

EVALUATION AND TESTING OF CLEAN AGENTS FOR U.S. ARMY COMBAT VEHICLE PORTABLE FIRE EXTINGUISHERS

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INTRODUCTION

The Montreal Protocol on substances that deplete the ozone layer and the Clean Air Act of 1990 originally ceased the production of halons by the year 2000: The Copenhagen Amendments (Nov. 1992) accelerated the production phase-out to 1 January 1994. "DoD Directive 6059.9" directs DoD components to conduct R&D on replacement agents and to adopt suitable substitutes that are consistent with mission requirements. Therefore, substitutes for Halon 1301 used in ground vehicle, hand-held fire extinguishers needs to be evaluated and substitute agents found.

Thus, such a project has been initiated by the U.S. Army Tank Automotive and Armament Command (TACOM), Warren, MI. Initially, CO₂ was considered to replace the Halon 1301 portable extinguishers. However, exposure tests with CO₂ indicated that toxicity concerns would make it unsuitable for use in crew compartments. High CO₂ (exceeding threshold values) concentrations were measured inside various vehicles.

Under research sponsorship by the U.S. Air Force, Wright Laboratory, Tyndall Air Force Base, Florida, the New Mexico Engineering Research Institute (NMERI) at The University of New Mexico (UNM) has been identifying, developing, and testing "clean" streaming agents for use in flight-line fire extinguishers. This research has identified several candidate agents and has established several unique experimental test techniques with applicability for evaluating agents suitable for use in portable fire extinguishers. Testing has shown that although some compounds and blends were not very effective on large fires (150 ft) and in flight-line extinguishers (requiring long throw distances), they demonstrate effectiveness on small-scale (< 10ft²) fires such as those experienced within combat vehicles. A project has been initiated to investigate replacements for the combat vehicle applications. A list of acceptable agent criteria has been included in Table 1.

Based on the selection criteria, NMERI submitted a list of compounds and compound blends to the TACOM project officer (Table 2). These compounds/blends were used for field-scale screening (up to 12.5 ft² [UL-2B and 5B], JP-8/Jet A-1 [ASTM D1655] pool fires) using the NMERI constant flow extinguisher and existing U.S. Army 2.5-lb CO₂ portable extinguishers.

Temperature conditioning (140 and -50 °F) of the tested extinguishers was also performed. After optimum agent nozzles, flow rates, fill densities, etc., were determined, the optimized extinguishers were used to suppress pool fires while decomposition products (HF, COF₂, CO₂, CO) were monitored "real-time." The "real-time" decomposition product monitoring was performed using the NMERI Fast Fourier Transform Infrared (FTIR) spectrometer technique. The results of this project are test data and a report documenting several effective agent and hardware combinations suitable for use in combat vehicle applications.

The project was initiated in January 1997. Agent selection and workplan reports were completed in March 1997. The testing phase was accomplished during April and May 1997, including the decomposition product tests. The data analysis and final report will be completed by July 1997. This paper summarizes the results of this project.

REVIEW OF TESTS PERFORMED AT ABERDEEN TEST CENTER (ATC)

Prior to conducting tests at NMERI, data and video tapes of preliminary tests conducted at Aberdeen Test Center (ATC) were reviewed. There were a series of preliminary tests conducted at ATC which were performed at three temperatures: ambient (65 - 70 °F), 0 °F, and -50 °F. Elevated temperature (heated) extinguishers were not tested (Table 3). There are four columns summarizing the data, with the first three columns showing the lowest, highest, and average amounts required for extinguishment. The fourth column shows the percent of fires that were actually extinguished. The average extinguishing amounts are determined only from tests where extinguishment was achieved.

TABLE 1. LIST OF ACCEPTABLE AGENT CRITERIA.

Criteria	value
ODP	0.00
Atmospheric Lifetime	< 250 yrs
GWP (100-yr relative to CO ₂)	< 4wo
Availability	Being manufactured in bulk now or in the near future.
Effectiveness	WEq < 3.0
Boiling Point Range	-5 to 200 °C
Toxicity	LC ₅₀ > 5.0 vol. %, NOAEL > 8.0 vol. %
Operating Temperature Range	-25 °F to 140 °F
Retrofittability	The agent shall be retrofittable into the existing 2.5-lb CO ₂ hand-held fire extinguisher.
Cost	< \$50 per lb

TABLE 2. LIST OF COMPOUNDS AND BLENDS THAT WERE TESTED.

Halocarbon No.	HFC-227ea	HFC-236fa	None	^b Bromoalkane Blends
IUPAC Name	1,1,1,2,3,3,3-hepta-fluoropropane	1,1,1,3,3,3-hexa-fluoropropane	Hydrofluoropolyether	None
Formula	CF ₃ CHFCF ₃	CF ₃ CH ₂ CF ₃	CF ₂ H-O-(CF ₂ -CF ₂ -O) ₀₋₁₅ (CF ₂ -O) ₀₋₁₀ -CF ₃	various
Common/ Trade Names	FM-200	FE-36	HFPE	N/A
CAS Number	431-89-0	690-39-1	161075-02-1	N/A
Molecular Wt.	170.0	152.0	325	various
Atmospheric Lifetime, yrs	41	250	< 1	<250
100-yr GWP (Relative to CO ₂)	3300	8000	—	—
500-yr GWP (Relative to CO ₂)	1100	6600	—	—
LC ₅₀ or ALC, vol.%	80	18.9	32	—
NOAEL, vol.%	9	10	11.6	—
LOAEL, vol.%	10.5	15	—	—
Boiling Point, °C	-164	-14	-84	—
Liquid Density at 25 °C, g/mL	1.39	1.37	1.65	1.5
Vapor Pressure, bar at 25 °C	4.58	2.72	0.026	—
NMERI cup Burner, n-heptane, vol. %	6.3	5.6	5.1	-4.0 to -5.0
Weight Equivalent (WEq)	2.5	2.0	3.8	-2.0
Storage Volume Equiv. (SVEq)	2.8	2.2	3.6	-2.0

^aWEq and SVEq are relative to Halon 1301 n-heptane cup-burner extinguishment concentration.

^b1-Bromopropane and 1-bromobutane were tested with the HFC compounds and the HFPE compound shown in this table.

After reviewing the video from the ATC tests some important observations were made:

1) In many cases the technique was inappropriate for this type of fire and this class of agents. The replacement agents being tested are not as chemically active, and are, therefore, less forgiving than Halon 1301. Often the agent was applied without any sweeping motion and not applied to the leading edge of the tire. In several tests the agent was directed to the middle of the tire, providing little extinguishment effectiveness.

2) The angle at which the agent was directed toward the fire (“angle-of-attack”) was too low in many tests, and not directed toward the base of the flame. As a result, the agent was sprayed over the top of the fire and out of the pan, and was therefore, not fully utilized.

TABLE 3. SUMMARY OF ATC TESTS.

Agent	Low Extinguishment Quantity, lbs	High Extinguishment Quantity, lbs	Average Extinguishment Quantity, lbs	Percent Fires Extinguished
HFC-236fa (ambient)	18	3.4	26	90% (9 of 10)
HFC-236fa (0 °F)	None Extinguished	None Extinguished	None Extinguished	0% (0 of 3)
HFC-236fa (-50 °F)	None Extinguished	None Extinguished	None Extinguished	0% (0 of 3)
HFC-227ea (ambient)	1.7	3.5	2.4	91% (10 of 11)
HFC-227ea (0 °F)	None Extinguished	None Extinguished	None Extinguished	0% (0 of 3)
HFC-227ea (-50 °F)	2.5	2.5	2.5	33% (1 of 3)
Halon 1301 (ambient)	0.9	26	1.5	100% (6 of 6)
Halon 1301 (0 °F)	0.8	0.8	0.8	100% (1 of 1)
Halon 1301 (-50 °F)	N/A	N/A	N/A	Not Tested
CO ₂ (ambient)	0.6	22	1.3	55% (6 of 11)
CO ₂ (0 °F)	1.8	1.8	1.8	50% (1 of 2)
CO ₂ (-50 °F)	N/A	N/A	N/A	Not Tested

3) There were problems with the cold shots at -50 °F. Although there were technique problems, there also appeared to be problems with agent flow rates. Several discharge times exceeded 20 seconds, indicating a very low agent flow rate. The low agent flow rate can be attributed to one of three things: (a) The handle was not depressed fully (highly unlikely), (b) the stem and handle were worn out (possible contributor), (c) the fill densities were so high that the cold temperature significantly decreased the pressure within the extinguisher, accounting for the low flow rate (most likely).

NMERI FIELD TEST RESULTS

Tests were performed at the NMERI test site located in Albuquerque, NM, inside a protective wind break enclosure. Underwriter's Laboratories (UL) 2B and 5B pans were used (1-minute preburn). The UL-2B pan was used for the primary testing, and the 5B pan was used to test each of the agents to their fullest extent. The test fuel was Jet A-1 (ASTM D1655) (equivalent to JP-8) which was floated on 2 inches of water, leaving a freeboard of 4 inches.

The extinguishers tested as part of this program were the U.S. Army 2.5-lb CO₂ portable extinguishers (Figure 1). Initially, six extinguishers were sent to NMERI by ATC. The extinguishers were obtained from the U.S. Army stock system, were brand new, filled with CO₂, and had steel cylinders.



Figure 1 Typical 2.5-lb CO₂ extinguisher that was used during this test series. The CO₂ cone nozzle that in shown was used; however, the internal nozzle was replaced with a nozzle similar to that used with the existing Halon 1301 extinguishers used by the U.S. Army.

Extinguisher Nozzle Design

A critical element of the extinguisher is the nozzle. The nozzle affects two primary items: agent flow rate and pattern. An approach was used whereby existing Halon 1301 nozzles were used for the initial tests and modifications were made accordingly. The standard halon nozzle, having a hole diameter of 0.090 inches, was found to work very effectively with the gaseous agents [HFC-227ea (FM-200) and HFC-236fa (FE-36)]. A similar nozzle having a slightly larger hole (0.100 inches) was tried, but increased performance was not obtained. The standard halon nozzle proved to be the optimized nozzle for the gaseous agents. This nozzle did not, however, work effectively with the HFPE, which is a more liquid compound. It produced a tight pattern, caused fuel to blow out of the pan, and produced flow rates that were too high. Therefore, nozzle design parameters were developed to predict flow rates and create an optimized spray pattern for the HFPE compound. It was necessary to design a nozzle capable of achieving an appropriate flow rate. At the same time the nozzle needed to produce a pattern similar to the gaseous agent patterns, with larger droplets. The compound was found to be completely ineffective when applied with a misting type nozzle, even though the nozzle produced a good pattern. With the basic criteria in mind, a set of nozzle design equations were developed.

From the equation for nozzle flow we find

$$Q = CA \sqrt{\frac{2P}{\rho}} \quad \text{DI}$$

$$C = 0.61 \text{ [nozzle coefficient from Figure 2]}$$

$$A = 0.035 \text{ cm}^2 \text{ [nozzle orifice area]}$$

$$P = 2.76 \times 10^6 \text{ dynes/cm}^2 \text{ [atmospheric pressure} = 1.013 \times 10^6 \text{ dynes/cm}^2\text{]}$$

$$\rho = 1.3 \text{ g/cm}^3 \text{ [agent density]}$$

Thus:

$$Q = 146 \text{ cm}^3/\text{sec} = 190 \text{ g/sec} = 0.42 \text{ lbs/sec} \quad [2]$$

Therefore, a 4 lb charge should be discharged in approximately 9.6 seconds for an operating pressure of 400 lbs/in². Increasing the pressure to 600 lbs/in² will increase the flow rate by a factor of $\sqrt{600/400} = 1.23$; i.e., to about 0.52 lbs/sec and the 4 lb charge will be discharged in about 7.7 seconds. On the other hand, a minor modification of the nozzle shape can change the flow rate by a factor of $0.92/0.63 = 1.46$ via its effect on the discharge coefficient. The only modification required is to produce a rounded shape onto the inside edge of the nozzle orifice.

The shape of the ejected material jet can be controlled or modified by converting the nozzle into a short channel instead of employing the simple orifice-in-a-wall configuration. For example, the use of a short tube (length on the order of 3 times the diameter) will produce a much more highly directed stream of fluid while only reducing the rounded orifice discharge coefficient from 0.98 to 0.92. The trade off is that the "footprint" of the ejected fluid at the target is significantly reduced even as the range of delivery is increased.

Based upon the nozzle equations discussed in this section, a series of nozzle design (evaluation) plots were developed. For the purposes of this study, the effects of nozzle design on extinguisher discharge can be noted to have the following properties:

(1) The discharge rate depends on the square root of driving pressure. Thus, doubling the driving pressure will produce a $\sqrt{2} = 1.4$ fold increase in flow rate for a given nozzle.

(2) For simple nozzles, the discharge coefficient can vary, at a given value of Reynolds number, from a value of about 0.50 to 0.98 by simple variations of nozzle configuration for a given nozzle cross-sectional area. Thus, the flow rate can be most easily modified by changing the nozzle configuration.

(3) The nozzle outflow pattern is most readily modified by changing the nozzle shape over a short distance from the nozzle orifice or point of constriction:





ORIFICES AND THEIR NORMAL COEFFICIENTS				
	SHARP EDGED	ROUNDED	SHORTTUEE	EORDA
				
C	0.61	0.98	0.80	0.51
C _ε	0.62	1.00	1.00	0.52
C _η	0.98	0.98	0.80	0.98

Figure 2. Discharge coefficients for several typical orifice configurations.

(a) An outward bell shaped nozzle produces a dispersed spray-like pattern which has a large area coverage but which will not project the jet at large distances from the nozzle. The discharge coefficient of such a nozzle approaches 1.0.

(b) A uniform tubular shape of the nozzle area over a dimension of several times the flow channel diameter will produce a strong jet which initially has the tubular shape of the nozzle area and which will project to much larger distances than the spray like pattern described above. The discharge coefficient of such a nozzle configuration usually approaches 0.80 - 0.85.

(c) A nozzle having a gradual constriction of the nozzle toward its discharge end, particularly if an additional inner element is employed to produce two distinctly separate regions of flow across the nozzle area, will produce the longest jet throw distance. This is due to the formation of an inwardly directed sheath surrounding a slower moving core. Again, the real coverage of such a jet is smaller than either of the above configurations, and the nozzle constriction further reduces the flow by real considerations. The discharge coefficient of such a nozzle, aside from real considerations, approaches 0.5 - 0.6.

Liquid Fill Densities

The liquid fill density of an extinguisher is the percent volume occupied by the extinguishing agent in the liquid form. The volume of the extinguisher cylinder was determined to be 1.70 L. Extinguisher fill weights and associated fill densities are shown in Table 4.

The importance of fill density cannot be overemphasized. Fill densities which are too high cause serious problems. High fill densities cause flow rate problems, particularly towards the end of the discharge. High fill densities leave less room for the nitrogen pressure charge. As a result, the pressure drops off quicker during the agent discharge resulting in a rapid decrease in agent flow rate. This problem is amplified when the extinguishers are cooled since cooling a pressurized extinguisher can reduce the internal pressure as much as 200 lbs/in².

Another problem occurs when the extinguisher is heated. At elevated temperatures the internal pressure is very sensitive to temperature increases. For example, the internal pressure within an extinguisher having a fill density of 75% and initially charged with 600 lbs/in² will increase to 1000 lbs/in² when heated to 140 °F. If the extinguisher has a fill density of 80%, the pressure would increase to 1,500 lbs/in² when heated to 140 °F. For example, going from a fill density of 75 to 80% for HFC-236fa would result in the addition of 0.25 lbs of agent, or roughly 6.5% more agent. The small percentage of agent gain results in a significant pressure increase upon heating. The agent flow rate will also diminish as the agent is being expelled. The pressure temperature relationships are dependent upon the initial charge pressure of the extinguisher and the agent.

TABLE 4. FILL DENSITY AND WEIGHT RELATIONSHIPS FOR THE TESTED AGENTS AND THE 2.5-LB CO₂ EXTINGUISHER.

Extinguisher Fill Density, %	HFC-236fa		HFC-227ea		HFPE	
	Agent Wt., lbs	Fill Density, lbs/ft ³	Agent Wt., lbs	Fill Density, lbs/ft ³	Agent Wt., lbs	Fill Density, lbs/ft ³
50	2.57	42.8	2.61	43.4	3.10	51.5
60	3.09	51.3	3.13	52.1	3.72	61.8
m	3.60	58.9	3.65	60.8	4.34	72.1
80	4.12	68.4	4.18	69.4	4.96	82.4
90	4.63	77.0	4.m	78.1	5.58	92.7
100	5.15	85.5	5.22	86.8	6.20	103



Figure 3. Firefighter finishing attacking the fire. Note, as shown it is important to hold the extinguisher in an upright position, maintain a steep “angle-of-attack,” keep the agent directed at the base of the fire (“at the leading edge”), and allow the agent concentration to build up over the fuel surface, while using a side-to-side sweeping motion.

The agents that appeared to be most effective were HFC-227ea, HFC-236fa, and blends of these two agents with 1-bromopropane. The other compound, HFPE, should not be ruled out since it has the advantage of being less volatile, thereby, releasing less of the compound in the vapor phase which would reduce the quantity breathed should the compound be discharged into a confined space, such as an occupied crew compartment. The compound may also be more effective on Class A fires since it is more liquid and may have more of an ability to penetrate the fire. It also has a very short atmospheric lifetime and low GWP compared to the other compounds. When blended with 1-bromopropane, the performance of the tested compounds, including HFPE, was enhanced approximately 30%, as observed in previous testing at NMERI.

NMERI DECOMPOSITION TESTING

Adding the tested halocarbon fire extinguishing agents during the fire suppression event increases the amount and types of combustion products. The resulting species generated are characterized as decomposition products and can be severely toxic. In addition to increased CO and CO₂, acid gases, such as hydrogen fluoride (HF) and hydrogen bromide (HBr) (with Halon 1301), as well as, carbonyl fluoride (COF₂) are formed. In some cases, chemical intermediaries (e.g., perfluoropropene from HFC-227ea) have also been identified. Generated during the suppression event, concentrations of decomposition products have been measured to be 10 to 1000 times those limits set by the Occupational Safety and Health Administration (OSHA) and other safety and health organizations. The results of various test programs indicates that the concentration of toxic products generated by the current halon replacements generally exceeds levels generated by the existing halons by 5 to 10 times.

There were two options considered for obtaining and analyzing the concentrations and types of decomposition products during this project: (1) conduct tests out in the open and hope that the sampling probe/fire plume locations would remain the same for each test, thus, ensuring test repeatability, or (2) conduct test within an enclosure, eliminating wind and other related variables which would affect test repeatability. The second option was chosen, due to the limited number of tests that would be conducted. The tests were conducted to compare the results from one agent to another and not necessarily to measure the exposures one would expect in suppressing an outdoor fire with a slight wind from behind. However, the test scenario may represent the exposure one would get if the agent were discharged within a crew compartment on a relatively “large” fire.

TABLE 5. SUMMARY OF NMERI JETA-I TEST FIRES (UL-2B [5 FT²]).

Agent	Low Extinguishment Quantity, lbs	High Extinguishment Quantity, lbs	Average Extinguishment Quantity, lbs	Percent Fires Extinguished
HFC-236fa (ambient)	1.91	2.32	2.06	100% (3 of 3)
HFC-236fa (-55 °F)	1.76	2.14	1.93	100% (3 of 3)
HFC-236fa (140 °F)	1.70	1.96	1.83	100% (2 of 2)
HFC-227ea (ambient)	1.30	2.40	1.63	100% (4 of 4)
HFC-227ea (-55 °F)	1.29	1.44	1.35	100% (3 of 3)
HFC-227ea (140 °F)	1.08	1.95	1.52	100% (2 of 2)
HFPE (ambient)	221	4.50	2.97	73.3% (11 of 15)
HFPE (-55 °F)	21	210	2.10	100% (1 of 1)
HFPE (1409)	231	3.78	3.01	100% (3 of 3)
CO ₂ (ambient)	0.98	1.69	1.32	100% (3 of 3)
10%1-bromopropane/90% HFPE (Ambient)	1.79	2%	2.29	100% (4 of 4)
15%1-bromopropane/85% HFC 227ea (Ambient)	1.08	1.08	1.08	100% (1 of 1)
15%1-bromobutane/85% HFC 227ea (Ambient)	1.70	1.70	1.70	100%(1 of 1)

TABLE 6. OPTIMUM TEST PARAMETERS FOR EACH COMPOUND.

compound	Fill Density, %	Nitrogen Pressure lb/in ²	Nozzle
HFC-236fa and blends with 1-bromopropane (all temperatures)	70 - 75	450 - 600	Halon 0.09 inch dia.
HFC-227ea and blends with 1-bromopropane (all temperatures)	70 - 75	450 - 600	Halon 0.09 inch dia.
HFPE and blends with 1-bromopropane (ambient)	75	400	0.83 in dia. C = 0.65
HFPE (cold)	testing req'd	testing req'd	testing req'd
HFPE (hot)	75	400	0.63 in dia. C = 0.65

The decomposition product tests were conducted inside an enclosed compartment using a 2.25 ft² fire pan and Jet A-I fuel. The optimized 2.5 lb-CO₂ handheld extinguisher for each agent were used. The test compartment was made up of one end of an 8 ft x 8 ft x 20 ft steel ocean shipping container (Figure 4). The test end of the container was equipped with large cargo doors. A steel partition placed in the center of the container divides it in half. One half is used as the "Test Chamber" while the other is the "Agent Filling and Equipment Storage Room." The as-built internal dimensions of the test chamber were 95.0 in high by 93.5 in wide by 125.5 in long yielding an internal volume of 645 ft³ (18.27 m³). The FTIR sampling trailer was located next to the test compartment.

The decomposition product test compartment was equipped with an automatic ventilation system that sustained the internal oxygen concentration to support combustion during the tests. The ventilation system, initialized prior to ignition, included a squirrel cage ventilator and one motorized damper (on the side of test compartment). Prior to agent discharge, the motorized damper was closed and the ventilator was turned off. Immediately after the fire was extinguished the compartment doors were closed and secured. The top vent in the chamber remained open throughout the test event, allowing convective ventilation to take place. This would likely be similar to a hatch remaining open on a typical combat vehicle.

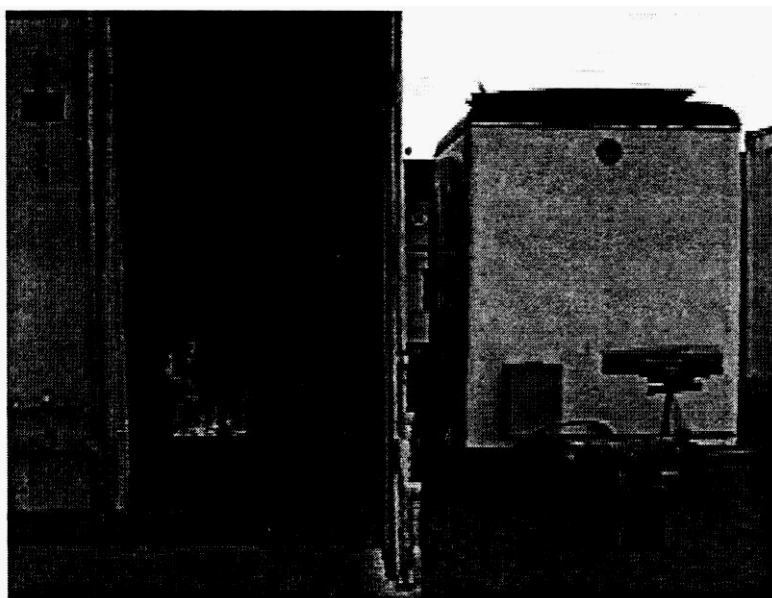


Figure 4. Test compartment showing test fire, one door open, and FTIR sampling trailer.

Test Sequence

The following decomposition product testing sequence was followed

- | | |
|------------|---|
| T + 0 | The test event was initiated, the firefighter was ready, fans were turned on, vents were opened, the FTIR sample pump was turned on, and the camera was started. |
| T + 10 sec | The test fire was lit |
| T + 52 sec | The fan was shut off and the vent was closed |
| T + 60 sec | The FTIR sampling sequence was initiated. Sample scans were collected at 5.5 second intervals for the first 60 seconds and then at 30 second intervals for the remain 14 minutes. |
| T + 70 sec | The firefighter began to extinguish the fire. Three techniques were used: (a) aggressively attack the fire and put it out as fast as possible, (b) attack the fire using a minimum flow rate attempting to extinguish the fire within 8 seconds, and (c) attack the fire using a varying flow rate and attempt to extinguish the fire within 5 seconds. |
| T f 75 sec | When the fire was extinguished, the test compartment door was closed and secured as quickly as possible. |
| T + 15 min | The FTIR sampling was halted, the vents were opened, and the fan was turned on. The test compartment was allowed to ventilate and then readied for the next test event. |

There were a total of 16 decomposition product tests conducted. The data is summarized in Table 7. Figures 5 and 6 compare the calculated average HF and COF₂ concentrations profiles for each of the tested agents. The average HF and COF₂ concentrations were normalized to the extinguishment time (e.g., HF concentration divided by the extinguishment time (ppm/sec)) for the tests with an extinguishment time greater than 3.0 seconds. This data is presented in Table 8. The concentrations of CO, HBr, and other decomposition products were below the detectable limits of the FTIR instrumentation that was used. No chemical intermediaries were encountered (observed) either. The minimum detectable limits are 10 ppm for CO and 50 ppm for HBr. Figure 6 shows HF concentration versus extinguishment time for the decomposition product tests. As expected, increased extinguishment times resulted in higher measured concentrations of HF. For extinguishment times greater than about 6 seconds the HF concentrations of the tested replacement agents exceed those measured for Halon 1301 by approximately 2 to 3 times.

TABLE 7. DECOMPOSITION PRODUCT AVERAGE TEST DATA COMPARISON.

Agent	No. of Tests	Ave Ext. Time, sec	Ave Amt. of Agent, lbs	^a Ave Max. HF Conc., ppm	^a Ave Max. COF ₂ Conc., ppm	Ave. HF Conc. (0 to 15 min), ppm	Ave. COF ₂ Conc. (0 to 15 min), ppm	Ave. HF Conc. (2 to 10 min), ppm	Ave. COF ₂ Conc. (2 to 10 min), ppm
Halon 1301	3	5.3	0.6	370	0.07	260	0.0	270	0.0
HFC-236fa (FE-36)	3	4.0	0.9	720	1.2	405	0.17	450	0.05
HFC-227ea (FM-200)	4	4.0	1.3	1020	4.1	650	2.1	710	2.4
HFPE	2	7.6	2.4	780	7.3	545	4.7	550	5.3
HFPE / Bromo Blend	1	2.1	0.75	485	1.5	280	0.2	310	0.0
FM-200 / Bromo Blend	3	3.7	1.1	900	6.5	715	2.0	730	2.1

^aValues based upon removal of the spike which occurred at the beginning (< 0.4 min) of the test.

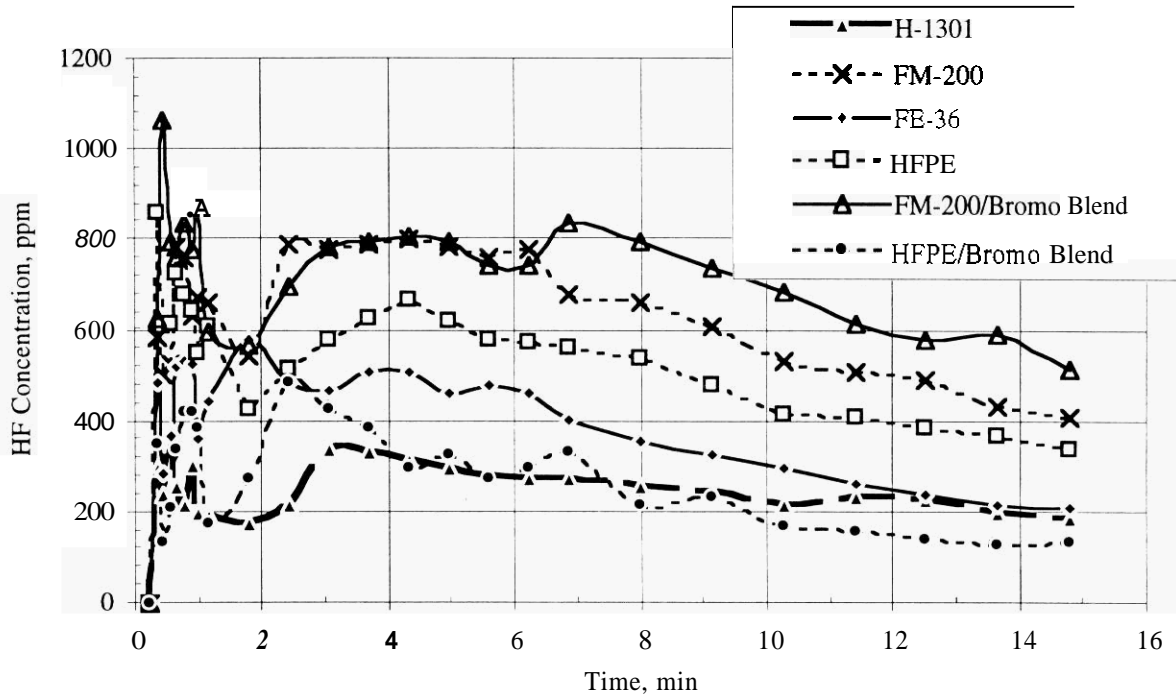


Figure 5. HF Concentration versus time for the calculated average results for each of the tested compounds.

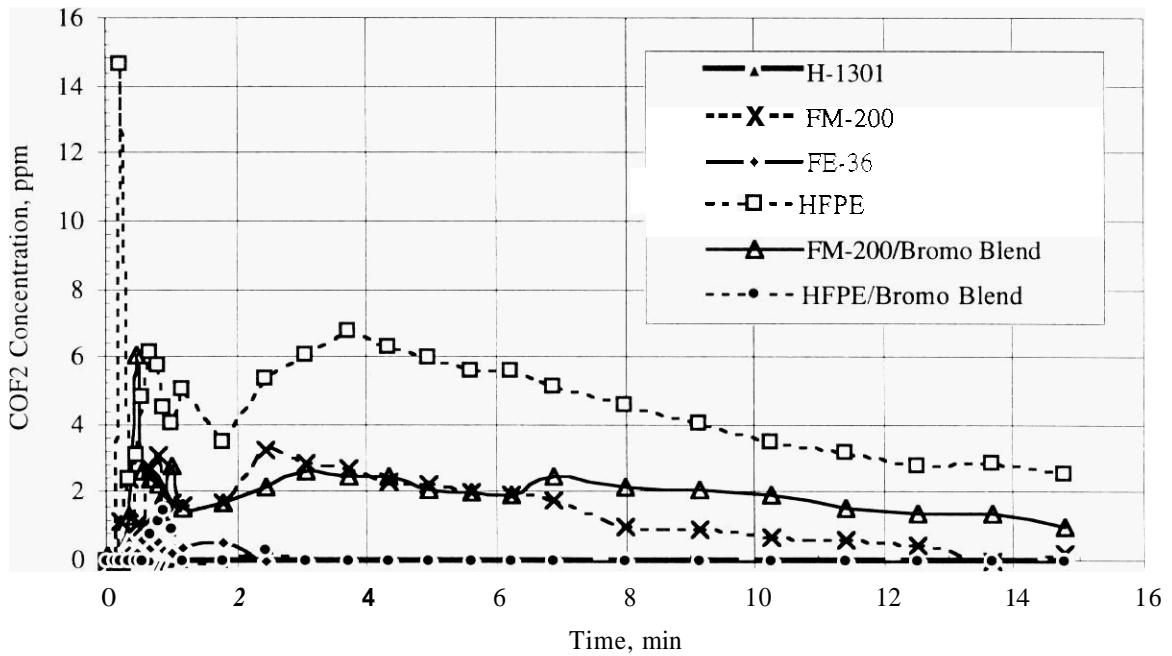


Figure 6. COF₂ Concentration versus time for the calculated average results for each of the tested compounds.

TABLE 8. DECOMPOSITION PRODUCT TEST DATA NORMALIZED TO EXTINGUISHMENT TIME.

Agent	No. of tests with ext. time greater than 3.0 sec	Ave. HF Conc. (0 to 15 min), ppm/sec	Ave. COF ₂ Conc. (0 to 15 min), ppm/sec	Ave. HF Conc (2 to 10 min), ppm/sec	Ave. COF ₂ Conc. (2 to 10 min), ppm/sec
Halon 1301	2	43	0.0	53	0.0
HFC-236fa (FE-W)	2	70	0.02	76	0.0
HFC-227ea (FM-200)	3	123	0.6	131	0.6
HFPE	2	71	0.6	71	0.7
HFPE/ Bromo Blend	none	^a 133	0.1	^a 148	0.0
FM-200/ Bromo Blend	1	135 (^b 266)	0.6 (^b 0.2)	139 (^b 293)	0.7 (^b 0.1)

^aData based upon 2.1 sec extinguishment time.

^bData based upon 2.0 sec extinguishment time.

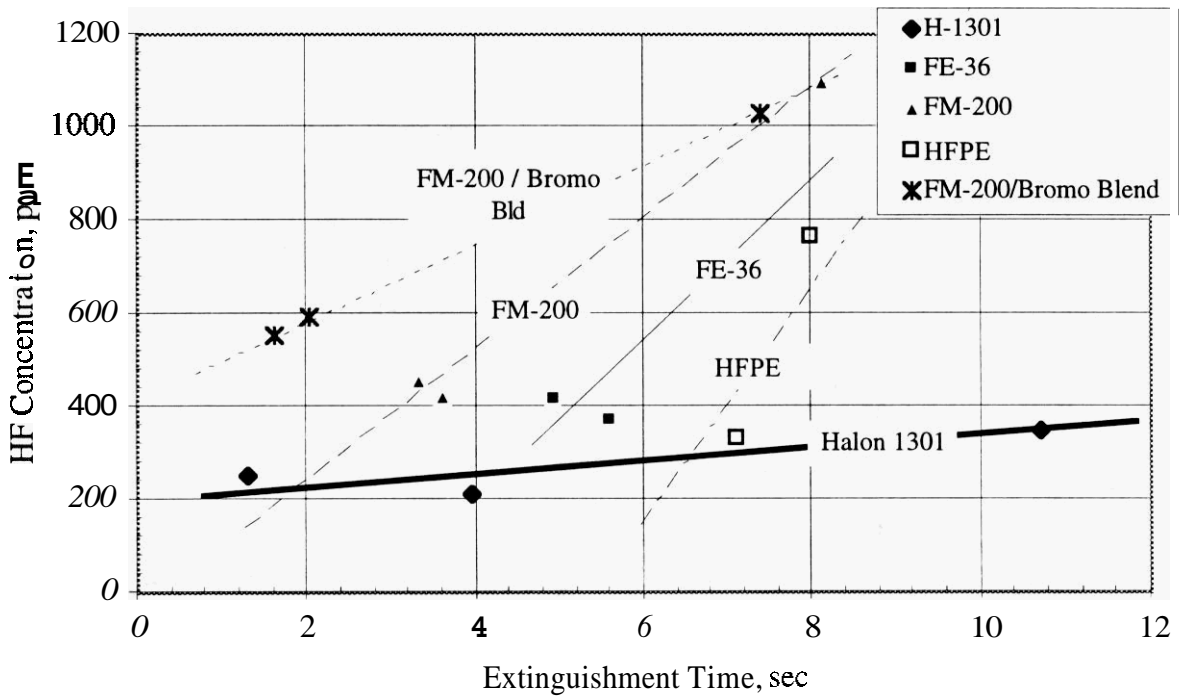


Figure 7. HF Concentration versus extinguishment time.

CONCLUSIONS

The overall goal of this project was to identify agents and agent blends capable of extinguishing a UL-2B jet fuel **fuels** using existing 2.5-lb CO₂ fire extinguishers at ambient, cold, and hot temperatures. During this test series NMERI was able to identify proper fill ratios, nozzle configurations, and nitrogen pressures which resulted in extinguishment for all of the compounds at all three conditions: ambient, hot, and cold. Since all of the compounds were able to extinguish the fire, the next step is to select one (or more) of the compounds and perform tests at ATC.

Overall, the agents that appeared to be most effective were HFC-227ea, HFC-236fa, and blends of all three agents with 1-bromopropane. The other compound, HFPE (HFPE) was the least effective but, should not be ruled out since it has the advantage of being less volatile, thereby releasing less of the compound in the vapor phase which would reduce the quantity breathed should the compound be discharged into an occupied crew compartment. The compound may also be more effective on Class A fires since it is a liquid and may have more of an ability to penetrate the fire. It also has a short atmospheric lifetime and lower GWP compared to the other compounds. When blended with 1-bromopropane, the performance of the tested compounds, including HFPE, was enhanced approximately 30%, as has been observed in previous testing conducted by NMEFU.

The amount of decomposition products generated during a fire suppression event is dependent upon the time required to extinguish the fire and the amount of extinguishing agent discharged. As shown in Table 9 the extinguishment time, discharge time, and amount of agent discharged were varied for each of the tested agents. The firefighter was instructed to vary the flow rate during each test in an attempt to increase or decrease the extinguishment time from test to test. By varying the extinguishment time, we have been able to investigate the effect of fire extinguishment time on decomposition product generation.

TABLE 9. SUMMARY OF THE ADVANTAGES AND DISADVANTAGES OF THE TESTED AGENTS.

Compound	Advantages	Disadvantages
<u>HFC-227ea</u>	<p>Low extinguishing weight (1.4 to 1.6lbs). Most effective aside from the bromoalkane blends.</p> <p>The agent is commercially available in bulk quantities and is approved for sale as a fire extinguishing agent.</p> <p>Commercially available extinguishers under development which will likely meet US Army criteria.</p> <p>Least expensive agent.</p>	<p>Marginally long atmospheric lifetime, moderately high GWP.</p> <p>The least effective agent on larger fires. more of a gaseous agent.</p>
<u>HFC-236fa</u>	<p>Low extinguishing weight (1.6 to 1.8lbs)</p> <p>The agent is commercially available in bulk quantities and is approved for sale as a fire extinguishing agent.</p>	<p>Long lifetime, high GWP, potentially future availability problems.</p>
<u>HFPE</u>	<p>Excellent global atmospheric properties (short lifetime, low GWP).</p> <p>Liquid agent, therefore, less volatile within dosed space.</p> <p>Low toxicity.</p>	<p>Marginally effective on small fires</p> <p>The agent is not commercially available in bulk quantities at this time. The required paperwork; however, has been submitted to EPA for approval.</p>
<u>1-Bromopropane Blends</u>	<p>Enhances the neat agent performance by 30%.</p> <p>the performance enhancement will be useful for inexperienced firefighters and larger fires.</p> <p>Reduced decomposition products due to the enhanced fire suppression performance</p>	<p>Additional toxicity studies required</p> <p>Issues associated with handling, storage, and transfer of blended materials will need to be addressed.</p>

The decomposition tests shows that the concentrations of HF and COF₂ exceed that generated by with Halon 1301 by 2 to 3 times. HFC-227ea generates higher HF concentrations than HFC-236fa or HFPE. The lowest HF concentrations were generated with HFPE based upon equal extinguishment times. The addition of I-bromopropane to HFC-227ea does not appear to reduce the amount of decomposition products that are generated for similar extinguishment times. However, the addition of 1-bromopropane will reduce the extinguishment time, therefore, lower HF and COF₂ concentrations will result if the HFC-227ea/1-bromopropane were used. The HFC-236fa generated less HF than HFC-227ea and HFC-227ea blended with 1-bromopropane and slightly more than the HFPE. As expected the least amount of HF was formed with Halon 1301. Interestingly enough, HF levels for the HFPE blended with I-bromopropane were similar to Halon 1301.

Higher levels of COF₂ were also measured during the HFC-227ea tests when compared to HFC-236fa. The HFPE generated higher COF₂ than either of the other tested compounds/blends. There was little to no COF₂ formed during the HFC-236fa and HFPE tests.

There is a two-fold benefit when blending the tested compounds with 1-bromopropane: increased agent performance and reduced decomposition products. This is especially true for HFPE.

RECOMMENDATIONS

- **Class A** testing should be performed.
- **Firefighter/operator** training programs should be developed. This project has shown that the fire suppression effectiveness of the tested agents is very sensitive to technique.
- A prototype HFC-227ea (FM-200) extinguisher that is being developed by Metalcraft should be investigated to include ambient, cold, hot, and decomposition tests, and repeatability studies, using the protocols presented.
- **Bromoalkane** blends should be evaluated in the Metalcraft prototype extinguishers. This would be an easy and cost effective way to increase the firefighting capacity of the extinguisher.
- Additional bromoalkene blend fire suppression and decomposition testing should be conducted if an additional 30% increase in agent performance is required for actual field applications since the blends had the best performance during both the fire suppression and decomposition testing.
- Exposure studies of neat agent discharges should be performed inside actual combat vehicles.
- In-vehicle exposure studies should be performed with live fires in order to determine the likely concentrations of decomposition products (mainly HF) within combat vehicle compartments.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support and funding provided Steve McCormick, GerMaine Fuller, and Michael Clauson with the US. Army, TACOM, Warren, MI, under Contract No. DAAEO7-97-C-XO42. The agent was provided for testing by the manufacturers: Great Lakes Chemical, DuPont, and Ausirmont. Also, the guidance and direction of Dr. Robert E. Tapscott is recognized.