Remote Mine Fire Suppression Technology

By

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Abstract

Underground coal mine fires in the United States continue to present a significant hazard to the safety and health of mine workers. The leading causes of mine fires include flame cutting and welding operations, frictional heating and ignitions, electrical shorts, mobile equipment malfunctions, and spontaneous combustion The National Institute for Occupational Safety and Health (NIOSH) is conducting an in-depth program of research to address mine fire prevention, early and reliable fire detection and mine fire suppression and control technologies. One segment of the research portfolio is focused on remote methods for addressing coal mine fires. This research is important because remote methods represent the primary means of fighting a mine fire when conditions are too dangerous to fight the fire directly underground. Technologies under investigation include remote methods for installing ventilation control devices (mine fire seals) and remote methods for suppressing the fire using, the injection of inert gas, gas-enhanced foam and jet engine exhaust gases into the fire zone. This paper presents a summary of remote mine firefighting technologies used in the U.S. and the results of completed NIOSH research.

1.0 Introduction

Unlike other types of mining accidents where an incident generally involves only a few workers, the danger of a mine fire extends to every person working in the underground mine environment. When a mine fire occurs, the toxic products of combustion can block avenues of escape and can rapidly create asphyxiating gases that can spread well beyond the fire zone in a short period of time. Previously, mine operators in the United States were required by law to report to the U.S. Mine Safety and Health Administration (MSHA) any unplanned mine fire event that was not extinguished within 30 minutes of discovery (CFR, 2007). Subsequent to the accidents at the Sago and Aracoma Alma mines in January 2006, this regulation has been modified to include all unplanned mine fire events that are not extinguished within 10 minutes of discovery. According to MSHA, in an underground environment, if miners attempt to fight a fire for 30 minutes and are unsuccessful, the fire will probably become uncontrollable. The revised reporting requirement will result in earlier fire-fighting plan activation as miners will notify supervisors more quickly who, in turn, can call in firefighting crews and allow miners to safely escape (Federal Register, 2006).

During the time period from 1990-2001, more than 975 reportable fires occurred in the U.S. mining industry (averaging about 81 fires per year), causing over 470 injuries, 6 fatalities, and the temporary closing of several mines. Over 95 of the fires occurred in underground coal mines. The leading causes of mine fires include flame cutting and welding operations, frictional

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heating and ignitions, electrical shorts, mobile equipment malfunctions, and spontaneous combustion (NIOSH, 2007). The technology used to control and extinguish a mine fire is usually focused on removal of one or more sides of the fire tetrahedron (oxygen, heat, fuel and the chemical reaction). When possible, during the early stages of a mine fire, water, foam, chemicals, rock dust or sand are directly applied to contain or extinguish the fire. This method, though limited to only the very early stages of a mine fire, can be very effective, because extinguishing material is placed directly on the fire. Unfortunately, this approach also places miners in close proximity to the fire and can expose them to the ever-present deadly hazards of the mine fire.

An indirect approach is applied when access to the fire zone cannot be obtained because of safety reasons (smoke, build-up of gases, bad mine roof conditions due to heat, etc), limited supply of available firefighting materials, a fire zone too large for available underground manpower, or blocked underground access. The indirect approach involves sealing the mine or the construction of mine fire seals. Mine fire seals can be constructed from within the mine or remotely through boreholes. The objective of sealing a mine (or the fire area if possible) is to control and extinguish the fire by eliminating or reducing the source of oxygen to a level that will not support combustion. The benefit of remote mine sealing technology is that the size of the fire zone enclosed by the seals can be reduced, thereby increasing the effectiveness of the remote fire fighting methods utilized. Once the fire zone is sealed, the affected area is flooded with water, inert gases or gas-enhanced foam to control and extinguish the fire.

The fact that mine fires occur with an alarming regularity reinforces the importance of recognizing and eliminating the potential hazards in underground mines and the overall need for fire control and suppression technology to ensure the best possible outcome during a mine fire. This paper presents a summary of remote mine firefighting technologies and the results of completed NIOSH research.

2.0 Remote Mine Fire Suppression Technology

NIOSH is conducting an in-depth program of research addressing mine fire prevention, early and reliable fire detection, and mine fire suppression technologies. One segment of the work is focused on remote methods for fighting coal mine fires when conditions are too dangerous to address the fire directly underground. Technologies under investigation include remotely installed ventilation control devices (mine seals) and low flow inert gas injection, gas-enhanced foam and jet engine exhaust gases. The following sections provide a technology overview and recent advances made through NIOSH research.

2.1 Remotely Installed Ventilation Control Devices (Mine Fire Seals) (Trevits, 2006)

Current commercially available remote mine seal placement technology delivers the mine seal material to the mine level in the following manner. A tubing string is placed into the borehole with a jet mixing tool attached at the lower end and grout set accelerator material is pumped in the borehole via the tubing string. Grout is concurrently pumped in the annular space between the tubing and the borehole casing. The grout and accelerator material then mixes in the lower portion of the borehole. The mixed grout flows into the mine opening and away from the borehole using high rate pumping techniques. The material is designed to set up quickly as it exits the borehole resulting in an accumulation of grout material at the bottom of the borehole that flows outward towards the mine ribs and upward towards the mine roof. When significant back pressure builds in the borehole, pumping is stopped and the pressure is monitored. If the pressure falls, pumping is resumed until another pressure build-up is observed. The cycle of pumping and observing pressure decline continues until the pressure does not fall. If the pressure does not decline, pumping is terminated. By design, the material is supposed to reach the mine roof-rib interface when pumping is terminated. However, this technology has not been successful. Underground observations of remotely installed mine seals installed in this manner have shown that the material often does not fully close the mine opening. If the mine seals do not completely close the opening, then oxygen inflow cannot be stopped which can lead to re-growth or further expansion of the mine fire.

The need to evaluate, improve and develop new technology to remotely construct mine seals was identified by NIOSH. NIOSH contracted Howard Concrete Pumping Company[3] of Cuddy, Pennsylvania and GAI Consultants, Inc. [3] of Homestead, Pennsylvania to develop an improved method for remotely constructing mine seals. After much testing at the NIOSH Lake Lynn Experimental Mine, an improved new grout-based material was developed along with a novel material placement technology. The system developed creates a mine seal in two stages. The first stage uses a string of pipe and a directional elbow that is positioned at the bottom of the injection borehole. The pipe string and elbow are designed to place bulk material into the mine void in a series of lifts to fill most of the mine opening. The second stage uses two strings of pipe (one inside of the other) in the injection borehole to convey two components of a specially designed grout material to a spray nozzle. The spray nozzle blends a two-part grout and accelerator mix while allowing sufficient air velocity to transport the grout to the mine roof-and-rib areas (figure 1).

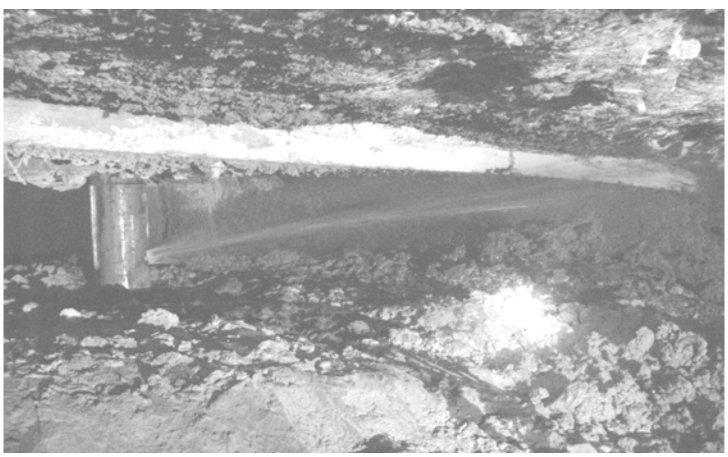

Figure 1. – Spray nozzle directing material towards mine rib.

Once the spray nozzle is positioned in the mine opening above the bulk fill, the spray nozzle is rotated in a back-and-forth motion towards the mine rib areas to fill in the gaps between the bulk fill and the mine roof-rib interface. As the mine roof-rib intersections areas are filled, the grout builds up and migrates back towards the spray nozzle and the injection borehole. Filling of the remaining area near the borehole is accomplished by lowering the spray nozzle into the accumulated wet grout material below the nozzle and then rotating the spray nozzle through a 360 degree arc. Eventually, the material builds-up around the nozzle and closes the mine opening. In practice, the spray nozzle could be used to construct the entire mine seal; however this would increase the cost of constructing the mine seal. This system can construct a 60 m^3

[3] Mention of a specific product or company name does not imply endorsement by NIOSH.

(80 yd^3) mine seal in about 12 hours. It should be noted that the potential for successful use of this technology can be increased by using a second nearby borehole that is outfitted with a downhole camera to observe and direct seal material placement. This new technology offers a viable alternative to the commercially available system and should improve cement-based remote mine seal construction.

2.2 Low Flow Inert Gas Injection (Mucho, 2005 and Trevits, 2005)

Inertisation, is a technique that has been used around the world to control and extinguish coal mine fires. Inertisation creates a mine atmosphere where the oxygen concentration is too low to sustain combustion (including ignitions) and is therefore inert. Some mine fire inertisation applications require methods and equipment which are limited, or only practical, in low volumetric flow ranges. Technology used in these cases includes nitrogen and carbon dioxide injection. Liquid or gaseous nitrogen or carbon dioxide is typically supplied by bulk tankers (figure 2). Bulk tanker shipments of these gases are normally converted to a gas phase at the mine site and injected into the mine via boreholes. The tankers normally carry about 17,000 m^3 (600,000 scf) of gas and can convey that volume to the mine level in about 15 to 30 minutes. Bulk gas usage can be affected by tanker availability and transport distance which can result in delayed arrival times disrupting what should be a controlled continuous injection process. Furthermore, bulk tankers are typically limited to good road surfaces and cannot be used in areas of rugged terrain.

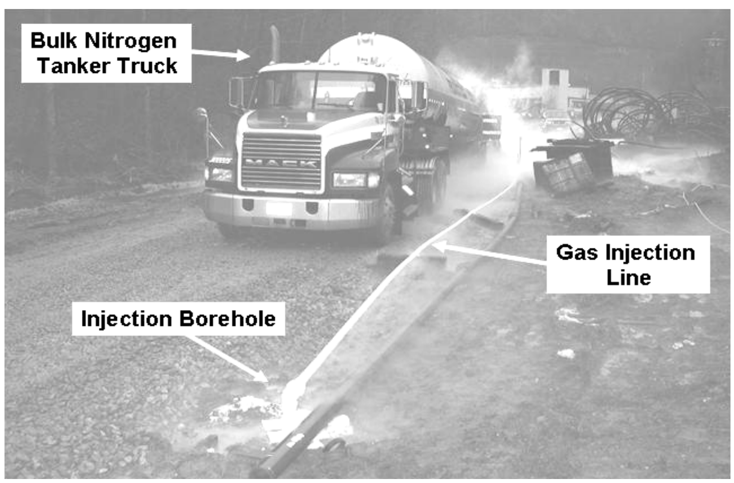

Figure 2. – Bulk tanker injection operations.

Nitrogen gas can also be produced by nitrogen membrane and pressure swing absorption plants. These plants strip nitrogen gas from the atmosphere at the mine site and can typically deliver from 95-99 pct pure gas in the range of 850 to 1,700 m^3/hr (500 to 1,000 cfm) or more depending on plant size. Nitrogen plants can be easily transported and readily moved from one borehole location to another and can be deployed using off-road equipment. Given the limitations of these low-flow methods and equipment they are best suited to applications where localized mine inertisation is desired (Stephan, 2000).

2.3 Gas-Enhanced Foam (Smith, 2005 and Trevits, 2005)

Foam addresses a fire condition through evaporation of contained water and cooling by energy removal. Foam also serves to blanket the combusting material and isolate it from oxygen. As the foam collapses, water is released and the temperature of the water increases by absorbing heat and eventually turns into steam. Water is released from foam either through bubble rupture or through the effects of gravity distorting the bubble walls. Because this process takes time, foam can act as a water reservoir, releasing water at a rate that allows absorption into the fuel, rather than running off the surface (Snuffer, 2007). If the foam is enriched with nitrogen gas, then it can serve to remove two sides of the fire tetrahedron by robbing the fire of heat and removing or displacing of oxygen.

NIOSH worked in partnership with US Foam Technologies Inc., to evaluate the use of a proprietary nitrogen-enriched remote foam delivery system for fighting mine fires known as the Hellfighter™. This system contains a pipeline manifold and a sophisticated mixing chamber that blends water, foam concentrate and nitrogen gas (from a membrane plant). Up to three small Hellfighter™ units (or one large unit) can be connected to a single borehole depending on the diameter of the hole. Water, foam concentrate and nitrogen gas flow rates can be adjusted to produce a variety of foam mixtures from a thin water-foam blend to a thick froth. In addition, injection can be switched with no downtime from nitrogen-gas enhanced foam to nitrogen gas by simply closing a valve. The gas-enhanced foam and nitrogen system provides an ideal platform for addressing mine fires because it can be readily moved from one borehole location to another and can be deployed quickly using off-road equipment.

The NIOSH experiments at the Lake Lynn Experimental Mine were very successful in evaluating many of the parameters that can affect the use of foam for remotely fighting mine fires. However, these experiments were limited in their scope with respect to the type of foam used, the geometry and slope of the mine entries, and the size and types of fires. Therefore, these results should be used as guidelines for the use of foam, and not as design specifications for its use. Foam stability is a function of the amount of foam concentrate, water volume, and the gas flow rate, so stability parameters can be varied based on the particular application. In addition, the life of the foam can be dependent on the mine temperature and wetness or dryness of the environment, water hardness, and pH. The NIOSH experiments also showed that the foam stability can be managed from the surface with a good degree of accuracy. Foam flow movement, speed, and ability to build to the mine roof and fill the entire cross-section of the mine entry were shown to be highly dependent on the slope of the mine floor. In two experiments, the foam did not reach the roof of the mine until its flow path was obstructed by crib blocks (figure 3). In a third experiment, foam build-up reached the mine roof very quickly when the foam was forced to flow upslope but the rate of advancement of the foam front was much slower than in the other experiments where the foam flowed down slope. In a situation where the location of the fire is below the foam entry point into the mine, the foam will flow quickly, but an obstruction such as a remotely installed mine seal, will be necessary to allow the foam to build up and completely fill the mine entry. In situations where the foam will need to be pushed upslope, it will be critical to get the location of the foam injection point as close to the fire as possible, and an obstruction (remotely installed mine seal) or obstructions (cribbing blocks) down dip from the foam injection point will be needed to make the foam build up and flow up an entry. In areas where the mine entry is level, the foam should flow in all directions away from the injection borehole, but the flow will be highly dependent on obstructions. In-mine observations showed that foam will flow around corners, but again the major influence on its effectiveness was change in mine floor elevation and obstructions. The ability of the foam to suppress a liquid pool fire was demonstrated. However, foam's ability to reach and cool a hot spot in a rock pile was not adequately addressed. In this experiment, foam was able to infiltrate and rock pile and quickly cool the heating elements in the rock pile, but the temperatures of the rock pile were not high enough to truly test the foam's cooling ability. Foam did, however, cool high temperatures in a deep-seated coal fire, but this was a relatively small fire.

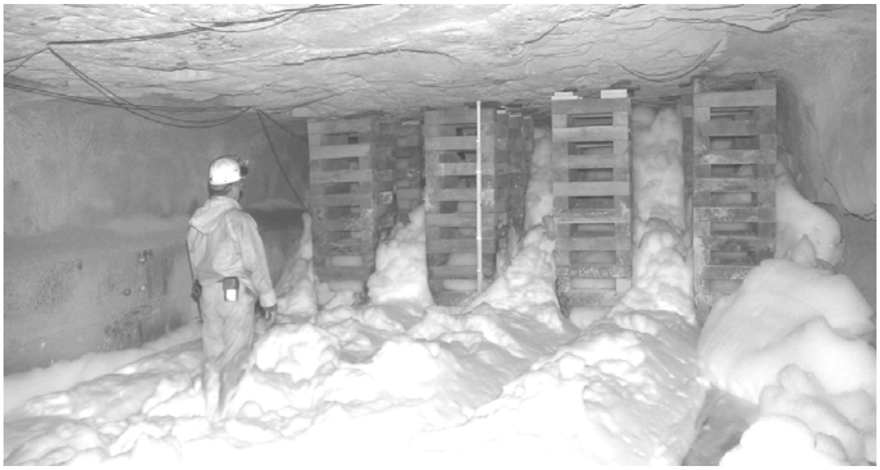

Figure 3. Gas-enhanced foam behavior at crib blocks.

2.4 Jet Engine Exhaust Gases (High-Flow Rate Injection) (Mucho, 2005)

In some coal mine fire events; localized or low-flow rate injection of inert gas may not be effective, or significant time may be needed to render a large mine area inert. This may occur when the location of the fire event can only be generalized; such as an event located in a longwall panel district gob area or large underground area that has been mined by the room-and-pillar method. In this case, the use of jet engine exhaust gases from the GAG 3A system may be ideal. The GAG 3A system (figure 4) is based upon a Russian designed agricultural jet engine which consumes aviation fuel with oxygen from the atmosphere and exhausts combustion gases, primarily carbon dioxide and water, along with nitrogen from the air. The system is designed to remove all of the oxygen from the intake air while approaching pure stoichiometric combustion.

The GAG 3A system was developed by the Polish mining industry in the early 1970's and has been used extensively in Poland, Czech Republic, and China. It was also used to address an extensive gold mine fire in South Africa. The acronym "GAG" is from the Polish term for gas-to-gas combustion. During a joint effort with the Polish Central Mining Institute in 1982, testing of the GAG 3A system was conducted at the U.S. Bureau of Mine's Safety Research Coal Mine in Bruceton, PA (USBM, 1982). For whatever reasons, the technology was not embraced by the U.S. coal mining industry. The technology was subsequently further refined and was successfully used in Poland and was imported into Australia in 1997.

A specially designed afterburner is utilized on the jet engine to achieve near stoichiometric combustion. This is achieved by varying fuel pressure and engine speed (air intake), and combustion chamber temperature. The heat produced by the afterburner is as high as approximately 700 °C (1,300 °F) in the chamber and temperatures of almost 1,760 °C (3,200°F) have been recorded at the flame tip. A diffusive cooler is used to provide a barrier between mine atmosphere and the GAG system and to cool the exhaust gases typically to 71 °C (160 °F) to 88 °C (190 °F) prior to mine injection.

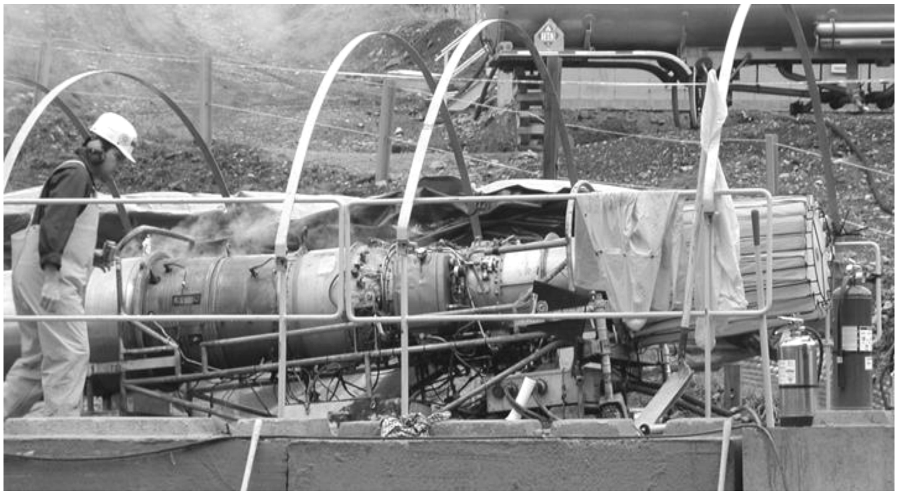

Figure 4. The GAG 3A jet engine and afterburner operating at U.S. mine site.

The afterburner cooling device, under operational conditions, will produce hydrogen and oxygen due to “thermal cracking” when the flame impinges on the water curtain. The concentrations of hydrogen produced in actual use at mine fires have been as low as 5 ppm and as high as 8,000 ppm and oxygen concentrations have been measured as high as 0.5 pct. The steam exiting the system is slightly acidic and is known to have produced a secondary reaction with carbonaceous material and/or steel, resulting in the production of hydrogen. The concentration levels of produced hydrogen have not been thoroughly studied during operation of the jet engine, but have been recorded as high as 125 ppm at 2,200 m (7,200 ft) from the mine injection point. Volumetric flows from the GAG 3A system have been stated in the literature and range from 85,000 m^3/hr (50,000 cfm) to as high as 109,000 m^3/hr (64,000 cfm). However, jet engine output is affected by site specific backpressure that is a function of ambient mine temperature, gas mixture and buoyancy effects, barometric fluctuations, and mine resistance to air flow.

The GAG 3A system has used to a limited degree in the U.S. to inert major portions of two large mines. One drawback to use of the jet engine is that it produces the similar combustion products as a mine fire and this can prove to be problematic when trying to determine the state of a mine fire during and after the use of the jet engine. NIOSH is planning a full series of detailed tests in 2008 at the Lake Lynn Experimental Mine to determine the overall effectiveness of this technology to suppress a deep-seated coal fire and the effects on the rock mass due to exposure to jet engine exhaust gases.

3.0 Summary and Conclusions

Mine fires represent one of the greatest threats to those working in the underground mine environment. NIOSH is conducting an in-depth program of research on remote methods for addressing coal mine fires, a technology believed to be important because it represents the primary means of fighting a mine fire when conditions are too dangerous to address the fire directly underground. Significant advances in cement-based remote mine seal construction technology have been made to improve mine entry closure capability. Low-flow inert gas injection technology is best suited for applications where localized mine inertisation is desired and is available from bulk tankers and nitrogen plants. Bulk tankers offer high volume capacity, but can be affected by tanker availability, transport distance and local road conditions. Nitrogen plants can be easily transported, readily moved and deployed using off-road equipment and typically deliver from 95-99 pct pure gas in the range of 850 to 1,700 m^3/hr (500 to 1,000 cfm). Foam created with nitrogen gas provides an ideal platform for addressing mine fires because foam can act as a water reservoir, releasing water at a rate that allows absorption into the fuel, rather than running off the surface. Foam flow movement, speed, and ability to build to the mine roof and fill the entire cross-section of a mine entry are highly dependent on the slope of the mine floor and obstructions in the entry (complete closure of the entry is not needed to build foam to the mine roof). Foam stability can be managed from the surface with a good degree of accuracy, however, periodic monitoring of the foam consistency on the surface is recommended to ensure that stable foam is entering the mine. The GAG 3A system is designed for high-flow, large volume mine inertisation needs but its use has been limited in the U.S. Gas flow rates up to 109,000 m^3/hr (64,000 cfm) have been observed, however jet engine output is affected by backpressure caused by site specific conditions. Jet engine use can cause complications at monitoring boreholes because the engine combustion products are similar to that of a mine fire.

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