24-011

Analyzing the Effectiveness of Fire Suppression Systems to Extinguish a Fire on Mobile Mine Equipment Used in the Mining Industry

James H Rowland III
National Institute for Occupational Safety and Health, Pittsburgh, PA

Davood Bahrami
National Institute for Occupational Safety and Health, Pittsburgh, PA

Richard A Thomas
National Institute for Occupational Safety and Health, Pittsburgh, PA

Liming Yuan
National Institute for Occupational Safety and Health, Pittsburgh, PA

ABSTRACT

To reduce the number of injuries resulting from fires on mobile, diesel-powered mine equipment, it is crucial to promptly suppress a fire once it is detected. The focus of this research was to determine the effectiveness of fire suppression agents. Large-scale tests were conducted using five different fire suppression systems based on: dry chemical, wet chemical, dual agent (dry and wet chemical), carbon dioxide, and water mist. Suppression nozzles were placed around the diesel engine where diesel fuel, engine motor oil, and hydraulic circulating oil spray fires were ignited. The results of this study can help mining companies and manufacturers by providing scientifically based data on the capabilities of the different fire suppression systems.

INTRODUCTION

Mineworkers often face a threat from mine equipment fires that can occur both at surface mines and in underground mine environments that can cause injuries or fatalities. The effectiveness of the fire suppression system installed on mine equipment can be limited by design quality, installation practices, and the type of fire suppressant employed. There are not any scientifically based measures available to help mine operators effectively prevent and suppress equipment fires. Most of the reportable mine fires are equipment fires caused by ignitions of combustible fluids such as hydraulic fluid released from a hose rupture onto hot engine surfaces. To reduce the number of equipment fires, it is necessary to develop effective measures to limit or prevent hot surface ignitions on mine equipment. To reduce the number of fire-related injuries and fatalities, it is important to improve the suppression techniques for the equipment fires to protect the equipment operators. Although some mine equipment include a fire suppression system, the efficacy of the system is compromised by poor design, ineffective installation, and fire damage to the system if not activated in time [1].

Various fire suppressing agents can be used for a fire suppression system such as dry chemical, wet chemical, carbon dioxide, water mist, and foam. Each fire suppressing agent has a different degree of effectiveness, depending on the type of fuel involved in the fire and fire conditions such as location, amount of fuel available, and ventilation surrounding the fire. The major fire-extinguishing mechanisms include cooling, separation or removal of fuel, dilution of oxygen, and breaking combustion chain reaction. Every fire suppressing agent acts on one or more mechanisms. Dry chemical fire suppressing agents generally consist of a chemical powder mixture that is electrically non-conductive. Dry chemical extinguishing systems are primarily suited for surface fires but are not effective on deep-seated fires. Wet chemical fire suppressing agents consist of a mixture of organic and inorganic salts in solution and were originally designed for cooking-oil fires. These agents can develop a temporary foam layer on the surface of a flammable liquid that permits the liquid to cool below the ignition temperature and prevents air from coming in contact with the liquid. Carbon-dioxide fire suppressing systems have been in use for many years and are used for the extinguishment of flammable liquids, gas fires, and fires involving electrically energized equipment. They extinguish fire by taking away oxygen but have a limited cooling effect. In this study, five fire-suppressant agents were tested to suppress three different types of fluid spray fires on diesel mobile equipment. The primary goal was to evaluate fire suppression effectiveness and they were not tested to evaluate environmental or health impacts.

EXPERIMENTAL APPROACH

Evaluating the effectiveness of fire suppression systems using a spray fire caused by different flammable liquids such as diesel fuel, motor oil, and hydraulic oil on a diesel engine requires a test facility to conduct the tests. A steel shipping container was modified to be used as a fire suppression test facility at the National Institute for Occupational Safety and Health (NIOSH) research center located in Pittsburgh, Pennsylvania. The dimensions of the shipping container, shown in Figure 1, are 40 ft (12.2 m) in length, 8 ft (2.4 m) in width, and 9.5 ft (2.9 m) in height. Steel plates were placed over the top of the wood floor inside the shipping container to prevent the floor from catching fire during a test. To control the ventilation, a 1-hp 42-inch (1.07-m) diameter variable speed fan was installed at one end of the shipping container, while the other end of the container was left open. The fan can be adjusted up to 500 ft/min (2.54 m/sec).

To measure the gases produced during the diesel engine fire tests, an infrared gas analyzer located in the control room is used to measure the carbon monoxide (CO), ranging from 0 to 5,000 ppm, carbon dioxide (CO_2), ranging from 0 to 1 percent, and oxygen (O_2), ranging from 0 to 25 percent. The output voltage from the infrared gas analyzer is converted using a software package to store the data on a laptop and display it graphically in real-time. Thermocouples are used to measure the gas temperatures at the exit section of the container. A diesel engine block with dimensions of 53-inch (1.35-m) length, 23-inch (0.58-m) width, and 36-inch (0.91-m) height was mounted onto a steel frame with casters on it to have the ability to roll it into the correct location for the test.

Five different fire suppression systems were evaluated with the following suppressants/agents: namely, dry chemical, wet chemical, dual agent (dry and wet chemicals), water mist, and carbon dioxide. The dry chemical agent chemical makeup is monoammonium phosphate and ammonium sulfate used for Class A, B, and C fires. It displaces the oxygen content of the air around the fire and absorbs heat. The wet chemical agent is a unique blend of organic and inorganic salts coupled with surface active ingredients to provide cooling and oxygen displacement. The dual agent is a combination of the two systems, dry and wet chemicals, used independently at the same time. The water mist suppressant uses high-pressure water to create mist, to provide cooling and oxygen displacement. The carbon dioxide suppressant is used for Class B and C fires by displacing oxygen from the fire.

Liquid spray fires using diesel fuel, engine oil, and hydraulic fluid were used in the suppression tests. The delivery system for the diesel fuel, motor, and hydraulic oils is set up by using a compressed air cylinder with a regulator on it to control the pressure and is connected to a 1-gal (3.8-l) stainless-steel cylinder filled with any fuel type delivered by ¼-inch stainless-steel tubing to the fuel nozzle. The output of the stainless-steel cylinder is fitted with a

Figure 1. Steel shipping container (a) outside and (b) inside, modified to be used as a fire suppression test facility

1/4-inch stainless-steel tubing. To generate a stable spray fire, the oil pressure and temperature need to reach certain threshold values. An electric heating strip is placed around the cylinder to increase the oil temperature and lower the viscosity when using the motor and hydraulic oils.

Two suppression nozzles are used for each suppression test except for the dual agent system due to the dual agent system requiring two nozzles for each side of the engine block. For each single-agent system, we have one nozzle on each side of the engine block facing the engine side at a 45-degrees upward configuration at 16-inch (0.41-m) from the floor. For the dual agent the nozzle with the wet chemical nozzle is placed facing the fire source while the dry chemical is facing the engine block. Then for consistency the dry chemical nozzle and the wet chemical nozzle are reversed.

The Fire Suppression Facility is equipped with two video cameras to record each test. The first camera is mounted in the center of the roof above the fan 7ft (2.13 m) from the floor to give a frontal view of the diesel engine during the test. The second video camera is placed on the left side of the Fire Suppression Facility on the side wall near the roof on the exit section, facing the Fire Suppression Facility to record the back end of the diesel engine. The video feed is recorded on a video recorder in the control room. The two video files are stored in an accessible network drive.

The schematic of all the components involved in the experiment are shown in Figure 2.

EXPERIMENT

The mocked-up diesel engine is placed 12 ft (3.66 m) from the fan and in the center of the Fire Suppression Facility, while the other end of the Fire Suppression Facility is open to the atmosphere, referred to as exit section. Prior to starting the test, the fan is set to an airflow of roughly 145 fpm (0.74 m/s) at the exit section. The airflow is measured in front of the diesel engine using a vane anemometer transverse method. Once the fan is set at the proper airflow, no adjustment is made to the fan. The data acquisition is turned on for 30 seconds prior to starting the test to record all the baseline data parameters. Once the baseline parameters are recorded, the fuel spray system is turned on, and as the fuel is spraying out of the nozzle, the fuel is ignited by using a propane burner. The spray fire nozzle used is a PJ20 [2] to atomize the fuel which is located 3 inches (0.08 m) centered in front of the diesel engine and 14 inches (0.36 m) off the floor as shown in Figure 3. Because this experiment was designed to test the effectiveness of the suppressing agent, the research did not investigate nozzle type or location as part of optimization for fire suppression. This procedure is repeated for the motor and the hydraulic oils except the heating strip is wrapped around the cylinder to lower the viscosity.

The spray fire is allowed to burn until the CO and CO_2 gas concentrations stabilize, in about 60 seconds or less, before initiating the fire suppression system. In this example, a wet chemical fire suppressant agent is being used. The

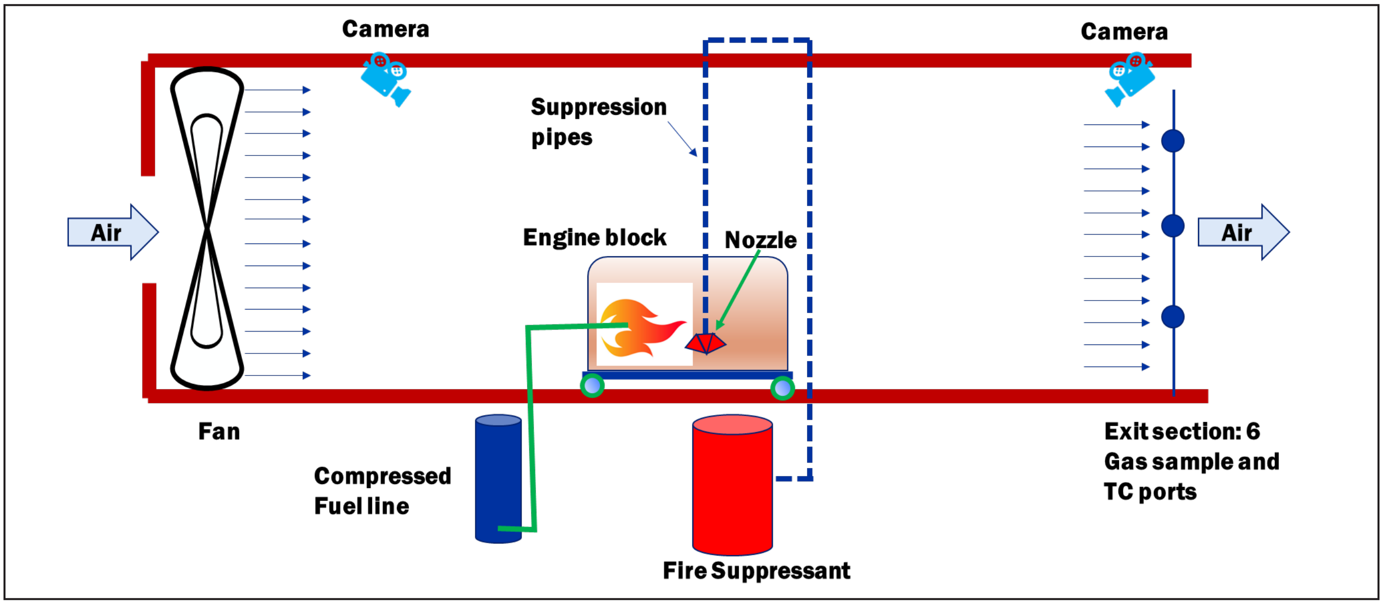

Figure 2. Schematic of components involved in the experiment

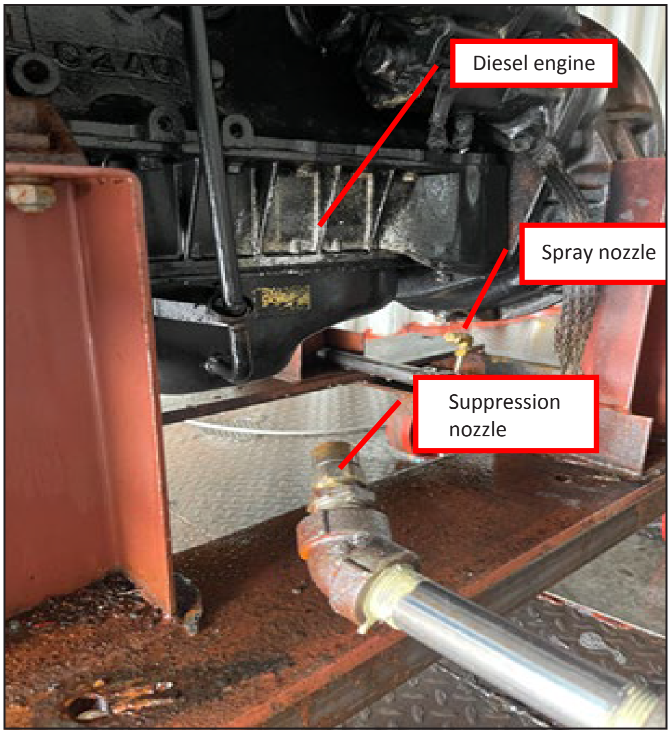

Figure 3. Locations of fuel spray nozzle and suppression nozzle

wet chemical suppressant agent is manually initiated from outside the Fire Suppression Facility to see if it will suppress the fire. After the fire suppression agent is emptied out from the cylinder, in about 45 seconds, if the fire is suppressed the fuel will continue to spray for another 20 seconds to see if the fire will reignite. If the fire does not ignite, then the fuel spray system is turned off. This will be a positive test due to the fire being suppressed. If the fire suppression system does not extinguish the fire, the diesel fuel dispersal system will be turned off, and this will be considered a negative test. The Fire Suppression Facility's water sprinkler suppression system is turned on until the fire is out.

The Fire Suppression Facility is equipped with a 6-point gas monitoring array at the exit section to measure the gas components produced from the fuel fire. The array is made of ½-in diameter PVC pipe positioned at the center of the Fire Suppression Facility. A total of six 1/8-in holes are drilled into the vertical section of the PVC pipe to sample the gases. The sample holes are spaced vertically from the floor at 53 inches (134.6 cm), 72 inches (182.9 cm), and 94 inches (238.8 cm). A ½-inch tube is connected to the two PVC pipes that lead back to the control room to a set of infrared gas analyzers where the mixed gas is analyzed. The gas analyzer measures CO, CO_2, and O_2 gas concentrations. The gas data is collected every 2 seconds and is recorded by a computer-based data acquisition system. The raw data is further analyzed to calculate gas concentrations.

A 6-point thermocouple array is also located at the exit section of the Fire Suppression Facility to measure the gas temperature at the six monitoring points three on the left and three on the right side. The thermocouples are attached to two ½-inch diameter PVC pipes, vertically oriented from the floor to the roof, at 53 inches (134.6 cm), 72 inches (182.9 cm), and 94 inches (238.8 cm) above floor level. The gas data temperature is recorded in the control room onto the data acquisition system. All the gas concentrations and temperature data are processed and stored in an Excel file for further analysis.

The method for calculating the Heat Release Rate (HRR) is based on the CO_2 and CO generation rates from the spray combustion. With this method, the HRR is calculated from measured data of gas concentrations of CO and CO_2 and measured gas velocity [3].

The HRR calculation using the CO and CO_2 generation rates measured at the exit section of the shipping container is expressed as:

$$Q_A = \left(\frac{H_C}{k_{CO_2}}\right)\dot{m}_{CO_2} + \left(\frac{H_C - k_{CO}H_{CO}}{k_{CO}}\right)\dot{m}_{CO_2}$$

where Q_A is the actual HRR, kW; H_C is the total heat of combustion of the fuel, kJ/g, and can be determined from the approximate analysis of the fuel; H_{CO} is the heat of combustion of CO, 10.1 kJ/g; k_{CO2} is the stoichiometric mass of CO_2 produced per unit mass of the fuel; k_{CO} is the stoichiometric mass of CO produced per unit mass of the fuel; $\dot{m}_{CO}$ is the production rate of CO_2 from the fire, g/s; and $\dot{m}_{CO}$ is the production rate of CO from the fire, g/s; k_{CO2} and k_{CO} are the fuel-dependent constants and can be calculated based on the experimental results from Egan [4] for diesel fuel:

For combustion of a fuel within a mine entry, the CO and CO_2 generation rates can be determined from their bulk-average concentrations downstream of the fire by the expressions:

$$\dot{m}_{CO_2} = VA_{CO2}CO_2$$

$$\dot{m}_{CO} = VA_{CO}CO$$

where V is the exit average air velocity, m/s; A is the entry cross-section area, m^2; r_{CO2} is the density of CO_2; r_{CO} is the density of CO; DCO_2 is CO_2 produced in the fire, ppm; and DCO is CO produced in the fire, ppm. Using the CO_2 density of 1.97 kg/m^3 and CO density of 1.25 kg/m^3, the expressions become:

$$\dot{m}_{CO_2} = 1.97 \times 10^{-3} VACO_2$$

$$\dot{m}_{CO} = 1.25 \times 10^{-3} VACO$$

RESULTS AND DISCUSSION

Figure 4 depicts the estimated HRR of a typical positive suppression test. The onset of the spray fire is marked with a small red circle. A few seconds after that, the HRR starts growing which is based on the result of CO and CO_2 gas concentrations measured at the gas analyzer. The delay is the result of the travel time of the CO and CO_2 gasses. It takes approximately 60 seconds for the fire to stabilize which can be seen from the HRR curve leveling off. At this time, the fire suppression system is engaged and suppression is initiated which is indicated by a rapid drop of the fire HRR as the result of diminishing the fire output, CO, and CO2 gasses. This is the result of a positive fire suppression test. In addition to interpreting the collected data and calculating the HRR, the fire suppression test is visually verified on the recorded video.

Figure 5 shows the evolution of the fire HRR for a typical negative suppression test. After the suppression system initiated, a temporary drop in the HRR curve can be seen which can be attributed to a partial suppression of fire. However, since the fire is not fully extinguished after the suppressant is depleted, the fire starts growing as indicated by the increase in the HRR around 120 seconds into the test.

Typical gas temperature patterns during positive and negative suppression tests are shown in Figures 6 and 7, respectively. The gas temperature at the installed temperature points are also identified in the figure corresponding to their distance from the floor in inches and the corresponding airflow rate in Feet Per Minute (FMP). Similar to the evolution of the fire HRR, in a typical positive suppression test the gas temperature increases until the fire suppression is initiated. Once the suppression is initiated, the gas temperature drops to the pre-fire condition. A typical negative suppression test shows an increase in the gas temperature. Once the suppression is initiated, the gas temperature decreases temporarily until the suppressant is depleted.

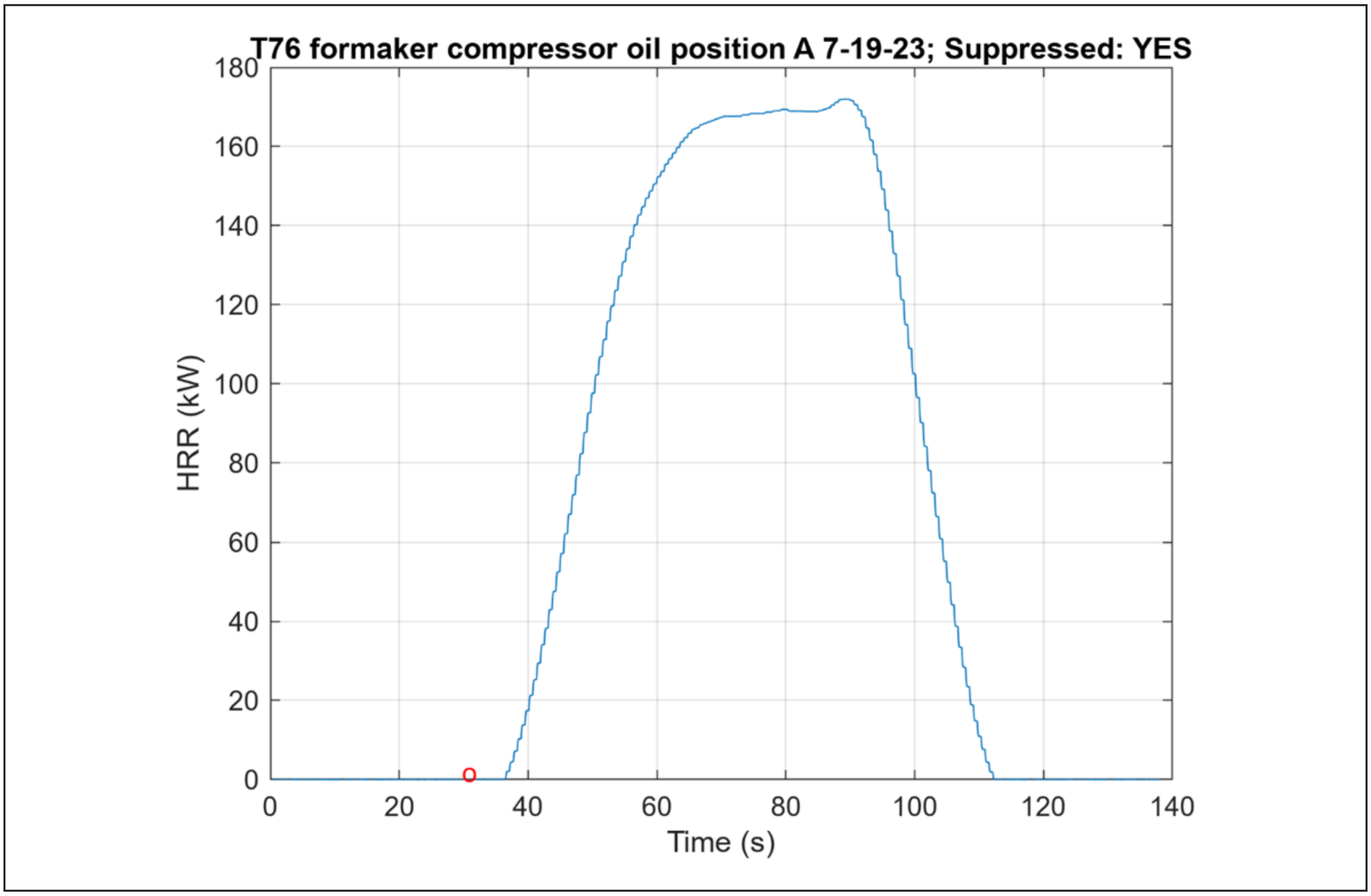

Figure 4. Fire size, HRR, evolution during a typical positive suppression test

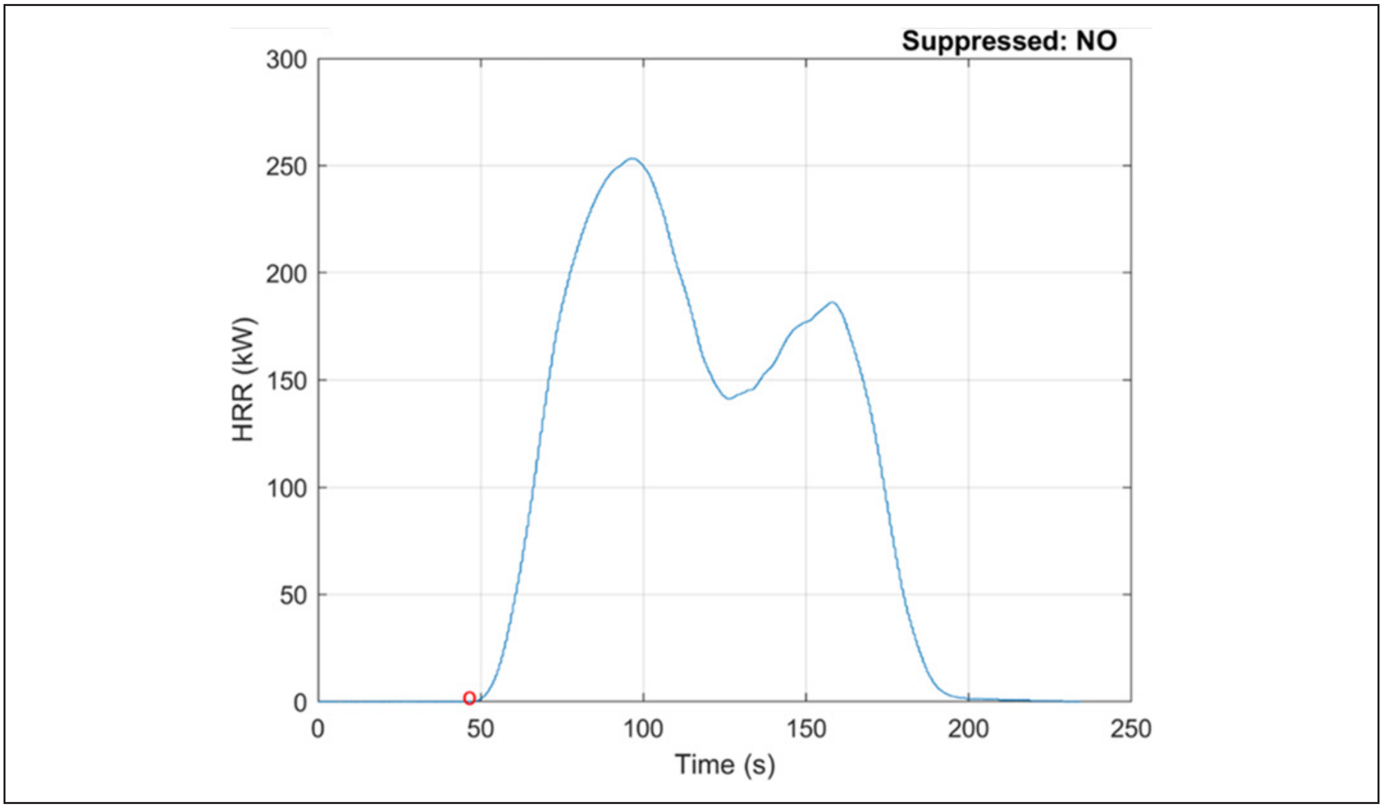

Figure 5. Fire size evolution during a typical negative suppression test

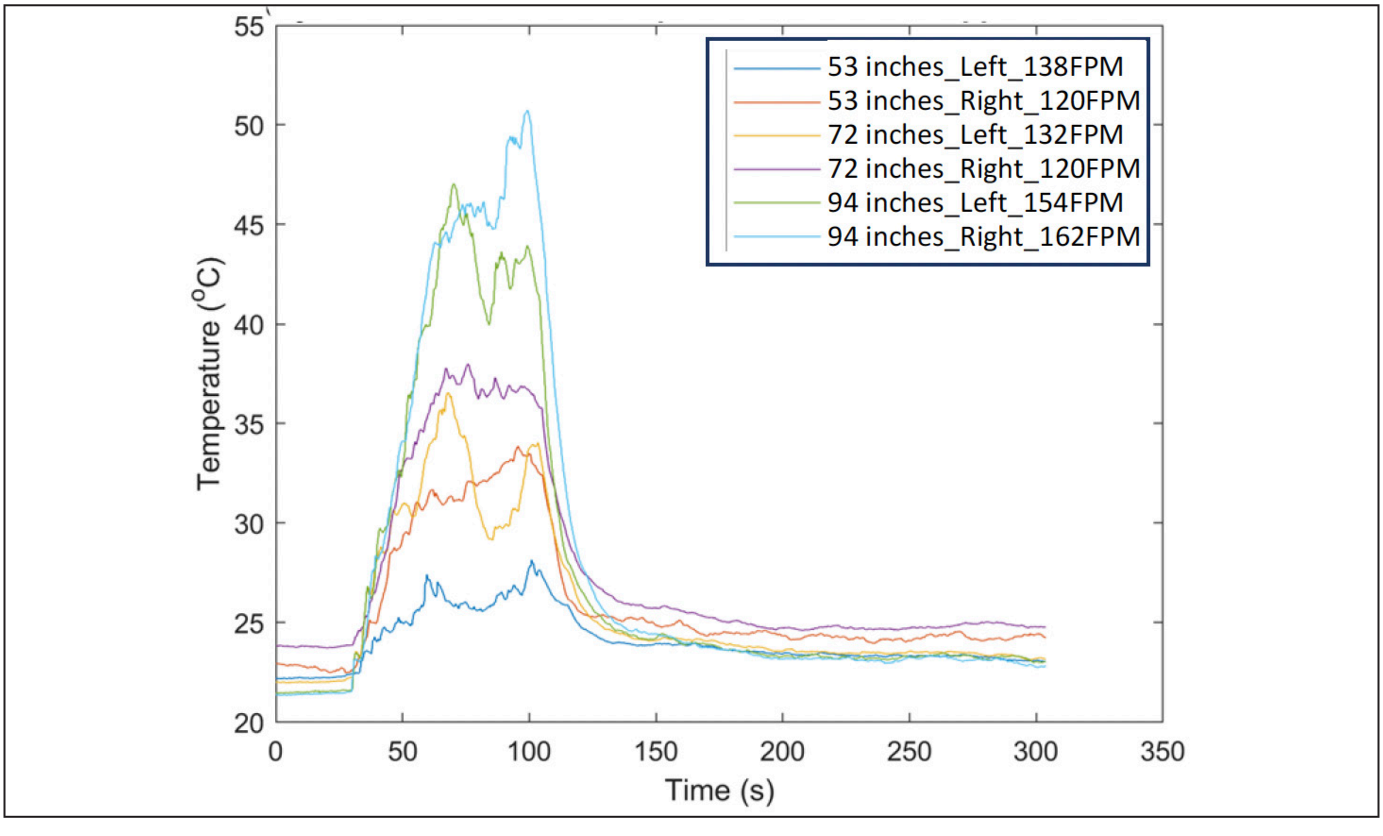

Figure 6. Typical gas temperature pattern during a positive suppression test

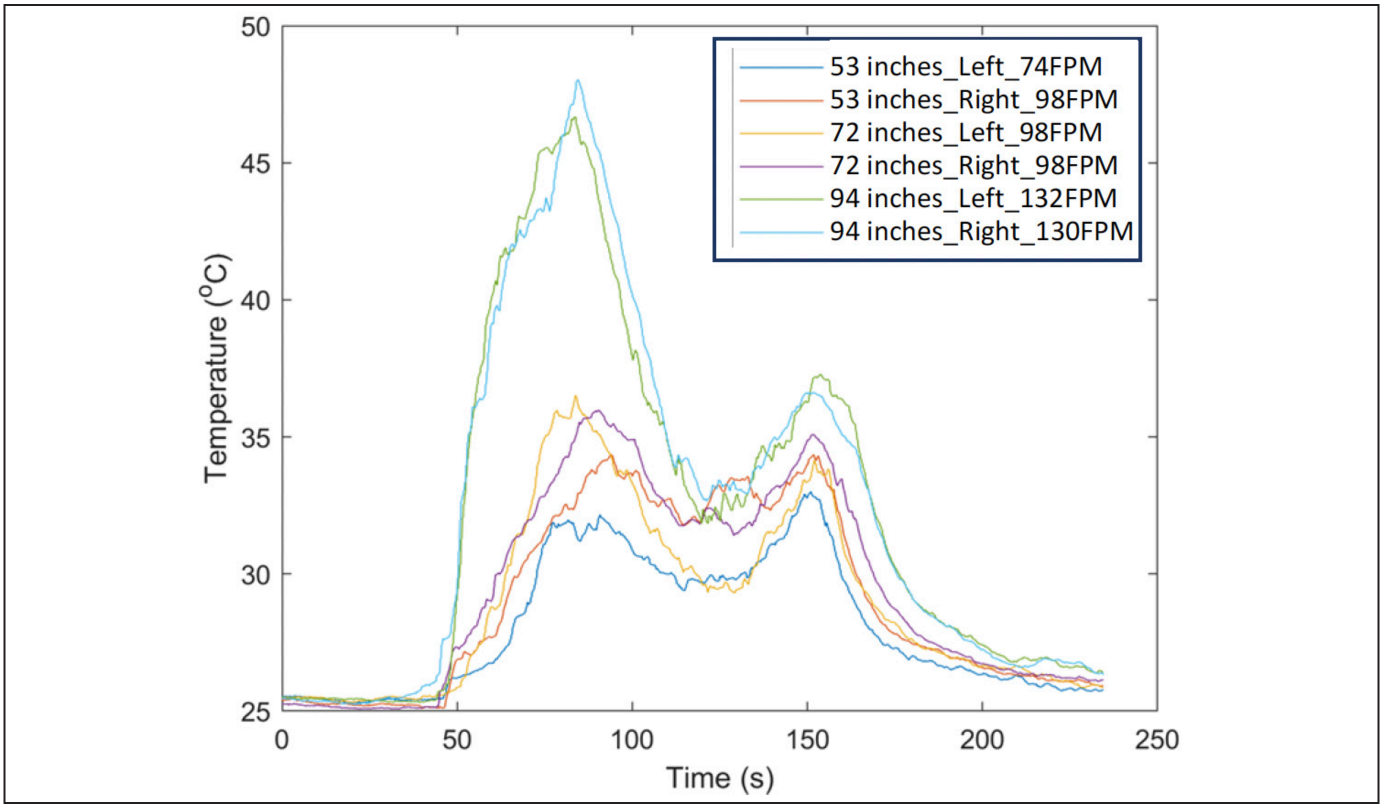

Figure 7. Typical gas temperature pattern during a negative suppression test

After that, the gas temperature starts increasing which indicates the fire is not extinguished.

All the suppression tests were tabulated. Table 1 summarizes the results of the overall suppression effectiveness. The effectiveness is determined as the ratio of the number of positive tests to the total number of tests for each suppression system. Note that the dual agent row accounts for two sets of experiments where the nozzles used to release the dry and wet agents were interchanged. The results suggest that the suppression systems using CO_2 or wet chemical agents achieve the least effectiveness, 17%, and zero, respectively. However, the systems using dry chemical alone or dry chemical together with wet chemical provided the highest success rate 100% and 92%, respectively. The water mist-based system has about an average success rate of 67%.

Table 2, Table 3, and Table 4 summarize the fire suppression results for each fuel type separately to understand the effect of fuel type on the effectiveness of fire suppression. In order to determine if there is a statistically significant relationship between the fire suppression agents and whether or not the fire was suppressed, the Fisher's Exact Test was applied to each table [5]. The application of the Fisher's Test to the suppression results for the diesel fuel and hydraulic fluid shown in Table 2 and Table 4 lead to p-values of 0.11 and 0.09, respectively. This indicates that there is no statistically significant relationship between the suppression agents in extinguishing the diesel fuel or hydraulic fluid spray fires, although the sample size is small and with a larger sample size statistically significant results may be achieved. However, the application of the Fisher's Exact

Table 1. Overall suppression effectiveness results.

Suppressant Agent	Count of not Suppressed	Count of Suppressed	Effectiveness, %
CO_2	5	1	17
Dry chemical	0	6	100
Dual agent	1	11	92
Water mist	2	4	67
Wet chemical	6	0	0

Table 2. Overall suppression effectiveness results for diesel fuel

Suppressant Agent	Count of not Suppressed	Count of Suppressed	Effectiveness, %
CO_2	1	1	50
Dry chemical	0	2	100
Dual agent	0	4	100
Water mist	0	2	100
Wet chemical	2	0	0

Table 3. Overall suppression effectiveness results for motor oil

Suppressant Agent	Count of not Suppressed	Count of Suppressed	Effectiveness, %
CO_2	2	0	0
Dry chemical	0	2	100
Dual agent	0	4	100
Water mist	2	0	0
Wet chemical	2	0	0

Table 4. Overall suppression effectiveness results for hydraulic fluid

Suppressant Agent	Count of not Suppressed	Count of Suppressed	Effectiveness, %
CO_2	2	0	0
Dry chemical	0	2	100
Dual agent	1	3	75
Water mist	0	2	100
Wet chemical	2	0	0

Test to the suppression results for the motor oil shown in Table 3 leads to a p-value of 0.009 which indicates that there is a statically significant relationship between the suppression agents in suppressing the motor oil spray fire. The suppression agents dry chemical and dual agent were better at suppressing motor oil fires than were CO_2 and water mist.

CONCLUSIONS

The focus of this research was to determine the effectiveness of five different fire suppressant agents to extinguish a fire on mining mobile equipment caused by a spray fires of diesel fuel, engine motor oil, and hydraulic circulating oil. The following conclusions can be drawn from the results of the fire suppression tests presented in this paper. The test results suggest that the dry chemical-based system, including the dual-agent system provide the best suppression effectiveness for the conditions tested. The test results revealed that there was no significant relationship between different suppression agents in extinguishing the spray fires caused by diesel fuel or hydraulic fluid except in the case of motor oil spray fire where the relationship was statistically significant.

These results are only applicable to the studied test conditions which is based on the fire not being 75% or more enclosed. However, it is expected that the fire suppressing agents will perform better under total system flooding conditions where the fire is 75% or more enclosed.

LIMITATIONS

The results of evaluating the five different suppression systems used in this experimental research reflect scientific data on fire suppression agent effectiveness under specific conditions. No testing was conducted to evaluate any health or environmental impacts of any of the agents used. Furthermore, the research employed one nozzle design at fixed locations for all tests and hence did not explore system installation or optimization. The conclusions drawn from this study speak to the performance of the limited number of agents tested and should not be construed as an endorsement nor a recommendation for use in similar scenarios.

DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute an endorsement by NIOSH.

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Best Practices for Ensuring Safety in Field Studies: A Comprehensive Guide for Mining Researchers and Operators

Matthew McElhinney
CDC NIOSH, Pittsburgh, PA

Todd Minoski
CDC NIOSH, Pittsburgh, PA

Craig Compton
CDC NIOSH, Pittsburgh, PA

Morgan Sears
CDC NIOSH, Pittsburgh, PA

ABSTRACT

In an effort to advance the science underlying ground control engineering, researchers with the National Institute for Occupational Safety and Health (NIOSH) are frequently involved in field studies at collaborating mines. Often, these field studies involve visiting the mine site, instrumentation installation, and data acquisition. Each of these aspects involve potential risks to NIOSH employees. As an organization whose mission it is to promote the health and safety of mine workers, the health and safety of our workforce is paramount.

This paper provides documentation of the best practices followed by NIOSH employees who are tasked with visiting and conducting work at underground and surface mines. This includes Mine Safety and Health Administration (MSHA) approved training, mine site specific training, and hazards associated with all aspects of mining that could be encountered by the employee. Additionally, this paper details best practices associated specifically with instrumentation installation including the mitigation of hazards associated with the proper equipment handling, drilling, and the mine environment.

The information showcased in this paper can be used as considerations for industry practitioners such as mine operators, consultants, and academic researchers engaged in the installation of instrumentation in the field. Furthermore, the best practices detailed in this paper can be used as a foundation for agreements made between mine operators and researchers to ensure safety procedures will be followed while on mine property. This will result in enhanced safety of both researchers involved in field studies as well as mine employees tasked with assisting and accompanying those researchers.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) is at the forefront of advancing the science of ground control engineering, often requiring its researchers to conduct field studies at collaborating mines. These studies, while essential, expose NIOSH employees to potential risks inherent in the mining environment. As NIOSH is an organization dedicated to the health and safety of mine workers, ensuring the well-being of its own workforce is of utmost importance.

This paper presents the best practices adopted by NIOSH employees during their visits and work at underground mines. From training to addressing specific hazards related to instrumentation installation, this paper provides a comprehensive guide to safe operations.

The insights presented in this paper are not just limited to NIOSH operations. They serve as valuable considerations for industry partners, including mine operators, consultants, and academic researchers. By highlighting the importance of collaboration between mine operators and researchers, the paper underscores the collective responsibility of ensuring a safe working environment.

TRAINING

Prior to identifying the hazards that researchers and operators need to recognize and identify while conducting field studies, it is important to start with the discussion of training. Training is the starting point for all underground worker safety, as it provides crucial information for new and experienced personnel working underground to stay safe.

Before any field studies can be completed, researchers and operators should complete training and refreshers to stay up to date on important safety guidelines and material.