US ARMY GROUND VEHICLE CREW COMPARTMENT HALON REPLACEMENT PROGRAM

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ABSTRACT

Halon 1301 is used as the primary fire and explosion extinguishing material for a multitude of industrial and military applications. However. halons have very high ozone-depleting potentials and their production was stopped in 1994 in most of the world. The Army's halon replacement program sought to identify and develop replacement technologies that will satisfy the performance and logistics requirements of fire protection for ground combat vehicles. Early investigations indicated that **a** universal solution would not be available to the fire protection community for all the systems that used halon. Hence. multiple agents would probably be required to address the wide range of military applications currently satisfied by halon. This paper summarizes the results and findings **of** the Army's Ground Vehicle Crew Compartment Halon Replacement Program. Two agents and several delivery system options have been identified that appear to provide equivalent performance to the halon systems without significant space or weight penalties. Future work includes the integration and testing **of** a crew fire and explosion suppression system in an actual combat vehicle before a final agent selection is validated.

INTRODUCTION

Halon-based fire extinguishing systems are widely used throughout the world to protect military ground combat vehicles. The US Army has aggressively pursued environmentally and toxicologically acceptable alternatives to Halon 1301 for its three ground vehicle applications: crew compartment automatic 'explosion' suppression systems, engine compartment fire extinguishing systems, and portable extinguishers. To date. the 2.75-pound 1301 portable extinguishers have been replaced with 2.5-pound CO_2 units in most vehicles. The M1 Abrams tank, due to health concerns, still retains the Halon 1301 handheld extinguisher. Final testing is underway for this application, and an alternative handheld may be qualified by the beginning of FY01. Replacements have also been selected for vehicle engine compartments. Sodium bicarbonate-based dry powder will be used in vehicles with an automatic extinguishing system (including the M1) because of its superior performance. HFC-227ea (a.k.a. FM-200) is being installed in vehicles that shut the engine off prior to agent discharge (including the M2/M3 Bradley fighting vehicle series) because of its ease of retrofit. This offers the lowest overall life cycle cost solution. The remaining research challenge is to perfect the application of a fire extinguishing agent and its distribution system for crew compartments. which can then be retrofit into current vehicles as well as address the needs of future vehicles.

CREW COMPARTMENT PROGRAM

With the exception of the former Soviet Bloc countries, Halon 1301 has been the agent of choice to protect vehicle crewmen against burns from ballistically initiated fuel or hydraulic fluid fires. The US Army currently has three fielded ground vehicles using Halon 1301 to protect their crew compartments: the M1 Abrams main battle tank, the M2/M3 Bradley Fighting Vehicle, and the M992 Field Artillery Ammunition Support Vehicle (FAASV). The crew compartments of these vehicles range in volume from 250 to 700 ft' and employ from seven pounds of Halon 1301 in a single shot to 21 pounds in each of two shots. We also must support future ground combat vehicles with crew protection, including the Interim Armored Vehicles, Crusader, Future Combat System, and the USMC Advanced Amphibious Assault Vehicle (AAAV).

The Army Surgeon General has established the guidelines shown in Table 1 as the minimum acceptable requirements of automatic fire extinguishing systems for occupied vehicle compartments. These parameters have been established at levels that would not result in incapacitation of the crew from the fire and its extinguishment, allowing them to take corrective action and potentially to continue their mission.

TABLE 1. CREW SURVIVABILITY CRITERIA.

Parameter	Requirement
Fire suppression	Extinguish all flames without re-flash
Skin burns	Less than second degree burns (<2400 °F-sec over 10 sec or heat flux <3.9 cal/cm^2)
Overpressure	Less than 11.6 psi
Agent concentration	Not to exceed LOAEL (Lowest Observed Adverse Effects Level)
Acid gasses	Less than 1000 ppm peak
Oxygen levels	Not below 16%

The Army's crew compartment test program was divided into three phases. Phase I was a proof of concept and screening phase of multiple agents and technologies. Phase II consisted of further developmental testing of several of the most promising concepts from Phase I. Testing was conducted at the Army's Aberdeen Test Center (Aberdeen, MD). Based on performance and system integration issues, two agents were recommended to the vehicle program managers for Phase III testing, where prototype fire extinguishing systems are to be evaluated in the affected ground vehicles.

TEST SETUP

The crew test fixture was constructed from an excess ground vehicle hull and turret. A top down layout of the fixture is shown in Figure 1. The fixture had an interior volume of approximately 450 ft^3 empty as used in Phase I testing. For Phase II, three "tin" mannequins and a four-unit TOW missile rack (added in dashed lines) were added to simulate partial vehicle stowage. The cargo and turret hatches and ramp door were secured during each test while the driver's hatch was allowed to pop open to relieve internal overpressures while minimizing airflow.

Instrumentation included high-speed and standard video, I-micron infrared detectors, heat flux gages, thermocouples, and pressure gages. Four types of instrumentation measured acid gas exposure levels: ion selective electrodes (grab bag sampling), sorbent tubes (NIOSH procedure 7903), midget impingers, and FT-IR analyzers. The FT-IR was the only one of these methods that reported levels of the gases themselves, as opposed to fluorine **or** bromine ions. Gas species tested for included oxygen **(as** O_2), hydrogen fluoride **(HF),** hydrogen bromide (HBr), and carbonyl fluoride (COF_2). Nitrogen oxide (NO), nitrogen dioxide (NO_2), carbon oxide (CO), and carbon dioxide (CO_2) levels were also monitored during certain gas generator tests.

Two test scenarios were conducted in Phases I and II: fuel spray fires and ballistic penetrations. The spray fire was generated with approximately 0.3 gallons of JP-8 heated to 180-190 °F and pressurized to 1200 psi using a specially designed nozzle. Fuel flow continued for approximately 1.2 sec with the igniter energized for the duration of the spray to simulate the reignition

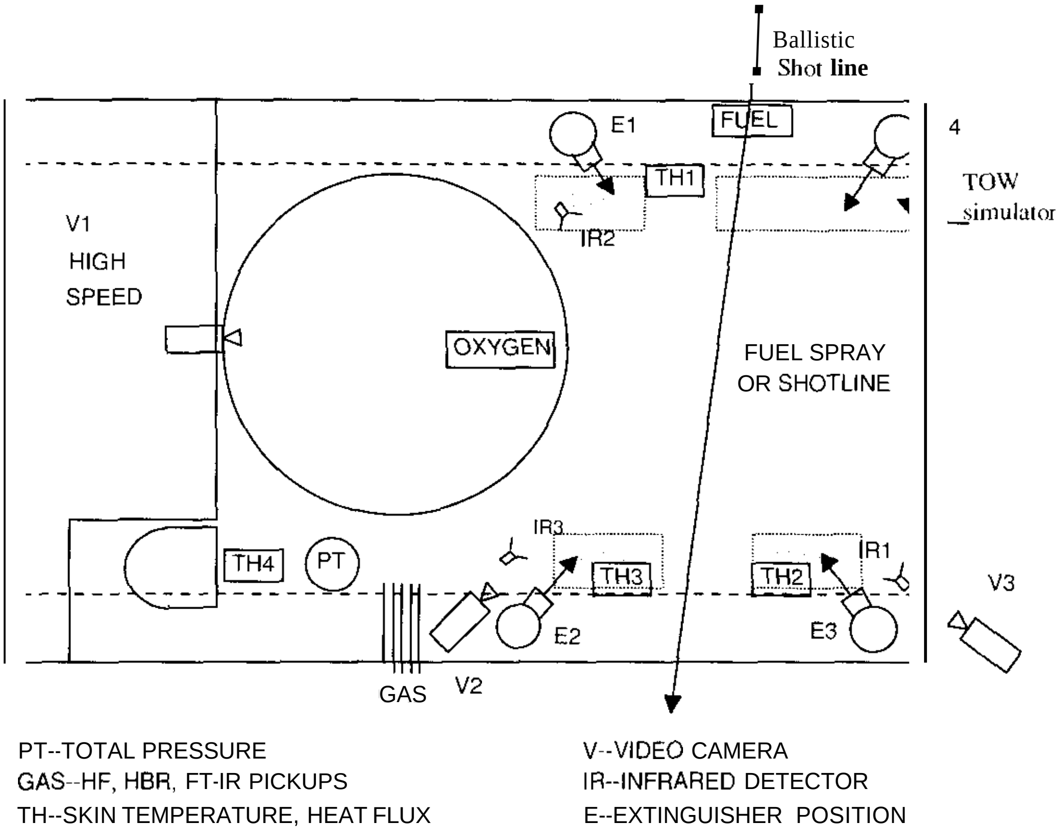

Figure 1. Crew compartment test fixture.

sources present during a typical ballistic event. The spray fires were monitored with three one-micron infrared detectors. The extinguishing system was activated automatically after an 11-msec delay from the time the fire energy reached a predetermined threshold. Ballistic fires were generated by firing a 2.7 inch shaped charge through an 18.7 gallon (2.25 ft^3) capacity aluminum fuel cell filled with 11 gallons of JP-8 heated to 165 °F. The fire extinguishing system was activated 25 msec after warhead initiation to eliminate the variability of the detection system.

PHASE I RESULTS

A sample of 6 baseline test results is reported in Table 2. The data are consistent with trends that we expected to find in this environment: (1) the delivery of the agent is as or more important than the agent itself, and (2) the faster the fire is extinguished, the lower the byproduct levels (acid gases).

Several alternative concepts were also evaluated under Phase I. They can be divided into five categories: fluorocarbons (i.e., HFCs and PFCs) with nitrogen overpressure, water spray with nitrogen overpressure. hybrid gas generators with HFCs, hybrid gas generators with water, and novel distribution systems (e.g., wet main systems) as illustrated in Figure 2. Various additives to inhibit freezing and enhance effectiveness of the water and to neutralize acid byproducts generated from the HFCs were also investigated. Representative data are displayed in Table 3 for several of the configurations tested. Thermocouple and heat flux data indicate that burn thresholds are not being exceeded under these scenarios for either the ballistic or the spray fire for the HFC-227ea/dry powder systems.

TABLE 2. PHASE I (W/O CLUTTER) BASELINE BALLISTIC TEST DATA.

Agent*	Total Weight (lbs)	Bottle Config # x in	IR fire-out (msec)	Video fire-out (msec)	2-Min Ave HF (ppm)	Peak HF (ppm)
Halon 1301	8.1	2 x 144	241 – 555	- 202	1473 – 2205	Unavailable
Halon 1301	10	3x144	161–384	120–368	316–995	1310
Halon 1301 + BCS	10 + 0.3	3 x 144	440–3000	120–142	274–498	320
FM-200	11.9	2 x 144	Reflash	220 – unk	19500 – 20561	Unavailable
FM-200	12.1	3 x 144	–2200	250 – 980	1741 – 4473	Unavailable
FM-200	14.7	3 x 144	2000 – 4000+	reflash	2801 – 2933	12700
FM-200	15	4 x 144	211–234	200–320	947–1176	1360
FM-200 + BCS	12.2 + 0.3	3 x 144	189 – 358	100 – 170	BDL	BDL

*All tests used the "standard" Army equipment bottles, valves and nozzles with nitrogen overpressure.
BCS – bicarbonate of soda
BDL – below detection limits (less than 35 ppm)

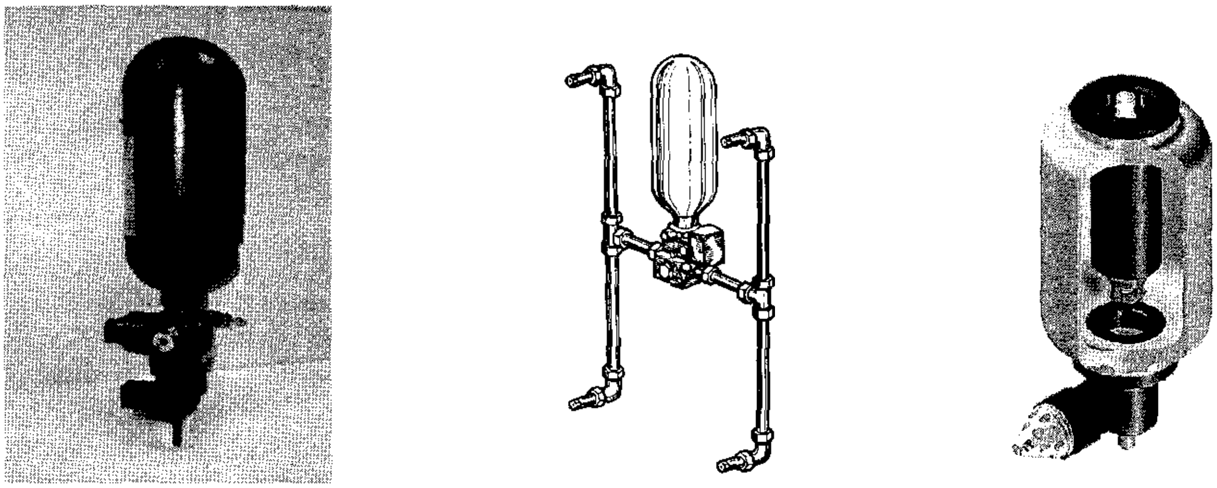

Figure 2. Candidate agent delivery methods.

PHASE II RESULTS

The baseline tests of Phase I using standard Army extinguishers were repeated with clutter and the results are shown in Table 4. As can be **seen** by comparing Tables 2 and 4, the clutter increased the fire suppression challenge. Based on the results of Phase I and guidance from the EPA Significant New Alternatives Policy (SNAP) program, wet mains and hybrid gas generators, and combinations thereof, and HFC-227ea/dry powder and water/potassium acetate agents were selected for further evaluation in Phase II.

Representative results of the Phase II ballistic tests with clutter are shown in Table 5. Note that the improved distribution systems accounted for reduced extinguishing times and lower HF levels even while using **less** agent and/or fewer extinguishers. Even for those tests with extended extinguishing times the byproducts levels were significantly lower than for equivalent tests in Phase I or baseline tests of Phase II.

TABLE 3. PHASE I (W/O CLUTTER) BALLISTIC TEST DATA.

Agent / Distribution System	Total Weight (lbs.)	Bottle Config # x in'	IR fire-out (msec)	Video fire-out (msec)	1-Min Ave HF (ppm)
CEA-308 – ss	19.1	4 x 144	120 – 123	100 – 110	4600 – 4794
CEA-308 + BCS – ss	19.4 + 0.5	4 x 144	157 – 181	120 – 150	1150 – 1784
FM-200 – ss	18.0	3 x 204	213 – 302	106 – 200	2600 – 2900 ¥
FM-200 – gg	15.9	3 x 126	186 – 239	106 – 150	1410 – 6798 ¥
FM-200 + BCS – ss	16.4 + 1.5	3 x 204	180 – 227	162 – 170	125 – 573
FM-200 + BCS – gg	10 + 1.25	3 x x4	134 – 149	104 – 150	85 – 440
H_2O/KAce – gg	33.6	2 x 244	1x4 – 253	118 – 250	n/a
H_2O/KAce – gg	21	3 x 147.4	160 – 383	92 – 168	n/a
H_2O/KAce – wm	10.5	3 x 204	124 – 215	YO – 300	n/a

¥ - 2 min average
ss - Standard Army type System with nitrogen overpressure
gg - Gas Generator for agent expulsion
wm - Wet Main distribution system

TABLE 4. PHASE II (W/CLUTTER) BASELINE TEST DATA.

Agent*	Total Weight (lbs)	Bottle Config # x in^3	IR fire-out (msec)	Video fire-out (msec)	2-Min Ave HF (ppm)	Peak HF (ppm)
1301	9.9	3x144	777-1023	750-1000	2063	10348
1301	16	4x144	159-167	150-180	1789	34x3
1301	12	4x144	179-193	180-220	1472	2031
1301	10	4x144	189-268	220-250	1086	1302
FM-200	16	4x144†	172-216	180-240	844	1051
FM-200	12	4x144	185-220	IYO-260	1344	1636
FM-200 + BCS ‡	12+1	4x144	173-214	180-220	70	134

* All tests used the 'standard' Army equipment bottles, valves, and nozzles.
† bottles reoriented for this and subsequent tests
‡ 0.25 pound of sodium bicarbonate was added to each extinguisher

OBSERVATIONS

Baseline tests with Halon 1301 and HFC-227ea using standard Army extinguishers and nozzles indicate that a total agent weight of 10 pounds of 1301 delivered by three extinguishers is required to extinguish both the fuel spray and ballistic fires successfully. Lower agent weights lead to longer fire-out times, and the byproduct levels rise significantly. Fifteen (15) pounds of HFC-227ea provided approximately equivalent performance except the HF levels were elevated. However. HFC-227ea with a small amount of sodium bicarbonate imbedded or "suspended" within the HFC required only 12 pounds of material (divided among four standard 144 in^3 extinguishers) and dramatically reduced the HF in both the spray and ballistic tests. Temperature and heat flux data indicate that burn thresholds were not being exceeded for either the ballistic or the spray fire for those HFC-227ea/dry powder systems tested.

TABLE 5. PHASE II (W/CLUTTER) BALLISTIC TEST DATA.

Agent/Delivery System	Total Weight (lbs.)	Bottle Config # x in^3	IR fire-out (msec)	Video fire-out (msec)	2-Min Ave HF (ppm)	Peak HF (ppm)
FM-200 -gg	18.0	3x195	93-96	92-140	317	333
FM-200 -gg	18.0	3x195	106-135	86-210	229	952
FM-200 + BCS - gg	18.0+0.6	2x192	159-188	152-180	52	73
FM-200 + BCS - gg	15.0+0.6	2x195	34-385	450	327	371
FM-200 + BCS - gg	12.0+0.6	2x142	277-431	400-730	562	791
FM-200 - wm	16.2	wet main	407-937	784-1000	1495	2077
FM-200 + BCS -wm	11.2+0.8	wet main	1272-1656	810-1290	681	1280
H2O/Kace -gg	10.2	3x142	180-245	102-350	n/a	n/a
H2O/Kace - gg	10.2	3x142	136-156	124-200	n/a	n/a
H_2O/Kace - wm	24.0 *	wet main	221-317	260-650	n/a	n/a

gg - gas generator for agent expulsion
wm - wet main distribution system
* -discharge extended well beyond extinguishing time

The baseline data for Phase II are slightly different than that of Phase I (Table 4). The data demonstrate the increased difficulty of extinguishing deflagrations while distributing the agent around clutter. It also points out that the delivery system is critical in the overall optimization process for a particular fire/explosion scenario.

Anomalies arise in the data for the Phase 2 baseline tests using Halon 1301 in the cluttered crew compartment. The HF data for halon can be explained by the increased ullage of nitrogen over the 1301 providing a mixing effect assisting the agent distribution around the manikins. This ability continues until the lack of agent forms a sharp reverse in the extinguishment trend. The data emphasize the "forgiveness" of Halon 1301 as **a** fire extinguishing agent. No optimization of the standard system was done for the halon system with clutter.

Please note also that the first line represents a poorly distributed system. There were only three 144 in^3 bottles versus the better distribution of a four bottle system (see the 4th line). The effect is dramatically demonstrated by the peak HF concentration value being reduced by an order of magnitude and the halving of the 2-min average HF concentration.

Based on a statistically small number of trials of each system configuration and agent quantity, especially for the ballistic tests, the following trends were observed.

- After achieving a successful fire extinguishment concentration, adding additional HFC does not necessarily further reduce the fire-out time. but can lead to significant reductions in observed byproduct levels.
- Discharging an acid scavenger along with the HFC can significantly reduce the HF levels, sometimes to below detectable **levels.** The effect of this reduction is great, as little as ***5%*** by weight added to the HFC or stored in the nozzle has shown dramatic reductions in overall HF production.

- Plain water sprays can suppress the initial fire event, but the fire typically reflashes within 1 sec using simple nitrogen overpressure for agent expulsion. Select freeze point suppressants (such as 50 wt% potassium acetate) can be added to the water sprays.
- Water/salt solutions successfully inhibit reflash of the fire and substantially reduce fire-out times. These solutions can be highly conductive in the liquid form (up to seven times that of water), but they may not present a significant conductivity problem when misted or vaporized during spray distribution.
- Water/antifreeze solutions delivered using gas generator hybrids successfully inhibit reflash and operate faster than Halon 1301 systems, providing cooling and operation against Class **A** and B fires. Visibility reduction due to water/antifreeze fog production and cleanup issues also need to be further addressed.

CONCLUSIONS AND RECOMMENDATIONS

Performance equivalent to Halon 1301 can he achieved with available agents and delivery system technologies. Crew survivability criteria have been satisfied against ballistic fires with HFC-227ea concentrations well below accepted exposure limits. Adding small amounts of sodium bicarbonate powder to the HFC reduces acid gas formation by half'. Water mist with potassium acetate salt also proved to be very effective with no concern of hazardous byproducts and simple cleanup. Hybrid gas generators offer a smaller overall envelope for the same agent weight, pressure on demand, and a more consistent agent discharge. Wet mains allow the agent *to* be prepositioned for very rapid agent dispersion and offer the flexibility of nozzle locations.

The following two agents were recommended to the ground vehicle program managers in December 1999:

(1) HFC-227ea with 5% sodium bicarbonate powder by weight added to minimize HF, and

(2) A 50/50 blend of water and potassium acetate by weight to suppress the freeze point to below –60 °F and to enhance suppression capability.

Because these agents do not vaporize as readily as 1301, more sophisticated delivery systems than the standard extinguisher with nitrogen overpressure may be required in certain vehicle applications. Other tradeoffs must also be considered before final agent and distribution hardware decisions can be made. These include system integration and retrofit impacts, initial purchase and sustainment costs, maintenance burden, long-term environmental policies, and the viability of the halon reserve. While commonality is a goal, it may turn out to bc more cost-effective to field both agents instead of trying to force a “one size fits all” situation as we learned in the engine compartment program.

Hence, it is recommended that individual vehicle PMs/WSMs requiring to convert (or programs needing to use) non-halon fire or explosion suppression systems for crew occupied compartments perform individual live-fire verification tests. This office is willing to provide engineering and applications expertise, as well as test coordination and test analysis.

SUMMARY

The Army has aggressively pursued alternatives to halon in its last remaining vehicle application --occupied compartments of ground combat vehicles. By far, this application poses the largest technical challenges because of the stringent performance, toxicological, logistical, and retrofit requirements involved. This research program has identified two potentially viable alternatives to Halon 1301 for crew compartments. But a significant amount of work remains to be completed before a final decision can be made whether or not either of these commercially available agents and technologies (with optimization) is suitable for this application. Test results to date have been extremely encouraging. However, individual system integration and testing must be successfully completed in the affected vehicle fleets (M1, M2/M3, FAASV, etc.) with their maximum credible live round threat scenarios before victory can be assured. In the meantime, the Army must continue to rely on its reserve of Halon 1301.