	specific volume of agent at temperature
V	protected volume
W	the weight of agent required for a specific concentration

SECTION I
INTRODUCTION

The initial work on halon substitutes under United States Air Force (USAF) sponsorship identified "first-generation" agents as being the most appropriate near-term (References 1-6). First-generation agents, readily available chemicals having known toxicological information, were selected for targeting for two reasons: (1) available chemicals could be economically tested in large-scale scenarios, and (2) toxicological testing is expensive and time consuming. The major focus was on chemicals developed primarily as chlorofluorocarbon (CFC) replacements. These replacements were available in bulk at a reasonable cost, and manufacturers were supporting toxicological testing since the chemicals were being considered for a variety of applications (e.g., refrigerants, solvents, foam blowing agents). This strategy proved successful. A number of chemicals were identified and evaluated as halon replacement candidates and several were commercialized by industry (References 7-11).

The first-generation agents, which now comprise the majority of newly commercialized halon replacements (Reference 12), were all halocarbons—hydrochlorofluorocarbons (HCFC), perfluorocarbons (FC or PFC), and hydrofluorocarbons (HFC). Hydrobromofluorocarbons (HBFC) were also evaluated very early in the program, but were dropped when it became apparent that they would be regulated under the Montreal Protocol, the international treaty regulating production of ozone depleting substances, due to their still significant Ozone Depletion Potential (ODP). Although the program successfully identified candidates that were available and did not require significant additional toxicological testing, the first-generation halocarbons are not as effective as Halon 1211. Approximately two to four times more agent is required to achieve the same degree of effectiveness (Reference 13). Moreover, some have toxicological and environmental drawbacks. In particular, environmental concerns have led to the several restrictions:

1. Due to their non-zero ODP, HCFCs will eventually be phased out of production under both the Montreal Protocol (for industrialized nations) (Table 1)* and the US Clean Air Act (for the United States) (Table 2; Reference 14), and some restrictions are already in place in parts of Europe (and to a limited extent in the USA). The European Community (EC) Regulation 3093/94, which entered into force on 1 June 1995, does not allow the use of HCFCs for fire protection.

2. Under the Significant New Alternatives Policy (SNAP) program, the US Environmental Protection Agency (EPA) has applied narrowed use limits to the use of perfluorocarbons. PFCs are fully fluorinated compounds, unlike HCFCs or HFCs, and have several attractive features. They are nonflammable, have low toxicity, are exempt from federal volatile organic compound (VOC) regulations, and do not contribute to stratospheric ozone

TABLE 1. CONSUMPTION CUTS UNDER MONTREAL PROTOCOL AS AMENDED IN 1995 FOR DEVELOPED COUNTRIES.

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

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

*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 2. CONTROLS UNDER CLEAN AIR ACT AMENDMENTS OF 1990.

Ozone depleting chemicals[a]	Baseline year	Allowed production	
		1 January	% of base year[b]
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,	1989	1994	25
212, 213, 214, 215, 216, 217		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
Group VI: Methyl bromide	1991	1994	100
		1995	100
		1996	100
		1997	100
		1998	100
		1999	100
		2000	100
		2001	0
Group VII: HBFCs	1991	1994	100
		1995	100
		1996	0
Class II Substances[c]			
HCFC-141b	not established	2003	0
HCFC-22, -142b	not established	2010	100
		2020	0
HCFC-123, -124, remaining HCFCs	not established	2015	100
		2030	0

[a]See Appendix A of Reference 15 for a discussion of halocarbon nomenclature.

[b]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.

depletion. The environmental characteristics of concern, however, is their high Global Warming Potentials (GWP), which are as high as 12,500 times that of carbon dioxide, and their long atmospheric lifetimes of up to 50,000 years (Table 3; References 16-19). Although the actual contributions to global warming depend upon the quantities emitted, the long lifetimes make any atmospheric environmental impacts 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.

TABLE 3. GWPS AND ATMOSPHERIC LIFETIMES FOR PERFLUOROCARBONS.

Halocarbon no.	Formula	GWP[a]	Lifetime, years
FC-14	CF_4	6,300	50,000
FC-116	CF_3CF_3	12,500	10,000
FC-218	$CF_3CF_2CF_3$	6,100	3,200
FC-3-1-10	$CF_3CF_2CF_2CF_3$	5,500	2,600
FC-4-1-12	$CF_3CF_2CF_2CF_2CF_3$	5,600	4,100
FC-5-1-14	$CF_3CF_2CF_2CF_2CF_2CF_3$	6,800	3,200
FC-C318	$-CF_2CF_2CF_2CF_2-$	9,100	3,200
FC-C6-1-14	$-CF_2CF_2CF_2CF_2CF_2CF_2CF_2-$	5,200	3,100

[a]GWP relative to carbon dioxide based on 100-year time horizon. See Reference 15 for an explanation of GWP and time horizons.

3. HFCs have been prominent as replacements for ozone depleting substances (ODS). Nevertheless, they are receiving increasing attention from environmental organizations due to their moderately long atmospheric lifetimes and high GWPs (Table 4). A 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 20). Moreover, the 1994 report of the United Nations Environment Programme (UNEP) Halon Technical Options Committee (HTOC) states that "...several governments have already restricted or banned the use of HFCs and PFCs" (Reference 21).

TABLE 4. GWPS AND ATMOSPHERIC LIFETIMES FOR HYDROFLUOROCARBONS.

Halocarbon no.	Formula	GWP[a]	Lifetime, years
HFC-125	CHF_2CF_3	3,200	36
HFC-134	CHF_2CHF_2	1,200	11.9
HFC-134a	CH_2FCF_3	1,300	14
HFC-143	CH_2FCHF_2	290	3.5
HFC-143a	CH_3CF_3	4,400	55
HFC-152a	CH_3CHF_2	140	1.5
HFC-227ea	CF_3CHFCF_3	3,300	41
HFC-23	CHF_3	12,100	250
HFC-236fa	$CF_3CH_2CF_3$	8,000	250
HFC-245ca	$CHF_2CF_2CH_2F$	610	7
HFC-32	CH_2F_2	580	6
HFC-356mcf	$CF_3CF_2CH_2CH_2F$	125	1.3
HFC-4-3-10mee	$CF_3CHFCHFCF_2CF_3$	1,600	20.8

[a]GWP relative to carbon dioxide based on 100-year time horizon.

Because of the concerns about the first-generation halon replacements (low efficiency and adverse environmental impacts), the USAF has initiated a search for advanced streaming agents. The criteria for advanced agents are firefighting efficiencies similar to that of Halon 1211 and environmental impacts lower than those of the first-generation agents.

The call for highly effective fire extinguishing agents requires that the search focus outside the chemical families being investigated as CFC replacements. The properties needed for effective firefighting are distinct from those required for effective refrigerants, solvents, and foam blowing agents. As a result, a candidate survey was performed for the USAF identifying a number of promising chemical families that appear to have desirable firefighting properties (Reference 22). In addition, work by the Advanced Agent Working Group (AAWG), which includes USAF, US Army, and US Navy participation, has identified non-halocarbon compounds (in particular, phosphorus compounds, metal compounds, and silicon compounds) and short-atmospheric lifetime tropodegradable halocarbons as promising halon replacements

(Reference 23). A number of reports, including toxicological information, have been written on several of these families (References 15, 24-27).

The first-generation halon replacement program identified a vital need to assess the risk associated with using halon replacement agents. In determining the applicability of the advanced agent candidates, it is essential that one determine toxicological criteria with respect to the use scenario. The present study was undertaken to develop a risk assessment approach to assess the dose-response relationships relative to the expected exposure concentrations.

SECTION II

NAS RISK ASSESSMENT PARADIGM

In 1983, the National Academy of Science (NAS) released its risk assessment/risk management paradigm to define a scheme for assessing the risk of hazards (Reference 28). This paradigm is the basis for this study. According to the NAS paradigm, the risk assessment process is broken down into four steps (Figure 1): (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization.

1. Hazard Identification

Hazard identification involves an evaluation of whether a particular chemical can cause an adverse health effects in humans. This step can be considered a qualitative risk assessment. It involves identifying the potential for exposure as well as the nature of the adverse effects expected. The hazard identification takes into account epidemiological and animal studies (*in-vitro* and *in-vivo*), the quality of the studies (choice of appropriate control groups, sufficient population size, etc.), and the severity of the health effect with comparisons between animal and human effects, if known. The outcome of a hazard identification is a scientific judgment about whether the chemical can, at some exposure concentration, cause adverse health effects in humans. This is not a "yes" or "no" evaluation but rather a weight-of-evidence estimation of the likelihood that the chemical has the potential of causing detrimental health effects.

2. Dose-Response Evaluation

The second step in the risk assessment process is the dose-response evaluation. Figure 2 shows typical dose-response curves for varying effects of a chemical. The curves A, B, and C denote increase severity of the end point. For example, curve A might be for no observable adverse effect, curve B for a significant effect, and curve C for lethality. In the latter case, an LD_{50} can be determined from the 50 percent response value and is marked on the curve.

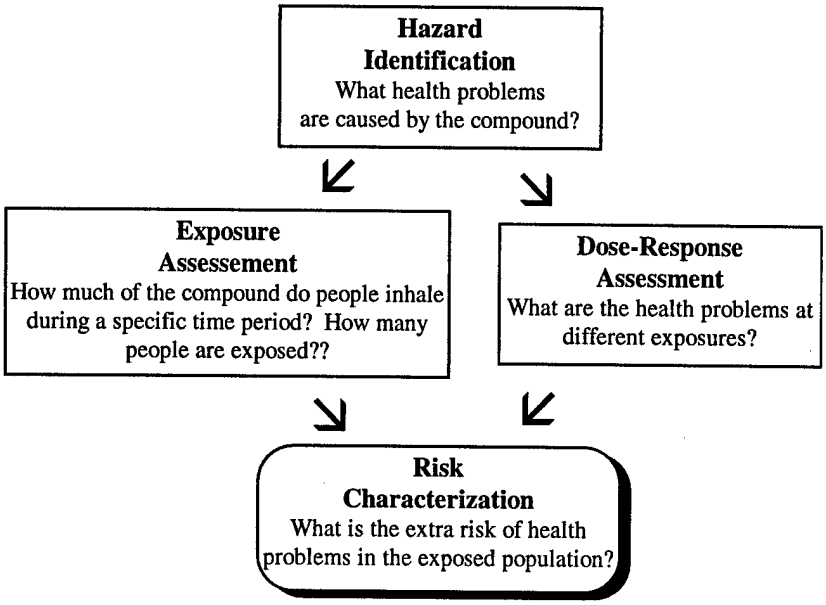

Figure 1. The 4-Step NAS Risk Assessment Process.

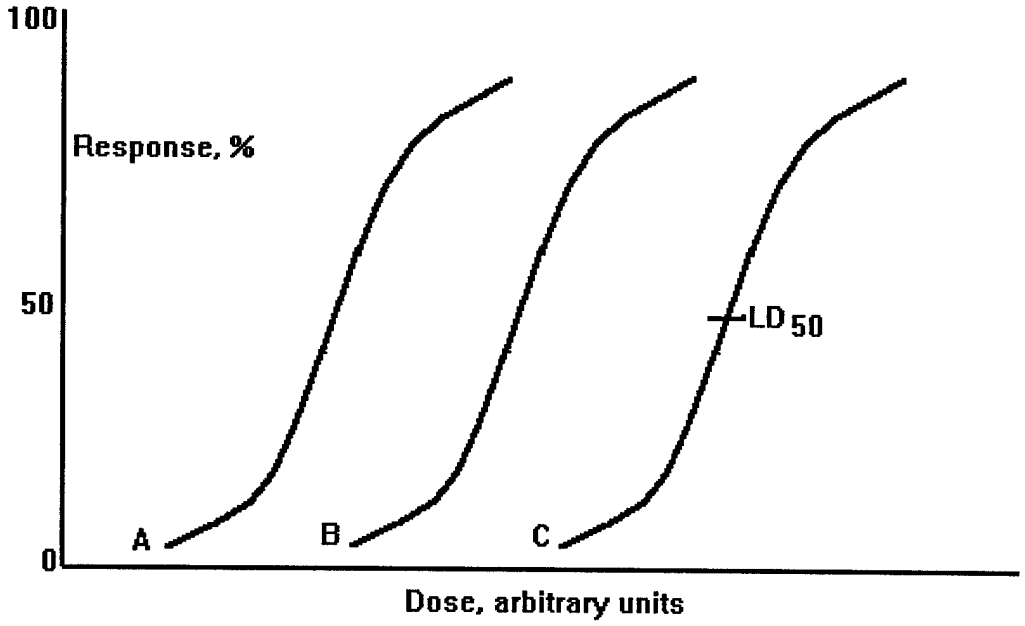

Figure 2. Dose-Response Curves.

The dose-response evaluation step involves the characterization of the relationship between the dose of a chemical needed to elicit a response and the severity of the response in the exposed population. Characterizing the dose-response relationship necessitates understanding the importance of the intensity of exposure (i.e., the concentration-time relationship, whether the chemical has a threshold, and the shape of the dose-response curve). These dose-response relationships are often studies in animal models where progressively higher doses of chemical are administered to animals and the responses are observed. These relationships also rely on rodent studies, which were originally designed to identify potential human hazards qualitatively, not to identify human risks (Reference 29). Exposure duration can also be a variable. These studies allow determination of concentration-time relationships, and usually show that the allowable concentration multiplied by time is a constant. Accordingly, higher concentrations can be withstood for short exposure periods and low concentrations for long exposure times. Responses can be graded or quantal. Graded responses such as protein concentrations versus enzyme activity or body weight versus food consumption are quantitative and continuous. Quantal effects such as lethality and pharmacotoxic effects are either all or none, either they happen or they do not. Quantal effects can also be quantified depending on the effect being observed. For example, central nervous system (CNS) effects such as performance decrement or anesthesia can be quantified if the endpoints are adequately defined. Dose response relationships are best determined for individual chemicals as opposed to classes of chemicals. Many of the chemicals being investigated as Halon 1211 replacements in this effort have not had the required toxicological studies performed. Accordingly, information on dose-response relationships is not available.

3. Exposure Assessment

The third step in managing and understanding risk is exposure assessment, which is a determination about how much chemical a person will be exposed to in given situations. Data on exposure concentrations are often very limited, and exposure models are sometimes used to estimate the likely exposure concentrations for particular scenarios. Sometimes, measurements of chemical concentrations are made for air, soil, water, or food sources, but uncertainty remains about the actual dose received by humans. Assumptions can be made about inhalation,

ingestion, and dermal contact rates and the bioavailability of the chemical from certain media. Models can be used to estimate the migration of chemicals through media. This information can be used to estimate the dose taken up by humans.

An important parameter of the exposure assessment is determing scenarios in which a chemical release will result in human exposure. Knowledge of chemical uses is imperative to understand likely exposure scenarios. For Halon 1211 replacements, these scenarios can be defined for firefighting and for extinguisher filling and maintenance. Historical incidence data offer one method of defining exposure scenarios, and personnel monitoring studies are a means of defining exposures concentrations.

4. Risk Characterization

The final step in risk assessment is risk characterization, which involves a prediction of the frequency and severity of effects in the likely exposed population due to chemical exposure. In this step, information from the dose-response evaluation (what effects are caused by exposure to a certain dose?) is compared to information from the exposure assessment (what dose is the person receiving?) to produce an estimate of the likelihood of observing adverse effects. Most risk assessments for regulatory purposes, especially for cancer, produce a single number estimating the increased incidence of disease. However, for the purposes of this effort, a quantitative risk assessment is impossible for all candidates because (1) not all candidates have been identified, and (2) information on most of the candidates is insufficient to allow a quantitative assessment. Therefore, where possible, a quantitative assessment will be performed; however, in most cases a qualitative assessment will be emphasized to determine whether a chemical or class of chemicals would pose a lesser or greater risk than Halon 1211.

SECTION III
CANDIDATE CHEMICAL FAMILIES

In an earlier effort, candidate chemical families were identified by combining properties that will (or may) enhance flame extinguishment with those properties necessary to limit the atmospheric lifetime, and thus the global environmental impacts of the chemicals (Reference 30). Chemical elements or structures known to or suspected of enhancing flame suppression include bromine, iodine, metals, and phosphorus. Although silicon does not appear to provide any intrinsic fire suppression capability, silicon compounds may provide the decreased atmospheric lifetime needed when bromine is present (see below).

Bromine and iodine are known to provide effective fire extinguishment (Reference 31). Transition metals, in particular iron compounds, are also known to be effective flame extinguishants. Phosphorus-containing materials are used as flame retardants in fabrics and appear, in some cases, to provide flame extinguishing ability. Of these four elements, iodine, phosphorus, and metals will probably lead to low atmospheric lifetimes. Compounds only containing bromine (as the active fire suppression species) must include additional groups that lower the atmospheric lifetimes (i.e., tropodegradable substituents). Silicon compounds are a special case. Although silicon compounds, at best, provide only a limited fire suppression capability, bromine can be added to silanes and siloxanes to give fire suppressants with low atmospheric lifetimes and hence low ODPs and GWPs.

Under a parallel effort, the Advanced Streaming Agent Development, individual reports have been prepared on tropodegradable bromocarbons (Reference 15), metals (Reference 25), phosphorus compounds (Reference 26), and silicon compounds (Reference 24). These reports contain detailed data on environmental factors such as ODP, GWP, and atmospheric lifetimes, as well as toxicity.

As noted above, bromine-containing compounds (specifically, bromocarbons) must contain substituents to reduce the atmospheric lifetime to provide acceptable ODPs. Tropodegradable substituents may act in one (or more) of five ways to reduce the atmospheric

lifetimes of molecules: (1) reaction with hydroxyl free radicals (•OH), (2) reaction with tropospheric ozone, (3) photodecomposition, (4) enhancement of physical removal (primarily, rainout and hydrolysis), and (5) thermal decomposition (Reference 15). Chemical families or features known to reduce atmospheric lifetimes through these mechanisms are shown in Table 5. A list of chemical classes identified for investigation as Halon 1211 replacements provided in Table 6.

TABLE 5. TROPOSPHERIC REMOVAL MECHANISMS.

Primary removal mechanism	Example families or features
Photodegradation	Iodides, carbonyls, bromides
Reaction with hydroxyl free radicals	Alkenes, aromatics, hydrogen-containing amines, hydrogen-containing ethers, carbonyls
Physical removal	Ketones, alcohols, esters
Reaction with tropospheric ozone	Alkenes
Thermal decomposition	[a]Reactive molecules (e.g., epoxides, peroxides)
Hydrolysis	[a]Compounds with direct silicon to halogen bonds, carbonyl halides

[a]Of little or no interest as halon replacement candidates.

TABLE 6. LIST OF CHEMICAL CLASSES IDENTIFIED FOR INVESTIGATION AS HALON 1211 REPLACEMENTS.

Chemical class	Examples
Tropodegradable bromocarbons	Bromoalkanes, Bromoalkenes, Bromoaromatics, Bromocarbonyls, Bromoalcohols, Bromoethers, Bromoamines, and Bromomorpholines.
Fluoroiodocarbons	CF_3I, CF_3CF_2 CF_2I
Metals	Cobalt, Iron, Manganese, Titanium, Zinc
Phosphorus compounds	Phosphonitriles (including bromine containing)
Silicon compounds	Siloxanes, Organochlorosilanes, etc.

SECTION IV
HAZARD IDENTIFICATION

The qualitative assessment or hazard identification part of a risk assessment contains a review of the biological and chemical information having relevance as to whether an agent may pose a hazard to those exposed. The following section presents the known possible health effects caused by exposure to Halon 1211 and the chemical classes identified in Section III. Toxicological effects of specific candidates are discussed if information is available; otherwise, general information on the chemical family as a whole is presented. Recommendations are made for further study.

A. HALON 1211

Halon 1211 ($CBrClF_2$, CAS Number 353-59-3) is colorless and has a faint sweet odor (Reference 32). Natural or undecomposed Halon 1211 produces minimal, if any, CNS effects at concentrations less than 4 percent for exposures of approximately 1-min duration. At concentrations above 4 percent, dizziness, impaired coordination, and reduced mental activities occur after a few minutes duration. These effects are not incapacitating at exposures of under 1 min. Little effect is noticed for the first 30 sec. At concentrations of between 5 and 10 percent, there is a risk of unconsciousness and possible death if exposure is prolonged. Effects are transitory, and recovery is expected to be rapid and complete, with no accumulation in the body. The cardiac No Observed Adverse Effect Level (NOAEL) is 0.5 percent, and the Lowest Observed Adverse Effect Level (LOAEL) is 1.0 percent (Reference 33). The LC_{LO} for 15-min rat inhalation is 32 percent (Reference 34). An LC_{50}, rat, 4-hr concentration of 8.5 percent has been determined.

The National Fire Protection Association (NFPA) standard for Halon 1211 (Reference 32) prohibits the use of Halon 1211 in total flooding systems in normally occupied areas and allows its use only in normally unoccupied areas where egress of personnel can be accomplished in 30 sec or less. It does not provide guidance on hand-held or wheeled units,

although it does provide that in local application systems, the volumetric concentration developed should not exceed 2 percent.

Decomposition products from Halon 1211 can be hazardous. The main decomposition products are halogen acids (HF, HCl, and HBr), free halogens (Br_2 and Cl_2), and small amounts of the carbonyl halides (COF_2, $COCl_2$, and $COBr_2$). Approximate Lethal Concentrations (ALC) range from 4750 ppm for HBr and HCl to 100-150 ppm for $COCl_2$, with dangerous concentrations in air ranging from 1000-2000 ppm for HCl to 50 ppm for $COCl_2$ and Cl_2. The Occupational Safety and Health Agency (OSHA) has established permissible exposure limits for a number the hazardous substances that formed from the decomposition of Halon 1211 and likely halon replacements. Table 7 presents these limits, as well as Immediately Dangerous to Life or Health (IDLH) levels established by the National Institute for Occupational Safety and Health. The amount of Halon 1211 expected to decompose depends on the fire size, the amount of Halon 1211, and the amount of time the agent is in contact with the fire or a heated surface above 900 °F (482 °C), the minimum decomposition temperature.

TABLE 7. OSHA PERMISSIBLE EXPOSURE LIMITS FOR POTENTIAL DECOMPOSITION PRODUCTS OF LIKELY HALON REPLACEMENTS.

Substance	[a]IDLH, ppm	8-Hr TWA, ppm	15-Min STEL, ppm	Ceiling, ppm
COF_2	---	2.0	5.0	---
$COCl_2$	2.0	0.1	---	---
HBr	50	---	---	3.0
HCl	100	---	---	3.0
HF	30	3.0	6.0	---
Br_2	10	0.1	0.3	---
Cl_2	30	0.5	1.0	---
F_2	25	0.1	---	---

[a]IDLH – Exposure concentration which a worker could survive for 30-min. with no ill effects while escaping a dangerous situation. Actual exposure concentrations range from 200 to 1200 ppm for Halon 1211 and 300 to 1000 ppm HF and 1 to 3 ppm COF_2 for the current halon replacements.

B. TROPODEGRADABLE BROMOCARBONS

In the following discussion, many, but not all, of the chemical classes considered are assumed to be fluorinated since fluorination reduces flammability and is likely to reduce hepatotoxicity. A toxicological overview of tropodegradable halocarbons is also presented in Reference 15.

1. Brominated Alkanes (Bromoalkanes)

Table 8 contains an overview of toxicological and safety information (with an emphasis on inhalation toxicity and flammability) for selected bromoalkanes, which are being considered for use as blending compounds in the development of a Halon 1211 replacement (References 34 and 35).* This review is not comprehensive; only the most important information is cited. Although some of the bromoalkanes are said to pose a dangerous fire hazard, testing indicates that the flammability is actually relatively low and that blending with a nonflammable material, such as an HFC, can eliminate flammability.

Because of the variation in species and time, it is difficult to judge the trends in inhalation toxicity. One can estimate that the LC_{50} scales inversely with the time. If this is the case, the 4-hr LC_{50} values can be estimated as 604 ppm (0.06 percent) for bromomethane, 4058 ppm (0.41 percent) for bromoethane, 6300 ppm (0.63 percent) for 1-bromopropane, and 5300 ppm (0.53 percent) for 1-bromobutane. These values are plotted as a function of number of carbon atoms in Figure 3. The data indicate that the toxicity decreases as the molecular weight increases. The relatively low LC_{50} of 7000 ppm (0.7 percent) reported for 2-bromopropane cannot be assessed since neither the mammalian species nor the time period is given.

The SAX Hazard Rating (HR, Reference 34) has been given for some compounds in Table 8 and elsewhere in this report. This rating indicates the relative hazard for toxicity, fire, and reactivity with three (3) denoting the worst hazard level. Careful consideration of the actual firefighter exposure threat, however, indicates that a lower rating may be more appropriate for

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*Throughout this report, "SAX" refers to the book *Dangerous Properties of Industrial Materials* by Sax and Lewis; "RTECS" denotes the *Registry of Toxic Effects of Chemical Substances.*

TABLE 8. TOXICOLOGICAL AND SAFETY INFORMATION FOR SELECTED BROMOALKANES.

Compound	Formula	CAS No.	Observations[a]
Bromomethane	CH_3Br	74-83-9	[BNM500] LC_{Lo} (man, inhalation, 2 hr) = 60,000 ppm (6.0%), LC_{Lo} (child, inhalation, 2 hr) = 1000 mg/m^3; TC_{Lo} (human, inhalation) = 35 ppm; LC_{50} (rat, inhalation, 8 hr) = 302 ppm (0.03%); LC_{50} (mouse, inhalation, 2 hr) = 1540 mg/m^3; LC_{50} (rabbit, inhalation, 30 min) = 28,900 mg/m^3; LC_{Lo} (guinea pig, inhalation, 9 hr) = 300 ppm; TC_{Lo} (rat, inhalation, 6hr) = 120 ppm. Human poison by inhalation. Experimental carcinogen by ingestion. Human systemic effects by inhalation: anorexia, nausea, vomiting. Corrosive to skin, can produce severe burns. Hemotoxic and narcotic with delayed action. Effects are cumulative and damaging to nervous systems. Reported to be 8 times more toxic on inhalation than ethyl bromide. HR = 3.
Bromoethane	CH_3CH_2Br	33-47-3	{RTECS KH6475000} LC_{LO} (rat, inhalation, 15 min) = 148,000 ppm (14.8%), LC_{50} (mouse, inhalation, 1 hr) = 16,230 ppm (16.2%). TC_{Lo} (rat, inhalation, 6 hr) = 100 ppm; TC_{Lo} (mouse, 6 hr) = 200 ppm; LC_{50} (rat, inhalation, 1 hr) = 26,980 ppm; LC_{50} (mouse, inhalation, 1 hr) = 16,230 ppm; TC_{Lo} (rat, inhalation, 6 hr) = 2000 ppm TC_{Lo} (rat, inhalation, 6 hr) = 1600 ppm; TC_{Lo} (mouse, inhalation, 6 hr) = 1000 ppm. [BNI250] Moderately toxic by ingestion. Mildly toxic by inhalation. Eye, skin irritant. Anesthetic, narcotic. Vapors markedly irritating to the lungs even for short periods. Dangerously flammable and moderately explosive. HR = 3.
1-Bromo-propane	$CH_3CH_2CH_2Br$	106-94-5	{RTECS TX4110000} LC_{50} (rat, inhalation, 30 min) = 253,000 mg/m^3 (50,300 ppm) (5.03%); TC_{Lo} (rat, inhalation, 30 min) = 98,408 mg/m^3. [BNX750] Moderately toxic by ingestion. Mildly toxic by inhalation. Dangerous fire hazard. HR = 2.

TABLE 8. TOXICOLOGICAL AND SAFETY INFORMATION FOR SELECTED BROMOALKANES (concluded).

Compound	Formula	CAS No.	Observations[a]
2-Bromo-propane	$CH_3CHBrCH_3$	75-26-3	{RTECS TX4111000} LC_{50} (mammal, inhalation) = 36,000 mg/m^3 (0.7%); TC_{Lo} (rat, inhalation, 30 min) = 172,000 mg^3. [BNY000] Flash point < 14 °C. Dangerous fire hazard. A recent report states that 2-bromopropane causes deterioration of ovaries and male reproductive organs (Reference 36). In a South Korean semiconductor plant, 17 or 25 females using the compound to clean semiconductors, experienced menstrual cycle interruptions; 6 of 8 males in the same plant experienced a decline in sperm production. Effects were also noted in rats inhaling the compound over a 9-week period.
1-Bromobutane	$CH_3CH_2CH_2CH_2Br$	109-65-9	{RTECS EJ6225000} LC_{50} (rat, inhalation, 30 min) = 237,000 mg/m^3 (4.23%) LC_{50} (mammal, inhalation, ? hr) = 25,800 mg/m^3. [BMX500] Dangerous fire hazard. HR = 3.
1-Bromo-2-methylpropane	$CH_2BrCH(CH_3)CH_3$	78-77-3	[BNR750] LC_{LO} (mammal, inhalation) = 50,500 mg/m^3 (0.90%). Moderately toxic by intraperitoneal. Mildly toxic by inhalation. Experimental neoplastigen. Dangerous fire hazard. Flash point = 22 °C. HR = 3.
2-Bromo-2-methylpropane	$CH_3CBr(CH_3)CH_3$		[BNS000] No toxicity data. Dangerous fire hazard. Flash point = -18 °C.

[a]The SAX No. (Reference 34) is given in brackets followed by information from that reference; the RTECS No. (Reference 35) is given in braces, followed by information from that source. "HR" denotes the SAX Hazard Rating.

some compounds. For example, in some cases only toxicity by intraperitoneal, subcutaneous, and/or intravenous routes (only indirectly related to exposure toxicities of interest here) is known. Moreover, emission of toxic combustion products, such as HBr (emitted by all or nearly all bromine-containing compounds including the present halons), appears to have been given undue weight.

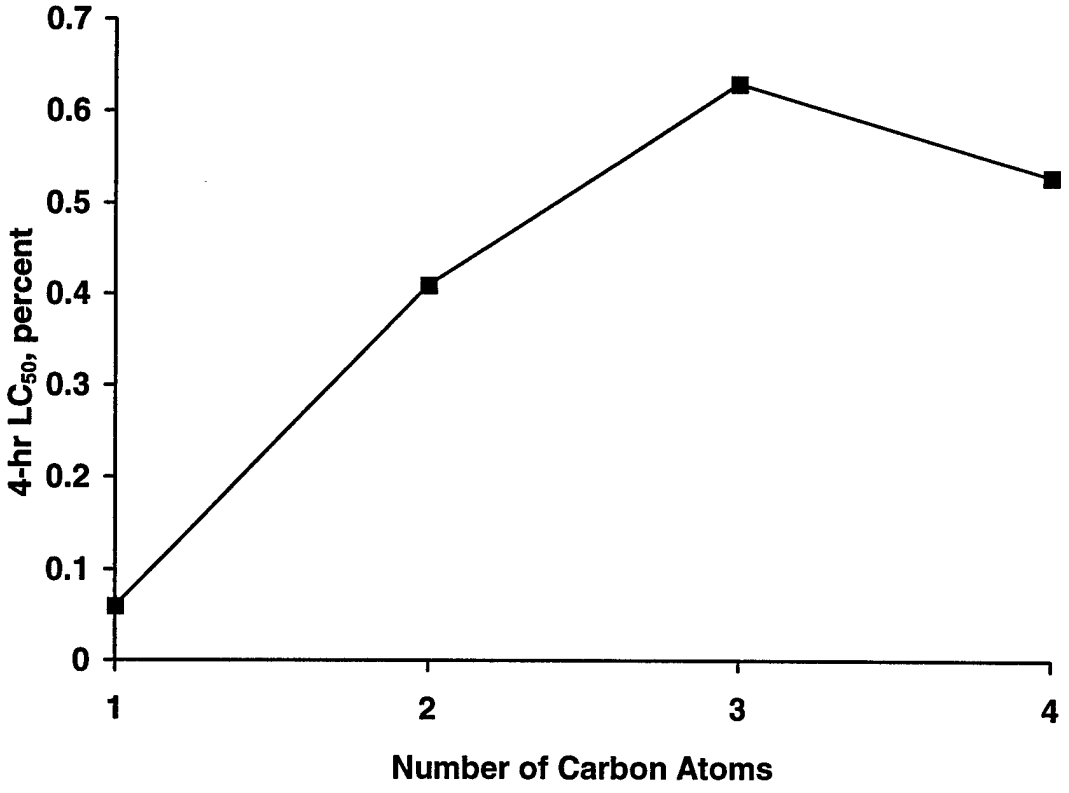


Figure 3. Estimated LC_{50} as Function of Chain Length for Bromoalkanes.

2. Brominated Alkenes (Bromoalkenes)

The incorporation of a double bond into fluorocarbons creates a unique chemical environment. The strong electronegative force of halogen substituents generates a region of low electron density between the adjacent carbon atoms, yielding a site susceptible to nucleophilic attack by bases or nucleophiles such as fluoride (F^-), hydroxide (OH^-) or amide (NH_2^-) (Reference 37). Saturated hydrocarbon bonds are not as susceptible to this nucleophilic attack. Generally, a fluorine substituent activates a double bond towards nucleophilic attack and the order of reactivity is related to the intermediate carbanion stability—tertiary is more reactive than secondary, which is more reactive than primary (Reference 38). The order of nucleophilic susceptibility follows the observed trend in toxicity for this series of perfluorinated alkenes: $(CF_3)_2C=CF_2 > CF_3CF=CF_2 > CF_2=CF_2$.

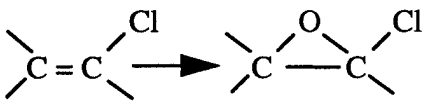
Fluoride (F^-) is related to fluoroalkene chemistry similar in the same way that protons (H^+) are related to the chemistry of hydroalkenes (Reference 39). Thus, protons will attack the double bond in a hydroalkene (Reaction 1), whereas, F^- ions attack the double bond in a fluoroalkene (Reaction 2).

$$H^+ + H_2C^+{=}CHCH_2CH_3 \rightarrow CH_3C^+HCH_2CH_3 \rightarrow CH_3CH{=}CHCH_3 + H^+ \quad (1)$$

$$F^- + CF_2{=}CFCF_2CF_3 \rightarrow CF_3C^-FCF_2CF_3 \rightarrow CF_3CF{=}CFCF_3 + F^- \quad (2)$$

In Reaction 2, the migration of the double bond is accomplished by the invasion of the nucleophile F^- into the electron-deficient double bond with elimination of F^- down the carbon chain. This sequence is similar for hydroalkenes (Reaction 1) except the attack site is electron rich, and an electrophilic proton is the reacting species. Consequently, the toxicity of fluoroalkenes is thought to parallel the susceptibility to nucleophilic attack.

The acute and chronic effects of haloalkenes must be considered when determining the potential of the candidates as halon replacements. Haloalkenes can act as other halocarbons during short-term exposures, but due to the highly metabolically active carbon-carbon double bond, long-term effects of exposure become highly important. For example, in acute exposures, there are still concerns with lethality, CNS effects, and cardiac sensitization. Pertaining to long-term effects, the bioactivation mechanisms and the reactivities of the metabolites formed from haloalkenes when activated by oxygen enzymes (oxidases, peroxidases, and mixed-function oxygenases) must be considered. In haloalkenes, the formation of oxiranes (epoxides) will be favored if the halogen is located on an unsaturated carbon (Reaction 3).



(3)

In haloalkanes, the electronegativity of activated oxygen will induce the formation of alkanols and free radicals.

Abreu investigated the acute toxicity of a series of mono-brominated and mono-chlorinated ethenes, propenes, and n-butenes and found that when the halogen was located on the unsaturated carbons, the anesthetic potency was increased, but there was also a decrease in the

irritation, tissue damage, and overall toxicity (Reference 40). In addition, haloalkenes with halogens located on the unsaturated carbons have less of a tendency to be metabolized in the body. The anesthetic potency is evidently due to the molecules themselves as opposed to metabolic products. Although none of the chemicals studied was a fluorinated derivative, halogen substituted unsaturated hydrocarbons were more stable and less toxic than saturated analogues. One beneficial effect of halogen substitution with chlorine, bromine, and iodine on the double bond may occur from steric protection from electrophilic attacks due to the bulky halogen atoms (Reference 41).

Halogenated ethenes were not considered as halon replacements in this survey of haloalkenes. Previous work indicates that most, if not all, mono-brominated ethenes are mutagenic and carcinogenic due to metabolic activation. A summary of the work is provided supporting these conclusions. Vinyl chloride (CH_2=CHCl) has been studied extensively and was found to be mutagenic and carcinogenic both *in vitro* and *in vivo* (Reference 41). Vinyl bromide and vinyl fluoride have not been studied in detail; however, their metabolism is thought to parallel that of vinyl chloride. Accordingly, these compounds are suspected to metabolize into halooxiranes, which would rearrange rapidly to form haloacetaldehyde. The oxiranes moieties alkylate DNA and proteins. Alkylation of DNA is one, and probably the most important, primary biochemical insult leading to mutations and cancer (Reference 42).

Vinylidene halides (1,1-dihaloethylenes, CH_2=CX_2, where X is a chlorine) are also fairly toxic compounds. They are generally extremely hepatotoxic and mutagenic after metabolic activation (Reference 41). Variable carcinogenic response have been reported with vinylidene halides, which is probably a result of interference of the acute toxicity with the tumor promotion. On the other hand, 1,2-dihaloethylenes are not metabolized to mutagenic products (Reference 41). The *cis* isomer is metabolized faster than the *trans* isomer, which is thought to be due to the steric opening of the *cis* molecule.

Of the tri- and tetrahaloethylenes, the chlorinated compounds have been studied most extensively. Again, information on mixed halogen compounds is limited, but generally trihaloethylenes are mutagenic. In addition, these chemicals such as trichloroethylene are often explosive in the vapor form (Reference 34). Tetrachloroethylene is also mutagenic and

carcinogenic. On the other hand, tetrafluoroethylene is considered only moderately to slightly toxic (Reference 43). Chlorotrifluoroethylene produces kidney dysfunction in rats after only a single 4-hr exposure to concentrations up to 460 ppm. Bromotrifluoroethylene ($CFBr=CF_2$) is a flammable gas and is considered poisonous (Reference 34). As a result of these toxicity and flammability findings on halogenated ethenes, no chemical in this two-carbon unsaturated class is recommended for further evaluation.

As seen from the information above, most of the data available on unsaturated chemicals are on fluoroalkenes. Little is known about mixed halogen fluoroalkenes. Some evidence from chlorinated and fluorinated ethylenes indicates that fluorochloroethylenes are less toxic than chlorine-only-substituted analogues. This trend is seen in Table 9, which gives results from 4-hr rat exposures unless noted otherwise. Nonetheless, increasing the degree of fluorination at the site of unsaturation increases the acute toxicity compared to alkenes containing hydrogen at the site of unsaturation. In other words, more hydrogen atoms attached to the double-bond carbons confer a lower acute toxicity. This point becomes important when determining which unsaturated chemicals listed on Table 9 will potentially have low toxicities.

Less information is available on haloalkenes with three or more carbons than for two-carbon haloalkenes. Most of the information is on halocarbon molecules that are not also fluorinated. For example, Henschler, in his review of metabolism of alkenes and alkynes (Reference 41), suggests that allyl halides are subject to nucleophilic attack by both the S_N1 and S_N2 mechanisms (Reactions 4 and 5)

$$CH_2=CHCH_2X \rightarrow [CH_2 \cdots CH \cdots CH_2]^+ + X^- \quad (4)$$

$$Nu + CH_2=CHCH_2X \rightarrow [Nu\text{-}CH_2CH=CH_2]+X^- \quad (5)$$

or by radical mechanisms (Reaction 6).

$$CH_2=CH\text{-}CH_2X \rightarrow [CH_2 \cdots CH \cdots CH_2]^+ + X^- \quad (6)$$

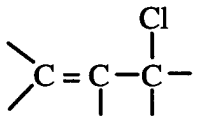
The free radicals formed are stabilized by resonance (e.g., $[CH_2 \cdots CH \cdots CH_2]^+$ is equivalent to $[CH_2=CHCH_2\bullet \leftrightarrow \bullet CH_2CH=CH_2]^+$).

TABLE 9. ACUTE INHALATION TOXICITY OF SEVERAL HALOGENATED ETHENES.

Chemical	Approximate lethal concentration, ppm	4- hr LC_{50}, ppm	Cardiac sensitization[a]
$CH_2=CH_2$	---	[b]950,000	---
$CCl_2=CH_2$	32,000	---	---
$CHCl=CCl_2$	8,000	---	---
$CCl_2=CCl_2$	4,000	---	---
$CCl_2=CF_2$	1,000	---	---
$CClF=CF_2$	---	1,000	4/4
$CH_2=CHF$	[c]>800,000	---	---
$CF_2=CH_2$	128,000	---	0/8
$CF_2=CF_2$	---	40,000	0/4

[a]Number of dogs experiencing cardiac sensitization from Reference 44 as presented in Reference 45.
[b]Mouse; exposure time and O_2 level unspecified.
[c]80 percent agent supplemented with 20 percent O_2; 12.5 hrs.

Alkenes that possess an allylic chlorine are mutagenic with or without metabolic activation (Reference 46). Therefore, chemicals that possess the following features are expected to be mutagenic:



(7)

This mutagenic feature holds true regardless of whether the other substituents are hydrogen or methyl (-CH3) groups. The mutagenic and carcinogenic potentials of allyl chloride and 1-chloro-2-cyclohexene are well known. *Cis*-1,3-dichloropropene is the most potent alkylating agent tested in the propene series. The trans isomer has reduce activity apparently due to steric hindrance and neighboring effects favoring cation stabilization. Good quantitative correlation exists between alkylating ability *in vitro* and direct mutagenic potencies in bacteria. Alkylating ability is measured in the NBP-Test (4-(p-nitrobenzyl)-pyridine test) where the test agent and NBP are reacted and the spectrophotometric extinctions are measured for the reaction

mixture (Reference 47). Conversely, if the chlorine is located in positions other than the allylic position for propenes, the molecules is mutagenic only with metabolic activation. Compounds containing vinylic chlorines such as 1-chloro-1-propene ($ClCH=CHCH_3$) and 2-chloro-2-butene ($CH_3CH=CClCH_3$) lack direct genotoxic activity, however, these become mutagenic with metabolic activation (Reference 46). Finally, compounds with the chlorine located on positions other than on carbons 1, 2, or 3, relative to the site of unsaturation (e.g., $CH_2=CHCH_2CH_2Cl$), are not mutagenic with or without metabolic activation.

From this information it becomes apparent that in order for an alkene not to possess mutagenic, and hence carcinogenic, potential, the leaving group, i.e., the chlorine, must be located at least two carbons away from the site of unsaturation. Unfortunately this trend has not been tested in fluorinated analogues. Nonetheless, Table 10 indicates which candidates will most likely be mutagenic, and hence potentially carcinogenic.

Since no toxicological information was found on bromofluoroalkenes, other mixed haloalkenes were investigated. Since two and three carbon alkenes have been discounted on the basis of mutagenicity, four or more carbon alkenes were the focus. One mixed halogen butene investigated in the past is 2,3-dichloro-1,1,1,4,4,4- hexafluorobutene-2 ($CF_3CCl=CClCF_3$, DCHFB). This chemical is an impurity of halothane in concentrations ranging from 2 to 100 ppm (Reference 43). Concern about its toxic effects were expressed because halothane has been used as a surgical anesthetic in humans. Several investigations of DCHFB have been performed to determine its toxicity. Cohen and associates observed the acute toxicity of DCHFB in dogs and found delayed anesthesia followed by convulsions and death in 1 hour (Reference 48). They also determined the LC_{50} for rhesus monkeys to be 54 ppm for a 3-hour exposure where delayed death occurred 4 to 9 days after the exposure. Chenoweth showed that DCHFB was lethal in rats at 100 ppm for 4 hrs. Some rats survived the exposure for 1 or 2 hrs (Reference 49). Lethal exposure was connected with signs of pulmonary irritation—pulmonary congestion and edema. Degenerative changes in the liver and kidney were also noted. Raventos and Lemon studied the toxicity of DCHFB in mice, rats, rabbits, monkeys, and dogs (Reference 50). A summary of their findings is presented in Table 11 illustrating that the rat is the most sensitive species tested. They also found that the trans isomer was about three times as toxic for mice as

TABLE 10. PREDICTED MUTAGENICITY OF HALOALKENES.

Chemical	Mutagenic potential[a]
$CH_2=CHCF_2Cl$	Mutagenic with or without activation
$CH_2=CHCFCClFCF_3$	Not mutagenic
$CH_2=CHClCF_3$	Mutagenic with activation only
$CH_2=CHCF_2CClF_2$	Not mutagenic
$CH_2=CClCClF_2$	Mutagenic with or without activation
$CH_2=CHCClFCClF_2$	Mutagenic with or without activation
$ClCH=CClCF_3$	Mutagenic with activation only
$CF_2=CHCClF_2$	Mutagenic with or with activation
$ClCH=CHCF_3$	Mutagenic with activation only

[a] Predicted from trends based on work presented in References 41, 46, and 47.

the cis isomer (1-hr LC_{50}: trans, 61 ppm; 1-hr LC50: cis, 179 ppm). These researchers also studied other fluoroalkene impurities of halothane and determined the mouse 1-hr LC_{50} of trans $CF_3CH=CBrCF_3$ to be 5000 ppm. Lung congestion and edema, as well as other changes, were the predominant pathological findings; however, fatty liver changes were also present. The chlorinated analog of this chemical, trans $CF_3CH=CClCF_3$, was not found to be lethal for mice at 16,000 ppm. However, convulsions were observed at concentrations higher than 5000 ppm. The approximate lethal concentration of a fluorinated analog, $CF_3CH=CFCF_3$, was determined to be 200 ppm for a 4-hr exposure in rats (Reference 43). This chemical acts predominately on the CNS and respiratory systems, and delayed death is the usual consequence. The long-term effects of these chemicals were not reported.

Hoechst Chemical Company reported the acute toxicity of $CH_2=CHCF_2CF_2Br$ (Reference 51). They performed an acute inhalation screening test wherein one mouse was exposed to 10,000 ppm for 1 hour. The mouse survived the exposure and an observation period of several days. Clinical signs were reported as normal. As a result of these findings, the researchers categorized the chemical as "weakly/practically not toxic."

TABLE 11. ACUTE INHALATION TOXICITY OF DCHFB.

Species	LC_{50}, ppm				
	1-hr exposure	2-hr exposure	3-hr exposure	4-hr exposure	6-hr exposure
Mice	55	39	--	26	20
Rats	47	28	--	16	--
Dogs	725	415	--	182	115
Monkeys	186	139	90	--	--

Several generalizations about the toxicity of fluoroalkenes become apparent:

(1) Halogenation around the site of unsaturation (C=C) increases the anesthetic potency, but decreases the irritant potential, tissue damage, and overall toxicity.

(2) Mono-halogenated ethenes are generally mutagenic and carcinogenic.

(3) 1,1-Dihaloethylenes ($CH_2=CX_2$, where X is a chlorine) are generally mutagenic after metabolic activation and hepatotoxic.

(4) 1,2-Dihaloethylenes (CHX=CHX, where X is a chlorine) are generally not mutagenic, and the cis isomer is metabolized faster than the trans isomer.

(5) Trihaloethylenes and tetrahaloethylenes are generally mutagenic.

(6) The more hydrogens attached to the C=C bond, the lower the toxicity.

(7) Alkenes with allylic chlorines (C=C-C-Cl) are generally mutagenic with or without metabolic activation.

(8) Chlorinated alkenes are least toxic if the halogens are not bound to the double bond; consequently, chlorinated alkenes require at least four carbon atoms in order for the bromine to be located far enough away from the unsaturated site.

3. Brominated Aromatics

Aromatic halocarbons have wide-ranging industrial use, and, therefore, significant toxicological information is available for these compounds. Like the haloalkenes, however, most of those in use are chlorine-containing compounds, rather than the fluorine derivatives, which are of particular interest here. Of some interest are various isomers of the chlorobenzotrifluorides.

Many of the aromatic halocarbons are irritants and can affect the respiratory system and liver. Table 12 gives some information on toxicity and safety of some aromatics structurally related to possible tropodegradable agents (References 34 and 35). Of particular interest is bromobenzene, which has been shown to cause liver damage in animal tests, although little information is available about this compound (Reference 52). Benzotrifluorides are under development as replacements for ozone-depleting solvents and are being considered for SNAP listing (Reference 53). The parent compound, (trifluoromethyl)benzene (trifluorotoluene, $C_6H_5CF_3$) is said to be "Highly toxic by inhalation. Flammable, dangerous fire risk" (Reference 54). The 4-hour rat LC_{50} of 70,810 mg/m^3 (Table 12) corresponds to a volumetric concentration of 1.18 percent. The chloro derivatives are also said to be toxic and flammable.

Perfluorotoluene ($CF_3C_6F_5$) has been investigated as an anesthetic, and it is reported to be mildly toxic with delayed death at levels as low as 0.5 to 0.9 percent (Reference 55). Hexafluorobenzene (C_6F_6) (Reference 56), and pentafluorobenzene (C_6HF_5) (Reference 55), have both been reported as anesthetics with relatively low toxicities. Of great interest is that bromopentafluorobenzene (C_6BrF_5) shows no anesthetic effects and has a low toxicity.

4. Brominated Carbonyls

Carbonyl compounds of interest include ketones, aldehydes, esters, and carboxylic acids. A brief description of the toxicity of each of the groups is included, followed by toxicity data on several specific members of the class.

a) Aldehydes

Lower aldehydes attack exposed moist tissue, especially eyes and mucous membranes. Higher aldehydes penetrate deeper into the respiratory tract and affect the lungs. Many members of the family are mutagens, and all have anesthetic properties. For example, acetaldehyde (CH_3CHO) is an irritant and CNS narcotic, while acrolein (2-propenal (CH_2=CHCHO)) is toxic by all routes. Some higher aldehydes and aromatic aldehydes may exhibit much lower toxicity. Aldehydes are converted to organic acids in the liver.

TABLE 12. TOXICOLOGICAL AND SAFETY INFORMATION FOR AROMATICS RELATED TO POSSIBLE TROPODEGRADABLE CANDIDATES.

Compound	Formula	CAS No.	Observations[a]
(Trifluoromethyl) benzene	$C_6H_5CF_3$	98-08-8	[BDH500] LC_{50} (rat, inhalation, 4 hr) = 70,810 mg/m^3 (11,800 ppm, 1.18%), LC_{50} (mouse, inhalation, 2 hr) = 92,240 mg/m^3, LD_{50} (rat, oral) = 15,000 mg/kg, LD_{50} (mouse, oral) = 10,000 mg/kg. HR = 3.
(Bromomethyl) benzene	$C_6H_5CH_2Br$	100-39-0	[BEC000] Intensely irritating, corrosive to skin, eyes, mucous membrane. Large doses cause CNS depression. Lachrymator. HR = 2.
Bis(4-bromophenyl) ether	BrC_6H_4-O-C_6H_4Br	2050-47-7	[BHJ000] Poison by intraperitoneal. HR = 3.
Bis(trifluoromethyl)-benzene	$C_6H_4(CF_3)_2$	402-31-3	[BLO270] No toxicity data.
2-Bromo-(trifluoromethyl) benzene	$BrC_6H_4(CF_3)$	392-83-6	[BOJ750] LD_{50} (rat, oral) = 2720 mg/kg. Moderately toxic by ingestion. Skin, eye irritant.
3-Bromo-(trifluoromethyl) benzene	$BrC_6H_4(CF_3)$	401-78-5	[BOJ500] LD_{50} (rat, oral) = 2870 mg/kg. Moderately toxic by ingestion. Skin, eye irritant.
4-Chloro-(trifluoromethyl) benzene	$ClC_6H_4(CF_3)$	98-56-6	[CEM825] LC_{50} (rat, inhalation, 4 hr) = 22,000 mg/m^3 (0.30%), LC_{50} (mouse, inhalation) = 20,000 mg/m^3 (0.27%), LD_{50} (rat, oral) = 13 g/kg, LD_{50} (mouse, oral) = 11,500 mg/kg. Mildly toxic by ingestion, inhalation. Human mutagenic data. Flammable. HR = 1.
1,3-Difluorobenzene	$C_6H_4F_2$	372-18-9	[DKF800] Very dangerous fire hazard. Flash point < 32 °C. HR = 3.
1,4-Difluorobenzene	$C_6H_4F_2$	540-36-3	[DKG000] Very dangerous fire hazard. Flash point = 23 °C. HR = 3.

[a] The SAX No. (Ref. 34) is given in brackets followed by information from that reference; the RTECS No. (Ref. 35) is given in braces, followed by information from that source. "HR" denotes the SAX Hazard Rating.
[b] Isomer not specified.

TABLE 12. TOXICOLOGICAL AND SAFETY INFORMATION FOR AROMATICS RELATED TO POSSIBLE TROPODEGRADABLE CANDIDATES (concluded).

Compound	Formula	CAS No.	Observations[a]
[b]Ethyldibromo benzene	$C_6H_3Br_2(C_2H_5)$	30812-87-4	[EHY000] LC_{LO} (rabbit, inhalation, 7 hr) = 731 mg/m^3 (0.30%), LD_{LO} (rat, oral) = 12,283 g/kg, LD_{LO} (rabbit, oral) = 5,536 mg/kg. Moderately toxic by ingestion, inhalation. HR = 2.
Fluorobenzene	C_6H_5F	462-06-6	[FGA000] LC_{50} (rat, inhalation) = 26,908 mg/m^3 (0.68%), LC_{50} (mouse, inhalation, 2 hr) = 45,000 mg/m^3 (1.1%), LD_{50} (rat, oral) = 4399 mg/kg. Mildly toxic by ingestion, inhalation. Dangerous fire hazard. HR = 2.
1-Fluoro-2-bromobenzene	C_6H_4BrF	1072-85-1	[FGX000] LD_{50} (rat, oral) = 1850 mg/kg. Moderately toxic by ingestion. Skin, eye irritant. HR = 2.
1-Fluoro-3-bromobenzene	C_6H_4BrF	1073-06-9	[FGY000] LD_{50} (rat, oral) = 670 mg/kg. Moderately toxic by ingestion. Skin, eye irritant. HR = 2.
Hexafluorobenzene	C_6F_6	392-56-3	[HDB000] LC_{50} (mouse, inhalation, 2 hr) = 95,000 mg/m^3. Mildly toxic by inhalation. Dangerous fire hazard. Flash point = 50 °F. HR = 3.
Perfluorotoluene	$C_6F_5CF_3$	434-64-0	[PCH500] LC_{LO} (mouse, inhalation, 10 min) = 5000 ppm. Mildly toxic by inhalation. HR = 1.

[a] The SAX No. (Ref. 34) is given in brackets followed by information from that reference; the RTECS No. (Ref. 35) is given in braces, followed by information from that source. "HR" denotes the SAX Hazard Rating.
[b] Isomer not specified.

b) Ketones

Ketones can act as a narcotic and dissolve fat in the skin (e.g., acetone ($CH_3C(O)CH_3$), can act as neurotoxins (methyl-*n*-butylketone, $CH_3C(O)CH_2CH_2CH_2CH_3$), and have been suspect in neuropathic disorders (methylethylketone, $CH_3C(O)CH_2CH_3$).

c) Carboxylic Acids

Carboxylic acids can be corrosive to tissue and are often relatively toxic orally and by skin contact. The presence of more than one carboxylic acid group per molecule, unsaturated bonds in the carbon skeleton, or the presence of a halogen atom group on an alpha carbon increases toxicity and corrosivity.

Acid halides, RC(O)X, hydrolyze readily to give the free carboxylic acid and toxic hydrogen halides (Reaction 7). For this reason, these highly corrosive and irritating compounds cannot be considered as halon substitutes.

$$RC(O)X + H_2O \rightarrow RC(O)OH + HX \qquad (7)$$

d) Esters

Esters are hydrolyzed in tissue. The toxicity of the esters is primarily that of the hydrolysis products. Since esters have high volatility, pulmonary effects are important, and they are asphyxiants and narcotics. Because they are solvents, they tend to dissolve body lipids. Some natural esters are nontoxic. Synthetic esters, however, may have high toxicity. In general, fluorinated esters have a lower toxicity than fluorinated ketones (Reference 34).

Toxicities of carbonyl compounds from the NIST exploratory list are shown in Table 13 (Reference 57). Table 14 gives information on toxicology and safety for some halogenated carbonyl compounds structurally related to compounds of interest here (Reference 34). In this table, all available inhalation toxicity data are given; however, intraperitoneal and intravenous toxicity data are not presented.

5. Brominated Alcohols

Lower molecular weight alcohols exhibit a range of toxicities. Methanol, also known as wood alcohol, causes mild inebriation followed in about 10-20 hrs by unconsciousness and cardiac depression; death may follow. Sublethal exposure may lead to blindness. The symptoms of ethanol are well known—decreased inhibitions and CNS depression are the first symptoms, followed by stupor, coma, and death at higher doses. Ethanol can be absorbed

TABLE 13. TOXICITY OF CARBONYL COMPOUNDS IN NIST EXPLORATORY LIST.

Formula	[a]Hazard rating	[b]Toxicity comments
CF_3COCF_3	3	Moderately toxic by ingestion and a poisonous irritant to the skin, eyes, and mucous membranes.[a]
$(iC_3F_7)_2CO$	Not available	No toxicity data available. Expected to be similar to CF_3COCF_3.
CF_3COOCH_3	Not available	No toxicity data available.
CF_3COCH_2Br	Not available	No toxicity data available. Expected to be similar to CF_3COCF_3.
CF_2BrOCF_3	Not available	No toxicity data available. Expected to be similar to other esters.
CF_3COOCH_2Br	Not available	No toxicity data available. Expected to be similar to other esters.

[a]Reference 34.
[b]Reference 57.

through the lungs and symptoms of intoxication observed at 1000 ppm. Ethylene glycol, the antifreeze/antiboiling formulation in most automotive cooling systems, stimulates the CNS and then depresses it; potentially fatal kidney damage can occur.

The toxicity of higher molecular weight alcohols range from relatively low to moderate. For example, 2-propanol ($CH_3CHOHCH_3$), or rubbing alcohol, is a food additive which can be an irritant and narcotic, but one with relatively low toxicity. Allyl alcohol ($CH_2=CHCH_2OH$) has a pungent odor and is strongly irritating to eyes, mouth, and lungs. Deaths have been reported in laboratory animals but not humans (Reference 58). The following irritants—1-butanol ($CH_3(CH_2)_2CH_2OH$), 2-ethylhexanol ($CH_3(CH_2)_3CH(C_2H_5)CH_2OH$), and 1-pentanol ($CH_3(CH_2)_3CH_2OH$)—have limited toxicity due to low vapor pressure. Most other higher molecular weight alcohols are also considered to be moderately toxic by ingestion or skin contact (Reference 34).

TABLE 14. TOXICITY AND SAFETY INFORMATION FOR SELECTED CARBONYL COMPOUNDS.

Compound	Formula	CAS No.	Observations[a]
1,2-Bis(bromo-acetoxy)-ethane	$CH_2BrC(O)OCH_2$-$CH_2OC(O)CH_2Br$	3785-34-0	[BHD250] Poison by intraperitoneal, intravenous. HR = 3.
2-Bromoethan-aldehyde	$CH_2BrC(O)H$	17157-48-1	[BMR000] Mutagenic data.
2-Bromoethanoic acid	$CH_2BrC(O)OH$	79-08-3	[BMR750] LC_{LO} (rat, inhalation, 30 min) = 114,000 mg/m^3 (2.02%). Poison by ingestion, intraperitoneal, intravenous. Irritating, corrosive to skin, mucous membranes. HR = 3.
1-Bromoacetoxy-2-propanol	$CH_2BrC(O)O$-$CH_2CH_2(OH)CH_3$	4189-47-3	[BMS250] LD_{50} (rat, oral) = 664 mg/kg, LD_{50} (rabbit, skin) = 813 mg/kg. Moderately toxic by ingestion, skin contact. HR = 2.
2-Bromo-2-propenal	CH_2=$CBrCHO$	14925-39-4	[BMT000] Mutagenic data.
2-Bromobutanoic acid	$CH_3CHBrCH_2$-$C(O)OH$	80-58-0	[BMY250] LD_{50} (mouse, oral) = 310 mg/kg. Poison by ingestion. HR = 3.
Bromo-2-propanone	$CH_2C(O)CH_3$	598-31-2	[BNZ000] LC_{LO} (human, inhalation, 10 min) = 572 ppm. Poisonous gas. Moderately toxic to humans by inhalation. HR = 3.
2-Bromopropionic acid	$CH_3CHBrC(O)OH$	598-72-1	[BOB000] LD_{50} (mouse, oral) = 250 mg/kg. Poison by ingestion. HR = 3.
3-Bromopropionic acid	$CH_2BrCH_2C(O)$ OH	590-92-1	[BOB250] TD_{LO} (mouse, skin) = 4800 mg/kg. Moderately toxic by intraperitoneal. Experimental tumorigen, carcinogen. Mutagenic data. HR = 3.

TABLE 14. TOXICITY AND SAFETY INFORMATION FOR SELECTED CARBONYL COMPOUNDS (continued).

Compound	Formula	CAS No.	Observations[a]
Diethyl hexafluoro-pentanedioate	$(C_2H_5)OC(O)CF_2$ CF_2-$CF_2C(O)CO$ (C_2H_5)	424-40-8	[DJK100] LC_{50} (rat, inhalation, 4 hr) = 1300 mg/m^3, LC_{50} (mouse, inhalation, 2 hr) = 10,000 mg/m^3, LD_{50} (rat, oral) = 5 g/kg, LD_{50} (mouse, oral) = 4200 mg/kg. Moderately toxic by inhalation. Mildly toxic by ingestion. HR = 2.
Ethyl fluoroethanoate	$CH_3CH_2OC(O)$ CH_2F	459-72-3	[EKG500] Poison by intraperi-toneal. HR = 3.
Ethyl 2,2,3-trifluoropropanoate	$C_2H_5OC(O)CF_2$ CH_2F	28781-86-4	[EQB500] No toxicity data. HR = 3.
Fluoroethanoic acid	$CH_2FC(O)OH$	144-49-0	[FIC000] LD_{50} (rat, oral) = 4680 µg/kg, LD_{50} (mouse, oral) = 7 mg/kg. Poison by ingestion, sub-cutaneous, intra-peritoneal, intra-venous. Causes convulsions and ventricular fibrillation in human CNS. HR = 3.
2-Fluoroethyl fluoroethanoate	CH_2FCH_2-$OC(O)CH_2F$	459-99-4	[FIM000] LC_{50} (rat, inhalation, 10 min) = 200 mg/m^3, LC_{50} (mouse, inhalation, 10 min) = 450 µg/m^3. Poison by inhalation, subcutaneous, parenteral. HR = 3.
2-Fluoroethyl 4-fluorobutanoate	CH_2FCH_2-$OC(O)CH_2$ CH_2CH_2F	371-29-9	[FIN000] LC_{50} (rat, inhalation, 10 min) = 200 mg/m^3, LC_{50} (mouse, inhalation, 10 min) = 73 mg/m^3. Poison by inhalation. HR = 3.
Heptafluorobutanoic acid	$C_4H_7C(O)OH$	375-22-4	[HAX500] Poison by intraperito-neal. Probable eye, skin, mucous membrane irritant. HR = 3.
Ethyl heptafluorobutanoate	$C_4H_7C(O)OC_2H_5$	356-27-4	[HAY000] Poison by intra-peritoneal. HR = 3.

TABLE 14. TOXICITY AND SAFETY INFORMATION FOR SELECTED CARBONYL COMPOUNDS (continued).

Compound	Formula	CAS No.	Observations[a]
Hexafluoro-2-propanone	$CF_3C(O)CF_3$	684-16-2	[HCZ000] LC_{50} (rat, inhalation, 3 hr) = 275 ppm, LD_{LO} (rat, oral) = 191 mg/kg. Poison by ingestion, possibly skin contact. Moderately toxic by inhalation. Poisonous irritant to skin, eyes, mucous membranes. Non-flammable. HR = 3.
Methyl bromoethanoate	$CH_3OC(O)CH_2Br$	96-32-2	[MHR250] Poison by intravenous route. HR = 3.
Methyl fluoroethanoate	$CH_3OC(O)CH_2F$	453-18-9	[MKD000] LC_{50} (rat, inhalation, 10 min) = 300 mg/m^3, LC_{50} (mouse, inhalation, 10 min) = 3200 mg/m^3, LD_{50} (rat, oral) = 3500 µg/kg, LD_{50} (mouse, oral) = 5 mg/kg. Poison by ingestion, inhalation, skin contact, subcutaneous, intramuscular, intraperitoneal, parenteral, intravenous. HR = 3.
Pentafluoropropanoic acid	$CF_3CF_2C(O)OH$	422-64-0	[PBF000] LD_{10} (rat, oral) = 750 mg/kg. Poison by intraperitoneal. Moderately toxic by ingestion. HR = 3.
Perfluorodecanoic acid	$CF_3(CF_2)_8C(O)OH$	335-76-2	[PCG725] Poison by intraperitoneal. Experimental reproductive effects. HR = 3.
Methyl perfluoromethoxy-propanoate	$CF_3OCF_2CF_2$-$C(O)OCH_3$	356-69-4	[PCH275] LC_{50} (mouse, inhalation) = 22,000 mg/m^3, LD_{50} (mouse, oral) = 8000 mg/kg. Moderately toxic by intraperitoneal. Mildly toxic by ingestion, inhalation. HR = 2.

TABLE 14. TOXICITY AND SAFETY INFORMATION FOR SELECTED CARBONYL COMPOUNDS (concluded).

Compound	Formula	CAS No.	Observations[a]
Methyl perfluoropropanoate	$CF_3CF_2C(O)OCH_3$	356-69-4	[PCH350] LC_{50} (mouse, inhalation) = 23,000 mg/m^3, LD_{50} (mouse, oral) = 7000 mg/kg. Moderately toxic by intraperitoneal. Mildly toxic by ingestion, inhalation. HR = 2.
Trifluoroethanoic acid	$CF_3C(O)OH$	76-05-1	[TKA250] LC_{50} (rat, inhalation) = 10,000 mg/m^3, LC_{50} (mouse, inhalation) = 13,500 mg/m^3, LD_{50} (rat, oral) = 200 mg/kg. Poison by ingestion, intraperitoneal. Moderately toxic by intravenous. Mildly toxic by inhalation. Corrosive irritant to skin, eyes, mucous membrane. HR = 3.

[a]The SAX No. (Ref. 34) is given in brackets followed by information from that reference. "HR" denotes the SAX Hazard Rating.

Based on the toxicity of the non-halogenated alcohols, there is reason to believe that compounds containing bromine with acceptable toxicity could be found. Table 15 gives information on some alcohols having structural features that could be included in compounds of interest here. Where available, inhalation data have been given. In general, information for toxicity by intravenous and intraperitoneal routes has been omitted.

6. Brominated Ethers

Ethers have relatively low toxicities due to the low reactivity of the C–O–C functional group arising from the high strength of the C–O bond. Several volatile ethers can affect the CNS. However, flammability and the formation of explosive peroxides tend to be more serious problems than toxicity.

Table 16 (Reference 57), Table 17,* and Table 18 (Reference 52) indicate that most of the HFEs exhibit relatively low toxicities and are not mutagenetic. Table 19 contains general toxicity and safety information from Reference 34 on ethers with structural features related to those of interest in this project.

7. Brominated Amines, Morpholines

The acute inhalation toxicity of some HFAs are give in Table 20.* In addition to these, the LC_{Lo} for mouse inhalation has been reported as 500 mg/m^3 for 2,2,2-trifluoroethyl-amine ($(CF_3CH_2)NH_2$, CAS No. = 753-90-2, SAX No. = TKA500) with a SAX HR of 2 (Reference 34). No information to date has been found on brominated amines.

C. FLUOROIODOCARBONS

Iodide is the heaviest halogen with an atomic weight of 126.9. In certain forms, it naturally occurs in biological tissues. The thyroid is the organ engaged in the accumulation of iodine and the synthesis and storage of iodotyrosines and iodothyroinines (Reference 59). In nonbiological molecules, iodine is usually considered an active leaving group that is thought to confer toxicity. This is demonstrated by the high toxicity of iodomethane (CH_3I) and 2- iodo-butane (C_4H_9I), which are both extremely hazardous materials and human mutagens (Reference 34). In 1961, Mathewson stated that alkyl iodides were not useful as anesthetic agents because they did not possess narcotic activity and were relatively nonvolatile (Reference 60). Krantz and colleagues refuted this statement by demonstrating that a number of iodinated compounds had anesthetic activity (Reference 61). Krantz showed that the addition of iodine to "trifluoroethane" increased the parent molecule's anesthetic activity. However, the stepwise fluorination of the terminal carbon atom, yielding mono-, di- and tri-fluoroethyl iodides, respectively, strengthens the carbon-iodine bond in proportion to the degree of fluorination.

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*Misaki, S., and Sekiya, A., "Development of a New Refrigerant," presented at the International Chemical Congress of Pacific Basin Societies, Honolulu, Hawaii, 17-22 December 1995.

TABLE 15. TOXICITY AND SAFETY INFORMATION FOR SELECTED ALCOHOLS.

Compound	Formula	CAS No.	Observations[a]
2,2-bis(2-Bromoethyl)-1,3-propanediol	$CH_2OHC-(CH_2CH_2Br)_2CH_2OH$	3296-90-0	[BHI000] Little toxicity data available. Suspected carcinogen. HR = 3.
1-Bromoacetoxy-2-propanol	$CH_2BrC(O)O-CH_2CH_2(OH)CH_3$	4189-47-3	[BMS250] LD_{50} (rat, oral) = 664 mg/kg, LD_{50} (rabbit, skin) = 813 mg/kg. Moderately toxic by ingestion, skin contact. HR = 2.
2-Bromoethanol	CH_2BrCH_2OH	540-51-2	[BNI500] TD_{Lo} (mouse, oral) = 43,000 mg/kg. Poison by intraperitoneal. Experimental neoplastigen, tumorigen. HR = 3.
2-Bromoethynyl-2-butanol	$CH_3CH_2C(C\equiv C-CH_2Br)(OH)CH_3$	2028-52-6	[BNK350] LD_{50} (mouse, oral) = 532 mg/kg. Moderately toxic by ingestion, other routes. HR = 2.
3-Bromopropanol	$CH_2BrCH_2CH_2OH$	627-18-9	[BNY750] Mutagenic data.
1,3-Dibromo-2-propanol	$CH_2BrCH(OH)-CH_2Br$	96-21-9	[DDR800] Poison by intraperitoneal. HR = 3.
2,3-Dibromo-1-propanol	$CH_2BrCHBrCH_2OH$	96-13-9	[DDS000] Poison by intraperitoneal. HR = 3.
1,3-Difluoro-2-propanol	$CH_2FCH_2CHF(OH)$	453-13-4	[DKI800] Poison by intravenous. HR = 3.
2-Fluoroethanol	CH_2FCH_2OH	371-62-0	[FIE000] LC_{50} (rat, inhalation, 10 min) = 200 mg/m^3, LC_{50} (mouse, inhalation, 10 min) = 1100 mg/m^3. Poison by inhalation, intraperitoneal, subcutaneous, intravenous. HR = 3.
2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9-Hexadecafluorononanol	$CHF_2(CF_2)_7CH_2OH$	376-18-1	[FIE000] LD_{LO} (rat, oral) = 4400 mg/kg. Poison by intraperito-neal. Mildly toxic by ingestion. HR = 3.

TABLE 15. TOXICITY AND SAFETY INFORMATION FOR SELECTED ALCOHOLS (concluded).

Compound	Formula	CAS No.	Observations[a]
1,1,1,3,3,3-Hexafluoro-2-propanol	$CF_3CH(OH)CF_3$	920-66-1	[HDC500] LC_{LO} (rat, inhalation, 4 hr) = 3200 ppm, LD_{50} (mouse, oral) = 600 mg/kg. Poison by intravenous, intraperitoneal. Mildly toxic by inhalation. Severe eye irritant. HR = 3.
[b]Octafluoro-1-pentanol	$C_5H_3F_8OH$	39660-55-4	[OBS800] LC_{50} (mouse, inhalation, 2 hr) = 10,500 mg/m^3, LD_{50} (rat, oral) = 1110 mg/kg. Moderately toxic by ingestion, intraperitoneal. Mildly toxic by inhalation. HR = 2.
2,2,3,3,4,4,5,5-Octafluoro-1-pentanol	$CHF_2CF_2CF_2CF_2$-CH_2OH	355-80-6	[OBU000] LC_{Lo} (rat, inhalation, 4 hr) = 2500 ppm. Mildly toxic by inhalation. HR = 1.
2,2,3,3,3-Pentafluoro-1,1-propanediol	$CF_3CF_2CH(OH)_2$	422-63-9	[PBE500] LD_{50} (mouse, oral) = 600 mg/kg. Moderately toxic by ingestion, intraperitoneal. HR = 2.
2,2,3,3,3-Pentafluoro-1-propanol	$CF_3CF_2CH_2OH$	422-05-9	[PBE500] LD_{Lo} (rat, oral) = 2250 mg/kg. Moderately toxic by ingestion, intraperitoneal. HR = 2.
2,2,2-Trifluoro-1,1-ethanediol	$CF_3CH(OH)_2$	421-53-4	[TJZ000] LD_{50} (mouse, oral) = 600 mg/kg. Moderately toxic by ingestion, intraperitoneal, intravenous. HR = 2.
2,2,2-Trifluoroethanol	CF_3CH_2OH	75-89-8	[TKA350] LC_{50} (mouse, inhalation) = 2900 mg/m^3, LD_{50} (rat, oral) = 240 mg/kg, LD_{50} (rat, skin) = 1680 mg/kg. Poison by ingestion, intraperitoneal, intravenous. Moderately toxic by inhalation, skin contact. Severe skin, eye irritant. HR = 3.

[a] The SAX No. (Ref. 34) is given in brackets followed by information from that reference. "HR" denotes the SAX Hazard Rating.
[b] Isomer not specified.

TABLE 16. TOXICITY OF ETHERS IN NIST EXPLORATORY LIST.

Formula	Hazard rating[a]	Toxicity comments[b]
CF_2HOCF_2H	Not available	No toxicity data available.
CF_2HOCHF_3	Not available	No toxicity data available.
CF_2HOCF_2CHFCl	2	Used as an anesthetic under names enflurane and enthrane. Mildly toxic by inhalation, ingestion, and subcutaneous routes.
$CF_3CHClOCHF_2$	Not available	Used as an anesthetic under name isoflurane.
$C_4F_9C_4F_7O$	Not available	Used as blood substitute.
CF_2BrOCF_2Br	Not available	No toxicity data available.
CF_2BrOCF_3	Not available	No toxicity data available.
CF_2BrOCF_2CHFCl	Not available	No toxicity data available. The non-brominated version is an anesthetic known as enflurane.
C_5F_8O	Not available	No toxicity data available. The perfluorobutyl substituted compound is used as a blood substitute, and the toxicity of this compound may be acceptable.
C_4F_7BrO	Not available	No toxicity data available.

[a] Reference 34.
[b] Reference 35.

TABLE 17. TOXICITY OF HFES.

Compound	[a,b]Acute oral LD_{50}, mg/kg	[a,c]Acute inhalation LC_{50}, mg/L	[a]Mutagenicity, Ames test	[a]Skin irritation, rabbit
$CH_3OCH_2CH_2F$	<30	0.5-2.0 mg/L	Negative	Not available
$CH_3OCF_2CHF_2$	>300	>20	Negative	Non-irritant
$CHF_2OCF_2CH_2F$	>300	>20	Negative	Non-irritant
$CH_3OCF_2CF_2CF_3$	>300	>20	Negative	Non-irritant
$CHF_2OCH_2CF_2CF_3$	>300	>20	Negative	Non-irritant
$CH_3OCH(CF_3)_2$	>300	>20	Negative	Non-irritant
$CH_3CH_2OCF_2CHF_2$	>300	>20	Negative	Slight irritant
$CF_3CH_2OCF_2CHF_2$	>300	>20	Negative	Non-irritant

[a] Misaki, S., and Sekiya, A., "Development of a New Refrigerant," presented at the International Chemical Congress of Pacific Basin Societies, Honolulu, HI, 17-22 Dec. 1995.
[b] Rat, 2 doses. The authors of the paper cited consider an $LD_{50} < 30$ mg/kg to be toxic.
[c] Rat, 4-hr. The authors of the paper cited consider an LC_{50} of 0.5-2.0 mg/L to be toxic.

TABLE 18. HFE TOXICITY EVALUATION.

Compound	Toxicity evaluation
$CH_3CF(CF_3)_2$	Acute inhalation, 3% for 4 hours: no observable effects Subacute inhalation, 6 hr/day for 7 days: NOAEL > 2000 mg/m^3
$CH_3OCF_2CF_3$	Acute inhalation, 3% for 4 hours: no observable effects Inhalation test, 28 days: NOAEL > 20,000 mg/m^3 Ames test: Negative Chromosome aberration: Negative
$CH_3OCF_2CF_2CF_3$	Acute inhalation, 3% for 4 hours: no observable effects Acute oral: LD_{50} > 2000 mg/kg Ames test: Negative Subacute inhalation: 6 hr/day for 7 days: NOAEL 7000 mg/m^3

TABLE 19. TOXICITY AND SAFETY INFORMATION FOR SELECTED ETHERS.

Compound	Formula	CAS No.	Observations[a]
(2-Bromoethyl) ethyl ether	CH_2BrCH_2O-CH_2 CH_3	Not available	[BNK250] No toxicity data available. An insecticide. Dangerous fire hazard. Flash point = 5 °C.
2-Chloro-1,1,2-trifluoroethyl methyl ether	$CHClFCHF_2OCH_3$	425-87-6	[CLR000] LD_{50} (rat, oral) = 5130 mg/kg, LD_{50} (rabbit, skin) = 200 mg/kg. Poison by skin contact. Mildly toxic by ingestion. Severe eye irritant. HR = 3.
2,2-Dichloro-1,1-difluoroethyl methyl ether	$CHCl_2CHF_2OCH_3$	76-38-0	[DFA400] LC_{50} (rat, inhalation, 4 hr) = 123,000 mg/m^3, LC_{50} (mouse, inhalation, 2 hr) = 118,000 mg/m^3, LC_{50} (mammal, inhalation) = 34,000 mg/m^3. Human poison by ingestion. Mildly toxic by inhalation. Eye irritant. HR = 3.
Heptafluoroisobutene methyl ether	$(CF_3)_2C{=}CFOCH_3$	360-53-2	[HAY500] LD_{50} (rat, oral) = 1070 mg/kg, LD_{50} (mouse, oral) = 1070 mg/kg. Poison by intraperitoneal, intravenous. Moderately toxic by ingestion. HR = 3.
Bis(pentafluoroethyl)-ether	$CF_3CF_2OCF_2CF_3$	358-21-4	[PCG750] LC_{50} (mouse, inhalation, 2 hr) = 177,000 mg/m^3, LD_{50} (rat, oral) = 20,000 mg/kg. Mildly toxic by ingestion, inhalation, intravenous. HR = 1.

[a] The SAX No. (Ref. 34) is given in brackets followed by information from that reference. "HR" denotes the SAX Hazard Rating.

TABLE 20. ACUTE INHALATION TOXICITY OF HFAS.

Type	Compound	LC_{50}, mg/m^3
3-hr rat	$(CF_3)_2NCH_3$	>20,000
3-hr rat	$(CF_3)_2NCF_2CF_2H$	>20,000
3-hr rat	$(CF_3)_2NCFHCF_3$	>20,000
3-hr rat	$(CF_3)_2NCH_2CF_3$	>20,000
4-hr rat	$(CF_3)_2NCH_2CF_2H$	>20,000
4-hr rat	$(CF_3)_2NCH_2CH_3$	>20,000

In other words, the adjacent carbon-fluorine bonds more firmly fix the iodine to the molecule, making the iodine a worse leaving group. This was demonstrated by Hine and Ghirardelli by measuring the rate constant for the second order reactions between sodium phenoxide and iodoethane, 1-fluoro-2-iodoethane, 1,1-difluoro-2-iodoethane, and 1,1,1-trifluoro-2-iodoethane (Reference 62). The rate constant for the first reaction proved to be 17,450 times greater than that for the latter reaction, i.e., the carbon-iodine bond was much stronger in 1,1,1-trifluoro-2-iodoethane than in iodoethane.

This limited evidence suggests that highly fluorinated iodocarbons may have the lowest toxicities of the iodinated chemicals. In particular, perfluoroiodocarbons appear to be the least toxic iodine-containing halocarbons, at least for anesthesia. This conclusion is based, in part, on the fact that perfluorinated halocarbons do not have acidic hydrogen. However, for cardiac sensitization this supposition may not be true. A summary of available toxicity information on fluoroiodocarbons is provided below.

Early in this century, intravenous radiolabeled trifluoroiodomethane (CF_3I^{131}) was used to measure cerebral blood flow in cats. The chemical appeared to have no observable toxic complications in the time period studied (12-36 hours) (Reference 63). Lu et al. investigated a number of mixed halocarbons as inhalation anesthetics and showed that inhalation of 50 percent CF_3I in a dog without the administration of adrenaline was not lethal or anesthetic, although the exposure produced coughing, choking, retching and convulsions after 30 sec (Reference 64). The effective fire extinguishment concentration for CF_3I is well below 50 percent.

As a result of the recent USAF Second Generation Streaming Agent program, the amount of toxicological information on CF_3I increased dramatically in a relatively short time span due to a coordinated working group effort (Reference 65). Within a year, short-term (acute) inhalation studies, cardiac sensitization tests, and preliminary genetic toxicity tests were performed (Table 21). Acute inhalation studies revealed that CF_3I has a low order of toxicity, with an LC_{50} value for a 15-min exposure in rats equal to 27.4 percent. Consequences of short-term exposures to CF_3I included anesthesia, salivation, and audible breathing. Blood chemistry measurements showed no abnormal results.

TABLE 21. SUMMARY OF TOXICOLOGICAL INFORMATION ON CF_3I.

Toxicological property	Value, vol.% or status
LC50, rat, 15 min	27.4
Cardiac Sensitization	
NOAEL	0.2
LOAEL	0.4
Carcengenticity/Mutengenicity	
Genotoxicity Tests	
Ames Test	4 out of 5 positive
Mouse Lymphoma	Unequivocally negative
Mouse Micronucleus	Borderline positive (reanalysis of data in progress)
Subchronic Test, 13 wks (90 days)	Unknown (in progress at Armstrong Labs)
Chronic Test, Whole Life	Unknown
Developmental Toxicity	Unknown (testing planned at Armstrong Labs)

Cardiac sensitization, a potential adverse effect from exposure to halons and CFCs, is the production of irregular heart beats and sometimes cardiac arrest in response to exposure of air-borne chemicals and intravenous adrenaline. CF_3I cardiac sensitization exposure studies indicated that the NOAEL, the highest concentration at which no detrimental responses occur, is 0.2 percent and the LOAEL, the lowest concentration at which negative effects do occur, is 0.4 percent. Since the expected design concentration for CF_3I will be in the range of 5 to 7 percent, this cardiac toxicity profile will preclude its use for total flooding applications in

normally occupied areas. However, CF_3I is still a highly promising alternative for total-flooding in unoccupied areas and for streaming applications.

The potential for carcinogenic effects of CF_3I has not been completely evaluated to date. The screening results in test-tube assays are mixed; some test indicate the potential for genetic alterations, while others suggest no changes leading to cancer-causing results. Mixed results on these types of screening tests are not unusual.

A number of toxicity studies have been performed on CF_3CH_2I (2,2,2-trifluoro-1-iodoethane), which is a liquid at room temperature (BP = 55 °C). Robbins exposed mice for 10 min to CF_3CH_2I and derived the LC_{50} at 5 percent and the AD_{50} at 1.25 percent (Reference 66). For comparison to a more well-known halon replacement candidate, Robbins derived values for HCFC-123 (CF_3CHCl_2) as 7.7 and 2.7 percent for the LC_{50} and AD_{50}, respectively. Questions about the purity of chemicals available for this study suggests these results should be viewed with some discretion.

Robbins also observed the anesthetic activity of this CF_3CH_2I in 3 dogs (Reference 66). The chemical was anesthetic and produced hypotension, variations in cardiac nodal rhythm, and ventricular extrasystoles. Burns and colleagues tested the anesthetic activity of CF_3CH_2I in mice by exposing them by inhalation for 30 min to varying concentrations (Reference 67). They found that anesthetic induction occurred within 1-2 min at concentration ranging from 5 to 7.3 percent and recovery was slow—between 5-12 min; however, all mice survived the exposure. Krantz et al. (Reference 61) also studied CF_3CH_2I in detail as a potent anesthetic agent and found that it had an anesthetic potency approximately the same as halothane ($CF_3CHBrCl$). Krantz found that it produced no functional hepatic impairment in dogs as shown by the sulfobromophthalein test. The blood pressure in dogs was not significantly lowered with this agent. The electroencephalograms in dogs and monkeys showed no unusual disturbances. The dog's heart did not show any significant alterations during anesthesia; however, variations in cardiac nodal rhythm and ventricular extrasystoles were observed in the monkey's heart. CF_3CH_2I did not appear to be decomposed by body tissues. No increase in protein-bound-iodine or iodide in serum was seen after exposure. In 1961, Krantz administered CF_3CH_2I by inhalation to a healthy male volunteer. The subject experienced anesthesia within 20 min using a dose of 11 mL. The induction was

without incidence and no changes were seen in the electrocardiogram or blood pressure recordings. The recovery was rapid and uneventful. The subject did not experience any post-anesthetic sequelae. The chemical was used in a series of patients after this trial, but was later abandoned owing to the frequent occurrence of cardiac arrhythmias. Consequently, CF_3CH_2I is not recommended for consideration as a halon replacement.

Krantz et al. (Reference 45) investigated the anesthetic potency of CF_3CF_2I and found that 10 percent was anesthetic in mice and rats but not dogs or monkeys, and the recovery from anesthesia in mice was uneventful. Even 50 percent was not anesthetic in monkeys; however, it did provoke severe cardiac arrhythmias in monkeys upon inhalation of the agent for 1 min. They also studied CF_3CHFI (BP = 39 °C) at 24 mL/min and found that anesthesia, with good relaxation and no irritation, was produced in mice, but not monkeys. Prominent cardiac arrhythmias were observed in monkeys. This research group also tested an iodinated ether, CH_3OCF_2CHFI (BP = 118 °C). While it caused anesthesia with good relaxation, it sensitized the heart to epinephrine causing cardiac arrhythmias.

Di Paolo and Sandorfy investigated the hydrogen bond-breaking ability of several chlorine-, bromine- and iodine-containing fluorocarbons in an attempt to link this mechanism with anesthetic potency (Reference 68). Using infrared spectroscopy, they measured the opening of N-H···N, O-H···O, and N-H···O=C types of hydrogen bonds in solution. They found that perfluorinated molecules have no hydrogen bond-breaking potency. Fluorocarbons containing only chlorine, fluorine and carbon had only a weak hydrogen bond-breaking ability. Bromine- and iodine-containing fluorocarbons were strong hydrogen bond breakers, and for nonhydrogen-containing halocarbons, the order of increasing hydrogen bond-breaking ability was Cl < Br < I. Also, chlorofluorocarbons became strong hydrogen bond breakers if they contained a hydrogen ($CF_3CCl_3 << CF_3CHCl_2$).

Ulm and colleagues (References 51 and 69) investigated a number of iodine-containing alkanes and determined that the toxicity of this class of chemicals was clearly related to the structure and decreased in the order of tertiary > secondary > primary. Thus, $(CF_3)_3CI$ (tertiary) was more toxic than $(CF_3)_2CFI$ (secondary), which in turn was more toxic than $CF_3CF_2CF_2I$ (primary). This can be seen in results obtained from Ulm on several iodocarbons (Table 22).

TABLE 22. ACUTE LETHALITY OF FLUOROIODOCARBONS.

Compound formula	1-Hr mouse LC_{50}, ppm[a]	4-Hr mouse LC_{50}, ppm[a]
[b]C_2F_5I	>10,000	82,000
ICF_2CF_2I	50-100	75
$CF_2ClCClFI$	50-100	Unknown
[b]CF_3CFICF_3	1,000-2,000	1,532 (900)
CF_3CFICF_2Cl	50-100	---
[b]C_4F_9I	>10,000	>20,000
$C_2F_5CH_2CH_2I$	100-500	219
$C_3F_7CH_2CH_2I$	250-500	
$C_4F_9CH_2CH_2I$	1,000-5,000	2,003
[b]*n*-$C_6F_{13}I$	>13,500	---
$CF(CF_3)_2CFICF_3$	250-500	---
$C(CF_3)_3I$	30-100	---
$C(C_2F_5)(CF_3)_2I$	<50	---
$C(C_3F_7)(CF_3)_2I$	<50 (<25)	---

[a]References 51, 69, and Ulm, K., Hoechst AG Wiss. Labor, personal communication, 1992.

[b]LC_{50} values for Wistar rats given in parentheses.

The authors stated that tertiary iodides react with nucleophiles under physiological conditions, forming other, sometimes more toxic, products such as perfluoro-2-hydro-2-methyl-pentane.

Several generalizations about the toxicity of fluoroiodocarbons can be made:

(1) For acute lethality of fluoroiodocarbons, the toxicity is lowest (highest LC_{50}) for 1-iodoperfluorocarbons (primary).

(2) Fully halogenated compounds have the lowest toxicity. Hydrogen-containing iodocarbons tend to be highly anesthetic.

D. METAL COMPOUNDS

In considering the toxic properties of metals, it is important to call attention to certain general properties of this class of chemicals. Metals seldom interface with biological systems in their elemental form. Rather, they occur as distinct compounds that vary considerably in their ability to pass across biological membranes and hence, potentially cause damage. Table 23 (Reference 70) presents a classification of the effects and concerns surrounding metals. Although the metal complex is crucial for determining the specific toxicity of metal compounds, Table 24 (Reference 70) shows several generalizations about the target organs for various types of metal compounds.

Soluble salts of metals dissociate readily in an aqueous environment of biological systems, thereby facilitating their transport as metal ions. On the other hand, insoluble metal salts are relatively poorly absorbed in the body, especially if they are in the polymeric state of aggregation. Even in the case of soluble salts, several factors influence their absorptivity, i.e., transport of soluble salts into biological systems may be hampered in the presence of anions that favor the formation of insoluble salts.

The metals being considered as firefighting agents include cobalt, iron, manganese, titanium, and zinc. Most of the metallics are alkyl metals where the metal is firmly bound to carbon atoms and remains largely intact in biological systems. They are lipid soluble which pass readily and unaltered across biological membranes into cells. After absorption, alkyl metals are distributed according to their lipid solubility characteristics.

As seen from Table 23, metal carbonyls are generally considered rather hazardous, more so than the metal itself or other compounds. For example, the acceptable level for metallic nickel and its soluble salts is 1.0 mg/m^3, whereas that for nickel carbonyl is 0.007 mg/m^3 (Reference 70). Hydrides of metals also tend to be more toxic than other metallic compounds.

The route of entry plays an important role in determining the toxicity of a metal compound. Inhalation of metals may occur in firefighting scenarios. Solubility is particularly important in determining the fate of metals deposited in the respiratory airways. The more insoluble the metal compound, the more likely it is to be cleared from the pulmonary tract by

TABLE 23. EFFECTS AND CONCERNS OF METALS.

Metal	Essential for mammals	Moderate to severe industrial hazard	Factors in environmental or nonoccupational disease	Accidental poison	Limited industrial hazard
Aluminum					+
Antimony		+		+	
Arsenic		+	+	+	
Barium					+
Beryllium		+	+		
Bismuth					+
Boranes		+			
Cadmium		+	+	+	
Cesium					+
Chromium (III)	+				
Chromium (VI)		+			
Cobalt	+		+		
Copper	+			+	+
Gallium					+
Germanium					+
Iron	+		+	+	+
Lanthanides					+
Lead		+	+	+	
Magnesium	+				+
Manganese	+	+			
Mercury		+	+	+	
Metal hydrides & carbonyls		+			
Molybdenum	+				+
Nickel		+	+		
Selenium	+	+	+		
Silver		+			
Strontium	+				+
Tin (organic)		+		+	
Titanium					+
Vanadium	+	+	?		
Zinc	+			?	+
Zirconium					+

TABLE 24. TARGET ORGANS OF METALS.

Metal	GI tract	Respiratory Tract	CNS	CV System	Liver	Skin	Blood	Kidney	Bone	Endocrine
Aluminum		+								
Antimony	+	+		+	+	+				
Arsenic	+	+	+		+	+	+			+
Barium	+	+	+	+		+				
Beryllium		+				+			+	
Bismuth					+	+		+		
Boranes		+			+			+		
Cadmium	+	+	+	+				+	+	
Chromium		+	+		+	+		+		
Cobalt	+	+	+	+		+				+
Copper	+						+			
Gallium			+			+		+	+	
Germanium	+	+		+						
Iron	+	+	+		+		+			+
Lanthanides		+			+		+			
Lead	+		+				+	+		
Magnesium			+							
Manganese		+	+							
Mercury		+	+					+		
Metal hydrides							+			
Molybdenum					+		+	+	+	
Nickel		+	+			+				
Selenium	+		+		+	+				
Silver		+				+		+		
Strontium				+						
Tin (organic)	+		+							
Titanium		+								
Vanadium		+	+			+		+		
Zinc	+						+		+	
Zirconium						+	+			

retrograde movement to the pharynx and then swallowed. With retrograde movement, systemic absorption is minimized.

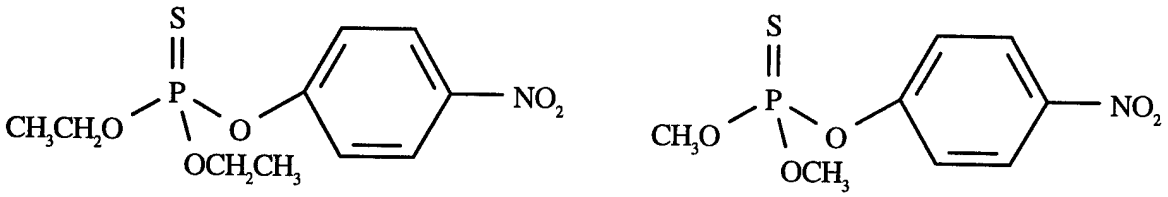
Lung levels of certain metals such as titanium, chromium, tin, cadmium, lead, and aluminum increases up to age 40 years due to the accumulation of insoluble particles. Levels of nickel, tin, strontium, cadmium, and lead increase in other tissues as well due to inhalation and then relocation within the body (Reference 70).

Topical exposure to certain metals may also present a hazard in firefighting settings resulting in skin and eye irritation or sensitization and also providing an avenue for absorption causing systemic toxicity. Dermal exposure to abraded skin can produced serious toxicity concerns. Cobalt and nickel are the only metals being presently considered that have the skin as a target organ.

E. PHOSPHORUS COMPOUNDS

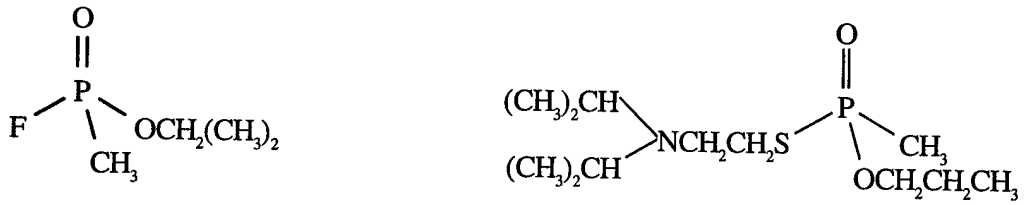
One concern is that a number of phosphorus compounds (particularly phosphate esters) are cholinesterase inhibitors. Among these are poisonous insecticides such as parathion and methyl parathion (Figure 4) and chemical warfare agents such as GB (Sarin) and VX (Figure 5; Reference 71). Some compounds with P-N bonds are cholinesterase inhibitors. One example is tetramethylpyrophosphoramide, $(CH_3)_2NP(O)OP(O)N(CH_3)_2$, which is a poison by numerous routes and has a 4-hour rat inhalation LC_{50} of 8 mg/m^3 (Reference 34).

Table 25 contains information on toxicity and safety of some common phosphorus-containing compounds (Reference 34). Relatively little information is available for compounds having structural features similar to the compounds of interest in this report. The information in Table 25 is for typical baseline phosphorus compounds for reference purposes. Much of the toxicity information is for esters of phosphoric and phosphorous (phosphonic) acid. In general, phosphite (phosphonate) esters appear to have a lower toxicity than the phosphate esters, which are often cholinesterase inhibitors. Many phosphites, however, decompose to give highly toxic phosphine (PH_3) when heated.



Parathion Methyl Parathion

Figure 4. Cholinesterase Inhibitor Insecticides.



GB (Sarin) VX

Figure 5. Chemical Warfare Agents.

TABLE 25. TOXICITY AND SAFETY INFORMATION FOR SELECTED PHOSPHORUS COMPOUNDS.

Compound	Formula	CAS No.	Observations[a]
bis(trifluoromethyl)-chlorophosphine	$PCl(CF_3)_2$	650-52-2	[BLO280] Ignites spontaneously in air. HR = 3.
dibutylphosphate	$O=P(OH)(OC_4H_9)_2$	107-66-4	[DEG600] LD_{50} (rat, oral) = 3200 mg/kg. Moderately toxic by ingestion. HR = 2.
dibutylphosphonate	$O=PH(OC_4H_9)_2$	1809-19-4	[DEG800] LD_{50} (rat, oral) = 3200 mg/kg, LD_{50} (rabbit, skin) = 1990 mg/kg. Moderately toxic by ingestion, skin contact. Severe eye irritant. HR = 2.
diethylphosphonate	$O=PH(OC_2H_5)_2$	762-04-5	[DJW400] LD_{50} (rat, oral) = 3900 mg/kg, LD_{50} (rabbit, skin) = 2165 mg/kg. Moderately toxic by ingestion, skin contact. HR = 2.
diisopropyl methylphosphonate	$O=P(CH_3)-[OCH(CH_3)_2]_2$	1445-75-6	[DJW400] LD_{50} (rat, oral) = 826 mg/kg, LD_{50} (mouse, oral) = 1041 mg/kg. Moderately toxic by ingestion, skin contact. HR = 2.
diisopropylphos-phonate	$O=PH[OCH(CH_3)_2]_2$	1809-20-7	[DNQ600] LD_{50} (rat, oral) = 3100 mg/kg, LD_{50} (rabbit, skin) = 5700 mg/kg. Moderately toxic by ingestion. Mildly toxic by skin contact. HR = 2.
dimethyl(1,2-dibromo-2,2-dichloroethyl) phosphate	$O=P(OCH_3)_2-(OCHBrCBrCl_2)$	300-76-5	[DRJ600] LD_{50} (rat, inhalation) = 7.70 mg/kg, LD_{50} (mouse, inhalation) = 156 mg/kg. LD_{50} (rat, oral) = 250 mg/kg, LD_{50} (rabbit, skin) = 1100 mg/kg. Poison by ingestion, inhalation. Moderately toxic by skin contact. Skin irritant. Insecticide of the cholinesterase inhibitor type. HR = 3.

Table 25. TOXICITY AND SAFETY INFORMATION FOR SELECTED PHOSPHORUS COMPOUNDS (continued).

Compound	Formula	CAS No.	Observations[a]
dimethyl(2,2-dichloroethenyl)-phosphate	$O=P(OCH_3)_2$-$(CH=Cl_2)$	62-73-7	[DRJ600] LC_{50} (rat, inhalation, 4 hr) = 15 mg/m^3, LC_{50} (mouse, inhalation, 4 hr) = 13 mg/kg, LD_{50} (rat, oral) = 25 mg/kg, LD_{50} (rabbit, skin) = 107 mg/kg. Poison by ingestion, inhalation, skin contact, intraperitoneal, intravenous, subcutaneous. Experimental teratogen, suspected carcinogen Cholinesterase inhibitor. HR = 3.
dimethylphosphonate	$O=PH(OCH_3)_2$	868-85-9	[DSG600] LD_{50} (rat, oral) = 3050 mg/kg, LD_{50} (rabbit, skin) = 2400 mg/kg. Moderately toxic by ingestion, skin contact. Experimental carcinogen. Skin, eye irritant. HR = 3.
hexaethyltetraphosphate	$OP(OC_2H_5)_2$-$[OP(O)(OC_2H_5)]_2$-$OP(O)(OC_2H_5)_2$	757-58-4	[HCY000] Liquid. MP = -40 °C (-40 F). LD_{50} (rat, oral) = 7 mg/kg, LD_{50} (mouse, oral) = 56 mg/kg, LD_{LO} (rat, skin) = 15 mg/kg. Poison by ingestion, skin contact, intraperitoneal, subcutaneous, intravenous, intramuscular. HR = 3.
tris(2-chloroethyl) phosphite	[b]$O=P(OCH_2CH_2Cl)_2$-(CH_2CH_2Cl)	149-08-9	[PHO000] LD_{50} (rat, oral) = 100 mg/kg, LD_{50} (rabbit, skin) = 810 mg/kg. Poison by ingestion, intraperitoneal. Moderately toxic by skin contact. Severe eye irritant. HR = 3.
tris(2-fluoroethyl) phosphite	[b]$O=P(OCH_2CH_2F)_2$-(CH_2CH_2F)	63980-61-0	[PHO250] LC_{LO} (rat, inhalation, 10 min) = 500 mg/m^3, LC_{LO} (mouse, inhalation, 10 min) = 1000 mg/m^3. Poison by inhalation. HR = 3.

Table 25. TOXICITY AND SAFETY INFORMATION FOR SELECTED PHOSPHORUS COMPOUNDS (continued).

Compound	Formula	CAS No.	Observations[a]
tetraethylpyrophos-phate	$P(O)(OC_2H_5)_2$-$OP(O)(OC_2H_5)_2$	107-49-3	[TCF250] LD_{50} (rat, oral) = 0.5 mg/kg, LD_{50} (mouse, oral) = 7 mg/m^3, LD_{50} (rat, skin) = 2.4 mg/m^3. Poison by ingestion, skin contact, intraperitoneal, intramus-cular, other. Cholinesterase inhibitor. HR = 3.
triethylphosphate	$O=P(OC_2H_5)_3$	78-40-0	[TJT750] LD_{LO} (rat, oral) = 1600 mg/kg, LD_{LO} (mouse, oral) = 1600 mg/m^3. Moderately toxic by ingestion, intraperitoneal, and intravenous. Reproductive effects. Mutagenic data. Cholinesterase inhibitor. HR = 2.
triethylphosphite	[b]$O=P(C_2H_5)(OC_2H_5)_2$	122-52-1	[TJT800] LD_{50} (rat, oral) = 3200 mg/kg. Moderately toxic by ingestion. Skin, eye irritant. HR = 2.
triisooctylphosphite	[b]$O=P[(CH_2)_5CH(CH_3)_2]$-$[O(CH_2)_5CH(CH_3)_2]_2$	25103-12-3	[TKT000] LD_{50} (rat, oral) = 9200 mg/kg, LD_{50} (rabbit, skin) = 3970 mg/kg. Moderately toxic by skin contact. Mildly toxic by ingestion. Skin irritant. HR = 2.
triisooctylphosphite	[b]$O=P[(CH_2)_5CH(CH_3)_2]$-$[O(CH_2)_5CH(CH_3)_2]_2$	25103-12-3	[TKT000] LD_{50} (rat, oral) = 9200 mg/kg, LD_{50} (rabbit, skin) = 3970 mg/kg. Moderately toxic by skin contact. Mildly toxic by inges-tion. Skin irritant. HR = 2.
triisopropylphosphite	[b]$O=P[CH(CH_3)_2]$-$[OCH(CH_3)_2]_2$	116-17-0	[TKT500] LD_{50} (rat, oral) = 167 mg/kg. Poison by ingestion. Moderately toxic by intraperi-toneal. HR = 3.
trimethylphosphite	[b]$O=P(CH_3)(OCH_3)_2$	121-45-9	[TMD500] LD_{50} (rat, oral) = 1600 mg/kg, LD_{LO} (rabbit, skin) = 2200 mg/kg. Moderately toxic by ingestion, skin contact. Experi-mental teratogen. Severe skin, eye irritant. HR = 2.

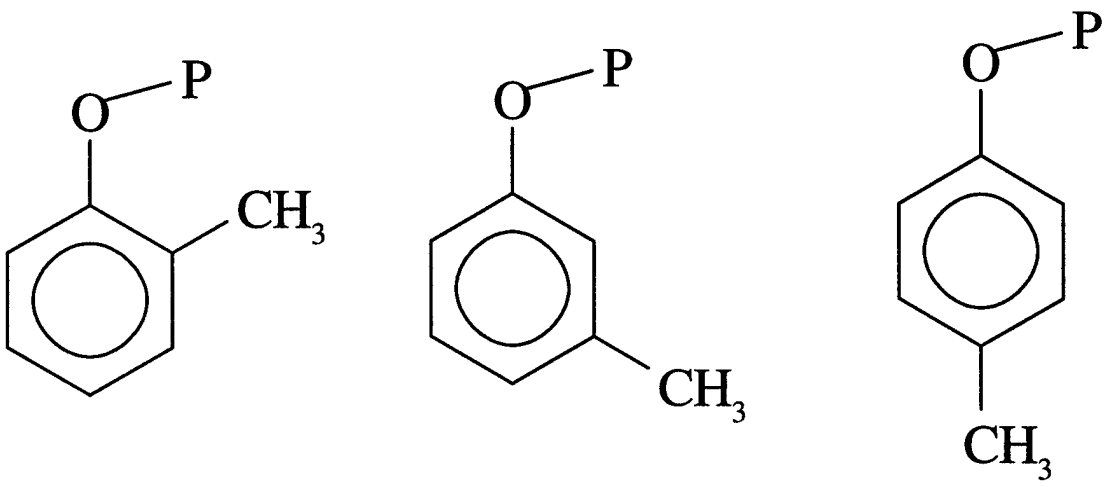
Table 25. TOXICITY AND SAFETY INFORMATION FOR SELECTED PHOSPHORUS COMPOUNDS (concluded).

Compound	Formula	CAS No.	Observations[a]
triphenylphosphite	[b]$O=P(C_6H_5)(OC_6H_5)_2$	101-02-0	[TMU250] LD_{50} (rat, oral) = 1600 mg/kg, LD_{50} (mouse, oral) = 1333 mg/kg. Poison by intraperitoneal, subcutaneous. Moderately toxic by ingestion. Severe skin irritant. HR = 3.
tris(1-bromo-3-chloro-isopropyl)-phosphate	$O=P[OCBr-(CH_3)(CH_2Cl)]_3$	7328-28-1	[TNE500] Mutagenic data only.
tris(2-bromoethyl) phosphate	$O=P(OCH_2CH_2Br)]_3$	27568-90-7	[TNE600] LC_{Lo} (rat, inhalation) = 260 mg/m^3. Poison by inhalation. HR = 3.
tributylphosphine oxide	$O=P(C_4H_9)_3$	814-29-9	[TNE750] Poison by intravenous. Eye irritant. HR = 3.
tritolylphosphate (tricresylphosphate)	$O=P(OC_6H_5CH_3)_3$	1330-78-5	[TNP500] LD_{50} (rat, oral) = 5190 mg/kg, LD_{50} (mouse, oral) = 3900 mg/kg. Poison by ingestion. Moderately toxic by skin contact. Eye, skin irritant. HR = 3.
tri-2-tolylphosphate (tri-*o*-cresylphosphate)	$O=P(OC_6H_5CH_3)_3$	78-30-8	[TNP500] LD_{50} (rat, oral) = 1160 mg/kg. Poison by ingestion, sub-cutaneous, intramuscular, intra-venous, intraperitoneal. Moder-ately toxic by ingestion. HR = 3.

[a]The SAX No. (Ref. 34) is given in brackets followed by information from that reference. "HR" denotes the SAX Hazard Rating.

[b]The most probable (phosphonate) structure is given for these compounds, which can also be assigned the phosphite structure, $P(OR)_3$. Both forms may exist.

Tricresylphosphate (tritolylphosphate, $O=P(OC_6H_4CH_3)_3$) is widely used as an organophosphate plasticizer in vinyl plastics and as a flame retardant additive for hydraulic fluids. The compound exists as *ortho*, *meta*, and *para* forms depending on the relative positions of the methyl and the oxy group on the phenyl rings (Figure 6). The isomer tri-*o*-cresylphosphate is more toxic than the *meta* form, and much more toxic than the *para* form (Reference 34). No evidence of carcinogenic activity has been found for tricresylphosphate during rat and mouse studies; however, non-neoplastic lesions have been found (Reference 72).



Ortho Meta Para

Figure 6. Isomers of Tolyl Groups on Cresylphosphate.

Extensive toxicity evaluations, including acute toxicity tests, inhalation, and skin kinetic studies, and 21-day repeated inhalation and dermal exposure testing have been carried out on a mixture formed from the reaction of $P_3N_3Cl_6$ with alkylphenols, phenol, and trifluoroethanol (Reference 73). This reaction produces compounds of the type $P_3N_3(OR)_6$, where the R groups are mixtures of aryloxy and fluoroalkoxy groups. The test sample had the "empirical" formula $P_3N_3(OCH_2CF_3)_{3.5}(OC_6H_5)_{1.25}(m\text{-}OC_6H_4CH_3)_{0.87}(p\text{-}OC_6H_4CH_3)_{0.38}$. The test data indicate no toxicity to test animals from the phosphazene fluid. The data also indicate that the fluid is poorly absorbed into the body by any route and appears to produce little or no effect when artificially introduced into the body.

As part of the AAWG work, 3M Company performed limited toxicity testing on the hexafluorocyclo-triphosphazene ($P_3N_3F_6$).* This compound, with a purity of greater than 99.9 percent, was screened for acute inhalation toxicity in two rodent species. A single rat was exposed to test material at a nominal concentration of 1000 ppm (0.1 percent) for 10 minutes. Within 3 minutes, the animal showed signs of hyperactivity and within 5 minutes had difficulty breathing and appeared moribund. The rat died 10 minutes after inhalation; necropsy revealed deep red, fluid-filled lungs. Mice exposed to the test material at a nominal concentration of 1000 ppm (0.1 percent) for 20 minutes exhibited symptomology identical to the rat. Death occurred 20 minutes after initiation of exposure; no necropsy was performed.

Death appeared to be due to pulmonary edema caused by the breakdown of the blood-air barrier. Other agents that cause this effect include hydrohalogen gases (including HF), alkylating agents, and several fluoroalkenes. However, the high purity of the test material (>99.9 percent) indicates that the toxic response was likely attributable to the test compound and not an impurity. The rapid onset of symptoms and death suggest that the eventual 4-hour rat inhalation LC_{50} for hexafluorocyclotriphosphazene would be much lower than 1000 ppm (0.1 percent).

Studies show that highly polymeric phosphazenes show no mutagenic activity toward Salmonella typhimurium tester strains TA 100 and TA 98 (Reference 74). They do, however, exhibit some antibacterial character.

In general, due to toxicity and combustibility, phosphines probably cannot be considered as candidates for halon substitution, even when highly fluorinated alkyl substituents are present. Tris(trifluoromethyl)phosphine, $P(CF_3)_3$, ignites spontaneously on contact with air (Reference 34) and it was observed during the course of the synthetic work that halogenated heptafluoropropylphosphines are highly corrosive to diverse materials including paper, some metals, silicones, and polyfluoroalkenes.

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*The official International Union of Pure and Applied Chemistry (IUPAC) name is 2,2,4,4,6,6-hexafluoro-2,2,4,4,6,6-hexahydro-1,3,5,2,4,6-triazatriphosphorine (CAS No. 15599-91-4); however, for convenience, the more common name hexafluorocyclotriphosphazene is used here.

F. SILICON COMPOUNDS

Many organosilicon compounds are relatively stable, inert, and have a low toxicity. Of particular importance is that silicon compounds have lower atmospheric lifetimes than do the closely related carbon compounds. Thus, all other things being equal, GWPs and ODPs are lower. In fact, it is likely that one can incorporate bromine in silanes and siloxanes without having unacceptably large ODPs, and this approach is evaluated in this study. Silicon compounds that do not contain bromine or other group providing chemical fire suppression (see below) do not appear to have a significant inherent fire suppression activity other than that provided by heat absorption and other physical processes.

Reference 24 contains significant amounts of data on the toxicity of silicon compounds in general, but no information on brominated silicon compounds. Silanes of major industrial importance are organochlorosilanes, methylchlorosilanes, trichlorosilane, tetrachlorosilane, phenylchlorosilanes, phenylethoxysilanes, methylethoxysilanes, and silane (Reference 75). Most of these contain direct Si-X bonds and are, therefore, strong irritants and cause pulmonary distress. In general, little is known about the toxicity of other silanes, particularly organosilanes not containing direct Si-X bonds (Reference 52). The silanes have been reported to be highly toxic by inhalation, ingestion, or skin contact, following acute exposure (Reference 75); however, this generality is likely to be due to the fact that most silanes in general use contain Si-X bonds. The American Conference of Governmental Industrial Hygienists (ACGIH) has proposed (1983/1984) a Threshold Limit Value (TLV) Time Weighted Average (TWA) exposure limits of 5 ppm (7 mg/m^3) for silane but no STEL value (Reference 75). Note that this is 10-fold higher than previous values set by ACGIH.

Relatively little toxicological and related information is available on pure siloxanes (Table 26; Reference 34), although a large amount is available for siloxane polymeric oils under tradenames. Note that very large differences in the hazard ratings are reported for hexamethyl-disiloxane listed under two different names. For the most part, the polymeric siloxanes, in particular, the methylpolysiloxanes have rather low toxicities. In most cases, the LD_{50} for oral routes are greater than 10 g/kg of body weight. Where significant toxicity or irritation is

TABLE 26. DANGEROUS PROPERTIES OF SILOXANES.

Compound	Formula	CAS No.	Observations[a]
hexamethyldisiloxane (designated bistrimethylsilyl oxide)	$(CH_3)_3SiOSi(CH_3)_3$	---	[BLR250] Dangerous fire hazard. Flash point = -1 °C. HR = 3.
hexamethyldisiloxane	$(CH_3)_3SiOSi(CH_3)_3$	107-46-0	[HEE000] LD_{LO} (guinea pig, oral) = 50 g/kg. Mildly toxic by ingestion and intraperitoneal. Skin irritant. HR = 1.

[a]The SAX No. (Ref. 34) is given in brackets followed by information from that reference. "HR" denotes the SAX Hazard Rating.

observed, it is often due to the presence of reactive termination groups on the polysiloxane chain. Some methylpolysiloxanes have been reported to be tumorigens (Reference 34).

G. HAZARD IDENTIFICATION SUMMARY

1. Bromoalkanes

The bromoalkanes, in particular 1-bromopropane, have some of the highest LC_{50} values (lowest toxicities) of the advanced chemical families investigated. The optimal number of carbons (considering toxicity and flammability) appears to be limited to three (e.g., 1-bromopropane). Although some of the bromoalkanes are said to pose a dangerous fire hazard, testing indicates that the flammability is actually relatively low and that blending with a nonflammable material, such as an HFC, can eliminate flammability. Blending will also likely reduce the toxicity effects of the blended bromoalkane. The global environmental characteristics of the 1-bromopropane are also acceptable. This compound is also being commercialized as an ODS replacement in the solvent sector (Reference 76).

2. Bromoalkenes

The lack of inhalation toxicity data on bromoalkenes, coupled with species, test duration, and effect (LC_{50} vs. LC_{LO}) differences, make it difficult to identify toxicity trends vis-à-vis the location of the double bond and the halogen atoms. Nonetheless, several conclusions can be made on alkenes in general based on the limited amount of data that is available.

(a) Chlorinated compounds tend to be more toxic.

(b) Compounds with more than type of one halogen atom appear to be more toxic than compounds with only a single halogen type.

(c) Fully fluorinated compounds, except those containing CF_3 groups, appear to be fairly non-toxic. The fully fluorinated propene appears to be more toxic than the ethene or the butene. Insufficient data exist to verify the effect of the location of the double bond in the fully fluorinated butene.

(d) The replacement of a halogen or hydrogen atom by a CF_3 group appears to increase toxicity significantly; however, this is based only on one case.

(e) Fully halogenated propenes appear to be more toxic than fully halogenated ethenes or butenes.

(f) This class of compounds (chemical family) has the greatest potential for producing an advance streaming agent with acceptable toxicity and non-flammability.

3. Brominated Aromatics

Aromatic halocarbons have wide-ranging industrial use, and, therefore, significant toxicological information is available for these compounds. Many of the aromatic halocarbons are irritants, can affect the respiratory system and liver, and are highly flammable. Because of the high toxicity (e.g., limited available acceptable data) and possible flammability of bromominated aromatics their consideration as halon replacements is of low priority at this time.

4. Brominated Carbonyls

Carbonyl compounds of interest include ketones, aldehydes, esters, and carboxylic acids. Many members of the family are mutagens, and all have anesthetic properties. These compounds tend to attack exposed moist tissue, some act as neurotoxins, and they can be asphyxiants and narcotics. For these reason, these highly corrosive and irritating compounds are not being considered as halon replacements at this time.

5. Brominated Alcohols

The toxicity of higher molecular weight alcohols range from relatively low to moderate. Based on the toxicity of the non-halogenated alcohols, there is reason to believe that alcohols containing bromine with acceptable toxicity could be found. However, little effort is being expended on these compounds, due to lack of data and minimal compound availability.

6. Brominated Ethers

The ether linkage enhances reactivity toward hydroxyl free radicals and, therefore, leads to lower atmospheric lifetimes. On the other hand, this is somewhat offset by fluorine substitution. It is possible that bromine substitution would be allowable; however, ethers are not as easily removed from the atmosphere as are amines, for example, and bromine substitution may lead to unacceptable ozone depletion potentials. The toxicity of ethers is relatively low compared to other materials evaluated in this report. The ether linkage has a relatively low biological and chemical reactivity. The low toxicity is due to the low reactivity of the C–O–C functional group arising from the high strength of the C–O bond. Several volatile ethers can affect the CNS. However, flammability and the formation of explosive peroxides tend to be more serious problems than toxicity. Thus, brominated ethers are not being considered at this time.

7. Fluorinated Amines

Totally fluorinated amines could cause atmospheric lifetime and global warming problems. On the other hand, amines with partial fluorination are likely to have relatively short

atmospheric lifetimes. It is difficult, however, to determine whether the lifetime would be sufficiently short to allow bromine substitution. Simple alkyl-substituted amines range from nontoxic in the case of totally fluorinated compounds to highly toxic for nonfluorinated materials. A major question is how the toxicity varies with partial fluorine substitution.

8. Fluoroiodocarbons

Limited evidence suggested that highly fluorinated iodocarbons may have the lowest toxicities of the iodinated chemicals. Fluoroiodocarbons, in particular CF_3I, was targeted early on as a halon replacement. However, the cardiac sensitization NOAEL/LOAEL values for CF_3I and the other tested fluorinated iodocarbons range from 0.1 to 0.2 vol.%, making them less desirable as halon replacements. However, their consideration as a streaming halon replacement is still warranted.

9. Metal compounds

The metals being considered as firefighting agents include cobalt, iron, manganese, titanium, and zinc. The route of entry plays an important role in determining the toxicity of a metal compound. Inhalation of metals will likely occur in firefighting scenarios. Solubility is particularly important in determining the fate of metals deposited in the respiratory airways. The more insoluble the metal compound, the more likely it is to be cleared from the pulmonary tract by retrograde movement to the pharynx and then swallowed. Topical exposure to certain metals may also present a hazard. Cobalt and nickel are the only metals being presently considered that have the skin as a target organ.

10. Phosphorus Compounds

It is highly unlikely that phosphorus compounds will create any global environmental problems. Atmospheric lifetimes are expected to be sufficiently short that global warming and ozone depletion (even with bromine substitution) would be negligible. The large variability in toxicity of phosphorus compounds and the possibility of cholinesterase inhibition causes toxicity concerns with these compounds. It appears that toxicity tends to decrease as the oxidation state of the phosphorus decreases (i.e., phosphines are generally the most toxic and

phosphates are the least toxic). Phosphonitriles appear to have relatively low toxicities, but mutagenicity may be of concern. Compounds with P-halogen bonds are probably unacceptable as halon substitutes.

11. Silicon Compounds

Silicon compounds are expected to have few if any global atmospheric impacts. This may be the case even when bromine is present. There is, however, a real need for studies of the photochemistry of bromine-containing silicon compounds. Little toxicity data are available on silicon compounds of interest as halon substitutes. On the other hand, many silicon compounds, particularly esters and siloxanes, are expected to have low toxicity. As in the case of phosphorus, compounds containing Si-halogen bonds are probably unacceptable as halon substitutes.

SECTION V
TOXICOLOGICAL PROPERTIES INCLUDING DOSE-RESPONSE FOR COMPOUNDS OF INTEREST

A. INTRODUCTION

It has been proposed that one can take multiples of a particular endpoint to determine the dose-response in humans based on animal studies (Reference 77). One example follows (Reference 77). The concentration-response relationships for a number of airborne chemicals appears to be linear when one plots the percent decrease in respiratory rate against the log of the concentration (Reference 78). The RD_{50}, the concentration that causes a 50 percent decrease in respiratory rate in animals, appears to correspond to eye, nose, and throat irritation in humans, and is known to be a concentration at which respiratory track lesions occur in mice (Reference 79). It has been proposed that the response in humans can be predicted by taking various multiples of the animal RD_{50} as shown in Table 27. Recent work, however, indicates that histopathological changes induced in the respiratory tract of mice exposed to repeated inhalation depends on the exposure duration and chemical, but do not depend on concentration (Reference 80).

B. COMPOUNDS OF INTEREST

Dose-response data were developed as part of the previous section. For purposes of the analysis presented in this section, only inhalation will be considered. Inhalation data is not available for many of the compounds of interest. However, Table 28 summarizes inhalation data (primarily LC_{50}) for those compounds discussed below which are being considered as potential advanced halon replacements (or to be blended with selected carriers) at this time. Halon 1211 information has been included for reference.

1. Bromoalkanes

Through a detailed review of the previous available information related to bromoalkanes, 1-bromopropane, $CH_2CH_2CH_2Br$, has been recommended for further

TABLE 27. PREDICTED HUMAN RESPONSE BASED ON RD_{50} VALUES FOR MICE.

Multiple of RD_{50}	Predicted human response	Uncertainty factor
10	Severe injury, possibly lethal	0.1
1	Intolerable to humans	1
0.1	Some sensory irritation	10
0.01	No sensory irritation	100
0.001	No effect of any kind on respiratory system	1000

TABLE 28. INHALATION DOSE-RESPONSE.

Compound	Formula	Endpoint, Species, time	Concentration, ppm
Bromochlorodifluomethane	$CBrClF_2$	LC_{50}, rat, 4-hr	85,000
(Halon 1211)		LC_{LO}, rat, 15-min	32,000
		Cardiac NOAEL	5,000
		Cardiac LOAEL	10,000
Bromoalkanes			
1-Bromopropane	$CH_3CH_2CH_2Br$	LC_{50}, rat, 30-min	50,300
		TC_{LO}, rat 30-min	20,000
		LC_{50}, rat, 4-hr	6,300 (est.)
Bromoalkenes			
4-Bromo-3,3,4,4-tetra-fluorobutene	$CF_2BrCF_2CH=CH_2$	ALC, rat, 4-hr	>19,300
		No effect, mouse, 1-hr	10,000
2-Bromo-3,3,3-trifluoro-propene	$CH_2=CBrCF_3$	---	---
3-bromo-3,3-difluoro-propene	$CF_2BrCH=CH_2$	~ALC, 4-hr	10,000 (est.)
Fluoroiodocarbons			
Trifluoroiodomethane	CF_3I	LC_{50}, rat, 4-hr	274,000
		Cardiac NOAEL	2000
		Cardiac LOAEL	4000

TABLE 28. INHALATION DOSE-RESPONSE (concluded).

Compound	Formula	Endpoint, Species, time	Concentration, ppm
Commercially Available Streaming Agents or Potential Blending Compounds			
2,2-Dichloro-1,1,1-trifluoroethane (HCFC-123)	CF_3CHCl_2	LC_{50}, rat, 4-hr	32,000
		Cardiac NOAEL	10,000
		Cardiac LOAEL	20,000
2-Chloro-1,1,1,2-tetrafluoroethane (HCFC-124)	CF_3CHClF	LC_{50}, rat, 4-hr	23,000 to 26,000
		Cardiac NOAEL	10,000
		Cardiac LOAEL	25,000
Perfluorohexane (FC-5-1-14)	$CF_3CF_2CF_2CF_2CF_2CF_3$	LC_{50}, rat, 4-hr	>300,000
		Cardiac NOAEL	>17,000
		Cardiac LOAEL	---
1,1,1,3,3,3-hexafluoropropane (HFC-236fa)	$CF_3CH_2CF_3$	ALC, rat, 4-hr	>189,000
		Cardiac NOAEL	150,000
		Cardiac LOAEL	100,000
1,1,1,2,3,3-hexafluoropropane (HFC-236ea)	CF_3CHFCF_2	LC_{50}, rat, 4-hr	>85,000
		Cardiac NOAEL	25,000
		Cardiac LOAEL	35,000

consideration as a halon replacement from the bromoalkane chemical family. A series of laboratory and field-scale tests have been conducted with 1-bromopropane blended with several HFC compounds (e.g., HFC-125, -227ea, and -236fa) (Reference 81). The 1-bromopropane enhanced the fire suppression effectiveness of the blending agents by as much as 30 percent. 1-Bromopropane has an LC_{50}, rat, 30 min inhalation value of 5.03 percent (2.53 g/m^3) (Table 28). Inhalation data for selected blending agents is also shown in Table 28. Due to the commercialization of 1-bromopropane as a solvent additional toxicity studies are ongoing (e.g., subchronic, chronic, developmental etc.) These data will be available in one to two years.

2. Bromoalkenes

There are three specific bromoalkenes recommended for further evaluation as halon replacements at this time. Details of these compounds are discussed below:

a) 4-Bromo-3,3,4,4-tetrafluorobutene Toxicity Summary — 4-Bromo-3,3,4,4-tetrafluorobutene, $CF_2BrCF_2CH=CH_2$, (CAS No. 18599-22-9) has been reported (Reference 82) to have a rat 4-hr ALC greater than 19,300 ppm. The compound is not mutagenic in Ames bacterial assay, with and without metabolic activation, in strains TA 1537, TA 1538, and TA 98, and it is not clastogenic in Chinese Hamster Ovary (CHO) cell assay with and without metabolic activation. In a 2-wk subchronic study, male rats were exposed to concentrations of 0, 1000 or 10,000 ppm, 6 hrs/day, 5 days/wk for 2 wks. Clinical observations during exposure included a decreased response to sound and loss of coordination in rats exposed to 10,000 ppm. Rats in this group had significantly lower body weights than controls during the exposure period but showed a normal rate of weight gain during recovery period. Rats exposed to 1000 ppm showed a normal rate of weight gain throughout the study. Pathological examination showed no compound-related macroscopic or microscopic changes in any of the rats. The mean relative liver weight of rats exposed to 10,000 ppm was significantly higher upon comparison with controls after Exposure 10 but was in the normal range after 14 days recovery. Mean absolute spleen weights for rats in both test groups were significantly lower than those of controls after 14 days recovery. In the absence of any microscopic changes, the relevance of these organ weight changes is questionable. Clinical chemistry measurements showed that rats exposed to 1,000 ppm excreted more fluoride than controls following exposure while rats exposed to 10,000 ppm showed an increase in both concentration and in the total amount of urine excreted. No other compound-related effects were seen.

b) 2-Bromo-3,3,3-trifluoropropene Toxicity Information — 2-Bromo-3,3,3-trifluoropropene, $CH_2=CBrCF_3$, has been reported to be an "excellent anesthetic with a rapid, uneventful recovery" in exposures of dogs (Reference 83). It is difficult to determine the potency of this chemical as an anesthetic since the concentrations used were not reported; however, since no adverse effects were observed, this material may have a low toxicity. In view of the low toxicity of 3,3,3-trifluoropropene, the mono-brominated trifluoroalkenes maybe worthy of future

consideration as halon replacement candidates. Determination of a 30-min rat LC_{50} for this compound has been recommended.

c) 3-Bromo-3,3-difluoropropene Toxicity Information — A report of acute inhalation toxicity studies on 3-bromo-3,3-difluoropropene, $CF_2BrCH=CH_2$, performed by DuPont under the sponsorship of the Alternative Agent Working Group (AAWG) was reviewed during their March 27, 1998 meeting. It was reported that at an average air concentration of 1 percent rats were observed to become unresponsive to sound after 30 min exposure and at 90 min they demonstrated a loss of gait. All four animals in this test died between the third and fourth hours of the exposure.

3. Fluoroiodocarbons

As a result of the recent USAF Second Generation Streaming Agent program, numerous toxicological studies (e.g., short-term (acute) inhalation studies, cardiac sensitization tests, and preliminary genetic toxicity tests) on CF_3I has been performed (Table 21). Acute inhalation studies revealed that CF_3I has a low order of toxicity, with an LC_{50} value for a 15-min exposure in rats equal to 27.4 percent. Consequences of short-term exposures to CF_3I include anesthesia, salivation, and audible breathing. Blood chemistry measurements have shown no abnormal results. CF_3I cardiac sensitization exposure studies determined a NOAEL of 0.2 percent and the LOAEL of 0.4 percent. Since the flame extinguishment concentration for CF_3I is in the range of 5 to 7 percent, this cardiac toxicity profile precludes its use for total flooding applications in normally occupied areas. However, CF_3I is still a highly promising alternative for total-flooding in unoccupied areas and for streaming applications. Thus, consideration is warranted in this risk assessment report.

4. Other Chemical Families

It has been determined that the other chemical families initially considered during this project are of little interest at this time, due to the limited availability of compound for testing and the high toxicities of the specific compounds that have been investigated thus far.

SECTION VI
EXPOSURE ASSESSMENT

A. ROUTES AND PATTERNS OF EXPOSURE

Halon 1211 has been used in streaming scenarios since the late 1950s. The Air Force adopted the use of Halon 1211 in the 1970s and has been using the agent successfully to the present. Halon 1211 has been used in handheld, wheeled, and mobile (vehicle mounted) units to protect aircraft and ground vehicles, sensitive electronics, generator areas, nuclear power plants, and shipboard electronics (Reference 84). Materials being protected include Class A (foam, textiles, fabrics, paper, wood, tires, plastics), Class B (fuel, hydraulics, diesel, lubricants, solvents, gasoline, and ethylene glycol), and Class C (cables and electronics). It is estimated that 35 percent of Halon 1211 was used to protect electronic equipment, 25 percent to protect transportation hazards (aviation, ships, and ground vehicles), 30 percent for other commercial, industrial and institutional uses, and approximately 10 percent for residential uses (Reference 85). It is possible that halon replacement agents would be used in transportation, electronic, commercial and industrial applications. Approval for use in residential areas is highly unlikely, therefore, use in this application will not be considered.

1. Exposure Variables

The exposure to halon-like streaming agents can be expected to vary a great deal depending upon:

- The amount of agent (extinguisher size) and time needed to extinguish the fire;
- Whether the fire occurs indoors or outdoors;
- The size of the room in which the fire occurs (indoor fire);
- The environmental conditions (wind, rain, ventilation system, etc.);

- The size of the fire;
- The agent being used; and
- The proximity of the firefighter, adjacent worker, or public to the point of agent discharge.

2. Exposure Pathways

In the above applications, the most likely exposure pathway would be inhalation. Contact exposure to the skin and eyes could conceivably occur depending on the chemical properties of the replacements, i.e., if the agents are liquids, contact exposure is more likely than if the agents are gases. Oral exposure is highly unlikely, unless the replacement agent is a liquid at room temperature and ground water contamination has occurred. Accidental ingestion could conceivably occur, but is not likely.

3. Exposure Patterns

Generally, two types of exposure patterns occur with streaming agents: firefighting, and service or maintenance. Three classes of people are typically exposed; those fighting fires, including trained firefighters; maintenance and service personnel or trained workers; or the general public who may be in the area during either of the scenarios.

Firefighting exposure is typified by periodic, short-duration exposures. However, the firefighter has typically elevated adrenaline levels due to the nature of fighting a fire. A trained firefighter may or may not have protective breathing gear during the fire-fighting episode. He/she may also be exposed to combustion byproducts and agent decomposition products. Service or maintenance exposure is typified by (1) potentially high exposures of short to medium duration due to agent release during servicing or maintenance or released as extinguishers are being filled, and (2) by low exposures for extended time periods due to poor ventilation or housekeeping in the area where extinguishers are being filled and/or serviced. Exposure of the general public would be coincidental to the other two scenarios.

B. MODELING STUDY ASSESSMENT FOR HCFC-123

One potential occupational exposure scenario for firefighting has been proposed for HCFC-123, an early proposed replacement for Halon 1211 (Reference 86). The exposure duration is a 1-min period in which a worker discharges either the contents of a small (1 to 3 lb) extinguisher or the partial contents of a large (150 lb) extinguisher while attempting to extinguish a fire and subsequently leaving the area. The emergency exposure level has been reported as 5 percent,* which is proposed as the dose-response estimate based on cardiac sensitivity.

An exposure assessment for HCFC-123 was reported in Reference 87. Two studies were performed to measure the concentrations of HCFC-123 following release during simulated firefighting. The first study monitored levels during outdoor fire training exercises:

1. A 150-lb extinguisher was used for either 4 minutes or 20 sec.
2. At the breathing zone, measured agent levels were 0.2 to 5.4 ppm
3. At ankle height, concentrations were approximately 10 times higher
4. HCFC-123 concentrations in the plume were 0.2 to 180 ppm
5. Downwind air samples were 0.2 to 129 ppm.

The second study involved monitoring HCFC-123 concentrations that a firefighter would experience in an outdoor pit and in an aircraft hangar. In the outdoor pit, using a 20-lb extinguisher (discharge time 2-3 sec) and a 150-lb extinguisher (discharge time 11-37 sec), breathing zone samples ranged from 5-300 ppm HCFC-123. In an aircraft hangar, using both extinguishers (all units completely discharged), breathing zone samples ranged from 5-300 ppm, while the maximum concentration achieved at the discharge point was 1000 ppm.

Similar studies were made to assess the concentration that could be experienced by an aircraft maintenance worker (2 to 650 ppm at the farthest point away in a large aircraft hangar, after discharge of a 150-lb extinguisher) and for the general public downwind from a fire (0.17 to 129 ppm).

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*Personal Correspondence, Bruce Warner, ICI Americas, Inc., April 18, 1985.

It is proposed that the results of the latter surveys be extrapolate to Halon 1211 and the other replacements, and used to develop exposure assessments according to the concentrations developed for HCFC-123. It must be noted that this extrapolation would only be a first approximation since the volatility, temperature of the agent at release, and other factors may vary significantly between agents.

C. USAF FIREFIGHTER EXPOSURE TESTS

Another assessment of exposures to halon replacement streaming agents was performed by the USAF in 1991 (References 88 and 89). Midwest Research Institute (MRI) conducted a project with the intent to measure all possible chemical compounds produced during a typical firefighting training exercise under field conditions. Several data collection techniques were used. A series of 10 tests were completed at the NMERI test site in Albuquerque, NM. The test fires consisted of JP-4 saturated 55-gallon drum hung 2-m above a 3-m dia. pit, simulating an aircraft engine fire (Figure 7). Samples were collected within the plume, beside the firefighter, and downwind of the plume. Mass emission rates were used as input to the Industrial Source Complex-Short Term (ISCST) air transport model to determine the plume center expected concentrations. The tests were conducted with burning JP-4 only with no attempt at extinguishment, and using three halocarbon firefighting agents: Halon 1211, HFC-123, and FC-5-1-14.

Taking relative toxicity into account, the most important measurements were the detection of acid gases. HCl, HBr, HF, and COF_2 were all formed and levels exceeded the IDLH limits in the downwind plume at distances from 30-m to as much as 200-m from the fire. Agent concentrations were up to 100 times greater at ankle height compared to breathing zone height. Indicating the agents could potentially reached toxic limits near ground level. Downwind agent plume concentrations were 2500 to 2900 ppm for Halon 1211; 350, 6200 and 23,000 ppm for HFC-123; and 1700, 1900, and 11,000 for FC-5-1-14. These concentration were measured up to 10-m from the agent discharge point. Typical firefighter exposure concentrations were measured at 1 to 4 ppm for Halon 1211, 1 to 5 ppm for HFCF-123, and 1 to 26 ppm for FC-5-1-14.

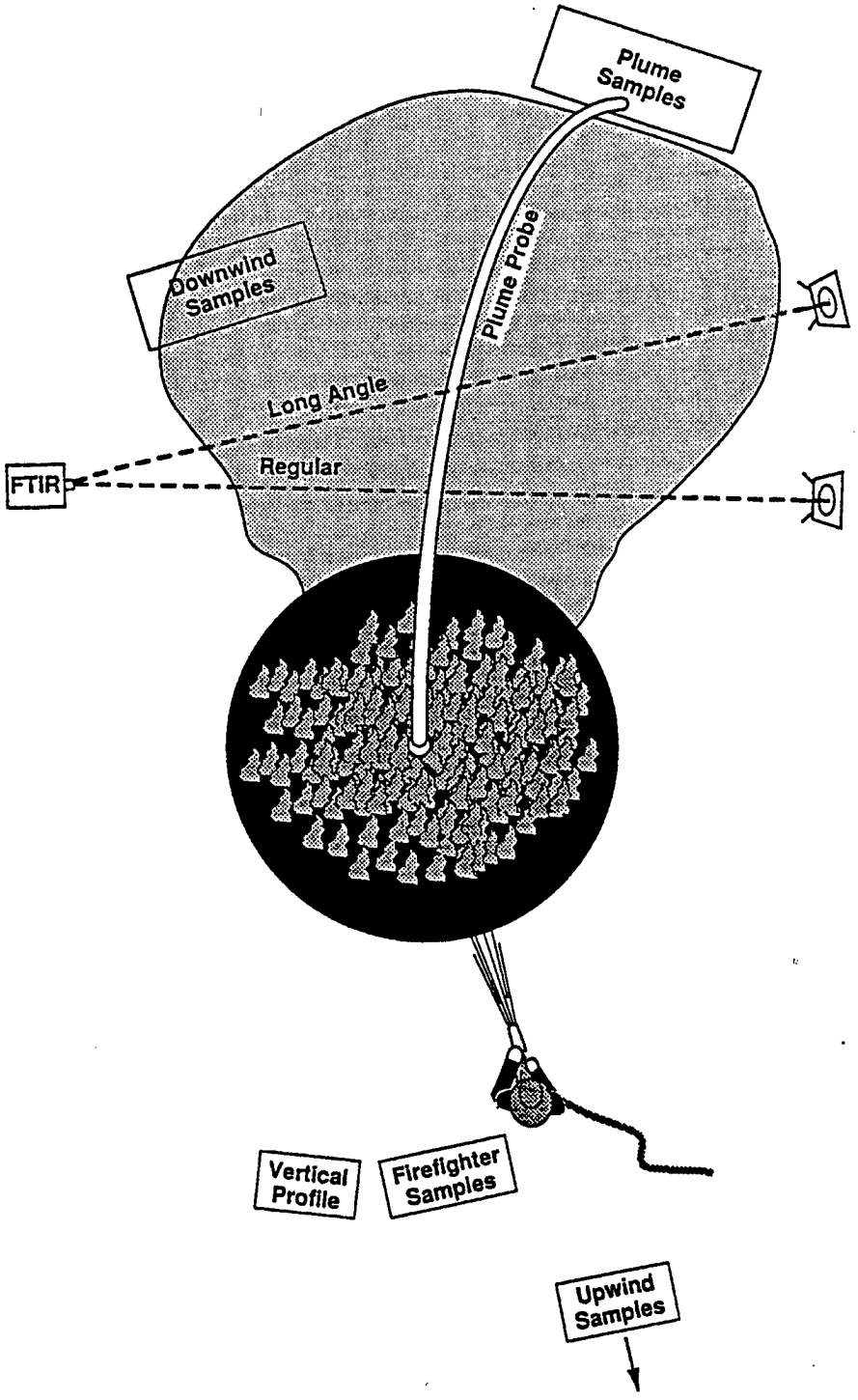


Figure 7. Vertical View of Sampling Array During MRI Firefighter Exposure Tests.

In the MRI report, estimates of exposures were compared to existing OSHA Permissible Exposure Limits (PEL) and Occupational Exposure Limits (OEL). Since firefighter exposures are normally short-term, but high concentration, acute toxicity reference points may have been more appropriate.

D. REGULATIONS AND STANDARDS: AN APPROACH TO EVALUATE EXPOSURE CONCENTRATIONS

Although this report treats streaming agents, some of the regulatory and standards issues for total-flood agents may apply. Allowable concentrations are often considered as if the agent were used in total flood applications. Documents which may apply include the NFPA Standards on Halon 1301 (Reference 90), Halon 1211 (Reference 32), and the clean agents (Reference 91). Paragraph 1-5.1.2.1 of NFPA 2001 (Reference 91) states the following on the permitted usage of halocarbon clean agents in confined spaces:

> 1-5.1.2.1 Unnecessary exposure to all halocarbon clean agents and their decomposition products shall be avoided. Halocarbon clean agents for which the design concentration is equal or less than the NOAEL shall be permitted for use in normally occupied areas. Halocarbon agents for which the design concentration is greater than the NOAEL shall not be permitted for use in normally occupied areas.
>
> *Exception: For Class B hazards and where acceptable to the authority having jurisdiction, concentrations up the LOAEL shall be permitted in normally occupied areas where a predischarge alarm and time delay are provided. The time delay shall be set to ensure that the occupants of the enclosure under consideration have time to evacuate prior to the start of the discharge.*

If the above reasoning can be adapted for streaming agents in confined spaces, no concentration above the NOAEL would be acceptable unless the exception noted above is met.

1. Minimum Room Volume (MRV) Calculation for Streaming Agents

The MRV for which an extinguisher of a set weight can be used in can be calculated based on a toxicity endpoint (e.g., NOAEL or LOAEL) and characteristics of the agent itself. A technique similar to that used to calculate the amount of agent required to achieve the

design concentration for a total flood agent (Reference 32), one can calculate the weight of agent required to achieve a specific toxic endpoint (Equation 1).

$$W = V/S[C/(100-C)] \quad [1]$$

Where:

V = protected volume (in ft^3),

W = weight of agent required for a specific concentration (in lbs),

S = specific volume of agent at temperature T (°F), and

C = the concentration at a specific toxicity endpoint (volume percent).

The specific volume is given by Equation 2, which is a linear equation determined by least squares curve fit techniques from data supplied by agent manufacturers. The zero intercept is k_1, and the slope is k_2. The values of k_1 and k_2 are available in References 32 for Halon 1211 and in Reference 91 for many of the commercialized halon replacements. Tables of S as a function of temperature have been developed and are also included in the references cited.

$$S = k_1 + k_2(T) \quad [2]$$

Rearrangement of Equation 1 gives Equation 3, where V is defined as the MRV for a confined space in which an extinguisher containing a weight of agent can be used without exceeding the toxicity endpoint concentration. The volume calculated is based on a uniform concentration throughout the room. In streaming applications, the concentration is normally much higher at the point where the extinguisher is discharged.

$$MRV = WS\ [(100-C)/C)] \quad [3]$$

Any toxicological endpoint can be used; however, the cardiac sensitization NOAEL or LOAEL are most likely to be used. The LOAEL is acceptable only if the range between the NOAEL and LOAEL is small, meaning that the known lowest effect of the LOAEL has been judged acceptable. Underwriters Laboratory (UL) has suggested the LOAEL as the

toxicity endpoint as part of the ANSI/UL 1093 Halogenated Standard (Reference 92). This standard also recommends a temperature of 120 °F (49 °C) when determining S. MRVs have been calculated using data for Halon 1211, HCFC-123, HFC-236fa, and CF_3I based upon this concept. The results are shown on Figure 8 and summarized in Table 29.

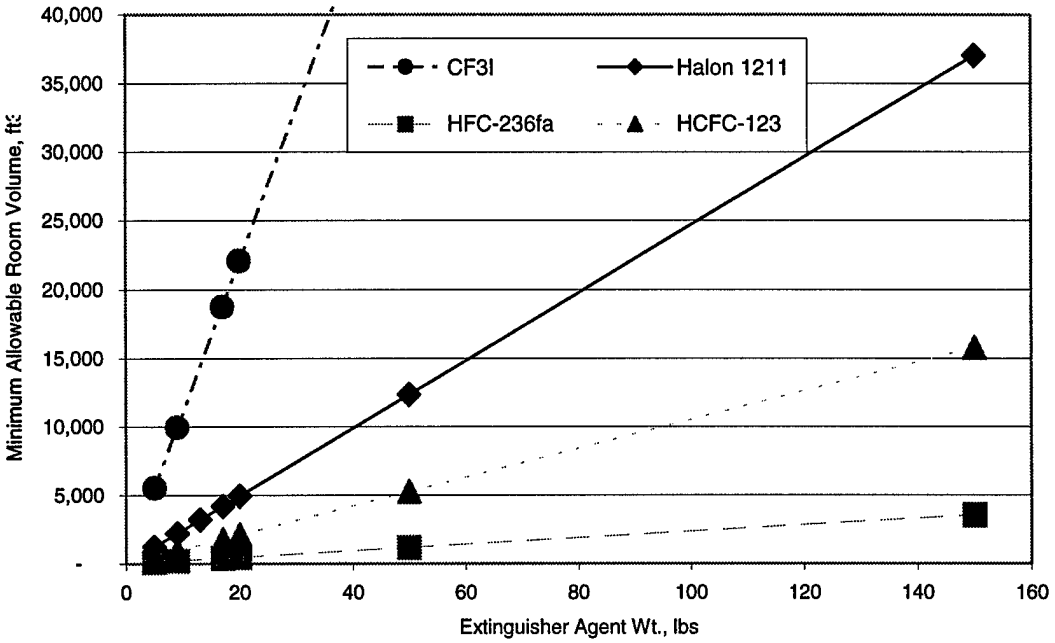
If three different extinguishers with three different agents are placed into an enclosed space, the extinguisher with the lowest MRV will be the most hazardous to the room occupants when the extinguisher is discharged. MRV values should be placed on the label of all streaming agent (portable) extinguishers. This will lower the overall risk to USAF personnel when using these extinguishers.

E. MODELING APPROACHES TO DETERMINE EXPOSURE CONCENTRATIONS

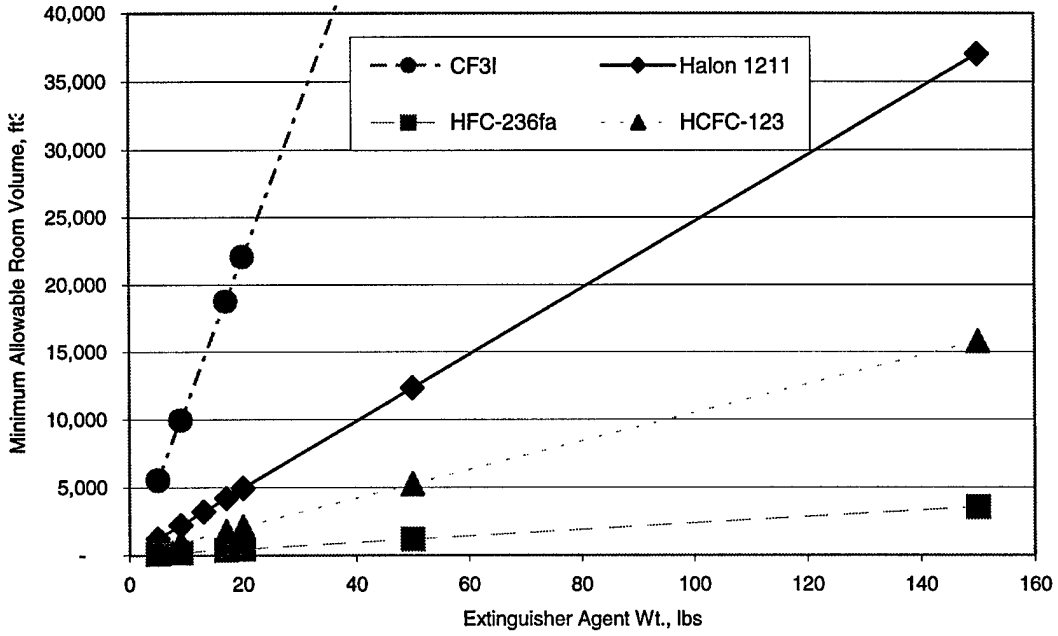
Under sponsorship from the US EPA, Meridian Research Inc. completed an assessment of the occupational exposures to halon replacement streaming agents (Reference 93). Estimates of worker exposure to halon replacements were compared to existing OSHA permissible exposure limits and to Occupational Exposure Limits (OELs) developed by the EPA Office of Air and Radiation for the purposes of evaluating potential occupational risks associated with the use of such materials.

Their approach relied upon a combination of (1) data from studies where occupational exposures to halons had been measured, and (2) use of a model to estimate occupational exposures where exposure data was not available. The model used was derived from a differential material balance that, when integrated, provided a basis for relating air concentration of a contaminate to the generation and removal rates of a contaminate:

$$\text{Rate of Accumulation} = \text{Rate of Generation} - \text{Rate of Removal} \qquad [4]$$



a) Data For Small Extinguishers.



b) Data For All Extinguisher Sizes.

Figure 8. Calculated Allowable Minimum Room Volumes for Various Sized Portable Extinguishers and a Variety of Halon Replacements.

TABLE 29. SUMMARY OF DATA USED TO DETERMINE ALLOWABLE MINIMUM ROOM VOLUMES SHOWN ON FIGURE 8.

Agent	k1	k2	Max. Desired Exposure Conc. In An Enclosed Space, vol.%
Halon 1211	1.905	0.0049	1
HFC-236fa	2.0098	0.0051	10
HCFC-123 and Bromo Blends	2.1 (est.)	0.005 (est.)	2.5
CF_3I	1.683	0.0044	0.2

Agent/Max. Allowable Conc.	Ext. Size, lbs (kg)		Min. acceptable vol. to discharge into (MRV), ft^3	Min. acceptable vol. To discharge into (MRV), m^3	Room Temp., °C
Halon 1211	5	(2.3)	1,234	35	120
1.0 vol.%	9	(4.1)	2,221	63	120
(LOAEL)	13	(5.9)	3,208	91	120
	17	(7.7)	4,196	119	120
	20	(9.1)	4,936	140	120
	50	(22.7)	12,340	349	120
	150	(68.1)	37,021	1,048	120
HFC-236fa	5	(2.3)	118	3	120
10 vol.%	9	(4.1)	212	6	120
(NOAEL)	17	(7.7)	401	11	120
	20	(9.1)	472	13	120
	50	(22.7)	1,180	33	120
	150	(68.1)	3,539	100	120

TABLE 29. SUMMARY OF DATA USED TO DETERMINE ALLOWABLE MINIMUM ROOM VOLUMES SHOWN ON FIGURE 8 (concluded).

Agent/Max. Allowable Conc.	Ext. Size, lbs (kg)		Min. acceptable vol. to discharge into (MRV), ft^3	Min. acceptable vol. To discharge into (MRV), m^3	Room Temp., °C
HCFC-123	5	(2.3)	527	15	120
2.0 vol%	9	(4.1)	948	27	120
(LOAEL)	17	(7.7)	1,790	51	120
	20	(9.1)	2,106	60	120
	50	(22.7)	5,265	149	120
	150	(68.1)	15,795	447	120
Bromo-Blends	5	(2.3)	527	15	120
2.5 vol%	9	(4.1)	948	27	120
(LOAEL)	17	(7.7)	1,790	51	120
	20	(9.1)	2,106	60	120
	50	(22.7)	5,265	149	120
	150	(68.1)	15,795	447	120
CF_3I	5	(2.3)	5,516	156	120
0.2 vol.%	9	(4.1)	9,930	281	120
(LOAEL)	17	(7.7)	18,756	531	120
	20	(9.1)	22,066	624	120
	50	(22.7)	55,164	1561	120

Note: CF_3I conc. exceeds cardiac LOAEL for protection of typical 1700-1900 ft^3 laboratory or office space.

Three scenarios and five streaming agents (Table 30) were considered in the Meridian assessment:

- Use of a 1-lb halon equivalent extinguisher [MRV = 700 ft^3] in a single-person office 2-ft x 10-ft x 8-ft (960 ft^3);
- Use of up to a 20-lb halon equivalent extinguisher [MRV = 5000 ft^3] in a 2- or 3-person office 22.5-ft x 10-ft x 8-ft (1780 ft^3); and
- Use of a large (150-lb halon equivalent) extinguisher [MRV = 37,000 ft^3] inside an enclosed area (such as an aircraft hangar).

Table 31 summarizes the Meridian results. For specific details of the modeling effort, Time Weighted Average (TWA) data, and decomposition concentration values the reader is referred to the Meridian report (Reference 93). Also, in the Meridian report, estimates of exposures were compared to existing OSHA PELs and OELs. Since firefighter exposures are normally short-term, but high concentration, acute toxicity reference points may have been more appropriate.

TABLE 30. AGENTS CONSIDERED DURING MERIDIAN MODELING EFFORT.

Agent	[a]Gas Volume Equivalent (GVEq)	[b]MRV for 1A:10 BC UL Listed Extinguishers, ft^3
Halon 1211	1.0	3200
HCFC-123	1.97	1600
HCFC-124	2.55	---
FC-5-1-14	1.37	~400
HBFC-22B1	1.37	---

[a]GVEq is the relationship between the concentration of a replacement agent needed to extinguish a flame in the cup burner test to that of Halon 1211.

[b]The lower the MRV the safer the extinguisher.

TABLE 31. SUMMARY OF PEAK MODEL DETERMINED EXPOSURE ASSESSMENT DATA FOR HALON REPLACEMENT STREAMING AGENTS.

			Vicinity of 850 ft^2 Fire, ppm		Conc. In 336,000 ft^3 Hanger, ppm	
Streaming Agent	[a]Small Office Scenario, ppm	[b]2- or 3-Person Office Scenario, ppm	[c]AER = 30	[c]AER = 360	[c]AER = 0.5	[c]AER = 3
Halon 1211	2,450	850 - 1000	---	---	---	---
HCFC-123	4,830	1,970	25,470	3,360	910	880
HCFC-124	6,250	2,550	---	---	---	---
FC-5-1-14	3,360	1,370	12,020	1,900	515	500
HBFC-22B1	3,360	1,370	---	---	---	---

[a]1-lb Halon 1211 = 1.5 to 2-lbs of replacement agent.
[b]3-lb Halon 1211 = 4.5 to 5-lbs of replacement agent.
[c]Assumed air exchange rate, CFM (ft^3/min).

F. FIREFIGHTER EXPOSURE TESTS WITH CF_3I

As a means of evaluating the potential risk associated with exposure to CF_3I, Pacific Scientific HTL/Kin-Tech Division sponsored a test series to determine indoor exposure concentrations when using CF_3I under normal circumstances. The tests were conducted at Tyndall AFB, Fl (Reference 94). Three different room sizes were investigated using eight cold shots (no fires). Extinguisher sizes varied from 2.5-lbs to 13-lbs. The test data and results are summarized in Table 32. A fire in the test room would likely have caused heating of the space which would have increased the measured agent concentrations. Increases in agent concentration on the order of 100 to 200 ppm or 7 percent would have been possible with a 40 °F temperature increase.

TABLE 32. TEST SCENARIOS AND FIREFIGHTER EXPOSURE RESULTS DURING TESTS WITH CF_3I.

Scenario	Room Vol., ft^3	Ventilation Rate, ft^3/min	Extinguisher Size, lbs	[c]Measured Firefighter Exposure Concentration, ppm
[a]1	912	110	2.5	1205
[a]2	3822	None	2.5	175
[a]3	3822	None	5	1470
[a]4	3822	400	2.5	6
[a]5	3822	185	5	1040
[b]6	5133	800	5	765
[b]7	5133	880	9	340
[b]8	5133	798	13	1700

[a]Suspended ceiling and raised floors with ventilation ducts.

[b]Simulated industrial or small shipping and receiving warehouse.

[c]A fire in the room would cause heating and also likely increase these concentration slightly.

G. HISTORICAL HALON 1211 EXPOSURE INCIDENCES

Despite the long use history of Halon 1211, relatively few lethal incidences have occurred with the chemical. Written records of death attributed to Halon 1211 exposure are difficult to obtain. While this is mainly due to the lack of incidences to document, of the few that have occurred, most have occurred prior to when good record keeping practices were established. There are five Halon 1211 death experiences known to the authors. Of these, two incidences have no data, one has limited data, and two are better documented. They are included in order to complete the exposure assessment. Accidental or intentional high acute exposures to halocarbon agents, such as those being investigated, can cause death.

1. Davis-Monthan AFB, Arizona

In the early 1980s an Air Force member was exposed to Halon 1211 during a training exercise. Death occurred. No additional information is available.

2. Denver, Colorado

No data are available except that a fatality occurred.

3. Marine Corps Air Station (MCAS), Yuma, Arizona

In the early 1990s, a Marine "apparently intentionally inhaled Halon [1211] gas from a glove while on duty" at the runway alert position at MCAS, Yuma, Arizona (Reference 95). The individual went onto cardiac arrest. Cardiovascular pulmonary resuscitation (CPR) attempts were not successful. One other individual was also involved in the activity but had no ill effects of the exposure. This activity was considered serious misuse of the firefighting agent.

4. Camp Lejeune, North Carolina

In June 1994, a marine was inventorying aircraft ground extinguisher units in a warehouse facility. He evidently inadvertently "squeezed the trigger on one fire bottle causing it to discharge a large amount of halon directly towards himself." The marine staggered and collapsed approximately 20 ft from the extinguisher bottles. Ambulatory EKG equipment demonstrated ventricular fibrillation. The marine was dead upon arrival at medical facilities.

5. Unknown

No information other than a fatality is believed to have occurred is known.

6. Chemical Company Provided the Data

Limited distribution data provided by Du Pont lists an additional fatality with similar circumstances as the above deaths. Little information is available on the cause of death.

H. EXPOSURE ASSESSMENT SUMMARY

There have been several tests conducted to assess the exposure concentrations likely to be encountered while using halons and their replacements in streaming applications. Exposures to the neat agent and decomposition products are likely in most all cases. The typical measured exposure concentrations to neat streaming agents are generally lower than modeled

concentrations. Measured concentrations range from a few ppm to near 1000 ppm. Seldom do the agent exposure concentrations exceed 3,000 ppm (0.3 percent) unless the discharge were accidental during servicing or intentional. Highest concentrations have been measured in downwind plumes and inside enclosed spaces. Because these agents are heavier than air, concentrations are also highest near the ground surface.

A summary of typical expected exposure concentrations when using halons and halon replacement streaming agents is shown in Table 33. This data has been summarized from the above discussions and will be used in the following section to characterize the health risk associated with the advanced agents being developed by the USAF under current and future efforts.

TABLE 33. SUMMARY OF EXPOSURE CONCENTRATIONS WHEN USING HALON 1211 AND VARIOUS REPLACMENT AGENTS IN STREAMING SCENARIOS.

Exposure Scenario	Agent	Typical Agent Exposure Conc., ppm	Comments
Small Office 1- to 2-persons (960 ft^3), 1-lb Halon 1211 equivalent extinguisher, 20 to 60 sec exposure duration.	Halon 1211	2,450	Modeled value.
	HCFC-123	4,830	Modeled value.
	HCFC-124	6,250	Modeled value.
	FC-5-1-14	3,360	Modeled value.
	HFC-236fa	4,900	Est. based upon HCFC-123 result.
	HFC-236ea	4,900	Est. based upon HCFC-123 result.
	CF_3I	1,200	Est. from measured data.
	Bromoalkane Blends	3000	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	2,500	Est. based upon Halon 1211 result.
Larger Office/Lab (1,780 ft^3) 3-lb to 20-lb Halon 1211 equivalent extinguisher, 20 to 60 sec exposure duration.	Halon 1211	950	Modeled value.
	HCFC-123	1,970	Modeled value.
	HCFC-124	2,550	Modeled value.
	FC-5-1-14	1,370	Modeled value.
	HFC-236fa	1,970	Est. based upon HCFC-123 result.
	HFC-236ea	1,970	Est. based upon HCFC-123 result.
	CF_3I	1,100	Est. from measured data and Halon 1211 data.
	Bromoalkane Blends	1,300	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	1,000	Est. based upon Halon 1211 result.

TABLE 33. SUMMARY OF EXPOSURE CONCENTRATIONS WHEN USING HALON 1211 AND VARIOUS REPLACMENT AGENTS IN STREAMING SCENARIOS (continued).

Exposure Scenario	Agent	Typical Agent Exposure Conc., ppm	Comments
Aircraft Hangar (336,000 ft^3)	Halon 1211	900	Modeled value.
	HCFC-123	910 650	Modeled value. Measured value.
	HCFC-124	2,000	Modeled value.
	FC-5-1-14	515	Modeled value.
	HFC-236fa	910	Est. based upon HCFC-123 result.
	HFC-236ea	910	Est. based upon HCFC-123 result.
	CF_3I	1,000	Est. based upon Halon 1211 result.
	Bromoalkane Blends	800	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	800	Est. based upon Halon 1211 results.
Firefighter training with 150-lb extinguisher outdoors. Conc. in downwind plume 10 to 30 m from fire.	Halon 1211	2,500 2,900	Measured values.
	HCFC-123	350; 6,200; 23,000	Measured values.
	HCFC-124	12,000	Est. based upon previous modeled results.
	FC-5-1-14	1,700; 1,900; 11,000	Measured values.
	HFC-236fa	9,000	Est. based upon HCFC-123 result.
	HFC-236ea	9,000	Est. based upon HCFC-123 result.
	CF_3I	2,900	Est. from measured data and Halon 1211 results.
	Bromoalkane Blends	6,000	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	4,000	Est. based upon Halon 1211 result.

TABLE 32. SUMMARY OF EXPOSURE CONCENTRATIONS WHEN USING HALON 1211 AND VARIOUS REPLACMENT AGENTS IN STREAMING SCENARIOS (concluded).

Exposure Scenario	Agent	Typical Agent Exposure Conc., ppm	Comments
Firefighter training with 150-lb extinguisher outdoors. Max expected conc. at breathing zone.	Halon 1211	500 5	Modeled value. Measured value.
	HCFC-123	1,000 180, 300	Modeled value. Measured values.
	HCFC-124	1,000	Modeled value.
	FC-5-1-14	1,000 26	Modeled value. Measured values.
	HFC-236fa	1,000	Est. based upon HCFC-123 result.
	HFC-236ea	1,000	Est. based upon HCFC-123 result.
	CF_3I	750	Est. based upon Halon 1211.
	Bromoalkane Blends	750	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	750	Est. based upon Halon 1211.
Firefighter training 20-lb extinguisher outdoors. Max expected conc. at breathing zone.	Halon 1211	500	Modeled value.
	HCFC-123	500 300	Modeled value. Measured value.
	HCFC-124	500	Modeled value.
	FC-5-1-14	500	Modeled value.
	HFC-236fa	500	Est. based upon HCFC-123 result.
	HFC-236ea	500	Est. based upon HCFC-123 result.
	CF_3I	500	Est. from measured data.
	Bromoalkane Blends	500	Est. based upon HCFC-123 and Halon 1211 result. Conc. should be less due to increased effectiveness.
	Advanced Bromocarbons	500	Est. based upon HCFC-123 result.

SECTION VII
RISK CHARACTERIZATION

A. INTRODUCTION

The final step in risk assessment is risk characterization, which involves predicting the frequency and severity of effects due to chemical exposure, in the likely exposed population. In this step, information from the dose-response evaluation (what effects are caused by exposure to a certain dose?) is compared to information from the exposure assessment (what dose is the person receiving?) to produce an estimate of the likelihood of observing adverse effects. Most risk assessments for regulatory purposes, especially for cancer, produce a single number estimating the increased incidence of disease. However, for the purposes of this effort, a quantitative risk assessment is impossible for all candidates because (1) not all candidates have been identified, and (2) information on most of the candidates is insufficient to allow a quantitative assessment. Therefore, where possible, a quantitative assessment will be performed; however, in most cases a qualitative assessment will be emphasized to determine whether a chemical or class of chemicals would pose a lesser or greater health threat than Halon 1211.

In this section a preliminary risk characterization methodology is developed and used to assess the health risk of various halon streaming agent replacements. It is proposed that this methodology be further refined to account for all the risk variables associated with halon replacements.

B. US EPA RISK CHARACTERIZATION PROCESS

The final risk assessment performed for any Halon 1211 replacement selected by the USAF will be produced by the US EPA for regulatory acceptance. A detailed overview of the US EPA risk characterization process is provided in Reference 96. A brief summary of this process is presented in this section.

Section 612 of the Clean Air Act Amendments (CAAA) of 1990 required the EPA to develop a program to evaluate the risks to human health and the environment posed by

substitutes to the ODSs being phased out under the Montreal Protocol and the CAAA. This risk characterization program has been referred to as the Significant New Alternatives Policy (SNAP) program. The SNAP process requires industry to submit information on substitutes and to identify additional alternative chemicals to be considered in the SNAP program. The data submitted to the SNAP program serve as the basis for assessments in the risk characterization approach to decisions listing the substitutes as either acceptable or unacceptable. Table 34 presents the risk factors that are being considered by the EPA under the SNAP program (Reference 97).

TABLE 34. KEY SNAP RISK ASSESSMENT CRITERIA.

Key Risk Criteria	Comments
Chlorine and Bromine Loading	Used to assess global ozone depletion effects.
ODP	
GWP, including atmospheric lifetime	
Flammability	
Toxicity	Acute, subchronic, chronic, carcinogenicity, etc.
Exposures	
- air, water, hazardous/solid waste	
- worker, consumer, general population, aquatic organisms	

The EPA examines the risks of the substitutes in a comparative framework using risks from continued use of the ODS or the use of the substitutes as reference points. The evaluation considers several factors: ODP (e.g., skin cancer and cataracts) as well as effects due to toxicity. Other factors include direct and indirect effects on air and water quality, direct and indirect contributions to global warming, and occupational health and safety. Evaluation of substitutes is also based upon atmospheric effects by predicting ODP and GWP using models. As shown in the previous section, exposure can vary significantly, depending upon the particular use scenario. Exposure assessments are used to estimate the concentrations to which workers, consumers, the

general population, and environmental receptors may be exposed and over what period of time. Toxicity data are used to develop dose-response estimates to assess the possible health and environmental effects for exposure to substitutes. Because the key goal of the SNAP program is to promote the use of a substitute over continued use of ODSs, some substitutes designated as acceptable during the risk characterization process may pose some limited toxic or other environmental risk.

C. CHARACTERIZATION OF PROPOSED STREAMING AGENTS

The risk characterization that follows does not consider all the environmental, cost/societal benefits, and/or other regulatory associated risks that are characterized by the EPA for halon replacements. It is assumed that the global benefit will be far superior to Halon 1211 (e.g., ODP and GWP near-zero). The increased risk due to the reduced fire suppression effectiveness of the compounds has also not been included; this risk is assumed to be offset by using additional quantities of the halon alternatives to provide equivalent effectiveness. The following characterization is a modified health assessment of that typically used in the assessment of a hazardous waste site. The characterization is based upon the previously presented hazardous identification, dose-response, and exposure assessment. A preliminary process is presented to assess the halon replacements being studied at this time by the USAF under the current project. Chronic and carcinogenic (long-term worker exposure, generally controllable manufacturing and maintenance) exposures have not be considered in the risk characterization. These exposures are considered controllable and, therefore, of low risk. The concern is the acute single high dose exposure scenario. A more detailed risk assessment will likely take place prior to introduction into the USAF of a final replacement candidate for Halon 1211 in flightline applications.

D. DERIVATION OF REFERENCE DOSES

Chemical and toxicity data are derived largely from animal experiments where the animals, mostly mice and rats, are exposed to increasingly higher concentrations or doses, and corresponding effects are observed. Response can vary widely—from no observable effect to temporary and reversible to permanent injury to organs, to chronic functional impairment to

malignant tumors, and finally to death. Tests can cost from thousands to millions of dollars. Although no scientific consensus exists, available biological and empirical evidence suggests that toxicities observed in experimental animals generally apply to humans with some exceptions. Carcinogenic and noncarcinogenic extrapolations are treated differently.

The reference dose (RfD) and reference concentration (RfC) for noncarcinogens and for noncarcinogenic effects of carcinogens in humans are derived by dividing the NOAEL by an uncertainty factor (UF) and/or modifying factor (MF) (Reference 98):

$$\text{RfD or RfC} = \frac{NOAEL}{UF \times MF} \qquad [5]$$

In extrapolating the results of animal experiments to predict effects in humans, uncertainty or safety factors of 10 to 1000 (Table 27) are generally used to allow for intraspecies and interspecies differences in sensitivities and to account for differences in exposure periods and routes of exposure. If NOAELs cannot be identified for a substance, then the RfDs are derived from the LOAEL so that the RfDs are protective of effects that would occur at higher does. In the following analysis, if LOAELs and NOAELs were within a small range, then the LOAELs were used in the following analysis, because of the conservative nature of the cardiac sensitization test.

E. HAZARDOUS QUOTENT (HQ)

The potential for non-cancer effects is assessed by comparing exposure of average intake of substances with corresponding RfDs and RfCs. The RfD [mg/kg*day] or RfC [mg/m^3 in air] are considered to be safe thresholds for the general population. These can be considered as acceptable intake values. In the following analysis the exposure risk to various halon replacements will be expressed in terms of a hazard quotient (HQ) for a single exposure test result (exposure pathway). The HQ is a ratio of chemical exposures to reference doses as shown below. The ratio of exposure level, intake, or dose to RfD or RfC for the same route of exposure

inhalation (inhalation, oral) and the same exposure period (acute, chronic, subchronic, etc.) is called a *hazard quotient*:

$$\text{Hazard Quotient (HQ)} = \frac{\text{intake [mg / (kg * day)]}}{\text{RfD [mg / (kg * day)]}} = \frac{\text{exposure(mg / m}^3\text{)}}{\text{RfC (mg / m}^3\text{)}} \qquad (6)$$

If the exposure or intake is less than the corresponding RfD (HQ less than 1), the hazard exposures are not considered to pose a threat to the exposed group. If the exposure level of the substance exceeds the corresponding RfD (if the HQ is greater than 1), there may be a concern for potential health effects. In general, the greater the value of the HQ above 1, the greater is the level of concern. The HQ does not represent a statistical probability of an effect occurring.

F. HAZARD INDEX (HI)

As a screening step, the overall toxic potential resulting from several different acute effects has been estimated by summing up HQs derived for various exposures tests. The resulting sum is referred to as the *hazard index* (HI). The approach assumes that multiple subthreshold exposures to a substance could cumulatively result in an adverse health effect. The HI is computed as follows:

$$\text{Hazard Index (HI)} = E_1/RfD_1 + E_2/RfD_2 + \ldots + E_i/RfD_i = HQ_1 + HQ_2 + \ldots + HQ_i \qquad [7]$$

Where E_i = exposure(average intake or dose) for the toxic route [mg/(kg*day)], RfD_i = reference dose for the toxic route. The RfD can be either acute, chronic, or subchronic for the specific species and route of exposure depending upon duration. Generally, RfCs and RfDs for inhalation and oral routes can be found in the EPA Integrated Risk Information System (IRIS) and Health Effects Assessment Summary (HEAST) databases. However, values for the halon replacements being considered in this project are not included in either of these databases.

G. UNCERTAINITY FACTORS (UF)

Three different UFs were used in assessing the available and advanced halon replacements. An UF of 1.0 was chosen to determine the RfD for cardiac sensitization because

of the already inherent safety factor associated with the test exposure method. In our initial analysis the LC_{50} exposure dose scenario has been chosen as another indicator of toxicity for assessment. Because the LC_{50} concentration value is a lethality endpoint, two different analysis have been performed with UFs equal to 10 and 100 to determine the LC_{50} associated RfD. Typically, UFs of 100 to 1000 would be chosen for subchronic or chronic exposure data.

H. RISK CHARACTIZATATION METHOLOGY AND RESULTS

A detailed risk characterization of several halon replacements along with Halon 1211 as a baseline for comparison has been performed using a spreadsheet model; the detailed results are included in Appendices B and C. A Halon 1211 example calculation follows. A summary of the results using the previously described dose-response and exposure data is included in Table 35 (LC_{50} UF = 10) and in Table 36 (LC_{50} UF = 100).

Example --- Halon 1211 3- to 5-lb extinguisher discharge in large office/small lab (1780 ft^3), equivalent to 6 to 10 lbs of halon replacement).

Max. Measured/Predicted/Modeled Exposure Conc. = 950 ppm (16,570 mg/m^3)

Geometric Mean (0.5 time the max. conc.) = 475 ppm (3,213 mg/m3)

Cardiac LOAEL = 35,000 ppm (236,712 mg/m3)

Cardiac UF = 1.0

Rat LC50 (4-hr) = 85,000 ppm (574,871 mg/m3)

Cardiac RfC = Cardiac LOAEL = 10,000 ppm (67,632 mg/m3)

Typical human wt. = 70 kg

Typical human respiration = 20 m3/8-hrs = 0.042 m3/min

Cardiac RfD = 41 [mg/(kg*exposure)]

[67,632 (mg/m3/exposure)*(0.042 m3/min)/70 kg]/1.0

LC50 RfD = 8,278 [mg/(kg*min)]

[574,871 (mg/m3)*(0.042 m3/min)*4 (hr)*60 (min/hr)/70 kg]/10.0

HQ Cardiac (max.) = 0.10

[(16,570 mg/m3)*(0.042 m3/min)/70 kg]/41 mg/(kg*exp)

HQ Cardia (geom.) = 0.10 *0.5 = 0.05

HQ LC50 (max.) = 0.007

[16,570 (mg/m3)*0.042 (m3/min)*15 (min)/70 kg]/ 8,278 mg/(kg*min)

HQ LC50 (geom.) = 0.007 *0.5 = 0.003

HI (max) = HQ Cardiac + HQ LC50 = 0.10 + 0.007 = 0.10

HI (geom) = 0.05 + 0.003 = 0.05

TABLE 35. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 10.

Halocarbon Chemical	Max	Cardiac	Rat	Rat	Compensated for LC50 Duration, UF = 10			Note: Value not compensated for species exposure time.			
and	Exposed Conc.	Sen. (LOAEL)	LC50	LC50 Duration	Hazard Index (HI)		Hazard Index Rel to H-1211				Hazard Index Rel to H-1211
Scenario	ppm	ppm	ppm	min	HI (geom)	HI (max)		LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	
Typ. Single Office (960 ft^3) 1-lb Halon 1211 equiv. ext.				0.47	g/ft^3						
Halon 1211	2,450	10,000	85,000	240	0.13	0.26	1	0.29	0.25	0.53	1
HFC-123	4,830	20,000	32,000	240	0.17	0.34	1	1.51	0.24	1.75	3
HCFC-124	6,250	25,000	300,000	240	0.13	0.26	1	0.21	0.25	0.46	1
FC-5-1-14	3,360	300,000	300,000	240	0.01	0.02	0	0.11	0.01	0.12	0
HFC-236fa	4,900	100,000	400,000	240	0.03	0.06	0	0.12	0.05	0.17	0
HFC-236ea	4,900	35,000	85,000	240	0.09	0.18	1	0.58	0.14	0.72	1
CF3I	1,200	2,000	270,000	15	0.32	0.64	2	0.04	0.60	0.64	1
Bromoalkane Blends	3,000	35,000 est	50,000 est	30	0.19	0.39	1	0.60	0.09	0.69	1
Advanced Bromocarbons	2,500	20,000 est	50,000 est	30	0.19	0.38	1	0.50	0.13	0.63	1
Larger Office/Lab (1,780 ft^3) 3-lb to 20-lb Halon 1211 equiv. ext.				5.11	g/ft^3						
Halon 1211	950	10,000	85,000	240	0.05	0.10	1	0.11	0.10	0.21	1
HCFC-123	1,970	20,000	32,000	240	0.07	0.14	1	0.62	0.10	0.71	12
HCFC-124	2,550	25,000	300,000	240	0.05	0.11	1	0.09	0.10	0.19	2
FC-5-1-14	1,370	300,000	300,000	240	0.00	0.01	0	0.05	0.00	0.05	1
HFC-236fa	1,970	100,000	400,000	240	0.01	0.02	0	0.05	0.02	0.07	1
HFC-236ea	1,970	35,000	85,000	240	0.04	0.07	1	0.23	0.06	0.29	5
CF3I	1,100	2,000	270,000	15	0.30	0.59	6	0.04	0.55	0.59	1
Bromoalkane Blends	1,300	35,000 est	50,000 est	30	0.08	0.17	2	0.26	0.04	0.30	5

TABLE 35. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 10 (continued).

Advanced Bromocarbons	1,000	20,000 est	50,000 est	30	0.08	0.15	1	0.20	0.05	0.25	4
Aircraft Hangar (336,000 ft^3)	0.20	g/ft^3									
Halon 1211	900	10,000	85,000	240	0.05	0.10	1	0.11	0.09	0.20	1
HCFC-123	910	20,000	32,000	240	0.03	0.06	1	0.28	0.05	0.33	2
HCFC-124	2,000	25,000	300,000	240	0.04	0.08	1	0.07	0.08	0.15	1
FC-5-1-14	515	300,000	300,000	240	0.00	0.00	0	0.02	0.00	0.02	0
HFC-236fa	910	100,000	400,000	240	0.01	0.01	0	0.02	0.01	0.03	0
HFC-236ea	910	35,000	85,000	240	0.02	0.03	0	0.11	0.03	0.13	1
CF3I	1,000	2,000	270,000	15	0.27	0.54	6	0.04	0.50	0.54	3
Bromoalkane Blends	800	35,000 est	50,000 est	30	0.05	0.10	1	0.16	0.02	0.18	1
Advanced Bromocarbons	800	20,000 est	50,000 est	30	0.06	0.12	1	0.16	0.04	0.20	1
Firefighter training or typical flightline use scenario with 150-lb extinguisher outdoors. conc. in downwind plume 5 to 30 m from fire.											
Halon 1211	2,700	10,000	85,000	240	0.14	0.29	1	0.32	0.27	0.59	1
HCFC-123	9,000	20,000	32,000	240	0.31	0.63	2	2.81	0.45	3.26	6
HCFC-124	12,000	25,000	300,000	240	0.25	0.51	2	0.40	0.48	0.88	1
FC-5-1-14	5,000	300,000	300,000	240	0.01	0.03	0	0.17	0.02	0.18	0
HFC-236fa	9,000	100,000	400,000	240	0.05	0.10	0	0.23	0.09	0.32	1
HFC-236ea	9,000	35,000	85,000	240	0.16	0.32	1	1.06	0.26	1.32	2
CF3I	2,900	2,000	270,000	15	0.78	1.56	5	0.11	1.45	1.56	3
Bromoalkane Blends	6,000	50,000est	50,000est	30	0.36	0.72	2	1.20	0.12	1.32	2
Advanced Bromocarbons	4,000	40,000est	50,000est	30	0.25	0.50	2	0.80	0.10	0.90	2

TABLE 35. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 10 (concluded).

Firefighter training or flightline use scenario (150-lb)											
Halon 1211	500	10,000	85,000	240	0.03	0.05	1	0.06	0.05	0.11	1
HCFC-123	1,000	20,000	32,000	240	0.03	0.07	1	0.31	0.05	0.36	3
HCFC-124	1,000	25,000	300,000	240	0.02	0.04	1	0.03	0.04	0.07	1
FC-5-1-14	1,000	300,000	300,000	240	0.00	0.01	0	0.03	0.00	0.04	0
HFC-236fa	1,000	100,000	400,000	240	0.01	0.01	0	0.03	0.01	0.04	0
HFC-236ea	1,000	35,000	85,000	240	0.02	0.04	1	0.12	0.03	0.15	1
CF3I	750	2,000	270,000	15	0.20	0.40	8	0.03	0.38	0.40	4
Bromoalkane Blends	750	50,000est	50,000est	30	0.05	0.09	2	0.15	0.02	0.17	2
Advanced Bromocarbons	750	40,000est	50,000est	30	0.05	0.09	2	0.15	0.02	0.17	2
Firefighter training or outdoor use scenario (20-lb)											
Halon 1211	500	10,000	85,000	240	0.03	0.05	1	0.06	0.05	0.11	1
HCFC-123	500	20,000	32,000	240	0.02	0.03	1	0.16	0.03	0.18	2
HCFC-124	500	25,000	300,000	240	0.01	0.02	0	0.02	0.02	0.04	0
FC-5-1-14	500	300,000	300,000	240	0.00	0.00	0	0.02	0.00	0.02	0
HFC-236fa	500	100,000	400,000	240	0.00	0.01	0	0.01	0.01	0.02	0
HFC-236ea	500	35,000	85,000	240	0.01	0.02	0	0.06	0.01	0.07	1
CF3I	500	2,000	270,000	15	0.13	0.27	5	0.02	0.25	0.27	2
Bromoalkane Blends	500	50,000est	50,000est	30	0.03	0.06	1	0.10	0.01	0.11	1
Advanced Bromocarbons	500	40,000est	50,000est	30	0.03	0.06	1	0.10	0.01	0.11	1

TABLE 36. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 100.

Halocarbon Chemical	Max	Cardiac	Rat	Rat	Compensated for LC50 Duration, UF = 100			Note: Value not compensated for species exposure time.			
and	Exposed Conc.	Sen. (LOAEL)	LC50	LC50 Duration	Hazard Index (HI)		Hazard Index Rel to H-1211				Hazard Index Rel to H-1211
Scenario	ppm	ppm	ppm	min	HI (geom)	HI (max)		LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	
Typ. Single Office (960 ft^3) 1-lb Halon 1211 equiv. ext.				0.47	g/ft^3						
Halon 1211	2,450	10,000	85,000	240	0.21	0.43	1	2.88	0.25	3.13	1
HFC-123	4,830	20,000	32,000	240	0.59	1.18	3	15.09	0.24	15.34	5
HCFC-124	6,250	25,000	300,000	240	0.19	0.38	1	2.08	0.25	2.33	1
FC-5-1-14	3,360	300,000	300,000	240	0.04	0.08	0	1.12	0.01	1.13	0
HFC-236fa	4,900	100,000	400,000	240	0.06	0.13	0	1.23	0.05	1.27	0
HFC-236ea	4,900	35,000	85,000	240	0.25	0.50	1	5.76	0.14	5.90	2
CF3I	1,200	2,000	270,000	15	0.52	1.04	2	0.44	0.60	1.04	0
Bromoalkane Blends	3,000	35,000est	50,000est	30	1.54	3.09	7	6.00	0.09	6.09	2
Advanced Bromocarbons	2,500	20,000est	50,000est	30	1.31	2.63	6	5.00	0.13	5.13	2
Larger Office/Lab (1,780 ft^3) 3-lb to 20-lb Halon 1211 equiv. ext.				5.11	g/ft^3						
Halon 1211	950	10,000	85,000	240	0.08	0.16	1	1.12	0.10	1.21	1
HCFC-123	1,970	20,000	32,000	240	0.24	0.48	3	6.16	0.10	6.25	75
HCFC-124	2,550	25,000	300,000	240	0.08	0.16	1	0.85	0.10	0.95	10
FC-5-1-14	1,370	300,000	300,000	240	0.02	0.03	0	0.46	0.00	0.46	6
HFC-236fa	1,970	100,000	400,000	240	0.03	0.05	0	0.49	0.02	0.51	6
HFC-236ea	1,970	35,000	85,000	240	0.10	0.20	1	2.32	0.06	2.37	28
CF3I	1,100	2,000	270,000	15	0.48	0.96	6	0.41	0.55	0.96	5

TABLE 36. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 100 (continued).

Bromoalkane Blends	1,300	35,000est	50,000est	30	0.67	1.34	8	2.60	0.04	2.64	32
Advanced Bromocarbons	1,000	20,000est	50,000est	30	0.53	1.05	6	2.00	0.05	2.05	24
Aircraft Hangar (336,000 ft^3)	0.20	g/ft^3									
Halon 1211	900	10,000	85,000	240	0.08	0.16	1	1.06	0.09	1.15	1
HCFC-123	910	20,000	32,000	240	0.11	0.22	1	2.84	0.05	2.89	3
HCFC-124	2,000	25,000	300,000	240	0.06	0.12	1	0.67	0.08	0.75	1
FC-5-1-14	515	300,000	300,000	240	0.01	0.01	0	0.17	0.00	0.17	0
HFC-236fa	910	100,000	400,000	240	0.01	0.02	0	0.23	0.01	0.24	0
HFC-236ea	910	35,000	85,000	240	0.05	0.09	1	1.07	0.03	1.10	1
CF3I	1,000	2,000	270,000	15	0.44	0.87	6	0.37	0.50	0.87	1
Bromoalkane Blends	800	35,000est	50,000est	30	0.41	0.82	5	1.60	0.02	1.62	1
Advanced Bromocarbons	800	20,000est	50,000est	30	0.42	0.84	5	1.60	0.04	1.64	1
Firefighter training or typical flightline use with 150-lb extinguisher outdoors. conc. in downwind plume 5 to 30 m from fire.											
Halon 1211	2,700	10,000	85,000	240	0.23	0.47	1	3.18	0.27	3.45	1
HCFC-123	9,000	20,000	32,000	240	1.10	2.21	5	28.13	0.45	28.58	8
HCFC-124	12,000	25,000	300,000	240	0.37	0.73	2	4.00	0.48	4.48	1
FC-5-1-14	5,000	300,000	300,000	240	0.06	0.12	0	1.67	0.02	1.68	0
HFC-236fa	9,000	100,000	400,000	240	0.12	0.23	0	2.25	0.09	2.34	1
HFC-236ea	9,000	35,000	85,000	240	0.46	0.92	2	10.59	0.26	10.85	3
CF3I	2,900	2,000	270,000	15	1.26	2.52	5	1.07	1.45	2.52	1
Bromoalkane Blends	6,000	50,000est	50,000est	30	3.06	6.12	13	12.00	0.12	12.12	4
Advanced Bromocarbons	4,000	40,000est	50,000est	30	2.05	4.10	9	8.00	0.10	8.10	2

TABLE 36. RISK CHARACTERIZATION RESULTS SUMMARY USING LC_{50} UF = 100 (concluded).

Firefighter training or typical flightline use scenario (150-lb)											
Halon 1211	500	10,000	85,000	240	0.04	0.09	1	0.59	0.05	0.64	1
HCFC-123	1,000	20,000	32,000	240	0.12	0.25	3	3.13	0.05	3.18	5
HCFC-124	1,000	25,000	300,000	240	0.03	0.06	1	0.33	0.04	0.37	1
FC-5-1-14	1,000	300,000	300,000	240	0.01	0.02	0	0.33	0.00	0.34	1
HFC-236fa	1,000	100,000	400,000	240	0.01	0.03	0	0.25	0.01	0.26	0
HFC-236ea	1,000	35,000	85,000	240	0.05	0.10	1	1.18	0.03	1.21	2
CF3I	750	2,000	270,000	15	0.33	0.65	8	0.28	0.38	0.65	1
Bromoalkane Blends	750	50,000est	50,000est	30	0.38	0.77	9	1.50	0.02	1.52	2
Advanced Bromocarbons	750	40,000est	50,000est	30	0.38	0.77	9	1.50	0.02	1.52	2
Firefighter training or outdoor use scenario (20-lb)											
Halon 1211	500	10,000	85,000	240	0.04	0.09	1	0.59	0.05	0.64	1
HCFC-123	500	20,000	32,000	240	0.06	0.12	1	1.56	0.03	1.59	2
HCFC-124	500	25,000	300,000	240	0.02	0.03	0	0.17	0.02	0.19	0
FC-5-1-14	500	300,000	300,000	240	0.01	0.01	0	0.17	0.00	0.17	0
HFC-236fa	500	100,000	400,000	240	0.01	0.01	0	0.13	0.01	0.13	0
HFC-236ea	500	35,000	85,000	240	0.03	0.05	1	0.59	0.01	0.60	1
CF3I	500	2,000	270,000	15	0.22	0.44	5	0.19	0.25	0.44	1
Bromoalkane Blends	500	50,000est	50,000est	30	0.26	0.51	6	1.00	0.01	1.01	2
Advanced Bromocarbons	500	40,000est	50,000est	30	0.26	0.51	6	1.00	0.01	1.01	2

I. DISCUSSION

The typical exposure concentrations for a few minutes to the replacement streaming agents range from a few ppm to up to 3000 ppm depending upon the specific agent and use scenario (application). These concentrations provide a HI well below one (1). In most cases the HIs for the current replacements are similar to Halon 1211. The bromoalkane blends and advanced agents have estimated HIs slightly greater than Halon 1211. The HIs for CF_3I have been calculated to be the highest for the agents considered and in some scenarios the HI exceeds one (1), indicating a potential for concern. When a LC_{50} UF of 100 was used (Table 36) to determine HIs several of the compounds being considered had a HI that approached or exceeded one (1) for the exposure scenarios considered.

SECTION VIII
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

In 1983, the National Academy of Science (NAS) released its risk assessment/risk management to define a scheme for assessing the risk of hazards (Reference 99). This paradigm is the basis for this study. According to the NAS paradigm, the risk assessment process is broken down into four steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization.

The qualitative assessment or hazard identification step of the risk assessment provided a review of the chemical information relevance as to whether a replacement agent may or may not pose a hazard to those exposed. Information on the possible health effects caused by exposure to Halon 1211 and several potential replacements. Toxicological effects of specific candidates were discussed when information was available; otherwise, general information on the chemical family as a whole has been presented. In most cases there is very little of the required toxicological data (dose-response) available on most of the advanced streaming agent being investigated under this present USAF project. This limited data has also limited the completeness of this risk assessment; however, a risk assessment methodology has been developed.

The most likely exposure pathway has been determined to be inhalation. Contact exposure to the skin and eyes could conceivably occur depending on the chemical properties of the replacements, i.e., if the agents are liquids, contact exposure is more likely than if the agents are gases. Oral exposure is highly unlikely, unless the replacement agent is a liquid at room temperature and ground water contamination has occurred. Accidental ingestion could conceivably occur, but is not likely. Generally, two types of exposure patterns occur with streaming agents: firefighting, and service or maintenance. Three classes of people are typically exposed; those fighting fires, including trained firefighters; maintenance and service personnel; or the general public who may be in the area during either of these scenarios. Exposure

concentrations depend upon the halon replacement chemical and physical properties. There have been several tests conducted to assess the exposure concentrations likely to be encountered while using halons and their replacements in streaming applications. Exposures to the neat agent and decomposition products are likely in most all cases. The typical measured exposure concentrations to neat streaming agents are generally lower than modeled concentrations. Measured concentrations range from a few ppm to near 1000 ppm. Seldom do the agent exposure concentrations exceed 3,000 ppm (0.3 percent) unless the discharge were accidental during servicing or intentional. Highest concentrations have been measured in downwind plumes and inside enclosed spaces. Because these agents are heavier than air, concentrations are also highest near the ground surface.

The final step in risk assessment is risk characterization, which involves predicting the frequency and/or severity of effects, due to chemical exposure, in the likely exposed population. In this step, information from the dose-response evaluation (what effects are caused by exposure to a certain dose?) is compared to information from the exposure assessment (what dose is the person receiving?) to produce an estimate of the likelihood of observing adverse effects. Most risk assessments for regulatory purposes, especially for cancer, produce a single number estimating the increased incidence of disease. However, for the purposes of this effort, a quantitative risk assessment is impossible for all candidates because (1) not all candidates have been identified, and (2) information on most of the candidates is insufficient to allow a quantitative assessment. Therefore, where possible, a quantitative assessment was performed; however, in most cases a qualitative assessment was emphasized to determine whether a chemical or class of chemicals would pose a lesser or greater risk than Halon 1211.

Several projects have been completed in which a variety of exposure concentrations have either been measured or calculated using computer models. The typical exposure concentrations for a few minutes to the replacement streaming agents range from 500 to 1000 ppm depending upon the specific agent and use scenario (application). These concentrations provide a well below HI < 1.0. In most cases the HIs for the current replacements are similar to Halon 1211. The bromoalkane blends and advanced agent have estimated HIs slightly greater than Halon

1211. The HIs for CF_3I have been calculated to be the highest for the agents considered and in some scenarios the HI exceeded 1.0, indicating a potential for concern.

B. RECOMMENDATIONS

The developed risk assessment technique shows that careful consideration can and should be given when applying (specifying) the current and future halon replacements. The Air Force fire suppression design engineers need a risk-based tool for assessing halon and replacement usage. It is not appropriate to recommend these agents without proper analysis of all the factors: GWP, ODP, Atmospheric Lifetime, Tox., etc. Therefore, the following projects are submitted for further developing a risk-based model for assessing new and existing USAF halon-like installations.

- Collect exposure data during all large-(field-)scale testing of halon replacements, compile additional literature data into exposure assessment dataset;
- Develop HQs for all dose-response data on desirable compounds;
- Investigate the RfC and RfD derivation algorithms, refine as required;
- Develop HQs for type of suppression application, GWP, lifetime, ODP, and other critical risk elements;
- Use the HQs and determine a HI for all chemicals being considered as replacements, initially look at HFC-23, -125, -227ea, -236fa, -236ea, and 1-bromopropane blended with these compounds; and
- Use the developed model and assess an existing USAF installation.

If three different extinguishers with three different agents are placed into an enclosed space, the extinguisher with the lowest MRV will be the most hazardous to the room occupants when the extinguisher is discharged. MRV values should be placed on the label of all streaming agent (portable) extinguishers. This will lower the overall risk of using these extinguishers.

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REFERENCES

1. Tapscott, R. E., and Morehouse, E. T., *Next-Generation Fire Extinguishing Agent, Phase I — Suppression Concepts*, ESL-TR-87-03, Vol. 1 of 5, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, July 1987.

2. Tapscott, R. E., May, J. H., Moore, J. P., Lee, M. E., and Walker, J. L., *Next Generation Fire Extinguishing Agents Phase II — Laboratory Tests and Scoping Trials*, ESL-TR-87-03, Vol. 2 of 5, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, April 1990.

3. Tapscott, R. E., Moore, J. P., Lee, M. E., Watson, J. D., and Morehouse, E. T., *Next Generation Fire Extinguishing Agents Phase III — Initiation and Training Agent Development*, ESL-TR-87-03, Vol. 3 of 5, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, April 1990.

4. Tapscott, R. E., Lee, M. E., Watson, J. D., Nimitz, J. S., and Rodriguez, M. L., *Next Generation Fire Extinguishing Agent, Phase IV — Foundation for New Training Agent Development*, ESL-TR-87-03, Vol. 4 of 5, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, December 1989.

5. Tapscott, R. E., Lee, M. E., Moore, T. A., Moore, J. P., Nimitz, J. S., Skaggs, S. R., and Floden, J. R., *Next-Generation Fire Extinguishing Agent, Phase V — Initiation of Halon Replacement Development*, ESL-TR-87-03, Vol. 5 of 5, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, September 1990.

6. Floden, J. R., and Tapscott, R. E., "The Quest for Chemical Alternatives to Halon 1211," *The Military Engineer*, Vol. 82, No. 537, pp. 13-15, August 1990.

7. Nimitz, J. S., Tapscott, R. E., Skaggs, S. R., and Moore, T. A., *Halocarbons as Halon Replacements: Technology Review and Initiation*, ESL-TR-89-38, Vol. 1 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, July 1990.

8. Tapscott, R. E., Dierdorf, D. S., Moore, T. A., and Skaggs, S. R., *Halocarbons as Halon Replacements: Technology Review and Initiation, Halon 1301 Replacements*, ESL-TR-89-38, Vol. 2 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, March 1993.

9. Tapscott, R. E., Nimitz, J. S., Walters, E. A., and Arneberg, D. L., *Halocarbons as Halon Replacements: Laboratory Testing of Halon 1211 Replacements*, ESL-TR-89-38, Vol. 3 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, March 1993.

10. Dierdorf, D. S., Tapscott, R. E., Skaggs, S. R., and Moore, T. A., *Halocarbons as Halon Replacements: Laboratory Testing of Halon 1301 Replacements*, ESL-TR-89-38, Vol. 4 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, March 1993.

11. Tapscott, R. E., and Lee, M. E., *Halocarbons as Halon Replacements: Medium-Scale Testing of Halon 1211 Replacements*, ESL-TR-89-38, Vol. 5 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, May 1993.

12. Tapscott, R. E., "Commercialized Halon Options," *Proceedings, International CFC and Halon Alternatives Conference*, Washington, DC, 23-25 October 1995, pp. 536-545.

13. Tapscott, R. E., "Update on Total Flood Options," *Proceedings, International Conference on Ozone Protection Technologies*, Washington, DC 21-23 October 1996, pp. 621-630,.

14. "Protection of Stratospheric Ozone: Notice of Final Rulemaking," *Federal Register*, Vol. 58, No. 236, pp. 65018-65082, 10 December 1993.

15. Heinonen, E. W., Lifke, J. L., and Tapscott, R. E., *Advanced Streaming Agent Development, Volume IV: Tropodegradable Halocarbons*, WL-TR-96-XX, Vol. 4 of 5, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, May 1996.

16. *Radiative Forcing to Climate Change: The 1994 Report of the Scientific Assessment Working Group of IPCC*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 1994.

17. *Risk Screen on the Use of Substitutes for Class I Ozone-Depleting Substances: Fire Suppression and Explosion Protection (Halon Substitutes)*, Snap Technical Background Document, USEnvironmental Protection Agency, Washington, DC, March 1994.

18. "Protection of Stratospheric Ozone: Final Rule," *Federal Register*, Vol. 60, No. 113, pp. 31092-31107, 13 June 1995.

19. *Scientific Assessment of Ozone Depletion: 1994*, Report No.: 37, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, United Nations Environment Programme, and World Meteorological Organization, February 1995.

20. "RIVM Study Assesses HFC Policy Options and Effects," *Global Environmental Change Report*, Vol. 7, No. 2, 27 January 1995, p. 4.

21. *Montreal Protocol on Substances that Deplete the Ozone Layer, Report of the Halon Fire Extinguishing Agents Technical Options Committee*, United Nations Environment Programme, Paris, France, pp. 1-2, December, 1994.

22. Skaggs, S. R., and Tapscott, R. E., *Advanced Streaming Agent Program: Candidate Survey*, Final Report, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, December 1994.

23. Tapscott, R. E., Heinonen, E. W., and Brabson, G. D., *Advanced Agent Identification and Preliminary Assessment*, WL-TR-95-XXX, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, December 1996.

24. Gobeli, G. W., Tapscott, R. E., and Kaizerman, J. A., *Advanced Streaming Agent Development, Volume I: Silicon Compounds*, WL-TR-96-XX, Vol. 1 of 5, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, May 1996.

25. Patterson, R. A., Gobeli, G. W., Brabson, G. D., and Tapscott, R. E., *Advanced Streaming Agent Development, Volume II: Metal Compounds*, WL-TR-96-XX, Vol. 2 of 5, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

26. Kaizerman, J. A., and Tapscott, R. E., *Advanced Streaming Agent Development, Volume III: Phosphorus Compounds*, WL-TR-96-XX, Vol. 3 of 5, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, May 1996.

27. Lifke, J. L., Moore, T. A., and Tapscott, R. E., *Advanced Streaming Agent Development, Volume V: Laboratory-Scale Streaming Tests*, WL-TR-96-XX, Vol. 5 of 5, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

28. Barnes, D. G., "Times are Tough—Brother, Can You Paradigm?," *Risk Analysis*, Volume 14, No. 3, June 1994, pages 219-223.

29. Paustenbauch, D. J., Jernigan, J. D., Finley, B. L., Ripple, S. R., and Keenan, R. E., "The Current Practice of Health Risk Assessment: Potential Impact on Standards for Toxic Air Contaminants," *Journal of the Air Waste Management Association*, Vol. 40, pp. 1620-1630, 1990.

30. Skaggs, S. R., and Tapscott, R. E., *Advanced Streaming Agent Program: Candidate Survey, Final Report*, Wright Laboratories (WL/FIVCF) and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, December 1994.

31. *Fire Extinguishing Agents*, Army Engineers Research and Development Laboratories, Fort Belvoir, VA, and Purdue Research Foundation and Department of Chemistry, Purdue University, West Lafayette, Indiana, 1950. Final Report for Contract W44-009-ENGR-507, AD654322.

32. *Halon 1211 Fire Extinguishing Systems*, NFPA Standard 12B, 1990 Edition, National Fire Protection Association, Quincy, Massachusetts, 1990.

33. Beck, P. S., Clark, D. G., and Tinston, D. J., "The Pharmacologic Actions of Bromochlorodifluoromethane (BCF)," *Toxicology and Applied Pharmacology*, Vol. 24, pp. 20-29, 1973.

34. Sax, N. I., and Lewis, R. J., Sr., *Dangerous Properties of Industrial Materials*, Seventh Edition, Van Nostrand Reinhold, New York, 1989.

35. *Registry of Toxic Effects of Chemical Substances*, Sweet, D. V., editor, USDepartment of Health and Human Services, National Institute for Occupational Safety and Health, Washington, DC, Report Number DHHS (NIOSH), Vols. 1-5, April 1987.

36. "CFC Substitute Found to Have Harmful Effects," *Ozone Depletion Today*, 28 October 1996.

37. Clayton, J. W., Jr., "Fluorocarbon Toxicity and Biological Action," in *Fluorine Chemistry Reviews*, Vol. 1, Tarrant, P., editor, Marcel Dekker, Inc., New York, USA, pp. 197-252, 1967.

38. Cook, E. W., and Pierce, J. S., "Toxicology of Fluoro-olefins," *Nature*, Vol. 242, pp. 337-338, 1973.

39. Krespan, C. G., "Organic Fluorine Chemistry," *Science*, Vol. 150, pp. 13-18, 1965.

40. Abreu, B. E., "Unsaturated Mono Halogenated Hydrocarbons as General Anesthetics," *Anesthesiology*, Vol. 2, pp. 393-397, 1941.

41. Henschler, D. "Halogenated Alkenes and Alkynes," In: *Bioactivation of Foreign Compounds*, Academic Press, Inc., New York, pp. 317-347, 1985.

42. Eder, E., Neudecker, T., Lutz, D., and Henschler, D., "Correlation of Alkylating and Mutagenic Activities of Allyl and Allylic Compounds: Standard Alkylation Test vs. Kinetic Investigation," *Chemical-Biological Interactions*, Vol. 38, pp. 303-315, 1982.

43. Clayton, J. W., Jr. "Toxicology of the Fluoroalkenes: Review and Research Needs," *Environmental Health Perspectives*, Vol. 21, pp. 255-267, 1977.

44. Burgison, R. M., O'Malley, W. E., Heisse, C. K., Forrest, J. W., and Krantz, J. C., Jr., "Anesthesia XLVI. Fluorinated Ethylenes and Cardiac Arrhythmias Induced by Epinephrine," *Journal of Pharmacology and Experimental Therapeutics*, Vol. 114, pp. 479-490, 1955.

45. Krantz, J. C. Jr., and Rudo, F.G., "The Fluorinated Anesthetics," In *Handbook of Experimental Pharmacology*, Smith, F. A., ed., Springer-Verlag, West Berlin, Vol. XX/I, pp. 501-564, 1966.

46. Neudecker, T., Lutz, D., Eder, E., and Henschler, D., "Structure-Activity Relationship in Halogen and Alkyl Substituted Allyl and Allylic Compounds: Correlation of Alkylating and Mutagenic Properties," *Biochemical Pharmacology*, Vol. 29, pp. 2611-2617, 1980.

47. Eder, E., Neudecker, T., Lutz, D., and Henschler, D., "Mutagenic Potential of Allyl and Allylic Compounds," *Biochemical Pharmacology*, Vol. 29, pp. 993-998, 1980.

48. Cohen, E. N., Brewer, H. W., Bellville, J. W., and Sher, R., "The Chemistry and Toxicology of Dichlorohexafluorobutene," *Anesthesiology*, Vol. 26, p. 140, 1965.

49. Chenoweth, M. B., "Communication of the Toxicity of 2,3-Dichloro-1,1,1,4,4,4-hexafluorobutene-2" to the National Research Council, Subcommittee on the National Halothane Study of the Committee on Anesthesia, 1963.

50. Raventos, J., and. Lemon, P. G. "The Impurities in Fluothane: Their Biological Properties," *British Journal of Anesthesia*, Vol. 37, p. 716, 1965.

51. Ulm, K., "Screening Results on the Toxicity of Numerous Fluoro Organic Compounds," *Abstracts of the International Symposium on Fluorine Chemistry*, Paris, France, 1986, p. 252.

52. Manahan, S. E., *Toxicological Chemistry*, Lewis Publishers, Inc., Chelsea, Michigan, 1989.

53. Tapscott, R. E., and Skaggs, S. R., *Identification of Alternatives to CFC-113 for Solvent Cleaning*, NASA White Sands Test Facility, Las Cruces, New Mexico, September 1994.

54. The *Condensed Chemical Dictionary*, 8th Edition, Revised by G. G. Hawley, Van Nostrand Reinhold Company, New York, 1971, p. 103.

55. Burns, T. H. S., Hall, J. M., Bracken, A., and Gouldstone, G., *Anaesthesia*, Vol. 19, p. 167, 1964.

56. Burns, T. H. S., Hall, J. M., Bracken, A., and Gouldstone, G., *Anaesthesia*, Vol. 16, p. 333, 1961.

57. Pitts, W. M., Nyden, M. R., Gann, R. G., Mallard, W. G., and Tsang, W., *Construction of an Exploratory List of Chemicals to Initiate the Search for Halon Alternatives*, NIST Technical Note 1279, Air Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, National Institute of Standards and Technology, Gaithersburg, Maryland, August 1990.

58. Sittig, M., *Handbook of Toxic and Hazardous Chemicals and Carcinogens*, Noyes Publications, Park Ridge, New Jersey, 1985.

59. Matovinovic, J., "Iodine," in *Nutrition Reviews' Present Knowledge in Nutrition*, Fifth Edition, The Nutrition Foundation, Inc., Washington, DC, 1984, pp. 587-606.

60. Mathewson, H. S., *Structural Forms of Anesthetic Compounds*, Charles C. Thomas, Springfield, Illinois, 1961.

61. Krantz, J. C. Jr.,. Lu, G. G, Speers, L., Rudo F. G., and Cascorbi, H. F., "Anesthesia LXV. The Anesthetic Properties of 2,2,2-Trifluoroethyl Iodide," *Anesthesia and Analgesia Current Research*, Vol. 42, pp. 12-18, 1963.

62. Hine, J., and Ghirardelli, R. G., "The S_n2 Reactivity of β-Fluoroethyl Iodides," *Journal of Organic Chemistry*, Vol. 23, pp. 1550-1552, 1958.

63. Sokoloff, L., "Local Blood Flow in Neural Tissue," in *New Research Techniques of Neuroanatomy*, W. F. Windle, ed., Symposium Sponsored by the National Multiple Sclerosis Society, Springfield, Illinois, pp. 51-61, 1957.

64. Lu, G. G., Ling, J. S. L., and Krantz, J. C., Jr., "Anesthesia XLI: The Anesthetic Properties of Certain Fluorinated Hydrocarbons and Ethers," *Anesthesiology*, Vol. 14, pp. 466-472, 1953.

65. Moore, T. A., Skaggs, S. R., Corbitt, M. R., Tapscott, R. E., Dierdorf, D., and Kibert, C., " The Development of CF3I as a Halon Replacement," Wright laboratory (WL/FIVCF), Tyndall AFB, FL, October, 1994, NMERI 1994/40.

66. Robbins, B. H., "Preliminary Studies of the Anesthetic Activity of Fluorinated Hydrocarbons," *Journal of Pharmacology and Experimental Therapeutics*, Vol. 86, pp. 197-204, 1946.

67. Burns, T. H. S., Hall, J. M., Bracken, A., and Gouldstone,G., "Fluorine Compounds in Anesthesia (5) Examination of Six Heavily Halogenated Aliphatic Compounds," *Anaesthesia*, Vol. 17, pp. 337-343, 1962.

68. Di Paolo, T., and Sandorfy, C., "Hydrogen Bond Breaking Potency of Fluorocarbon Anesthetics," *Journal of Medicinal Chemistry*, Vol. 17, pp. 809-814, 1974.

69. Probst, A., Raab, K., Ulm, K., and von Werner, K., "Synthesis and Chemistry of Perfluoro-2-iodo-2-methyl Alkanes," *Journal of Fluorine Chemistry*, Vol. 37, pp. 223-245, 1987.

70. Beliles, R. P., "Metals," in *Toxicology, The Basic Science of Poisons*, Casarett, L. J., and Doull, J., editors, Macmillian Publishing Co, Inc., New York, 1975, pp. 454-502.

71. Parshall, G. W., "Chemical Warfare Agents - How Do We Rid Ourselves of Them?," *The Chemist*, Vol. 72, No. 4, pp. 5-7, May/June, 1995.

72. *Toxicology and Carcinogenesis Studies of Tricresyl Phosphate In F344/N Rats and B6C3F$_1$ Mice*, NTP TR 433, NIH Publication No. 94-3164, US Department of Health and Human Services, National Toxicology Program, Research Triangle Park, North Carolina, September 1994.

73. Kinkhead, E., Kimmel, E., Wall, H., and Grabau, J., "Determination of the Toxicity of Cyclotriphosphazene Hydraulic Fluid by 21-Day Repeated Inhalation and Dermal Exposure," *American Industrial Hygiene Association Journal*, Vol. 51, pp. 583-587, 1990.

74. Allcock, H. R., Pucher, S. R., Fitzpatrick, R. J., and Rashid, K., "Antibacterial Activity and Mutagenicity Studies of Water-Soluble Phosphazene High Polymers," *Biomaterials*, Vol. 13, No. 12, pp. 857-862, 1992.

75. Sittig, M., *Handbook of Toxic and Hazardous Chemicals and Carcinogens*, Second Edition, Noyes Publications, Park Ridge, New Jersey, pp. 781-782, 1985.

76. Liimatta, E. and Shubkin, R. L., "*normal*-Propyl Bromide Based Cleaning Solvents," Proceeding, International Conference on Ozone Protection Technologies, November 12-13, 1997, pp. 443-452.

77. Alarie, Y., "Dose-Response Analysis in Animal Studies: Prediction of Human Responses," *Environmental Health Perspectives*, Vol. 42, pp. 9-13, December 1981.

78. Barrow, C. S., Alarie, Y., Stock, M. F., "Sensory Irritation and Incapacitation Evoked by Thermal Decomposition Products of Polymers and Comparisons with Known Sensory Irritants," *Archives of Environmental Health*, Vol. 33, pp. 79-88, 1978.

79. Buckley, L. A., Jiang, X. Z., James, R. A., Morgan, K. T., and Barrow, C. S., "Respiratory Tract Lesions Induced by Sensory Irritants at the RD_{50} Concentration," *Toxicology and Applied Pharmacology*, Vol. 74, pp. 417-429, 1984.

80. Zissu, D., "Histopathological Changes in the Respiratory Tract of Mice Exposed to Ten Families of Airborne Chemicals," *Journal of Applied Toxicology*, Vol. 15, pp. 207-213, 1995.

81. Moore, T. A. and Lifke, J.L., "Evaluation and Testing of Clean Agents for US Army Portable Fire Extinguishers-Vol. III: Test Results and Recommendations," Final Report, US Army Tank Automotive and Armament Command (TACOM), June 1997.

82. William J. Brock, DuPont, Wilmington, Delaware, personal communication to Tom Cortina, Halon Alternatives Research Corporation, Arlington, Virginia, 22 April 1997.

83. Krantz, J. C., Jr., and Rudo, F. G., "The Fluorinated Anesthetics," in *Handbook of Experimental Pharmacology*, Vol. 20/1, Eichler, O., Farah, A., Herken, H., and Welch, A. D., editors, Springer-Verlag, Berlin, Germany, Chapter 10, pp. 501-564, 1966.

84. Steciak, J., Buckley, J. L., Stavrianidis, P., Merritt, R. C., Noel, W., *An Analysis of Fire and Deflagration Hazards Currently Protected by Halon 1301 and Halon 1211*, ICF Incorporated, Washington, DC; Factory Mutual Research, Norwood, Massachusetts, 21 April 1992.

85. United Nations Environment Program, *Halon Fire Extinguishing Agents*, Technical Options Report, Montreal Protocol Assessment, August 11, 1989.

86. Jarabek, A. M., Fisher, J. W., Rubenstein, R., Lipscomb, J. C., Williams, R. J., Vinegar, A., and McDougal, J. N., "Mechanistic Insights Aid the Search for CFC Substitutes: Risk Assessment of HCFC-123 as an Example," Risk Analysis, Vol. 14, June 1994, pp. 231-250.

87. McDougal, J. N., Dodd, D. E., and Skaggs, S. R., "Recommending Exposure Limits for Halon Replacements," *Proceedings, Halon Alternatives Technical Working Conference*, Albuquerque, New Mexico, 11-13 May 1993, pp. 63-73.

88. *Assessment of Occupational Exposures to Halon Substitutes Used For Fire Protection*, EPA Contract No. 68-D90068; Work Assignment No. 4-68, Environmental Protection Agency, Washington, DC, Meridian Research, Inc., Silver Spring, MD, 18 June 1992.

89. Scheil, G., Klamm, S., and Dahlquist, B., "A Comparision of Toxic Compounds Produced by Three Different Halocarbon Agents During Firefighter Training Exercises," Halon Alternatives Technical Working Conference 1992 Proceedings, Albuquerque, New Mexico, 12-14 May 1992,

90. *Standard on Halon 1301 Fire Extinguishing Systems*, NFPA Standard 2001, 1992 Edition, National Fire Protection Association, Quincy, Massachusetts, 1992.

91. *Standard on Clean Agent Fire Extinguishing Systems*, NFPA Standard 2001, 1996 Edition, National Fire Protection Association, Quincy, Massachusetts, 1996.

92. Halogenated Agent Standard, Standard ANSI/UL 1093, Underwriters Laboratory, Northbrook, Illinois, 1996.

93. Meridian Research Inc., "Assessment of Occupational Exposures to Halon Substitutes Used for Fire Protection – Final Report," Global Change Division, Office of Air and Radiation, Environmental Protection Agency, EPA Contract No. 68-D90068, Work Assignment No. 4-68, June 1992.

94. Skaggs, S.R., and Cecil, M.A., "Exposure Assessment to Triodide™ in Streaming Scenarios," *Proceedings*, 1995 International CFC and Halon Alternatives Conference, October 23-25, 1995, Washington, DC.

95. Mishap Report, Department of the Navy, Naval Safety Center, Norfolk, Virginia, 10 March 1995.

96. *Risk Analysis, An International Journal*, "Special Issue: The Risk Assessment Paradigm After Ten Years: Policy and Practice Then, Now, and in the Future," Plenum Press, New York and London, Vol. 14, No. 3, June 1994.

97. Haemisegger, E., and Sheehan, J. "EPA's New Regulatory Program for Evaluating CFC and Halon Substitutes," *Proceeding, 1992 Halon Alternatives Technical Working Conference*, Albuquerque, NM, pp. 26-45, May 12-14, 1992.

98. Kolluru, R., Bartell, S., Pitblado, R., and Stricoff, S., *Risk Assessment and Management Handbook, For Environmental, Health, and Safety Professionals,* McGraw-Hill, Inc., 1996.

99. Barnes, D. G., "Times are Tough—Brother, Can You Paradigm?," *Risk Analysis*, Volume 14, No. 3, June 1994, pp. 219-223.

APPENDIX A

GLOSSARY

Alkane—A saturated hydrocarbon with the general formula C_nH_{2n+2} (e.g., butane, $CH_3CH_2CH_2CH_3$) and derivatives thereof.

Alkene—A hydrocarbon containing one or more carbon-carbon double bonds or derivatives thereof. Hydrocarbons with a single double bond have the general formula C_nH2_n (e.g., 1-butene, $CH_2{=}CHCH_2CH_3$).

Aliphatic—Straight-chain, branched-chain, or cyclic hydrocarbon structures containing carbon atoms linked by single sp^3-sp^3 bonds.

Alkoxy—A group of the type -OR, where R is an aliphatic hydrocarbon radical or a substituted aliphatic radical. Examples are methoxy ($-OCH_3$) and ethoxy ($-OC_2H_5$).

Alkyl—An aliphatic substituent. Examples are methyl ($-CH_3$), ethyl ($-CH_2CH_3$ or $-C_2H_5$), *n*-propyl ($-CH_2CH_2CH_3$ or $-C_3H_7$), *i*-propyl ($-CH(CH_3)_2$), *n*-butyl ($-CH_2CH_2CH_2CH_3$ or $-C_4H_9$), *t*-butyl ($-C(CH_3)_3$).

Aromatic—Cyclic molecules or fused cyclic molecules containing formally alternating single and double bonds with delocalized π electrons. The most common simple aromatic compound is benzene.

Aryl—Aromatic substituents derived from benzene and related compounds. Examples are phenyl ($-C_6H_5$), tolyl ($-C_6H_4CH_3$), and naphthyl ($-C_{10}H_7$).

Aryloxy—A group of the type -OR, where R is an aryl group. Examples are phenoxy ($-OC_6H_5$) and naphthoxy ($-OC_{10}H_7$).

Chlorofluorocarbon (CFC)—A saturated halocarbon containing only chlorine, fluorine, and carbon [e.g., CCl_2F_2 (CFC-12)].

Covalent—Bonding in which electrons are shared by two atoms, both of which contribute to the bonding pair(s).

Cyclic—Arranged in a closed ring rather than an open chain.

Edema—Accumulation of fluid, often in lungs.

Ester—A compound formed from an alcohol and an oxyacid by elimination of water. This includes compounds containing the groups -BOR, -P(O)OR, -C(O)OR, and -SiOR, where R is an organic group.

Ethyl—The $-C_2H_5$ group, second of the homologous series of saturated aliphatic radicals of the type C_nH_{2n+1}.

Haloalkane—Saturated halocarbons containing only carbon, halogen, and, in some cases, hydrogen atoms.

Halocarbon—A compound of carbon and one or more halogen atoms with or without hydrogen.

Halide—A compound a halogen atom. Alternatively, a negative ion of one of the halogen atoms (e.g., fluoride, F^-; chloride, Cl^-; bromide, Br^-; or iodide, I^-).

Halogen—One of the elements or atoms fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At). The last element is radioactive and is not considered in this project.

Homolog—A compound forming part of a homologous series, and hence closely related to the other compounds in that series in structure, composition, and physical properties.

Homologous—An adjective used to describe homologs.

Hydride—A binary compound of hydrogen with some other element.

Hydrocarbon—A binary compound of carbon and hydrogen. This term includes aliphatic compounds (paraffins), compounds containing double bonds (olefins), and aromatics.

Hydrochlorofluorocarbon—An aliphatic compound containing only hydrogen, fluorine, chlorine, and carbon. An example is HCFC-123, $CHCl_2CF_3$.

Hydrofluorocarbon—An aliphatic compound containing only hydrogen, fluorine, and carbon. An example is HFC-134a, CH_2FCF_3.

Hydrolysis—The reaction of a material with water. Here, this usually refers to the reaction of a halide with water to form a hydrogen halide, e.g., $RX + H_2O \rightarrow ROH + HX$, where X is a halogen atom and R is any group.

Hydroxyl—The -OH group, common to alcohols, ROH, and water or the unattached •OH free radical.

Iso—Here, an adjective designating a 3-carbon alkyl group attached at the middle carbon atom. The isopropyl group (also designated as the *i*-propyl group) is $-CH(CH_3)_2$.

Methyl—The $-CH_3$ group, simplest member of the homologous series of saturated aliphatic radicals of the type C_nH_{2n+1}.

Olefin—An unsaturated hydrocarbon containing one or more double bonds, an alkene. An example is ethene (ethylene), $H_2C{=}CH_2$.

Perfluorocarbon—An aliphatic compound containing only fluorine and carbon. An example is FC-218 (sometimes called PFC-218), $CF_3CF_2CF_3$.

Phenyl—The cyclic $-C_6H_5$ group derived from benzene.

Phosphorus Nitride—A compound containing phosphorus and nitrogen including such families as phosphazenes, phosphonitriles, and phosphazanes.

Polymer—A chemical compound in which some relatively simple unit structure or group is repeated throughout the molecules.

Propyl—The $-C_3H_7$ group, third in the homologous series of saturated aliphatic radicals of the type C_nH_{2n+1}.

Saturated—Chemically combined to the extent allowed by the most commonly exhibited valence. Containing no double or triple bonds.

Silane—Hydrides of silicon of the type Si_nH_{2n+2} or derivatives thereof.

Siloxane—A compound of silicon containing alternating silicon and oxygen atoms, sometimes called silicones. Examples are disiloxane, $H_3Si\text{-}O\text{-}SiH_3$, trisiloxane, $H_3Si\text{-}O\text{-}SiH_2\text{-}O\text{-}SiH_3$, etc.

Synergism-An effect wherein a mixture shows an activity greater than would be predicted from the activities of the components. Synergism can be observed in fire suppression performance, toxicity, and other characteristics.

Tertiary—An adjective designating a 4-carbon alkyl group containing one carbon attached to three others. The tertiary butyl group (also designated as the *t*-butyl or *tert*-butyl group) is $-C(CH_3)_3$.

Trifluoromethyl—The $-CF_3$ group, derived from the methyl group, $-CH_3$, by substitution with fluorine.

Tropodegradable—An adjective applied to compounds that are rapidly removed from the earth's troposphere by such mechanisms as photolysis, reaction with hydroxyl free radical, rainout, and physical removal.

Unsaturated—Containing one or more double or triple bonds. Also used to denote that further bonding is possible for one or more of the elements present in a compound.

Valence—A whole number that gives the combining power of an element with other elements. For covalent compounds, the valence is the number of bonds, with a double bond counting as two and a triple bond counting as three, that an atom can form with other atoms. For example, in CH_4 and O=C=O, carbon has a valence of four (it is said to be tetravalent). This is the only valence observed for carbon except in some very rare solid state metal compounds and unstable, short-lived gaseous species.

APPENDIX B

DETAILED RISK CHARACTERIZATION RESULTS FOR LC_{50} UF = 10

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Halocarbon/Scenario															
Typ. Single Office (780 ft^3)															
Halon 1211	15	165.36	2,450	16,570	1,225	8,285	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	4,830	30,211	2,415	15,105	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	6,250	34,888	3,125	17,444	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	3,360	46,453	1,680	23,227	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	4,900	30,470	2,450	15,235	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	4,900	30,470	2,450	15,235	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	1,200	7,313	600	3,656	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	3,000	14,724	1,500	7,362	35,000	171,779	1	50,000	245,399	30	10	1000	4908
Min Tox. Bromocarbons	15	250	4,830	49,387	2,415	24,693	40,000	408,998	1	50,001	511,258	31	10	1000	10225
Advanced Bromocarbons	15	200	2,500	20,450	1,250	10,225	20,000	163,599	1	50,000	408,998	30	10	1000	8180
Larger Office/Lab (1,780 ft^3)															
Halon 1211	15	165.36	950	6,425	475	3,213	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	1,970	12,322	985	6,161	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	2,550	14,234	1,275	7,117	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	1,370	18,941	685	9,470	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	1,970	12,250	985	6,125	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	1,970	12,250	985	6,125	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	1,100	6,703	550	3,352	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	1,300	6,380	650	3,190	35,000	171,779	1	50,000	245,399	30	10	1000	4908
Advanced Bromocarbons	15	200	1,000	8,180	500	4,090	20,000	163,599	1	50,000	408,998	30	10	1000	8180

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Aircraft Hanger (336,000ft^3)															
Halon 1211	15	165.36	900	6,087	450	3,043	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	910	5,692	455	2,846	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	2,000	11,164	1,000	5,582	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	515	7,120	258	3,560	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	910	5,659	455	2,829	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	910	5,659	455	2,829	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	1,000	6,094	500	3,047	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	800	3,926	400	1,963	35,000	171,779	1	50,000	245,399	30	10	1000	4908
Advanced Bromocarbons	15	200	800	6,544	400	3,272	20,000	163,599	1	50,000	408,998	30	10	1000	8180
Vicinity of 850 ft^2 Fire (150-lb ext)															
Halon 1211	15	165.36	2,700	18,261	1,350	9,130	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	9,000	56,293	4,500	28,147	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	12,000	66,984	6,000	33,492	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	5,000	69,127	2,500	34,563	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	9,000	55,966	4,500	27,983	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	9,000	55,966	4,500	27,983	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	2,900	17,673	1,450	8,836	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	6,000	29,448	3,000	14,724	50,000	245,399	1	50,000	245,399	30	10	1000	4908
Advanced Bromocarbons	15	200	4,000	32,720	2,000	16,360	40,000	327,198	1	50,000	408,998	30	10	1000	8180

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Firefighter Training (150-lb)															
Halon 1211	15	165.36	500	3,382	250	1,691	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	1,000	6,255	500	3,127	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	1,000	5,582	500	2,791	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	1,000	13,825	500	6,913	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	1,000	6,218	500	3,109	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	1,000	6,218	500	3,109	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	750	4,571	375	2,285	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	750	3,681	375	1,840	50,000	245,399	1	50,000	245,399	30	10	1000	4908
Advanced Bromocarbons	15	200	750	6,135	375	3,067	40,000	327,198	1	50,000	408,998	30	10	1000	8180
Firefighter Training (20-lb)															
Halon 1211	15	165.36	500	3,382	250	1,691	10,000	67,632	1	85,000	574,871	240	10	1000	6763
HCFC-123	15	152.93	500	3,127	250	1,564	20,000	125,096	1	32,000	200,154	240	10	1000	6255
HCFC-124	15	136.48	500	2,791	250	1,396	25,000	139,550	1	300,000	1,674,601	240	10	1000	5582
FC-5-1-14	15	338.03	500	6,913	250	3,456	300,000	4,147,607	1	300,000	4,147,607	240	10	1000	13825
HFC-236fa	15	152.04	500	3,109	250	1,555	100,000	621,840	1	400,000	2,487,362	240	10	1000	6218
HFC-236ea	15	152.04	500	3,109	250	1,555	35,000	217,644	1	85,000	528,564	240	10	1000	6218
CF3I	15	149	500	3,047	250	1,524	2,000	12,188	1	270,000	1,645,399	15	10	1000	6094
Bromoalkane Blends	15	120	500	2,454	250	1,227	50,000	245,399	1	50,000	245,399	30	10	1000	4908
Advanced Bromocarbons	15	200	500	4,090	250	2,045	40,000	327,198	1	50,000	408,998	30	10	1000	8180

Adult Inhalation Rate = .042 m^3/min

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Halocarbon/Scenario															
Typ. Single Office (780 ft^3)															
Halon 1211	67,632	41	57,487.12	8,278	0.12	0.25	0.01	0.02	0.13	0.26	1	0.29	0.25	0.53	1
HCFC-123	125,096	75	20,015.38	2,882	0.12	0.24	0.05	0.09	0.17	0.34	1	1.51	0.24	1.75	3
HCFC-124	139,550	84	167,460.12	24,114	0.13	0.25	0.01	0.01	0.13	0.26	1	0.21	0.25	0.46	1
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.01	0.01	0.00	0.01	0.01	0.02	0	0.11	0.01	0.12	0
HFC-236fa	621,840	373	248,736.20	35,818	0.02	0.05	0.00	0.01	0.03	0.06	0	0.12	0.05	0.17	0
HFC-236ea	217,644	131	52,856.44	7,611	0.07	0.14	0.02	0.04	0.09	0.18	1	0.58	0.14	0.72	1
CF3I	12,188	7	164,539.88	1,481	0.30	0.60	0.02	0.04	0.32	0.64	2	0.04	0.60	0.64	1
Bromoalkane Blends	171,779	103	24,539.88	442	0.04	0.09	0.15	0.30	0.19	0.39	1	0.60	0.09	0.69	1
Min Tox. Bromocarbons	408,998	245	51,125.77	951	0.06	0.12	0.23	0.47	0.29	0.59	2	0.97	0.12	1.09	2
Advanced Bromocarbons	163,599	98	40,899.80	736	0.06	0.13	0.13	0.25	0.19	0.38	1	0.50	0.13	0.63	1
Larger Office/Lab (1,780 ft^3)															
Halon 1211	67,632	41	57,487.12	8,278	0.05	0.10	0.003	0.007	0.05	0.10	1	0.11	0.10	0.21	1
HCFC-123	125,096	75	20,015.38	2,882	0.05	0.10	0.02	0.04	0.07	0.14	1	0.62	0.10	0.71	12
HCFC-124	139,550	84	167,460.12	24,114	0.05	0.10	0.00	0.01	0.05	0.11	1	0.09	0.10	0.19	2
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.00	0.00	0.00	0.00	0.00	0.01	0	0.05	0.00	0.05	1
HFC-236fa	621,840	373	248,736.20	35,818	0.01	0.02	0.00	0.00	0.01	0.02	0	0.05	0.02	0.07	1
HFC-236ea	217,644	131	52,856.44	7,611	0.03	0.06	0.01	0.01	0.04	0.07	1	0.23	0.06	0.29	5
CF3I	12,188	7	164,539.88	1,481	0.28	0.55	0.02	0.04	0.30	0.59	6	0.04	0.55	0.59	1
Bromoalkane Blends	171,779	103	24,539.88	442	0.02	0.04	0.07	0.13	0.08	0.17	2	0.26	0.04	0.30	5
Advanced Bromocarbons	163,599	98	40,899.80	736	0.03	0.05	0.05	0.10	0.08	0.15	1	0.20	0.05	0.25	4

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Aircraft Hanger (336,000ft^3)															
Halon 1211	67,632	41	57,487.12	8,278	0.05	0.09	0.00	0.01	0.05	0.10	1	0.11	0.09	0.20	1
HCFC-123	125,096	75	20,015.38	2,882	0.02	0.05	0.01	0.02	0.03	0.06	1	0.28	0.05	0.33	2
HCFC-124	139,550	84	167,460.12	24,114	0.04	0.08	0.00	0.00	0.04	0.08	1	0.07	0.08	0.15	1
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.00	0.00	0.00	0.00	0.00	0.00	0	0.02	0.00	0.02	0
HFC-236fa	621,840	373	248,736.20	35,818	0.00	0.01	0.00	0.00	0.01	0.01	0	0.02	0.01	0.03	0
HFC-236ea	217,644	131	52,856.44	7,611	0.01	0.03	0.00	0.01	0.02	0.03	0	0.11	0.03	0.13	1
CF3I	12,188	7	164,539.88	1,481	0.25	0.50	0.02	0.04	0.27	0.54	6	0.04	0.50	0.54	3
Bromoalkane Blends	171,779	103	24,539.88	442	0.01	0.02	0.04	0.08	0.05	0.10	1	0.16	0.02	0.18	1
Advanced Bromocarbons	163,599	98	40,899.80	736	0.02	0.04	0.04	0.08	0.06	0.12	1	0.16	0.04	0.20	1
Vicinity of 850 ft^2 Fire (150-lb ext)															
Halon 1211	67,632	41	57,487.12	8,278	0.14	0.27	0.01	0.02	0.14	0.29	1	0.32	0.27	0.59	1
HCFC-123	125,096	75	20,015.38	2,882	0.23	0.45	0.09	0.18	0.31	0.63	2	2.81	0.45	3.26	6
HCFC-124	139,550	84	167,460.12	24,114	0.24	0.48	0.01	0.03	0.25	0.51	2	0.40	0.48	0.88	1
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.01	0.02	0.01	0.01	0.01	0.03	0	0.17	0.02	0.18	0
HFC-236fa	621,840	373	248,736.20	35,818	0.05	0.09	0.01	0.01	0.05	0.10	0	0.23	0.09	0.32	1
HFC-236ea	217,644	131	52,856.44	7,611	0.13	0.26	0.03	0.07	0.16	0.32	1	1.06	0.26	1.32	2
CF3I	12,188	7	164,539.88	1,481	0.73	1.45	0.05	0.11	0.78	1.56	5	0.11	1.45	1.56	3
Bromoalkane Blends	245,399	147	24,539.88	442	0.06	0.12	0.30	0.60	0.36	0.72	2	1.20	0.12	1.32	2
Advanced Bromocarbons	327,198	196	40,899.80	736	0.05	0.10	0.20	0.40	0.25	0.50	2	0.80	0.10	0.90	2

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Firefighter Training (150-lb)															
Halon 1211	67,632	41	57,487.12	8,278	0.03	0.05	0.00	0.00	0.03	0.05	1	0.06	0.05	0.11	1
HCFC-123	125,096	75	20,015.38	2,882	0.03	0.05	0.01	0.02	0.03	0.07	1	0.31	0.05	0.36	3
HCFC-124	139,550	84	167,460.12	24,114	0.02	0.04	0.00	0.00	0.02	0.04	1	0.03	0.04	0.07	1
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.00	0.00	0.00	0.00	0.00	0.01	0	0.03	0.00	0.04	0
HFC-236fa	621,840	373	248,736.20	35,818	0.01	0.01	0.00	0.00	0.01	0.01	0	0.03	0.01	0.04	0
HFC-236ea	217,644	131	52,856.44	7,611	0.01	0.03	0.00	0.01	0.02	0.04	1	0.12	0.03	0.15	1
CF3I	12,188	7	164,539.88	1,481	0.19	0.38	0.01	0.03	0.20	0.40	8	0.03	0.38	0.40	4
Bromoalkane Blends	245,399	147	24,539.88	442	0.01	0.02	0.04	0.08	0.05	0.09	2	0.15	0.02	0.17	2
Advanced Bromocarbons	327,198	196	40,899.80	736	0.01	0.02	0.04	0.08	0.05	0.09	2	0.15	0.02	0.17	2
Firefighter Training (20-lb)															
Halon 1211	67,632	41	57,487.12	8,278	0.03	0.05	0.00	0.00	0.03	0.05	1	0.06	0.05	0.11	1
HCFC-123	125,096	75	20,015.38	2,882	0.01	0.03	0.00	0.01	0.02	0.03	1	0.16	0.03	0.18	2
HCFC-124	139,550	84	167,460.12	24,114	0.01	0.02	0.00	0.00	0.01	0.02	0	0.02	0.02	0.04	0
FC-5-1-14	4,147,607	2,489	414,760.74	59,726	0.00	0.00	0.00	0.00	0.00	0.00	0	0.02	0.00	0.02	0
HFC-236fa	621,840	373	248,736.20	35,818	0.00	0.01	0.00	0.00	0.00	0.01	0	0.01	0.01	0.02	0
HFC-236ea	217,644	131	52,856.44	7,611	0.01	0.01	0.00	0.00	0.01	0.02	0	0.06	0.01	0.07	1
CF3I	12,188	7	164,539.88	1,481	0.13	0.25	0.01	0.02	0.13	0.27	5	0.02	0.25	0.27	2
Bromoalkane Blends	245,399	147	24,539.88	442	0.01	0.01	0.03	0.05	0.03	0.06	1	0.10	0.01	0.11	1
Advanced Bromocarbons	327,198	196	40,899.80	736	0.01	0.01	0.03	0.05	0.03	0.06	1	0.10	0.01	0.11	1

Adult Inhalation Rate = .042 m^3/min

APPENDIX C

DETAILED RISK CHARACTERIZATION RESULTS FOR LC_{50} UF = 100

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Halocarbon/Scenario															
Typ. Single Office (780 ft^3)															
Halon 1211	15	165.36	2,450	16,570	1,225	8,285	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	4,830	30,211	2,415	15,105	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	6,250	34,888	3,125	17,444	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	3,360	46,453	1,680	23,227	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	4,900	30,470	2,450	15,235	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	4,900	30,470	2,450	15,235	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	1,200	7,313	600	3,656	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	3,000	14,724	1,500	7,362	35,000	171,779	1	50,000	245,399	30	100	1000	4908
Min Tox. Bromocarbons	15	250	4,830	49,387	2,415	24,693	40,000	408,998	1	50,001	511,258	31	100	1000	10225
Advanced Bromocarbons	15	200	2,500	20,450	1,250	10,225	20,000	163,599	1	50,000	408,998	30	100	1000	8180
Larger Office/Lab (1,780 ft^3)															
Halon 1211	15	165.36	950	6,425	475	3,213	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	1,970	12,322	985	6,161	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	2,550	14,234	1,275	7,117	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	1,370	18,941	685	9,470	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	1,970	12,250	985	6,125	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	1,970	12,250	985	6,125	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	1,100	6,703	550	3,352	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	1,300	6,380	650	3,190	35,000	171,779	1	50,000	245,399	30	100	1000	4908
Advanced Bromocarbons	15	200	1,000	8,180	500	4,090	20,000	163,599	1	50,000	408,998	30	100	1000	8180

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Aircraft Hanger (336,000ft^3)															
Halon 1211	15	165.36	900	6,087	450	3,043	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	910	5,692	455	2,846	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	2,000	11,164	1,000	5,582	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	515	7,120	258	3,560	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	910	5,659	455	2,829	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	910	5,659	455	2,829	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	1,000	6,094	500	3,047	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	800	3,926	400	1,963	35,000	171,779	1	50,000	245,399	30	100	1000	4908
Advanced Bromocarbons	15	200	800	6,544	400	3,272	20,000	163,599	1	50,000	408,998	30	100	1000	8180
Vicinity of 850 ft^2 Fire (150-lb ext)															
Halon 1211	15	165.36	2,700	18,261	1,350	9,130	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	9,000	56,293	4,500	28,147	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	12,000	66,984	6,000	33,492	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	5,000	69,127	2,500	34,563	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	9,000	55,966	4,500	27,983	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	9,000	55,966	4,500	27,983	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	2,900	17,673	1,450	8,836	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	6,000	29,448	3,000	14,724	50,000	245,399	1	50,000	245,399	30	100	1000	4908
Advanced Bromocarbons	15	200	4,000	32,720	2,000	16,360	40,000	327,198	1	50,000	408,998	30	100	1000	8180

Chemical	Exposure Duration, min	Mole Wt. g/mole	Max Exposed Conc. ppm	Max Exposed Conc. mg/m^3	Geom. Mean, ppm	Geom. Mean, mg/m^3	Cardiac Sen. (LOAEL) ppm	Cardiac Sen. (LOAEL) mg/m^3	Cardiac UF	Rat LC50 ppm	Rat LC50 mg/m^3	Rat LC50 Duration min	Rat UF	Appl. Worker Std (TWA), ppm	Appl. Worker Std (TWA), mg/m^3
Firefighter Training (150-lb)															
Halon 1211	15	165.36	500	3,382	250	1,691	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	1,000	6,255	500	3,127	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	1,000	5,582	500	2,791	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	1,000	13,825	500	6,913	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	1,000	6,218	500	3,109	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	1,000	6,218	500	3,109	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	750	4,571	375	2,285	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	750	3,681	375	1,840	50,000	245,399	1	50,000	245,399	30	100	1000	4908
Advanced Bromocarbons	15	200	750	6,135	375	3,067	40,000	327,198	1	50,000	408,998	30	100	1000	8180
Firefighter Training (20-lb)															
Halon 1211	15	165.36	500	3,382	250	1,691	10,000	67,632	1	85,000	574,871	240	100	1000	6763
HCFC-123	15	152.93	500	3,127	250	1,564	20,000	125,096	1	32,000	200,154	240	100	1000	6255
HCFC-124	15	136.48	500	2,791	250	1,396	25,000	139,550	1	300,000	1,674,601	240	100	1000	5582
FC-5-1-14	15	338.03	500	6,913	250	3,456	300,000	4,147,607	1	300,000	4,147,607	240	100	1000	13825
HFC-236fa	15	152.04	500	3,109	250	1,555	100,000	621,840	1	400,000	2,487,362	240	100	1000	6218
HFC-236ea	15	152.04	500	3,109	250	1,555	35,000	217,644	1	85,000	528,564	240	100	1000	6218
CF3I	15	149	500	3,047	250	1,524	2,000	12,188	1	270,000	1,645,399	15	100	1000	6094
Bromoalkane Blends	15	120	500	2,454	250	1,227	50,000	245,399	1	50,000	245,399	30	100	1000	4908
Advanced Bromocarbons	15	200	500	4,090	250	2,045	40,000	327,198	1	50,000	408,998	30	100	1000	8180

Adult Inhalation Rate = .042 m^3/min

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Halocarbon/Scenario															
Typ. Single Office (780 ft^3)															
Halon 1211	67,632	41	5,748.71	828	0.12	0.25	0.09	0.18	0.21	0.43	1	2.88	0.25	3.13	1
HCFC-123	125,096	75	2,001.54	288	0.12	0.24	0.47	0.94	0.59	1.18	3	15.09	0.24	15.34	5
HCFC-124	139,550	84	16,746.01	2,411	0.13	0.25	0.07	0.13	0.19	0.38	1	2.08	0.25	2.33	1
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.01	0.01	0.04	0.07	0.04	0.08	0	1.12	0.01	1.13	0
HFC-236fa	621,840	373	24,873.62	3,582	0.02	0.05	0.04	0.08	0.06	0.13	0	1.23	0.05	1.27	0
HFC-236ea	217,644	131	5,285.64	761	0.07	0.14	0.18	0.36	0.25	0.50	1	5.76	0.14	5.90	2
CF3I	12,188	7	16,453.99	148	0.30	0.60	0.22	0.44	0.52	1.04	2	0.44	0.60	1.04	0
Bromoalkane Blends	171,779	103	2,453.99	44	0.04	0.09	1.50	3.00	1.54	3.09	7	6.00	0.09	6.09	2
Min Tox. Bromocarbons	408,998	245	5,112.58	95	0.06	0.12	2.34	4.67	2.40	4.79	11	9.66	0.12	9.78	3
Advanced Bromocarbons	163,599	98	4,089.98	74	0.06	0.13	1.25	2.50	1.31	2.63	6	5.00	0.13	5.13	2
Larger Office/Lab (1,780 ft^3)															
Halon 1211	67,632	41	5,748.71	828	0.05	0.10	0.035	0.070	0.08	0.16	1	1.12	0.10	1.21	1
HCFC-123	125,096	75	2,001.54	288	0.05	0.10	0.19	0.38	0.24	0.48	3	6.16	0.10	6.25	75
HCFC-124	139,550	84	16,746.01	2,411	0.05	0.10	0.03	0.05	0.08	0.16	1	0.85	0.10	0.95	10
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.00	0.00	0.01	0.03	0.02	0.03	0	0.46	0.00	0.46	6
HFC-236fa	621,840	373	24,873.62	3,582	0.01	0.02	0.02	0.03	0.03	0.05	0	0.49	0.02	0.51	6
HFC-236ea	217,644	131	5,285.64	761	0.03	0.06	0.07	0.14	0.10	0.20	1	2.32	0.06	2.37	28
CF3I	12,188	7	16,453.99	148	0.28	0.55	0.20	0.41	0.48	0.96	6	0.41	0.55	0.96	5
Bromoalkane Blends	171,779	103	2,453.99	44	0.02	0.04	0.65	1.30	0.67	1.34	8	2.60	0.04	2.64	32
Advanced Bromocarbons	163,599	98	4,089.98	74	0.03	0.05	0.50	1.00	0.53	1.05	6	2.00	0.05	2.05	24

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Aircraft Hanger (336,000ft^3)															
Halon 1211	67,632	41	5,748.71	828	0.05	0.09	0.03	0.07	0.08	0.16	1	1.06	0.09	1.15	1
HCFC-123	125,096	75	2,001.54	288	0.02	0.05	0.09	0.18	0.11	0.22	1	2.84	0.05	2.89	3
HCFC-124	139,550	84	16,746.01	2,411	0.04	0.08	0.02	0.04	0.06	0.12	1	0.67	0.08	0.75	1
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.00	0.00	0.01	0.01	0.01	0.01	0	0.17	0.00	0.17	0
HFC-236fa	621,840	373	24,873.62	3,582	0.00	0.01	0.01	0.01	0.01	0.02	0	0.23	0.01	0.24	0
HFC-236ea	217,644	131	5,285.64	761	0.01	0.03	0.03	0.07	0.05	0.09	1	1.07	0.03	1.10	1
CF3I	12,188	7	16,453.99	148	0.25	0.50	0.19	0.37	0.44	0.87	6	0.37	0.50	0.87	1
Bromoalkane Blends	171,779	103	2,453.99	44	0.01	0.02	0.40	0.80	0.41	0.82	5	1.60	0.02	1.62	1
Advanced Bromocarbons	163,599	98	4,089.98	74	0.02	0.04	0.40	0.80	0.42	0.84	5	1.60	0.04	1.64	1
Vicinity of 850 ft^2 Fire (150-lb ext)															
Halon 1211	67,632	41	5,748.71	828	0.14	0.27	0.10	0.20	0.23	0.47	1	3.18	0.27	3.45	1
HCFC-123	125,096	75	2,001.54	288	0.23	0.45	0.88	1.76	1.10	2.21	5	28.13	0.45	28.58	8
HCFC-124	139,550	84	16,746.01	2,411	0.24	0.48	0.13	0.25	0.37	0.73	2	4.00	0.48	4.48	1
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.01	0.02	0.05	0.10	0.06	0.12	0	1.67	0.02	1.68	0
HFC-236fa	621,840	373	24,873.62	3,582	0.05	0.09	0.07	0.14	0.12	0.23	0	2.25	0.09	2.34	1
HFC-236ea	217,644	131	5,285.64	761	0.13	0.26	0.33	0.66	0.46	0.92	2	10.59	0.26	10.85	3
CF3I	12,188	7	16,453.99	148	0.73	1.45	0.54	1.07	1.26	2.52	5	1.07	1.45	2.52	1
Bromoalkane Blends	245,399	147	2,453.99	44	0.06	0.12	3.00	6.00	3.06	6.12	13	12.00	0.12	12.12	4
Advanced Bromocarbons	327,198	196	4,089.98	74	0.05	0.10	2.00	4.00	2.05	4.10	9	8.00	0.10	8.10	2

Chemical	Dose Factors *Cardiac Sen. Values* Inhalation RFCs mg/m^3	mg/(kg* exposure)	*LC50 Values* Inhalation RFCs mg/m^3	mg/(kg*min)	Cardiac Sen. HQ Inhalation (geom)	(max)	Rat LC50 HQ Inhalation HQLC50 (geom)	HQLC50 (max)	Hazard Index HI (geom)	HI (max)	Hazard Index Rel to H-1211	Note: Value not compensated for species exposure time. LC50 HQ (ppm/ppm)	Cardiac HQ (ppm/ppm)	HI (max)	Hazard Index Rel to H-1211
Firefighter Training (150-lb)															
Halon 1211	67,632	41	5,748.71	828	0.03	0.05	0.02	0.04	0.04	0.09	1	0.59	0.05	0.64	1
HCFC-123	125,096	75	2,001.54	288	0.03	0.05	0.10	0.20	0.12	0.25	3	3.13	0.05	3.18	5
HCFC-124	139,550	84	16,746.01	2,411	0.02	0.04	0.01	0.02	0.03	0.06	1	0.33	0.04	0.37	1
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.00	0.00	0.01	0.02	0.01	0.02	0	0.33	0.00	0.34	1
HFC-236fa	621,840	373	24,873.62	3,582	0.01	0.01	0.01	0.02	0.01	0.03	0	0.25	0.01	0.26	0
HFC-236ea	217,644	131	5,285.64	761	0.01	0.03	0.04	0.07	0.05	0.10	1	1.18	0.03	1.21	2
CF3I	12,188	7	16,453.99	148	0.19	0.38	0.14	0.28	0.33	0.65	8	0.28	0.38	0.65	1
Bromoalkane Blends	245,399	147	2,453.99	44	0.01	0.02	0.38	0.75	0.38	0.77	9	1.50	0.02	1.52	2
Advanced Bromocarbons	327,198	196	4,089.98	74	0.01	0.02	0.38	0.75	0.38	0.77	9	1.50	0.02	1.52	2
Firefighter Training (20-lb)															
Halon 1211	67,632	41	5,748.71	828	0.03	0.05	0.02	0.04	0.04	0.09	1	0.59	0.05	0.64	1
HCFC-123	125,096	75	2,001.54	288	0.01	0.03	0.05	0.10	0.06	0.12	1	1.56	0.03	1.59	2
HCFC-124	139,550	84	16,746.01	2,411	0.01	0.02	0.01	0.01	0.02	0.03	0	0.17	0.02	0.19	0
FC-5-1-14	4,147,607	2,489	41,476.07	5,973	0.00	0.00	0.01	0.01	0.01	0.01	0	0.17	0.00	0.17	0
HFC-236fa	621,840	373	24,873.62	3,582	0.00	0.01	0.00	0.01	0.01	0.01	0	0.13	0.01	0.13	0
HFC-236ea	217,644	131	5,285.64	761	0.01	0.01	0.02	0.04	0.03	0.05	1	0.59	0.01	0.60	1
CF3I	12,188	7	16,453.99	148	0.13	0.25	0.09	0.19	0.22	0.44	5	0.19	0.25	0.44	1
Bromoalkane Blends	245,399	147	2,453.99	44	0.01	0.01	0.25	0.50	0.26	0.51	6	1.00	0.01	1.01	2
Advanced Bromocarbons	327,198	196	4,089.98	74	0.01	0.01	0.25	0.50	0.26	0.51	6	1.00	0.01	1.01	2

Adult Inhalation Rate = .042 m^3/min