(U) Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles

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(U) ABSTRACT

(U) Historically the US Army (USA) used Halon 1301 (bromotrifluoromethane), a chemical with high Ozone Depletion Potential (ODP), to protect the crews of armored vehicles from the effects of peacetime and combat fires. Since the phase-out of Halon production the USA has directed that zero ODP materials be used wherever possible. Subsequently, major new vehicle platforms have been deployed with Automatic Fire Extinguishing Systems (AFES) that rely on HFC-227BC, a zero-ODP-agent blend of HFC-227ea (heptafluoropropane) and sodium-bicarbonate-based dry chemical. Unfortunately, hydrofluorocarbons (HFCs) generally have high Global Warming Potential (GWP) - thousands of times that of carbon dioxide on a weight basis. Hence, as part of a larger effort to reduce its carbon footprint, USA Program Managers have asked that more environmentally friendly fire extinguishing agents be evaluated as part of ongoing vehicle modernization efforts. Several agents are being investigated, including FK-5-1-12, water with additives, and dry chemicals. This report describes the findings of more than 150 live-fire tests using nine agents and four extinguisher technologies. The basic conclusion is that no alternate agent can yet be considered to be a drop-in replacement for Halon 1301 or HFC-227BC for this application. However, a blend of Halon 1301 and dry chemical has been found to be about twice as effective as Halon 1301 alone. Thus, pending confirmation tests on vehicles, it may be feasible to use less Halon in legacy systems without compromising fire protection performance.

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(U) INTRODUCTION

(U) By 1982 the first modern, automatic fire extinguishing system (AFES) designed to protect the crew from combat-induced fires was deployed on a US Army (USA) vehicle, the M1 Abrams main battle tank. AFES are comprised of four major components: fast fire sensors, control electronics, fast-opening fire extinguishers, and integration wiring and bracketry (ref. 1, 2). Subsequently, the USA fielded similar systems on other platforms including the Bradley Fighting Vehicle (BFV) and Field Artillery Ammunition Support Vehicle (FAASV).

(U) In Army tests, AFES were able to detect and suppress combat fires (i.e., fast-growth fuel oil deflagrations) in a fraction of a second (ref. 1, 2). In Desert Storm battle damage assessments, the systems were reported to have been effective (ref. 3). These systems all used extinguishers filled with Halon 1301 (bromotrifluoromethane).

(U) In compliance with the requirements of the US Clean Air Act Amendments of 1990 and in conformity with the Montreal Protocol (MP) of 1987, Halon 1301was phased out of production at the end of 1993. Subsequently, the USA decided to use substances with zero ozone depletion potential (ODP) wherever possible. Since then, AFES have been deployed on STRYKER, Up-Armored High Mobility Multipurpose Wheeled Vehicles (Up-Armored HMMWV or UAH), Mine Resistant Ambush Protected (MRAP) vehicles and other platforms, including the US Marine Corps' (USMC) Light Armored Vehicle (LAV) and Expeditionary Fighting Vehicle (EFV). These AFES use similar detection and controls as used in older systems but rely on extinguishers filled with a more environmentally friendly agent: HFC-227BC (also known as FM-200BC), a blend of HFC-227ea (heptafluoropropane) and sodium-bicarbonate-based dry chemical. HFC-227ea, an HFC, has zero ODP so its continued production is acceptable under the MP. The blend was developed by the Army as part of an effort to find Halon-alternate fire extinguishing agents, and was demonstrated to be essentially as effective as Halon 1301 and adequate as a Halon replacement (ref. 4). The STRYKER Brigade Combat Team (BCT) was the first USA vehicle to be qualified with HFC-227BC as its crew agent (refs. 5, 6). New vehicles, including Joint Light Tactical Vehicle (JLTV) and MRAP All-Terrain Vehicle (MATV), currently specify HFC-227BC for the crew AFES. Table 1 lists (in order of qualification) the agent used in the crew AFES of major USA and USMC platforms. The Army relies on its Halon reserve to support legacy vehicles.

(U) However, HFC materials such as HFC-227ea have high Global Warming Potential (GWP) - thousands of times that of carbon dioxide. Hence, as part of a larger effort to reduce its carbon footprint, the USA has begun looking at more environmentally friendly fire extinguishing agents. Several agents are being evaluated, including FK-5-1-12, water with additives, and dry chemicals. This report describes the findings of that project based on more than 150 live-fire tests using nine agents and four extinguisher technologies. It should be noted that converting an existing system from one agent to another involves many steps, achieving acceptable fire suppression performance discussed in this paper being a key one. Other steps are listed in ref. 7.

Table 1. (U) Crew AFES agents in order of qualification.

Platform	**Crew AFES Agent**
Abrams Main Battle Tank	Halon 1301
Bradley Fighting Vehicle (BFV)	Halon 1301
*Field Artillery Ammunition Support Vehicle (FAASV)	Halon 1301
USMC Expeditionary Fighting Vehicle (EFV)	HFC-227BC
STRYKER Brigade Combat Team (BCT)	HFC-227BC
Up-Armored HMMWV (UAH)	HFC-227BC
Mine Resistant Ambush Protected (MRAP)	HFC-227BC
USMC Light Armored Vehicle (LAV)	HFC-227BC
MRAP All-Terrain Vehicle (MATV)	HFC-227BC
**Joint Light Tactical Vehicle (JLTV)	HFC-227BC
***Future Combat Systems (FCS)	HFC-227BC

*Upgrade to HFC-227BC in process **In development ***Manned Ground Vehicle Cancelled

Table 2. (U) Agent Properties.

	Property	Halon 1301	HFC-227ea[a]	FK-5-1-12[b]	Water+[c]	Dry Chemical[d]
Environmental	Ozone Depletion Potential[e]	16	0	0	0	0
	Global Warming Potential[f]	6900	3500	1	0	0
	Atmospheric Lifetime (yr)	65	33	0.014	0	0
Safety	Design Concentration (%v/v)	5	8.7	6.7[g]	~300 g/m^3	~300 g/m^3
	NOAEL[h] (%)	5	9.0	10	NA	TBD[j]
	LOAEL[i] (%)	7.5	>10.5	10	NA	TBD[j]
Physical	Boiling Point (°C)	-58	-16	49	115	N/A
	Vapor Pressure @ 21°C (bar)	13.7	4.1	0.41	0.03	N/A
	Liquid Density (g/cm^3)	1.56	1.39	1.60	1.27	2.16
	Molecular Weight (g/mol)	149	170	316	31	84
	Heat of Vaporization (J/g)	117	132	88	>2250	N/A

a) HFC-227ea is a form of heptafluoropropane and is sold as a fire extinguishing agent. b) FK-5-1-12 is a perfluorinated six-carbon ketone manufactured and sold as a fire extinguishing agent. c) Water with 50% Potassium Acetate. d) Values given are for sodium bicarbonate-based dry chemical. Potassium bicarbonate crystal density is 2.17 g/cm^3. e) CFC11 baseline, ref. 8. f) CO_2 baseline, ref. 9. g) Concentration advised by the agent manufacturer representative for this application. h) No Observed Adverse Effects Level. i) Lowest Observed Adverse Effects Level. j) Acceptable concentration levels for this application to be determined by the USA.

(U) Table 2 lists key properties for the basic agents used in the tests described in this paper. The agents that are mixtures of a fluorocarbon agent (i.e., Halon 1301; HFC-227ea; or FK-5-1-12), and dry chemical have essentially the same environmental and safety properties as the base fluorocarbon agent. The environmental properties illustrate part of the motivation for this study: Halon and HFC-227BC, the agents currently used in Army crew systems, have high GWP, and Halon has a relatively high ODP so its production is prohibited by the MP and its use is limited by Army policy. FK-5-1-12 has zero ODP but a finite GWP – equivalent to carbon dioxide (CO_2). A recent EPA finding has listed several Green House Gases (GHGs), including CO_2, as a threat to public health (ref. 10) and recent legislation has proposed significant reductions in GHG production (ref. 11). Although future limitations on the use of near-zero GWP materials such as FK-5-1-12 are not anticipated, if limitations are imposed, they should be mitigated by the fact that relatively little FK-5-1-12 and similar fire suppression chemicals are emitted compared to CO_2.

(U) APPROACH

(U) The Tank and Automotive Research, Development and Engineering Center's (TARDEC) purpose for the tests described herein was to compare the performance of deployed suppression agents and more environmentally friendly ones. Distinguishing the performance of the agents was facilitated by operating close to where the extinguisher system is overmatched by the fire; the ideal was to bracket the fire with successful and failed suppression in a repeatable way for each agent tested. We therefore invited three extinguisher suppliers to support the tests – and asked them to provide suppression systems based on various agents and concentrations that would yield marginal suppression 'passes' and 'failures' based on current vehicle performance criteria. Note that the amount of agent used was often less than the design concentration used in production systems.

(U) The tests were conducted at the Army's Aberdeen Test Center (ATC) in a 260 ft^3 (7.36 m^3) box with relatively little clutter, no active air flow, and hatches closed (Figure 1). Although the exploratory test box volume is similar to some legacy vehicle crew compartment volumes, it does not represent a specific application. Tests were conducted at the outdoor ambient temperature at the test site which ranged from approximately 25 to 90°F (-4 to 32°C).

(U) Figure 2 shows the test box with sampling points, fire position and flame path, extinguisher positions and agent discharge directions indicated.

(U) The test box was instrumented to measure blast overpressures, temperatures and the chemistry of the atmosphere, in particular the combustion byproducts. The response times of the thermocouples were too long to effectively measure the brief excursions that could have caused skin-burn injury – however they gave a gross indication of the air temperature. For this reason and because the thermal excursions measured were benign, those results are not reported. A high-speed video camera recorded the fire and its suppression from the top of the box.

(U) The fires were detected by a production infrared optical fire sensor that, via a simple controller, released the extinguishers. The average time to valve activation was approximately 40 ± 5 ms after the first pressure and/or infrared signature was observed in the ballistic data.

(U) The Field Chemistry Sampling and Analysis Team at ATC measured the combustion byproducts during the tests, including carbonyl fluoride (COF_2) and hydrofluoric (HF) acid. The atmosphere was sampled from four positions within the test box (Figure 2). A technique specifically developed by the ATC Field Chemistry group to distinguish FK-5-1-12 and COF_2 (ref. 12) was employed. ATC subsequently reported the chemistry results (ref. 13) including casualty assessments for each test based on current vehicle performance criteria (ref. 14).

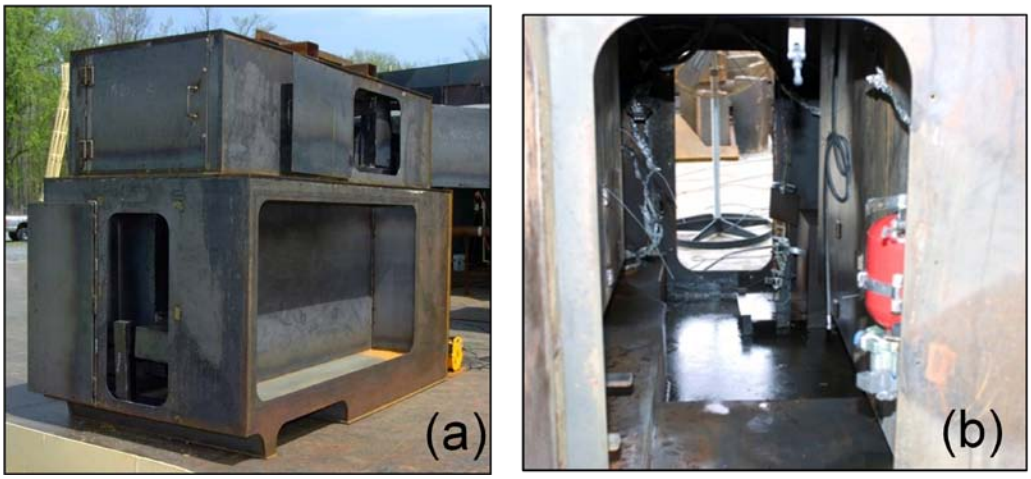

Figure 1. (U) Exploratory Test Box a) Exterior and b) Interior.

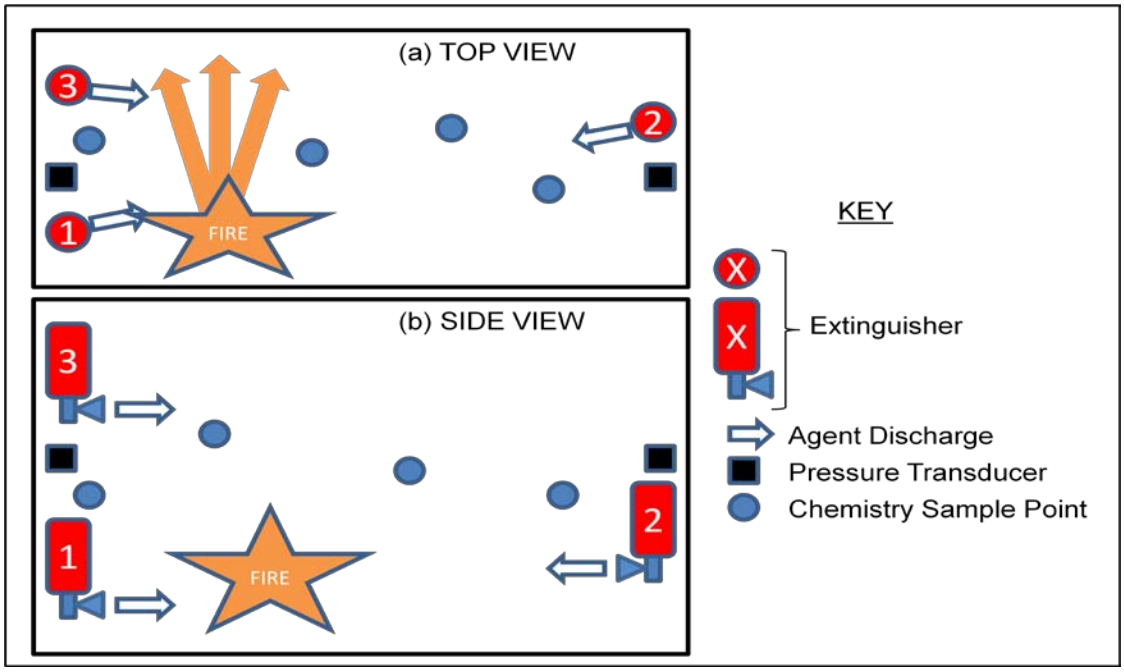

Figure 2. (U) Extinguisher Positions, Blast Overpressure and Chemistry Sample Points in the Test Box.

(U) The 'Pass/Fail' criteria used are based on the current USA crew casualty criteria applied to armored ground vehicles. Table 3 lists major excerpts and derivations from the formal requirements (ref. 14). It is important to note that current criteria are under review and may be revised (ref. 15).

Table 3. (U) Selected Crew AFES Performance Criteria.

Parameter	**Requirement**[a]	**Test**[b]
Fire Suppression	Extinguish all flames without reflash	Y
Skin Burns	Less than second degree burns (<2400°F-sec over 10 seconds or heat flux < 3.9 cal/cm^2)	c
Overpressure	Less than 11.6 psi	Y
Agent Concentration	Not to exceed LOAEL[d]	Y
Acid Gases ($HF + HBr + 2\cdot COF_2$)	Less than 746 ppm-min (5 min dose)	Y
Oxygen Levels	Not below 16%[e]	Y
Discharge Impulse Noise	No hearing protection limit: <140 dBP[f] Single hearing protection limit: <165 dBP[f]	N
Discharge Forces	Not to exceed 8 g[g] and <20 psi at 5 inches[h]	N

(a) Based on reference 14a except as noted. (b) Addressed in Exploratory Tests. (c) Temperature recorded with thermocouples. (d) Lowest Observed Adverse Effects Level per ref 16. (e) ref. 14b. (f) ref. 14c. (g) Extrapolated from ref. 14a. (h) ref. 15.

(U) In industrial explosion protection tests, the volume-normalized speed of an explosion is often calibrated using a parameter called K_{max}, defined as (ref. 17)

$$K_{max} = \left[\frac{dP}{dt}\right]_{max} \sqrt[3]{V} \qquad (1)$$

where P is the blast overpressure, t is the time and V is the test box volume. The results for five baseline fire tests with no suppression yielded an average K_{max} of 2.7 bar-meter/seconds with a standard deviation of 0.2. Due to significant fluctuations in the pressure traces after the agent and fire interact, and to better facilitate the 'real-time' nature of these exploratory tests, a variant of K_{max} given in equation (1) was used:

$$K = \frac{\Delta P}{\Delta t} \sqrt[3]{V} \qquad (2)$$

(U) In equation (2), ΔP is the pressure change during a time interval Δt. In these tests, K was determined using a predetermined interval starting at the time the extinguishers were activated. The target for the fires was a K value of 1 to 2 bar-meter/seconds.

(U) AGENTS AND EXTINGUISHERS

(U) Nine suppression agents were used (the short-hand names in parenthesis are used in subsequent charts and tables):

- Halon 1301 ('Halon')
- Halon 1301 with Sodium Bicarbonate-based Dry Chemical ('Halon+')
- Halon 1301 with Potassium Bicarbonate-based Dry Chemical ('HalonK')
- HFC-227ea with Sodium Bicarbonate-based Dry Chemical ('HFC227BC')
- FK-5-1-12 ('FK-5-1-12')
- FK-5-1-12 with Sodium Bicarbonate-based Dry Chemical ('FK-5-1-12+')
- Water with Potassium Acetate-based additives ('Water+')
- Sodium Bicarbonate-based Dry Chemical ('NaBC')
- Potassium Bicarbonate-based Dry Chemical ('KBC')

(U) As indicated in Table 1, Halon 1301 is used in the crew compartment of legacy vehicles such as the Abrams and Bradley. 'Halon+' is a mixture of Halon 1301 and sodium-bicarbonate-based dry chemical. Although never fielded, this mixture is expected to be compatible with most or all fielded hardware, in which case current Halon 1301 extinguishers could be recharged with 'Halon+.' 'HFC-227BC' is also a mixture of a clean agent and sodium-bicarbonate-based dry chemical. A specific blend of HFC-227BC (i.e., HFC-227ea with 5% by weight dry chemical) is fielded in the AFES used to protect the crew in STRYKER (refs. 5, 6, 7), Up-Armored HMMWV, MRAP, upgraded FAASV, and the USMC's Expeditionary Fighting Vehicle (EFV) and Light Armored Vehicle (LAV). Some MRAP vehicles allow up to 10% by weight dry chemical.

(U) The amount of sodium bicarbonate-based dry chemical added to the clean agents tested varied from 5% by weight, the usual fielded mix, to a much higher fraction. Crew AFES based on HFC-227BC use a HFC-227ea design concentration of about 9% by volume at 20°C – a level that ensures the LOAEL is not exceeded at temperature extremes. In such a system, a 5% by weight mix of sodium bicarbonate corresponds to a dry chemical density of 40 g/m^3 in the protected volume. The Army specifies a 5 to 10% by weight mix of dry chemical in HFC-227BC systems. Therefore, the maximum amount of dry chemical additive used in the tests described herein was 80 g/m^3.

(U) FK-5-1-12 is widely available but has never been fielded in an Army crew-AFES. Although the 'FK-5-1-12+' mixture was tested, FK-5-1-12 and sodium-bicarbonate-based dry chemical interact chemically and so cannot be stored together for long periods of time as is done with HFC-227ea and dry chemical. However, the chemical interaction between FK-5-1-12 and the dry chemical did not appear to be significant in the brief period they were stored together for the tests described herein.

(U) An industrial explosion protection study concluded that, given the phase-out of Halon, sodium-bicarbonate-based dry chemical offered "the best compromise between effectiveness and practical acceptance for all but the special cases of occupied spaces" (ref. 18). No discussion or reference is given for why dry chemical is not an acceptable agent for occupied spaces; it may be due to the common-sense bias against breathing dust. In any case, the sodium-bicarbonate-based

dry chemical used in the test series described herein (ref. 19) was previously found to be acceptable for use in crew compartments by the USA (ref. 20). When dry chemical was tested alone, the concentrations used were as high as 300 g/m^3, higher than the levels seen in fielded HFC-227BC systems (40 to 80 g/m^3 based on a 5 to 10% by weight dry chemical to HFC-227ea mix, with the HFC-227ea at the maximum safe level). Operational issues including clean-up and obscuration remain to be fully addressed (ref. 21).

(U) This study also compared potassium bicarbonate (ref. 22) and sodium bicarbonate, both as sole suppression agents and as additives to Halon 1301. Previous studies have found that for certain types of fires, potassium-based dry chemical can be as much as twice as effective as sodium-based dry chemical by weight (ref. 23). Consequently, in the tests described herein, suppression performance was compared with half the potassium-based agent with respect to the sodium-based dry chemical.

(U) 'Water+' is a 50-50 mix of water and potassium acetate. This mix is available commercially (for example it is used for de-icing operations at airports), and was one of two agents TARDEC originally recommended as a Halon 1301 replacement (ref. 4). However, special care must be taken to prevent reflash fires when integrating a water-based AFES (ref. 4). In addition, operational issues, such as clean-up and effects on electrical equipment, remain to be fully addressed.

(U) Agents were delivered by four extinguisher configurations from three independent suppliers:

- Nitrogen charged cylinder with a solenoid valve (used in Abrams, BFV, FAASV, STRYKER, UAH, and some MRAPs); 'N_2 Solenoid' in Table 4
- Nitrogen charged cylinder with a linear actuated valve (designed for use in the crew and mission bay of FCS' NLOS-C); 'N_2 Linear' in Table 4
- Nitrogen charged cylinder with a squib actuated valve (used in some MRAPs); 'N_2 Squib' in Table 4
- Gas Generator driven Hybrid Fire Extinguisher (developmental); 'GG HFE' in Table 4

(U) DESCRIPTION OF TESTS AND RESULTS

(U) A total of 157 live-fire tests in four series were conducted in the December 2008 through September 2009 period. Each test used two equivalent extinguishers (in positions 1 and 2 indicated in Figure 2) unless otherwise noted.

(U) The agents and extinguisher configurations tested are summarized in Table 4. Table 5 shows the best results obtained for each agent; note that the best performance and minimum agent weights are not obtained simultaneously. The agent weight listed is the least used while obtaining a reliable (e.g., repeated) 'pass.' Both tables show the number of 'passes' obtained – agent quantities were adjusted to try to achieve 'passes' in half the tests. Table 6 summarizes the failure mechanism(s) (i.e., limiting criteria) for each agent tested.

Table 4. (U) Exploratory Test Result Summary by Extinguisher, Agent, and Hardware.

Agent	N_2 Solenoid	N_2 Linear	N_2 Squib	GG HFE	Total Tests	*Total 'Passes'
Halon	19	0	0	2	21	12 (57%)
Halon+	19	0	0	0	19	16 (84%)
HalonK	7	0	0	0	7	4 (57%)
HFC-227+	16	8	1	11	36	17 (47%)
FK-5-1-12	10	0	4	7	21	0
FK-5-1-12+	6	0	2	7	15	0
Water+	12	0	1	10	23	12 (52%)
NaBC	13	0	0	0	13	7 (54%)
KBC	2	0	0	0	2	2 (100%)
TOTAL	104	8	8	37	157	70 (45%)

*The goal for each agent was to pass half the tests.

Table 5. (U) Exploratory Test Result Summary Showing Best Results for Each Agent.

				**Performance			
Agent	Total	*Pass	**Least Agent Weight (lb)	Lowest Acid Dose (ppm-min)	Lowest Pressure Peak (psi)	Fastest Fire Out Time (ms)	Note
Halon	21	12	~5	~500	<1	<200	Legacy fielded product
Halon+	19	16	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HalonK	7	4	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HFC227BC	36	17	~5	<20	<1	<200	Fielded product
FK-5-1-12	21	0	>25	~2,000	1.2	<200	Available
FK-5-1-12+	15	0	>15	~1,300	1.6	<200	Invention required
Water+	23	12	~4	0	1.5	~400	Development required; operational issues?
NaBC	13	7	~3	0	<1	<200	Available; operational issues?
KBC	2	2	~2	0	<1	<200	Available; operational issues?
Total	**157**	**70**					

*The goal for each agent was to pass half the tests. **Best Performance and Least Agent Weight are not obtained simultaneously. Acid doses are obtained from ref. 13.

Table 6. (U) Summary of Limiting Criteria for Agents Tested.

Agent	Limiting Criteria	Collateral Criteria	Other Issues
Halon	Acid Gas	Pressure & Temperature	Deployed & Stockpiled
Halon+, K	Pressure	Acid Gas & Temperature	New Agent Mix
HFC227BC	Acid Gas & Reflash	Pressure & Temperature	Deployed
FK-5-1-12	Acid Gas	Reflash	Weight
FK-5-1-12+	Acid Gas	Reflash	Weight, Agent Compatibility
Water+	Reflash	Pressure & Temperature	Clean-up
Dry Chem	Reflash	Pressure & Temperature	Obscuration & Clean-up

(U) Figure 3 shows the acid-gas dose measured versus the amount of agent released for all of the fluorinated agents for one of the extinguisher configurations. The maximum acceptable acid dose and safe agent weights are also indicated. The minimum measurable acid dose was 20 ppm-min.

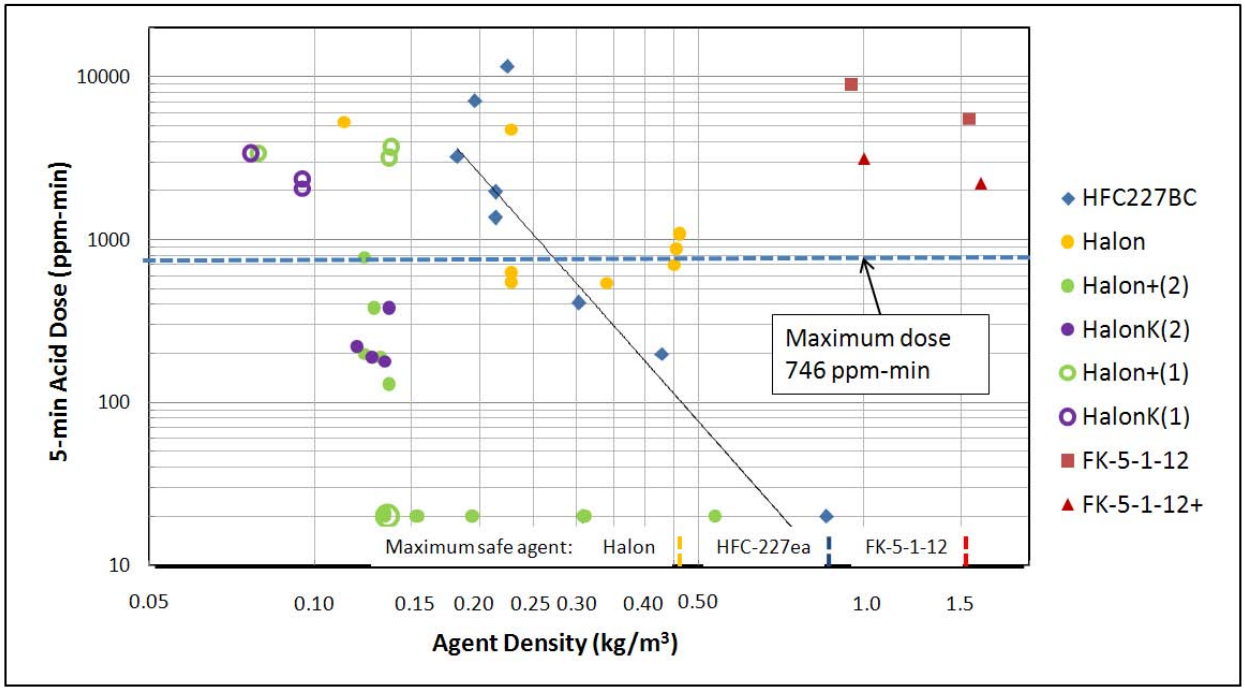

Figure 3. (U) Average Acid Dose Integrated over 5-Minutes versus Agent Density (ref. 13d,e). The solid line is a 'best fit' trend using a Power Series based on the 'HFC-227BC' data.

(U) The 'FK-5-1-12' and 'FK-5-1-12+' tests with approximately 25 pounds of agent used equivalent extinguishers in all three locations shown in Figure 2. The relative trends for 'FK-5-1-12,' 'FK-5-1-12+' and 'HFC-227BC' indicated in Figure 3 were observed for all extinguishers tested with those agents.

(U) Interestingly, the Halon 1301 results shown in Figure 3 indicate little or no advantage to using maximum safe concentrations. The high acid levels measured are consistent with earlier results (ref. 4) and indicate that the test fire is nearly an overmatch of the Halon systems described herein.

(U) Halon+ and HalonK agents were tested with one (in position 2) and two (in positions 1 and 2) extinguishers per test, as parenthetically indicated in Figure 3. None of the tests using two extinguishers failed, even when very low Halon concentrations were used. Consequently, tests with a single extinguisher were necessary to achieve the desired failures. Note that one of the four 'Halon+(1)' tests using sodium-bicarbonate-based dry chemical 'passed,' while none of the three 'HalonK(1)' tests, using approximately half the amount of potassium-bicarbonate-based dry chemical, 'passed.' This suggests that, when mixed with Halon, potassium-bicarbonate-based dry chemical is not significantly more effective that sodium-bicarbonate-based dry chemical.

(U) Figure 4 shows the acid gas dose versus minimum oxygen levels observed for the tests using Halon with potassium-bicarbonate and sodium-bicarbonate-based dry chemical additives. The results indicate that the test fires were limited by the amount of oxygen (versus fuel) available and clearly distinguish the 'Passes' and 'Fails.' Also indicated is that, in a failed suppression, potassium-bicarbonate-based dry chemical with Halon yields somewhat lower acid than Halon with sodium-bicarbonate-based dry chemical.

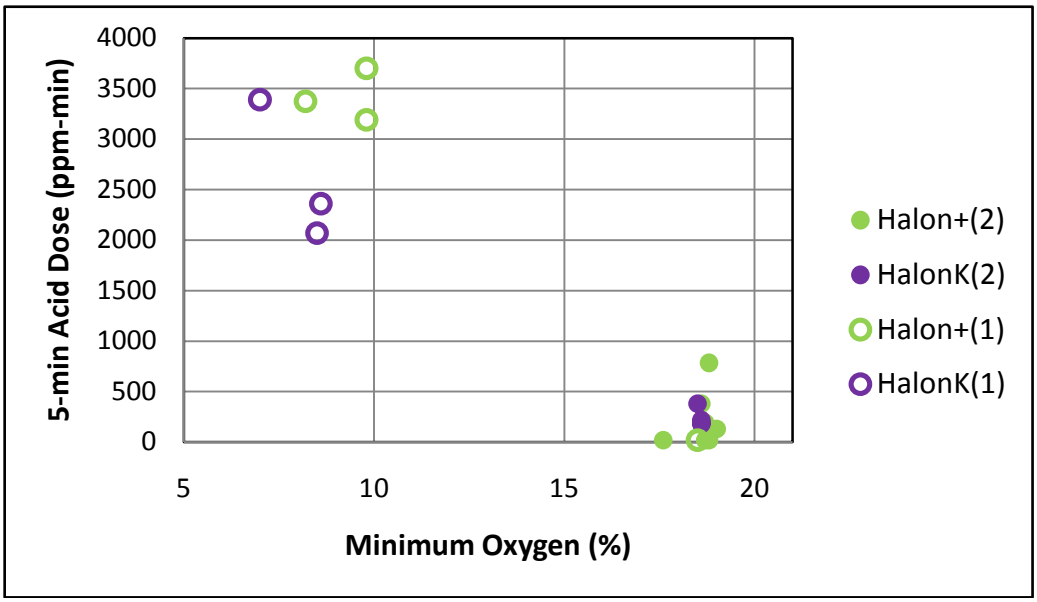

Figure 4. (U) Five-Minute Acid Dose versus Minimum Oxygen Level for Halon with Sodium- and Potassium-Bicarbonate Dry Chemicals (ref. 13e).

(U) Figure 5 compares the integrated blast overpressure versus agent mass density for all agents tested. Although integrated pressure is not a casualty criteria, because the 'passes' and 'failures' based on established casualty criteria are distinguished using this parameter, it is a convenient method for comparing fluorinated agents that produce acid gas with nonfluorinated agents that do not produce acid gas. The threshold between a 'pass' and a 'fail' appears to be

about 0.2 bar-s. It is interesting to note that Halon and HFC-227BC fail at agent densities of a little less than 0.25 kg/m^3; the other agents described herein (except for the FK-5-1-12-based agents) appear to require densities of at least 0.15 kg/m^3. Because the FK-5-1-12-based agents yielded unacceptably high acid levels at the maximum safe concentration (as shown in Fig. 3), they were not tested at low concentrations where a failed suppression resulting in high integrated pressures would have occurred.

(U) Figure 5 includes the results for dry chemical agents alone, and allows another comparison of sodium-bicarbonate- and potassium-bicarbonate-based dry chemicals: When mixed with Halon, the potassium-based dry chemical performs about the same as the sodium-based dry chemical, consistent with the results shown in Figures 3 and 4. However, when used alone, the potassium-based dry chemical ('KBC') is almost twice as effective by weight compared to sodium-based agent ('NaBC'), consistent with earlier findings (ref. 23).

(U) The 'Water+' tests using proprietary (non-production) distribution systems performed about as well as other agents on a weight basis as indicated in Figure 5. The successful 'Water+' tests resulted in fire-out times about twice as long as the other agents, as indicated in Table 5. However, other suppression parameters were comparable to the other agents.

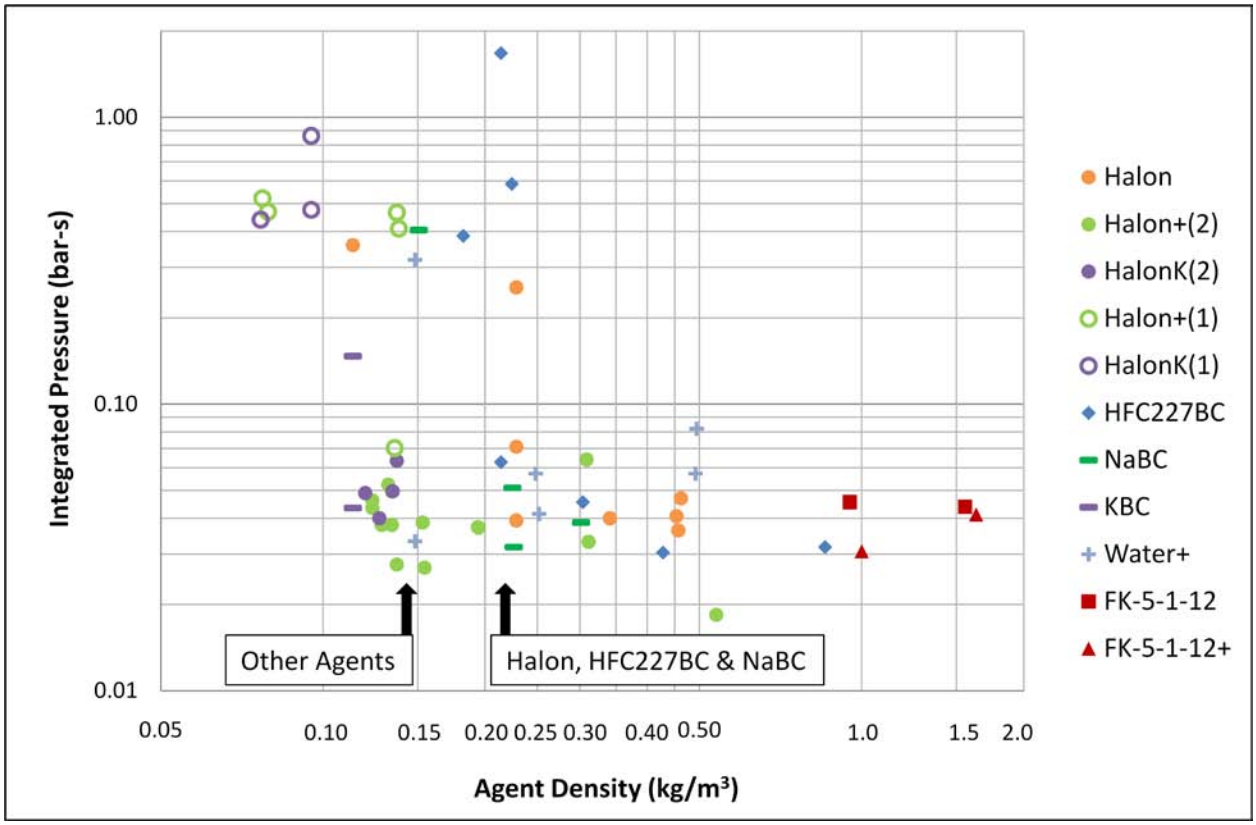

Figure 5. (U) Integrated Blast Pressure versus Agent Density for Halon with and without Dry Chemical Additives, HFC-227BC, Sodium- and Potassium-Bicarbonate Dry Chemicals and Water with Freeze-Point Suppressant. The arrows indicate the minimum agent densities required for successful suppression.

(U) DISCUSSION

(U) A few observations can be made based on the results described above:

- Figure 3 indicates that Halon 1301 and HFC-227BC performed similarly, although Halon 1301 yielded relatively higher acid doses, consistent with earlier findings (ref. 4).
- Tables 4 and 5 show that FK-5-1-12 was not effective whether used alone or mixed with dry chemical due to high acid gas levels.
- Tables 4 and 5 and Figure 5 indicate that dry chemical and water with additives may become viable but further analysis, development and testing are required.
- Figure 5 indicates that when used as the sole suppression agent, potassium-bicarbonate-based dry chemical is almost twice as effective by weight as sodium-bicarbonate-based dry chemical, consistent with earlier findings (ref. 23).
- Figures 3, 4 and 5 indicate that the mixes of Halon with sodium- or potassium-bicarbonate-based dry chemicals performed similarly.
- Figures 3 and 4 indicate that Halon with sodium- or potassium-bicarbonate-based dry chemicals is twice or more as effective by weight as currently deployed crew agents (Halon and HFC-227BC). This result needs to be verified in vehicle-level tests.
- None of the non-Halon agents as evaluated are drop-in replacements (i.e., have the same form factor and comparable performance) for Halon or HFC-227BC.

(U) It should be noted that a mix of Halon 1301 and dry chemical was evaluated previously in one live-fire test with reasonably good results. In that test, where a much lower fraction of dry chemical was used compared to the tests described herein, a significantly reduced acid level was measured compared to the test without the dry chemical (ref. 4). This is consistent with the findings reported herein where the amount of Halon 1301 required to successfully extinguish a fire was found to be reduced by a factor of more than two when mixed with dry chemical. This result needs to be verified with live-fire tests on application-representative vehicles.

(U) 'Water+' consistently knocked the initial fire down but reflash was reliably prevented only when proprietary developmental nozzles were used. Dry chemical systems did relatively well when higher-than-currently accepted concentrations were applied but were more prone to reflash than all the other agents except 'Water+.' The higher levels of dry chemical are probably safe for occupied areas but may pose unacceptable operational limitations; for example, a period of obscuration may last many seconds, and clean-up may be necessary more quickly than the current minimum acceptable delay of 48 hours.

(U) Earlier tests directed at understanding whether FK-5-1-12 is a viable Halon 1301 replacement in crew AFES were conducted by TARDEC (ref. 24) and the National Research Council of Canada (ref. 25) using fast-growth fires. These tests yielded similar results: total acid levels were well above current USA incapacitation limits. The tests described herein confirmed those results and extended them by using a wider range of agent concentrations, extinguisher technologies, and distribution nozzles. Although a custom nozzle developed for FK-5-1-12 in this application was used (ref. 25), further improvements in distribution may be possible.

(U) Insight into why FK-5-1-12 performed relatively poorly in these and similar tests may be obtained by considering that other FK-5-1-12 tests were 'total flooding' and used pan-fires, not

fast-growth, explosive fire threats (see ref. 26 for example). Total flooding systems typically inert a protected volume with sufficient agent concentrations to prevent combustion, and the fires are typically small with respect to the protected volume. The tests reported herein matched relatively large, fast-growing fires with rapid but essentially local agent application, a very different scenario than typical total flooding.

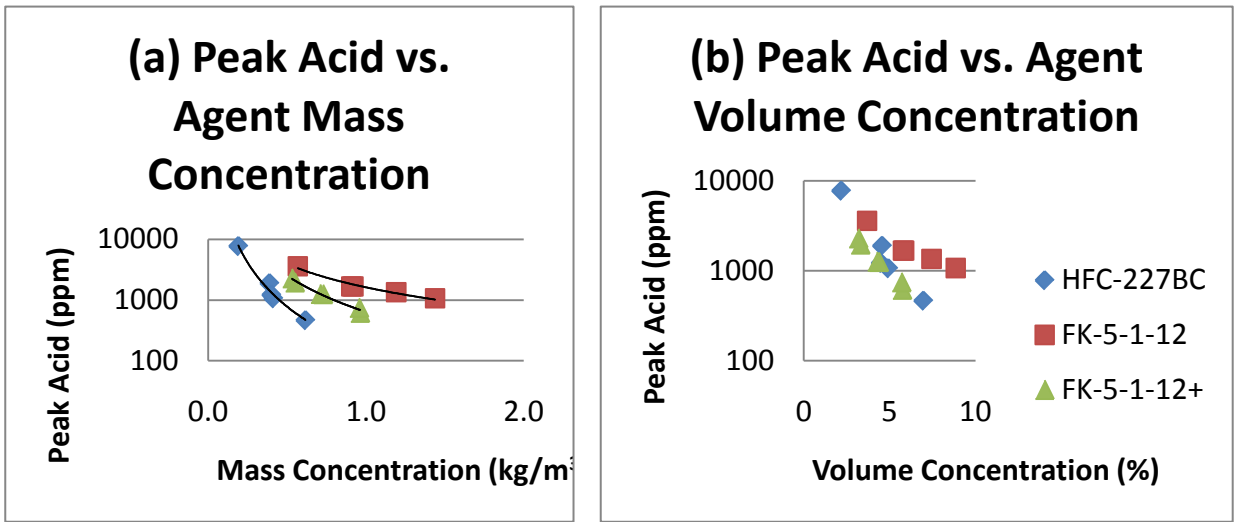

Figure 6. (U) Peak Acid levels for 'HFC-227BC,' 'FK-5-1-12+' and 'FK-5-1-12' (ref. 13b) versus Agent a) Mass and b) Volume Concentrations. The solid lines in (a) are power curve fits. Note: Although the peak acid levels for 'HFC-227BC' and 'FK-5-1-12+' are similar, the integrated levels used in casualty assessments were very different: none of the FK-5-1-12-based tests 'passed.'

(U) Fire protection professionals often evaluate suppression agents in terms of the required concentration (usually on a volume percent basis as in ref. 26). While comparisons based on concentration are valid and useful, it must be remembered that other agent properties such as required mass must be considered separately. Figure 6 compares peak acid levels measured (ref. 13b) in 'HFC-227BC,' 'FK-5-1-12+' and 'FK-5-1-12' tests versus mass and volume concentrations (ref. 16). Although the peak acid levels versus concentration for the agents are very similar, especially for the 'HFC-227BC' and FK-5-1-12+,' the mass of agent that yields a given acid level is very different: far more 'FK-5-1-12+' than 'HFC-227BC' by mass must be delivered to achieve the same acid level.

(U) Note that although the peak acid levels for 'HFC-227BC' and 'FK-5-1-12+' in Figure 6 are similar, the integrated levels used in casualty assessments were very different: none of the FK-5-1-12-based tests 'passed,' as shown in Figure 3. The difference is related to the relative evolution in time of COF_2 and HF. Halon and HFC-227BC tests with good fire suppression show COF_2 quickly peaking and then slowly decaying as the HF level slowly rises; in FK-5-1-12 tests both COF_2 and HF peak quickly and then slowly decay. The result is that the total integrated acid level used in casualty assessments (see Table 3) is higher in FK-5-1-12-based tests (ref. 13).

(U) As noted earlier, the tests described herein were conducted using a test box without significant clutter and at the ambient temperature at the test site. More comprehensive, vehicle level tests should address the effects of clutter and operation at temperature extremes (especially low temperatures).

(U) CONCLUSION

(U) Meeting current performance requirements for crew AFES in USA ground vehicles using alternatives to Halon 1301 and HFC-227BC tested to date will require some combination of invention, development and/or increase in space claim and weight compared to fielded systems. The basic result is that, with current products, none of the alternate agents are drop-in replacements for Halon 1301 or HFC-227BC. However, a blend of Halon 1301 and dry chemical has been found to be about twice as effective as Halon 1301 alone. Thus, pending confirmation tests on vehicles, it may be feasible to use less Halon in legacy systems without compromising fire protection performance.

(U) Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

(U) ACKNOWLEDGEMENTS

(U) This program was funded by Ground Systems Survivability (GSS) at TARDEC and is a continuation of the work reported previously (ref. 27). Valuable support and discussions with Ron Sheinson of the Naval Research Laboratory and Joe Senecal of United Technology Fire & Security are gratefully acknowledged. The excellent support of Aberdeen Test Center's Poverty Island Range 12 team was crucial to completing these tests.

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NFPA SUPDET
February 2010

Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Steve Hodges
Alion Science & Technology

Steve McCormick
TARDEC GSS

Background

- The US Army plans to modernize legacy vehicle platforms, including Automatic Fire Extinguishing Systems (AFES).
- Legacy vehicles use Halon 1301 or HFC-227BC to protect the crew. 1301 has high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). HFC-227 has high GWP.
- The Army is considering replacing legacy agents with more environmentally friendly suppression agents.
- TARDEC was tasked to test alternate agents, including FK-5-1-12.
  - FK-5-1-12 suppression agent has zero ODP and low GWP. The manufacturer has claimed that it is essentially a drop-in replacement for 1301 or HFC-227ea.

Environmental Legislation

- AAE: Requires modification of a vehicle to include replacement of ozone-depleting material(s). Waiver process available.
- Legislation to continue and accelerate phase-out of Ozone Depleting Substances (ODS) *and lower 'Carbon footprint'* are being developed:
  - International
    - Montreal Protocol Amendments (4May09)
      - *Proposal made to "*regulate and phase down the production of hydrofluorocarbons (HFCs) and promote the destruction of banks of ozone-depleting substances (ODS).*"*
    - *New Protocol to regulate GHG's?*
  - In the US
    - State
      - *CA (AB32) – reduce GHG emissions to '90 levels starting in '12*
      - *MN (SF 3337) – requires reporting of high GWP material usage*
    - National
      - *On 24April09 the EPA announced that GHG's including HFC's "…*in the atmosphere threaten the public health and welfare of current and future generations." This is referred to as the endangerment finding.
      - *HR2454 proposes to amend the Clean Air Act to limit GHG's (15May09)*

Current Applications

Crew AFES agents in order of qualification.

Platform	Crew AFES Agent
Abrams Main Battle Tank	Halon 1301
Bradley Fighting Vehicle (BFV)	Halon 1301
*Field Artillery Ammunition Support Vehicle (FAASV)	Halon 1301
USMC Expeditionary Fighting Vehicle (EFV)	HFC-227BC
STRYKER Brigade Combat Team (BCT)	HFC-227BC
Up-Armored HMMWV (UAH)	HFC-227BC
Mine Resistant Ambush Protected (MRAP)	HFC-227BC
USMC Light Armored Vehicle (LAV)	HFC-227BC
MRAP All-Terrain Vehicle (MATV)	HFC-227BC
**Joint Light Tactical Vehicle (JLTV)	HFC-227BC
***Future Combat Systems (FCS)	HFC-227BC

*Upgrade to HFC-227BC in process **In development ***Manned Ground Vehicle Cancelled

Agent Comparisons

	Property	Halon 1301	HFC-227ea[a]	FK-5-1-12[b]	Water+[c]	Dry Chemical[d]
Environmental	Ozone Depletion Potential[e]	16	0	0	0	0
	Global Warming Potential[f]	6900	3500	1	0	0
	Atmospheric Lifetime (yr)	65	33	0.014	0	0
Safety	Design Concentration (%v/v)	5	8.7	6.7[g]	~300 g/m^3	~300 g/m^3
	NOAEL[h] (%)	5	9.0	10	NA	TBD[j]
	LOAEL[i] (%)	7.5	>10.5	10	NA	TBD[j]
Physical	Boiling Point (°C)	-58	-16	49	115	N/A
	Vapor Pressure @ 21°C (bar)	13.7	4.1	0.41	0.03	N/A
	Liquid Density (g/cm^3)	1.56	1.39	1.60	1.27	2.16
	Molecular Weight (g/mol)	149	170	316	31	84
	Heat of Vaporization (J/g)	117	132	88	>2250	N/A

a) HFC-227ea is a form of heptafluoropropane and is sold as a fire extinguishing agent. b) FK-5-1-12 is a perfluorinated six-carbon ketone manufactured and sold as a fire extinguishing agent. c) Water with 50% Potassium Acetate. d) Values given are for sodium bicarbonate-based dry chemical. Potassium bicarbonate crystal density is 2.17 g/cm^3. e) CFC11 baseline, ref. 8. f) CO_2 baseline, ref. 9. g) Concentration advised by the agent manufacturer for this application. h) No Observed Adverse Effects Level. i) Lowest Observed Adverse Effects Level. j) Acceptable concentration levels for this application to be determined by the USA.

Exploratory Tests

Purpose

TARDEC's Exploratory tests are intended to compare various suppression agents, including new, more environmentally friendly ones, with those currently deployed.

Approach

- Three extinguisher suppliers supported the tests (12/08-9/09) – they were asked to provide suppression systems that would yield marginal suppression 'passes' and 'failures' based on current vehicle performance criteria.
- The tests were conducted in a 260 ft^3 (7.36 m^3) box with relatively little clutter, no stowage, and no active air flow.

Tests (continued)

Seven test series conducted between Dec08 and Sep09

- 157 live-fire tests
- 9 suppression agents
  - Halon 1301 - ‘halon’ (*used in legacy vehicles)*
  - Halon 1301 with Dry Chemicals (DC) – ‘halon+’ & ‘halonK’
  - HFC-227ea with DC – ‘HFC227BC’ (*used in vehicles since 2001)*
  - FK-5-1-12
  - FK-5-1-12 with DC – ‘FK-5-1-12+’
  - Water with Potassium Acetate – ‘water+’
  - Two Dry Chemicals – Sodium (+) and Potassium (K) Bicarbonates
- 4 Extinguisher configurations from 3 suppliers
  - N_2 charged with solenoid valve (Abrams, BFV, FAASV, STRYKER, UAH, & some MRAP)
  - N_2 charged with linear actuated valve (NLOS-C Crew & Mission)
  - N_2 charged with SQUIB actuated valve (some MRAP)
  - Hybrid Fire Extinguisher actuated by Gas Generator (experimental)

Unsuppressed Fire (BL1)

Suppressed Fire (KHBC1)

Selected Crew Casualty Criteria

Parameter	Requirement[a]	Test[b]
Fire Suppression	Extinguish all flames without reflash	Y
Skin Burns	Less than second degree burns (<2400°F-sec over 10 seconds or heat flux < 3.9 cal/cm^2)	c
Overpressure	Less than 11.6 psi	Y
Agent Concentration	Not to exceed Lowest Observed Adverse Effects Level	Y
Acid Gases ($HF + HBr + 2 \cdot COF_2$)	Less than 746 ppm-min (5 min dose)	Y
Oxygen Levels	Not below 16%[d]	Y
Discharge Impulse Noise	No hearing protection limit: <140 dBP[e] Single hearing protection limit: <165 dBP[e]	N
Discharge Forces	Not to exceed 8 g[g] and <20 psi at 5 inches[f]	N

(a) Based on "*Medical Evaluation of Non Fragment Injury Effects in Armored Vehicle Live Fire Tests,*" Walter Reed Army Institute of Research, September 1989 except as noted.

(b) Addressed in Exploratory Tests. (c) Temperature recorded with thermocouples.

(d) "Fire Survivability Parameters for Combat Vehicle Crewmen," Memo to the US Army Surgeon General, 20 February 1987.

(e) "Hearing Conservation Program," US Army Pamphlet 40-501, 10 December 1998.

(f) "Evaluation of Potential Physical Injury from Mechanical Forces Due to Automatic Fire Extinguisher System Discharge in the STRYKER Combat Vehicle: An Initial Assessment and Recommendations to Prevent Injury," Walter Reed Army Institute of Research, 21 August 2003

Results

Agent	N_2 Solenoid	N_2 Linear	N_2 Squib	GG HFE	Total Tests	*Total 'Passes'
Halon	19	0	0	2	21	12 (57%)
Halon+	19	0	0	0	19	16 (84%)
HalonK	7	0	0	0	7	4 (57%)
HFC227BC	16	8	1	11	36	17 (47%)
FK-5-1-12	10	0	4	7	21	0
**FK-5-1-12+	6	0	2	7	15	0
**Water+	12	0	1	10	23	12 (52%)
NaBC	13	0	0	0	13	7 (54%)
KBC	2	0	0	0	2	2 (100%)
TOTAL	104	8	8	37	157	70 (45%)

*Based on vehicle criteria. The goal was to 'pass' half the tests.

** Prototype Hardware

Overview of Results

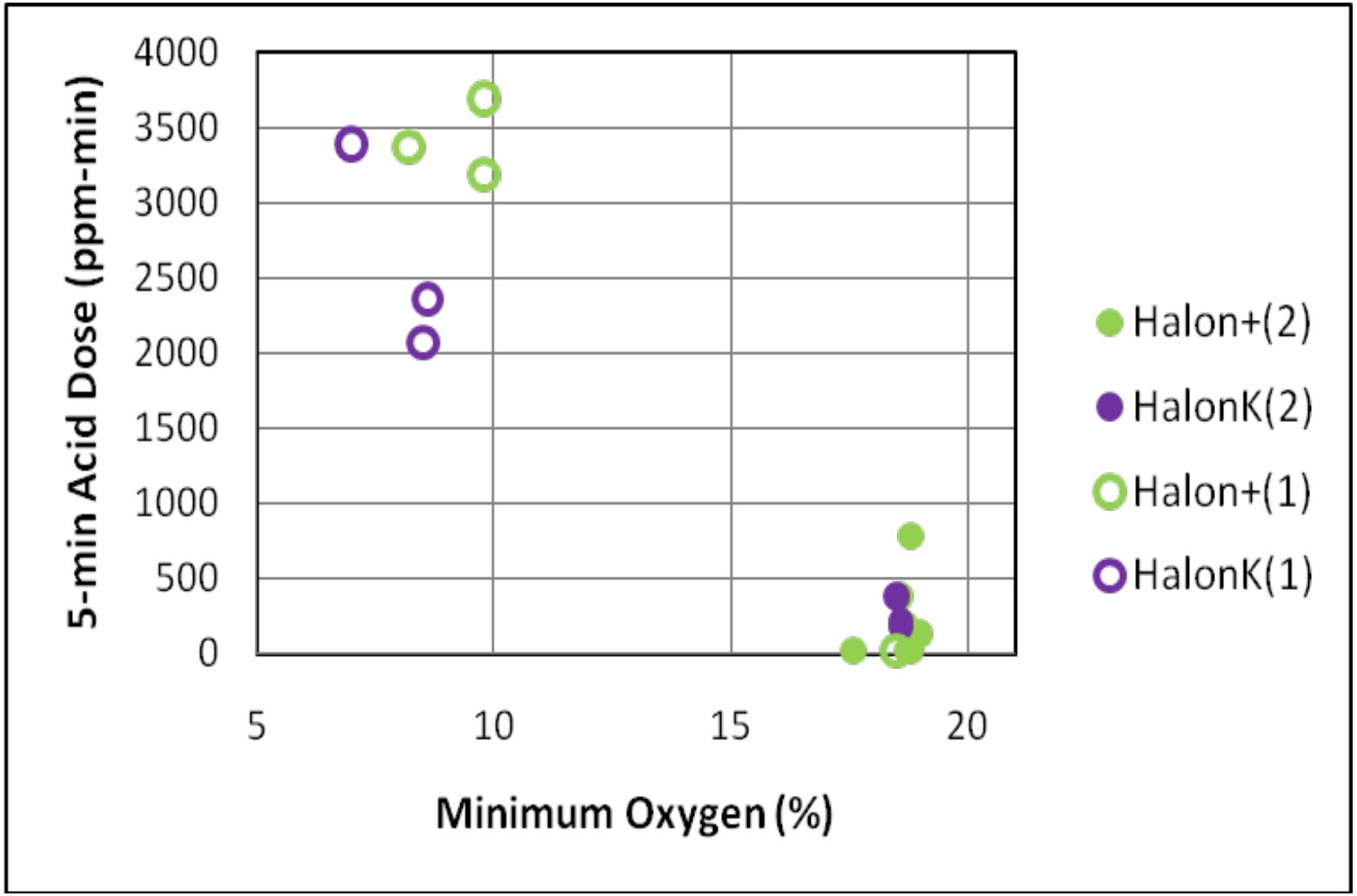
				**Best Performance			
Agent	Total	*Pass	**Least Agent Weight (lb)	Lowest Acid Dose (ppm-min)	Lowest Pressure Peak (psi)	Fastest Fire Out Time (ms)	Note
Halon	21	12	~5	~500	<1	<200	Legacy fielded product
Halon+	19	16	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HalonK	7	4	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HFC227BC	36	17	~5	<20	<1	<200	Fielded product
FK-5-1-12	21	0	>25	~2,000	1.2	<200	Available
FK-5-1-12+	15	0	>15	~1,300	1.6	<200	Invention required
Water+	23	12	~4	0	1.5	~400	Development required; operational issues?
NaBC	13	7	~3	0	<1	<200	Available; safety & operational issues?
KBC	2	2	~2	0	<1	<200	Available; safety & operational issues?
Total	**157**	**70**					

* The goal was to 'pass' half the tests

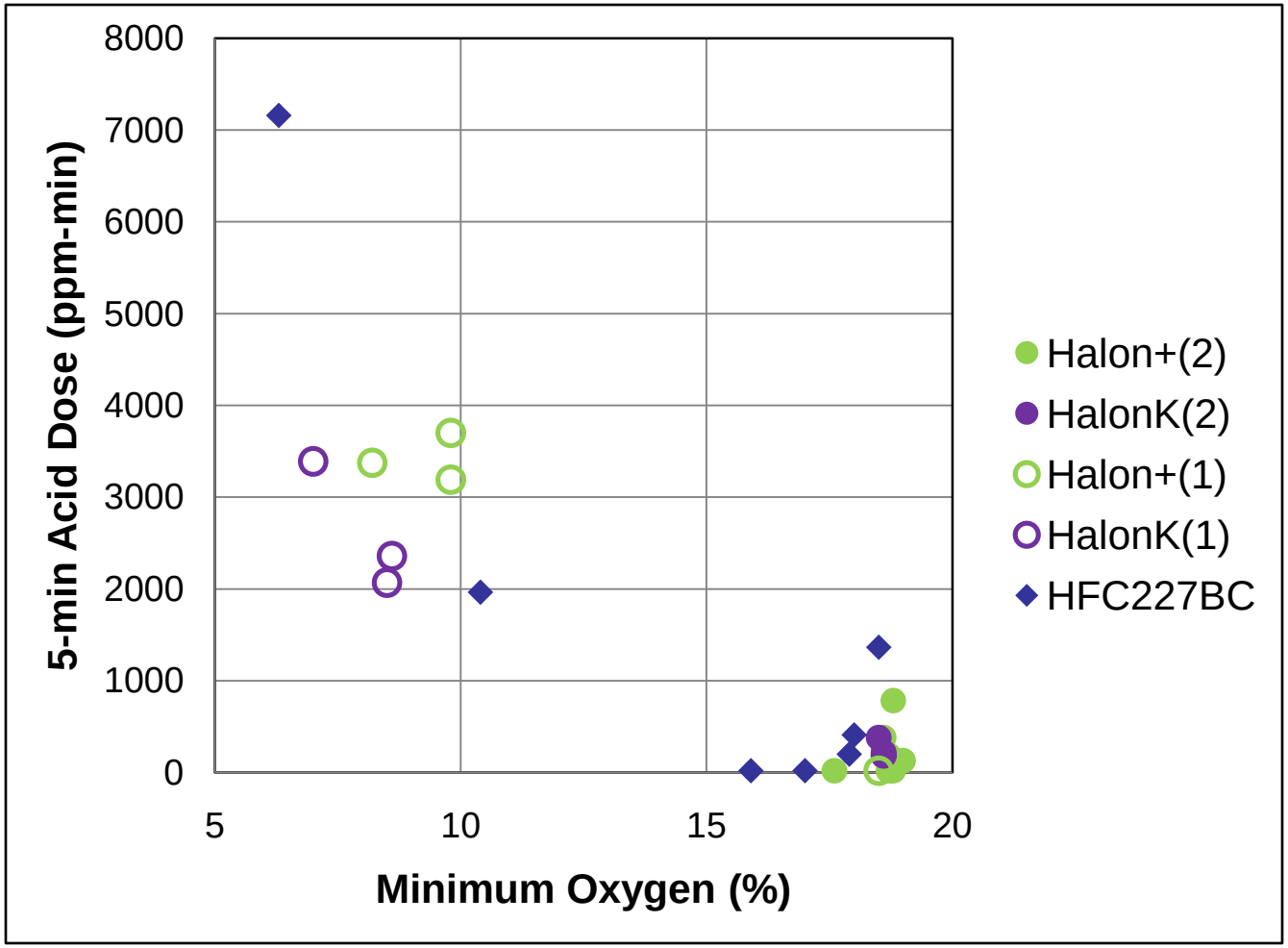
** Best Performance and Least Agent Weight are not obtained simultaneously

Comparison of Fluorinated Agents

Oxygen Limited

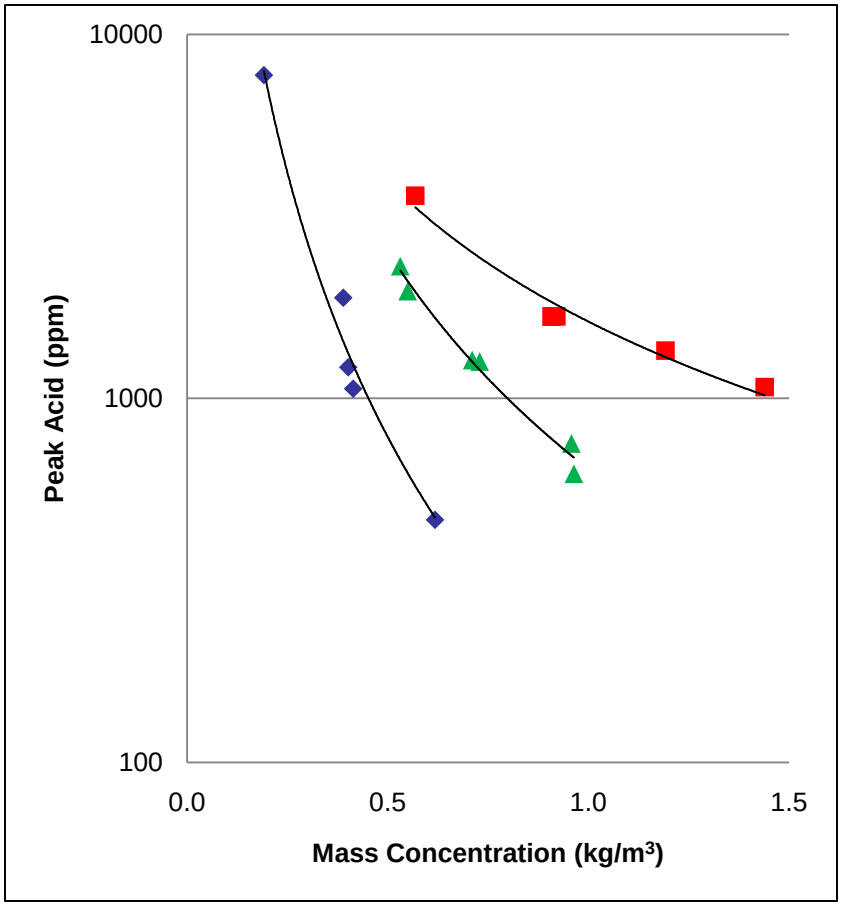


Oxygen Limited



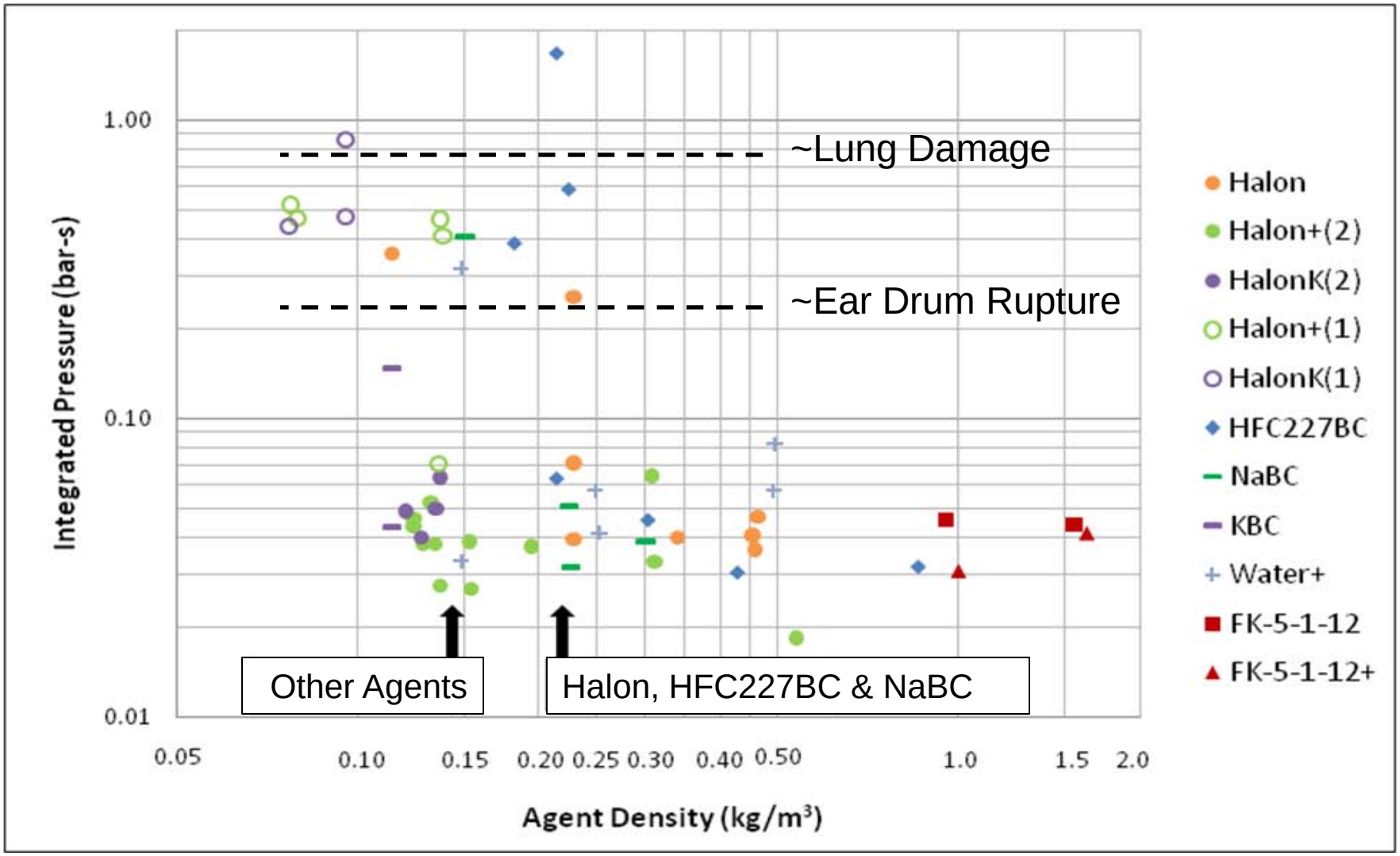
Some Insight

- Acid vs. Mass and Volume Concentrations



Note: Although the peak acid levels for 'HFC227BC' and 'FK-5-1-12+' are similar, the integrated levels used in casualty assessments were very different: none of the FK-5-1-12-based tests 'passed.'

Comparison of Agents



Results Summary

Agent	Limiting Criteria	Collateral Criteria	Other Issues
Halon	Acid Gas	Pressure & Temperature	Deployed & Stockpiled
Halon+, K	Pressure	Acid Gas & Temperature	New Agent Mix
HFC227BC	Acid Gas & Reflash	Pressure & Temperature	Deployed
FK-5-1-12	Acid Gas	Reflash	Weight
FK-5-1-12+	Acid Gas	Reflash	Weight, Agent Compatibility
Water+	Reflash	Pressure & Temperature	Availability, Clean-up
Dry Chems	Reflash	Pressure & Temperature	Safety, Obscuration & Clean-up

Summary

Results from 157 Tests using 9 agents indicate:

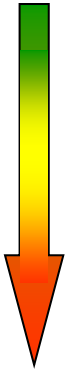
- Halon 1301 and HFC-227BC performed similarly, although Halon 1301 yielded relatively higher acid doses, consistent with earlier findings.
- FK-5-1-12 was not effective whether used alone or mixed with dry chemical due to high acid gas levels.
- Dry chemical and water with additives may become viable but further analysis, development and testing are required.
- When used as the sole suppression agent, potassium-bicarbonate-based dry chemical is almost twice as effective by weight as sodium-bicarbonate-based dry chemical, consistent with earlier findings.
- Mixes of Halon with sodium- or potassium-bicarbonate-based dry chemicals performed similarly.
- Halon with sodium- or potassium-bicarbonate-based dry chemicals is twice or more as effective by weight as currently deployed crew agents (Halon and HFC-227BC). This result needs to be verified in vehicle tests.
- None of the non-Halon agents as evaluated are drop-in replacements for Halon or HFC-227BC.

Path Forward: Alternate Agents

Long-Term Path Forward: Evaluate zero ODP agents

HFC-227BC

- Used in other vehicles
- Only qualified crew alternative
- Can use existing extinguishers
- Reasonable purchase cost
- Limited R&D funding required
- Potential future controls due to GWP



FK-5-1-12

- Extremely low GWP
- Very low Atmospheric Lifetime
- Comparable cost to HFC-227ea
- Highest acid gas
- Requires redesigned delivery system
- Additional R&D required

Water+ or Dry Chemical

- Long Term Environmental Friendly Agent – no GWP
- No acid gas
- Extremely low purchase cost
- Requires redesigned delivery system
- Additional R&D required

Agent	Surgeon General Approved	Zero ODP	GWP	Environ. Legislation	Fire Suppression		Size/ Weight	Ops	Extinguisher Design for Discard
Halon 1301	Yes	No	6900	Yes	OK		OK	Clean	Probable
Halon 1301+	Probable	No	6900	Yes	Low Acid		Least	OK	Probable
HFC227BC ?7+	Yes	Yes	3500	Proposed	OK		OK	OK	FCS
FK-5-1-12	TBD	Yes	1	No	Highest Acid		Heaviest	Clean	TBD
FK-5-1-12+	TBD	Yes	1	No	High Acid		Heavy	OK	TBD
Water+	Yes	Yes	0	No	No acid	Reflash	TBD	TBD	TBD
Dry Chemical	TBD	Yes	0	No	No acid	Reflash	Low	TBD	Aviation

Future Approach

Short-Term

Bradley M2A3 AFES Upgrade includes effort to evaluate environmentally friendly (zero ODP, short atmospheric lifetime, and low GWP) extinguishing agents for the crew compartment.

Long-Term Options

Three potential options for modernization efforts:

1. Use current reserve of Halon 1301 until depleted
   - Perhaps with reduced usage and improved performance using Halon/Dry Chemical
2. Integrate HFC-227BC into crew AFES
3. Investigate alternative agents including: Water with Additives, Dry Chemical, and FK-5-1-12 with Dry Chemical

Next Steps

- Agent Down-Select
  - Performance
  - Operational Issues
  - Environmental Concerns
- Follow-on tests in vehicles

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