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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1007/s10694-007-0008-6>

Fire Technology, 43, June 2, pp. 145-172, 2007-06-01

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NRCC-47012

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A version of this document is published in / Une version de ce document se trouve dans:
Fire Technology, v. 43, no. 2, June 2007, pp. 145-172 doi: [10.1007/s10694-007-0008-6](https://doi.org/10.1007/s10694-007-0008-6)

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Study of Explosion Protection in a Small Compartment

ABSTRACT

A series of full-scale explosion suppression experiments were conducted in a compartment. The suppression performance of three extinguishing systems with two suppressants for the deflagration-type explosion was studied. The impact of agent discharge direction, the presence of an obstacle and the use of additives on suppression performance were investigated with extensive data collection and analysis. The negative aspects and toxicity issues associated with the protection systems are also addressed in the paper. The three extinguishing systems evaluated in this project were a high pressure HFC-227ea (FM-200) extinguisher, a hybrid gas generator with FM-200, and a hybrid gas generator with water, with full-system hardware including optical flame sensors and electronic controllers. The experimental results showed that the explosion in a compartment originating from a fuel spray was a serious threat to any occupant in the compartment and could cause major damage to equipment, but, the explosion generated in the experiments was controlled or extinguished by appropriate extinguishing systems.

1.0 INTRODUCTION

Explosion caused by ignition of fuel spray in a small compartment, such as the crew compartment of armoured vehicles, is a serious threat to the occupants and the equipment in the compartment [1-3]. In order to protect the occupants and equipment, the deflagration flame in an explosion must be extinguished in a few hundred milliseconds. In addition, the suppressants must be non-toxic, must not produce excessive toxic by-products, and explosion suppression must not cause excessive temperature and overpressure and must not deplete oxygen below the safe level. The key for explosion suppression is to detect and arrest combustion while it is still in the incipient stage. This is achieved by rapidly discharging a suppressant to directly

terminate the explosion reaction and flame propagation before a destructive pressure rise is reached.

The suppression approach requires 3 integrated elements: detection, agent delivery and suppression. A fire can be detected in milliseconds and then a control unit will trigger the discharge of the suppressant once it receives signal from the sensors. A suppressant may work chemically by directly interfering with the explosion reaction. The suppressant may also work physically by removing heat from the combustion wave and creating a barrier for heat transfer between the combustible particles. The effectiveness of the explosion suppression is dependent on the explosion hazard (e.g., compartment geometry and size, explosible material), the choice of explosion suppressant (e.g., type, mass and efficiency of the agent), and the effectiveness of the suppression system (e.g., fire detecting and agent delivering capability) [4].

Until recently, Halon 1301 has been widely used for the protection of an occupied compartment, not only from a fire hazard, but also from a possible explosion hazard. However, the production of halon has been banned by the Montreal protocol due to its environmental impact. In order to pursue environmentally and toxicologically acceptable alternatives to Halon 1301, some new explosion suppression systems have been developed and initial studies on their capability have been carried out [5-7]. Among these systems, three have been identified as potential candidate systems, based on their extinguishing performance, environmental impact and other requirements for an occupied compartment protection. They are: a high pressure/FM-200 extinguishing system, a hybrid gas generator/FM-200 extinguishing system, and a hybrid gas generator/water extinguishing system. These extinguishers can very quickly discharge suppressants, once an explosion is detected. However, these systems are still in the development stage and information on their performance is limited.

The National Research Council of Canada (NRC) has recently carried out a project to study deflagration-type explosions that could be encountered in the crew

compartment of military armoured vehicles. The performance of these three explosion suppression systems for the crew compartment protection was evaluated.

This paper describes the deflagration-type explosion experiments and provides experimental results, as well as concerns on toxicity issues associated with the protection systems. The impact of agent discharge direction, the presence of the obstacle and the use of additives on suppression performance is also reported.

2.0 EXPERIMENTAL SET-UP AND PROCEDURES

The full-scale explosion suppression experiments were conducted in a compartment constructed to simulate the crew compartment of armored vehicles. Three explosion suppression systems, with full-system hardware including optical fire sensors and electronic controller, were evaluated.

2.1 Test Compartment

A test compartment simulating the back half of an armoured vehicle crew compartment was constructed to carry out explosion suppression experiments. Its isometric view is shown in Figure 1. The cross-section area of the test compartment was 2.52 m^2 , and it was 1.5 m in length and the total volume of the test compartment was 3.78 m^3 .

The test compartment was built with a steel frame and lexan walls (5 mm thick), allowing viewing of the interior of the compartment during explosion suppression testing. The compartment was designed to be airtight except for an access door opening. The access door had dimension of 1.04 m x 1.04 m. This door also acted as a pressure relief vent to protect the compartment integrity, which would relieve over-pressurization in the test compartment that is generated by fire explosion and ultra-fast discharge of a suppression system in the test compartment. The door was hinged at the top, and during tests, the bottom of the door was chained to allow the opening of the door to a maximum

of 0.1 m. Therefore, in the tests, the maximum ventilation opening was limited to 0.0208 m^2 .

To study the impact of obstacles on the explosion suppression performance, an obstacle, which simulated the command turret in an armoured vehicle compartment, was placed in the test compartment in some experiments. The obstacle was a cylindrical tube with a diameter of 0.25 m, and placed from floor to ceiling in the test compartment, as shown in Figure 1.

2.2 Explosion Scenario

The explosion scenario used in the experiments simulated a projectile penetrating the hull of the vehicle through a fuel tank, and causing fuel spray and ignition in the crew compartment. The explosion in the test compartment was generated with a fuel spray using a twin-fluid (fuel and air) nozzle and a hot wire ignition source. The twin-fluid nozzle had operating pressures of 5.78 bar and 5.57 bar for fuel and air, respectively, and produced a fuel spray distribution of 90° angle. The fuel spray nozzle was located at one corner of the compartment and 0.74 m high from the floor. An electric igniter was used to ignite the fuel spray and produce an explosion in the test compartment. The igniter was made of 0.91 m of 14 gauge nichrome wire looped around a 15.87 mm rod. It was located 0.47 m away from the fuel spray nozzle. The electric igniter was powered with 40 Amps. The locations of the spray nozzle and igniter are shown in Figure 2.

Gasoline was used as the testing fuel, which made the explosion very challenging for suppression due to its volatility. During the experiments, the fuel spray was maintained for approximately 2 to 3 seconds to limit the total amount of gasoline discharged (170 mL to 250 mL). Air supply to the compartment through the twin fluid nozzle was continuously maintained at approximately $0.4 \text{ m}^3/\text{min}$ during the whole duration of the experiments, simulating an actual case of fresh air flowing into the crew compartment through the opening on the wall made by a projectile. At the same time, the hot wire igniter was maintained hot during the experiments to simulate the presence of

hot fragments in the crew compartment when a projectile penetrates the wall. A continuous supply of air and the presence of hot ignition wire increased the possibility of fire re-ignition, resulting in a very challenging scenario for explosion suppression.

2.3 Explosion Extinguishing Systems

Three types of fire extinguishing systems with two suppressant agents for suppressing explosions were used in the experiments; a high pressure/FM-200 extinguisher, a hybrid gas generator with FM-200 and a hybrid gas generator with water. The fire extinguishing systems with their flame detectors were mounted on the wall of the test compartment, opposite to the fuel spray, as shown in Figure 2.

Figure 3 shows a high pressure FM-200 extinguisher with a flame detector used in the experiments. It used “standard” US Army halon bottles, which had a volume of approximately 0.014m^3 . FM-200 was stored in the bottle and pressurized up to 40 bar (600 psi) with nitrogen. The initiation of the explosion in the test compartment was detected by a high speed optical UV/IR flame detector. The detection of the explosion activated the discharge of the extinguishing agent. The agent in the cylinder could be discharged in less than 100 ms, using an ultra fast solenoid valve. The design concentration of FM-200 in the compartment was 7%[9], which required 2.26 kg of FM-200 in the extinguisher for the test compartment. In some experiments, the effect of an additive on the explosion suppression, as well as the scavenging effect of the additive on acidic gas products, were studied. The additive used in the experiments was sodium bicarbonate, and the amount used in the experiments was 250 g.

The hybrid gas generator fire extinguisher consists of an initiator, a solid propellant and liquid fire suppression agent [6-8]. Figure 4 shows the hybrid gas generator fire extinguisher with a flame detector. The discharge nozzle was the same as the high pressure extinguisher nozzle. Once a fire is detected, the flame detector sends an electrical stimulus and ignites a small pyrotechnic charge in the initiator, which then ignites the solid propellant. The heat and pressure generated by the combustion of the

solid propellant are used to heat and expel the liquid suppression agent. Typically, liquid suppression agents used in hybrid gas generator fire extinguishers are water and halocarbon agents. The combustion of solid propellants also generates a large quantity of inert gases (such as N_2 , CO_2 and water vapour) that are used as extra suppression agents. The discharge time of the hybrid gas generator is shorter than that of a high pressure extinguisher [8].

The hybrid gas generator fire extinguishers used in this project contained either FM-200 or water (with and without additives). The additive used in the hybrid gas generator with FM-200 was sodium bicarbonate, and the additive used in the hybrid gas generator with water was potassium acetate. The size of the FM-200/hybrid fire extinguisher was approximately 0.0125 m^3 , and the amount of FM-200 contained in the extinguisher was 2.26 kg, enough to produce 7% concentration in the test compartment. The size of the water hybrid fire extinguisher was 0.018 m^3 . The amount of potassium acetate additive used in the water hybrid fire extinguisher was enough to produce 48% or 58% solution by weight.

Two different agent discharge directions were used in the experiments. The first one was that the discharge direction of the agent nozzle was aimed at the fuel spray nozzle, or the fire source. The second one was that the discharge direction of the agent nozzle was aimed sideways toward the back of the compartment.

2.4 Instrumentation and Experimental Procedure

The instrumentation used in the experiments includes photodiodes, thermocouples, pressure sensor, simulated skin indicator, gas analyzers and a Fourier Transform Infrared (FTIR) Spectrometer. They were used to measure the fire ignition and extinguishment times, compartment temperatures and pressures, and the type and concentration of fire gases in the compartment. Their locations in the compartment are shown in Figure 5. Also, video cameras were used to monitor the fuel discharge, fire

ignition, agent discharge and explosion extinguishment. A detailed description of these instruments is given as follows:

Photodiode: four SFH 205F silicon planar PIN photodiodes were used in the experiments to monitor the times of fire ignition, extinguishment and re-ignition. They were installed on three side walls of the compartment, near the spray fire location. The sensors were connected to the high speed data acquisition system. The spectral ranges of the photodiodes were 800 to 1000 nm and the switch time (rise and fall time of photocurrent) was 20 ns.

Thermocouples: three different gauges of Type-K thermocouples were used in the experiments: 56 gauge (0.0127 mm diameter in wire size), 36 gauge (0.127 mm diameter in wire size) and 26 gauge (0.4 mm diameter in wire size). One 56 gauge thermocouple was installed near the gas sampling port to monitor changes in the gas temperature during suppression. Its response time was less than 50 ms in still air and 4 ms in air with a flow velocity of 18.6 m/s, according to the information provided by the manufacturer. However, the 56 gauge thermocouple was very fragile and could not survive many experiments. After the first two experiments, it was damaged and replaced with a 36 gauge thermocouple.

Seven 36-gauge thermocouples were used in the experiments, including thermocouples #1 and #2 near the gas sampling ports, thermocouples #3 and #4 near the fire source, thermocouple #5 placed in the simulated skin indicator, thermocouple #6 near the extinguisher, and thermocouple #7 near the compartment floor. The response time of 36 gauge thermocouples was 1.0 sec in still air and 80 ms in air with a flow velocity of 18.6 m/s. The 36 gauge thermocouples were connected to the high speed data acquisition system. They were used to monitor the times of fire ignition and development, agent discharge, and fire extinguishment.

One thermocouple tree with five 26 gauge thermocouples was set up in the middle of the testing compartment. The thermocouples were placed in the tree at 100 mm

intervals vertically from the bottom to the ceiling of the compartment. The response time of 26 gauge thermocouple was 10 sec in still air and 600 ms in air with a flow velocity of 18.6 m/s. They were connected to the standard data acquisition system and were mainly used to monitor changes in average room temperatures.

Pressure Sensor: one pressure sensor (SDX01G2) was installed near the gas sampling port to monitor the pressure changes in the compartment. It was connected to the high speed data acquisition system and its measuring range was 0 to 6896 Pa (1 psi).

Simulated Skin Indicator: one simulated skin indicator that was placed near the gas sampling port was used to study possible skin burns during the explosion suppression experiments. It was made from 2 layers of polyethylene plastic sheets, each with 0.051 mm thickness. One 36-gauge thermocouple and one non-reversible temperature monitor (8MA) were placed between the plastic sheets. The temperature monitor had 6 display temperature indicators, ranging from 38°C to 116°C. The temperature indicator turned black once the temperature reached the rated temperature. This set-up simulated the temperature sensing by human skin. When human skin is exposed to a high temperature, it is the underside of the skin that feels the temperature and it takes a very short time for the temperature to conduct through the outer skin layer. It is hypothesized that the set-up used in this experiment measures the temperature on the underside of the thin polyethylene sheet simulating outer skin layer. If the explosion in the compartment was controlled, so that the flash temperature in the compartment lasts less than a few hundred milliseconds, the temperature transmission through the polyethylene sheet would be minimal, and the temperature indicator on the underside of the polyethylene sheet would not register the temperature, indicating that human skin under similar conditions would not feel the high flash temperature. On the other hand, when the temperature indicator on the underside of the polyethylene sheet turns black, it means that the underside of the skin would feel the temperature higher than the rated temperature of the indicator.

Gas Analyzers: a Siemens Ultramat 22P Series CO₂/CO analyzer and a Siemens Oxymat 5E O₂ analyzer were used to measure CO, CO₂ and O₂ concentrations in the compartment during the experiments. Fire gases were drawn from the compartment through a copper sampling port (12 mm in diameter). They were then fed to the gas analyzers. The maximum measurement ranges of the gas analyzers were 1.0% CO and 4.0% CO₂.

FTIR Spectrometer: a BioRad Excalibur spectrometer was used to monitor the composition of the fire gases during the experiments, and to measure the concentrations of the agent and its thermal decomposition products generated by the reaction between the agent and flame. The FTIR spectrometer was calibrated for FM-200, hydrogen fluoride (HF), CO and CO₂ with commercial standard sample gases. The quantification of COF₂ was based on a single point commercial database. During the experiments, gas samples were drawn from the compartment through a heated sampling line to the FTIR spectrometer via a manual three-way valve to isolate the cuvette from deflagration pressure changes. The valve was switched to connect to the FTIR at 10 s after the suppression of the explosion in the compartment or termination of the fuel spray.

Video Cameras: one standard and one digital video camera were set up outside the test compartment to obtain visual records of the experiment.

Experimental data from a wide array of instrumentation were collected by two data acquisition systems: a high speed system and a low speed system. The high speed data acquisition system was used to monitor fuel discharge, fire ignition, agent discharge and fire suppression, and the pressure rise during the explosion suppression period. All channels were scanned at 100 kHz (10 μ s/channel). The low speed data acquisition system was used to monitor the average compartment temperatures and the fire gas compositions (CO, CO₂ and O₂) generated during the experiments at 1 s intervals.

During the experiment, the low speed data acquisition system and the FTIR were started at time $t = 0$ s. At $t = 60$ s, the high speed data acquisition system was started. At

$t = 61$ s, the fuel spray was activated and maintained for approximately 2 to 3 s. At $t = 71$ s, the three-way valve of the sampling line was switched to connect to the FTIR. Measurements were taken for approximately 5 min.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

Experiments were carried out to study deflagration-type explosion hazards and the performance of three explosion suppression systems in extinguishing explosions in the testing compartment.

3.1 Explosion Hazards in the Compartment

Five explosion experiments without suppression were conducted to understand explosion hazards encountered in the compartment and their potential damaging effect. Table 1 summarizes the experimental results without explosion suppression.

As shown in Table 1, fuel spray duration in the experiments ranged from 1624 ms to 3000 ms, and approximately 135 to 250 ml of the gasoline was sprayed into the compartment. The ignition delay period in the experiments ranged from 119 ms to 1040 ms and fire duration lasted approximately 1600 ms to 3000 ms.

Figures 6a to 6f show the images of the explosion process in experiment EXP-05. Once the fuel was ignited, the fire quickly spread and filled the whole compartment. The compartment door was pushed to fully open as the explosion occurred. With the door fully open, the overpressure in the compartment was quickly released, and some fire gases leaked out of the compartment as flames were spreading out of the compartment. At the same time, fresh air was brought into the compartment through the open door.

Flame signals measured from photodiodes near the fire source (see Figure 7) showed the occurrence of the explosion at 124 ms after the fuel spray in EXP-05. Figure 8 shows the variation of the overpressure generated in the explosion with time.

The maximum overpressure in the experiment was 1100 Pa. It was generated in the early stage of the explosion at 155 ms after the fuel discharge, and with the door being open, the overpressure in the compartment quickly declined.

Figure 9 shows the variation of temperatures measured near the fire source with time. The temperatures showed a quick increase as the fuel ignited, and the maximum compartment temperature reached 800°C.

During the explosion experiment in EXP-05, the minimum oxygen concentration in the compartment dropped to 10.6%, and maximum CO concentration generated in the experiment was 0.55%, while the maximum CO₂ concentration exceeded the maximum range of the gas analyzer setting (4%).

Test results in five experiments showed that the level of overpressure generated in the explosion was affected by the length of the ignition delay period, as the fuel quantity involved in the explosion increased with the ignition delay period. In experiment EXP-03, the fuel ignition was significantly delayed until 1040 ms after the start of the fuel spray. When the explosion occurred, a large fire ball was generated in the compartment. The overpressure (2300 Pa) generated in the explosion was much higher than those generated in other experiments with shorter ignition delay times.

The experimental results also indicate that although only a small amount of fuel was involved, the explosion in the compartment was quite severe, creating high temperatures and large overpressure, as well as low oxygen and high CO and CO₂ concentrations in the compartment. The maximum temperatures generated in the five experiments ranged from 820 to 1020°C. The minimum oxygen concentrations ranged from 9.0 to 13.4%, depending on the amount of fuel sprayed into the compartment. The maximum CO₂ concentrations generated in the experiments exceeded 4.0%, the maximum setting of the gas analyzer. The maximum CO concentrations ranged from 0.55% to higher than 1.0%. In all five experiments, the simulated skin indicator placed inside the compartment was damaged, and its plastic sheet melted. The temperature

indicators ranging from 88°C to 116°C turned black, indicating that skin would be exposed to higher than those temperatures. With this type of explosion, the equipment and personnel in the crew compartment would have little chance of survival when no protection was provided.

3.2 Explosion Suppression

27 full-scale explosion suppression experiments were conducted using three extinguishing systems with and without an additive, and involving different agent discharge directions and use of an obstacle in the compartment. The summary of experimental conditions and results are shown in Tables 2, 3, 4 and 5.

The agent discharge delay time in the experiments was defined as the time interval between the occurrence of the fire ignition and the start of the agent discharge. The explosion extinguishing time was defined as the time interval between the fuel ignition and explosion extinguishment. The fire re-ignition time was defined as the time interval between the first fire extinguishment and the occurrence of fuel re-ignition. They were determined by the four photodiodes and the digital video camera used in the experiments.

During the experiments, the agent discharge delay time ranged from 10 to 21 ms for the high pressure/FM-200 extinguisher, 9 to 54 ms for the hybrid/FM-200 extinguisher and 12 to 24 ms (124 ms only in one experiment) for the hybrid/water extinguisher. These results showed that the three extinguishing systems were able to quickly detect the fire and activate the agent discharge. However, explosion suppression performance was dependent not only on the fire detection capability, but also on the type of agent used, agent discharge direction, presence of an obstacle in the compartment, and additives in the suppression agents.

3.2.1 Explosion Suppression without Additive

3.2.1.1 Agent Discharging toward Fire Source

In the experiments, one extinguisher was installed in the mock-up compartment and the nozzle of the extinguisher was aimed towards the fire source located at one corner of the compartment. A high pressure FM-200 extinguisher, a hybrid/FM-200 or hybrid/water extinguisher was used in each experiment. Table 2 summarizes the experimental results.

Using a high pressure FM-200 extinguisher, the explosion was extinguished in 396 ms and 317 ms, in experiments EXP-02 and EXP-26, respectively. However, the fire quickly re-ignited in 495 ms and 357 ms, respectively, after the initial extinguishment. The re-ignited fire lasted for a few seconds until the fuel in the compartment was burnt up.

Since the level of thermal decomposition products generated during suppression was determined by the fire intensity and the duration of the contacting time between the agent and flame, fire re-ignition resulted in very high HF and COF₂ concentrations in the compartment. The average HF concentrations over a 2 min period in the two experiments ranged from 4,600 to 9,400 ppm and the 2 min average COF₂ concentration from 4,600 to 7400 ppm. At the same time, the oxygen concentration in the compartment dropped to 6.3 and 11.5%, respectively, and CO and CO₂ concentrations exceeded 1.0 and 4.0%. The plastic sheets of the simulated skin indicator in both experiments were melted and the temperature sensors turned black, indicating a serious threat to personal safety.

Figures 10a to 10f show explosion suppression process in experiment EXP-08 with the hybrid/FM-200 extinguisher. The agent discharge was actuated once the fire was detected as shown in Figure 10c. The explosion was extinguished at 228 ms after the ignition. However, the fire re-ignited at 2840 ms after the first explosion was extinguished, as shown in Figure 10f. At the re-ignition moment, both the agent discharge and fuel spray were completed, but the igniter was still maintained hot. The

extinguishing time of the hybrid/FM-200 extinguisher was shorter than that of the high pressure/FM-200 extinguisher.

The re-ignition in experiment EXP-08 also led to high thermal decomposition products. The 2-min average concentrations were 7400 ppm for HF, and 8400 ppm for COF_2 , respectively. The skin indicator placed in the compartment was damaged and all the temperature sensors, ranging from 88°C to 116°C, in the skin indicator turned black.

Experiments showed that both the high pressure and hybrid FM200 extinguishers, when the agent discharge was aimed toward the fire source, were able to extinguish the explosion, but could not prevent the fire from re-ignition. As observed in the experiments, when the agent was discharged aiming towards the fire source, the air and unburned fuel mixture were pushed against the flame front. This created a strong turbulent mixing between the air and fuel vapor, resulting in a large fire flare-up, as shown in Figure 10d. The overpressure generated in the fire flare-up pushed the door fully open, and a part of the agent together with fire gases leaked out of the compartment. As a result, agent concentration in the compartment could not be maintained at the design level, creating the opportunity for re-ignition. Figure 11 shows the FM-200 concentration in the compartment with time, measured by FTIR in experiment EXP-26, 10 s after the fuel discharge. FM-200 concentration in the compartment decayed very slowly with time, and the maximum concentration was approximately 5.8%, lower than the target concentration of 7%, due to the leakage during explosion suppression.

The hybrid extinguisher with 1.5 kg of water could not extinguish the explosion in experiment EXP-16. When the amount of water was increased from 1.5 kg to 2.25 kg in experiment EXP-17, the explosion was extinguished at 240 ms after the fire ignition, but the fuel spray quickly re-ignited at 300 ms after the first explosion was extinguished. The visibility in the compartment was reduced with the formation of a large amount of steam during the suppression. At the moment of re-ignition, water discharge from the extinguisher was completed, but fuel spray was continuing. The fire in the compartment lasted a few seconds.

Compared to experiment EXP-16, increasing the amount of water from 1.5 kg to 2.25 kg allowed the explosion to be extinguished but could not prevent re-ignition. During the experiment, the compartment door was pushed open and a part of the steam and fire gases leaked out of the compartment. The oxygen concentration in the compartment dropped to 12.8%, and CO and CO₂ concentrations exceeded 1.0 and 4.0%, respectively. The skin indicator placed in the compartment was not damaged but the temperature sensors, ranging from 38°C to 66°C, in the simulated skin indicator turned black.

3.2.1.2 Agent Discharging Sideways

In order to evaluate the impact of agent discharge direction on the explosion suppression, the direction of the extinguisher nozzle was adjusted to aim sideways toward the back of the compartment. The experimental results are listed in Table 2.

Figures 12a to 12f show the explosion suppression sequence of the high pressure extinguisher with 2.26 kg of FM-200 used in experiment EXP-18. The fire was quickly extinguished at 310 ms after ignition and no re-ignition occurred in the compartment (see Figure 12f). The suppression performance was better than that with the agent discharging toward the fire source. The successful explosion suppression resulted in low fire gases and thermal decomposition products generated in the experiment. The 2-min average HF and COF₂ concentrations were 820 and 260 ppm, respectively. The simulated skin indicator placed in the compartment was not damaged, and no temperature sensors, ranging from 38°C to 107°C, in the simulated skin indicator turned black.

In experiment EXP-09, a hybrid extinguisher with 2.26 kg of FM-200 extinguished the explosion at 153 ms after ignition, and there was no subsequent re-ignition. The suppression performance of the hybrid/FM-200 extinguisher was significantly improved with discharging sideways, compared to discharging toward the

fire source. Its extinguishing performance was also better than the high pressure/FM-200 extinguisher under the same testing conditions.

Since the explosion was quickly extinguished, the maximum temperature measured by the regular thermocouple in experiment EXP-09 was only 25°C. Thermal decomposition products generated in the experiment were also significantly reduced. The 2-min average HF and COF₂ concentrations were 60 and 20 ppm, respectively. The skin indicator placed in the compartment was not damaged, and no temperature sensors in the skin indicator turned black.

Experiments showed that with agent discharging sideways, performance of both the high pressure and hybrid/FM200 extinguishers was improved. As observed in the experiments, there was also a fire flare-up during the fire suppression, however, its size was smaller than the one with the agent discharging toward the fire source, because the air and unburned fuel mixture were not directly pushed against the flame. Also, the path of the agent flow in the compartment reduced the leakage of the agent through the door. Figure 13 shows the FM-200 concentration in the compartment in the two experiments involving a high pressure extinguisher and a hybrid extinguisher. FM-200 concentrations in the compartment in both experiments were maintained near or above 7%, the target concentration, which helped in preventing re-ignition in the compartment.

However, the performance of the hybrid/water extinguisher was not improved by discharging water sideways. In experiment EXP-33, the hybrid extinguisher with 2.25 kg of water reduced the fire size, but could not extinguish the explosion. As observed in the experiment, unlike gaseous agent, some of the discharged water was lost when discharged sideways, as fine water droplets hit the side and back walls and adhered to them before reaching the fire source. The failure of explosion suppression led to high temperatures (1018°C) and large overpressure (3049 Pa) in the compartment. The oxygen concentration in the compartment was also dropped to 13.0%, and CO and CO₂ levels in the compartment were higher than 0.45% and 4.0%, respectively.

3.2.1.3 Presence of an Obstacle in the Compartment

To evaluate the impact of an obstacle on the explosion suppression, a 25.4 cm diameter tube obstacle was placed in the compartment, as shown in Figure 1. Explosion suppression experiments were conducted using both the high pressure and hybrid FM-200 extinguishers with different agent discharging directions. Table 3 summarizes the experimental results.

In experiment EXP-19, the nozzle direction of the high pressure FM-200 extinguisher was toward the obstruction and the fire source. It was observed that the obstacle blocked the agent from directly reaching the flame. The extinguisher extinguished the explosion at 540 ms after ignition. The extinguishing time was longer than those observed in experiments without an obstacle. Also, the explosion re-ignited at 1416 ms after the first explosion was extinguished.

In experiment EXP-21, the nozzle direction of the high pressure extinguisher was changed to face away from the obstacle. The nozzle was aimed sideways towards the back of the compartment. The explosion was extinguished at 373 ms after the ignition, and there was no subsequent re-ignition. The suppression performance of the extinguisher was better than that observed in experiment EXP-19 with the agent discharging toward the obstacle. However, the extinguishing time was still longer than that observed in experiment EXP-18, in which the agent was discharged sideways, but without the obstacle.

Since the explosion was quickly extinguished, the maximum temperature and the HF and COF₂ concentrations measured in experiment EXP-21 were low. The simulated skin indicator placed in the compartment was not damaged, and no temperature sensors, ranging from 38°C to 107°C, in the simulated skin indicator turned black.

Three experiments involving the hybrid extinguisher with 2.26 kg of EM-200 were conducted with the obstacle in the compartment. In two experiments, EXP-10 and

EXP-12, with the nozzle of the extinguisher aimed directly towards the center of the obstacle, the explosion was extinguished at 189 and 960 ms after ignition, respectively. However, the fire re-ignited at 1336 and 340 ms, respectively, after the first explosion was extinguished. The re-ignited flame did not expand to fill the whole compartment and was limited to the area around the igniter. Since the re-ignited flame was mainly limited to the area around the igniter, the skin indicator placed in the compartment was not damaged and no temperature sensors in the skin indicator turned black.

In the experiment with the nozzle of the hybrid extinguisher aimed sideways towards the back of the compartment, the explosion was extinguished at 206 ms after ignition. However, the fuel re-ignited at 2259 ms after the first explosion was extinguished. These experiments clearly showed that the presence of an obstacle in the compartment created a much more challenging condition for the extinguishers in suppressing explosions in the compartment.

3.2.2 Explosion Suppression with Additive

To evaluate the effect of an additive on the explosion suppression and the generation of thermal decomposition products, full-scale experiments were carried out using three extinguishing systems with different types of additives. Test results showed that the use of the additive improved the extinguishing performance, and for the FM-200 extinguishers, reduced the generation of thermal decomposition products as well.

3.2.2.1 High Pressure FM-200 Extinguisher

Sodium bicarbonate (250 g) was added into 2.26 kg of FM-200 in the high pressure extinguisher. Full-scale explosion suppression experiments were carried out with an obstacle in the compartment. Table 4 summarizes the experimental results involving a high pressure extinguisher with sodium bicarbonate additive.

In experiment EXP-22, the nozzle direction of the extinguisher was aimed at the edge of the obstacle, facing towards the fire source. The explosion was extinguished at 388 ms after ignition, and there was no subsequent re-ignition. The suppression performance was significantly improved, compared to experiment EXP-19 without the additive under the same testing conditions.

FTIR spectra of fire gases showed that the major thermal decomposition products generated in the explosion suppression with the additive were still HF and COF₂. In experiment EXP-22, the 2-min average HF and COF₂ concentrations were 590 ppm and 160 ppm, respectively. These values are much lower than those measured in experiment EXP-19 without the additive.

The maximum temperature measured near the fire source was approximately 390°C, and the skin indicator placed in the compartment was not damaged, and no temperature sensors, ranging from 38°C to 107°C, in the simulated skin indicator turned black.

In experiment EXP-23, the nozzle direction of the extinguisher was aimed sideways towards the back of the compartment. The explosion was extinguished at 364 ms after ignition. There was no re-ignition afterwards. The extinguishing time was also shorter than that observed in experiment EXP-21 without additive under the same testing condition.

HF and COF₂ concentrations produced in experiment EXP-23 were very low. Both 2-min average HF and COF₂ concentrations were 150 and 50 ppm, respectively.

It was noted that after each experiment, the whole compartment surface was covered with a light dusting of the additive (sodium bicarbonate).

3.2.2.2 Hybrid Gas Generator/FM-200 Extinguisher

The additive used in the hybrid FM-200 extinguisher was also sodium bicarbonate but three different quantities of the additive were used in the experiments. The fire scenarios in the experiments were the same as those used in the experiments with the high pressure extinguisher, in which an obstacle was placed inside the compartment. Table 4 summarizes the experimental results involving the hybrid FM-200 extinguisher.

In experiment EXP-13, 25 g of sodium bicarbonate was added into the solid propellant of the gas generator. The nozzle of the hybrid extinguisher was aimed at the edge of the obstacle and towards the fire source. The explosion was extinguished at 277 ms after ignition, and there was no subsequent re-ignition. Compared to experiment EXP-12 without the additive, the additive not only helped in reducing the extinguishing time but also in preventing re-ignition.

Since the explosion was quickly extinguished, the amount of HF and COF₂ generated in the experiment was small. The 2-min average HF and COF₂ concentrations in the experiment were 940 and 210 ppm, respectively. The maximum temperature measured near the fire source was approximately 461°C. The skin indicator placed in the compartment was not damaged, and no temperature sensors, ranging from 38°C to 107°C, in the simulated skin indicator turned black.

In experiment EXP-27 with the nozzle direction facing sideways towards the back of the compartment, the explosion was extinguished at 215 ms after ignition, which was shorter than the extinguishment time with the nozzle facing the obstacle. There was no re-ignition in the experiment. COF₂ concentration in the experiment was further reduced to 50 ppm.

In experiment EXP-24, the amount of sodium bicarbonate was increased from 25 g to 250 g and the additive was mixed with FM-200 in the cylinder of the hybrid extinguisher instead of the solid propellant. Other testing conditions were the same as in experiment EXP-13. The explosion was extinguished at 193 ms after ignition, and there was no subsequent re-ignition in the experiment. The maximum temperature measured

near the fire source was approximately 72°C. The 2-min average HF and COF₂ concentrations measured were below the detection limit.

The experiments showed that increasing the amount of additive (from 25 g to 250 g) improved the suppression performance of the extinguisher and substantially reduced the generation of thermal decomposition products. However, it resulted in more dust or sodium bicarbonate present on the compartment walls after the explosion suppression.

3.2.2.3 Hybrid Gas Generator/Water Extinguisher

The additive used in the hybrid/water extinguisher was potassium acetate. Six full-scale explosion suppression experiments with different weight percentages of the additive in the water were carried out. Table 5 summarizes the experimental results involving the hybrid/water extinguisher

In experiment EXP-25, 2.25 kg of the water solution with 48% potassium acetate and 4% soap was used in the hybrid water extinguisher. The nozzle direction of the hybrid extinguisher was towards the fire source. There was no obstacle in the compartment. The explosion was extinguished at 264 ms after the fire ignition. However, when the water discharge was completed, blue flame appeared around the igniter. The fuel re-ignited at 415 ms after the first explosion was extinguished and the fire quickly spread to the whole compartment. Compared to the results of experiment EXP-17 using pure water in the extinguisher, suppression performance of the extinguisher was improved by the use of additives. However, using additives in the water produced some residue, and left water marks on the compartment walls during the test.

Figure 14 shows the species spectrum measured by FTIR. The major combustion products generated in experiment EXP-25 were CO and CO₂, and there was no thermal decomposition product generated in the experiment. The maximum flash temperature measured near the fire source was 440°C. The oxygen concentration in the compartment

dropped to 18.8%. Maximum CO and CO₂ concentrations measured in the experiment were 0.41% and 2.7%, respectively. The skin indicator placed in the compartment was not damaged, and only one temperature sensor, rated at 38°C, in the simulated skin indicator turned black.

To study the effect of additive quantity on the suppression performance, the weight percentage of the additive used in experiment EXP-29 was increased. The water solution contained 38% water, 4% soap and 58% potassium acetate. Other testing conditions in experiment EXP-29 were the same as in experiment EXP-25. The explosion was extinguished at 297 ms after the fire ignition. However, the fuel was re-ignited at 1996 ms after the first explosion was extinguished. Compared to experiment EXP-25, the re-ignition was delayed as more potassium acetate was added into the water solution.

Experiment EXP-30 was a repeat of experiment EXP-29, but the nozzle direction of the hybrid water extinguisher was changed to face sideways towards the back of the compartment. The explosion was extinguished at 462 ms after the fire ignition. The extinguishing time was longer than that in other experiments, but there was no subsequent re-ignition.

Since the explosion was extinguished, the maximum flash temperature measured near the fire source was 180°C in experiment EXP-30. The maximum CO and CO₂ concentrations measured in the experiment were 0.12% and 1.12%, respectively. The skin indicator placed in the compartment was not damaged, and no temperature sensor in the skin indicator turned black.

Experiment EXP-32 was also a repeat of experiment EXP-29, but one obstacle was placed in the compartment. Its size and location in the compartment were the same as those in the previous experiments using the high pressure and hybrid/FM-200 extinguishers. With the extinguisher discharge, the fire size was controlled but the explosion could not be extinguished. It was observed that some discharged water

droplets directly hit the obstacle and adhered to it, reducing the amount of water solution available for attacking the flame.

The maximum flash temperature measured in experiment EXP-32 was very high at 1180°C. The maximum overpressure generated in the experiment was 2200 Pa. The oxygen concentration in the compartment dropped to 10.6%, and the maximum CO and CO₂ concentrations exceeded beyond 1.0 and 4.0% that were the maximum settings of the analyzers.

In experiment EXP-34, the nozzle direction of the hybrid extinguisher was changed to face sideways towards the back of the compartment and other testing conditions were the same as in experiment EXP-32. The explosion was extinguished at 464 ms after the fire ignition. However, the fuel re-ignited at 1185 ms after the first explosion was extinguished. Compared to experiment EXP-32, the suppression performance of the extinguisher was improved when the nozzle direction was changed to face sideways, away from facing the obstacle.

6.0 CONCLUSION

The experimental results showed that an explosion in a compartment by a fuel spray would be a serious threat to any occupant in the compartment and would cause major damage to equipment. However, the explosion can be controlled or extinguished by appropriate extinguishing systems.

The three extinguishing systems evaluated in this project were a high pressure FM-200 extinguisher, a hybrid gas generator with FM-200, and a hybrid gas generator with water, with full-system hardware including optical flame sensors and electronic controllers.

The experiments showed that all three extinguishing systems could extinguish an explosion in the compartment, but, they could not prevent re-ignition of the explosion in

the compartment in some cases. The explosion suppression performances of the extinguishers were affected by the agent discharge direction, presence of an obstacle in the compartment and the use of additives.

A high pressure FM-200 extinguisher and a hybrid gas generator with FM-200, both extinguished the explosion in the compartment when there was no obstacle in the compartment. The hybrid gas generator with FM-200 extinguished the explosion much sooner than the high pressure FM-200 extinguisher, with an extinguishing time of less than 250 ms compared to 300 – 400 ms for the high pressure FM-200 extinguisher. This is probably due to its faster agent discharge and extra suppression agents generated by the hybrid gas generator.

The test results showed that the nozzle direction of the extinguisher plays a significant role in the extinguishment and re-ignition prevention of explosion in the compartment. When the nozzle of the extinguisher was aiming towards the fire source, the extinguisher extinguished the explosion, but there was a re-ignition of the explosion in the compartment. The overpressure generated during the explosion suppression pushed the door fully open, and since the door was close to the fire source, by aiming the nozzle of the extinguisher toward the fire source, it was easier for the agent to leak out of the compartment. This may have contributed to the re-ignition of the fire.

When the direction of the extinguisher nozzle was adjusted to aim sideways towards the back of the compartment and away from the door, the extinguishers extinguished the explosion sooner and prevented the re-ignition of the explosion in the compartment. The experiments showed that discharging the agent sideways, instead of directing it toward the fire source, improved the suppression performance of the extinguishers. Also, discharging the agent sideways would be less affected by any obstacles present in the compartment.

Placing an obstacle in the compartment made it more challenging for the extinguishers to extinguish and prevent re-ignition of the explosion. With a 25.4 cm

diameter cylindrical tube obstacle in the compartment, the extinguishers extinguished the explosion, but there was subsequent re-ignition of the explosion.

When an additive was used to reduce the amount of thermal decomposition products generated from FM-200, it improved the suppression performance of the extinguishers. Using 250 g of sodium bicarbonate mixed with 2.26 kg of FM-200 made the extinguisher perform better. With the additive, a hybrid gas generator with FM-200 extinguished the explosion in the compartment with an obstacle in less than 250 ms, and there was no subsequent re-ignition of the explosion in the compartment. However, it produced sodium bicarbonate residue on the compartment walls.

A hybrid gas generator extinguisher with 1.5 kg of water failed to extinguish the explosion in the compartment without any obstacles present. However, when the hybrid extinguisher cylinder was changed to a larger one, the new hybrid water extinguisher containing 2.25 kg of water was able to extinguish the explosion in less than 250 ms, but the fuel spray quickly re-ignited after the first explosion was extinguished.

Adding potassium acetate to water as an additive improved the explosion suppression performance of the hybrid water extinguisher. The hybrid water extinguisher containing 2.25 kg of the water solution with a weight percentage of 58% potassium acetate, extinguished the explosion at 462 ms when there was no obstacle in the compartment, and there was no subsequent re-ignition. When an obstacle was present in the compartment, the hybrid water extinguisher, even with an additive, had difficulty in extinguishing the explosion.

Among the three extinguishing systems evaluated in this project, the hybrid gas generator with FM-200 performed best. The extinguishers with additives, such as sodium bicarbonate, reduced the generation of the thermal decomposition products from FM-200, and also improved the explosion suppression performance. With the additive, the hybrid FM-200 extinguisher can suppress an explosion in the compartment containing an obstacle within the target extinguishment time of 250 ms and can prevent

re-ignition of the explosion. However, it was observed during the tests that the hybrid FM-200 extinguisher with the additive produced sodium bicarbonate residue and the whole compartment surfaces were covered with a light dusting of the additive.

7.0 ACKNOWLEDGEMENTS

Authors would like to acknowledge the assistance of Drs. Malgosia Kanabus-Kaminska and Joseph Su in operating the FTIR apparatus and analyzing the gas measurement data. Authors would also like to acknowledge the assistance of Mr. Cameron McCartney in the planning of the experiment, and Mr. Michael Ryan in setting up and instrumenting the test compartment. The assistance of General Dynamics by providing the necessary hardware for the extinguishing systems is greatly appreciated. Special appreciation goes to Mr. Paul Wierenga and Mr. Gary Gregg of General Dynamics for their assistance in setting-up the extinguishing systems and their controllers during the experiments. This study was conducted under the Halon Alternatives Performance Evaluation Program, a joint research project between the Department of National Defence and the National Research Council of Canada.

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Table 1 Summary of Experimental Results without Explosion Suppression

Test No.	EXP-01	EXP-03	EXP-04	EXP-05	EXP-06
Extinguisher	n/a	n/a	n/a	n/a	n/a
Fire ignition delay (ms)	150	1040	125	124	119
Fuel discharge duration (ms)	>3000	2083	1624	2498	2473
Fire duration (ms)	n/a	1595	1945	2904	2952
Max. Temp. (°C)	n/a	1020	898	820	950
Max. Pressure (Pa)	n/a	2300	1060	1100	1050
Min. O₂ (%)	9.2	12.7	13.4	10.7	9.0
Max. CO₂ (%)	> 4.0	> 4.0	> 4.0	> 4.0	> 4.0
Max. CO (%)	0.81	> 1.0	> 1.0	> 0.55	> 1.0
Skin indicator	Damaged	Damaged	Damaged	Damaged	Damaged

n/a : no available data

Table 2 Summary of Experimental Conditions and Results with different agent discharge direction

Test No.	EXP-02	EXP-26	EXP-08	EXP-16	EXP-17	EXP-18	EXP-09	EXP-33
Extinguisher	High pressure	High pressure	Hybrid	Hybrid	Hybrid	High pressure	Hybrid	Hybrid
Agent	FM-200	FM-200	FM-200	Water	Water	FM-200	FM-200	Water
Agent weight (kg)	2.26	2.26	2.26	1.5	2.25	2.26	2.26	2.25
Agent con. (%)	7	7	7			7	7	
Discharge direction	Facing fire	Facing fire	Facing fire	Facing fire	Facing fire	Sideways	Sideways	Sideways
Ignition delay (ms)	n/a	106	113	125	118	133	121	115
Discharge delay (ms)	n/a	12	46	16	12	11	16	18
Fire ext. (ms)	396	317	228	Not ext.	240	310	153	Not ext.
Fire re-ignition (ms)	495	357	2840		300	No re-ignition	No re-ignition	
Fuel discharge period (ms)	>3000	2112	3058	1850	2065	2605	2162	2096
Max. Temp. (°C)	n/a	n/a	900	1150	780	315	25	1018
Max. Pressure (Pa)	n/a	n/a	2400	2400	2400	820	3500	3049
Max. HF (ppm)	11,900	5,900	10,300	n/a	n/a	890	80	n/a
Ave. HF (ppm)	9,400	4,600	7,400	n/a	n/a	820	60	n/a
Max COF₂ (ppm)	11,000	5,600	19,000	n/a	n/a	320	50	n/a
Ave. COF₂ (ppm)	7,400	4,600	8,400	n/a	n/a	260	20	n/a
Min. O₂ (%)	6.3	11.5	6.5	11.2	12.8	18.4	18.7	13.0
Max. CO₂ (%)	> 4.0	> 4.0	> 4.0	> 4.0	> 4.0	0.51	0.88	> 4.0
Max. CO (%)	> 1.0	> 1.0	> 1.0	> 1.0	> 1.0	n/a	n/a	0.45

n/a : no available data

Table 3 Summary of Experimental Conditions and Results with Present of Obstacle in the Compartment

Test No.	EXP-19	EXP-21	EXP-10	EXP-11	EXP-12
Extinguisher	High pressure	High pressure	Hybrid	Hybrid	Hybrid
Agent	FM-200	FM-200	FM-200	FM-200	FM-200
Agent weight (kg)	2.26	2.26	2.26	2.26	2.26
Agent con. (%)	7	7	7	7	7
Discharge direction	Facing obstacle	Facing sideways	Facing obstacle	Facing sideways	Facing obstacle
Fire ignition delay (ms)	131	120	108	104	202
Agent discharge delay (ms)	11	10	16	16	13
Fire ext. (ms)	540	373	189	206	960
Fire re-ignition (ms)	1416	No re-ignition	1336	2259	340
Fuel discharge period (ms)	2103	2474	1993	2340	2167
Max. Temp. (°C)	566	227	420	n/a	510
Max. Pressure (Pa)	2250	1050	4400	4800	2750
Max. HF (ppm)	5,000	1,060	6,200	1,700	5,000
Ave. HF (ppm)	4,400	900	5,000	1,600	4,600
Max COF₂ (ppm)	4,400	300	9,100	900	5,500
Ave. COF₂ (ppm)	3,000	200	5,000	700	4,500
Min. O₂ (%)	17.1	18.5	11.1	18.3	17.1
Max. CO₂ (%)	2.37	0.57	> 4.0	1.24	> 4.0
Max. CO (%)	> 1.0	n/a	> 1.0	0.17	> 1.0

n/a : no available data

Table 4 Summary of Test Conditions and Results with High Pressure and Hybrid/FM200 Extinguisher Using Additive

Test No.	EXP-22	EXP-23	EXP-13	EXP-27	EXP-24
Extinguisher	High pressure	High pressure	Hybrid	Hybrid	Hybrid
Agent	FM-200	FM-200	FM-200	FM-200	FM-200
Agent weight (kg)	2.26	2.26	2.26	2.26	2.26
Agent con. (%)	7	7	7	7	7
Additive (Sodium bicarbonate)	250 g	250 g	25 g	25 g	250 g
Discharge direction	Facing obstacle	Facing sideways	Facing obstacle	Facing sideways	Facing obstacle
Obstacle	Yes	Yes	Yes	Yes	Yes
Fire ignition delay (ms)	108	523	253	102	111
Agent discharge delay (ms)	21	13	54	26	10
Fire ext. (ms)	388	364	277	215	193
Fire re-ignition (ms)	No re-ignition	No re-ignition	No re-ignition	No re-ignition	No re-ignition
Fuel discharge period (ms)	2661	3020	2112	2542	2235
Max. Temp. (°C)	370	n/a	461	72	27
Max. Pressure (kPa)	1490	870	2800	2000	3950
Max. HF (ppm)	770	340	1,300		120
Ave. HF (ppm)	590	150	940		15
Max COF₂ (ppm)	200	60	290	60	12
Ave. COF₂ (ppm)	160	50	210	50	7
Min. O₂ (%)	18.5	18.4	18.4	18.6	18.8
Max. CO₂ (%)	0.73	0.54	1.32	0.88	0.93
Max. CO (%)	0.06	n/a	0.03	n/a	n/a

n/a : no available data

Table 5 Summary of Experimental Conditions and Results with Hybrid/Water Extinguisher Using Additive

Test No.	EXP-25	EXP-31	EXP-29	EXP-30	EXP-32	EXP-34
Agent	Water	Water	Water	Water	Water	Water
Agent weight (kg)	2.25	2.25	2.25	2.25	2.25	2.25
Additive	48% water, 4% soap, 48% acetate	48% water, 4% soap, 48% acetate	38% water, 4% soap, 58% acetate	38% water, 4% soap, 58% acetate	38% water, 4% soap, 58% acetate	38% water, 4% soap, 58% acetate
Discharge direction	Facing fire	Facing sideways	Facing fire	Facing sideways	Facing obstacle	Facing sideways
Obstacle	No	No	No	No	Yes	Yes
Fire ignition delay (ms)	106	102	133	132	114	108
Agent discharge delay (ms)	19	24	14	20	23	124
Fire ext. (ms)	264	262	297	462	Not ext.	464
Fire re-ignition (ms)	415	1388	1996	No re-ignition		1185
Fuel discharge period (ms)	2025	2079	2282	2099	2026	1990
Max. Temp. (°C)	440	620	960	180	1180	950
Max. Pressure (Pa)	2380	3550	2500	2600	2200	2300
Min. O₂ (%)	18.8	18.8	18.9	20.0	10.6	18.4
Max. CO₂ (%)	2.7	2.5	1.8	1.12	> 4.0	2.43
Max. CO (%)	0.41	0.3	0.27	0.12	> 1.0	0.45

All dims in mm

Figure 1 Mock-up test compartment (isometric)

Figure 2. Fire source and extinguishing system in the test compartment

Figure 3 Photograph of a high pressure extinguisher

(a)

(b)

Figure 4 Photograph of the hybrid extinguisher

Figure 5. Instrumentation in the test compartment

(a) Ignition at 124 ms

(b) Development at 157 ms

(c) Full involvement at 223 ms

(d) Full involvement at 553 ms

(e) Termination of fuel spray at 2498 ms

(f) Fire termination at 3028 ms

Figure 6 Explosion experiment without suppression in experiment EXP-05

Figure 7 Variation of flame signals with time (experiment EXP-05)

Figure 8 Variation of overpressure with time (experiment EXP-05)

Figure 9 Variation of temperatures measured by 36 gauge thermocouples near the fire source with time (experiment EXP-05)

(a) Ignition at 113 ms

(b) Development at 146 ms

(c) Activation at 179 ms

(d) Interaction at 245 ms

(e) Extinguishment at 341 ms

(f) Re-ignition at 3181 ms

Figure 10 Explosion suppression with a hybrid FM-200/gas generator in experiment EXP-08 when agent discharge facing the fire source

Figure 11 FM-200 concentrations measured in the experiment involving a high pressure extinguisher with agent discharge facing fire source

(a) Ignition at 133 ms

(b) Development at 166 ms

(c) Activation at 199 ms

(d) Interaction at 265 ms

(e) Interaction at 430 ms

(f) Fire termination at 463 ms

Figure 12 Explosion suppression with a high pressure extinguisher in experiment EXP-18 when agent discharge facing sideways

Figure 13 FM-200 concentrations measured in two experiments with two different extinguishers, with agent discharge aiming sideways

Figure 14 Major gases present in experiment EXP-25 with a hybrid/water extinguisher