

# **Explosion Protection of an Armoured Vehicle Crew Compartment with Water Mist**

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## **INTRODUCTION**

Halon has been widely used for the protection of an armoured vehicle crew compartment until recently. Due to the Montreal protocol, however, the use of halon has been severely restricted. Halocarbon agents have been introduced recently for the explosion protection of crew compartments. But, halocarbon agents generate large quantities of acid gas by-product, and also there are growing environmental concerns over the atmospheric lifetime and the global warming potential of most halocarbon agents.

Water has a tremendous cooling effect and can mitigate an explosion hazard if used properly. Recently, two companies have developed water mist systems to provide explosion protection in the crew compartment of military vehicles. These systems combine gas generator and water mist technologies. They incorporate an extinguisher container, which contains water with a solid propellant gas generator. When an explosion is detected, the gas generator ignites, and the pressure from the combustion of the gas generator discharges the water in the container through water mist nozzles.

The National Research Council of Canada (NRC) has recently carried out a project to evaluate the performance of the two water mist extinguishing systems in providing protection from a deflagration-type explosion in a crew compartment of military armoured vehicles.

This paper describes the full-scale evaluation testing of the two hybrid water mist systems, including the description of the test scenario, water mist systems and the experimental results.

## **DESCRIPTION OF EXPERIMENTS**

### **Test Compartment**

The real-scale explosion suppression tests were conducted in a compartment simulating the back half of an armoured vehicle crew compartment. The cross-section area of the test compartment was  $2.52 \text{ m}^2$ , and it was 1.5 m in length and the total volume of the test compartment was  $3.78 \text{ m}^3$ . The test compartment had an access door with a dimension of 1.04 m x 1.04 m. This door also acted as a pressure relief vent to protect the compartment integrity.

### **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 igniter. The fuel spray nozzle was located at one corner of the compartment and 0.74 m high from the floor. 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. The electric igniter was maintained hot during the experiments to simulate the presence of hot fragments in the crew compartment when a projectile penetrates the wall. The presence of hot ignition wire increased the possibility of fire re-ignition, providing a challenging scenario for explosion suppression.

### **Explosion Extinguishing Systems**

Two water mist explosion suppression systems, with full-system hardware including optical fire sensors and electronic controller, were used in the study. The two water mist fire suppression systems are hybrid gas generator/water system and EXWA water mist system.

The hybrid gas generator/water system uses the fire suppression effect of a gas generator with water mist. A gas generator can produce a large quantity of inert gases (mainly  $\text{N}_2$ ,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  vapour) through combustion of solid propellants.

The hybrid gas generator fire extinguisher consists of an initiator, a solid propellant and water [2-4]. Once a fire is detected, the flame detector sends an electrical stimulus to ignite a small pyrotechnic charge in the initiator, which then ignites the solid propellant. The heat and pressure generated by the combustion of the propellant in the gas generator are used to heat and expel the water as fine water mist with strong momentum. The super fast discharge of a large quantity of inert gases, combined with the fire suppression and cooling characteristics of water mist, can be used to provide explosion protection for the crew compartment.

The hybrid gas generator fire extinguishers used in this project contained 1.5 kg or 2.25 kg of water. It was tested with and without an additive. The additive used was

potassium acetate. The hybrid fire extinguishing systems with their flame detectors was mounted on the wall of the test compartment, opposite to the fuel spray.

The EXWA system, a hybrid fire suppression system using gas generator and water, consists of a detector, controller, extinguishing container and nozzles. The principle behind the EXWA system is to use the pressure generated by the combustion of a gas generator in the container and discharge water through several nozzles using a piping network. The container has a solid gas generator in the bottom, and water in the upper portion of the container. They are separated by a cylinder head. When the solid gas generator ignites, the pressure generated by the combustion pushes the cylinder head, and pressurizes and expels the water through piping. This provides super fast discharge of a large quantity of water. In this study, four water mist nozzle heads with many different size orifices were mounted at the ceiling of the mock-up compartment. The EXWA system was evaluated for its explosion suppression performance with an additive (60% potassium lactate solution).

The EXWA system used in this study was a two-shot system. It had two extinguishing containers mounted side-by-side. When a flame is first detected, one container is discharged, and if there is re-ignition of the flame, then the second container is discharged to extinguish the re-ignited explosion in the compartment. Normally, flame detector sensor sensitivity is very high to detect explosion at an incipient stage, but after the initial detection and activation of the system, the sensor sensitivity is reduced to deter a second activation of the system for a certain period of time. The EXWA system tested in this study had at least a 0.7 s delay for a second discharge. The sensor sensitivity was reduced to very low for 0.7 s after the initial activation. After the 0.7 s, the sensor sensitivity was raised to a normal condition, so if the explosion was not extinguished by the first discharge, or if re-ignition of the explosion occurs, the system would detect the flame and would activate the second time.

## **Instrumentation**

The instrumentation used in the experiments included photodiodes, thermocouples, pressure sensor, simulated skin indicator and gas analyzers. They were used to measure the fire ignition and extinguishment times, compartment temperatures and pressures, and the concentrations of CO, CO<sub>2</sub> and O<sub>2</sub> in the compartment. Video cameras were also used to monitor the fuel discharge, fire ignition, agent discharge and explosion extinguishment.

## **TEST RESULTS**

### **Explosion Experiments without Suppression**

Baseline experiments were conducted in the mock-up crew compartment to determine the explosion conditions in the compartment, such as fire size, maximum compartment temperature and pressure, and to evaluate the potential damage to the crew

compartment caused by explosion incidents when it was not protected by the suppression system.

The experimental results 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 CO<sub>2</sub> levels in the compartment. For example, the maximum temperatures generated in the experiments ranged from 820 to 1020°C, and the maximum overpressure from 1050 to 2300 Pa. The minimum oxygen concentrations in the experiments ranged from 8.96 to 13.37%, depending on the amount of fuel discharged into the compartment. The maximum CO<sub>2</sub> 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%, the maximum range of the CO gas analyzer setting. The results showed that the explosion intensity was dependent on the amount of fuel discharged and the length of the ignition delay period. The explosion intensified as the ignition delay period increased and more fuel was discharged into the compartment.

In all baseline experiments, the simulated skin indicator placed inside the compartment was damaged, and its plastic sheet melted, indicating that skin would be exposed to very high 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.

### **Explosion Suppression with Hybrid Gas Generator/Water System**

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.

The hybrid extinguisher with 1.5 kg of water could not extinguish the explosion. When the amount of water was increased to 2.25 kg, the explosion was extinguished in 240 ms, but quickly re-ignited at 300 ms after the first explosion was extinguished.

Repeated experiments showed that the hybrid water extinguisher, when it was discharged toward the fire source, was able to extinguish the explosion, but could not prevent the fire from re-ignition.

In order to evaluate the impact of the water discharge direction on the explosion suppression, the direction of the extinguisher nozzle was adjusted to aim sideways toward the back of the compartment.

Experiments showed that the performance of the hybrid water extinguisher was reduced by discharging water sideways. The hybrid extinguisher with 2.25 kg of water reduced the fire size, but could not extinguish the explosion. It was observed in the experiment that 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.

To evaluate the effect of an additive on the explosion suppression, several experiments were carried out with an additive. The additive used in the hybrid/water extinguisher was potassium acetate. When 2.25 kg of water solution with 48% potassium acetate and 4% soap was used in the hybrid water extinguisher, it extinguished the explosion in 264 ms. However, when the water discharge was completed, a 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. For the hybrid/water extinguisher, the additive did not improve the fire suppression performance of the extinguisher.

### **Explosion Suppression with EXWA Water Mist System**

Several explosion suppression experiments with the EXWA system were conducted in the mock-up crew compartment. Experiments were conducted using 4.3 L (3.2 kg) of water with potassium lactate additive (40% water, 60% potassium lactate). The EXWA system with two extinguisher containers (each containing 4.3 L of water solution) was installed in the mock-up compartment. This was a two-shot system, and each extinguisher container was for each shot. Four nozzle heads were mounted at the ceiling of the mock-up compartment, and the nozzles were aimed towards the bottom.

The EXWA system detected the ignition of the explosion in the compartment, however, the explosion detection was much slower than the hybrid gas generator/water system. With the system activation, the explosion in the compartment was extinguished in 435 ms after the ignition. However, soon after the extinguishment (956 ms after the extinguishment), the explosion re-ignited. The EXWA system detected the re-ignition of the explosion and activated the system for the second time. The second explosion was extinguished in 67 ms. However, the explosion was re-ignited for the third time. Since the EXWA system was a two-shot system, it can suppress the re-ignition of the explosion only once. The explosion in the compartment was self-extinguished when the fuel spray was stopped.

In all experiments with the EXWA system using a water solution (60% potassium lactate), FTIR measurements showed that there was no abnormal or harmful by-products present in the test compartment during the tests. However, the presence of potassium lactate residue was noted on the walls of the test compartment after each test.

## **DISCUSSION**

In all experiments with water mist systems, initial extinguishment of explosion in the compartment was achieved, however, re-ignition of the explosion was a problem. In our test set-up, ignition source was a hot element powered continuously during the test. Water mist was able to cool the hot element, however, since it was powered continuously, the element became hot again.

The re-ignition of the explosion in the compartment depends on the ignition scenario. If ignition source does not exist after the initial extinguishment, then there would be no re-ignition. In our experiments, we were simulating a projectile penetrating the crew compartment wall and spraying fuel and hot fragments. In our experiments, we assumed that the hot fragments are large enough, so they would not be cooled down sufficiently during the water mist discharge period. In a case where the hot fragments are small, water mist spray may cool down the hot fragments sufficiently at the time of initial extinguishment of the explosion. If the hot fragments are cooled down, then there would be no ignition source, and no possibility of re-ignition in the compartment after the initial extinguishment by water mist.

## **SUMMARY**

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. The deflagration-type explosion can be controlled or extinguished by water mist systems, however, there would a strong possibility of re-ignition of the explosion in the compartment depending on the ignition scenario.

A hybrid gas generator water extinguishing system with 1.5 kg of water failed to extinguish the explosion in the compartment. However, the hybrid water extinguisher containing 2.25 kg of water was able to extinguish the explosion in 240 ms when discharged toward the fire source, but the fuel spray quickly re-ignited after the first explosion was extinguished.

Experiments showed that the performance of the hybrid water extinguisher was reduced by discharging water sideways. The hybrid extinguisher with 2.25 kg of water reduced the fire size, but could not extinguish the explosion. It was observed in the experiment that 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.

Experiments with the EXWA system showed similar results. It could extinguish the explosion in the compartment, but it could not prevent re-ignition of the explosion.

In all experiments with water mist systems, initial extinguishment of explosion in the compartment was achieved, however, re-ignition of the explosion was a problem. The re-ignition of the explosion in the compartment depends on the ignition scenario. In the experiments, it was assumed that the hot fragments are large enough, so they would not be cooled down sufficiently by water mist. In a case where the hot fragments are small, water mist spray may cool down the hot fragments sufficiently at the time of initial extinguishment of the explosion, and there would be no ignition source afterwards.

## **ACKNOWLEDGEMENTS**

The authors would like to acknowledge the assistance of Dr. Zhigang Liu in carrying out the project, and Mr. Michael Ryan in setting up the test compartment. The assistance of Mr. Paul Wierenga and Mr. Gary Gregg of General Dynamics in setting up the extinguishing systems is also acknowledged. 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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