EVALUATION OF ALTERNATIVE AGENTS FOR SUPPRESSION OF FUEL SPRAY EXPLOSIONS IN MILITARY VEHICLE CREW COMPARTMENTS

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INTRODUCTION

Background

Halon 1301 is the universally accepted agent-of-choice for the protection of military vehicle crew compartments. This is due to its unique combination of suppression efficiency and its acceptable toxicological profile. However the cessation of production at the end of 1993. and the dwindling supply of recycled material, has led to the search for replacement agents during the last few years. KI Research and Kidde Aerospace companies such as Walter Kidde Aerospace and Santa Barbara Dual Spectrum in the US and Kidde Graviner in the UK have been active in this area. The results and conclusions from two separate KI Research trials programs are described in this paper. The first was carried out during 1992-1994, and the second, more detailed, investigation was carried out during 1997-1998.

Agents Tested

Phase I: Halons, HFCs, and PFCs. Several agents of each type were investigated to assess the effect of varying agent properties such as liquid density, volatility, etc., within each chemical class.

Phase II: **Halon** 1301, HFCs (FM-200 and FE-36). aqueous agents (water. water plus surfactants. potassium salts, and combinations of the above).

PHASE I TESTS

Experimental Arrangement

The tests were carried out in a 6.2 m^3 test vessel, depicted in Figure 1. This vessel is suitable for closed-vessel explosions, and has heen proof tested *to* 30 bar (435 psi). The data that can be obtained provide the pressure/time history of the event. The pressure rise represents an integral of the total combustion that has occurred, and is thus *a* useful parameter in assessing the effectiveness of **a** particular suppressant. Explosion suppression in a closed vessel results in one of two outcomes: successful suppression of the incipient explosion. resulting in a *reduced explosion pressure* (P_{red}) typically 0.5-1 bar(g), or a complete failure, and a P_{red} of 7-8 bar(g). There are no "borderline" suppressions.

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Item	Description
1	6.2m^3 Explosion Test Vessel
2	Suppressor
3	Diesel Spray Apparatus
4	Pressure Transducers
5	Pyrotechnic Igniters (2)
6	Diesel Spray Bar

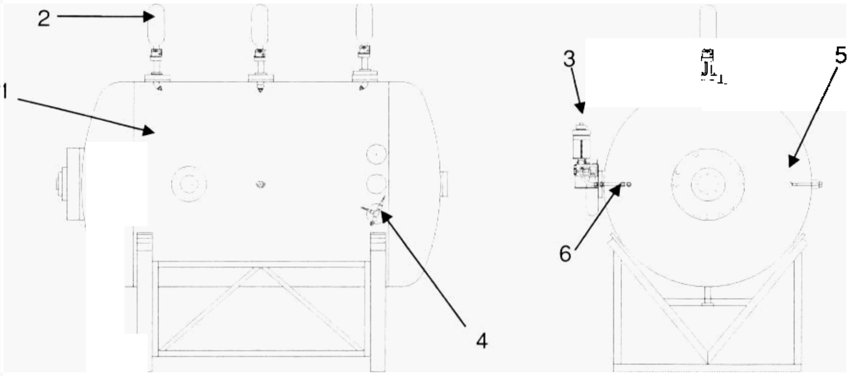

Figure 1: 6.2m^3 Explosion Test Vessel (Configured for Phase I Tests)

The fire threat was a diesel spray. The diesel was preheated to 90 °C in a vessel (3), and discharged through a spray bar *(6)* at a pressure of 41.4 bar (600 psi). These parameters were set to give a reproducible diesel spray explosion. The explosion rate constant, **K,** was 15–18 bar.m.s^{-1} and P_{max} was –4.5 bar(g).† After a fixed delay period the diesel spray was ignited with two 5 kJ pyrotechnic igniters (5). The explosion suppression system was actuated and the pressure rise was recorded by the pressure transducer (4). Three suppressors (2) were used as shown in Figure 1. This system was highly optimised, having a short distance to travel to the explosion fireball, and low till ratio in the suppressors, resulting in a large amount of stored energy (SE), and consequent high discharge rate.

Results

The results relevant to this discussion are summarised in Table 2 below. It can be seen that the performance of some of the HFCs and perfluorobutane is very nearly equal to that of Halon 1301. This was attributed to the fact that Halon 1301 is a relatively poor explosion suppressant. Furthermore, it is believed that explosion suppression is a largely physical process, i.e., the chemical suppression benefit of halon does not come into play (see Agents Tested, Phase **I).**

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† **An** explosion rate constant, K, is a standardised measurement of the maximum rate of pressure rise, normalised to a volume **of** 1m^3 such that $K = (dP/dt)_{max}.V^{1/3}$, where V = volume of vessel.

TABLE 1. PHASE I RESULTS (GASEOUS AGENTS).

Agent	Minimum Extinguishing Concentration		Relative Performance	
	kg m^{-3}	L.m^{-3}	By Mass	By Liquid Volume
Halon 1301	0.76	0.49	1.00	1.00
FM-200	0.75	0.52	0.99	1.07
FE-36*	<0.80	<0.58	<1.06	<1.18
FE-25	1.06	0.85	1.41	1.74
PFC-410	0.80	0.53	1.06	1.07
PFC-614	**0.90**	0.54	1.19	1.09

* Agent in short supply: Pass/fail criterion was not precisely determined.

PHASE II TESTS

Experimental Arrangement

The experimental set up was similar to that used in Phase I, save from the following important differences:

- The explosion severity was significantly reduced (K value = 6.4 bar.m.s^{-1} and P_{max} =2.5 bar(g)). The number of suppressors was reduced to 2, sited at Positions D and E (Figure 2). This makes suppression much more difficult, and the agent needs a greater "throw."
- Attempts were made to keep the stored energy within the suppressors within sensible bounds. This was achieved by tailoring the size of the suppressor to the amount of agent used.
- For some of the tests. clutter was placed **in** the test vessel, to make the situation more representative of a real crew compartment. The clutter was so arranged that there was no line of sight from the suppressors to the developing explosion fireball (Figure 3). This experimental arrangement very much represents "worst-case" clutter/configuration, although Phase I used a worst-case explosion.
- As an additional criterion for assessing post-fire survivability. the HF concentration was measured. The technique was to draw a known volume of gas through distilled water and measure the resulting solution with a fluoride ion-selective electrode (ISE). Two samples were obtained simultaneously (Figure 2). The left position consistently gave higher values, indicating that the atmosphere following the suppression was far from homogeneous. Inhomogeneous HF concentrations have been noted before by Sheinson [1]. The values quoted in this paper are the geometric mean of the two values. The worst-case nature of the experimental arrangement should be borne in mind when assessing the HF values.
- In addition to gaseous agents, Phase II included a subsidiary test programme focussing on aqueous agents.

Item	Description
1	$6.2m^3$ Explosion Test Vessel
2	Suppressor
3	Diesel Spray Apparatus
4	Pressure Transducers
5	Gas Sampling Points

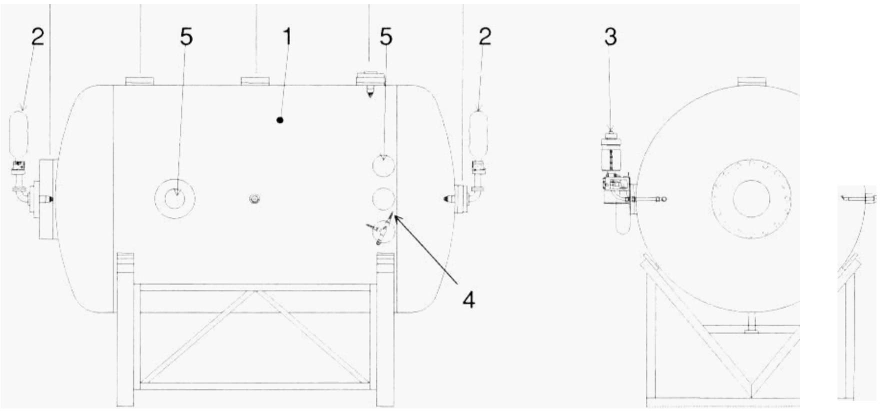
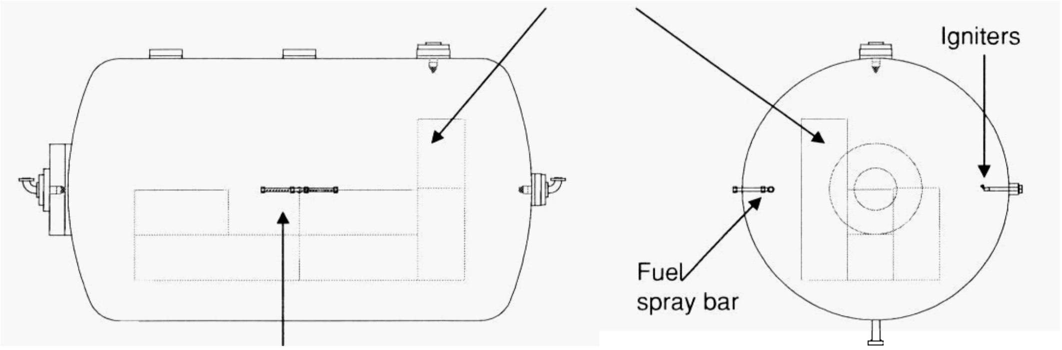


Figure 2: $6.2m^3$ Explosion Test Vessel (Configured for Phase II Tests)



Steel Boxes

Igniters

Fuel spray bar

Notch (allows fuel spray to reach igniters)

Figure 3: Clutter Situated in Test Vessel

Results

Gaseous Agents

The effect of the reduced explosion threat is now apparent (Table *2)* in that the concentration of Halon 1301 required is now 0.45 kg.m^{-3} (7 vol.%). However. the effects of longer throw and the presence of the clutter are clearly present. The **HFC** agents now require approximately double the mass concentration of Halon 1301 and, even then. the acid gas decomposition products (mainly **HF)** are unacceptably high. This led to further tests being carried out with the suppressors mounted at positions **C** and E, restoring partial line-of-sight to the developing explosion fireball (Figure *2).* One study carried out in this configuration was to investigate the effect of different suppressor sizes and of chilling the suppressors to –32 **°C (-25** °F). The results are given in Figures 4 and *5.*

TABLE 2. PHASE II RESULTS (GASEOUS AGENTS).

Agent	**Minimum Extinguishing Concentration**		**Relative Performance**		**HF Concentration**
	kg m^{-3}	L m^{-3}	**by Mass**	**by Liquid Vol.**	**(ppm)**
Halon 1301	0.45	0.29	**I.no**	**1.00**	900
FM-200	1.0	0.70	*2.2*	2.4	6300
FE-36	0.9	0.66	2.0	2.3	5600

Aqueous Agents

The majority of the tests with aqueous agents were carried out prior to the inclusion of the clutter in the test vessel. Table 3 summarises the results obtained.

Potassium hydrogen carbonate is a proven dry chemical. both as Purple-K™ and as an aerosol suppressant [2-3]. Potassium acetate and lactate have been previously investigated by Finnerty et al. and found to be effective additives for water [4-5]. The addition of surfactants should lower the surface tension of the water, resulting in more efficient atomisation [6]. and hence superior suppression. **A** limited number of tests were carried out with the clutter present; these are summarised in Table 4.

TABLE 3. AQUEOUS AGENT RANKING (NO CLUTTER).

Agent	**Minimum Extinguishing Concentration**		**Relative Performance**	
	Kg m^{-3}	L m^{-3}	**hy Mass**	**by Liquid Vol.**
Potassium hydrogen carbonate	*ca 0.20*	***0.*IX**	**0.40**	0.62
Potassium lactate *(50* wt.%)	0.45	0.35	1.00	**1.20**
Halon 1301	0.45	0.29	**1.00**	**1.00**
Potassium lactate (20 wt.%)	0.55	0.49	1.22	1.69
Potassium **acetate (S0** wt.%)	*0.65*	0.51	1.44	1.76
Water plus surfactant	0.65	0.65	**1**.44	2.24
Water plus **AFFF**	0.80	***0.80***	**1**.78	2.76
Water	1.4	**1.4**	3.1	4.x

Figure 4: Effect of Stored Energy (Ambient Temperature)

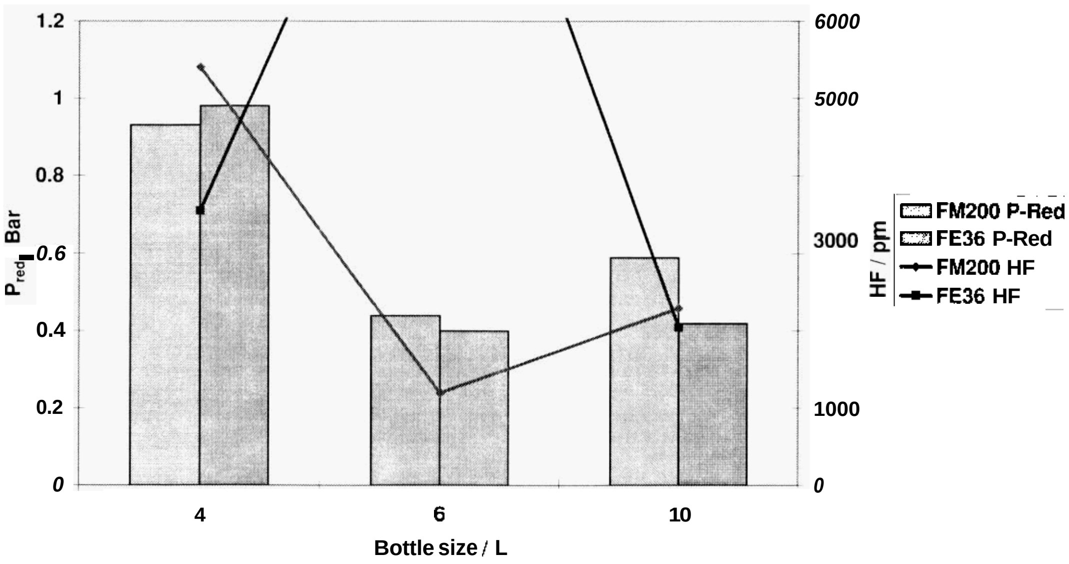


Figure 5: Effect of Stored Energy (Low Temperature)

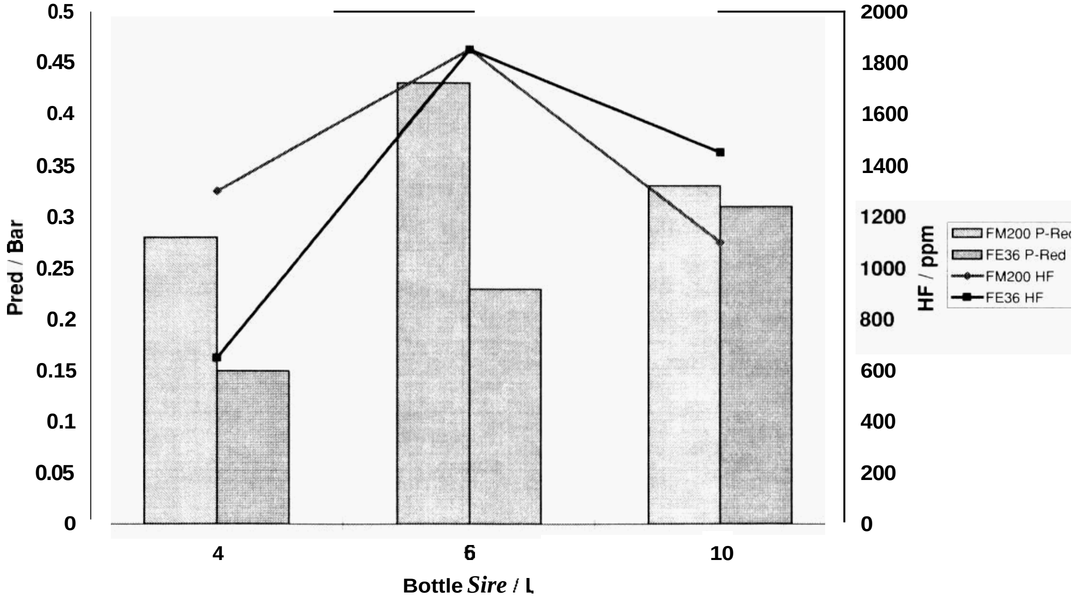


TABLE 4. AQUEOUS AGENT RANKING (CLUTTER PRESENT),

Agent	Minimum Extinguishing Concentration		Relative Performance	
	Kg m^{-3}	L m^{-3}	by Mass	by Liquid Vol.
Potassium hydrogen carbonate*	< 0.2	< 0.18	< 0.44	< 0.62
Potassium citrate plus surfactant	0.45-0.55	0.35-0.42	1.0 – 1.2	1.2 – 1.4
Potassium lactate plus surfactant	0.45-0.55	0.35-0.42	1.0 - 1.2	1.2 – 1.4
Water plus surfactant	0.65	0.65	1.44	2.24
Potassium lactate	> 0.65	> 0.50	> 1.44	> 1.72

* High stored energy

In these tests (Table 4), the use of the surfactant had the effect of restoring the perfonnance of potassium lactate to that obtained without the clutter. Potassium hydrogen carbonate achieved suppression when stored in an oversized bottle (i.e., high stored energy).

DISCUSSION

Explosion K Kate Constants

As mentioned above, explosion rate constants for the Phase 1 tests were 16 – 18 bar.m.s^{-1} and those for Phase II were around 6. In comparison. a turbulent dust explosion, such as might occur in a powder handling plant. can have a K value of 200 bar.m.s^{-1} or higher.'

The explosion rate constant is a function of the fundamental burning velocity of the fuel-air mixture. which in practice depends on the following:

- The thermodynamics of combustion $(\Delta H_{combust})$
- The degree of atomisation of the fuel
- Turbulence (both intrinsic and induced)
- Fuel concentration.

Gaseous Agents

Fires vs. Explosions

One possible explanation for the differences in the relative behaviour between Halon 1301 and the HFCs observed in Phase I and II is that in Phase I the threat was an explosion, and in Phase II the threat was more characteristic of a fire. The suppression of explosions is largely a thermal process (heat abstraction), and the catalytic radical recombination process that the bromine atom affords [7] does not appear to play any significant role. This has been noted before in studies comparing inerting with suppression [8], and it is one of the reasons why halons were rarely used for the suppression of dust explosions, dry chemicals being the preferred option [9] (see above). Supporting evidence for the hypothesis that the Phase II threat was more characteristic of a fire is that the relative concentrations required for suppression in Phase II closely track conventional

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This threat has been successfully suppressed using Halon 1011 (chlorobromomethane, CH_2BrCl). which is a superior explosion suppressant than Halon 1301. A concentration of 3.2 kg.m^{-3} is required (theoretically equivalent to 69 vol.% !).

n-heptane cup burner ratios, whereas in Phase I this is not the case. Table 5 below summarises this discussion.

TABLE 5. COMPARISON OF THREATS **USED.**

Parameter	Phase I	Phase 11 (Positions D and E)	Phase II (Positions **C** and E)
Explosion K value (bar.m.s.-1)	18	6	6
Configuration/clutter	**Easy**	**V** difficult	Difficult
Number of suppressors	3	**2**	2
Mean throw distance (m)	0.97	1.43	1.26
Halon 1301 suppression requirements ($kg.m^3$)	0.76	0.45	0.45

Effect of Stored Energy

Generally in industrial explosion suppression, the higher the stored energy, the higher the discharge rate of the suppressant. and the more effective the suppression. However, in this case, at ambient temperature better results were obtained with the 6L suppressors than the 10L. This is believed to be due to *induced turbulence*, where the comparatively slow spray fire is "stirred up" by the extremely energetic discharge of the HRD suppressors.

Effect of Chilling Agent

Contrary to initial expectations. chilling the suppressors to –32 "C actually improved the performance, as lower values of P_{red} and HF concentration were recorded. However when it is considered that the suppressors now have partial line of-sight of the developing fireball (suppressors at positions C and E), this makes more sense. The agent is now discharged as a liquid, and even the 4L suppressors have enough stored energy to get the agent to the fireball quickly enough. Note that in the real situation where the entire vehicle is cold, the fraction of agent vaporising will be much lower, and suppression much harder.

Aqueous Agents

Effect of Clutter

As shown above in the uncluttered case, aqueous solutions of potassium salts offer significant enhancement over water where there is line-of-sight between the suppressor(s) and the explosion fireball. Either potassium lactate or citrate offers proven benefit over pure water. However, the introduction of clutter removes a significant proportion of the advantage that the chemical additive brings. As expected. the incorporation of a surfactant into the formulation, by reducing the surface tension of the solution, served to enhance the atomisation of the solution, creating, in effect, a high rate discharge water mist system.

CONCLUSIONS

Gaseous Agents

The difference in the results between Phase I and II serves to illustrate the pitfalls in system design. The fire threat needs to be characterised adequately. and. if HFC agents are to be used, the suppression system needs to be optimised. This means adequate stored energy (high nitrogen overpressure or low fill ratios) and line-of-sight access to **all** risk areas. Halon 1301. having both physical and chemical suppression mechanisms, was a very versatile agent: the HFCs are less versatile.

Aqueous Agents

If the requirement for a “clean” agent could relaxed, aqueous agents offer a promising alternative. The immediate advantage is the absence of HF. but there are also environmental and cost/ logistical benefits. However. there are still problems associated with agent freezing. Potassium lactate at 50 wt.%, although a liquid, is viscous at –40 “C.

SUMMARY

The two phases of work taken together show that under certain circumstances Halon 1301 can be replaced, by either gaseous or aqueous agents. **As** predicted [10], none is a “drop-in“ replacement. **and** all require some sort of compromise. Considering all of the agents tested, several options emerge (Table 6).

TABLE *6*. HALON REPLACEMENT OPTIONS.

Agent	Volume Ratio: Halon 1301	Advantages	Drawbacks	Solution
Potassium hydrogen carbonate	≤ 1	Very efficient	Freezes. not a clean agent	Trickle heat suppressor
Potassium lactate	1.2	Efficient. does not freeze	**Poor** performance against clutter. not a clean agent	**Position** suppressors with care
Potassium lactate **plus** surfactant	1.2	Efficient. does not freeze, good against clutter	**Not** a clean agent	Clean up after discharge
HFC **Agents**	2.2-2.4	Does **not** freeze. conventional. clean agent	**Space** requirements. GWP. HF	Scavengers’!

REFERENCES

1. Alexander Maranghides, Sheinson, R. S., Cooke, James III, Wellens, Jill C., Wentworth, Bryce, Williams, Bradley A., and Darwin, Robert, "Flammable Liquid Storeroom 1: Halon 1301 Replacement Testing Results," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, pp. 180-189, 1998.
2. Chattaway, A., R. G. Dunster, and D. J. Spring, "The Evaluation of Non-Pyrotechically-Generated Aerosols as Fire Suppressants," *Proceedings,* Halon Options Technical Working Conference Albuquerque, NM, pp. 473-484, 1995.
3. Chattaway, A., D. J. Spring, and R. Gall. "Dry Chemical Extinguishing Systems," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, pp. 216-*221,* 1997.
4. Finnerty, A. E., "Water-Based Fire-Extinguishing Agents," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, pp. 461-470. 1995.
5. Moore, T. A., et al., "Laboratory Optimization and Medium-Scale Screening of Iodide Salts and Water Mixtures," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, pp. 477-496, 1996.
6. Perry, R. H. and D. W. Green, eds., *Perry's Chemical Engineer's Hundhook,* 5th ed., 1984. McGraw-Hill: New York. 18:50.
7. Sheinson, R.S., J.E. Penner-Hahn, and D. Indritz, *Fire Safety Journal,* 1989 15:437-450.
8. Finnerty, A. E., "The Importance of Mechanisms," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, **pp.** 251-258, 1994.
9. Eckhoff, R. **K.,** *Dust Explosions in the Process Industries.* 1st ed. 1991: Butterworth-Heinemann. Ltd.
10. Ball, D. N., **A. Chattaway,** and D. J. Spring, "There Will be no "Son of Supergas," *Proceedings,* Halon Options Technical Working Conference, Albuquerque, NM, pp. 45-56, 1998.