United Nations Environment Programme
Montreal Protocol Assessment
Technology Review

Final Report of the Halons - Technical Options Committee

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Pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer four panels of international experts have completed Scientific, Environmental Effects, Economic and Technology Reports.

This Report of the Halons - Technical Options Committee is one of six volumes on technology. **The Technology Review Panel Report**, chaired by Victor Buxton of Canada and co-chaired by Dr. Stephen Andersen of the United States of America provides the overview and integrated statement of findings. There are five other, sector specific Technical Options Reports, as follows:

Refrigeration, Air Conditioning and Heat Pumps
Chair - Dr. L. Kuijpers, Netherlands.

Flexible and Rigid Foams
Chair - Ms. Jean Lupinacci, United States of America.

Electronics, Degreasing and Dry Cleaning Solvents
Chair - Dr. Stephen Andersen, United States of America

Aerosols, Sterilants and Miscellaneous Uses
Chair - Mrs. Ingrid Kökeritz, Sweden

Halon Fire Extinguishing Agents
Chair - Mr. Gary Taylor, Canada
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Significant technical content of this report was developed for the National Fire Protection Research Foundation (U.S.A.), on behalf of the United States Environmental Protection Agency. A technical review was undertaken by an advisory committee established by the National Fire Protection Research Foundation.

The opinions expressed regarding social and economic values and the feasibility of reduced availability levels of the halons are those of the committee members and do not necessarily reflect the views of any sponsoring or supporting organizations.

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Executive Summary

of the

Report

of the

Halons - Technical Options Committee

EXECUTIVE SUMMARY OF THE REPORT OF THE HALONS - TECHNICAL OPTIONS COMMITTEE

Halons are fully halogenated hydrocarbons that exhibit exceptional fire fighting effectiveness. They are electrically nonconductive, dissipate quickly, leave no residue, and have proven remarkably safe for human exposure. This unique combination of properties has led to their selection as the agent of choice for many fire protection situations: computer, communications, and electronic equipment facilities; museums; engine spaces on ships and aircraft; ground protection of aircraft; general office fire protection and industrial applications. Recently, portable fire extinguishers using halons have achieved popularity in some countries for home use.

Annual halon (Group II Substances) consumption, as defined by the Montreal Protocol, is less than 3% of the CFCs' (Group I Substances), however Ozone Depletion Potential (ODP) values are high. Recognizing the environmental threat posed by the halons, this report offers technical options intended to reduce or eliminate dependency on halons. The use of halons as a substitute for other fire protection measures is unacceptable. Social benefit and human safety considerations are considered to be the only justifications to offset the environmental risk associated with halon use.

The Halons - Technical Options Committee recognizes that global halon emissions can be reduced by:

- Restrictions on halon usage to ensure that use is limited to essential applications only
- Improvements in procedures for servicing halon fire equipment
- Reduction of unnecessary discharges of fixed halon systems by more stringent requirements for detection and control equipment used with halon fire protection systems
- Use of alternative, environmentally acceptable simulant gases for testing halon fire protection systems.
- Requirements to manage the existing bank of halons with the eventual re-allocation to most essential applications
- Development of means to destroy halons that have been contaminated to such an extent that recycle is not possible

The Halons - Technical Options Committee has sought to quantify the reduction in halon dependency that can be achieved without jeopardizing the provision of necessary fire protection. The majority of our members and technical advisors consider the following as a feasible and achievable schedule, resulting in a complete phase-out:

Year	Halon Consumption[1]
1992	Cap at 1986 level
1995	75% of 1986 level
1997	50% of 1986 level
2000	25% of 1986 level
2005	0% of 1986 level

Two of our members and one of our technical advisors consider the following as feasible and achievable:

> Halon 1211 Possible short term replacement by other existing products (reduction of 50...60 % ? of the usage in 4...5 years). Then phasing out procedure if acceptable substitute (today under study) is available (year 2000 ?).
>
> Halon 1301 Focusing on the essential use (to be defined) could lead to a reduction in the usage of (30...50 % ?) within (4...5 years?) keeping in mind that phase-out seems difficult to achieve if as stated in this report the "development of replacement agents with the very low toxicity of halon 1301 for use in total flooding systems for occupied enclosures may not be a realistic expectation."

Two other members are of the opinion that:

> It is premature to consider quantifiable levels of possible reduced halon availability as more experience is required in working with the proposed alternative measures outlined in the full report. These members support a complete phase-out when viable substitutes become available to the market.

There are three types of halons in general use in the world today, halons 1211, 1301, and 2402. Ozone Depleting Potential (ODP) factors or the three halons identified in Group II of the Montreal Protocol are as follows:

Halon	ODP
1211	3
1301	10
2402	6

---

[1] - As defined by the Montreal Protocol

The extinguishing mechanism by which the halons extinguish fires is not yet fully understood. However, it is believed that halons interfere with the complex chain reaction that occurs during a fire.

Halon 1301 has a boiling point of -57.75^{0}C and a vapour pressure of approximately 15 Bars at 20^{0}C. As a result, it can be discharged rapidly, mixing with air, to create an extinguishing concentration. Halon 1301 is, therefore best suited for use in total flooding fire protection systems. Most fires extinguished by halon 1301 are put out by a 5% concentration by volume. At this concentration human exposure for up to 10 minutes is generally acceptable. Thus halon 1301 is most often used to protect occupied enclosures that house equipment or property having high value.

Halon 1211 has a boiling point of -3.4^{0}C and a vapour pressure of approximately 2.5 Bars at 20^{0}C. As a result, it can be discharged in the form of a liquid stream. Therefore halon 1211 is suited for use in portable fire extinguishers, by large capacity handline equipment and in local application fire protection systems. Human exposure of up to 4% concentration by volume for one minute has been studied and found to produce minimal, if any, effects on the central nervous system. Nevertheless halon 1211 is not generally used in occupied areas where the resultant residual concentration by volume could exceed 2% by volume if the area or enclosure is normally occupied.

Halon 2402 has a boiling point of 47.3^{0}C. It can be discharged in the form of a liquid stream and is therefore best suited for use as a manually applied fire extinguishant in portable fire extinguishers or hand hose line equipment. Halon 2402 is also used in fire protection systems for specialized applications. Human exposure of 0.2% after two minutes has been found to produce definite central nervous system effects such as dizziness and impaired coordination. Halon 2402 is generally used outdoors.

CURRENT USE

Halon 1301 fixed fire protection systems are typically provided for the protection of computer rooms, tape libraries, telephone exchanges, defense facilities, ship machinery spaces, pipeline pumping stations, aircraft engine nacelles and repositories of cultural heritage. The committee estimates halon 1301 usage as follows:

Electronic Equipment Facilities	65%
Records Storage	5%
Cultural Heritage	5%
Pipeline pumping stations and other Flammable Liquids Hazards	10%
Aviation	2%
Ships	10%
Miscellaneous	3%

Halon 1211 applications include use in portable fire extinguishers for protection of electronic equipment, important records and cabin protection of aircraft. Handline systems using halon 1211 are used to protect aircraft during ground maintenance operations and for crash rescue purposes. Local application systems have been provided for printing presses used to produce currency or other important documents. The committee estimates halon 1211 usage as follows:

Transportation (Aviation, Ships and Vehicles)	25%
Electronic Equipment	35%
Other Commercial/Industrial/Institutional	30%
Residential	10%

Halon 2402 is used in portable fire extinguishers, handline equipment and fixed systems. Halon 2402 fixed systems have been used to protect off-road mobile equipment and the seal areas of floating-roof petroleum storage tanks. The committee lacks sufficient data to estimate percent usage of halon 2402.

Total world production and usage for the base year 1986 is estimated (in metric tonnes) as follows:

Halon	**1301**	**1211**	**2402**	**Total**
Banked	7000	11200	850	19050
Test/Training	1100	840	20	1960
Unwted. Disch.	300	140	10	450
Service	900	420	20	1340
Fires	700	1400	100	2200
Total	10000	14000	1000	25000
% Use	40%	56%	4%	100%

KNOWN FIRE PROTECTION ALTERNATIVES

The provision of a fire suppression system is only one part of an adequate fire protection scheme for a particular installation or facility. Other fire protection features include, but are not limited to: detection systems; fire resistive enclosures; smoke control systems; manual fire fighting equipment; provision of high ignition resistance, low flammability, cable and wire insulation, furnishings and interior finish, and "smoke resistant" electronics components. The total fire risk of a facility is also reduced by such methods as: redundant facilities, backups of records and other media, proper planning, minimizing of single point failures (relative to the facility mission or objective) and adequate post fire reclamation procedures and contingencies.

Halogenated fire suppression systems have been installed primarily to provide a very high level of property protection with minimal secondary damage and minimal disruption to resumption of operations. This has been accomplished by the actuation of the system at very early stages in the fire development and through the application of a clean agent with minimum secondary damage.

Additional positive aspects of halon 1301 are: low toxicity at typical flame extinction concentrations, low space and weight requirements and electrically non-conductive (hence non damaging to energized electrical and electronic equipment). Halon systems are used to meet very limited and specific property protection objectives.

The requirement for a fire protection system is also driven by the risk posture of the organization. Obviously as the exposure increases, the justification for fire protection increases. Fire loss is very rarely entirely born by the property owner but is spread through the use of insurance. The fire protection cost includes expected losses, installed cost of fire protection systems and maintenance. Most specific fire safety analyses are not quantitative in nature.

In the final analysis the decision is financial but many uses of halons make purely financial decisions very difficult. Military systems and public safety systems (e.g., air traffic control, aircraft avionics, etc.) are especially difficult to evaluate in this way.

For this reason, it is useful to concentrate on the engineering aspects of protecting a particular hazard. That is, assume that a computer room operator has evaluated the fire risk and has decided that a fire suppression system is required, that the fire suppression system must be of low toxicity, cause minimum collateral damage, and that the total direct and indirect fire damage must not exceed one cabinet. In the past, the system of choice would have been a total flooding halon 1301 system. Use of a clean agent is obviously desirable; however, use of a high secondary damage agent results only in increased damage and perhaps increased downtime or business interruption. It is a matter of balancing costs including environmental cost.

More difficult choices lie in the consideration of more toxic fire suppression agents. Suppose that CO_2 could be used as a replacement for halon 1301 except for the increased risk of accidental death caused by discharge of the system. How does this risk balance against the fire risk and / or the environmental risk? These are not technical issues - they are political, social and economic questions and to some extent, independent of the desirable features of any particular fire suppression system/agent combination.

The concept of a selection matrix is that the benefits of halon total flooding systems, given in terms of low toxicity, permeability, low space/weight requirements, minimum collateral damage, minimum down time etc., are not equally important in all applications. The primary disadvantage of halon considered in these selection matrices is its environmental risk.

An important consideration is that the system, not the agent, impacts the relative benefits of a particular choice. The system in this context is limited to the fire suppression system. It does not include such important factors as the existence of other fire protection features, the fire hazard, and the risk associated with a particular facility. The full report of the Halons - Technical Options Committee outlines a matrix approach and shows alternative fire protection means reviewed by the committee. The matrix enabling other choices is somewhat driven by the weighting factor assigned to the halons as ozone depleting substances. Other factors in the matrix include: space and weight, secondary damage, direct damage, reliability, downtime and clean-up, tri-dimensional fire suppression capability, use on energized electrical equipment, and installed cost.

Detection systems, halon systems, carbon dioxide systems, dry chemical systems, foam systems and water sprinkler systems are compared in various configurations and combinations.

HALON EMISSION REDUCTIONS

On a weight basis, it is estimated that over 70% of all halons produced annually are banked to provide stand by fire protection. Studies have indicated that less than 10% of annual production are used to extinguish fires. The remaining 20% of annual production is emitted to the atmosphere by test/training procedures, accidental or unwanted discharges or service procedures. These categories of emissions are considered controllable. Major research programs and training programs have been undertaken within the worldwide fire protection community to significantly reduce these emissions.

Research program results indicate that virtually all use of halon 1301 as a test agent can be eliminated by other testing means and/or use of environmentally acceptable simulant testing gases.

Trade associations within the largest user nations have developed training programs and procedures to significantly reduce service related emissions. More efficient training techniques are being developed to reduce training related emissions of halon 1211.

MANAGEMENT OF THE BANKED HALONS

The existing bank of halons has been estimated at approximately 150 000 tonnes. This bank can be considered as both an important fire protection asset and an environmental threat.

The quantities of halons banked in extinguishing systems containers, portable extinguishers, and mobile units is greater than the quantities emitted each year for extinguishing fires, discharge testing, training, and unwanted discharges. For the year 1986, an estimated 70% of halon 1301 and 80% of halon 1211 produced were stored in cylinders or containers installed on end-users premises.

Managing this bank at a national level is desirable for the following reasons:

- to recover the highest possible quantities for recycling and reuse in new systems for critical applications.
- to eliminate controllable emissions associated with periodic maintenance of pressure vessels or dismantling of installations.

- to provide a precise means of evaluating the quantities of halons emitted to the atmosphere and to pursue efforts to reduce unnecessary emissions.

- to destroy quantities, in an environmentally acceptable manner, which cannot be recovered due to contamination.

Bank management consists of keeping track of halon quantities identified at each stage: initial fill, installation, recovery, recycle (or destruction) and recharge. This management is possible through the companies which are in charge of these various operations. A national organization would have to be authorized to certify these companies and to centralize the data and information necessary to assume the responsibility of this bank management.

The possibilities of creating a procedure, within individual countries, which is flexible and sufficiently motivating must be analyzed separately for fixed systems and for portable extinguishers.

In the event that replacement agents are developed or other considerations make it necessary, it would be possible to destroy the banked halons by high temperature incineration.

ALTERNATIVE AGENT RESEARCH

Halon producers have research programs to examine and develop alternative agents. In the United States, research consortia with the United States Environmental Protection Agency and Department of Defense have been formed as a means to provide further funding, optimize efforts, and hasten the process.

General purpose, "direct" replacements having attributes equal to those of the present halons are unlikely in the foreseeable future. However, clean alternative agents, with lower ODP's for specific uses are a realistic goal, particularly for use in manually applied equipment and local application systems, if trade-off's in fire extinguishment capabilities, toxicity and/or other characteristics are acceptable.

CONCLUSIONS

The choice of other means to reduce fire risk to acceptable levels, improved procedures to effectively reduce halon emissions and management of the existing Halon bank are important steps to reduce dependency, achieve conservation and reduce potential ozone destruction. Means to destroy halons at the end of useful life, in the event alternatives are found, or should scientific evidence make it necessary, appear to be relatively simple. However destruction facilities and procedures could require appreciable time to construct and implement. Major programs to develop alternative extinguishing agents have begun. The development of clean agents with high extinguishing capability and low ozone depletion potential appear possible. Human tolerance is of concern and development of replacement agents with the very low toxicity of halon 1301 for use in total flooding systems for occupied enclosures may not be a realistic expectation.

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Section One
Introduction

INTRODUCTION

Halons are fully halogenated hydrocarbons that exhibit exceptional fire fighting effectiveness. They are electrically nonconductive, dissipate quickly, leave no residue, and have proven remarkably safe for human exposure. This unique combination of properties has led to their selection as the agent of choice for many fire protection situations: computer, communications, and electronic equipment facilities; museums; engine spaces on ships and aircraft; ground protection of aircraft; general office fire protection and industrial applications. Recently, portable fire extinguishers using halons have achieved popularity in some countries for home use.

Annual halon (Group II Substances) consumption, as defined by the Montreal Protocol, is less than 3% of the CFCs' (Group I Substances), however Ozone Depletion Potential (ODP) values are high. Recognizing the environmental threat posed by the halons, this report offers technical options intended to reduce or eliminate dependency on halons.

A draft, preceding this final version of the report was peer reviewed by individuals from over 60 organizations from around the world. Interest groups represented included fire protection associations, users, fire equipment manufacturers, fire equipment installers and maintainers, halon producers, environmental organizations, government regulatory agencies and fire research organizations. A listing of those that offered peer review comments will be found in Appendix A of this report.

Section Two
Historical Development
Of Halon Usage

HISTORICAL DEVELOPMENT OF HALON USAGE

The halon terminology system was devised by James Malcolm of the U.S. Army Corps of Engineers. The system provides a convenient means to reference halogenated hydrocarbon fire extinguishants. Halogenated hydrocarbons are hydrocarbons in which one or more of the hydrogen atoms have been replaced by atoms from the halogen series; i.e. fluorine, chlorine, bromine, iodine. By definition the first digit of the halon numbering system represents the number of carbon atoms in the compound molecule; the second digit, the number of fluorine atoms; the third digit, the number of chlorine atoms; the fourth digit, the number of bromine atoms; and the fifth digit, the number of iodine atoms. Trailing zeros are not expressed. Valence requirements not accounted for are assumed to be hydrogen atoms.

# of hydrogen atoms = [((# of carbon atoms x 2)+2)-(Sum of halogen atoms)].
Example: Bromotrifluoromethane - CF_3Br - halon 1301

The first member of this family of chemicals was carbon tetrachloride (halon 104). Use as a fire extinguishant probably occurred before 1900 and by 1910 portable fire extinguishers, tested by independent agencies, had appeared. The growing popularity of the automobile and other uses of internal combustion engines signalled an increasing need for fire extinguishants, suitable for use on flammable liquid fires. By 1917, there were discussions regarding the possible effects that carbon tetrachloride could have on the human system. During 1919 the first recorded deaths due to carbon tetrachloride use occurred. Two men working on the construction of a submarine were killed. One man's clothing had caught fire and the other man extinguished the fire with a carbon tetrachloride agent fire extinguisher. Both were overcome by the fumes and later died. During the 1920's the discussions regarding the toxicity of carbon tetrachloride continued with particular attention to the possibility that freezing point depressants and impurities were contributing factors.

Methyl bromide (halon 1001) gained popularity after it was discovered in the late 1920s. Due to its high toxicity it was never popular for use in portable extinguishers although it was used in British and German aircraft and ships during World War II. During World War II Germany developed chlorobromomethane (halon 1011) to replace methyl bromide. In 1947 a report by Underwriters' Laboratories (U.S.A.) showed that the toxicity of carbon tetrachloride (halon 104) and chlorobromomethane (halon 1011) were comparable, however chlorobromomethane (halon 1011) was a more efficient fire extinguishing agent.

In the post World War II era, the addition of stearate to sodium bicarbonate based dry chemical provided improved flow and moisture repellency characteristics to sodium bicarbonate based dry chemical. This in turn encouraged the use of portable dry chemical fire extinguishers as a viable alternative to vaporizing liquid extinguishers that used early halons as extinguishants.

By the 1950's the era of the early halons (halons 104, 1001 and 1011) was ending. Increased popularity of dry chemical had decreased the need for widespread use of these early halons and growing concerns with their toxic effects resulted in their "official" death by the 1960's.

In 1947, the Purdue Research Foundation performed a systematic evaluation of more than 60 new candidate extinguishing agents. Simultaneously, the U.S. Army Corps of Engineers undertook toxicological studies of these same compounds. As a result four halons were selected for further study: dibromodifluoromethane (halon 1202), bromochlorodifluoromethane (halon 1211), bromotrifluoromethane (halon 1301) and dibromotetrafluoroethane (halon 2402). Testing indicated that halon 1202 was the most effective fire extinguishant however it was also the most toxic. Halon 1301 ranked second in fire extinguishing effectiveness and least toxic. As a direct result of this program a portable fire extinguisher employing halon 1301 was developed for use by the U.S. Army, primarily for use inside armoured personnel carriers and tanks. The U.S. Air Force selected halon 1202 for military aircraft engine protection and the U.S. Federal Aviation Administration approved the use of halon 1301 for commercial aircraft engine fire protection.

As a result of this basic research some general conclusions were drawn about the contribution of the various halogens to resultant characteristics of the halon as a useful fire extinguishant. These are outlined in the following table:

Characteristic/Halogen	**Fluorine**	**Chlorine**	**Bromine**
Stability of Compound	Enhances	-	-
Toxicity	Reduces	Enhances	Enhances
Boiling Point	Reduces	Enhances	Enhances
Thermal Stability	Enhances	Reduces	Reduces
Extinguishing Effectiveness	-	Enhances	Enhances

In 1966, attention began to focus on the use of halon 1301 as a total flooding extinguishant for the protection of computer rooms. In the past twenty years halon 1301 has grown in usage as an agent for use in fixed fire protection systems primarily for the protection of vital electronics facilities, such as computer rooms and communications equipment rooms. Other significant applications for halon 1301 systems have included: repositories of cultural heritage; shipboard machinery spaces and pipeline pumping stations. Halon 1211 has been the halon of choice for portable fire extinguisher usage. In commercial and industrial applications halon 1211 portable fire extinguishers have been used in computer rooms, museums, art galleries and in offices for photocopy machines, personal computers and other electronic equipment. The recent use of halon 1211 and blends of halon 1211 and halon 1301 as extinguishing agents in aerosol type residential portable fire extinguishers has resulted in significantly increased consumption of halon 1211 in countries where these fire extinguishers have achieved popularity.

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5. Traité Pratique de Sécurité Incendie, Centre National de Prévention et de Protection, Paris, France

Section Three
Usage Patterns

USAGE PATTERNS

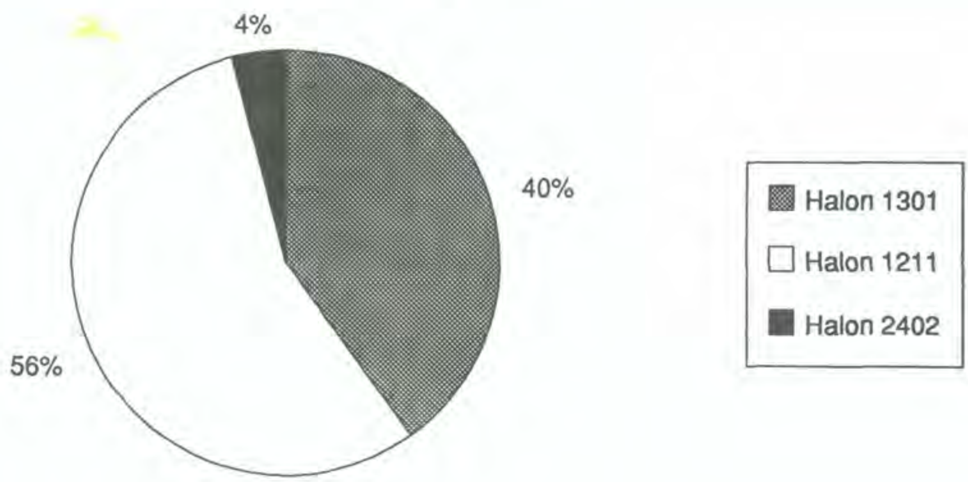
Estimates of halon use have been developed on the basis of data reported, for 1986, to UNEP by signatory nations to the Montreal Protocol. This data was then compared with total production figures reported to CEFIC by Atochem, Du Pont, Great Lakes Chemicals, ICI and Kali Chemie. Historical total world production figures for halons are not available; as such the committee estimated historical and projected halon usage based on partial industry figures multiplied by a factor to equate to the UNEP total for 1986. These figures were then used as the basis for a trend calculation. These calculated figures have been used to provide estimates of historical and projected usage of halons. Fire protection trade associations in both North America and Europe have published estimates of emissions. These estimates have been used in conjunction with total consumption estimates that can be seen in Appendix B, to provide an order of magnitude estimate of the size of the bank of halons.

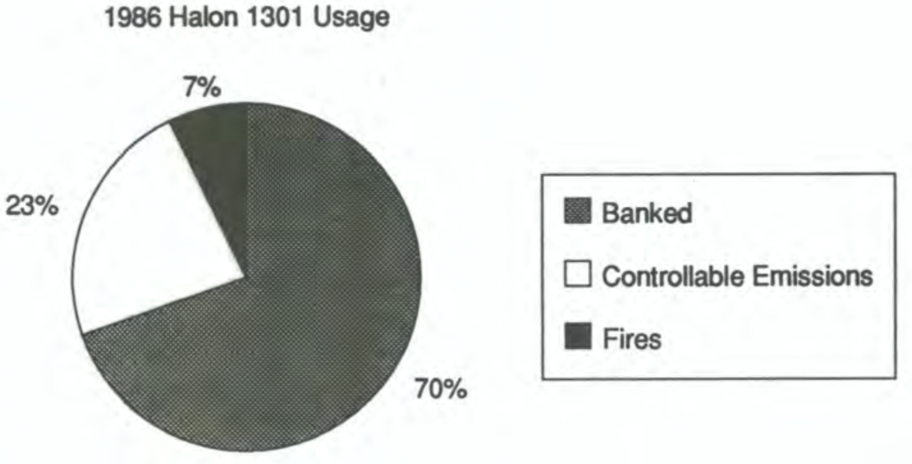
The estimates of 1986 consumption and emission have been circulated for peer review, however, they should be regarded as "best guess" estimates for information only. The historic and projected estimates of consumption of halons, presented in Appendix B of this report, have not been circulated for peer review.

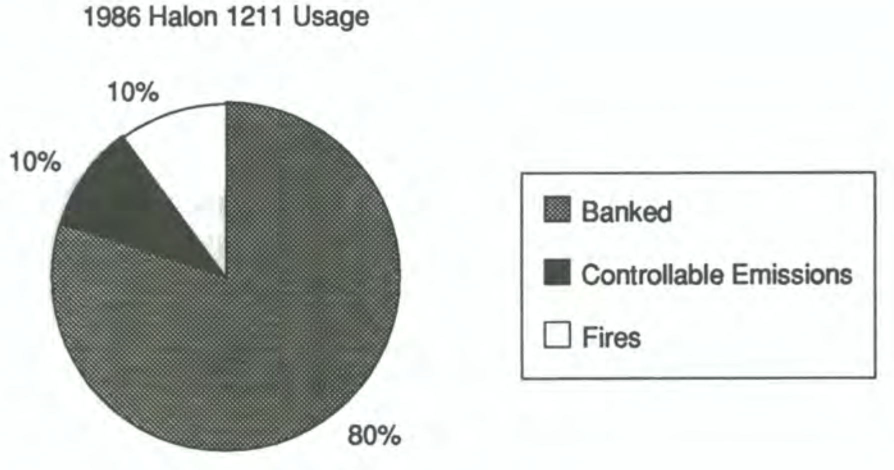
ESTIMATED WORLD CONSUMPTION OF HALONS - 1986
by actual weight (metric tonnes)

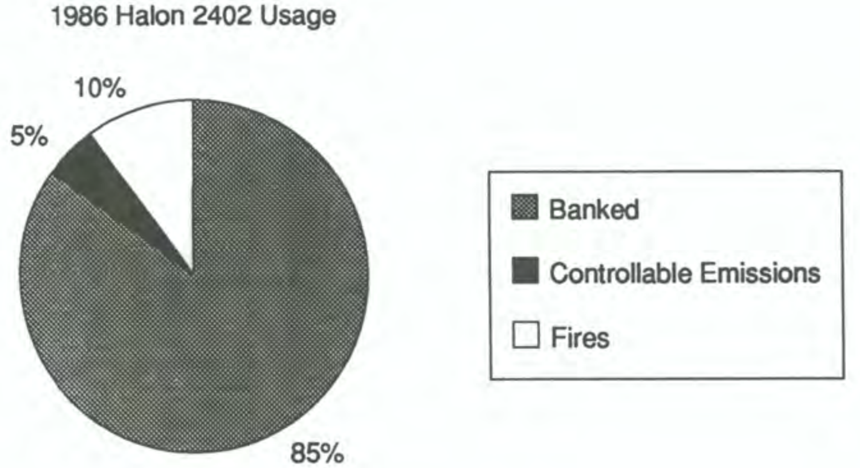
Portion of Production	**1301**	**1211**	**2402**	**Total**
Banked	7000	11200	850	19050
Controllable Emissions				
Test/Training	1100	840	20	1960
Unwanted Use/Discharge	300	140	10	450
Service Losses	900	420	20	1340
Fires	700	1400	100	2200
Total	**10000**	**14000**	**1000**	**25000**
% Use	40%	56%	4%	100%

1986 Halon Usage - By Weight




1986 Halon 1301 Usage
7%
23%
70%
Banked
Controllable Emissions
Fires


1986 Halon 1211 Usage
10%
10%
80%
Banked
Controllable Emissions
Fires

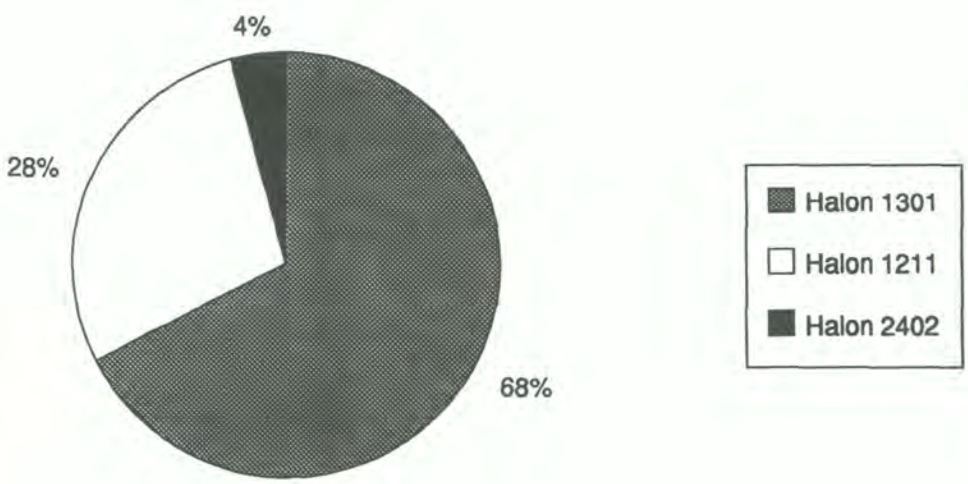

1986 Halon 2402 Usage
10%
5%
85%
Banked
Controllable Emissions
Fires

The Montreal Protocol establishes a cap on the halons as a total, weighted on the basis of Ozone Depletion Potential (ODP). Trading is allowed between Group II substances, however trading between allowable consumption levels of Group I and Group II substances is not allowed. The following chart is based on usage of the halons, as weighted by ODP (consumption X ODP).

Estimated World Consumption of Halons - 1986
ODP weighted (weight X ODP) (1301 = 10, 1211 = 3, 2402 = 6)

Portion of Production	1301	1211	2402	Total
Banked	70000	33600	5100	108700
Controllable Emissions				
Test/Training	11000	2520	120	13640
Unwanted Discharge	3000	420	60	3480
Service Losses	9000	1260	120	10380
Fires	7000	4200	600	11800
Total	**100000**	**42000**	**6000**	**148000**
% Use	68%	28%	4%	100%

1986 Halon Usage - ODP Weighted



Emissions of halons as the result of training with portable extinguishers or testing of fixed systems installations, unwanted discharge of fixed systems and portable fire extinguishers and service related emissions from both systems and portable fire extinguishers are considered as "controllable emissions". Estimates for halon 1211 and halon 1301 emissions are based on a review of industry data from North America and Europe. Halon 2402 emissions are estimates based on similiar use in manually applied fire equipment as halon 1211.

Estimated Controllable Emissions of Halons - 1986
by actual weight (metric tonnes)

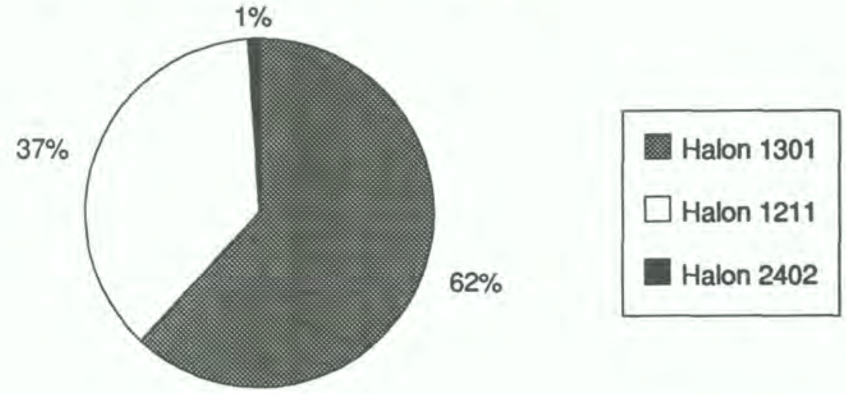
Controllable Emission	**1301**	**1211**	**2402**	**Total**
Test/Training	1100	840	20	1960
Unwanted Use/Discharge	300	140	10	450
Service Losses	900	420	20	1340
Total	**2300**	**1400**	**50**	**3750**
%	62%	37%	1%	100%

Estimated Controllable Emissions of Halons - 1986
ODP Weighted (weight X ODP) (1301 = 10, 1211 = 3, 2402 = 6)

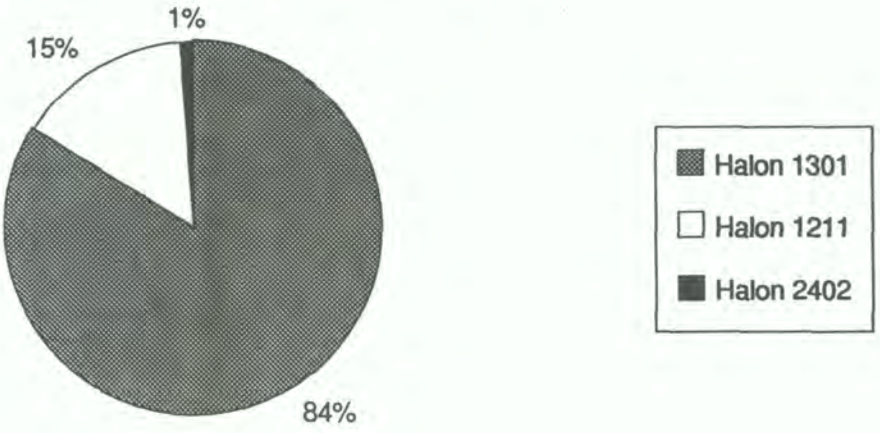
Controllable Emission	**1301**	**1211**	**2402**	**Total**
Test/Training	11000	2520	120	13640
Unwanted Release/Discharge	3000	420	60	3480
Service Losses	9000	1260	120	10380
Total	**23000**	**4200**	**300**	**27500**
%	84%	15%	1%	100%

The following charts compare controllable emissions of the three halons, on a weight basis and on an ODP weighted basis:

1986 Controllable Halon Emissions - By Weight

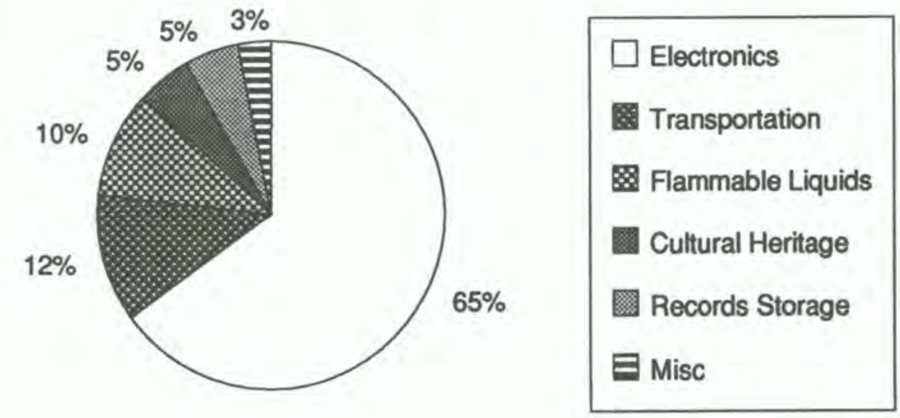


1986 Controllable Halon Emissions - Weighted by ODP

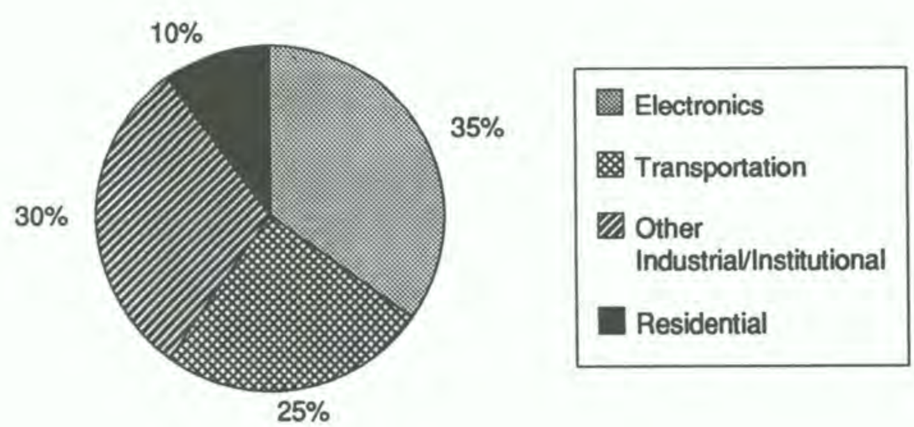


Committee estimates of the use of halon 1301 and halon 1211 are shown in the following graphs. Estimates for halon 2402 are not provided as there was not sufficient data or experience to provide meaningful estimates.

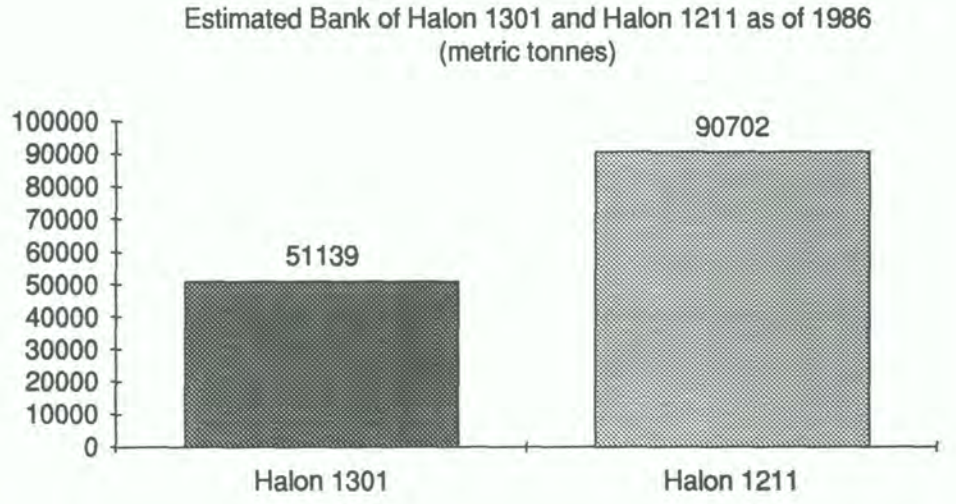
Estimated Usage of Halon 1301 by Application

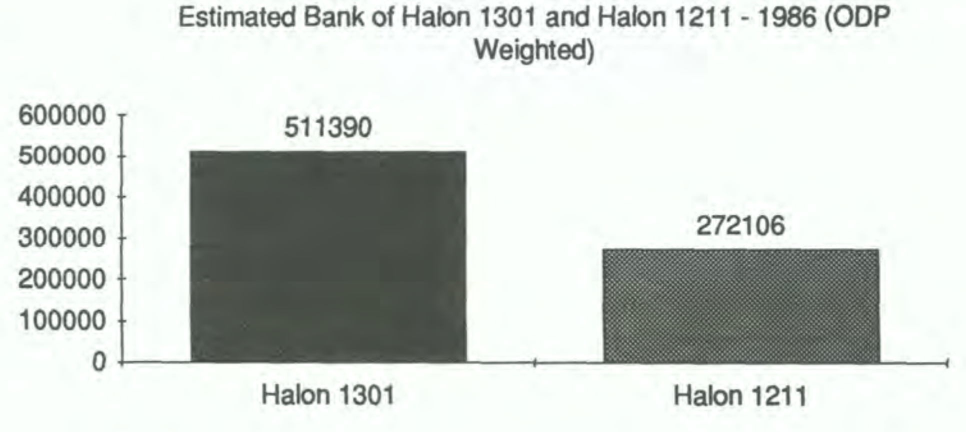


Estimated Usage of Halon 1211 by Application

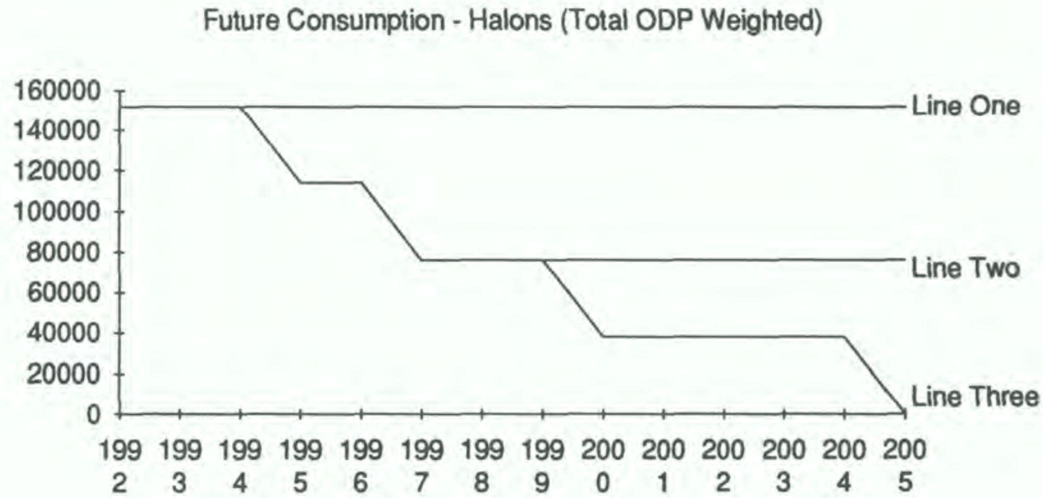


The following figures represent the estimated bank of halon 1301 and halon 1211, as of 1986. These charts are based on estimated figures for halon 1301 and halon 1211, as shown in Appendix I. Quantities are given in metric tonnes.





The following chart depicts the three different views of future availability held by various members of the Halons - Technical Options Committee. Line one of the chart depicts compliance with the Montreal Protocol in effect at this time. Line two depicts a 50% reduction in consumption by 1997 and line three depicts a total phaseout by 2005. The chart is based on estimated consumption of halon 1301 and halon 1211 as shown, plus an allowance for halon 2402 based on 4% of halon 1301 consumption.



Section Four
Fire Protection Alternatives
Halon Total Flooding Systems

FIRE PROTECTION ALTERNATIVES
HALON TOTAL FLOODING SYSTEMS

4.1 Background/Philosophy

This section of the report investigates procedures for evaluating the properties of suppression systems and agents, the optimum uses of specific agent/system combinations and a method to evaluate alternatives. This section concentrates on the technical capabilities of fire suppression systems, but does not fully address the important issues of hazard reduction and risk management. The primary purpose is to present a logical framework in which to evaluate alternatives to halon total flooding systems which preserve the necessary advantageous technical features of halon systems. It is also intended that the evaluation system be sensitive to the features and requirements of the hazard being protected.

The provision of a fire detection and suppression system is only one part of an adequate fire protection scheme for a particular installation or facility. Other fire protection features include, but are not limited to: fire resistive enclosures; smoke control systems; manual fire fighting equipment; provision of high ignition resistance, low flammability cable and wire insulation, furnishings and interior finish; and "smoke resistant" electronics components. The total fire risk of a facility is also reduced by such methods as: preventative maintenance, redundant facilities, backup of records and other media, proper planning, minimizing of single point failures (relative to the facility, mission or objective), adequate post fire reclamation procedures and contingencies.

Halogenated fire suppression systems have been installed primarily to provide a very high level of property protection with minimal secondary damage and minimal disruption to resumption of operations. The ability of halon 1301 total flooding systems to extinguish fires very quickly with minimal potential disruption to the facility being protected often has effects on safety, other than direct fire safety. For example, protecting a telecommunications facility has numerous societal impacts, many of which are related to public safety, such as the ability to communicate a medical emergency. In a very limited number of installations, halon systems are installed primarily to protect human life from fire. In some cases the protection is directly related to safety, although not fire safety; an example of this case might be the protection of an aircraft engine. In most installations however, the system is installed to protect equipment, facilities, and their associated mission, not to protect human life. This has been accomplished by the actuation of the system at very early stages in the fire development curve and of course through the application of a clean agent with minimum secondary damage.

Additional positive aspects of halon 1301 are: low toxicity at typical flame extinction concentrations, low space and weight requirements, electrically non-conductive (hence non-damaging to energized electrical and electronic equipment).

Halogenated fire suppression systems are generally not legally required by Building Codes and Standards. The objectives of these Codes and Standards are to establish an acceptable level for:

life safety/egress capability, safety for responding fire fighting crews, limitation of expected fire sizes to those which can be reasonably addressed by the fire department and some consideration for preventing fire spread between structures. Hence halon 1301 systems are used to meet specific property protection objectives and the mission associated with the property protected. The remainder of this report section assumes this point of view. The remaining issue is to what extent halon 1301 systems are required as opposed to alternative systems and agents to achieve similar property protection levels.

The requirement for a fire protection system is also driven by the risk posture of the organization. Obviously as the exposure increases, the justification for fire protection increases. The loss is very rarely entirely born by the corporation or organization but is spread through the use of insurance. The fire protection cost includes expected losses, installed cost of fire protection systems and maintenance. Most fire safety analyses are not quantitative in nature. In the final analysis the decision is financial, but many uses of halon make purely financial decisions very difficult. Military systems and public safety (e.g., air traffic control, aircraft avionics, etc.) are especially difficult to evaluate in this way.

For this reason, it is useful to concentrate on the engineering aspects of protecting a particular hazard. That is, assume for example, that a computer room operator has evaluated the risk and has decided that a fire suppression system is required, that the fire suppression system must be of low toxicity, cause minimal collateral damage, and that the total direct and indirect fire damage must not exceed one cabinet. In the past the system of choice would have been a total flooding halon 1301 system. The use of a system other than halon 1301 will cause the owner to bear other costs, such as increased damage levels, water damage, etc. In effect, the use of alternative systems will "cost" the facility owner more.

More difficult choices lie in the area of the use of more toxic fire suppression agent. Suppose that CO_2 could be used as a replacement to halon 1301 except for the increased risk of accidental death caused by discharge of the system. How does the risk balance against the fire risk and/or the environmental risk? These are not technical issues; rather, they are political, social and economic questions and to some extent, independent of the desirable features of any particular fire suppression system/agent combination.

4.2 Other Fire Safety Features

As mentioned earlier, the need for a fire suppression system is driven by the risk associated with the facility to be protected and the presence of other fire protection features and fire safety design and installation aspects. For the specific example of a computer, these include but are not limited to:

- ignition resistant wire, cable, and electronic components
- minimum ignition source severity from external sources
- low or slow rate of fire development

- low rates of smoke production
- components hardened to the effects of heat and smoke
- low smoke corrosivity
- isolation of HVAC system
- fire resistive compartment boundaries
- detection and alarm systems
- full time manning
- training of staff
- availability of manual fire suppression equipment

This partial list of other fire protection features reflects on several aspects of a best and essential use of an ozone depleting fire suppressant. First, the provision of additional fire safety features may obviate the need for a suppression system. Secondly the provision of these features may reflect (albeit indirectly) on the value of the facility as perceived by the owner. An owner who has invested in the protection of a facility through these other fire protection measures is indicating the relative value of the facility.

The use of halons as a trade off for other fire protection features if unacceptable. Social benefit and human safety consideration are the only justifications to offset the risk associated with halon use.

There is therefore some rationale for providing a scheme for dealing with these additional fire safety features in the evaluation of need to utilize halogenated fire suppressants. The most straightforward approach is to prescribe some minimum set of requirements for a facility before a halogenated fire suppression system can be considered. For example a computer facility may be required to meet all aspects of a technical standard such as NFPA 75 "Standard for the Protection of Electronic Computer/Data Processing Equipment".

Since the details of alternative fire protection features will vary dramatically depending upon the particular hazard being evaluated, it is difficult to treat this problem in general. Some consideration should be given to requiring a baseline level of other fire protection features before considering the use of halons.

4.3 Agent/System Selection Matrices

The concept of a selection matrix is that the benefits of halon total flooding systems, given in terms of low toxicity, ability to permeate, low space/weight requirements, minimum collateral damage, minimum down time, etc. are not equally important in all applications. The primary disadvantage of halon considered in these selection matrices is its ozone depletion potential, which of course is not a fire protection feature.

The method proposed in this report should be viewed as a guide. The important features of halon 1301 systems are described, but the weighing of the relative importance of these features is not rigorously derived. It is the result of the consensus opinion of the committee responsible for this report. The weighing values are deemed reasonable but the method is developed primarily as a means of structuring the thought process relative to the evaluation of the need for halon 1301 for a particular use and more importantly, the evaluation of alternatives. It is fully expected that any application of point values may vary between countries. It must also be understood that any weighing of the benefits of halon 1301 total flooding systems in any application may be offset by consideration of environmental risk posed by the ozone depletion potential of the agent. The issue distills to one of balancing the fire risk agent against the environmental risk. If the environmental risk is deemed grave enough, a political decision, **no** applications of halon 1301 may be considered important enough to tolerate its use.

An important consideration is that the system, not just the agent, impacts the relative benefits of a particular choice. The system in this context is limited to the fire suppression system. It does not include, but perhaps should, other important factors such as the existence of other fire protection features, the fire hazard and the risk associated with a particular facility. These factors could be considered in a more detailed fashion using a decision tree.

The method developed to compare uses and alternative systems of halon 1301 total is comprised of three distinct parts:

1. An evaluation of the attributes of halon 1301 systems and alternative in general. This section is independent of the particular application being evaluated.

2. The importance of these system attributes to a particular application is then evaluated by using weighing factors which determine how important a particular attribute (e.g., occupant risk, toxicity) is in a particular application. Note that a given attribute (e.g., ability to extinguish flammable liquids) may be unimportant in some applications (e.g., computer rooms) and very important in others (flammable liquid stores).

3. Societal impact is measured in terms of environmental risk due to ozone depletion which is offset by important societal impacts. Such societal impacts include but are not limited to: national defense, protection of cultural heritage, public safety, etc. The most important societal impact cases will balance the environmental risk.

Aspects of the agent/system are assigned a numeric score. Higher values imply higher positive features. For example, a halon system has a higher score for ability to permeate than automatic sprinklers, but has a negative value for ozone depletion. **Figure 4-1** gives base values in comparing selected aspects of agent/systems or combinations of systems. Note that these scores are independent of end use application and a higher score implies a positive feature.

Figure 4-1

Base Case	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)
Monitored Early Warning Detection (EWD)	0	0	5	0	10	0	5	1	5
Automatic Sprinklers + EWD	0	0	5	0	10	0	10	2	4
Fast Response Sprinklers (FRS) + EWD	0	0	8	0	10	0	10	3	4
Pre-Action Sprinklers (includes EWD)	0	0	5	0	10	0	8	3	3
In Cabinet & Subfloor CO2 (C&SCO2) + EW	0	5	8	5	8	0	3	5	4
FRS + EWD + C&SCO2	0	0	9	5	8	0	10	2	3
EWD + Total Flood Halon 1301	-200	5	10	5	9	10	8	5	2
EWD + Total Flood Halon 1211	-60	5	10	5	7	10	8	5	1
EWD + Total Flood CO2	0	4	9	5	2	8	8	5	1
Detection + Total Flood Dry Chemical	0	4	4	1	7	7	7	4	1
Detection + Deluge Water Spray	0	0	3	0	10	1	9	1	3
Detection + Low Expansion Foam	0	1	3	0	9	7	7	1	3
Detection + CO2 + Low Expansion Foam	0	0	3	5	2	10	10	1	1
Detection + High Expansion Foam	0	2	6	0	2	5	7	3	3

The particular application then weights the importance of each parameter. A flammable liquid pump room would have a lower weighing factor for ability to permeate than a typical computer application. By multiplying the agent/system score by the application weighing factor, the relative merits of a particular system/agent in a particular application can be compared.

This procedure has some obvious limitations; these include:

- Any generic procedure is limited in that unique requirements of a particular proposed installation are ignored. It is by nature a method which loses the detail which may be critical to the decision making process. It is possible and we have attempted to outline the important parameters in a logical way.

- The efficacy of any particular alternative is driven by the engineering details of both the proposed alternative and the facility which it is proposed to protect. This makes such alternatives very cost variable.

- The issue of cold shock from carbon dioxide on electronics must be resolved.

- The sensitivity of electronic components to heat, smoke and water is highly variable. Further technical resolution would be helpful in determining the real importance of direct and secondary damage with respect to the use of water as a suppression agent in electronic facilities.

- The logic and structure of the proposed approach must be field verified. If the logic and structure of the method hold, the field verification can be used to fine tune the scoring and weighing values.

- The ability of detection systems coupled with manual fire suppression activities as an alternative to fixed fire protection systems needs to be further addressed. Given adequate training and manpower the issue becomes one of response time and reliability.

- Direct substitution of halon 1301 with typical standard fire protection options without loss of some of the positive aspects of halon 1301 is difficult. Some additional engineering and creativity in design will be required. The results thus far indicate that some of the positive aspects of halon 1301 can be preserved.

- The requirement for "other fire safety features" as prerequisites for the installation of a halon system needs to be developed.

- Substitution of fixed fire protection systems with other hazard and risk reduction concepts needs to be developed.

- The relative scores and weighting factors given in this report are preliminary estimates based on judgement. More detailed and objective analysis should be conducted in addition to the field trials to provide a more rigorous technical basis for the evaluation system.

- Additional alternative technologies should also be incorporated into this analysis as appropriate.
- The risk/need assessment procedure, if found useful in evaluating the need for alternative approaches, should be further developed.

4.4 Definition of Agent Selection Parameters

Each fire suppression agent has specific properties which may be advantageous in a particular application. In addition, the system which discharges and applies the agent will have associated advantages and disadvantages. Each parameter is discussed in detail below. Potential environmental damage associated with certain fire protection alternatives is not integrated into the matrix, such as water runoff. This should be evaluated on a case specific basis.

4.4.1 Societal Value Factor (Maximum Value 10)

The Societal Value Factor is used to indicate the importance of the facility to a large number of people. A fire in a telephone exchange, for example, could affect the lives and businesses of a great many people and would have a higher societal value than a general purpose accounting computer of an individual commercial enterprise.

4.4.2 Controlled Substances Penalty

An agent is scored as to whether or not it has been identified as an ozone depleting substance. All ozone depleting compounds are scored at a value of -20 x ODP. The matrix is adjusted by the following formula that recognizes that societal values and/or human safety considerations may be considered as justifying halon usage:

Environmental Risk Score = -((20-(Societal Factor+Occupant Risk Factor))xODP) (Controlled Substance)

Note that the balance between environmental risk and societal benefit are largely social and political decisions.

4.4.3 Low Space or Weight (Maximum Value 5)

An agent or system is scored against the weight based effectiveness of the agent and system. The weight and space based score is compared against halon 1301/1211 which are taken as the best possible scores.

4.4.4 Damage Limiting Capability (Maximum Value 10)

This parameter refers to the relative level of direct and secondary fire damage expected for a similar fire using a particular fire suppression system. It is primarily a measure of response time of the system. Systems actuated by early warning detectors have higher scores than those actuated by fusible links. Presumably manual intervention would be scored lower still. Quick Response Sprinklers are scored higher than standard response sprinklers.
This parameter also refers to damage that is caused by the agent and system to the equipment protected and to the expected downtime resulting from the re-conditioning of equipment not directly damaged by fire.

4.4.5 Ability to Permeate (Maximum Value 5)

This property refers to the ability of the agent to be effective in obstructed geometry situations. It implies that the agent need not be directly applied to the burning surfaces. This property is especially important in subfloor areas, in electronics cabinets, etc. All gaseous total flooding agents will have a high score for this property.

4.4.6 Occupant Risk (Maximum Value 10) (Toxicity)

The toxicity of undecomposed agent in the concentrations necessary for extinction is scored. Water of course has the highest score, CO_2 the lowest.

The need for a low toxicity fire suppression system is evaluated for each proposed application.

4.4.7 Flammable Liquid Extinguishing Capability (Maximum Value 10)

This parameter refers to the ability of the agent and application method to extinguish liquid fuel fires in two dimensions and liquid and gas phase fuel fires in three dimensions. Examples include liquid spray fires and gas jets. Total flooding gaseous agents CO_2 and halons are scored highest in this parameter.

4.4.8 Efficacy (Maximum Value 10)

This parameter refers to the effectiveness of a particular system in a given application and its reliability on that application. It is taken both as a measure of the effectiveness of the system in a particular application as well as how reliable it will be in that particular application.

Of critical importance in any fire suppression system is reliability. This variable refers to both hardware and agent reliability. Automatic sprinklers are assumed to have the highest reliability score at 10. Typical total flooding applications are scored at 8.

4.4.9 Use on Energized Electrical Equipment (Maximum Value 5)

Since halon 1301 and halon 1211 are electrically non-conductive, they can be applied to energized equipment without causing shorts and damage and without safety risk to nearby occupants. Hence halon 1301, halon 1211 and CO_2 are scored high in this regard. Automatic sprinklers of course are scored lower. This agent property is also related to minimum secondary damage. The importance of this feature can be minimized by isolating power upon detector actuation, prior to release of conductive agents.

4.4.10 Installed Cost (Maximum Value 5)

This parameter refers to the installation and maintenance cost for the system being evaluated. It should be considered in the evaluation of alternatives, especially since for some alternatives there is at least an order of magnitude in cost difference over total flooding halon 1301 systems.

4.5 Application Specific Weighting Factors

The next section of the evaluation requires that the relative importance of the desirable agent/system characteristics be weighted for specific applications.

It is an implicit assumption that all agent/system features are not of equal importance in any given application. Obvious examples include low weight as an unimportant parameter in typical computer rooms. Toxicity should be weighted lightly in unoccupied flammable liquid risks. Each parameter (except ozone depletion) is weighted separately for each application or use. The weighting factors range from 0 to the maximum value of the factor, with 0 being unimportant and the maximum being very important. Examples used in this report are given in Appendix C as follows: a typical general purpose computer room (**Figure C-1**), a power plant control room (**Figure C-2**), a communications facility manned 50% of the time (**Figure C-3**) and a shipboard military application (**Figure C-4**). These examples are meant to be just that; the need for specific agent/system features will be driven by the specific requirements of a specific application. These examples set weighting factors intentionally high to demonstrate differences between agent/system parameters in the total scores.

4.6 Alternative Fire Suppression Methods

4.6.1 Monitored Early Warning Detection System

A monitored early warning detection system has an external connection to a constantly manned facility or fire department dispatch station. This is intended to result in a rapid fire department response and thus provide extinguishment at an earlier stage in fire development than would be expected otherwise.

4.6.2 Automatic Sprinklers + Early Warning Detection

Automatic sprinklers with early warning detection is a system based on a network of piping installed throughout a protected structure and incorporating heat sensitive sprinkler heads (nozzles) spaced at regular intervals. As proposed, an early warning system, connected to a constantly manned facility would also be provided as systems are paralyzed.

4.6.3 Fast Response Sprinklers + Early Warning Detection

This alternative attempts to limit the amount of direct damage caused by the relatively slow actuation of the sprinkler head by decreasing the lag time of the fusible link. It is recognized that short of using detector actuated heads the response characteristics will never equal products of combustion detectors. The impact of this response delay on direct fire damage is a strong function of the growth rate of the fire and the exposed equipment. In addition an early warning fire detection system is proposed. It may be desirable to isolate the HVAC on the actuation of a smoke detector to minimize the delay time of the sprinkler actuation.

4.6.4 Pre-Action Sprinkler System

In this case, a separate detection system is provided. The sprinkler system is normally dry with water to the system controlled by a valve. Upon detection of a fire, the valve opens, admitting water to the system. The remainder of operation is similar to that of a conventional sprinkler system.

4.6.5 In Cabinet and Sub-Floor Carbon Dioxide

This refers to an hybrid system involving a total flooding carbon dioxide system for underfloor spaces and independently actuated, hazard specific carbon dioxide systems for individual equipment enclosures. A separate early response detection system is used to actuate the carbon dioxide system(s).

4.6.6 Fast Response Sprinklers + In Cabinet and Sub-Floor Carbon Dioxide

This approach is a hybrid of 4.6.3 and 4.6.5

4.6.7 Total Flood Carbon Dioxide

A total flood carbon dioxide system is designed to provide an extinguishing concentration of carbon dioxide throughout the complete enclosure. An early warning fire detection system would be provided to cause actuation of the carbon dioxide system.

4.6.8 Total Flood Dry Chemicals

This type of system has the capability of extinguishing three dimensional running fuel fires and pressurized fuel fires, however, upon completion of discharge there is no sustained capability to extinguish or prevent re-ignition. This type of system utilizes a separate detection system to cause actuation of the dry chemical system.

4.6.9 Deluge Water Spray

A sprinkler system with open heads or controllable heads. Actuation is caused by a separate detection system.

4.6.10 Low Expansion Foam

A low expansion foam system is similar to the deluge water spray system but Aqueous Film Forming Foam (AFFF) concentrate is added to the water supply. This type of system is capable, within limits, of preventing ignition or re-ignition of pooled flammable liquid by forming a residual vapor suppressing film on the surface of the flammable liquid. This type of system can be actuated automatically in response to fire by a separate fire detectionsystem.

4.6.11 Total Flood Carbon Dioxide System + Low Expansion Foam

This is a hybrid of 4.6.7 and 4.6.10

4.6.12 High Expansion Foam System

A high expansion foam system is designed to generate 500:1 - 1000:1, expansion ratio foams having three dimensional fire fighting capabilities. It is suitable for a wide range of fires involving flammable liquids and ordinary combustibles. This system is actuated by a separate detection system.

4.7 Use Evaluation

The evaluation of the appropriateness of a particular application is summarized. The total score is an indication of how that particular agent/system combination meets the requirements for that particular application.

The example given in **Figure C-1** is a typical commercial data processing facility with no real time requirements. The use evaluation is performed for a range of possible agent and system combinations. Each cell of the matrix shows the multiplication of the agent score for that property and the weighting factor placed on that property for a typical computer room facility. The total score is then the summation of each weighted score and is given for a range of system/agent combinations. A higher score indicates a better application. The highest score, in this case, is obtained using a hybrid automatic sprinkler system with CO_2 in the cabinets and subfloor area, watertight cabinets or other hardened components and Quick Response Sprinklers.

The more typical systems CO_2 total flooding, halon 1301 and automatic sprinklers are ranked with an ozone depletion penalty applied to the halon systems. Obviously the value of the environmental risk factor has a significant effect. This factor can be modified to appropriately balance halon availability with the quantifiable needs of most essential applications.

Section Five
Fire Protection Alternatives
Manual Application Usage of Halon 1211

FIRE PROTECTION ALTERNATIVES
MANUAL APPLICATION USAGE OF HALON 1211

5.1 Introduction

Halon 1211 is manually applied through the use of portable extinguishers, wheeled extinguishing units, mobile fire fighting vehicles, and through hose reels with fixed storage containers. Among the many uses of halon 1211, approximately 25% is used in transportation, including aviation, either on board aircraft, or in ground support fire fighting capability. Usage in electronics facilities where effectiveness on a clean agent for use on Class A fires, with no electrical conductivity are primary considerations is estimated to be approximately 35% of the banked halon 1211 production. Approximately 30% of the usage is in industrial facilities, commercial and institutionnal buildings, and repositories of cultural heritage.

A special type of halon 1211 application is seen in factory sealed units designed primarily for residential use. Such extinguishers often use a blend of halon 1211 and 1301 in order to obviate the need for an expellant gas. Residential usage is estimated as 10% of halon 1211 usage.

This brief review of usage indicates that the applications of halon 1211 are widespread and varied. The desirable attributes of 1211, including high fire extinguishing effectiveness, limited toxicity, low secondary damage, stream range, and no electrical conductivity are important to varying degrees across the range of applications. In light of this, the committee has developed a use evaluation matrix for manually applied halon 1211 similar to that presented in the discussion of halon total flooding systems.

5.2 Agent Selection Matrix

Manually applied halon 1211 and other agents are evaluated relative to their ability to meet certain objectives. These technical objectives include effectiveness on Class A and B fires, electrical non-conductivity, ability to permeate, stream range, high effectiveness to weight ratio, minimal secondary damage and cost.

Each agent is scored from 0 to 5, 0 being the lowest score, 5 the highest, relative to the agent's ability to meet these objectives. The baseline scoring which does not include weighting for particular applications is given in Figure 5-1. The weighting for particular applications is discussed in section 5.3.

The parameters evaluated for each agent are discussed below.

Figure 5-1

Base Case									
Societal Weighting Factor (Max 10) =	0								
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)
Application Specific Factor		1	1	1	1	1	1	1	1
Halon 1211 and Blends	-60	4	3	5	5	4	5	8	0
CO2	0	1	2	5	5	1	1	10	0
Multipurpose Dry Chemical	0	5	5	3	1	4	5	0	3
AFFF	0	5	2	0	0	4	3	2	2
Straight Stream Water	0	5	0	0	0	5	1	4	2
Water Spray	0	5	1	1	0	3	2	4	2
Water Spray + CO2	0	5	2	1	5	3	0	4	0

5.2.1 Effectiveness on Ordinary Combustibles

This parameter scores the ability of the agent to extinguish fires in ordinary solid polymer combustibles, including cellulosics. It includes consideration of deep seated burning. The lowest score is given to carbon dioxide, the highest to water based, halon 1211, and multipurpose dry chemical extinguishers as seen in Figure 5-1.

5.2.2 Effectiveness on Flammable/Combustible Liquid Fires

The agents are scored on the ability to extinguish flames above liquid fuels. No consideration is given to preventing reignition. The ability to extinguish three dimensional liquid fires (sprays or fuels cascades) is evaluated. The most effective agent is multipurpose dry chemical with a score of 5, halon 1211 is next highest at 3, with straight stream water being scored at 0.

5.2.3 Electrical Conductivity

The electrical conductivity of the agent is scored in this category. The highest scores are given to halon 1211 and CO_2. Dry chemical is scored at 3, water spray at 1 and all other agents at 0.

5.2.4 Ability to Permeate

This parameter reflects the ability of the agent as typically discharged to extinguish fires in locations where direct application to the fuel surface or flame reaction zone is not possible, for example, inside electronics equipment cabinet. As expected, the gaseous agents are scored highest in this category.

5.2.5 Range

This parameter reflects the ability of the agent to maintain a coherent effective stream over a modest distance. The highest score is given to straight stream water extinguishers, the lowest to carbon dioxide. Halon 1211 is ranked just beneath water.

5.2.6 Effectiveness to Weight Ratio

This parameter considers the relative fire suppression capability across all fuels per unit weight of agent. In this category, halon 1211 and multipurpose dry chemical are rated highest.

5.2.7 Secondary Damage

This category refers to the "clean agent" aspects of the agents, i.e. secondary damage caused by the suppressant agent itself. Here carbon dioxide is rated highest, halon 1211 is slightly lower due to decomposition products, the lowest score is given to multipurpose dry chemical.

5.2.8 Cost

This parameter reflects the average cost of typical portable fire extinguishers. Carbon dioxide portables are expensive due to the shell costs, AFFF, and water based portables are scored just slightly lower than multipurpose dry chemical. Halon 1211 portables are scored equal to $C0_2$.

5.3 Use Evaluation

Each parameter evaluated (e.g., electrical conductivity, effectiveness on Class A fires) is weighted as to its importance for each application. Three example use evaluations are given in Appendix D. These include: residential, telephone exchange, and a commercial computer room.

The weighting and final score is performed in a similar manner to halon 1301 total flooding systems as previously described.

Environmental risk (negative) and associated societal impact (positive) are determined in a manner similar to that done for halon total flooding system.

Section Six
Halon Emission Reduction Strategies

HALON EMISSION REDUCTION STRATEGIES

6.1 Introduction

Reduction in the emission levels of halon 1301 and halon 1211 are occurring. Continued and future reductions in emissions are possible in the following areas:

1. emissions due to discharge testing
2. emissions caused by inadvertent activation of halon 1301 systems
3. emissions resulting from training use of halon 1211 in manually applied fire fighting equipment
4. emissions incurred in the servicing of halon 1301 systems and halon 1211 portable fire extinguishers.

Progress has been made in the past 12-18 months in each of these areas. It is as of yet not possible to estimate the reduction levels achieved.

6.2 Halon 1301 Emissions Due to Discharge Testing

The greatest progress in reducing halon 1301 emissions has occurred in the reduction of discharge tests using halon 1301 as a test gas. A study performed by the National Fire Protection Association [1] indicated that virtually all discharge testing with halon 1301 could be eliminated without degradation in system reliability through the use of simulant test gases [2], compartment leakage testing [3], and additional non-destructive testing procedures [4]. Du Pont has indicated that they will no longer provide halon 1301 for discharge testing purposes.

Additional work in the area of alternate test gases and procedures is continuing.

It is not possible to estimate the reduction in emissions caused by the reduction in discharge testing at this time, although at least in North America and Europe, the reduction has been substantial.

6.3 Emissions Due to Inadvertent System Discharge

Although this component of halon 1301 emissions is relatively small, it is an area where technical improvements in system hardware and detection devices could have substantial impact. The normal commercial pressures for limiting accidental discharge have improved system hardware over the past 10-20 years.

If additional limitations are desirable, clear motivation and encouragement would be required in order to allow manufacturers and users to pursue these improvements, particularly in a shrinking total flooding systems market.

6.4 Emissions Caused During Initial Fill and Servicing

This component of halon 1301 and halon 1211 emissions could be substantially reduced if sufficient motivation was provided. The use of approved filling and pumping equipment which was increasing at the time of the Montreal Protocol would most likely have reduced this emission component independent of regulation.

Obviously any operation relating to a high pressure gas must conform to the appropriate safety standards in line with all relevant local, national and international regulations. The equipment used must be of a safe standard and be compatible for halon usage.

Refillers of both halon 1211 and 1301 should have a recovery rig including vapour capture and recovery. Subsequent recycling will be covered later.

6.4.1 Halon Transfer

Over pressurisation of vapour space needs to be done using dry nitrogen (<0.006%M/M water) or use of positive displacement pumps. Venting to atmosphere should be specifically prohibited. Physical specifications determining tank/pump proximity, pump recycle provision and hardware specifications should be developed on a local basis.

6.4.2 Filling Rig

Environmental and operator safety dictates that all filling procedures should be carried out by trained personnel. Filling operations should be carried out in a well-ventilated area with all safety relief valves from the rig connected directly to the outside atmosphere.

The fabrication of the filling equipment can be carried out using most common metals such as steel, brass, copper, etc. and flexible connections using a hose of a suitable pressure rating. Flexible connections should be checked at monthly intervals for signs of deterioration. The filling hose shall be valved at its outlet and be as short as possible. All pipe lengths should be kept to a minimum . To avoid corrosion problems, it is essential that the halon not be allowed to come into contact with water. All parts of the rig must be dry before filling commences.

6.4.3 Leak Testing of the Filling Rig

The filling rig must be leak tested to twice its normal pressure prior to its initial use and regularly during the filling operation either by use of a soap solution or an electronic leak detector. This procedure does not include the Halon container.

It is recommended that all new portable fire extinguishers or system cylinders be leak tested before being filled with halon. After filling, all containers should be leak tested. Fire extinguishers or systems that leak during filling should be connected immediately to a recovery rig and the contents discharged into the recovery container.

6.4.4 Recovery Rig

The recovery rig should be completely separate from the filling rig due to the risk of contamination. Equipment may be emptied by pressurising with nitrogen or pumping and put into a clearly labelled recovery vessel. The transfer has to be continued until the halon liquid has been transferred. This might need the addition of extra nitrogen. In the case of halon 1301, the vapour should also be recovered.

Halons must not be mixed, it is vital that the recovery vessel only holds one of the halons and be clearly marked. Care must be taken to ensure that the recovery vessel is not overfilled. This can be checked either by weighing or by using a suitable liquid level indicating device.

References

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4. Eckholm, William A., "Testing One of the World's Biggest Halon Systems . . . Without Using Halon," Fire Journal, July/August 1989, pp. 71-74.

Section Seven
Management of the Bank of Halons

MANAGEMEMENT OF THE BANK OF HALONS

The quantities of halons banked in extinguishing systems containers, portable extinguishers and mobile units is far greater than the quantities emitted each year for extinguishing fires, discharge testing, training and unwanted discharges. For the year 1986, it is estimated that 70% of the halon 1301 and 80% of the halon 1211 produced was stored in cylinders or containers installed on end-users premises.

Managing this bank at a national level is necessary for the following reasons:

- to provide a precise means of evaluating the quantities of halon emitted to the atmosphere and to pursue ef

- to eliminate controllable emissions associated with periodic maintenance of pressure vessels or dismantling of installations.

- to recover the highest possible quantities for recycling and reuse in new systems.

- to destroy quantities which cannot be recovered due to contamination in an environmentally acceptable manner.

Bank management consists of keeping track of halon quantities identified at each stage: initial filling, installing, recovery, recycling (or destruction) and recharging. This management is only possible through the companies which are in charge of these various operations. A national organization would have to be authorized to certify these companies and to centralize the data and information necessary to assume the responsibility of this bank management.

Procedures which are flexible and motivating enough must be developed specifically for fixed systems and for portable extinguishers, as well as for new systems and existing equipment.

7.1 Fixed extinguishing systems

7.1.1 Filling of Cylinders

Filling of cylinders should be conducted in facilities where:

- the condition of the cylinder is checked before filling
- equipment to fill with the exact required quantity of halon is provided
- nitrogen is available for pressurization
- halon leak detection equipment is provided
- a recovery rig is available

In order to properly manage the halon bank and to facilitate proper tracking of quantities, companies which have facilities for filling should keep written records of quantities of halons received from producers and quantities shipped to installers and/or end-users. They should be required to systematically supply the organization in charge of the bank management with all required data.

This implies a quality control on both technical and administrative aspects. The organization in charge of qualifying companies which do filling operations must be entitled to verify the quality control procedures.

7.1.2 Installation

Fixed extinguishing systems should be installed by companies capable of designing efficient systems, that are reliable and specifically designed for the risk to be protected. These companies should be capable of providing preventive maintenance and recharging and re-commissioning after a discharge.

Certification of components in conformity with technical standards or rules, and the qualification of installers by an independent organization, are measures which will assist in achieving best use of the available halons.

Preventive maintenance is an important factor in the elimination of unwanted operation of the system, for the extinguishing sub-system as well as for the detection sub-system. To ensure the efficiency of the system, preventive maintenance should include periodic verification of the room integrity in the case of total flooding systems. This can be accomplished, for example, by use of door fans and room pressurization techniques to determine enclosure leakage and estimate halon leakage rates after discharge.

Installing companies should keep written records of the quantities of halon used in each installed system, as well as for the recharge or replacement of containers after a discharge. Quantities of recovered and recycled halon should also be recorded.

Even when preventive maintenance is done directly by the end-user, a fire equipment maintenance company should be called upon to undertake periodic testing of the halon storage containers (pressure vessels). A qualified fire protection contractor should be consulted when a halon system is dismantled for modification or removal.

All containers should bear a label that:

1. Advises that the halon contained is an ozone depleting substance and provides a warning to avoid unnecessary emission

2. Encourages or requires return for recycle at the end of useful equipment life

Installers should educate users in the operation of these systems in order to avoid unwanted discharge, and in the maintenance and verification operations that can be performed by the user.

The quality of all types of services provided by installers shall be controllable by the organization in charge of their qualification. The case of suspension of activities of an installing company shall be resolved within the national qualification system.

7.1.3 Return or exchange (of halon containers)

When mandatory testing of pressure vessels is required, containers are often taken back and exchanged by the installing company. This should be the opportunity for a complete inspection of both the detection and the extinguishing parts of the system. Modifications of the protected risk which would not have been taken into account during periodic maintenance should be considered at this point.

The case of dismantling without reinstallation of a system is more complex to deal with. Any incentive that could be developed at a national level should be considered.

When containers are not taken back by the original installer - if he has ceased his activities for example - an exchange may not be possible due to incompatibility between equipment. The owner then has the choice between a modification of the system to make it compatible with new containers or refilling the original containers, after verification, which implies that the risk will not be protected during the period of time necessary for this testing.

7.1.4 Re-cycling (of products)

Installing/recovering companies should hand over the containers to companies in charge of recycling unless they have adequate facilities themselves for this task. Recycling includes:

- analyzing products by chromatography to ensure that halon quality is acceptable (with dissolved nitrogen).

- emptying the container in an installation designed and constructed for recovering the liquid phase, while minimizing waste emissions to the atmosphere, and reconditioning the halon in accordance with the ISO requirements for the original product, except for the dissolved nitrogen.

- re-filling clean and dry containers.

Applicable fire protection equipment standards should require containers valves to be equipped with a means for recovery at recycling stations.

Several configurations are possible for the recycling facilities. It is estimated at this date that 70% of the banked halon could be recycled in an economical way.

Unless means are developed to economically recycle contaminated halons and separate blends of halons it appears that the halon will have to be destroyed.

As in previous steps, records will allow identification of quantities of halons received by recycling stations, quantities recycled with their destination (filling station or installer) as well as quantities shipped to producers who would establish a destruction certificate.

Recovery and recycling of halon contained in a system installed in a country with no recycling facilities raises a particular problem of import/export that should be resolved at the international level. Indeed, if it is possible to require the installer to recover the product, the contents of cylinders cannot be identified before analyzing it in the recycling station. Therefore, it should be counted as waste intended for destruction.

7.1.5 Existing Installations

Quantities of halon contained in existing installations can be dealt with in the same way as halon in new installations after they have been identified.

Installations which are covered by a maintenance contract with a qualified installer will be identified immediately. For others, all possible means have to be put in place to make owners aware of the necessity of getting their system registered. As soon as procedures for new installations are established, a national information campaign should be undertaken with the participation of the halon bank administrator, insurance companies, professional associations of fire contractors, fire protection associations, fire engineers associations, etc. Incentives should probably be established at a national level, as a supplement.

Proof of registration of the halon could be the labelling of the containers, with the identification (name, address, etc,) of the recovering contractor which has registered the installation in its records.

For installations which would not have been included in this registration procedure, instructions could be given to government inspectors of the workplace to record such installations during their visits.

If the contractor who installed the system in the first place is no longer in business or did not obtain the qualification, a qualified installing-recovering contractor should be in charge of the installation, under a special procedure put in place by the national organization in charge of management of the halon bank.

7.2 Portable Fire Extinguishers

The management of that part of the halon bank contained in portable and mobile units (portable extinguishers, wheeled units, fire trucks), is far more problematic than for fixed systems due to the great number of suppliers, the small quantities per unit, the lack of precise identification of the contents, and the differences in the applicable regulations from country to country.

Several measures may allow an acceptable level of management:

- Forbid extinguishers that do not allow for a high percentage recovery of contained halon

- Limit the use of halon extinguishers to the protection of risks where there is no alternative and take dissuasive measures to discourage use in less than essential applications

- Institutionalize the bonds between suppliers and companies which fill these units within the context of the qualification of companies, in order to ensure the traceability of halon banks to the owner and to get all information back to the organization in charge of managing the halon bank.

- Fix a limit for service life, 10 years for instance, at the end of which the units have to be sent back to qualified vendors.

All these measures should allow the same measures applicable to fixed systems to be applied to the portable extinguishers for filling, recovery, recycling and destruction.

Labelling should be applied to the extinguishers that:

1. Advises that the halon contained is an ozone depleting substance and provides warning to avoid unnecessary emission

2. Encourages or requires return for recycle at the end of useful equipment life

3. Advises that in case of partial use, remaining halon should be retained and the extinguisher should be returned for recharge without emptying it

The use of various blends in extinguishers makes recycling a difficult and onerous operation. It is possible that significant quantities of halon will have to be returned to the producer for destruction. International standardization of the extinguishing agent, of its propelling gas and of a recovery connection would encourage recycling.

7.3 Halon Destruction Options

The Halons - Technical Options Committee does not advocate unnecessary destruction of the uncontaminated halon bank, however destruction of contaminated halons must be considered.

7.3.1 Alternate Uses of Halons

When once useful products become obsolete, they are considered waste and therefore have to be disposed off. The best way of handling waste, however, is to consider them as resources or feedstock for other products. This conserves energy and materials and minimizes the general waste problem. Before evaluating destruction technologies for obsolete halons, alternates uses for these products are considered.

Unfortunately, they are only a very limited number of alternate chemical and physical utilizations for the Halons currently in use:

Halon 1211	-	No chemical or physical usage known
Halon 1301	-	Can be used as a reagent chemical in bioorganic synthesis, but the market is extremely small. No commercial feedstock potential. Minimal usage as a refrigerant (CFC 13B1)
Halon 2402	-	Is used as a standard reference compound for analytical purposes (NMR reference). Only minute amounts are used, less than 1kg/year.

We conclude from our present knowledge that there are no viable alternate uses for the Halons in question.

7.3.2 Chemical Destruction

In principle, all halons may be chemically decomposed by various means, however a literature search indicates that toxic by-products often are created in the process. As such chemical destruction does not appear feasable on the basis of present knowledge.

7.3.3 Physical Destruction

Halons, like all organic compounds can be destroyed by high temperature incineration or by plasma decomposition technologies.

Due to their fire extinguishing capabilities, burning halons will require a large sustaining fire. This is also required for incinerating highly chlorinated waste compounds such as PCBs or chlorinated solvents. They are commonly added at 10% levels together with flammable liquids. No references dealing with the destruction of halons were found, although stufdies by Japanese and American researchers have recently been completed. Experiments with high temperature incineration are recommended to evaluate the practical limits for incineration concentrations. A 5% addition should present no problems in continuously run HT-incineration ovens.

Stack gas cleaning of the resulting halogenated acids (HF, HCl and HBr) present no special problems as these acids are always generated in HT-incineration and gas washing is standard procedures for state-of-the-art plants.

The required capacity for the destruction of all halons presently banked (estimated to be approximately 150 000 tonnes) is estimated as 50-130 oven years. This assumes oven capacities of 15 000 - 40 000 tonnes/year and a 5% addition of halons. It is questionable whether such a capacity is presently available, considering the shortage of high temperature incineration in general as a means of eliminating hazardous wastes.

As halons are not toxic products like other chlorinated compounds, there is no need to ensure a >99% destruction efficiency. Therefore incineration in municipal waste incineration plants appears to be another possibility for destroying halons at the end of their useful life. However, little is known about incinerating halons under the conditions to be found in these plants. Stack gas washing would be an absolute requirement and other changes in the process might also be necessary. The rate of addition and required changes in the operating conditions would require further research, as would the technolgy of high temperature incineration.

7.4 Recovery and Recycle of Halons

7.4.1 Reprocessing of Halons

For halon cylinders that are removed from service due to service related requirements or at the end of usefull life, it has been the consistent practice in some countries for them to be returned to a halon producer so that the contained agents can be extracted from the cylinders and fed back to the associated production process for recovering.

The reasons behind it are very simple, in some countries this is the most economical way to ensure acceptable quality of the recycled product. This method of handling the agents is predominantly for cylinders that are used in system applications, however it is applicable for all refillable containers and all three halons. Some aerosol type extinguishers may not be suitable for such handling.

After receiving the returned cylinder at the premises of the halon producer, the agent contained in the cylinder is sampled and subjected to gas chromatography analysis for a check of purity. If the agent purity is found to be within acceptable limits, it is fed into the process. At the end of the production process, the halon is again inspected by Gas chromatography for purity confirmation and the re-processed halon is then placed into a cylinder. There are no known plants solely dedicated to recovering and recycling of halons.

7.4.2 Method of Identifying Halons

There are detectors suitable for detection of halons, available and in use in some countries. These detectors are capable of distinguishing halons from other chemicals, however they are not suitable for identifying specific halons.

To specifically identify halon 1301, 1211 or 2402, each sample of halons should be analyzed by gas chromatography. Ambiguous and unreliable data from other detectors is not suitable to identify a specific halon.

7.5 Conclusion

Management of the bank of halons at a national level is possible through the various trades, producers, installers of fixed systems, extinguisher suppliers, companies in charge of filling, recovery or recycling. A national organization could be appointed to manage the bank of halons and could be responsible for certifying the companies involved in the process, in addition to the certification of equipment and installers. Environmental concern and restricted availabilty of the halons will likely encourage achievement of initiatives to manage the bank of halons.

Section Eight
Clean Extinguishing Agent Research

CLEAN EXTINGUISHING AGENT RESEARCH

In this section, an overview of alternative agent development is presented. Appendix E contains a brief summary of combustion and fire extinguishment science.

8.1 Approaches to Alternative Agents

The halon/ozone issue is not a simple problem, and there is no single solution. Multiple alternative agents, varying according to application, are the most likely outcome. It is unlikely that one or two general-purpose "drop-in" replacements having all significant characteristics equal to those of the existing halons will be available over the next decade. Thus, "development of a halon replacement" is an ambiguous and misleading objective for alternative agent research. On the other hand, alternative low-ODP clean agents for specific applications are realistic objectives.

Five requirements make halons difficult to replace: cleanliness, low ODP, low toxicity, effectiveness, and low GWP (global warming potential, the calculated ability of a volatile compound to affect global climate through absorption and emission of infrared radiation). There are, of course, other considerations for replacement agents; cost, storage stability, and compatibility with engineering materials are among these.

Commonly used halon fire extinguishants can be separated into two groups according to their application: Halons 1211 and 2402 in one group and Halon 1301 in the second. Different types of chemicals will likely be needed for replacement of each group. Halons 1211 and 2402 are usually applied by streaming (directed discharge from a nozzle positioned remote from the fire). Such agents are used in localized applications and are often applied manually. Halon 1301 is most often used in total-flood applications (filling of an enclosed volume with sufficient agent to suppress combustion). Both clean streaming agents and clean total-flood agents are needed. Some very specialized applications (for example, fire protection systems for aircraft engines) may be best served by agents that combine characteristics of both streaming and total-flood agents. Other applications may be difficult to categorize exactly. Nevertheless, it is useful to consider and contrast streaming and total-flood agents.

Both alternative streaming agents and alternative total-flood agents must be clean and must have low ODPs. Cleanliness is the primary reason for the use of halon agents in most applications, and acceptable ODP is the primary driving force for development of new agents. However, there are important differences in certain other requirements for the two agent types. A streaming agent requires good deliverability; the material must not be too gaseous. Toxicity requirements are less stringent for streaming agents, since personnel are not usually exposed to high agent concentrations. In contrast, a total-flood agent must be more gaseous to encourage dispersion and to avoid stratification, and a very low toxicity is essential for application in normally inhabited spaces.

The steps needed to determine alternative agents have been vigorously debated. Some favour a broadly based effort with a foundation and/or parallel effort of basic research. This type of program begins with consideration of all possible families of chemicals and screen these to end up with a set of final agents. Others favour a targeted approach, directing their effort toward those chemical families considered to offer the most promise as alternative agents.

8.2 Existing Efforts to Develop Alternative Agents

A portion of the following is taken from the Report on the Tyndall Conference, which contains information on some of the ongoing efforts in alternative agent research.[1] Letters were also written to major producers of halons and related chemicals inviting comments on agent development programs; however, little definitive information was obtained.

Most of the work to date on alternative agents has emphasized low-ODP halocarbons due to 1) cleanliness, 2) fire suppression capabilities, and 3) relatively well developed commercial processes for manufacture. Three major problems exist.

First, no limits on "acceptable" ODP values have been established. In fact, some doubt exists in the mind of many as to whether any ODP value greater than zero is acceptable. (Controversy about the reliability of ODP calculations is beyond the scope of this report.) While many consider very low-ODP halocarbons to be a solution to the problem, rather than the source of the problem, this is not universally accepted. Unfortunately, even if the international environmental and political community were to adopt values for acceptable ODPs, there is no guarantee that these limits would not change.

Second, the concern about global warming is increasing. GWPs are calculated from atmospheric models similar to those used for ODP. GWP is becoming of increasing concern and many of the candidates being evaluated as alternative clean firefighting agents have significant GWPs. Particularly bothersome about this is that one group of halocarbons having zero ODPs, perfluorocarbons, have very high GWPs.

Third, owing to legal liability concerns, the toxicity and environmental evaluations required by chemical manufacturers may greatly exceed those required by regulation. While it is difficult to fault such an approach, this cautious attitude significantly increases the time required to introduce new halon replacements.

Research and development programs for halon alternatives have been established by a number of CFC and halon producers. Much of this research is proprietary, and little information on direction and probability of success is available. Some industry sources state that promising candidates are now undergoing testing. Others give a minimum of six years, probably more, as the time required for a halon alternative to become available, assuming that one can ever be found.

More information on non-industrial developmental projects is available. However, projects are now limited to only a few academic and research institutions. An overview of this work follows.

The U.S. Environmental Protection Agency (EPA) and the Electric Power Research Institute (EPRI) have jointly funded two projects for development of new CFC alternatives: Dr. James Adcock in the Department of Chemistry, University of Tennessee (USA), has been funded for work on fluoroethers; Dr. Darryl DesMarteau and Dr. Adolph Beyerlein in the Department of

Chemistry, Clemson University (USA), have been funded for synthetic work on (primarily) new 2-carbon and 3-carbon hydrochlorofluorocarbons (HCFCs). These projects arose, in part, from a study by the Chlorofluorocarbon Chemical Substitutes International Committee funded by the USEPA.[2] Though both of these projects are directed toward CFC replacements, the compounds are also of interest as components of potential halon substitutes.

A general development program for new halon replacement agents is under way at the Center for Technologies to Protect Stratospheric Ozone at the New Mexico Engineering Research Institute (NMERI), University of New Mexico (USA). Most of this work has been funded by the United States Air Force. The program, under the direction of Dr. Robert Tapscott, has produced several technical reports[3,4] on halon replacement--the first to have appeared since the implication of halon in ozone depletion became generally known in 1986.

Battelle, Columbus, Ohio (USA), is also pursuing work on alternative halon extinguishing agents. The effort is being led by Dr. James Reuther.

Work needed for halon alternatives is in the planning stage at the National Institutes for Standards and Technology in the United States under the direction of Dr. Richard Gann. This work will consist of two projects: computer studies of critical extinguishment reaction paths and development of test procedures for alternative agents.

A Consortium for Alternatives to Halons has been established in the United States to facilitate research and development activities. This Consortium is a group of government and industry leaders who are supporting cooperative efforts for information exchange and complimentary research programs. These efforts are intended to develop the scientific basis for development and commercialization of clean, safe, and reliable fire extinguishing agents.

8.3 Conclusions

Work to date indicates that general purpose, direct replacements having attributes equal to those of the present halons are unlikely to be available within the next decade. On the other hand, clean alternative agents with lower ODPs for specific uses are a realistic goal if trade-offs in fire extinguishment capability, toxicity, and/or other characteristics are acceptable. In particular, such agents could be available in the short term for selected manually applied equipment and local application systems. Toxicity considerations make total flooding agents for normally inhabited areas much more problematical. Streaming agents are inherently easier to develop since 1) physical properties that give improved streaming performance can partially offset poorer inherent flame suppression capabilities and 2) toxicity requirements are not as stringent for an agent delivered by streaming as they are for a total-flood agent. It is likely that uncertainties about future ODP, GWP, and toxicity requirements will form the greatest barrier development of halon alternatives.

It should be pointed out that fully halogenated chlorofluorocarbons have significant fire extinguishing capabilities. Furthermore, a number of these materials have well-defined, low toxicities. Since these CFCs have lower ODPs than do the present halon fire extinguishing agents, substitution of CFCs for halons in selected fire protection applications could give a reduced threat to the ozone. On the other hand, these materials are regulated under the Montreal

Protocol and are in a different category than are the halons. This makes substitution a highly sensitive issue and unlikely to be widely supported. Certainly, such substitutions could not be regarded as a long-term solution.

REFERENCES

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2. Findings of the Chlorofluorocarbon Chemical Substitutes International Committee, EPA-600/9-88-009, EPA Contract No. 68-02-3994, Washington DC, USA, April 1988.

3. Next-Generation Fire Extinguishing Agent, four reports (Phases I-IV), Air Force Engineering and Services Laboratory, Tyndall AFB, Florida, USA. (Available from National Technical Information Service, USA).

4. Initial Fire Suppression Reactions of Halons., Air Force Engineering and Services Laboratory, Tyndall AFB, Florida, USA, July 1988.

Section Nine
Conclusions

CONCLUSIONS

9.1 Use of halons

The use of halons as a substitute for other fire protection measures is unacceptable. Social benefit and human safety considerations are considered to be the only justifications to offset the environmental risk associated with halon use.

9.2 Emission reductions

The Halons - Technical Options Committee recognizes that global halon emissions can be reduced by:

- Restrictions on halon usage to ensure that use is limited to essential applications only. The matrix approach presented in this report offers one method of comparing other fire protection extinguishing choices on an application specific basis. This in turn can assist the user in limiting halon use to the most essential applications.

- Proper management of the existing bank of halons, by ensuring that halons in new and existing equipment will be recovered and re-allocated to essential applications.

- Improvements in equipment, servicing procedures and personnel training to reduce emissions resulting from leakage, service and unwanted discharge.

- Improvements in requirements for detection and control methods and equipment to reduce unnecessary discharges of fixed halon systems.

- Development and implementation of technologies to destroy halons that have been contaminated to such an extent that recycle is not feasable.

- Use of alternative, environmentally acceptable simulant gases for testing halon fire protection systems

9.3 Alternative Clean Extinguishing Agent Research

Work to date indicates that general purpose, direct replacements having attributes equal to those of the present halons are unlikely to be available within the next decade. However, clean alternative agents with lower ODPs for specific uses are a realistic goal if trade-offs in fire extinguishment capability, toxicity and/or other characteristics are acceptable. Development of a replacement agent with the very low toxicity of halon 1301 for use in total flooding systems for occupied areas may not be a realistic expectation.

9.4 Future halon availability

The Committee has sought to quantify achievable halon reductions without jeopordizing the provision of necessary fire protection. The Committee did not reach a full concensus however, the majority our members and our technical advisors consider the following as a feasible and achievable schedule, resulting in a complete phase-out:

Year	**Halon Consumption** [1]
1992	Cap at 1986 level
1995	75% of 1986 level
1997	50% of 1986 level
2000	25% of 1986 level
2005	0% of 1986 level

Two of our members and one of our technical advisors consider the following as feasible and achievable:

Halon 1211	Possible short term replacement by other existing products (reduction of 50...60 % ? of the usage in 4...5 years). Then phasing out procedure if acceptable substitute (today under study) is available (year 2000 ?).
Halon 1301	Focussing on the essential use (to be defined) could lead to a reduction in the usage of (30...50 % ?) within (4...5 years ?) keeping in mind that phase-out seems difficult to achieve if as stated in this report that "development of replacement agents with the very low toxicity of halon 1301 for use in total flooding systems for occupied enclosures may not be a realistic expectation."

Another two of our members are of the opinion that:

> It is premature to consider quantifiable levels of possible reduced halon availability as more experience is required in working with the proposed alternative measures outlined in the full report. These members support a complete phase-out when viable substitutes become available to the market.

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[1] - As defined by the Montreal Protocol

Appendix A
Peer Reviewers

List of Peer Reviewers

Fenwal Controls of Japan	Japan
Fire Equipment Manufacturers Institute	Canada
C0-DUE	Italy
ICI	U.K.
Incendex	Canada
Swedish Fire Equipment Manufacturers Association	Sweden
National Association of Fire Equipment Distributors	U.S.A.
Department of Labour	Canada
Canadian Association of Fire Chiefs	Canada
Fire Protection Association of Southern Africa	South Africa
The Loss Prevention Council	U.K.
Center for Fire Research - NIST	U.S.A.
A.E. Willey - NFPA	U.S.A.
Ansul Fire Protection	U.S.A.
Canada Museums Construction Corporation	Canada
Japan Halon Committee	Japan
Fire Suppression Systems Association	U.S.A.
French Halon & Environment Committee	France
Underwriters Laboratories of Canada	Canada
Du Pont	Canada
US Air Force - Engineering Branch	U.S.A.
ICI America	U.S.A.
Cerberus Guinard	France
Association of Factory Sealed Fire Extinguisher Mfrs.	U.S.A./Canada
Office of the Canadian Forces Fire Marshall	Canada
Ministry for Planning and Environment	Australia
Standards Association of Australia	Australia
Telecom Australia - HQ	Australia
Environmental Protection Authority	Australia
State Pollution Control Commission	Australia
Insurance Council of Australia	Australia
The Swedish Fire Protection Association	Sweden
FSAB	Sweden
National Rescue Services Board	Sweden
Fire Equipment Manufacturers Association	U.S.A.
Du Pont	U.S.A.
National Association of Fire Equipment Distributors	U.S.A.
EUROFEU	E.E.C.
Federal Aviation Administration - US-DOT	U.S.A.
Transportation Systems Center - US-DOT	U.S.A.
U.S. Navy	U.S.A.
Underwriters Laboratories	U.S.A.
Insurers Advisory Organization	Canada
Great Lakes Chemical Corporation	U.S.A.

List of Peer Reviewers
(continued)

Manitoba Environment	Canada
Stanchem	Canada
Transport Canada	Canada
Greenpeace International	
Fenwal Inc.	U.S.A.
BP Exploration	U.S.A.
Swedish Employers Confederation	Sweden
Smithsonian Institution	U.S.A.
Fireline Corporation	U.S.A.
Casey Grant - NFPA	U.S.A.
Department of Transport	U.K.
Kemper Insurance	U.S.A.
Telecom Australia - Property Services	Australia
Northern Telecom	Canada
Department of Public Works - National Capital Region	Canada
Loss Prevention Association of India	India
Florida Power Corporation	U.S.A.

Appendix B
Estimated Historic and Future Usage of Halon 1301 and Halon 1211

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)

Year	1970	1971	1972	1973	1974	1975	1976	1977
Halon 1301								
Estimated World Production	74	147	294	587	1300	2014	2727	3441
Estimated Emissions as a % of production	50%	50%	50%	45%	40%	35%	30%	30%
Estimated Total Emissions	37	74	147	264	520	705	818	1032
Estimated Added to Bank	37	74	147	323	780	1309	1909	2409
Estimated Total Bank	37	111	258	580	1360	2669	4578	6987
Estimated Total Emissions as a % of the bank	100%	67%	57%	46%	38%	26%	18%	15%
Estimated Fire Usage	1	2	4	8	19	37	63	96
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	36	72	143	256	501	668	755	937
Estimated Other Emissions as a % of the bank	98.63%	65.15%	55.72%	44.15%	36.86%	25.04%	16.50%	13.41%
Halon 1211								
Estimated World Production	150	300	495	1592	2689	3786	4882	5979
Estimated Emissions as a % of production	50%	50%	50%	45%	40%	35%	30%	25%
Estimated Total Emissions	75	150	248	716	1076	1325	1465	1495
Estimated Added to Bank	75	150	248	876	1613	2461	3417	4484
Estimated Total Banked	75	225	473	1348	2962	5422	8840	13324
Estimated Total Emissions as a % of the bank	100%	67%	52%	53%	36%	24%	17%	11%
Estimated Fire Usage	1	3	7	21	46	84	136	206
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	74	147	240	696	1030	1241	1328	1289
Estimated Other Emissions as a % of the bank	98.46%	65.12%	50.84%	51.60%	34.78%	22.89%	15.02%	9.67%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates. Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)								
Year	1978	1979	1980	1981	1982	1983	1984	1985
Halon 1301								
Estimated World Production	4154	4868	5581	6295	7008	7722	8435	9149
Estimated Emissions as a % of production	30%	30%	30%	30%	30%	30%	30%	30%
Estimated Total Emissions	1246	1460	1674	1889	2102	2317	2531	2745
Estimated Added to Bank	2908	3408	3907	4407	4906	5405	5905	6404
Estimated Total Bank	9895	13303	17209	21616	26521	31927	37831	44236
Estimated Total Emissions as a % of the bank	13%	11%	10%	9%	8%	7%	7%	6%
Estimated Fire Usage	135	182	235	296	363	437	518	605
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	1111	1278	1439	1593	1740	1880	2013	2140
Estimated Other Emissions as a % of the bank	11.23%	9.61%	8.36%	7.37%	6.56%	5.89%	5.32%	4.84%
Halon 1211								
Estimated World Production	7076	8173	9270	10366	11463	12560	13657	14754
Estimated Emissions as a % of production	25%	25%	25%	25%	25%	25%	25%	25%
Estimated Total Emissions	1769	2043	2318	2592	2866	3140	3414	3689
Estimated Added to Bank	5307	6130	6953	7775	8597	9420	10243	11066
Estimated Total Banked	18631	24761	31713	39488	48085	57505	67748	78813
Estimated Total Emissions as a % of the bank	9%	8%	7%	7%	6%	5%	5%	5%
Estimated Fire Usage	288	382	489	609	742	888	1046	1216
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	1481	1661	1828	1982	2124	2252	2369	2472
Estimated Other Emissions as a % of the bank	7.95%	6.71%	5.76%	5.02%	4.42%	3.92%	3.50%	3.14%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates. Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)								
Based on Compliance with 1987 Montreal Protocol								
Year	1986	1987	1988	1989	1990	1991	1992	1993
Halon 1301								
Estimated World Production	9862	10576	11289	12003	11289	10576	9862	9862
Estimated Emissions as a % of production	30%	30%	30%	30%	25%	20%	20%	21%
Estimated Total Emissions	2959	3173	3387	3601	2822	2115	1972	2071
Estimated Added to Bank	6903	7403	7902	8402	8467	8461	7890	7791
Estimated Total Bank	51139	58542	66445	74847	83313	91774	99664	107455
Estimated Total Emissions as a % of the bank	6%	5%	5%	5%	3%	2%	2%	2%
Estimated Fire Usage	700	801	909	1024	1140	1255	1363	1470
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	2259	2372	2478	2577	1683	860	609	601
Estimated Other Emissions as a % of the bank	4.42%	4.05%	3.73%	3.44%	2.02%	0.94%	0.61%	0.56%
Halon 1211								
Estimated World Production	15851	16947	18044	19141	18044	16947	15851	15851
Estimated Emissions as a % of production	25%	25%	25%	23%	23%	22%	21%	23%
Estimated Total Emissions	3963	4237	4511	4307	4150	3728	3329	3566
Estimated Added to Bank	11888	12710	13533	14834	13894	13219	12522	12285
Estimated Total Banked	90702	103412	116945	131780	145673	158892	171414	183699
Estimated Total Emissions as a % of the bank	4%	4%	4%	3%	3%	2%	2%	2%
Estimated Fire Usage	1400	1596	1805	2034	2248	2452	2646	2835
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	2563	2641	2706	2273	1902	1276	683	731
Estimated Other Emissions as a % of the bank	2.83%	2.55%	2.31%	1.72%	1.31%	0.80%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates.

Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)

Based on Compliance with 1987 Montreal Protocol

Year	1994	1995	1996	1997	1998	1999	2000
Halon 1301							
Estimated World Production	9862	9862	9862	9862	9862	9862	9862
Estimated Emissions as a % of production	23%	24%	26%	27%	29%	30%	31%
Estimated Total Emissions	2265	2412	2555	2696	2835	2970	3103
Estimated Added to Bank	7597	7450	7307	7166	7027	6892	6759
Estimated Total Bank	115091	122541	129848	137014	144041	150932	157691
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	1574	1676	1776	1874	1970	2065	2157
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	691	735	779	822	864	906	946
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211							
Estimated World Production	15851	15851	15851	15851	15851	15851	15851
Estimated Emissions as a % of production	24%	25%	27%	28%	30%	31%	32%
Estimated Total Emissions	3795	4034	4259	4480	4697	4910	5118
Estimated Added to Bank	12056	11817	11592	11371	11154	10941	10733
Estimated Total Banked	195755	207572	219163	230534	241688	252629	263361
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	3021	3204	3383	3558	3730	3899	4065
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	773	830	877	922	967	1011	1053
Estimated Other Emissions as a % of the bank	0.39%	0.40%	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates. Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)					
Based on Compliance with 1987 Montreal Protocol					
Year	2001	2002	2003	2004	2005
Halon 1301					
Estimated World Production	9862	9862	9862	9862	9862
Estimated Emissions as a % of production	33%	34%	35%	37%	38%
Estimated Total Emissions	3234	3362	3487	3610	3731
Estimated Added to Bank	6628	6500	6375	6252	6131
Estimated Total Bank	164319	170820	177194	183446	189577
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	2248	2337	2424	2510	2593
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	986	1025	1063	1101	1137
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211					
Estimated World Production	15851	15851	15851	15851	15851
Estimated Emissions as a % of production	34%	35%	36%	37%	39%
Estimated Total Emissions	5323	5524	5721	5914	6103
Estimated Added to Bank	10528	10327	10130	9937	9748
Estimated Total Banked	273889	284217	294347	304284	314032
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	4227	4387	4543	4697	4847
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	1096	1137	1177	1217	1256
Estimated Other Emissions as a % of the bank	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates. Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)							
Based on Reduction of Consumption Rights to 50% of 1986 Levels							
Year	1994	1995	1996	1997	1998	1999	2000
Halon 1301							
Estimated World Production	9862	7397	7397	4931	4931	4931	4931
Estimated Emissions as a % of production	23%	32%	33%	51%	52%	53%	54%
Estimated Total Emissions	2265	2364	2461	2509	2556	2601	2646
Estimated Added to Bank	7597	5033	4936	2422	2375	2330	2285
Estimated Total Bank	115091	120124	125060	127482	129857	132187	134472
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	1574	1643	1711	1744	1776	1808	1840
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	691	721	750	765	779	793	807
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211							
Estimated World Production	15851	11888	11888	7926	7926	7926	7926
Estimated Emissions as a % of production	24%	33%	35%	53%	54%	55%	55%
Estimated Total Emissions	3795	3959	4110	4183	4254	4324	4393
Estimated Added to Bank	12056	7929	7778	3743	3672	3602	3533
Estimated Total Banked	195755	203684	211463	215206	218878	222480	226014
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	3021	3144	3264	3322	3378	3434	3489
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	773	815	846	861	876	890	904
Estimated Other Emissions as a % of the bank	0.39%	0.40%	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates.
Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)

Based on Reduction of ConsumptionRights to 50% of 1986 Levels

Year	2001	2002	2003	2004	2005
Halon 1301					
Estimated World Production	4931	4931	4931	4931	4931
Estimated Emissions as a % of production	55%	55%	56%	57%	58%
Estimated Total Emissions	2690	2734	2776	2818	2859
Estimated Added to Bank	2241	2197	2155	2113	2072
Estimated Total Bank	136712	138909	141064	143177	145250
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	1870	1900	1930	1959	1987
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	820	833	846	859	871
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211					
Estimated World Production	7926	7926	7926	7926	7926
Estimated Emissions as a % of production	56%	57%	58%	59%	60%
Estimated Total Emissions	4460	4526	4591	4654	4717
Estimated Added to Bank	3466	3400	3335	3272	3209
Estimated Total Banked	229480	232880	236215	239486	242696
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	3542	3594	3646	3696	3746
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	918	932	945	958	971
Estimated Other Emissions as a % of the bank	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates. Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)

Based on Elimination of Consumption Rights by 2005

Year	1994	1995	1996	1997	1998	1999	2000
Halon 1301							
Estimated World Production	9862	7397	7397	4931	4931	4931	2466
Estimated Emissions as a % of production	23%	32%	33%	51%	52%	53%	105%
Estimated Total Emissions	2265	2364	2461	2509	2556	2601	2599
Estimated Added to Bank	7597	5033	4936	2422	2375	2330	-133
Estimated Total Bank	115091	120124	125060	127482	129857	132187	132054
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	1574	1643	1711	1744	1776	1808	1806
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	691	721	750	765	779	793	792
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211							
Estimated World Production	15851	11888	11888	7926	7926	7926	3963
Estimated Emissions as a % of production	24%	33%	35%	53%	54%	55%	109%
Estimated Total Emissions	3795	3959	4110	4183	4254	4324	4317
Estimated Added to Bank	12056	7929	7778	3743	3672	3602	-354
Estimated Total Banked	195755	203684	211463	215206	218878	222480	222126
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%	2%	2%
Estimated Fire Usage	3021	3144	3264	3322	3378	3434	3429
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	773	815	846	861	876	890	889
Estimated Other Emissions as a % of the bank	0.39%	0.40%	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates.
Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Table B-1

Estimated Historic and Projected Future Usage of Halons (in metric tonnes)

Based on Elimination of Consumption Rights by 2005

Year	2001	2002	2003	2004	2005
Halon 1301					
Estimated World Production	2466	2466	2466	2466	0
Estimated Emissions as a % of production	105%	105%	105%	105%	n/a
Estimated Total Emissions	2596	2594	2591	2589	2539
Estimated Added to Bank	-130	-128	-125	-123	-2539
Estimated Total Bank	131924	131796	131671	131548	129009
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	1805	1803	1801	1800	1765
Estimated Fire Usage as a % of the bank	1.37%	1.37%	1.37%	1.37%	1.37%
Estimated Other Emissions	792	791	790	789	774
Estimated Other Emissions as a % of the bank	0.60%	0.60%	0.60%	0.60%	0.60%
Halon 1211					
Estimated World Production	3963	3963	3963	3963	0
Estimated Emissions as a % of production	109%	109%	108%	108%	n/a
Estimated Total Emissions	4310	4304	4297	4291	4209
Estimated Added to Bank	-347	-341	-334	-328	-4209
Estimated Total Banked	221779	221438	221104	220776	216567
Estimated Total Emissions as a % of the bank	2%	2%	2%	2%	2%
Estimated Fire Usage	3423	3418	3413	3408	3343
Estimated Fire Usage as a % of the bank	1.54%	1.54%	1.54%	1.54%	1.54%
Estimated Other Emissions	887	886	884	883	866
Estimated Other Emissions as a % of the bank	0.40%	0.40%	0.40%	0.40%	0.40%

Note: Estimated World Production has been calculated based on CEFIC published data for the years 1978 - 1987, these figures were then multiplied by a factor of 1.412537 to agree with UNEP 1986 audit data. Halon 1301 production for 1970-1972 and halon 1211 production for 1970-1971 are estimates.
Fire usage % estimates are based on usage studies reported by industry in North America and Europe. Other emission figures are estimates based on U.S. industry data for 1986.

Appendix C
Example Matrices
Fire Protection Alternatives
Halon Total Flooding Systems

EXAMPLE ANALYSES

This section demonstrates the application of the proposed procedure for a few selected examples and includes some alternative protection schemes.

C.1 Computer and Electronic Applications

The agent/system selection matrices are used to compare the following generic applications involving computers and electronics:

- General Purpose Commercial Computer Room (Figure C-1)
- Power Plant Control Room (Figure C-2)
- Communications Facility (Figure C-3)
- Military Electronics Facility (Figure C-4)

The application specific weighting factors for each of these applications are shown. The net weighted scores for each application as a function of the proposed agent/system alternatives are also provided.

C.2 Flammable Liquid Hazard Areas

A typical application of Halon total flooding systems is in flammable liquids handling areas including fuel fired boilers and turbines. Using the agent/system scoring method previously described and appropriate application specific weighting factors, the following examples are provided.

- Manned shipboard boiler/turbine space (Figure C-5)
- Unmanned Flammable Liquid Pump Room (Figure C-6)

C.3 Cultural Heritage

An example of fire protection alternatives for protection of a collection room is provided (C-7)

Figure C-1

General Purpose Commercial Computer Room										
Societal Weighting Factor (Max 10) =	0									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	5	10	0	10	0	5	
Monitored Early Warning Detection (EWD)	0	0	50	0	100	0	50	0	25	225
Automatic Sprinklers + EWD	0	0	50	0	100	0	100	0	20	270
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	100	0	100	0	20	300
Pre-Action Sprinklers (includes EWD)	0	0	50	0	100	0	80	0	15	245
In Cabinet & Subfloor CO2 (C&SCO2) + EWD	0	0	80	25	80	0	30	0	20	235
FRS + EWD + C&SCO2	0	0	90	25	80	0	100	0	15	310
EWD + Total Flood Halon 1301	-100	0	100	25	90	0	80	0	10	205
EWD + Total Flood Halon 1211	-30	0	100	25	70	0	80	0	5	250
EWD + Total Flood CO2	0	0	90	25	20	0	80	0	5	220

Figure C-2

Power Plant Control Room										
Societal Weighting Factor (Max 10) =	10									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	5	10	0	10	5	0	40
Monitored Early Warning Detection (EWD)	0	0	50	0	100	0	50	5	0	205
Automatic Sprinklers + EWD	0	0	50	0	100	0	100	10	0	260
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	100	0	100	15	0	295
Pre-Action Sprinklers (includes EWD)	0	0	50	0	100	0	80	15	0	245
EWD + Total Flood Halon 1301	0	0	100	25	90	0	80	25	0	320
EWD + Total Flood Halon 1211	0	0	100	25	70	0	80	25	0	300
EWD + Total Flood CO2	0	0	90	25	20	0	80	25	0	240

Figure C-3

Communications Facility (Manned 50% of the time)										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	5	5	0	10	5	0	
Monitored Early Warning Detection (EWD)	0	0	50	0	50	0	50	5	0	155
Automatic Sprinklers + EWD	0	0	50	0	50	0	100	10	0	210
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	50	0	100	15	0	245
Pre-Action Sprinklers (includes EWD)	0	0	50	0	50	0	80	15	0	195
EWD + Total Flood Halon 1301	-70	0	100	25	45	0	80	25	0	205
EWD + Total Flood Halon 1211	-21	0	100	25	35	0	80	25	0	244
EWD + Total Flood CO2	0	0	90	25	10	0	80	25	0	230

Figure C-4

Military Electronics Facility										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	5	10	0	10	5	0	40
Monitored Early Warning Detection (EWD)	0	0	50	0	100	0	50	5	0	205
Automatic Sprinklers + EWD	0	0	50	0	100	0	100	10	0	260
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	100	0	100	15	0	295
Pre-Action Sprinklers (includes EWD)	0	0	50	0	100	0	80	15	0	245
In Cabinet & Subfloor CO2 (C&SCO2) + EWD	0	0	80	25	80	0	30	25	0	240
FRS + EWD + C&SCO2	0	0	90	25	80	0	100	10	0	305
EWD + Total Flood Halon 1301	-20	0	100	25	90	0	80	25	0	300
EWD + Total Flood Halon 1211	-6	0	100	25	70	0	80	25	0	294
EWD + Total Flood CO2	0	0	90	25	20	0	80	25	0	240

Figure C-5

Military Shipboard Machinery Space (Manned)										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	0	5	10	10	0	0	35
Monitored Early Warning Detection (EWD)	0	0	50	0	50	0	50	0	0	150
Automatic Sprinklers + EWD	0	0	50	0	50	0	100	0	0	200
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	50	0	100	0	0	230
Pre-Action Sprinklers (includes EWD)	0	0	50	0	50	0	80	0	0	180
EWD + Total Flood Halon 1301	-70	0	100	0	45	100	80	0	0	255
EWD + Total Flood Halon 1211	-21	0	100	0	35	100	80	0	0	294
EWD + Total Flood CO2	0	0	90	0	10	80	80	0	0	260
Detection + Total Flood Dry Chemical	0	0	40	0	35	70	70	0	0	215
Detection + Deluge Water Spray	0	0	30	0	50	10	90	0	0	180
Detection + Low Expansion Foam	0	0	30	0	45	70	70	0	0	215
Detection + CO2 + Low Expansion Foam	0	0	30	0	10	100	100	0	0	240
Detection + High Expansion Foam	0	0	60	0	10	50	70	0	0	190

Figure C-6

Unmanned Flammable Liquid Pump Room										
Societal Weighting Factor (Max 10) =	0									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	0	0	10	10	0	5	30
Monitored Early Warning Detection (EWD)	0	0	50	0	0	0	50	0	25	125
Automatic Sprinklers + EWD	0	0	50	0	0	0	100	0	20	170
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	0	0	100	0	20	200
Pre-Action Sprinklers (includes EWD)	0	0	50	0	0	0	80	0	15	145
EWD + Total Flood Halon 1301	-200	0	100	0	0	100	80	0	10	90
EWD + Total Flood Halon 1211	-60	0	100	0	0	100	80	0	5	225
EWD + Total Flood CO2	0	0	90	0	0	80	80	0	5	255
Detection + Total Flood Dry Chemical	0	0	40	0	0	70	70	0	5	185
Detection + Deluge Water Spray	0	0	30	0	0	10	90	0	15	145
Detection + Low Expansion Foam	0	0	30	0	0	70	70	0	15	185
Detection + CO2 + Low Expansion Foam	0	0	30	0	0	100	100	0	5	235
Detection + High Expansion Foam	0	0	60	0	0	50	70	0	15	195

Figure C-7

Cultural Heritage Collection Room										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Low Space Weight (max 5)	Damage Limiting (max 10)	Ability To Permeate (max 5)	Occupant Risk (max 10)	Flam Liq Ext Cap (max 10)	System Efficacy (max 10)	Energized Elec Equip (max 5)	Installed Cost (max 5)	Total
Hazard Specific Weighting		0	10	5	10	0	10	0	5	
Monitored Early Warning Detection (EWD)	0	0	50	0	100	0	50	0	25	225
Automatic Sprinklers + EWD	0	0	50	0	100	0	100	0	20	270
Fast Response Sprinklers (FRS) + EWD	0	0	80	0	100	0	100	0	20	300
Pre-Action Sprinklers (includes EWD)	0	0	50	0	100	0	80	0	15	245
EWD + Total Flood Halon 1301	-20	0	100	25	90	0	80	0	10	285
EWD + Total Flood Halon 1211	-6	0	100	25	70	0	80	0	5	274
EWD + Total Flood CO2	0	0	90	25	20	0	80	0	5	220

Appendix D
Example Matrices
Fire Protection Alternatives
Manual Application Usage
of Halon 1211

Figure D-1

Passenger Aircraft Cabin										
Societal Weighting Factor (Max 10) =	10									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	0	5	5	5	5	10	0	
Halon 1211 and Blends	0	20	0	25	25	20	25	80	0	195
CO2	0	5	0	25	25	5	5	100	0	165
Multipurpose Dry Chemical	0	25	0	15	5	20	25	0	0	90
AFFF	0	25	0	0	0	20	15	20	0	80
Straight Stream Water	0	25	0	0	0	25	5	40	0	95
Water Spray	0	25	0	5	0	15	10	40	0	95
Water Spray + CO2	0	25	0	5	25	15	0	40	0	110

Figure D-2

Communications Facility										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	0	5	5	2	0	10	1	
Halon 1211 and Blends	-12	20	0	25	25	8	0	80	0	146
CO2	0	5	0	25	25	2	0	100	0	157
Multipurpose Dry Chemical	0	25	0	15	5	8	0	0	3	56
AFFF	0	25	0	0	0	8	0	20	2	55
Straight Stream Water	0	25	0	0	0	10	0	40	2	77
Water Spray	0	25	0	5	0	6	0	40	2	78
Water Spray + CO2	0	25	0	5	25	6	0	40	0	101

Figure D-3

General Purpose Computer Room										
Societal Weighting Factor (Max 10) =	0									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	0	5	5	2	1	10	3	
Halon 1211 and Blends	-60	20	0	25	25	8	5	80	0	103
CO2	0	5	0	25	25	2	1	100	0	158
Multipurpose Dry Chemical	0	25	0	15	5	8	5	0	9	67
AFFF	0	25	0	0	0	8	3	20	6	62
Straight Stream Water	0	25	0	0	0	10	1	40	6	82
Water Spray	0	25	0	5	0	6	2	40	6	84
Water Spray + CO2	0	25	0	5	25	6	0	40	0	101

Figure D-4

Cultural Heritage Collection Room										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	0	0	5	2	1	10	3	
Halon 1211 and Blends	-12	20	0	0	25	8	5	80	0	126
CO2	0	5	0	0	25	2	1	100	0	133
Multipurpose Dry Chemical	0	25	0	0	5	8	5	0	9	52
AFFF	0	25	0	0	0	8	3	20	6	62
Straight Stream Water	0	25	0	0	0	10	1	40	6	82
Water Spray	0	25	0	0	0	6	2	40	6	79
Water Spray + CO2	0	25	0	0	25	6	0	40	0	96

Figure D-5

Flammable Liquid Pump Room										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	5	-0	0	5	0	0	3	
Halon 1211 and Blends	-12	20	15	0	0	20	0	0	0	43
CO2	0	5	10	0	0	5	0	0	0	20
Multipurpose Dry Chemical	0	25	25	0	0	20	0	0	9	79
AFFF	0	25	10	0	0	20	0	0	6	61
Straight Stream Water	0	25	0	0	0	25	0	0	6	56
Water Spray	0	25	5	0	0	15	0	0	6	51
Water Spray + CO2	0	25	10	0	0	15	0	0	0	50

Figure D-6

Military Electronics Facility										
Societal Weighting Factor (Max 10) =	10									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond. (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	0	5	5	0	0	10	0	
Halon 1211 and Blends	0	20	0	25	25	0	0	80	0	150
CO2	0	5	0	25	25	0	0	100	0	155
Multipurpose Dry Chemical	0	25	0	15	5	0	0	0	0	45
AFFF	0	25	0	0	0	0	0	20	0	45
Straight Stream Water	0	25	0	0	0	0	0	40	0	65
Water Spray	0	25	0	5	0	0	0	40	0	70
Water Spray + CO2	0	25	0	5	25	0	0	40	0	95

Figure D-7

Military Shipboard Machinery Space										
Societal Weighting Factor (Max 10) =	8									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		1	5	0	0	5	5	2	0	
Halon 1211 and Blends	-12	4	15	0	0	20	25	16	0	68
CO2	0	1	10	0	0	5	5	20	0	41
Multipurpose Dry Chemical	0	5	25	0	0	20	25	0	0	75
AFFF	0	5	10	0	0	20	15	4	0	54
Straight Stream Water	0	5	0	0	0	25	5	8	0	43
Water Spray	0	5	5	0	0	15	10	8	0	43
Water Spray + CO2	0	5	10	0	0	15	0	8	0	38

Figure D-8

Power Plant Control Room										
Societal Weighting Factor (Max 10) =	10									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor	-	5	0	5	5	0	0	10	3	-
Halon 1211 and Blends	0	20	0	25	25	0	0	80	0	150
CO2	0	5	0	25	25	0	0	100	0	155
Multipurpose Dry Chemical	0	25	0	15	5	0	0	0	9	54
AFFF	0	25	0	0	0	0	0	20	6	51
Straight Stream Water	0	25	0	0	0	0	0	40	6	71
Water Spray	0	25	0	5	0	0	0	40	6	76
Water Spray + CO2	0	25	0	5	25	0	0	40	0	95

Figure D-9

Private Residential										
Societal Weighting Factor (Max 10) =	0									
	Controlled Substance Penalty	Ordinary Combust (Max 5)	Flammable Liquids (Max 5)	Electrically Non-Cond (Max 5)	Ability To Permeate (Max 5)	Range (Max 5)	Weight/ Effectiveness (Max 5)	Secondary Damage (Max 10)	Cost (Max 3)	Total Score
Application Specific Factor		5	3	5	2	3	2	2	2	
Halon 1211 and Blends	-60	20	9	25	10	12	10	16	0	42
CO2	0	5	6	25	10	3	2	20	0	71
Multipurpose Dry Chemical	0	25	15	15	2	12	10	0	6	85
AFFF	0	25	6	0	0	12	6	4	4	57
Straight Stream Water	0	25	0	0	0	15	2	8	4	54
Water Spray	0	25	3	5	0	9	4	8	4	58
Water Spray + CO2	0	25	6	5	10	9	0	8	0	63

Appendix E
Combustion and Extinguishment
An Overview of the Science

COMBUSTION AND EXTINGUISHMENT: AN OVERVIEW OF THE SCIENCE

In this appendix, the science of combustion and extinguishment is reviewed, and an overview of halon replacement research and development is presented. It must be noted that for some of the critical reactions listed, the reaction rates at flame temperatures are quite high. In these cases, thermodynamic data, particularly at 298 K, are of less value than are rate constants. However, to keep this section as simple as possible, discussions of kinetics have been avoided.

COMBUSTION

Combustion is an oxidation/reduction reaction sufficiently intense to give off heat and visible light. Fire is uncontrolled combustion. The oxidizing agent for nearly all fires is oxygen from the air. In unusual cases, the oxidizing agent may be pure oxygen, hydrogen peroxide, organic peroxides, ozone, metal peroxides, dinitrogen tetroxide, or other oxidants. The reducing agents (fuels) for typical fires are cellulosic materials (paper, wood), which give Class A fires; liquid fuels (gasoline, alcohol, kerosine, aviation fuels, petroleum), which give Class B fires; and metals (magnesium, lithium, sodium, titanium), which give Class D fires. Class C fires involve live electrical components. Of primary concern are Class A and B diffusion fires where the oxidizing agent is air that enters the flame zone by diffusion. Halon fire extinguishing agents are not suitable for Class D fires.

Fires can be examined from either a microscopic or a macroscopic standpoint. The second approach is usually considered the realm of the engineer; the first is that of the chemist. A fundamental understanding of fire characteristics is required to comprehend extinguishment mechanisms.

MICROSCOPIC APPROACH TO COMBUSTION

Chain Branching

Free radicals are highly reactive molecular species with unsatisfied chemical bonding requirements. Hydrogen atoms (H), oxygen atoms (O), hydroxyl free radicals (OH), and methyl free radicals (CH_3) are among the many free radicals occurring in combustion.

Fires are initiated and sustained by free-radical reactions. Since free radicals are lost by a variety of mechanisms (including diffusion out of the combustion zone and recombination), free radicals must be generated continually if a fire is to be sustained. In a stable flame, free radical loss is balanced by free radical generation. The principal path generating free radicals is the chain branching reaction, in which a single free radical reacts with a molecule to yield two free radicals. The following reactions are two of the most important chain branching reactions.

$$H + O_2 \rightarrow OH + O, \Delta H(298\ K) = 70\ kJ \quad (1)$$

$$O + H_2 \rightarrow OH + H, \Delta H(298\ K) = 8\ kJ \quad (2)$$

The ΔH values (reaction enthalpies) give the heat released or absorbed during a reaction. The enthalpies given here are in kilojoules, kJ, and are taken from the JANAF Tables.[1] A negative ΔH value indicates a heat releasing ("exothermic") reaction. A positive ΔH value indicates a heat absorbing ("endothermic") reaction. The chain branching reactions shown above are endothermic and are sustained by the heat released by recombination reactions (vide infra).

Initiation

The science of thermodynamics determines whether a reaction is spontaneous; the science of kinetics determines whether a reaction proceeds with sufficient speed to be of importance. At lower temperatures, exothermic reactions are usually spontaneous; endothermic reactions are usually not. At higher temperatures, as found for combustion, this rule holds less often since the effect of entropy change becomes more important. Fortunately, not all reactions that could occur do so with sufficient speed to be important. Before a spontaneous reaction can occur, sufficient energy must be available to initiate and sustain the reaction. The minimum energy required for initiation is termed the "activation energy."

The activation energy for direct reaction of most common fuels with diatomic oxygen (normal oxygen as found in air) is very high. For this reason, at room temperature, most fuels can coexist with air without combustion. At higher temperatures, bonds can break to give free radicals and initiate combustion. For example, pyrolysis of methane gives hydrogen and methyl free radicals.

$$CH_4 \rightarrow CH_3 + H, \Delta H(298\ K) = 439\ kJ \quad (3)$$

The source of the energy needed to drive this reaction is the heat released by the flame. Since the reaction enthalpies of these pyrolysis reactions are much larger than those for typical chain branching reactions, the latter are the dominant reactions by which radicals are generated in a flame.

Propagation

Many reactions serve to propagate free-radical chains without changing the total number of radicals in the flame. The following reactions are typical.

$$CH_4 + H \rightarrow CH_3 + H_2, \Delta H(298\ K) = 3\ kJ \quad (4)$$

$$OH + H_2 \rightarrow H_2O + H, \Delta H(298\ K) = -63\ kJ \quad (5)$$

These propagation reactions are usually bimolecular and may be either endothermic or exothermic.

Recombination

Recombination reactions differ in two important respects from the reactions described above: they are highly exothermic and they require a third body (M) to carry off part of the energy. Consider the following:

$$H + H + M \rightarrow H_2 + M, \Delta H(298\ K) = -436\ kJ \quad (6)$$

$$H + OH + M \rightarrow H_2O + M, \Delta H(298\ K) = -499\ kJ \quad (7)$$

Recombination reactions are the primary sources of energy to sustain the endothermic chain branching reactions. Moreover, since these reactions involve three reacting species and the probability of a three-body collision is small, recombination reactions are much slower than other flame reactions. Radicals are, therefore, relatively long-lived in a flame and may diffuse significant distances before they undergo reaction.

MACROSCOPIC APPROACH TO COMBUSTION

Convective Transport

Although it seems trivial to note that flames rise, the consequences are profound. Convective transport (followed by recombination) is an important loss mechanism for radicals (which might otherwise become engaged in chain branching reactions). Convective transport is also an important mechanism for loss of thermal energy (which is required to sustain the chain branching reactions).

Eddy Transport (Entrainment)

As the hot gases rise, they accelerate with respect to the surrounding gases and generate small eddies which may evolve into large scale turbules. The eddies not only result in a counterflow movement of flame species, they also entrain gases (oxidizers, diluents, suppressants) into the flame. Entrainment can increase burning rates by facilitating the mixing of fuel and oxidizer and by assisting chain branching reactions (by mixing free radicals present in the combustion products with the fuel and oxidizer mixture). However, high turbulence can also decrease burning rates by causing separation of pockets of burning gas, which are only slowly consumed. Eddy transport provides an important but little studied mechanism for entrainment of extinguishing agents in fires. Once the initial momentum of a discharged fire suppressant has been lost, further penetration into the flame depends almost entirely on entrainment.

Diffusive Transport

Along with entrainment, diffusive transport accounts for the fact that a flame propagates upstream from the zone of high free-radical concentration. As expected, atomic and small molecular species (especially hydrogen atoms) diffuse at the highest rates.

Radiation

Radiation is a major contributor to flame spread and it dominates fuel vaporization. With high particulate loading (luminous flames), radiation plays a particularly large role in heat emission. On the other hand, bond breakage by molecular interactions with radiation is insignificant.

Heat Loss to the Fuel Pool

Pools of liquid fuels represent heat sinks. For flames supported on pools of fuel, the temperature and, therefore, the flame speed in the vicinity of the heat sink must be lower than that in the hottest part of the flame. As a result, it is necessary to describe the dynamics of a flame in the terms of the relative velocities of the flame and of the fuel/oxidizer/diluent stream. Since the adiabatic flame velocity is typically larger than the linear stream velocity, the flame will tend to propagate upstream toward the fuel pool However, the heat loss to these heat sinks will reduce the flame speed until it equals the stream velocity. At this point, equilibrium is established. This equilibrium accounts for the fact that a flame can take up a stable position a short distance above the fuel pool, and that a change in stream velocity or in diluent ratio can have a significant influence on the location and/or stability of the flame.

Heat losses to fuel surfaces can greatly influence the behaviour of flames and fires. The temperature of a pool of fuel sustaining a fire may approach the boiling point. A Class A fire is an extreme case in that the smouldering fuel provides a hot "flame holder." Moreover, the interface between a cold fuel and a flame represents a fragile equilibrium, which can be easily disturbed by introduction of even small amounts of extinguishing agent. By contrast, the latter stages of a flame are more robust.

FIRE EXTINGUISHMENT

Four things are needed for combustion: fuel, oxidizer, heat, and free radicals. These four components of a fire are said to form the "fire tetrahedron." If any component is removed (or inhibited), the fire can be extinguished. Based on this simple picture, seven basic methods have been used for fire extinguishment: 1) isolate the fuel, 2) isolate the oxidizer, 3) cool the condensed phase, 4) cool the gas phase, 5) blow away the flame, 6) inhibit the chemical reaction homogeneously, and 7) inhibit the chemical reaction heterogeneously.

Extinguishment mechanisms are divided into two types: physical and chemical. It is difficult to describe a particular extinguishment method as belonging entirely to one type or another; however, methods 1-5 above are generally considered physical and methods 6 and 7 are considered chemical.

A number of physical extinguishment methods exist. Smothering isolates the fuel from the oxidizing agent. Foams can effect this separation; however, the overall mode of action of foams is more complicated. A fuel may also be isolated by creation of backfires or by pumping liquid fuels from a burning tank to another vessel. Air can be removed by displacement with an inert gas.

Cooling, another physical extinguishment mechanism, can be affected by the addition of materials which absorb large amounts of heat. Water is an excellent example of such a material. Simple dilution can also lower the flame temperature to the point that combustion cannot be sustained.

Blowing away a flame separates the free-radical zone from the fuel. This procedure moves the free radicals to a location where they can combine harmlessly and effectively terminates the free-radical chain reaction. Extinguishment by blowing away flames, of which extinguishment by shock waves and sound are variations, also works in some cases because heat is removed faster than it is generated.

Chemical means of extinguishment depend on termination or suppression of one or more reactions within the free radical chain. This is most often accomplished by removing certain highly reactive chemical species, usually hydrogen atoms or hydroxyl free radicals. Heterogeneous chemical agents (such as potassium bicarbonate) may do this by providing surfaces on which atoms and other free radicals can combine. The surfaces are needed to carry away the energy given off during bond formation. The most common homogeneous chemical agents are the halons. The action of halons is described in the following section.

EXTINGUISHMENT BY HALONS

Since the key reactive species in the principal chain branching reactions are the hydrogen and oxygen atoms, and since these reactions are endothermic, the flame may be extinguished by any process which either reduces the concentrations of these atoms or reduces the temperature of the flame (and thus reduces the energy available to drive the endothermic reactions). Table 1 lists five extinguishment mechanisms in which halons may participate. Clearly, each interferes with the chemistry of a fire; nevertheless, it is convenient to consider the first four mechanisms as "physical" and the last as "chemical."

TABLE 1 - EXTINGUISHMENT MECHANISMS OF HALONS

Mechanism	Effect
Dilution	Reduces concentrations of reactive species
Vaporization	Absorbs energy from flame; reduces temperature
Heat Transfer	Absorbs energy from flame; reduces temperature
Dissociation	Absorbs energy from flame; reduces temperature
Reaction	Removes reactive species from flame

By way of illustration, consider the chain branching reaction shown in Reaction 1. Its rate equation is

$$\text{rate} = k[H][O_2] \qquad (8)$$

where the square brackets [ ], represent the concentration of the species in the bracket. Since the rate is proportional to the concentration of each of the reactants, any agent which dilutes the reaction mixture necessarily reduces the concentrations of the reactive species and, thus, reduces the rate of the reaction. At some point, the rate becomes so slow that the rate of generation of radical falls below the rate of loss and the flame goes out.

The extinguishant not only dilutes the reactants in a fire, it also absorbs energy from the fire. In this process, energy is removed from the reactant species and the fraction of reactant molecules (and atoms) having enough energy to surmount the activation energy barriers is reduced. Once again, the consequence is a reduction in the rate of generation of radicals. The degree to which a particular material may act as a heat sink in a flame depends on the physical state and on the molecular properties. Vaporization is unique to liquid phase extinguishants. Once the extinguishant is in the gas phase, the energy from the flame may be transferred to translational, rotational, vibrational, and/or electronic degrees of freedom in the extinguishant molecule. The amount of energy that may be transferred to each molecule depends on its number of degrees of freedom and on the separation between the energy levels in each degree of freedom.

The average translational energy of an atom or molecule depends only on its temperature. Thus, if both hydrogen atoms and, e.g., CF_3Br molecules are in thermal equilibrium in a flame, both will have the same kinetic energy. With respect to translational energy alone, both H atoms and CF_3Br molecules are equally good thermal sinks. However, hydrogen atoms will have much higher velocities and can, therefore, transport energy much more rapidly than can CF_3Br molecules.

Heat can also be absorbed due to increased molecular rotation and vibration. As a rule of thumb, larger, heavier molecules can absorb more energy in rotation and vibration than can smaller, lighter molecules.

The dissociation of a molecule typically requires a substantial input of energy. For this reason, dissociation rarely serves as a significant heat sink.

In contrast with the four physical extinguishment mechanisms described in the preceding paragraphs, the chemical mechanism actually removes key free radicals from the flame. The most thoroughly studied of the chemical fire suppressants is Halon 1301, CF_3Br. Despite considerable debate on the detailed extinguishment mechanism, it is generally agreed that the first step is the abstraction of the bromine atom by a hydrogen atom.

$$CF_3Br + H \rightarrow CF_3 + HBr, \Delta H(298K) = -76 \text{ kJ} \quad (9)$$

This reaction is then followed by reactions such as the following:

$$H + HBr \rightarrow H_2 + Br, \Delta H(298K) = -70 \text{ kJ} \quad (10)$$

$$Br + HR \rightarrow HBr + R, \Delta H(est, 298K) = 46 \text{ kJ} \quad (11)$$

In Reaction 11, HR represents a fuel molecule from which the bromine atom abstracts a proton. The net result is the catalyzed recombination of H atoms to form H_2 gas (Reaction 12).

$$H + H \rightarrow H_2, \Delta H\ (298K) = -436 \text{ kJ} \quad (12)$$

Reactions 9 to 11 thus interfere with the key chain branching reactions in which hydrogen atoms react with oxygen molecules (Reaction 1).

The bromine atoms from the halon catalyze the hydrogen atom recombination. Each bromine atom is used over and over owing to recycling reactions such as those shown in Reactions 13 and 14. The exceptional effectiveness of halons is attributable to this catalytic process.

$$Br + Br + M \rightarrow Br_2 + M, \Delta H(298K) = -224 \text{ kJ} \quad (13)$$

$H + Br_2 \rightarrow HBr + Br, \Delta H(298K) = -143\ kJ$ (14)

Of course, the extinguishment mechanism is more complex than suggested by the above equations. Other reactions, such as the following, contribute as well.

$R + Br_2 \rightarrow RBr + Br, \Delta H(298K) = -69\ kJ$ (15)

$CF_3Br + Br \rightarrow CF_3 + Br_2, \Delta H(298K) = -67\ kJ$ (16)

The importance of the CF_3 radical in the extinguishment of flames is less clear. Among the several plausible reactions are the following, which have been deduced from products found in typical flames.

$H + CF_3 + M \rightarrow HCF_3 + M, \Delta H(298K) = -445\ kJ$ (17)

$OH + CF_3Br \rightarrow OCF_2 + HF, \Delta H(298K) = -339\ kJ$ (18)

In addition, CF_3Br may react directly with other important radicals in the flame.

$O + CF_3Br \rightarrow CF_3 + OBr, \Delta H(298K) = +56\ kJ$ (19)

$OH + CF_3Br \rightarrow CF_3 + HOBr, \Delta H(298K) = +60\ kJ$ (20)

The effectiveness of halogenated fire suppressants increases as the atomic weight and number of halogen atoms increase. Thus, in order of increasing effectiveness, $F < Cl < Br < I$, and a molecule containing two atoms of a given halogen is usually more effective than a molecule containing only one.[2]

The relative importance of the physical and chemical mechanisms has been strongly debated. Perhaps because much of the work has been done by chemists, the majority of the published works have emphasized the chemical mechanism. However, advocates of the physical mechanisms periodically point out that most of the available fire suppression data can be correlated without the need to invoke chemical processes.[3,4] It should be noted that the ability to correlate fire suppression effectiveness with the physical attributes (notably molar heat capacity) of a fire suppression agent does not necessarily abrogate the need to invoke a chemical mechanism. The molecules which have the highest molar heat capacities are precisely those which contain the heavy atoms (Br and/or I), which are important in the chemical mechanism.

Both physical and chemical mechanisms are believed to contribute to the extinguishment of flames by halons; however, the relative importance of each mechanism is debatable. Moreover, even though it is possible to draw a correlation between extinguishment efficiency and such physical properties as heat capacity, the importance of a chemical mechanism (which also correlates with physical properties) cannot be discounted.

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