Mine Fires – Measuring the Efficacy of Gas-Enhanced Foam

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH), with US Foam Technologies, Inc. and On Site Gas Systems, Inc., conducted research on the remote application of extinguishing agents with the intent of improving deployment strategies to limit miner exposure and to help ensure the best possible outcome during a mine fire. Full-scale in-mine were conducted at the NIOSH Lake Lynn Experimental Mine to determine the flow characteristics, stability and fire-suppression capability of gas-enhanced foam. The in-mine experimental work was designed to evaluate movement of gas-enhanced foam through mine workings closely simulating an underground coal mine environment and how long gas-enhanced foam would remain stable. This paper presents results of the experiments and provides valuable insight into mine fire deployment strategies for gas-enhanced foam technology.

1 INTRODUCTION

The occurrence of mine fires continues to be one of the most persistent problems facing the mining industry. Since 2000 there have been 19 major mine fires (including thermal events) in underground mines in the United States (figure 1). The National Institute for Occupational Safety and Health (NIOSH), in partnership with the Mine Safety and Health Administration, is conducting on-going field and laboratory investigations that are focused on the remote application of extinguishing agents, deployment strategies for firefighting equipment, and permanent and temporary fire containment sealing technology. The goals of this research are to evaluate new and existing technologies and to limit miner exposure by developing or improving control and extinguishment strategies to help ensure the best possible outcome during a mine fire.

Fire fighting foam technology has been available for many years, and has been used extensively to fight flammable and combustible liquid fires on the surface (Colletti, 1992, Brackin et al. 1992, Omans, 1993a, Omans, 1993b, Omans, 1993c). The application of fire fighting foam in underground mines was developed in the 1950’s (Hartman et al. 1958, Nagy et al. 1960). Its use has been mostly limited to direct fire fighting application using high-expansion foam generators located underground to push the foam and flood the fire area (Scott and Nagy, 1968, Banerjee and Acharya, 1986, Conti, 1995, Conti and Weiss, 1998). Other applications include pumping of nitrogen-enhanced high expansion foam into gob areas to control spontaneous combustion (Komai et al. 1989, Voracek, 1993).

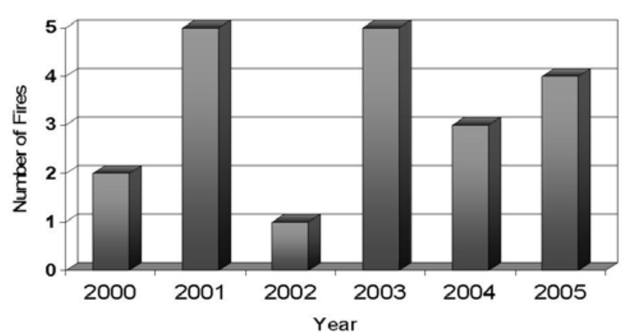

Figure 1. Major underground mine fires in the United States (2000-2005).

More recently, the methods that employ compressed gas foams have been developed, resulting in smaller, more uniform bubbles (Grady, 1994). The chemicals used to create foam concentrate are claimed to reduce the surface tension of water, greatly increasing the penetrating and wetting abilities of the water used, and significantly increases the effectiveness of the water supply (US Foam, 2004). The addition of gas to the mixture increases the resulting foam volume to between five and fifteen times the volume of water used.

Foam addresses a fire condition through evaporation of contained water and cooling by energy removal. Foam 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 the water 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 Corp, 2004). The four components of a fire include: the oxidizing agent (any of the various gases that support combustion), the reducing agent (any material that is reducible to combustible materials thus becoming a fuel), heat from within or without the material, and a self-sustaining chemical chain reaction (the action of the first three) (Gottschalk, 2002). If the foam is enriched with nitrogen gas, then it can serve to remove two components of the fire tetrahedron by robbing the fire of heat and removal or displacement of oxygen. Given sufficient stability and the capability to efficiently move and migrate through a mine opening, it is thought that nitrogen-enriched foam could provide an ideal technology for addressing mine fire conditions.

The use of remotely-applied foam from the surface through boreholes is a relatively new concept. Because of the lack of experience with this new technology, there are uncertainties with respect to the foam's ability to maintain its composition when pumped under pressure through deep boreholes and its ability to move away from the downhole location. In order to quantify these and other parameters, a series of full-scale experiments were conducted in NIOSH's Lake Lynn Experimental Mine (LLEM) located approximately 60 miles southeast of Pittsburgh, PA. The LLEM is a world-class, highly sophisticated underground facility where large-scale explosion trials and mine fire research is conducted. This work is being conducted under the tenets of the NIOSH Research to Practice (r2p) initiative which is aimed at reducing or eliminating occupational disease and injury by increasing the use of research findings in the workplace. During the in-mine experiments, the components of the foam were mixed together on the surface and the resulting foam was injected through a borehole into the mine void. Experiments were designed to measure the foam's stability, flow speed and length of flow. In addition, the ability of the foam to flow through non-linear mine void configurations, through and around obstructions, and over pooled water was evaluated. Foam's fire suppression effectiveness was measured against a deep-seated coal fire and a diesel pool fire. Lastly, its ability to flow up a sloped entry was measured.

2 FOAM DELIVERY SYSTEM

US Foam Technologies, Inc. together with On Site Gas Systems provided nitrogen gas-enhanced foam services during the experiments. US Foam Technologies Inc. offers a specialized gas-enhanced foam generating system and On Site Gas Systems provides nitrogen gas for the system using portable skid-mounted nitrogen plants that extract nitrogen gas from the atmosphere using membrane technology (On Site Gas Systems, 2005).

US Foam Technologies Inc. owns a proprietary nitrogen-enriched foam delivery system known as the Hellfighter™ which includes a pipeline manifold and a sophisticated mixing chamber. Water is pumped at a controlled rate and pressure into a line that is connected to one of the inlet ports on the Hellfighter™. Mine Fire Fighting Foam™ (MFFF) concentrate, a proprietary formulation of chemicals designed to produce long-lasting foam that can withstand higher temperatures than Class-A Fire Fighting Foam (AFFF), is added to the waterline using precision injection pumps. Nitrogen gas from On Site Gas Systems' membrane plant is then injected at a controlled rate into another inlet port on the Hellfighter™. The fluid (water and foam concentrate) and nitrogen gas is mixed within the Hellfighter™ and creates nitrogen-enhanced foam that flows from the outlet port of the Hellfighter™ to wellhead assembly attached to the injection borehole and into the mine void. A schematic of the foam system is shown in figure 2.

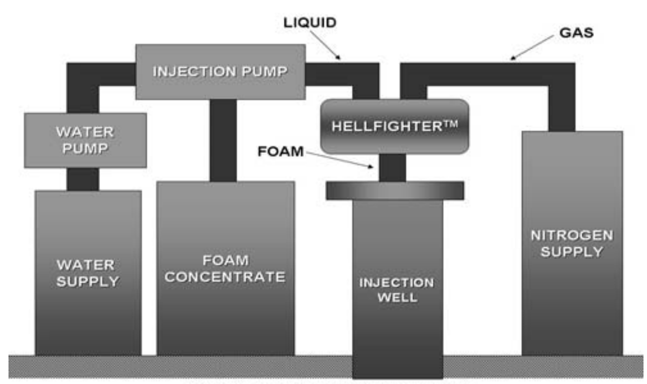

Figure 2. Schematic of the foam system

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 similar to shaving cream. In addition, the material being injected can be switched (with no downtime) from foam to only nitrogen gas simply by closing a valve. The gas-enhanced foam and nitrogen membrane plant combination provides an ideal platform for addressing mine fires because it can be readily moved from one borehole location to another and can be deployed using off-road equipment. Bulk liquid nitrogen trucks can deliver more nitrogen in a unit of time but their use is limited by rugged road conditions.

For these experiments, water was stored in a 10,000 gallon tank at the surface location of the borehole and a fire engine was used to pump the water. The foam concentrate was supplied in 250 gallon plastic "tote" containers. The nitrogen was supplied by a 1,000 ft^3/min membrane separation plant. Three Hellfighter™ units were attached to the injection borehole.

3 LAKE LYNN EXPERIMENTAL MINE

A layout map of the LLEM is shown in figure 3. The underground mine entries were developed adjacent to an abandoned commercial limestone quarry and underground limestone mine. The entries of the abandoned limestone mine, labeled as the old workings, are approximately 49 ft wide by 33 ft high. The LLEM contains 5 drifts openings called A, B, C, D, and E as shown in figure 3. These entries were developed to approximate the size of a typical Pittsburgh Coalbed mine, about 20 ft wide by 6 ft high, and range from 500 to 1500 ft in length. The entries, in conjunction with the use of two explosion-proof bulkhead doors that can be positioned to open or close an entry, can be made to simulate room-and-pillar and longwall mine configurations (NIOSH, 1999).

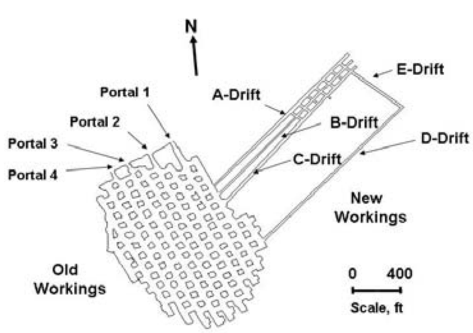

Figure 3. Layout map of the Lake Lynn Experimental Mine.

The injection borehole penetrated the mine void at a depth of 197 ft. The injection borehole intercepts the mine workings in the first crosscut outby the face area between the B and C drifts. The borehole is completed to the mine opening with 6-in diameter casing. At the location of the borehole, the mine opening is 7-ft high and slopes towards B drift on a 1.13 percent gradient.

4 EXPERIMENT NO. 1

Experiment No. 1 was designed to evaluate the physical characteristics and flow behavior of foam. Air was used as the gas in this experiment so researchers could observe foam movement without the need to use self-contained breathing apparatuses. The parameters studied in this experiment included measuring the condition and volumetric changes of the foam as it was pumped into the borehole and entered the mine, foam stability, flow speed, length of flow, stacking characteristics, movement through and around obstructions, movement over a pool of water, and flow through non-linear mine configurations. To accomplish this, the multiple entry section of the mine was configured as shown in figure 4. To evaluate the long-term stability of the foam under the typical mine temperature and humidity conditions, a 4.3-ft high concrete block stopping was construct in the closed end of the A drift to create an isolated area that could be filled with foam. This area measured 92 ft-long by 20 ft-wide. To transport the foam to this area, a flexible hose was attached to the bottom of the injection borehole and extended to this enclosure. The volume of this chamber to the top of the stopping (7,912 ft^3) was then filled with foam.

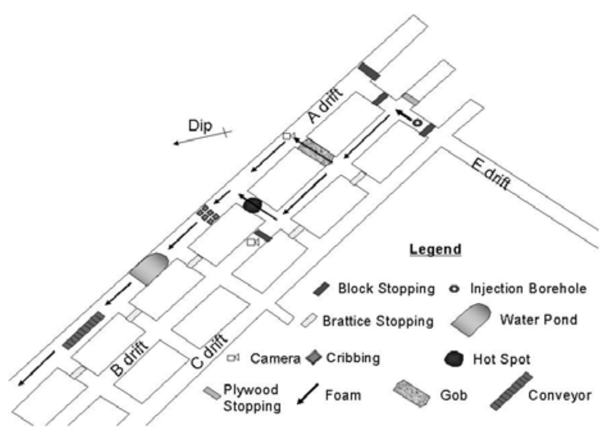

Figure 4. Layout map of mine workings for Experiment No. 1.

A combination of block, plywood, and brattice stoppings was used to direct the foam as it exited the borehole. A plywood stopping at the outby end of the B drift stub and a concrete block stopping in the first crosscut between A and B drifts were installed to direct the foam down B drift. The second crosscut between A and B drifts was filled rib-to-rib and floor-to-roof with broken rock to simulate compacted gob. This area was used to determine if foam would penetrate the broken rock mass or if the rock only served to block the flow path. Another block stopping was placed in the B drift just outby the third crosscut. One block was replaced with a window and a camera was located behind the stopping window to record the foam movement. Brattice stoppings were placed in the second and third crosscuts between B and C drifts and in the fourth, fifth, and sixth crosscuts between A and B drifts. Because of the slope of the mine floor, this combination of stoppings directed the flow of the foam across a broken rock pile in crosscut 3 between the A and B drifts. This rock zone was approximately 3-ft high and spanned the width of the opening. Three electric resistance heating elements were buried at the center of this rock pile to simulate a deep-seated hot spot, to determine if the foam could infiltrate the broken rock and reduce the temperature of the hot spot.

Two rows of four crib blocks were constructed in the A drift between the third and fourth crosscuts and a pool of water was created in A drift between the fourth and fifth crosscuts. The purpose of the pool of water was to determine whether foam would move over a body of water, if the pool created a barrier to foam flow, or if the pool served to degrade the foam. The water pool was created by constructing a watertight 2-ft high block stopping across the width of A drift to act as a dam. Because of the slope of the mine floor, a pool of water approximately 50 ft long was made in the A drift. Lastly, a 26 ft long conveyor belt structure was placed 3.5 ft from the rib area in the A drift between the fifth and sixth crosscuts to observe the behavior of the foam as it flows through or around mine structures.

The initial attempts to deliver high quality foam to the mine entry required some adjustment to liquid components and the rate of gas injection. This is typical of foam use and is usually done on the surface by the equipment operator. In this case, the adjustment was made through communications between in-mine personnel and personnel on the surface at the pump site. After adjustment, foam having a shaving cream-like consistency was achieved at the bottom of the borehole. The foam moved down and around the corner of the first crosscut into B drift. The foam reached a height of 3-to 4-ft through B drift as it moved down slope and away from the borehole.

The first obstacle encountered in B drift was the rock pile in the second crosscut between A and B drifts. The camera mounted on the A drift side of the rock pile showed that foam did not penetrate the broken rock mass. Water, however, that apparently settled out from the foam was observed flowing from the bottom of the rock pile.

The mine stopping configuration then caused the foam to turn into the third crosscut between A and B drifts, where the foam encountered the 3-ft high rock pile with the heating elements. Figure 5 shows the temperature profiles for the thermocouples attached to the four heating elements located in the rock pile. Unfortunately, the heating elements failed after reaching temperatures ranging from 28º to 34º C, just 15º to 20º C above ambient temperature. Unfortunately, the limited exposure of rock to the heating elements did not raise the rock temperature enough to measure the effect of the foam on the rock temperature. However, it is clearly obvious that the foam quickly infiltrated the rock pile and cooled the heating elements within minutes.

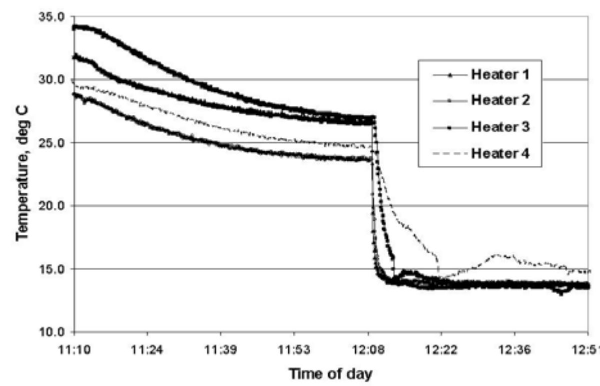

Figure 5. Rock pile heater element temperature profiles.

After turning the corner into the A drift, the foam moved until it encountered the sets of crib blocks. Figure 6 shows that the crib blocks formed an effective barrier to the foam, causing it to build up to roof height behind the crib blocks. Once past the crib blocks, the foam height in the entry was reduced to about 2-ft. The foam then approached the water pool in the A drift. The water had no apparent effect on the foam as it moved over it without any apparent affect on foam quality. Finally, the foam encountered the conveyor belt structure. The structure acted much like the sets of crib blocks in the A drift, causing foam build-up upstream of the structure. Since the structure only occupied 4.8 ft of the entry width, the foam moved through the unobstructed part of the entry similarly to the way it moved through the B drift.

As mentioned previously, the closed end of the A drift was filled with foam to a height of 4.3 ft. Figure 7 shows the rate of decay of the foam versus time. The foam lasted for 9 days and the rate of decay was linear over the 9 day period at about 900 ft^3. It should be noted that this area was not exposed to mine ventilation air flow and was strictly a measure of the rate of foam degradation.

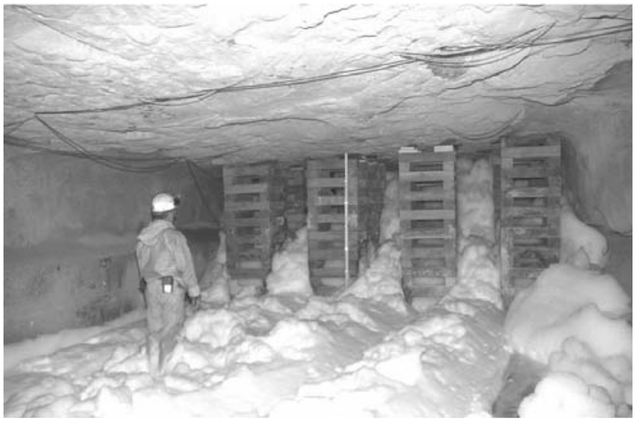

Figure 6. Foam flow and build-up in the crib block area.

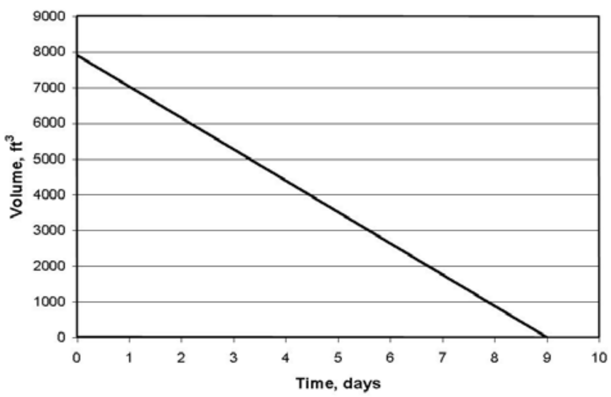

Figure 7. Rate of decay of foam volume versus time.

5 EXPERIMENT NO. 2

Experiment No. 2 was designed to evaluate the fire fighting effectiveness of foam against a deep-seated coal fire and a flammable liquid (diesel fuel) pool fire. In this experiment, nitrogen was used as the gas. The mine configuration to direct the flow of the foam was the same as in Experiment No. 1. The obstructions in the A drift were removed since the purpose of this experiment was to evaluate the ability of foam to extinguish the test fires. A concrete block stopping was placed in the third crosscut to contain the foam to B drift. Because of this configuration, B drift was not ventilated. The diesel fuel fire was located in the center of the third crosscut in B drift. Five gallons of diesel fuel was floated on a 1-in water layer in a 3-ft by 3-ft square metal tray. This fire was ignited just prior to the arrival of the foam front. The size of fire was approximately 600 kW. The deep-seated coal fire was placed just up slope of the diesel fuel fire in the center of the mine entry. To create the coal fire, approximately 250 lb of coal was placed on top of 25 lb of commercial cooking charcoal in a 3-ft by 3-ft square metal tray. This fire was ignited approximately 60 minutes before the foam flow was initiated. Figure 8 shows a layout map of the mine for Experiment No. 2.

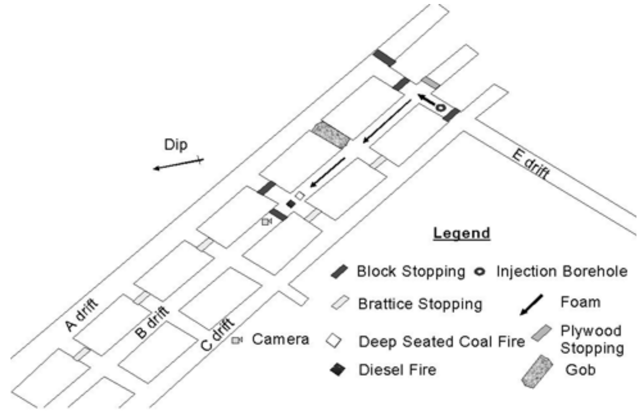

Figure 8. Layout map of mine workings for Experiment No. 2.

The diesel fuel fire was monitored using two thermocouples located 4-in above the fuel layer. The coal fire was monitored using seven thermocouples located throughout the coal pile. Both fuel and coal trays were also monitored by a thermal imaging infrared camera that enabled researchers to remotely view the fire through the foam. Figure 9 shows the temperature-time trace for the thermocouples located above the diesel fuel tray fire. The fire was ignited and allowed to burn for 10 minutes before the foam reached the fire. Temperatures of about 800 ºC were recorded 4 inches above the fuel layer. When the foam reached the fuel tray, it easily enveloped and extinguished the fire.

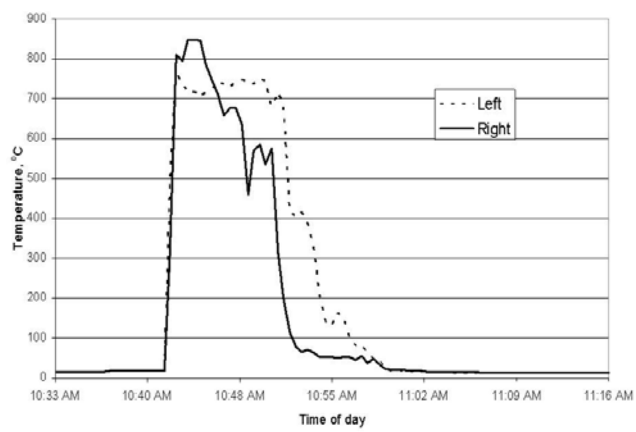

Figure 9. Temperature-time trace for thermocouples located above the diesel fuel fire.

Figure 10 shows the temperature-time plot for the thermocouples located in the coal fire tray. Temperatures near the top of the coal pile reached about 850º and 625 º C. Other areas of the coal pile were between 100º and 250º C, with the exception of the two thermocouples located on the outer edge of the coal pile which only reached about 50º C. The foam reached and enveloped the coal fire tray and quickly cooled the hot spots. Temperatures deeper inside the coal pile slowly decreased over the next hour.

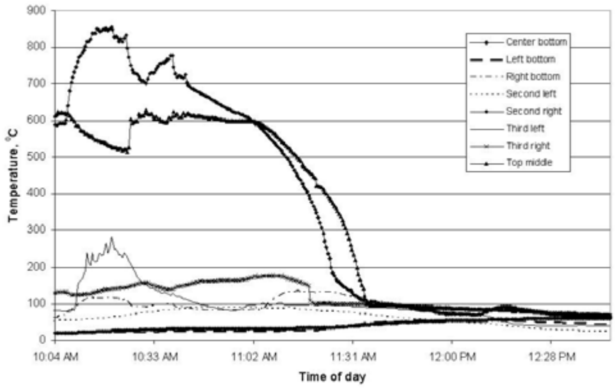

Figure 10. Temperature-time trace for thermocouples located in the coal fire.

Data from the infrared camera that was used to image the fuel and the space above the coal tray showed the space above the fire tray was reduced to about 15º C. The temperature of the foam downstream from the fuel tray was above the ambient temperature of the foam showing that it carried heat away from the fire. At the same time, the maximum temperature in the coal pile, as measured by the thermocouples, was about 90º C. This suggests that foam be used to quickly cool the airspace near a deep-seated fire, reducing the chance for spreading the fire. Furthermore, the nitrogen gas used to create the foam reduces the oxygen concentration in the airspace, thereby reducing the chance of a methane ignition.

During this experiment, foam reached the roof in B drift because of the stopping configuration, which essentially closed off B drift. In this confined experiment, foam filled the mine void and then moved upslope towards the injection borehole. Foam was also observed penetrating through the top of the rock pile located in the second crosscut between A and B drifts.

6 EXPERIMENT NO. 3

Experiment No. 3 was designed to evaluate the ability of the foam to fill a single mine entry. The 500 ft long E drift was used for this experiment. A layout map of the LLEM for this experiment is shown in figure 11. The slope of E drift (6.2 percent) is much more severe than in the multiple entry section of the mine. In this experiment, concrete stoppings were constructed in the crosscut between B and C drifts and in C drift to isolate E drift, creating a long single entry. Several blocks were removed from the first course of blocks in these stoppings to allow water to flow from the degradation of the foam. It was thought that water could collect in this area possibly causing the block structure to fail. A longwall shearer was located near the distal end of E drift and was utilized to evaluate foam's ability to move around the obstruction after flows a long distance.

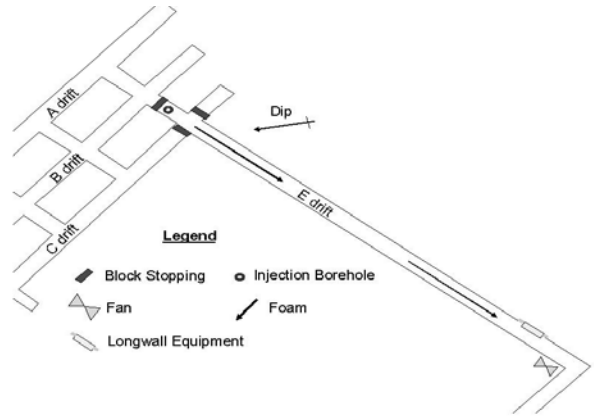

Figure 11. Layout map of mine workings for Experiment No. 3.

The foam was delivered through the borehole and filled the closed area (crosscut between B and C drift and area that was closed at the opening to the C drift) and then began moving up into the E drift. The foam reached the mine roof quickly because of the severe slope of the entry in this area. The rate of advance of the foam plug, as measured by the lowest point of the leading edge of the foam, was constant at 1.5 ft/min once the foam reached the mine roof and began moving up the E drift. Over the first 50 minutes, the foam had not yet reached the roof since it was filling the first crosscut at the intersection of C and E drifts. The pressure exerted on the concrete stoppings was measured and was approximately equal to the foam density. Figure 12 shows the progression of the body of foam along the E drift.

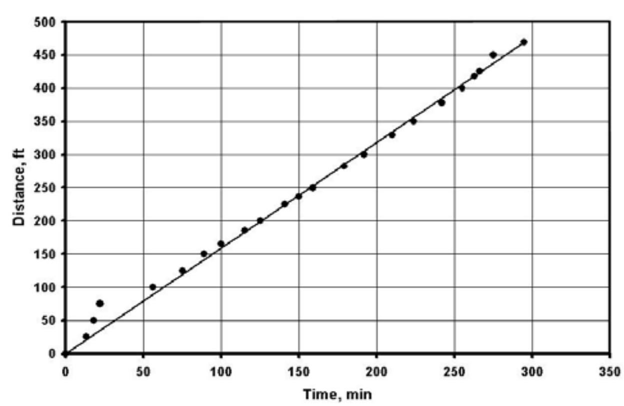

Figure 12. Progression of the body of foam along the E drift.

The foam filled the entire length of E drift in five hours. The experiment was stopped when the foam reached the fan shaft at the end of E drift to prevent disruption of the ventilation system. The rate of foam dissipation was measured over the next seven days, and is shown in figure 13. At the time the foam injection was stopped, the length of the E drift filled with foam was 469 ft. Initially, the foam was quite stable, decaying at a rate of only about 8.8 ft/day (1,145 ft^3/day) after the first day. The rate eventually increased to about 64.7 ft/day (8,410 ft^3/day) at seven days. The rate of decay over the first three days is comparable to the results from the stability test conducted earlier in the A drift stub. The rapid increase in decay rate after three days is possibly attributed to air pathways developing over the top of the body of foam as it degraded allowing airflow to pass over the foam. This likely increased the rate of dehydration of the foam.

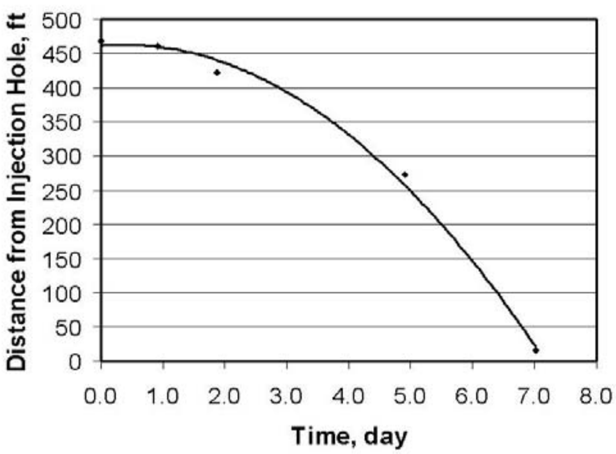

Figure 13. Rate of foam dissipation in the E drift.

7 SUMMARY

The foam experiments 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 also limited in 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.

The foam used in Experiment No. 1 showed good stability over time. Foam stability is a function of foam concentrate, water volume, and gas flow, and these parameters can be varied based on the particular application. Observations during the experiments suggested that the life of gas-enhanced foam is highly dependent on the quality of the foam (relative ratio of water, foam concentrate and nitrogen gas). “Wet” foam had shorter life (from a few minutes to a few hours) and “dry” foam lasted as long as several days. During the LLEM experiments when “wet” foam was created and the system was shutdown the foam degraded quickly and flowed away from the injection borehole. 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. However, the effect of varying these parameters was not measured in this experiment. This experiment also showed that the foam quality can be adequately managed from the surface. However, periodic monitoring of the foam consistency on the surface is recommended to ensure stable foam is entering the mine.

Foam flow, speed, and ability to reach the mine roof and fill the entire cross-section of the mine opening were shown to be highly dependent on the slope of the mine floor. In the first two experiments, the foam flowed quickly and did not reach the roof of the mine until it was obstructed by the sets of crib blocks. In the third experiment, the foam reached the mine roof very quickly because of the upslope of the mine floor and the obstructions that did not permit down slope flow, but the rate of advancement of the foam front was much slower than in the first two experiments.

In confined applications where the objective is to flow foam from the borehole to a fire location some distance away, this parameter is extremely important. In a situation where the elevation of the fire is below the foam entry point into the mine, the foam will flow quickly, however an obstruction, such as a remotely installed mine seal, will be neededl to cause the foam to completely fill the mine void from the floor-to-roof. In situations where the foam will need to move up slope, it will be critical to get the location of the foam injection borehole as close as practicable to the fire and position obstructions down slope from the foam injection point. Again, the use of remotely installed mine seals could be necessary. In situations where the mine entry is level, foam should flow in all directions away from the injection borehole, but the flow will be highly dependent on obstructions. Unfortunately, this scenario was not tested at the LLEM.

The nonlinear configuration of the mine openings used in the first two experiments demonstrated that foam will flow around corners, but again the major influence on its effectiveness was elevation and obstructions. In the first two experiments, foam flowed past the rock rubble pile in the second crosscut between A and B drifts, essentially treating it as a stopping. The stopping in B drift acted to turn the foam into the crosscut between A and B drifts. However, when the foam reached A drift, which was open in both directions, the foam only flowed in the down slope direction.

The ability of foam to suppress a liquid pool fire was shown in the second experiment. However, foam’s ability to cool a hot, deep-seated fire was not completely addressed in these experiments. Foam did cool the high temperatures in the coal fire, but this was a relatively small fire. Foam was able to infiltrate the rock pile and quickly cool the heating elements in the second experiment, but the temperatures were not high enough to truly test the foam’s cooling ability. Foam’s inability to penetrate through the rock pile in the first experiment was noted. In the second experiment, foam moved through the rock pile near the mine roof when it was confined to the B drift. This indicates that the compaction of gob material and other possible pathways will determine the foam's ability to infiltrate and penetrate deeply into a gob area.

ACKNOWLEDGMENTS

The authors acknowledge the support of Frank A. Karnack, William Slivensky, Donald D. Sellers, Kenneth Jackson, and Frances J. Goff, and Richard A. Thomas in preparation of the experimental setups and data acquisition and analysis, and William Monaghan for gathering the thermal imaging data.

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