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SUPPRESSION OF POOL FIRES USING HALOCARBON STREAMING AGENTS

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ABSTRACT

Handheld FM-200, FE-36, CF₃I and Halotron I extinguishers with 2B:C, 5B:C and 10B:C ratings (or equivalent) were tested for extinguishing Class B heptane pool fires in small and large enclosures (45, 120 and 21000 m³). Relative extinguishment effectiveness of these extinguishers was determined. The concentrations of the halocarbons and acid gas by-products in the operator breathing zone and surroundings were measured during the tests. Measurements showed that the agent concentrations were below the levels that would pose life or health risk to the operator. The concentrations of acid gas by-products generated during suppression, however, were at dangerous levels in the small enclosures (45 and 120 m³). Heat flux towards the operator was also measured. Heat exposure presented a severe hazard to the operator during the pool fire suppression. Test results suggest that a self-contained breathing apparatus and heat-protective clothing should be used to protect the operator when fighting a pool fire.

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Key words: halon replacements / alternatives, streaming agents, portable extinguisher, fire testing, by-products, exposure risk.

1.0 INTRODUCTION

In response to the production ban on ozone-depleting halons by the Montreal Protocol, several halocarbon agents with a zero or reduced ozone depletion potential have been developed for streaming applications. These include HFC-227ea (1,1,1,2,3,3,3-heptafluoropropane, C_3HF_7 , FM-200), HFC-236fa (1,1,1,3,3,3-hexafluoropropane, $C_3H_2F_6$, FE-36), FC-5-1-14 (perfluorohexane, C_6F_{14} , CEA-614), FIC-1311 (trifluoroiodomethane, CF_3I , Triodide), HCFC-123 (2,2-dichloro-1,1,1-trifluoroethane, $C_2HCl_2F_3$, FE-232), HCFC-124 (2-chloro-1,1,1,2-tetrafluoroethane, C_2HClF_4 , FE-241), HCFC Blends B, C, D and E (Halotron I, NAF P-III, Blitz III and NAF P-IV).

Among these agents, FE-36 extinguishers, Halotron I extinguishers, FM-200 extinguishers and CF_3I extinguishers have become commercially available. The National Research Council of Canada (NRC) conducted a series of tests using the commercialized halocarbon extinguishers to evaluate the performance of these Halon 1211 substitutes. The potential levels of human exposure to the substitute agents, toxic by-products and heat during fire suppression were measured, in order to assess exposure risk to the operator of portable fire extinguishers and to other personnel.

2.0 TEST FACILITY AND DESCRIPTION

Streaming fire suppression tests were conducted in a 21000 m³ large burn hall (Series 1), a 120 m³ medium compartment (Series 2) and a 45 m³ small room (Series 3), respectively. The 45 m³ small room was connected to a corridor. Handheld FM-200, FE-36, CF₃I and Halotron I extinguishers were used in the fire tests. CO₂ and dry chemical extinguishers were also included in some tests for comparisons.

2.1 Extinguisher

Table 1 shows technical data of the commercial halocarbon extinguishers that were used in the fire tests, along with extinguishers of dry chemical (mono-ammonium phosphate-based) and carbon dioxide. The FE-36 extinguishers and Halotron I extinguishers have obtained the Underwriters Laboratories (UL) certification with ratings of 2B:C to 10B:C. The FM-200 extinguishers and CF₃I extinguishers do not have a UL rating yet. (At the present time, halocarbon extinguishers with a rating of higher than 10B:C are not available in the marketplace.) Figure 1 shows the cost of new extinguishers used in the fire tests. The weight and volume of the extinguishers tested are in the following decreasing order: CO₂ > FE-36 > FM-200 > Halotron I > CF₃I > Dry Chemicals. The chemical, physical, environmental and toxicological characteristics of these streaming agents are shown in Table 2.

2.2 Test Fire

Test fires were Class B heptane pool fires. Square pans were filled with heptane fuel as test fires. The pan sizes used in the NRC tests are 0.372, 0.836 and 1.486 m², which are 80, 72 and 64% of the pans used in the UL listing tests for the 2B, 5B and 10B extinguishers, respectively. The heat release rates of the 0.372, 0.836 and 1.486 m² pan fires were measured as 300, 900, 2000 kW, respectively. The 0.836 m² pan was replaced by a 0.580 m² pan (550 kW heat release rate) in the small enclosure, which is 50% of the pan used in the UL listing tests for the 5B extinguishers. Although these pans were smaller than the ones used by expert firefighters in the UL listing, these pans were larger than the ones intended for non-expert users.

2.3 Test Scenario

Series 1 tests were conducted in the large burn hall. The extinguishers with 2.61 kg FM-200, 2.0 kg CF₃I, 2.72 kg FE-36, 2.27 kg Halotron I, 2.27 kg CO₂ and 1.25 kg dry chemicals were used to suppress the 0.836 m² pan fire (2.5 L heptane), which is referred to as Series 1-1 hereafter. The extinguishers with 4.88 kg FM-200, 4.54 kg FE-36, 4.99 kg Halotron I, 4.54 kg CO₂ and 2.27 kg dry chemicals were used to suppress the 1.486 m² pan fire (4.5 L heptane), which is referred to as Series 1-2 hereafter.

Series 2 tests were conducted in the 120 m³ compartment. The extinguishers with 1.25 kg FM-200, 1.13 kg Halotron I and 1.0 kg CF₃I were used to extinguish the 0.372 m² pan fire (0.8 L heptane), which is referred to as Series 2-1 hereafter. The extinguishers with 2.61 kg FM-200, 2.16 kg FE-36, 2.27 kg Halotron I, 2.27 kg CO₂ and 1.25 kg dry chemicals were used to extinguish the 0.836 m² pan fire (1.8 L heptane), which is referred to as Series 2-2 hereafter.

Series 3 tests were conducted in the 45 m³ small compartment, which was connected to a 75 m³ corridor. The extinguishers with 1.25 kg FM-200, 1.13 kg Halotron I and 1.0 kg CF₃I were used to extinguish the 0.372 m² pan fire (0.8 L heptane), which is referred to as Series 3-1 hereafter. The extinguishers with 2.16 and 2.72 kg FE-36, 2.27 kg Halotron I, 2.27 kg CO₂ and 1.25 kg dry chemicals were used to extinguish the 0.580 m² pan fire (1.4 L heptane), which is referred to as Series 3-2 hereafter.

2.4 Test Set-up and Instrumentation

Figure 2 shows a common test set-up used in all tests. A thermocouple (TC) tree was placed over the square pan to measure the flame temperatures, with six thermocouples vertically distributed at 2.84, 2.28, 1.72, 1.17, 0.60 and 0.20 m above the floor. A cross averaging tube (with 20 small holes, 1.1 mm in diameter) was placed beside the pan as a gas sampling probe, which was connected through a heated line to gas analyzers to measure gas products at the fire source.

NRC staff had practised firefighting techniques using the extinguishers before the tests and represented average extinguisher users. To prevent exposure to excessive heat and gas by-products, the extinguisher operator wore an aluminum heat protective suit with self-contained breathing apparatus during all tests. The test fires were allowed 20 s preburn. The operator started to spray the agent towards the front edge of the fire pan, standing at a distance of 2.4 m from the fire in the burn hall tests or 2.9 m from the fire in the compartment tests. The operator stopped discharging the extinguisher as soon as the fire was extinguished.

To simulate operator exposure to the suppression agents and by-products produced during fire suppression, a dedicated gas sampling probe was positioned close to where the operator stood during firefighting. This probe was positioned at 1.5 m height, approximately the operator's nose height. It was connected to an FTIR spectrometer through a gas sampling line. The FTIR spectrometer measured the gas samples that flowed through a cylindrical gas cell (10 cm pathlength, 32 mm aperture, 110 mL volume) at a flow rate of 8 L/min. The spectrometer scanned the gas samples in the frequency range of 400 to 4500 cm^{-1} at 1 cm^{-1} resolution.

A heat flux meter (air-cooled, 20 kW/m^2) was also placed beside the operator at 1.2 m height to simulate operator heat exposure.

A second FTIR spectrometer was used to measure the agents and gaseous by-products in other areas. During the large burn hall tests (Series 1), the second

spectrometer was used to measure the gas samples from the cross averaging tube near the fire source. During the tests in the 120 m³ compartment (Series 2), an *in situ* FTIR measurement was conducted through a corner of the compartment. The spectrometer and reflecting mirrors were placed outside the compartment. The infrared light from the spectrometer passed the corner of the compartment through holes on the walls. The mirrors reflected the light through the compartment back to the detector of the spectrometer. The optical pathlength inside the compartment was 7.65 m. During the tests in the 45 m³ compartment (Series 3), the spectrometer was used to measure the gas samples in the corridor area. Gas samples were drawn from the three gas sampling ports that were placed in the corridor area (mounted at 1.5 m above the floor). The entire sampling lines were heated to reduce the condensation of sample gases. A solenoid valve-switching device was used to connect the FTIR spectrometer to the gas sampling lines in sequence. The gas samples from the three locations in the corridor area were alternately forwarded to the FTIR spectrometer for measurement. (A CO/CO₂ gas analyzer was also used to monitor the CO and CO₂ concentration in the corridor area and the CO/CO₂ gas probe was placed in the corridor area at nose height.)

For the tests conducted in the 45 and 120 m³ compartments, pressure taps and additional thermocouple trees were used to monitor the pressure and temperature in the compartments. Each TC tree was 2.8 m high and contained six thermocouples. In the 120 m³ compartment (Series 2), three TC trees were used; nine pressure taps were installed on the same wall at three elevations (0.29, 1.47 and 2.67 m) and connected to pressure gauges; the compartment door was kept open during each test. During the tests in the 45 m³ room (Series 3), one pressure tap (at the 1.5 m height on one wall)

was used in the small room and nine pressure taps were used in the corridor area (at three elevations of 0.29, 1.47 and 2.67 m). Three TC trees were placed in the corridor area to monitor the temperature. Fan pressurization tests indicated that the small room had an equivalent leakage area of 0.09 m². The door of the small room was kept open during preburn and firefighting; the door was closed after the operator left the room. The corridor had a door to the outside, which was kept open during each test.

3.0 RESULTS AND DISCUSSION

Tables 3 to 8 summarize the test results. In some tests, there was a considerable quantity of the agents remained in the extinguishers after fire extinguishment and the tables show the actual quantity discharged. In the tests with unsuccessful extinguishment, the extinguishers were fully discharged and the tables show the discharge times.

3.1 Extinguisher Performance

Fire extinguishing performance of handheld extinguishers depends heavily on the operator's technique. In a real fire incident, the person who will use a handheld extinguisher is most likely not an expert operator. NRC's staff who operated the extinguishers in these tests was certainly not an expert operator but an average

extinguisher user. The extinguisher performance discussed here is in the context of the average extinguisher user, which represents a real world situation.

The results from the CO₂ and dry chemicals tests are used as a basis for comparison. For both CO₂ and dry chemicals, the 5B extinguishers extinguished the 550 and 900 kW pan fires while the 10B extinguishers failed to extinguish the 2000 kW pan fire.

In fact, the 2000 kW pan fire was not extinguished by any 10B extinguishers (or equivalent) used in Series 1-2. The fire fighting challenge increased with fire size. Fire extinguishment depended more on the operator's technique (such as attack angle and sweeping motion) when the fire size was large. Except for the CO₂ extinguishers, the extinguishers used in the tests produced very narrow agent spray, which also made it difficult to extinguish the larger test fires.

Only Halotron I matched the performance of CO₂ and dry chemicals, successfully extinguishing the 550 and 900 kW pan fires using the 5B extinguishers. The 2B Halotron I extinguisher also successfully extinguished the 300 kW pan fire in 4 s with 0.8 kg agent discharged (approximately 2/3 of the agent in the extinguisher) when the extinguisher was stored at the room temperature (20°C) before the test.

Halotron I has a relatively high boiling point (27°C) and the extinguisher storage temperature can affect the performance of the agent. To study this effect, the 2B Halotron extinguishers were stored at 10 and 0°C, respectively, before the fire tests and

were used to suppress the same 300 kW fire. When started to spray, the operator felt that the pressure kick was weak and the spray was not as strong as that from the extinguisher stored at 20°C. The fire was not extinguished in these tests since the agent spray lost dynamic forces required for fire extinguishment. Low storage temperature can result in drastic decrease of the extinguisher's internal pressure during spray, especially for small extinguishers.

The TR-1A CF₃I extinguisher (charged with 1 kg CF₃I) repeatedly extinguished the 300 kW fire in 3-5 s with less than 0.6 kg CF₃I discharged. The TR-2A CF₃I extinguisher (charged with 2 kg CF₃I), however, failed to extinguish the 900 kW fire. Purple clouds were observed during the CF₃I tests.

The 5B FE-36 extinguishers also had trouble in extinguishing the 900 kW fire. Only when the fire size was reduced to 550 kW, the 5B FE-36 extinguishers then extinguished the fire.

The FM-200 extinguishers (C-20, C-50 and C-100) failed to extinguish all the respective fires (300, 900 and 2000 kW). The only successful extinguishment was when two C-20 extinguishers were sequentially used to suppress the 300 kW fire — after one FM-200 extinguisher was fully discharged, the operator grabbed and discharged the second extinguisher, putting the fire out.

In all tests with unsuccessful extinguishment, most parts of the fuel surface were clear of the flame after the initial fireball moved away; only the edges of the pan still had

small flames during the extinguisher spray. However, the whole fuel surface re-ignited after the extinguishers were fully discharged.

The test results showed that the Halotron I and CF_3I extinguishers performed better than the FE-36 and FM-200 extinguishers for the Class B test fires. Relative extinguishment effectiveness of the extinguishers in these tests is in the following increasing order: $\text{FM-200} < \text{FE-36} < \text{CF}_3\text{I} < \text{Halotron I}$.

3.2 Heat Exposure

Tables 3 to 8 also show the heat flux measured near the operator in each test. During the preburn, the heat flux was 1.3 kW/m^2 for the 300 kW fire, 3.0 kW/m^2 for the 550 kW fire, 3.5 kW/m^2 for the 900 kW fire, 6.0 kW/m^2 for the 2000 kW fire. During the preburn, except for the 300 kW fire, the heat flux the operator was exposed to was beyond the value that is bearable without the protective clothing.

Fire extinguishment by streaming agents was often achieved by separating the fire plume from the fuel surface. In every test, when the operator started to discharge the extinguisher, a large fireball was produced. Figure 3 shows the fireballs produced during the initial spray of the six different agents in Series 1-1. The size of the fireball was proportional to the initial fire size.

As a result of the fireball, the heat flux to the operator was intensified to a peak value in each test, which was also proportional to the initial fire size. Figures 4 and 5 show typical heat flux profiles measured near the operator (Series 1-1 tests with both successful and unsuccessful fire extinguishment). Figure 6 shows the peak heat flux values for all tests. All peak heat flux values were much higher than the respective preburn values and exceeded the tenability limit of 2.5 kW/m^2 [1].

The fireballs induced by discharge of the four halocarbon agents produced much higher heat fluxes than that by the dry chemical discharge and, in some cases, than that by the CO_2 discharge. The fireballs induced by FM-200 discharge always gave the highest heat flux.

The fireball formed during suppression presents a severe heat exposure hazard to the operator. This heat exposure hazard was more severe in confined spaces than in an open space or a large enclosure. For the 900 kW fire tests, room temperatures measured near the operator indicated that the operator was facing 120 to 200°C temperatures, except for the tests with dry chemicals. The peak heat flux towards the operator was up to 17 kW/m^2 for FM-200, 15 kW/m^2 for FE-36, 11 kW/m^2 for Halotron I and 10 kW/m^2 for CF_3I during initial spray, largely exceeding the tenability limit. It would put an operator's life at risk to fight the fire without protective clothing.

3.3 Gas Exposure

Figures 7 to 11 are FTIR spectra obtained during the fire suppression tests. The FTIR spectra of the gas samples taken near the fire show the "finger prints" of fuel vapour, water vapour, CO₂, CO, and the halocarbon agents, as well as HF, HCl and COF₂ from the agent decomposition. Figures 12 to 17 show the spectra from the *in situ* FTIR measurement in Series 2 tests, indicating clearly the gaseous by-products generated during suppression. HF was the major by-product produced during the FM-200, FE-36, Halotron I and CF₃I tests due to the interaction of the agents with flame.

The concentrations of the halocarbon agents, HF, CO and/or HCl presented in this paper were measured by the gas sampling FTIR method. The *in situ* FTIR measurement, which was only used in Series 2, gave similar results for HF, CO and HCl concentrations.

3.3.1 Exposure to Agent

The "no observed adverse effect level" (NOAEL) is a measure of cardiotoxicity for a halocarbon agent. Exposure to an agent above its NOAEL value may lead to cardiac sensitization. The NOAEL values are 10.0% for FE-36, 9.0% for FM-200, 1.0% for Halotron I and 0.2% for CF₃I (see Table 2). Human exposure to CO₂ below 5% is tolerable, above which would endanger health and life [1, 2].

Figures 7 to 11 also show the FTIR spectra of the gas samples taken in the operator breathing zone in Series 1-1. There is no obvious sign of the presence of the

halocarbon agents in the operator breathing zone during suppression. Similarly in Series 1-2, no halocarbon agents were detected in the operator breathing zone.

Tables 5 to 8 show the maximum concentrations of the agents in the operator breathing zone in Series 2 and 3, which were determined using the FTIR measurement. The maximum concentrations of FM-200, FE-36, Halotron I and CF_3I in the operator breathing zone were all below their NOAEL values, respectively. The maximum CO_2 concentrations in the operator breathing zone were also well below the dangerous level. In Series 3, the agent concentrations in the corridor were even lower than those in the operator breathing zone. The agent concentrations were below the levels that would pose life or health risks to the operator and other personnel in all test scenarios.

3.3.2 Exposure to By-Products

Hydrogen fluoride produced during the fire tests can cause sensory and pulmonary irritation, depending on its concentration, exposure duration and the health of individuals. The "Emergency Response Planning Guideline-3" (ERPG-3) value, established by the American Industrial Hygiene Association, is relevant for firefighting emergency situations. The 10 min ERPG-3 value for HF is 170 ppm, which is the maximum non-lethal concentration for a healthy individual [3]. At the 200 ppm HF concentration, a 5 min exposure may result in irreversible damage to health [3]. For CO, the permissible exposure limit is 200 ppm and the level that is immediately dangerous to life or health is 1500 ppm [2].

In the fairly large open space of the burn hall, there was no obvious sign of the presence of HF, HCl or COF₂ in the operator breathing zone during suppression, as shown in Figures 7 to 11. The only outstanding species were CO₂ and water vapour. Series 1 results indicate little risk of exposure to these gaseous by-products for the operator.

Series 2 and 3 were conducted in smaller confined spaces. Except for the tests in Series 2-1 with successful extinguishment, the four halocarbon agents generated HF in the order of 10³ ppm concentrations in the operator breathing zone. Halotron I also generated HCl in the 10³ ppm concentration range in the operator breathing zone. This presented a severe life hazard if inhaled. The concentrations of the by-products depended on the sizes of the fire and room and on whether the fire was extinguished. The HF concentration was higher when the fire was not extinguished. The HF (or HCl) concentration increased with the ratio of the fire size to compartment volume. Series 3 represents the worst case scenarios for potential gas exposure in all tests. Figure 18 shows the HF concentration profile inside the small 45 m³ compartment during the FE-36 test; after the initial peak during firefighting, the HF concentration stayed above 2000 ppm for more than 10 minutes (the door was closed after extinguishment).

The potential exposure to the acid by-products was tolerable in the large burn hall tests. In Series 2 and 3, this exposure risk to the operator became a serious concern, as the confined spaces were smaller. Figure 19 shows the peak HF concentrations in the operator breathing zone, which are in the following order:

FM-200 $\approx$ FE-36 > Halotron I > CF₃I. Except for one Halotron I test in Series 3-2, the peak CO concentrations in the operator breathing zone were all below the level that is immediately dangerous to life or health.

In the corridor area, peak HF (or HCl) concentrations occurred near the door of the small room during firefighting (the door was open during firefighting). The peak HF (or HCl) concentrations in the corridor were below 100 ppm during the Halotron I and CF₃I tests, and below 200 ppm during the FE-36 tests. The corridor conditions were tenable for evacuation purpose. Closing the door prevented excess heat and toxic gases moving from the fire origin to the corridor area. During the FM-200 tests, however, the peak HF concentrations were 450 to 1100 ppm in the corridor, since more HF was produced inside the small room than in the other tests. Figure 20 shows the HF concentration profile in the corridor during the test where two FM-200 extinguishers were used, which represented the worst case in all Series 3 tests. After the fire was extinguished and the small room door was closed, the HF concentration in the corridor decayed from the peak to below 200 ppm within 60 s. Although the HF concentration decayed quickly, exposure risk would be a concern. The gas analyzer readings showed less than 0.75% CO₂ and 100 ppm CO in the corridor area in all tests.

The corrugated steel panels inside the test compartments became rusty because of exposure to the acid gas products (HF, COF₂ and HCl). Part of the aluminum coating on the protective clothing was lost due to the acid gas exposure. The acid gas products corroded the reflecting mirrors located outside the compartment, which were used in the *in situ* FTIR measurement in Series 2. The silver coating of the mirrors was ripped off by

the acid gas effluent through the holes on the wall of the compartment that allowed the passage of the infrared light. Potential corrosion damage to sensitive equipment is also a concern for real application.

4.0 CONCLUSIONS

The test results show that potential exposure by the operator to the suppression agents is tolerable and that the agents themselves do not pose life or health risk to the operator and other personnel.

Potential exposure to the acid by-products is tolerable in the open space. In small confined spaces, however, the concentrations of the acid gas by-products (HF and/or HCl) were at very high levels during the halocarbon extinguisher tests. Operator exposure to these gaseous by-products is a serious concern and a self-contained breathing apparatus must be used to protect the operator during firefighting. After firefighting, closing the door prevented excess heat and toxic gases from moving from the fire origin to the corridor area, which could enable corridor conditions to remain tenable for evacuation purposes in a real fire.

The acid gas by-products are corrosive. The test compartment and some equipment used in the tests showed significant signs of corrosion damage. In applications of halocarbon streaming agents, measures should be taken to prevent potential corrosion to sensitive equipment.

Heat exposure presents the most severe hazard to the operator in all test scenarios. A fireball was always induced during suppression and presented a heat exposure hazard to the operator. This hazard became much more severe in small confined spaces than in an open space or a large enclosure. The operator must wear heat-protective clothing before engaging in firefighting.

The test results have also demonstrated that the Halotron I and CF_3I extinguishers are better performers than the FE-36 and FM-200 extinguishers in fire extinguishment. Halotron I has a relatively high boiling point (27°C) and its extinguishers should be stored at room temperatures to ensure good fire suppression performance.

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NOMENCLATURE

ALT	atmospheric lifetime in years
CB	agent concentration by volume for extinguishing the cup burner heptane flame
$C_{p,g, 25^{\circ}\text{C}}$	heat capacity of an agent at the gaseous state in J/(mol K) at 25°C
ERPG-3	Emergency Response Planning Guideline-3
FC	perfluorocarbon
FIC	fluoroiodocarbon
FTIR	Fourier transform infrared
GWP	global warming potential relative to carbon dioxide (CO ₂)
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
$\Delta H_{\text{vap}, T_b}$	molar heat of vaporization in kJ/mol at the normal boiling point T_b
LC ₅₀	lethal concentration fifty for acute toxicity (agent concentration by volume)
LOAEL	lowest observed adverse effect level for cardiac sensitization (agent concentration by volume)
MW	molecular weight in g/mol
NOAEL	no observed adverse effect level for cardiac sensitization (agent concentration by volume)
ODP	ozone depletion potential relative to CFC-11 (CCl ₃ F)
ppm	parts per million (by volume)
$P_{V, 25^{\circ}\text{C}}$	vapour pressure in kPa at 25°C
$\rho_{L, 25^{\circ}\text{C}}$	density of a liquefied gas in kg/m ³ at 25°C
T_{boiling}	normal boiling point in °C at a pressure of 101.325 kPa
T_{melting}	melting point in °C

TC thermocouple

UL / ULC Underwriters Laboratories / Underwriters Laboratories of Canada

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TABLE 1
Extinguishers Used in NRC Fire Tests

Manufacturer	Agent	Capacity (kg lb)		UL Rating	Pressure (kPa psi)		Model
Amerex	Halotron I	1.13	2.5	2B:C	690	100	A385TS
		2.27	5	5B:C	690	100	A386T
		4.99	11	1A10B:C	863	125	387 ^A
Orion Safety Industries	CF ₃ I	1	2.2	No	690	100	TR-1A
		2	4.4	No	1345	195	TR-2A ^A
MetalCraft	FM-200	1.25	2.75	No	2482	360	C-20 ^A
		2.61	5.75	No	2482	360	C-50 ^A
		4.88	10.75	No	2482	360	C-100 ^A
Ansul	FE-36	2.16	4.75	5B:C ^B	517	75	CA-0581 ^A
		2.72	6.0	5B:C	517	75	CA-0681 ^A
		4.54	10	1A10B:C ^B	517	75	CA-1081 ^A
Ansul	Dry Chemicals	1.25	2.75	1A5B:C ^B	1345	195	SY-0216
		2.27	5.0	3A10B:C ^B	1345	195	SY-0517 ^A
Ansul	CO ₂	2.27	5.0	5B:C ^B			SY-0572 ^A
		4.54	10	10B:C ^B			SY1072 ^A

^A with hose

^B ULC rating

TABLE 2
Chemical, Physical, Environmental and Toxicological Characteristics of Tested Streaming Substitutes

Agent	HFC-227ea	HFC-236fa	FIC-1311	HCFC Blend B (primarily HCFC-123)	Carbon Dioxide	Dry Chemicals
Formula	C ₃ HF ₇	C ₃ H ₂ F ₆	CF ₃ I	primarily C ₂ HCl ₂ F ₃	CO ₂	NH ₄ H ₂ PO ₄ Based
Chemical Name	1,1,1,2,3,3,3-heptafluoropropane	1,1,1,3,3,3-hexafluoropropane	Trifluoroiodomethane	primarily 2,2-dichloro-1,1,1-trifluoroethane	Carbon Dioxide	Mono-ammonium Phosphate Based
Trade Name	FM-200	FE-36	Triodide	Halotron I	Carbon Dioxide	FORAY
MW (g/mol)	170.0	152.0	195.9	150.7	44.01	115
T _{melting} (°C)	-131			-107	-56.57	190
T _{boiling} (°C)	-16.4	-1.5	-22.5	27		
ρ _{L, 25°C} (kg/m ³)	1395	1356	2064	1480	720 ^A	
P _{V, 25°C} (MPa)	0.458	0.275	0.54	0.077 ^B	6.08 ^A	
C _{p,g, 25°C} (J/mol/K)	137.4	121.6	70.9		37.1	
ΔH _{vap, Tb} (kJ/mol)	22.3	22.8	20.8	26.3	15.3	
CB (%)	5.8-6.6	5.3-6.5	3.0-3.2	6-7	20.4-28	
ODP (CFC-11=1)	0.0	0.0	0.0001	0.014	0	0
GWP _{100yr} (CO ₂ =1)	2900	6300	< 1	90	1	0
ALT (year)	36.5	209	< 0.005	3.5-11	120	0
NOAEL (%)	9.0	10.0	0.2	1.0	n/a	n/a
LOAEL (%)	10.5	15.0	0.4	2.0	n/a	n/a
LC ₅₀ (%)	80 ^C	13.5 ^C	27.4 ^D	> 3 ^C	65.8 ^D	

^A under saturated pressure at 22°C

^B at 20°C

^C 4-hour LC₅₀

^D 15-min LC₅₀

n/a: not applicable

TABLE 3
CO₂ Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)	
					preburn	peak
3-2	550	SY-0572	1.22 kg	8	3.0	9.5
2-2	900	SY-0572	1.48 kg	10	3.5	11.5
1-1	900	SY-0572	fully	16	3.5	9.5
1-1	900	SY-0572	fully	20	3.5	11.8
1-2	2000	SY-1072	fully in 18 s	no ext.	6.0	16.9
1-2	2000	SY-1072	fully in 20 s	no ext.	6.0	15.4
1-2	2000	SY-1072	fully in 19 s	no ext.	6.0	15.3

no ext.: no extinguishment

TABLE 4
Dry Chemicals Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)	
					preburn	peak
3-2	550	SY-0216	0.780 kg	6	3.0	7.6
2-2	900	SY-0216	0.848 kg	6	3.5	6.3
2-2	900	SY-0216	0.635 kg	5	3.5	7.2
1-1	900	SY-0216	fully	11	3.5	5.6
1-2	2000	SY-0517	fully in 25 s	no ext.	6.0	17.2
1-2	2000	SY-0517	fully in 25 s	no ext.	6.0	10.8

no ext.: no extinguishment

TABLE 5
FE-36 Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)		Peak Concentration in					
							Operator Breathing Zone				Corridor	
					preburn	peak	Agent (%)	HF (ppm)	HCl (ppm)	CO (ppm)	Agent (%)	HF (ppm)
3-2	550	CA-0681	1.82 kg	8	3.0	13.1	0.4	9000	nil	750	0.05	<200
3-2	550	CA-0581	fully	11	3.0	9.7	0.7	8000	nil	600	0.07	<200
2-2	900	CA-0581	fully in 14 s	no ext.	3.5	14.2	0.25	6500	nil	500	n/a	n/a
2-2	900	CA-0581	fully in 12 s	no ext.	3.5	14.9	0.31	6000	nil	400	n/a	n/a
1-1	900	CA-0681	fully in 18 s	no ext.	3.5	11.2	-	-	nil	-	n/a	n/a
1-1	900	CA-0681	fully in 20 s	no ext.	3.5	11.8	-	-	nil	-	n/a	n/a
1-2	2000	CA-1081	fully in 15 s	no ext.	6.0	23.0	-	-	nil	-	n/a	n/a
1-2	2000	CA-1081	fully in 17 s	no ext.	6.0	15.1	-	-	nil	-	n/a	n/a

-: below FTIR sensitivity

n/a: not applicable

no ext.: no extinguishment

TABLE 6
FM-200 Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)		Peak Concentration in					
							Operator Breathing Zone				Corridor	
					preburn	peak	Agent (%)	HF (ppm)	HCl (ppm)	CO (ppm)	Agent (%)	HF (ppm)
3-1	300	C-20	fully in 12 s	no ext.	1.3	3.8	0.17	5000	nil	400	.03	450
3-1	300	C-20	1.1+.97 kg ^A	20	1.3	5.6	0.45	7000	nil	400	.10	1100
2-1	300	C-20	fully in 13 s	no ext.	1.3	4.2	0.14	2500	nil	150	n/a	n/a
2-1	300	C-20	fully in 14 s	no ext.	1.3	6.6	0.13	3000	nil	200	n/a	n/a
2-2	900	C-50	fully in 10 s	no ext.	3.5	13.8	0.35	6000	nil	700	n/a	n/a
2-2	900	C-50	fully in 11 s	no ext.	3.5	16.9	0.26	6500	nil	600	n/a	n/a
1-1	900	C-50	fully in 15 s	no ext.	3.5	15.8	-	-	nil	-	n/a	n/a
1-1	900	C-50	fully in 16 s	no ext.	3.5	15.2	-	-	nil	-	n/a	n/a
1-2	2000	C-100	fully in 17 s	no ext.	6.0	23.0	-	-	nil	-	n/a	n/a
1-2	2000	C-100	fully in 14 s	no ext.	6.0	22.3	-	-	nil	-	n/a	n/a

^A Two C-20 extinguishers were used consecutively to extinguish the fire; the first extinguisher was fully discharged in 9 s and the second extinguisher was partially discharged in 8 s.

-: below FTIR sensitivity

n/a: not applicable

no ext.: no extinguishment

TABLE 7
Halotron I Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)		Peak Concentration in					
							Operator Breathing Zone				Corridor	
					preburn	peak	Agent (%)	HF (ppm)	HCl (ppm)	CO (ppm)	Agent (%)	HF (ppm)
2-1	300	A385TS	0.798 kg	4	1.3	4.5	0.14	300	500	200	n/a	n/a
2-1	300	A385TS	fully in 10 s	no ext. ^A	1.3	4.5	0.28	1000	1000	100	n/a	n/a
3-1	300	A385TS	fully in 16 s	no ext. ^B	1.3	3.8	0.20	3000	1700	700	.05	<100
3-1	300	A385TS	fully in 15 s	no ext. ^B	1.3	3.0	0.20	3500	2000	800	.03	<100
3-2	550	A386T	1.81 kg	8	3.0	11.2	0.46	4500	3200	1200	.03	<100
3-2	550	A386T	2.07 kg	7	3.0	10.0	0.77	6000	4200	2000	.03	<100
2-2	900	A386T	2.06 kg	10	3.5	11.4	0.70	3000	2500	500	n/a	n/a
2-2	900	A386T	1.97 kg	8	3.5	8.0	0.60	2000	2000	500	n/a	n/a
1-1	900	A386T	fully	10	3.5	10.2	-	-	-	-	n/a	n/a
1-1	900	A386T	fully	9	3.5	9.7	-	-	-	-	n/a	n/a
1-2	2000	387	fully in 16 s	no ext.	6.0	19.0	-	-	-	-	n/a	n/a
1-2	2000	387	fully in 20 s	no ext.	6.0	23.0	-	-	-	-	n/a	n/a

^A This extinguisher stored at about 10 °C

^B This extinguisher stored at 0 °C; other extinguishers stored at the room temperature.

-: below FTIR sensitivity

n/a: not applicable

no ext.: no extinguishment

TABLE 8
CF₃I Test Results

Series	Fire Size (kW)	Extinguisher Model	Agent Discharged	Ext. Time (s)	Heat Flux (kW/m ²)		Peak Concentration in					
							Operator Breathing Zone				Corridor	
					preburn	peak	Agent (%)	HF (ppm)	HCl (ppm)	CO (ppm)	Agent (%)	HF (ppm)
3-1	300	TR-1A	0.572 kg	5	1.3	4.9	0.06	1200	nil	500	.01	<100
2-1	300	TR-1A	0.599 kg	3	1.3	4.2	0.16	200	nil	30	n/a	n/a
2-1	300	TR-1A	0.590 kg	3	1.3	3.2	0.14	100	nil	30	n/a	n/a
1-1	900	TR-2A	fully in 22 s	no ext.	3.5	10.4	-	-	nil	-	n/a	n/a

-: below FTIR sensitivity

n/a: not applicable

no ext.: no extinguishment

Figure Captions

Figure 1. Cost of new extinguisher

Figure 2. Common test set-up

Figure 3. Fireballs induced during firefighting (Series 1-1)

Figure 4. Heat flux near operator during successful extinguishment (Series 1-1)

Figure 5. Heat flux near operator during unsuccessful extinguishment (Series 1-1)

Figure 6. Peak heat flux in streaming fire tests

Figure 7. FTIR spectra of gas samples during the CO₂ test (Series 1-1)

Figure 8. FTIR spectra of gas samples during the FE-36 test (Series 1-1)

Figure 9. FTIR spectra of gas samples during the FM-200 test (Series 1-1)

Figure 10. FTIR spectra of gas samples during the Halotron I test (Series 1-1)

Figure 11. FTIR spectra of gas samples during the CF₃I test (Series 1-1)

Figure 12. Spectrum of *in situ* FTIR measurement during the CO₂ test (Series 2-1)

Figure 13. Spectrum of *in situ* FTIR measurement during the Halotron I test (Series 2-1)

Figure 14. Spectrum of *in situ* FTIR measurement during the FM-200 test (Series 2-1)

Figure 15. Spectrum of *in situ* FTIR measurement during the CF₃I test (Series 2-1)

Figure 16. Spectrum of *in situ* FTIR measurement during the FE-36 test (Series 2-2)

Figure 17. Spectrum of *in situ* FTIR measurement during the dry chemical test
(Series 2-2)

Figure 18. HF concentration inside the 45 m³ room during the FE-36 test (the worst case in all Series 3 tests)

Figure 19. Maximum HF concentration in operator breathing zone

Figure 20. HF concentration in corridor during the FM-200 test (the worst case in all Series 3 tests)