Investigations of a Water Based Fire Extinguisher System for Use On Ground Combat Vehicles (U)

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ABSTRACT (U)

(U) A novel fire extinguishing system containing carbon dioxide (CO_2), water/antifreeze and CO_2 mixtures was developed and tested. The extinguisher system and water mixtures were designed to extinguish violent fuel fires ignited by ballistic attack in ground combat vehicles in 250 ms or less. Two tests in an actual vehicle demonstrated that the fire extinguishing system containing a 60% potassium lactate and 40% water mixture extinguished the ballistic fire in an average of 131 and 138 ms, respectively.

INTRODUCTION (U)

(U) Fire protection on military platforms, including ground fighting vehicles, is being challenged by the impending loss of the ubiquitous fire-fighting agent halon 1301 (CF_3Br) due to environmental concerns related to the destruction of the stratospheric ozone layer. Replacement fire extinguishment agents need to be found that will satisfy numerous criteria, including fast fire suppression, minimum production of toxic gases when used, low toxicity, compatibility with storage materials, and environmental acceptability.

(U) The U.S. Army's search for halon replacement agents has largely involved an empirical approach of testing and evaluation of commercially available compounds/systems. Testing and evaluation of a novel fire extinguishing system containing mixtures of water and commercially available antifreeze agents will be presented. Testing was conducted in two facilities, one of which is an actual combat vehicle. For the combat vehicle studies, the extinguisher system was used to suppress a mist-fireball explosion in the crew compartment of an armored vehicle following penetration of a fuel cell by a ballistic event [ref. 1]. Recently designed ground combat vehicles are equipped with automatic fire suppression systems to extinguish fuel and hydraulic fluid fires. These suppression systems are designed to extinguish fire events in 250 ms or less in order to minimize exposure of personnel to extreme heat and toxic fumes. To date such an ideal system has yet to be developed and used.

(U) Until recently, the use of water as an alternative to halon for fire suppression has not been considered. Specifically, water is not very effective in extinguishing a hydrocarbon fire unless delivered to the flame front in the form of finely nebulized mist. Unfortunately, fine water mist droplets do not travel through air easily due to aerodynamic drag. On the contrary, large droplets have less air resistance than small droplets and thus travel through the air more easily, but due to the large droplets' small surface-to-volume ratio, the droplets can pass through a flame with little-to-no evaporation. Other problems associated with the use of water for fire suppression include storage in cold weather environments and electrical conductivity. Once in a fire, water can cause extinction through three nonchemical mechanisms [ref. 2]; cooling, displacement of oxygen, and radiant heat attenuation. With renewed interest in water fire suppression as well as years of fundamental research in our lab with water based fire suppressants [ref. 3, ref. 4], we will demonstrate the effectiveness of a novel water-based fire suppression system. Measurements of extinguisher pressures as a function of time during discharge and the amount of time needed to extinguish a fire (i.e. fire-out times) in different testing scenarios will be discussed to quantify the test system effectiveness.

Unclassified, approved for public release.

EXPERIMENTAL (U)

Extinguisher System (U)

(U) **Figure 1** shows a schematic diagram of the novel extinguisher system. The system consists of two standard 4.6 kg halon 1301 (CF_3Br) extinguisher bottles (Marotta Scientific Controls Model MV121KJ-1) with solenoid actuated valves. Each solenoid valve output is attached to a 15.24-cm-long, 3.81-cm-diameter standard plumbing pipe. The plumbing pipes bring the contents of the two extinguishers into a 19.68-cm-long, 3.81-cm-diameter standard plumbing tee which connects the two extinguisher bottles. The output of the plumbing tee is attached to a fire extinguishing nozzle currently used on the M992 Field Artillery Ammunition Support Vehicle (FAASV) CF_3Br fire extinguisher. The FAASV nozzle (shown in **Figure 2**) is cone shaped, approximately 3.81 cm in length, and has 18, 1.27-cm-concentric holes arranged in a pattern of 4, 6, and 8 holes from tip to base.

Figure 1(U) Schematic diagram of the novel extinguisher system.

Figure 2 (U) Fire extinguishing nozzle currently used on the M992 Field Artillery Ammunition. Support Vehicle (FAASV) halon 1301 fire extinguisher.

(U) To monitor temporal bottle discharge pressures, the extinguisher bottle fill valve (MS28889-2, Schrader type) was adapted with an adapter fitting containing a piezoelectric pressure transducer (PCB Model 102A04). The pressure transducer signals are outputted through BNC cables to a LeCroy 9354CM digital oscilloscope. The oscilloscope was set to acquire signals from pressure transducers on both extinguishers using one of the pressure signals as the oscilloscope trigger. With this arrangement, pressure vs. time records were obtained. The oscilloscope was set for data acquisition rates on the order of 400 μs/data point. The two extinguishers were filled with different combinations of water and anti-freeze chemicals along with CO_2 as described below for each testing facility.

Test Facilities (U)

(U) Prior to actual combat vehicle tests, a parametric evaluation of the extinguisher system and extinguisher contents was conducted in an experimental test facility [ref. 5]. The most realistic assessment scenario for the extinguishing system is the combat vehicle test facility shown in **Figure 3**.

Figure 3 (U) Schematic diagram of combat vehicle test facility.

The dimensions of the personnel space within the combat vehicle test facility are 1.27 x 1.68 x 1.17 m, giving an interior volume of approximately 2.5 m^3. Unlike the experimental test facility, the combat facility is quite cluttered. As seen in **Figure 3,** there are three aluminum boxes that are used to simulate three crew members in the compartment, as well as provide mounts for thermocouple and heat flux gauges. In the right, lower corner of the diagram, four aluminum cylinders are located to simulate four munitions that are carried in the crew space of some vehicles. **Figure 3** also shows a number of diagnostics in combat vehicle: three video cameras and three infrared (IR) sensors are mounted around the crew space and are labeled as IR1, IR2, IR3 and Video1, Video2, and Video3. For the combat vehicle tests, two extinguisher systems were utilized to provide maximum fire protection. The extinguishers, as shown in **Figure 3**, were arranged in two pairs labeled as Ramp(Extinguisher 1, Extinguisher 2) and Turret(Extinguisher 3, Extinguisher 4). The extinguisher pairs were mounted against the outer turret basket and rear ramp of the vehicle, respectively. The FAASV nozzles from each extinguisher system were directed somewhat toward the fire source. The extinguishers were filled with various fire extinguishing contents, as listed in Table I.

Table I (U): Test sequence and experimental conditions for tested fire extinguishers. Note: The system consists of extinguisher 1 and 2 combined as a pair and extinguishers 3 and 4 combined as a pair giving two extinguisher systems for each test.

Test #	Ramp Extinguisher 1	Ramp Extinguisher 2	Turret Extinguisher 3	Turret Extinguisher 4
1	CO_2	CO_2 + H_2O & Potassium Acetate	CO_2	CO_2 + H_2O & Potassium Acetate
2	CO_2	CO_2 + H_2O & Potassium Acetate	CO_2 + H_2O & Potassium Acetate	CO_2

3	CO_2 + H_2O & Propylene Glycol	CO_2	CO_2	CO_2 + H_2O & Propylene Glycol
4	CO_2 + H_2O & Potassium Lactate	CO_2	CO_2 + H_2O & Potassium Lactate	CO_2
5	CO_2 + H_2O & Propylene Glycol	CO_2	CO_2 + H_2O & Propylene Glycol	CO_2
6	CO_2	CO_2 + H_2O & Propylene Glycol	CO_2 + H_2O & Propylene Glycol	CO_2
7	CO_2	CO_2 + H_2O & Potassium Lactate	CO_2 + H_2O & Potassium Lactate	CO_2
8	CO_2	CO_2 + H_2O & Potassium Lactate	CO_2 + H_2O & Potassium Lactate	CO_2
9	CO_2 + H_2O & Propylene Glycol	CO_2	CO_2 + H_2O & Propylene Glycol	CO_2
10	CO_2	CO_2 + H_2O & Potassium Lactate	CO_2	CO_2 + H_2O & Potassium Lactate

(U) Tests 1-7 were conducted using the fuel mist fireball simulator. Tests 8-10 were actual ballistic shots. The extinguishers containing CO_2 and the water/antifreeze mixtures were typically filled with 0.91 kg of CO_2 and approximately 2.4 L of the water/antifreeze mixtures giving a ratio of 40% water and 60% of the antifreeze chemical. The antifreeze chemicals are commercially available. The potassium lactate ($CH_3CH(OH)COOK$) and potassium acetate (CH_3CO_2K) are research grade (Cryotech, Inc.), while the propylene glycol and ethylene glycol (respective brand names: Summit and Peak) are commercial grade antifreeze agents commonly used in automobiles. The extinguisher containing only CO_2 was filled with 2.61 kg of CO_2. All extinguisher bottles were filled in such a way as to maintain a 20% ullage in the bottles. CO_2 was used in the extinguishers because of its unique physical properties and availability. CO_2 is a compressible fluid which is normally stored in high pressure cylinders as a liquid under its own vapor pressure of 830 psi at 21 °C. Thus, for the extinguisher containing the water mixture and CO_2, the CO_2 vapor provides enough pressure to expel the water mixture. For the extinguisher containing only CO_2, the rapid discharge of CO_2 liquid from high-pressure to low pressure (atmospheric) into the plumbing tee with the water mixture from the other extinguisher allows the two to combine. Once the water/antifreeze/CO_2 mixture is propelled from the extinguisher, the CO_2 rapidly vaporizes causing the water/antifreeze to nebulize. The total amount of CO_2 released into the test facility is 23.5% by volume, which is well above the critical exposure level [ref. 6].

Test Fires (U)

(U) In order to test the extinguisher system and the various extinguisher content combinations, different types of fire scenarios were developed, usually to increase the extinguishment difficulty. That is, testing in the combat vehicle test facility involved two different fire scenarios to evaluate the effectiveness of the fire extinguishing system. The first fire scenario is a fuel spray fire (**Figure 4**) where a fireball is generated by spraying 0.4 L of JP8 at 1200-psi pressure and a temperature of 93 °C into the interior of the crew space for 1 second, producing a 13-MW fire.

Figure 4 (U) Video snapshots of combat vehicle fuel spray fireball simulator. The eight photos from left to right, top to bottom, illustrate initial ignition to full-size fire.

The fire is ignited with a glow plug and is observed by the three IR sensors. The fire extinguishing system is electrically triggered to release 11 ms after the sensors detect the fire. This fire scenario is used to screen various fire extinguisher systems that are tested in the vehicle. Successful fire extinguishment with the mist fireball simulator leads to testing during an actual ballistic event fire.

(U) The ballistic fire event (**Figure 5**) consists of a shaped charge at a standoff of 13.34-cm being directed through a 38-L aluminum fuel tank into the crew fixture. During the violent ballistic event, approximately 30-L of JP8, which was heated to 93 °C prior to the shape charge shot, is carried into the crew compartment where it mixes with air and molten aluminum from the fuel tank. Approximately 25 ms after the ballistic event, the fire extinguishing system is activated with four 24-V electrical pulses sent to each individual extinguisher. This fire event is by far the most difficult one tested as well as least predictable on a shot-to-shot basis, but represents the worst case scenario that can be tested in an experimental situation.

Figure 5 (U) Video snapshots of ballistic initiated fire event inside combat test vehicle. The eight photos from left to right, top to bottom, illustrate initial ignition to full-size fire.

RESULTS (U)

(U) Table II lists the discharge times for the two extinguisher sets along with the IR and video recorded, frame-by-frame analyzed, fire-out times test conducted in the combat testing facility (Fig 3). It should be noted that in some tests, either pressure, IR, or video diagnostics failed to register data, thus making a discharge or fire-out times not available (NA) as denoted in Table II. Test 5 was declared a no test (NT) since the extinguishers were activated after the fuel mist occurred.

Table II (U): Test sequence with corresponding fire extinguisher discharge times, IR and video fire-out times. All times listed are in units of ms.

Test #	Ramp Extinguisher 1	Ramp Extinguisher 2	Turret Extinguisher 3	Turret Extinguisher 4	IR 1	IR 2	IR 3	Video 1	Video 2	Video 3
1	484	452	NA	NA	104	96	102	72	140	90
2	NA	NA	NA	NA	109	107	111	76	80	150
3	NA	512	NA	NA	158	150	151	400	200	180
4	642	705	712	701	75	77	91	84	140	150
5	633	659	662	658	NT	NT	NT	NT	NT	NT
6	705	708	760	753	98	94	98	NA	110	100
7	739	599	719	706	94	85	105	70	NA	NA
8	707	715	741	741	106	266	180	144	46	44
9	726	744	726	744	118	356	139	172	89	78
10	751	743	773	770	119	120	119	92	180	190

(U) The extinguisher discharge times are obtained from monitored pressure vs. time records. **Figure 5** illustrates two pressure vs. time records representing two typical discharge times experienced.

Figure 6 (U) Representative pressure vs. time record for two extinguishers discharge.

(U) Using the pressure time records, the discharge times are calculated from the time of the initial pressure change (pressure decrease, t_o) to the peak pressure (maximum negative pressure, t_f). From **Figure 6**, one extinguisher (open-circle symbols) discharges slightly faster than the other. Since the first extinguisher contained CO_2 only and second extinguisher contained CO_2 with a mixture of water and potassium acetate, it seems logical that the water mixture takes slightly longer to discharge than the CO_2 only extinguisher. Using the discharge time data, an estimate of the flow velocity can be made from the following equation [ref. 6]

$$\upsilon = \frac{0.4085 \cdot Q}{d^2}$$ **Equation 1**

where Q is the flow rate in gallons per minute and d is the orifice diameter in square inches. Converting to SI units, a typical CO_2 only extinguisher has an exit velocity entering the plumbing tee of 6.53 m/s. A representative water/antifreeze mixture extinguisher has an exit velocity into the plumbing tee of 4.2 m/s. More importantly, though, the two extinguishers discharge at roughly the same times, which enables the bottle contents to mix well. Homogeneous mixing is important because the integration of pure CO_2 from one extinguisher with the water mixture from the other extinguisher causes the CO_2 to accelerate the water mixture out in a fine mist. As the water mixture is propelled out of the nozzle, the CO_2 flash vaporizes, causing the water to break up into fine droplets. Previous testing has demonstrated that the average water droplet sizes are on the order of 1–2 microns with a spherical morphology [ref. 4].

(U) For Tests 1-3 only, the ramp Extinguishers (1 and 2) were monitored, while the turret Extinguishers (3 and 4) were not. The ramp extinguishers were monitored with the same PCB piezoelectric gauges used in previous tests in the experimental facility. After Test 1, the PCB gauges were observed to malfunction, and following Test 3, were no longer used. For Tests 4-10, all four extinguishers were monitored with piezoresistive gauges (ENDEVCO, Model 8530-1000). Unfortunately, the piezoresistive gauges do not possess rise times as fast as the piezoelectric gauges (i.e. 1-2 μs). Thus, for Tests 4-10, the extinguisher discharge times are somewhat longer than those measured previously, approximately 200 ms, which is attributed to the slower rise time of the pressure measurement device. Finally, after Tests 1 and 2, which assessed the potassium acetate mixture, a significant amount of residue was observed in the extinguishers and valves, which caused a malfunction to occur in Test 3. At this time, it was decided to stop further testing of this particular water mixture because it was believed to be precipitating out of solution under the test conditions present.

(U) Table III lists the average fire-out times observed with the three IR and three video sensors along their respective standard deviations. An average of the IR and video fire-out times is also listed in the last column of the table.

Table III (U): Test sequence with corresponding average IR and video fire-out times, IR and video statistical deviations, and a mean of the IR and video averages. All times listed are in units of ms.

Test #	IR Average	IR Standard Deviation	Video Average	Video Standard Deviation	Average of IR and Video
1	100.7	4.2	100.7	35.2	100.7
2	109.0	2.0	102.0	41.6	105.5
3	153.0	4.4	260.0	121.7	206.5
4	81.0	8.7	124.7	35.6	102.8
5	NT	NT	NT	NT	NT
6	96.7	2.3	105.0	7.1	100.8
7	94.7	10.0	70.0	NA	82.3
8	184.0	80.1	78.0	57.2	131.0
9	204.3	131.8	113.0	51.4	158.7
10	119.3	0.6	154.0	53.9	136.7

Even though the Test 9 data indicate that the ballistic induced fireball was extinguished in 158 ms, video recordings indicated that a fire re-flash occurred almost 350 ms later. The re-flashing is believed to be due to water boiling off the water/propylene glycol mixture, which left the flammable propylene glycol exposed to extremely hot surfaces inside of the test fixture, which probably caused re-ignition. Nevertheless, all the data in Table III, except the video average of Test 3, show fire-out times less than the U.S. Army requirement of 250 ms. Further, the average IR and video fire-out times indicate that the fires are being extinguished before at least half the extinguisher contents are discharged. The obtained results indicate that the extinguisher combinations are probably more than adequate for the tested fire situations, which implies the system could be reduced in size and volume.

(U) Further averaging of the data in Table IV, in terms of extinguisher contents and fire situations (Table IV) indicates that extinguishment tests using the potassium lactate mixture in both the fuel mist fireball simulator and ballistic-induced fire are the most effective.

Table IV (U): Fire extinguisher contents and fire situation with corresponding average IR and video fire-out times as well as a mean value of the IR and video average. All times listed are in units of ms.

Extinguisher Content/ Fire Situation	IR Test Average	Video Test Average	Average of IR and Video
CO_2 + H_2O & Potassium Acetate/ Fuel Mist Fireball	105	101	103
CO_2 + H_2O & Propylene Glycol/ Fuel Mist Fireball	125	183	154
CO_2 + H_2O & Potassium Lactate/ Fuel Mist Fireball	88	97	93
CO_2 + H_2O & Potassium Lactate/ Ballistic Fireball	152	116	134

(U) The addition of potassium lactate or potassium acetate to water in the second extinguisher was chosen primarily because of the freezing point lowering capabilities of the salts. A recent study by Yang et al. [ref. 7] has shown that a mixture of 60% potassium lactate and 40% water is more effective at extinguishing a flame than a 50/50% mixture. The increased effectiveness of the water/potassium lactate mixture is attributed to the suppression ability of potassium. That is, as a 60% potassium salt and 40% water aqueous mixture, it is more than likely that the water evaporates quickly as the salt-water droplets enter the fire. Once the water evaporates, the solid potassium salts are released [ref. 3]. Potassium is an alkali metal, like sodium, and has been widely used as a fire suppressant agent in either powder or aqueous forms of salt. Laboratory scale experiments have shown that potassium in the form of potassium bicarbonate is about 7.5 times more effective at extinguishing cup burner flames than CF_3Br [ref. 8]. Flame inhibition by potassium is believed to be due to chemical scavenging of major radical species in the flame. A recent kinetic modeling study by Williams and Fleming [ref. 9] suggests that the dominate radical scavenging reactions for potassium in a flame are

$$KOH + H \leftrightarrow K + H_2O$$
$$K + OH + M \leftrightarrow KOH + M$$
$$K + O_2 + M \leftrightarrow KO_2 + M$$

This mechanism is adapted from the work of Jensen and Jones [ref. 10], Hynes et al. [ref. 11], and Slack et al. [ref. 12]. The net mechanism results in the loss of radical species OH and H to H_2O, which can further inhibit a flame through thermal mechanisms. Thus, the combination of a chemical inhibiting agent, potassium lactate, with a physical suppressing agent, H_2O, gives synergistic suppressant enhancement.

CONCLUSIONS (U)

(U) Testing and evaluation of a novel fire extinguishing system-containing mixtures of water and commercially available antifreeze chemicals were performed. The system was evaluated in its ability to suppress several different fire scenarios, including a mist-fireball explosion in the crew compartment of an armored vehicle following penetration of a fuel cell by a ballistic event.

(U) The tested fire extinguishing system consists of two standard 4.6-kg extinguisher bottles. The extinguishers contain CO_2 in one bottle and a water/antifreeze mixture in the other. The extinguisher bottles are plumbed together into a standard plumbing tee. The output of the plumbing tee is attached to a fire extinguishing nozzle currently used on CF_3Br fire extinguishers on-board the Field Artillery Ammunition Support Vehicle (FAASV). The most successful water/antifreeze mixture tested consisted of 40% water and 60% potassium lactate. From the combat vehicle study, two tests of the fire extinguishing system using the water/potassium lactate mixture demonstrated the ballistic induced fire event being extinguished in an average of 134 ms. The observation of fire suppression in less than the required 250 ms illustrates the effectiveness of the fire extinguisher system and agent which can be potentially used in current and future combat vehicle designs.

(U) Future efforts included evaluating an extinguisher system reduced in both size and volume, as well as replacing CO_2 with trifluoromethane (HFC-23 or FE-13). Exchanging CO_2 with trifluoromethane is advantageous because both chemicals have similar physical properties and trifluoromethane is less toxic than CO_2 in terms of inhalation exposure.

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