APPLICATION OF GAS-ENHANCED FOAM AT THE EXCEL NO. 3 MINE FIRE

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ABSTRACT

The Excel No. 3 Mine is a room-and-pillar mining operation owned by MC Mining, LLC, a subsidiary of Alliance Resource Partners, LP, which produces coal from the Pond Creek Coalbed in Pike County, Kentucky. Late on December 25, 2004, a fire was discovered near the bottom of the slope and, after an unsuccessful attempt to fight the fire underground, it was decided to address the fire remotely from the surface. The mine operator developed a plan to fight the fire that called for the installation of temporary seals at the slope and mine shafts to eliminate the inflow of oxygen. In addition, the plan called for drilling and completion of vertical boreholes into select areas of the mine workings to monitor the mine atmosphere and inject nitrogen gas and gas-enhanced foam. Over the next 9 days, nitrogen gas was injected almost continuously and gas-enhanced foam was injected periodically as deemed necessary. On January 7, 2005 it was determined that the fire was successfully suppressed. This paper presents a discussion of the fire-fighting approach and an analysis of the results of the application of gas-enhanced foam technology.

INTRODUCTION

The occurrence of mine fires continues to be one of the most persistent problems facing the mining industry. Since 2000 there have been 17 mine fires 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 (MSHA), is conducting ongoing field and laboratory investigations that are focused on 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 deployment strategies to help ensure the best possible outcome during a mine fire.

Full-scale underground experiments were conducted to determine the effectiveness of remote mine seal technology and gas-enhanced foam at the NIOSH Lake Lynn Experimental Mine (LLEM), located approximately 60 miles southeast of Pittsburgh, Pennsylvania. The LLEM is a world-class, highly sophisticated underground facility where large-scale explosion trials and mine fire research is conducted. The objectives of the in-mine experiments were to identify and remedy existing technology shortcomings or to develop novel technologies and to transfer these new and improved technologies to the mining industry as soon as possible. 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.

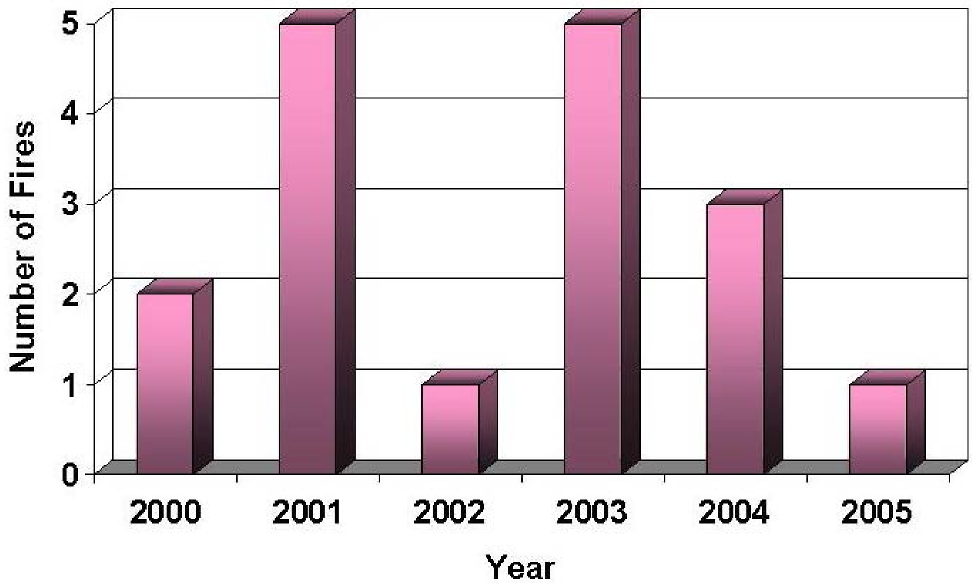

Figure 1. US underground mine fires 2000 to 2005 (through May 2005).

OVERVIEW OF THE MINE FIRE EVENT

The Excel No. 3 Mine is a room-and-pillar mining operation that is owned by MC Mining, LLC, a subsidiary of Alliance Resource Partners, LP. The mine produces low-sulfur coal from the Pond Creek Coalbed in Pike County, Kentucky (figure 2). The mine employees about 250 workers and production from the mine during 2004 averaged approximately 160,000 tons per month (1)[1].

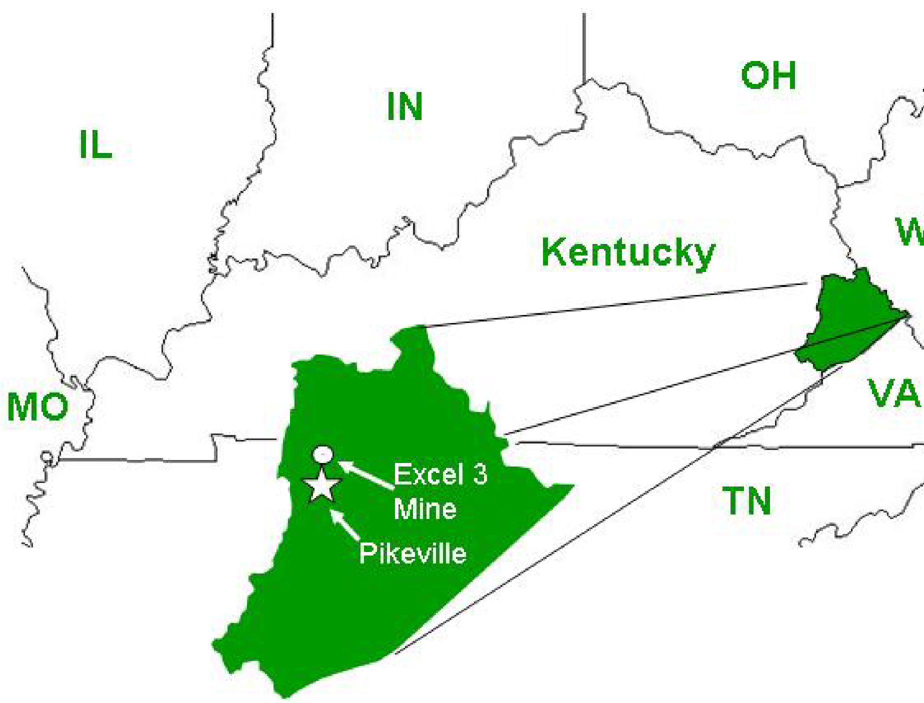

Figure 2. Location map for the Excel No. 3 Mine.

[1] Underlined numbers in parenthesis refers to the list of references at the end of this paper.

Late on December 25, 2004, a fire of unknown origin was discovered near the bottom of the dual compartment slope. After detecting the fire, the mine operator took immediate actions to fight and control the fire and simultaneously notified the Mine Safety and Health Administration (MSHA) and the Kentucky Office of Mine Safety and Licensing (OMSL). Mine emergency response teams from MSHA and OMSL joined with MC Mining firefighting personnel to try and extinguish the fire. The work continued until late morning of December 26, 2004, at which point it was deemed too hazardous to continue the direct suppression efforts and the mine was evacuated (1). The fire had been initially confined to the area near the bottom of the slope. When it was last observed, the fire had progressed in a northwest direction through cross-cuts located near the base of the slope and then in a westward direction towards the B-Return Shaft (figure 3). This path was most likely due to air coursing through the mine ventilation system or because of convection currents created by the fire.

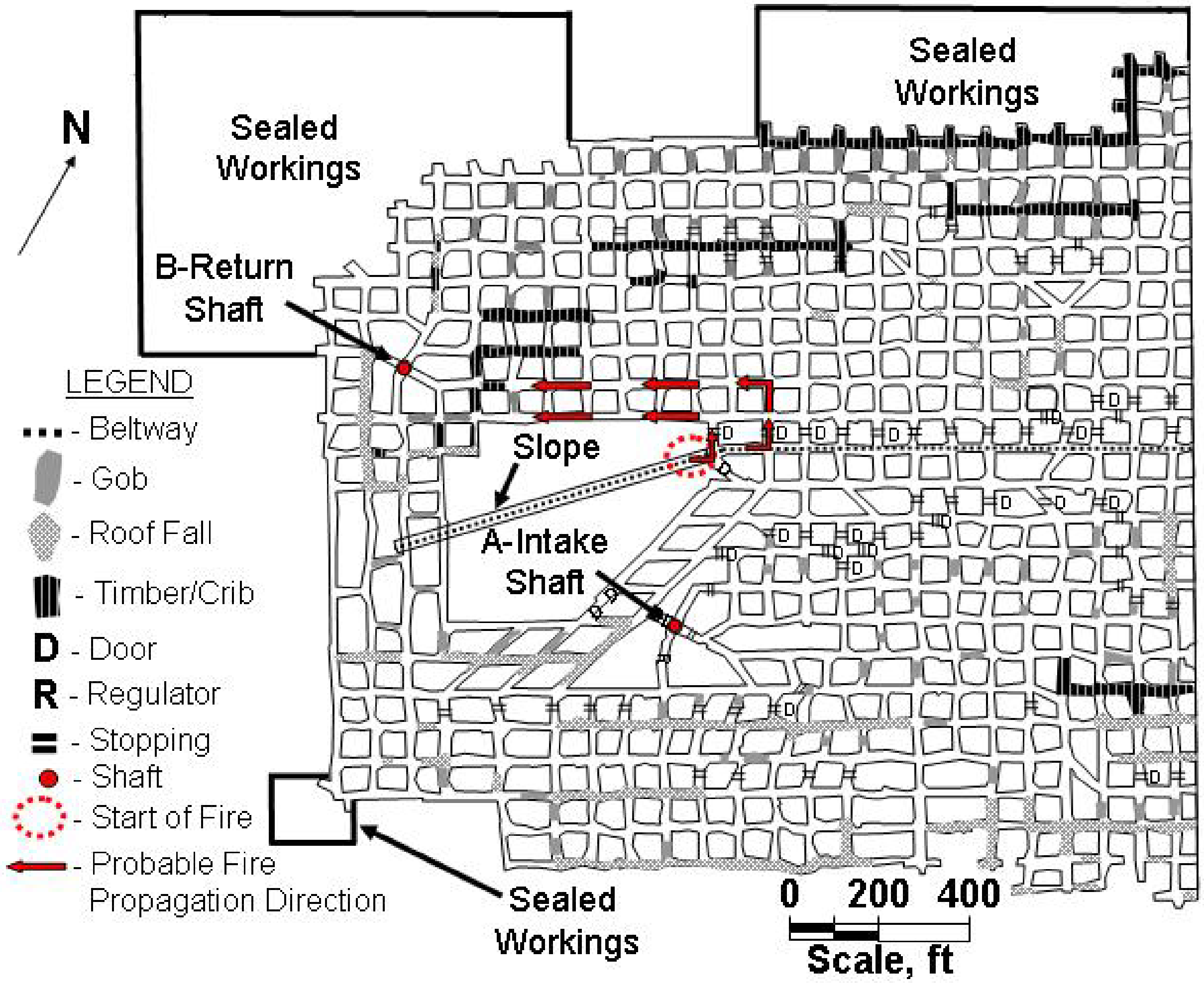

Figure 3. Map showing location of the fire zone.

By the afternoon of December 26, 2004, temporary seals had been installed on the slope and the three shafts at the mine. This work was done to limit the inflow of oxygen to the fire zone. A short time later, the B-Return shaft was permanently sealed when it was discovered that it was leaking air. Concurrently, the mine operator along with representatives from MSHA and OMSL developed a plan to isolate and extinguish the fire remotely from the surface. The plan called for drilling and completion of several boreholes to monitor the mine atmosphere and for the injection of nitrogen gas and nitrogen gas-enhanced foam to render the mine atmosphere inert (1). Once the mine was evacuated and sealed, further information about the progress and extent of the fire was limited to interpretation of gas samples collected from the monitoring boreholes and air shafts.

REMOTE MINE FIRE SUPPRESSION ACTIVITIES

For the purpose of this study, only those boreholes that were used to suppress the fire and monitor mine conditions in the vicinity of the fire area will be discussed. Several other boreholes were also drilled on the mine property and were used as gas injection points to maintain the mine atmosphere in preparation for and during mine reentry and recovery operations. Gas monitoring results and the volume of nitrogen injected into these boreholes are not the focus of this paper and will not be discussed further.

A total of thirteen boreholes were drilled in and around the area of the mine fire to monitor mine conditions and inject nitrogen gas and nitrogen gas-enhanced foam (figure 4). Borehole V15 was drilled to the mine level, but encountered fill material that was used to seal the B-Return Shaft during the fire-fighting efforts and this borehole was not used. Mine atmosphere data was collected from boreholes V3, V5-8 and V16. Additional mine atmosphere information was collected from monitoring tubing that was installed in the Slope, the A-Intake Shaft and the 3A-Intake shaft that was located far from the mine fire site.

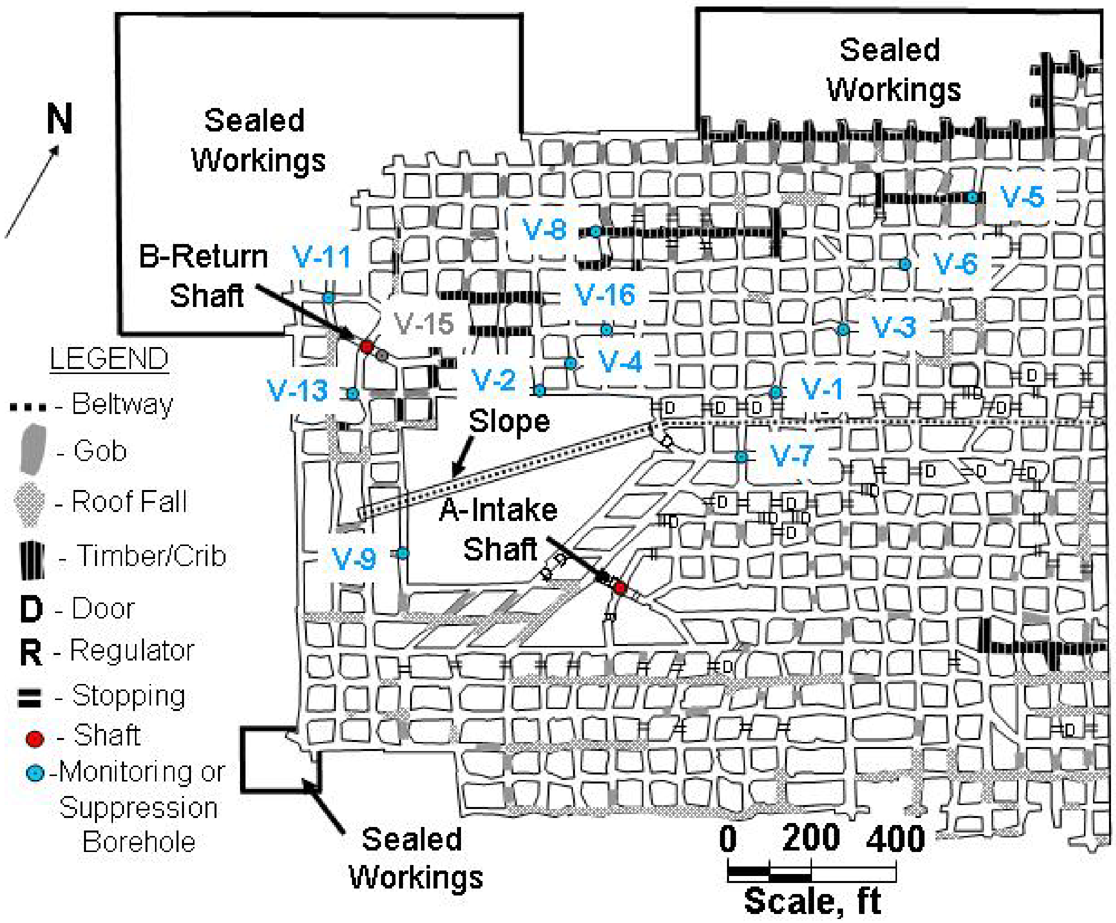

Figure 4. Boreholes used to monitor or suppress the fires (shown in blue).

Small diameter perforated tubing (0.75-in) was placed into each monitoring borehole down to the depth of the Pond Creek Coalbed to provide a means of sampling the mine atmosphere. At some locations, gas samples were collected continuously via overland plastic lines that were connected to MSHA's infrared and electro-chemical gas analysis equipment. At other sites, samples were collected periodically by evacuating the downhole tubing at the borehole and drawing a sample into a syringe. The gas in the syringe was then analyzed at the mine site by MSHA using gas chromatography. The samples were analyzed for the presence of hydrogen, oxygen, nitrogen, methane, carbon dioxide, carbon monoxide, acetylene, ethylene and ethane.

Injection of Liquid Nitrogen

As discussed earlier, in addition to sealing the mine from oxygen inflow, liquid nitrogen and gas-enhanced foam were used to suppress the mine fire (2, 3). Boreholes V1 and V9 and the Slope were used as bulk liquid nitrogen injection points (figure 5). Nitrogen was brought to the mine site in bulk tanker trucks and was injected into the mine void as a liquid. The nitrogen changed state from a liquid to a gas at or near the mine level and was subsequently dispersed into the mine void. Figure 6 shows a typical liquid nitrogen injection operation. Figures 7-9 shows the volume of nitrogen injected for each bulk tanker delivery (expressed in cubic feet and shown as a blue diamond in the figures) and the cumulative amount of gas injected for boreholes V1, V9, and the Slope. Note, borehole V1 was lost on January 6, 2005 due to a downhole accumulation of ice from an attempted carbon dioxide injection. The borehole was rendered unusable for the duration of the mine fire suppression work. Also, injection of liquid nitrogen was terminated at the Slope on January 5, 2005 as workers began construction of an air-lock for mine reentry. Two interesting observations can be made from these figures. First, the delivery schedule for tankers was not regular. This can be observed by the change in the slope of the curves showing the cumulative volume of nitrogen injected. Second, the amount of nitrogen delivered varied greatly at each site. The large variation observed in the figures for borehole V9 and the Slope was due to the fact that some of the nitrogen delivered was split between the two locations. The remaining variation observed in the graphs was due to the variable tanker volume, pressure and temperature.

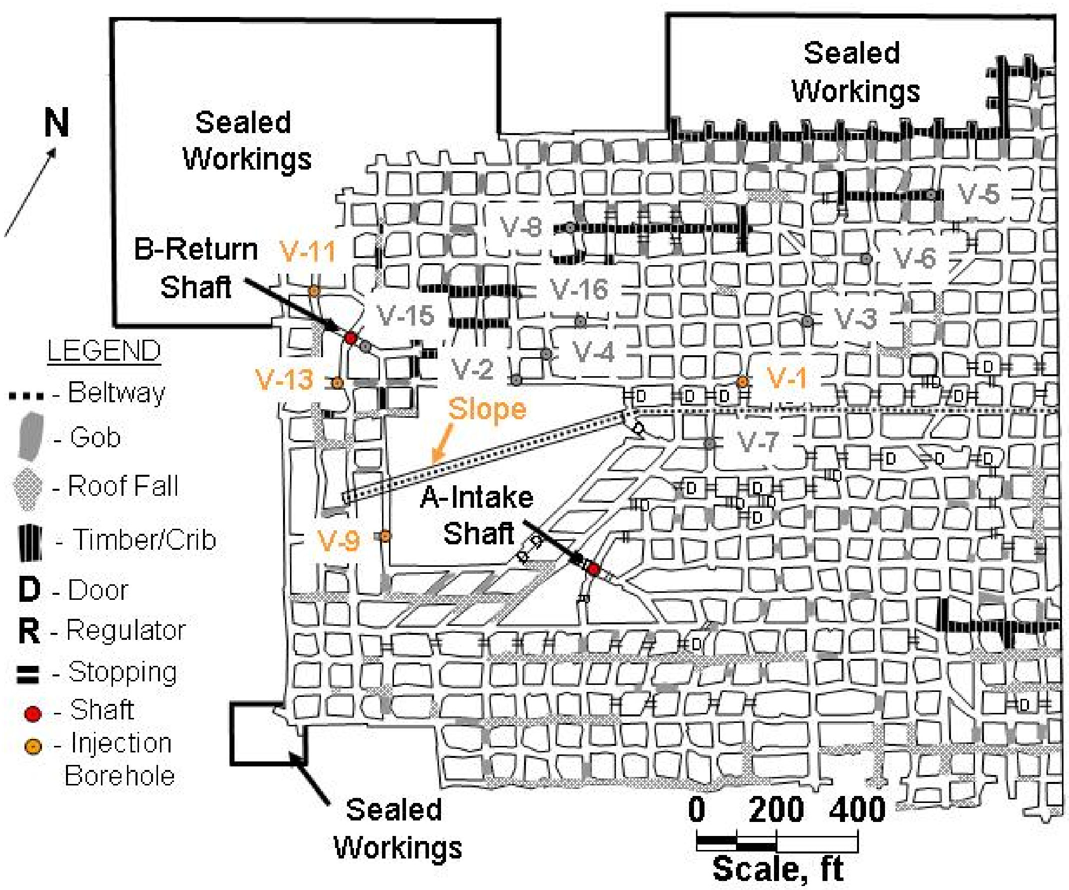

Figure 5. Borehole used to inject liquid nitrogen into the mine (shown in orange).

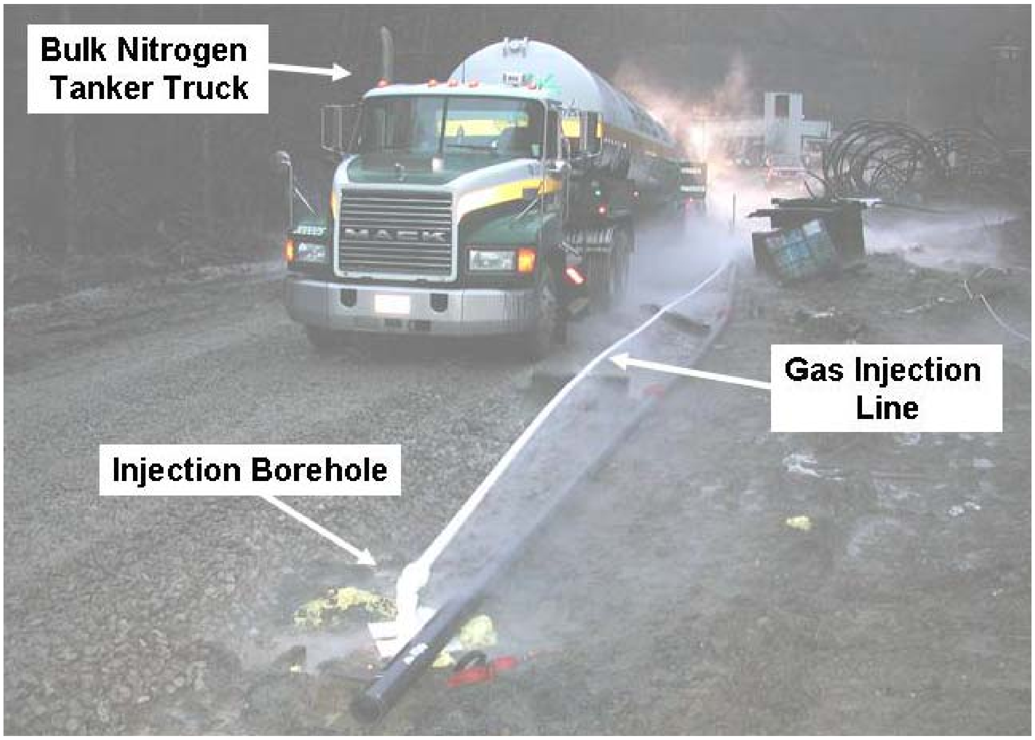

Figure 6. Liquid nitrogen injection operations.

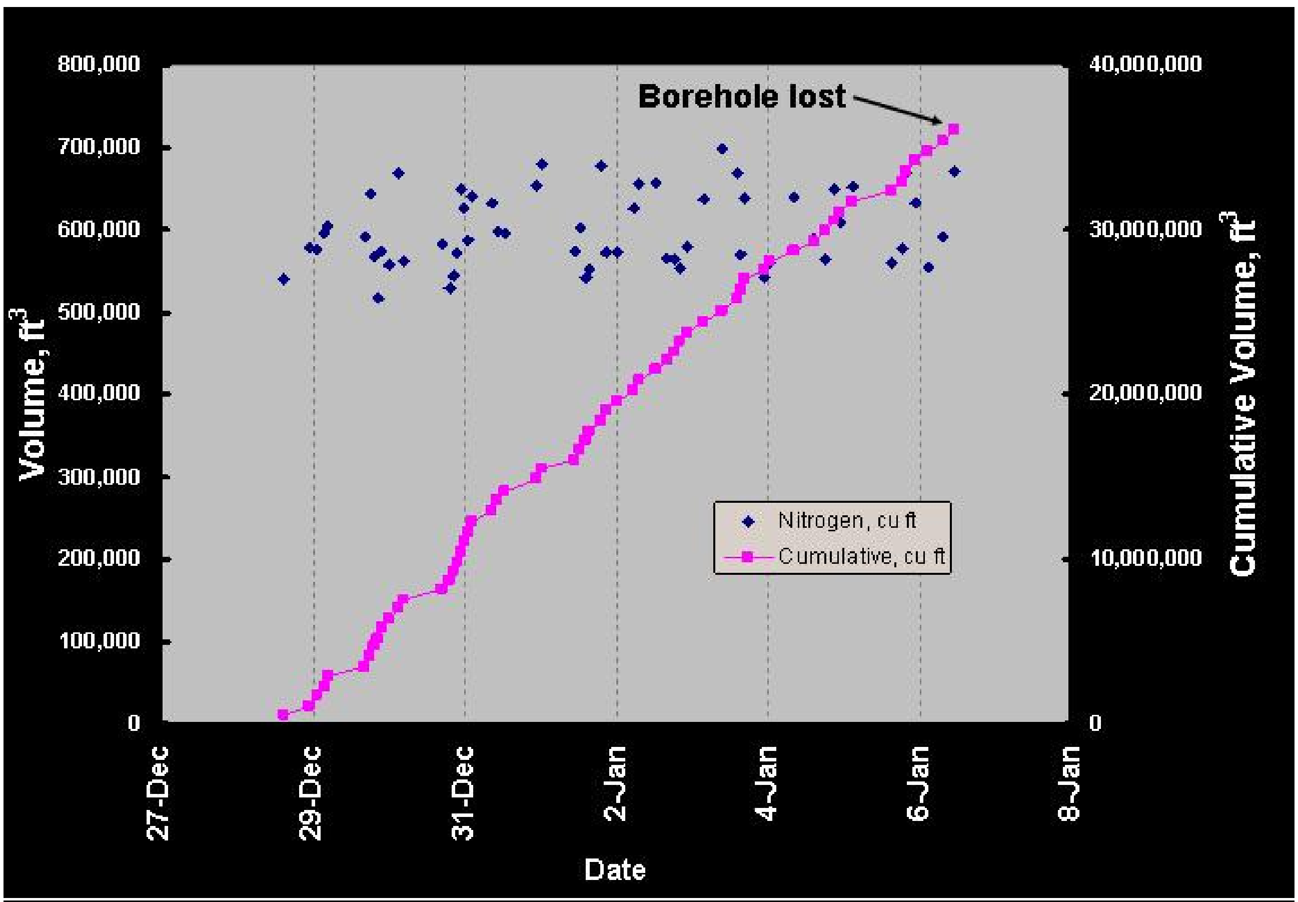

Figure 7. Nitrogen injection history for borehole V1.

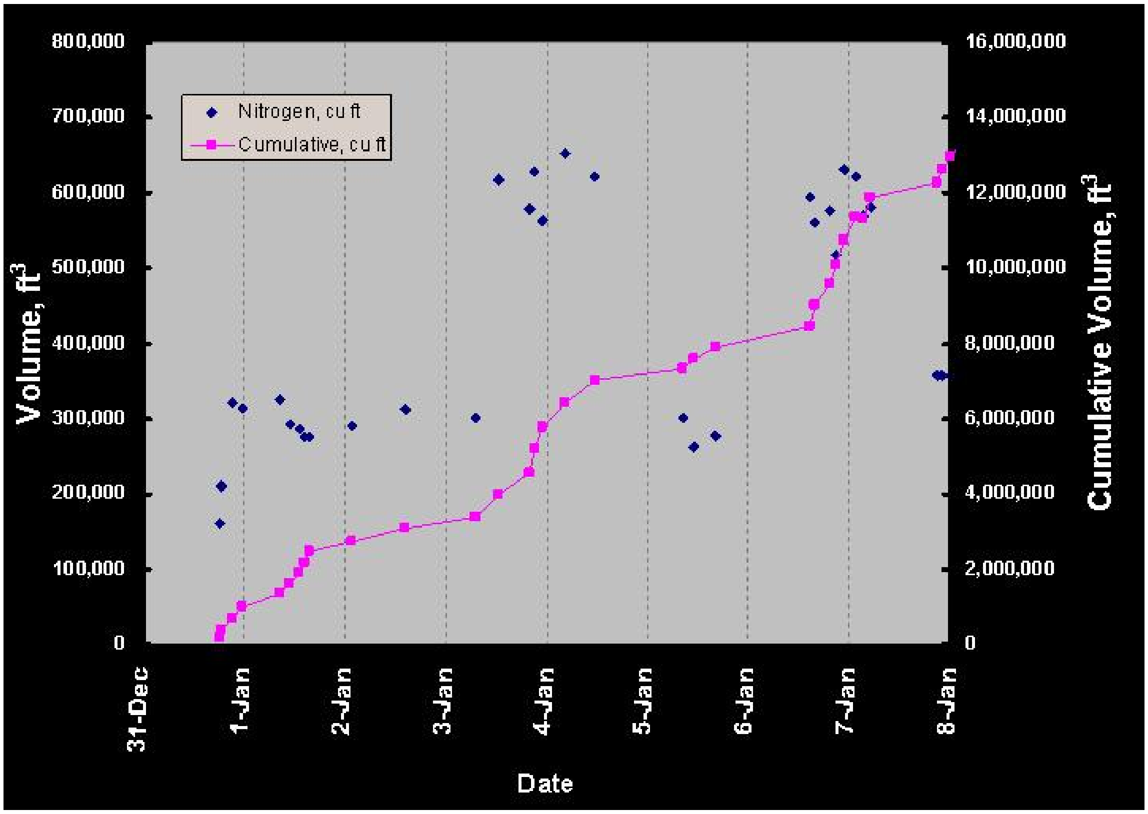

Figure 8. Nitrogen injection history for borehole V9.

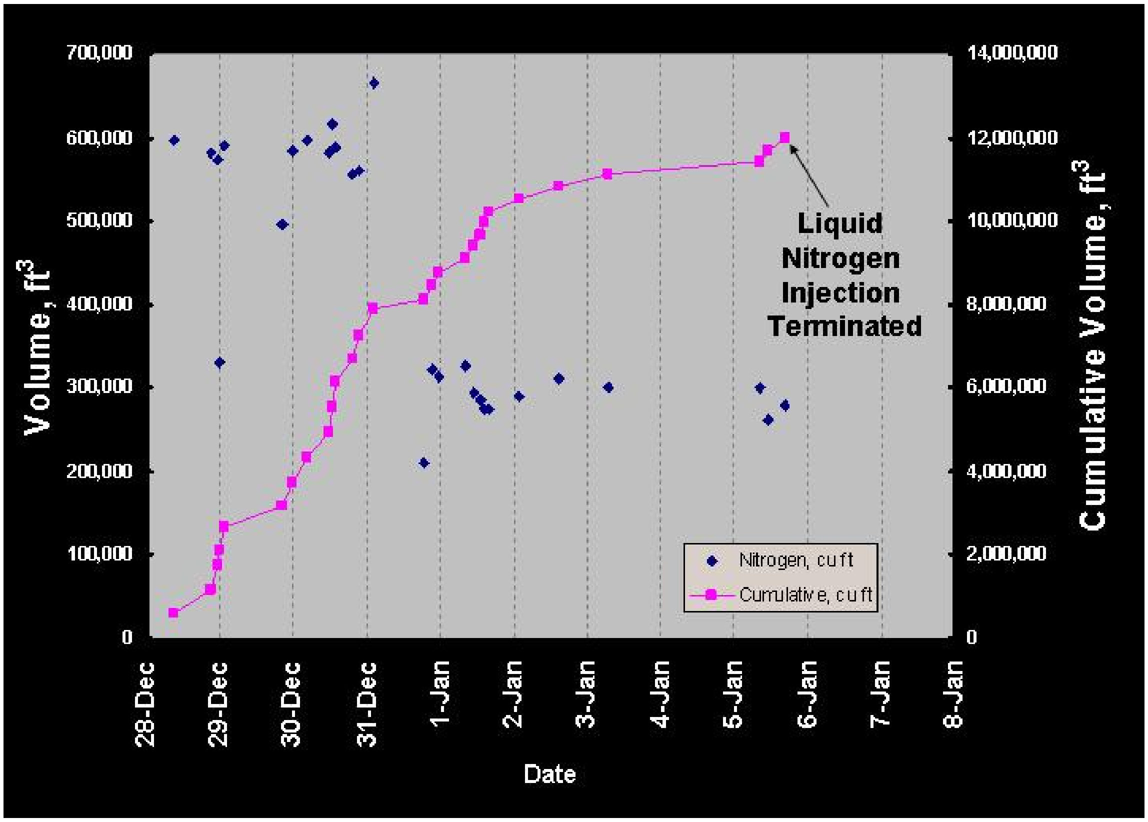

Figure 9. Nitrogen injection history for the Slope.

Nitrogen-Gas Enhanced Foam Injection

U.S. Foam Technologies, Inc.[2] (with On-Site Gas Systems as a subcontractor) was contracted to provide nitrogen gas-enhanced foam to aid in the fire suppression work. U.S. 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 (4). The chemicals used to create the gas-enhanced 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 (5). 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 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 (6). If the foam is enriched with nitrogen gas, then it can serve to remove two legs of the fire triangle 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.

US Foam Technologies Inc. utilizes a proprietary nitrogen-enriched foam delivery system known as the Hellfighter™ which contains 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 the 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. Figure 10 shows a Hellfighter™ unit installed on an injection borehole. 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 (figure 11). In addition, injection can be switched with no downtime from nitrogen-gas enhanced foam to only nitrogen gas by simply closing a valve.

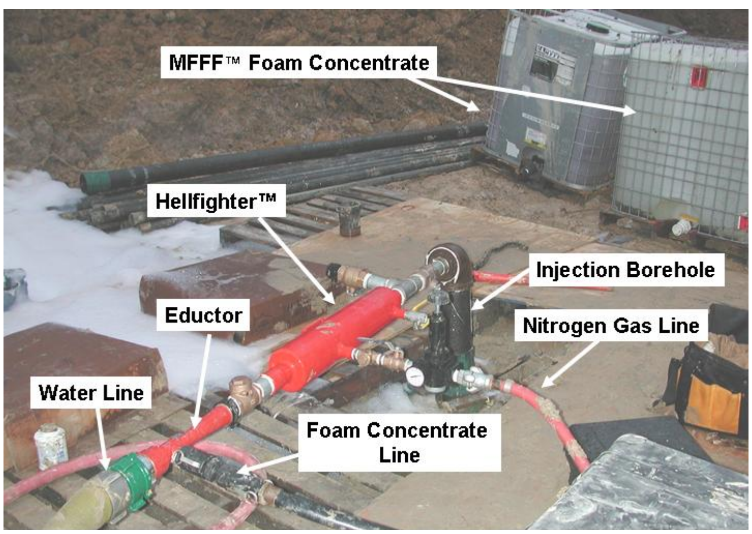

Figure 10. A Hellfighter™ unit installed on an injection borehole.

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

Figure 11. Testing foam quality.

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.

Delivery of the foam concentrate injector pumps to the Excel No. 3 Mine site was delayed significantly. Eductors were borrowed from a local fire company and were used in place of the injector pumps. Eductors pump or move liquids using suction created by liquid flowing through the unit. Using this equipment, one must know the exact water flow rate in order to correctly adjust the foam concentrate feed rate. Any inaccuracy in measuring the water flow rate will result in an incorrect addition of foam concentrate and will dramatically change the characteristics of the foam. Figure 10 shows an eductor in use with the Hellfighter™ system.

During the Excel No. 3 Mine fire, gas-enhanced foam was injected into the mine periodically from January 2-4, 2005 and January 5-6, 2005 at boreholes V2, V4, and during a twelve-hour period on January 4, 2005 at borehole V13 (figure 12). When gas-enhanced foam was not being injected into the boreholes, nitrogen gas from the membrane plant was injected in boreholes V2 and V4 or it was directed into boreholes V11 and V13. As can be observed in figure 12, boreholes V2 and V4 were drilled into the area of the fire and were deemed critical to the fire suppression work. Figures 13-15 show the volume of nitrogen gas injected when the foam system was operating and the cumulative amount of nitrogen injected. Figure 16 shows the volume of nitrogen injected into borehole V11. Periodic failure of the mine's water supply line was the reason for intermittent operation of the foam system during the January 2-4, 2005 and January 5-6, 2005 time periods.

The interruption of the foam injection operations from the afternoon of January 4, 2004 until the evening of January 5, 2005 occurred at the request of the mine operator so they could evaluate the mine conditions with a downhole video camera, make downhole temperature measurements and analyze mine atmosphere data to determine if the fire had been extinguished. The results of the downhole temperature survey showed that the mine level temperature was below 100º F in all of the holes surveyed. Furthermore, no visible sign of the fire was seen in the holes that could be surveyed by the downhole video camera.

During the downhole video surveys it became apparent that gas-enhanced foam was only seen in borehole V2. The mine operator was unable to make any firm conclusions from the video surveys because downhole obstructions prevented mine level observations in some boreholes and it was not clear if the boreholes where the in-mine observations were made were actually in the foam flow path from boreholes V2 and V4. Furthermore it was unknown if the foam injected into boreholes V2 and V4 had more or less broken-down to its gas and water components and flowed away from the injection boreholes.

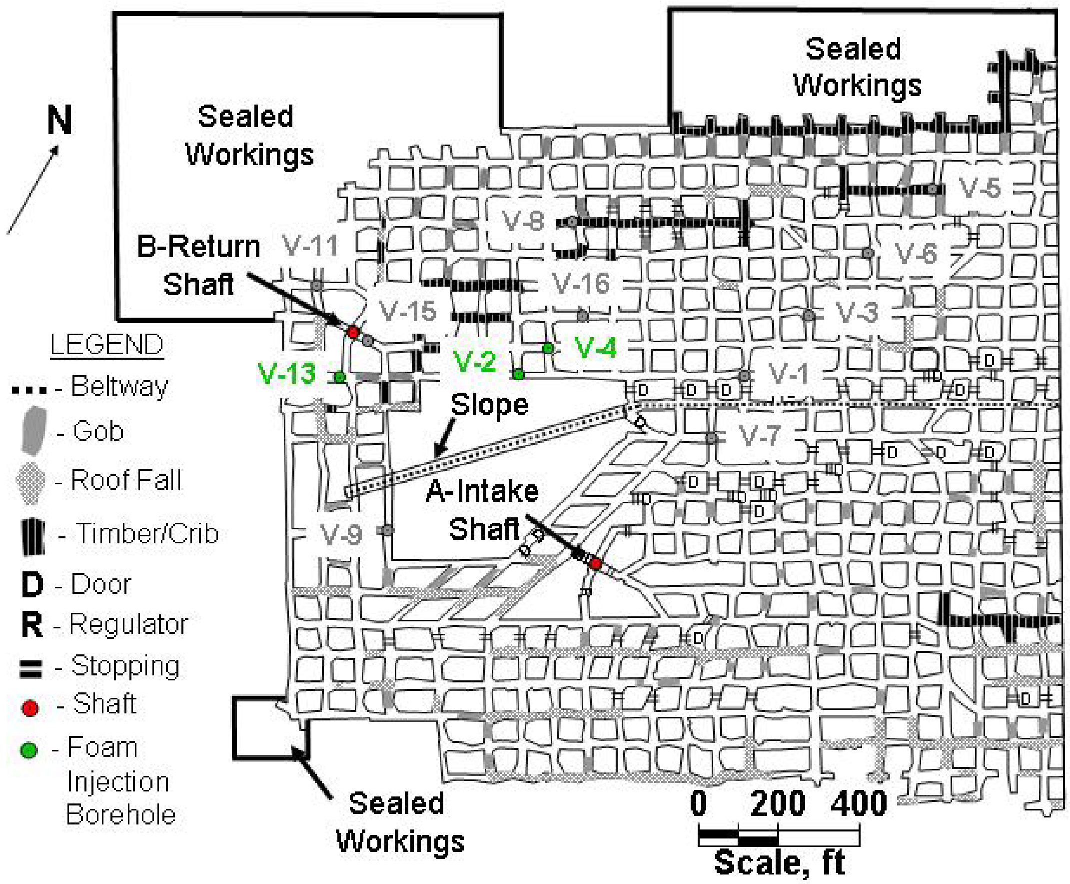

Figure 12. Boreholes used to inject nitrogen-gas enhanced foam into the mine (shown in green).

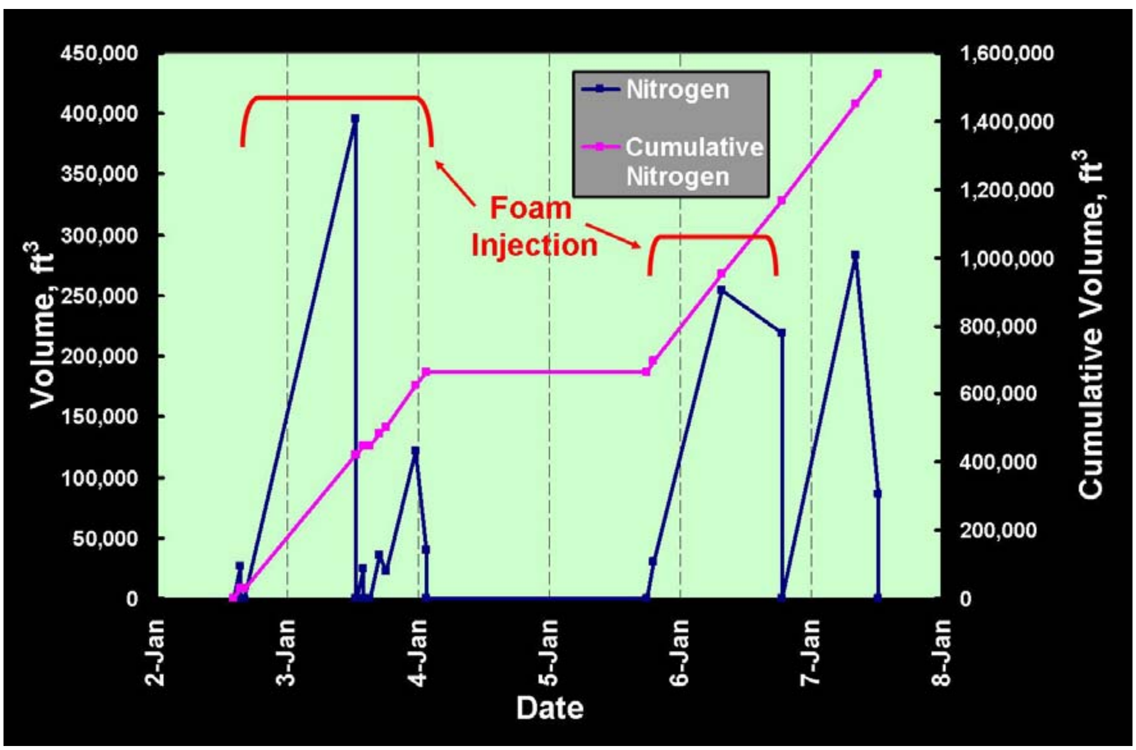

Figure 13. Nitrogen-gas enhanced foam injection history for borehole V2.

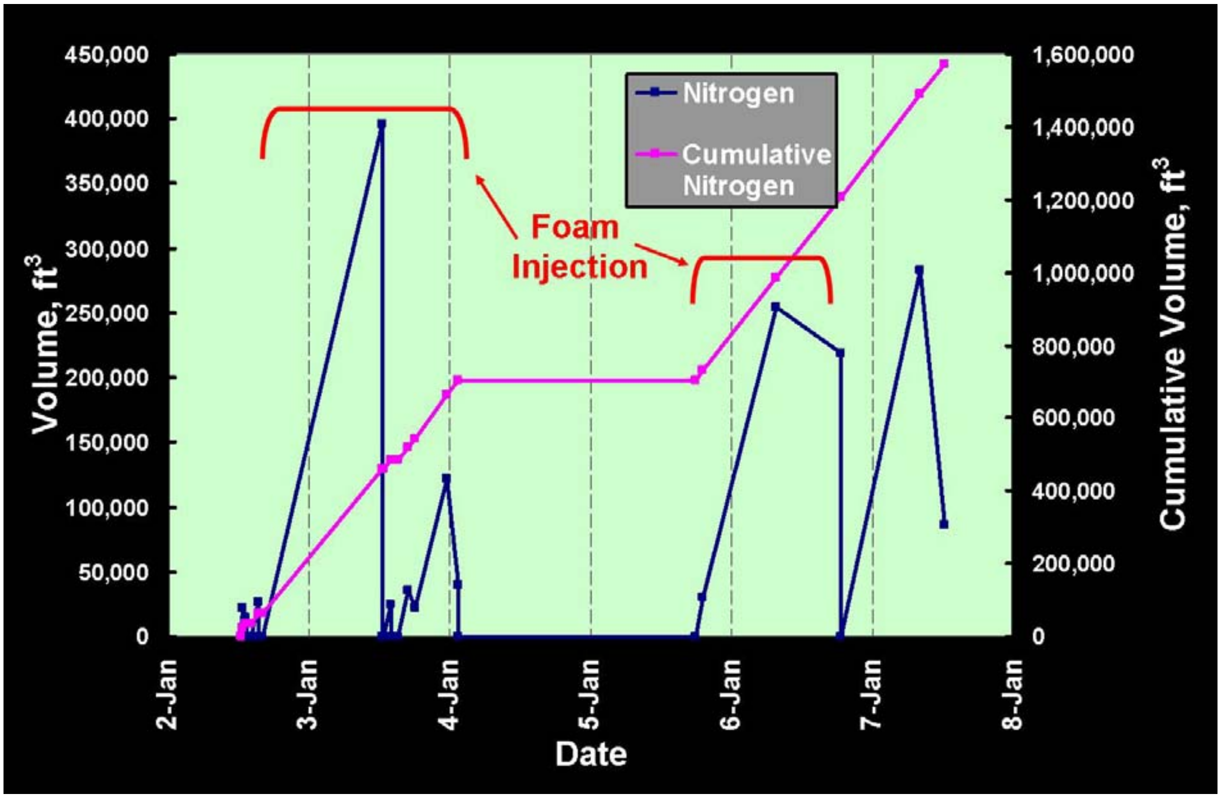

Figure 14. Nitrogen-gas enhanced foam injection history for borehole V4.

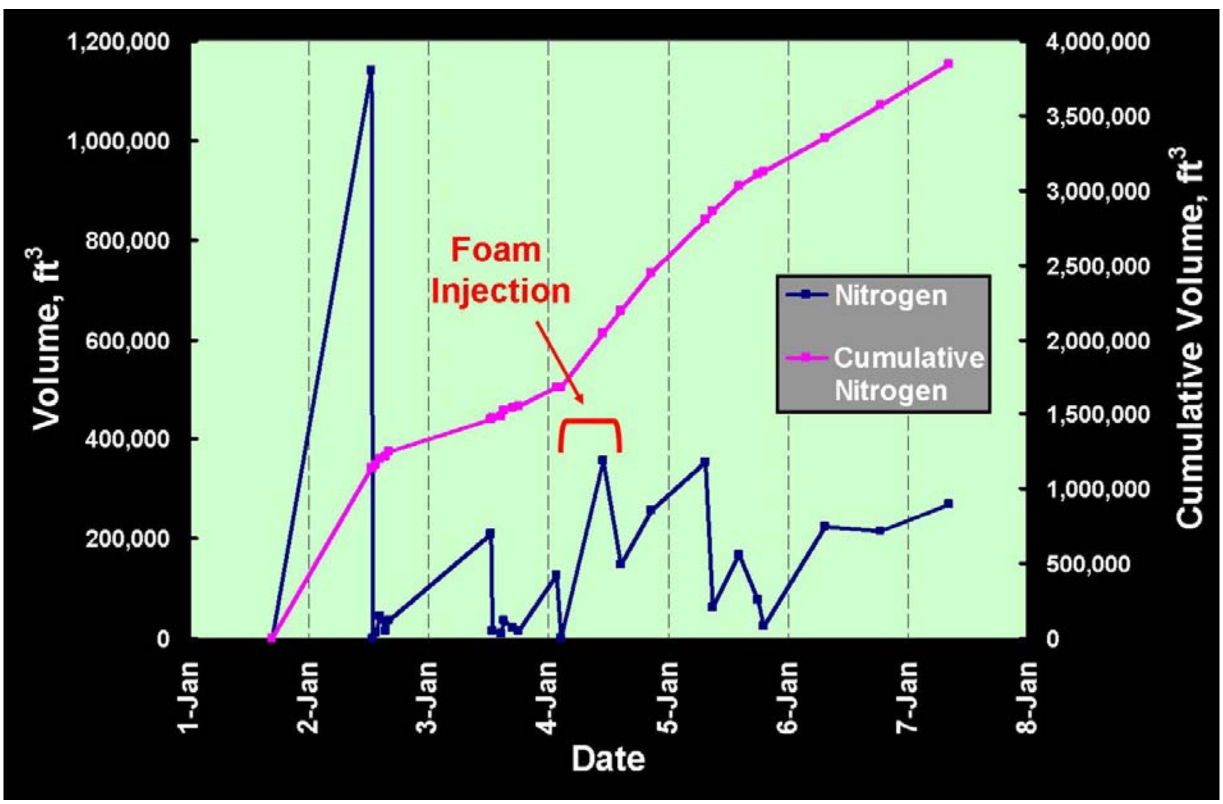

Figure 15. Nitrogen-gas enhanced foam injection history for borehole V13.

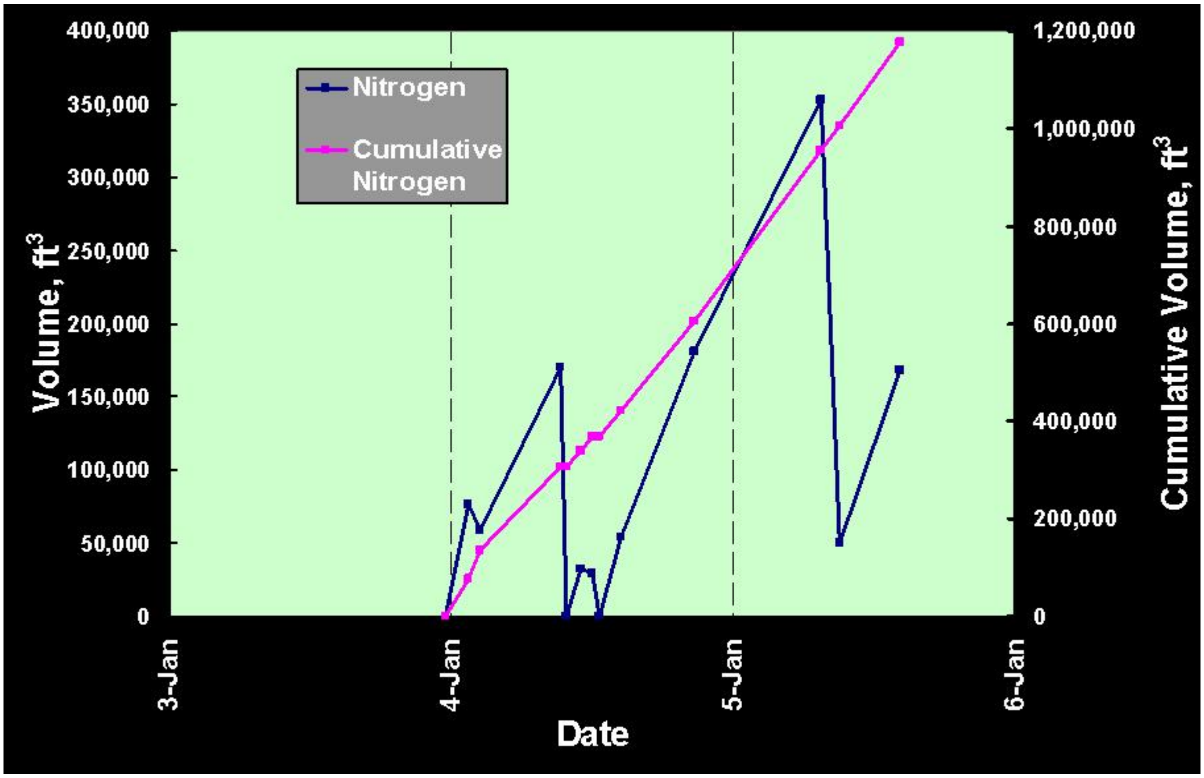

Figure 16. Nitrogen gas injection history for borehole V11.

Experiments conducted at the LLEM showed 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 shut-down the foam degraded quickly and flowed away from the injection borehole. It was determined that barriers of any sort (cribbing, conveyor structures, roof fall material, gob piles, etc) would cause the foam to stack-up and fill the mine opening and observations suggested that the "dry" foam had a tendency to stack-up more quickly than "wet" foam. Also, underground topography played a key role in how the foam moved in the mine opening as it flowed down a sloping entry in preference to uphill entry orientations. Finally, when the foam was forced to flow upslope, it had a tendency to stack-up and build towards the mine roof. An examination of the elevation of the Excel No. 3 mine data in the vicinity of boreholes V2 and V4 suggests that foam would most likely flow down slope in a northeast direction towards the area where the fire burned from the bottom of the slope (and away from the boreholes viewed with the downhole video equipment) through to nearby crosscuts (refer to figure 3). It was hoped that foam would flow against material on the mine floor or supplemental roof support structures and would backfill to the injection borehole and onward towards the B-Return Shaft.

The foam system was brought back on line at boreholes V2, and V4 in the early evening on January 5, 2005 when it was determined that the carbon monoxide concentration in the mine has begun to increase. At borehole V13, gas-enhanced foam operations were not restarted and only nitrogen gas was injected. Foam injection operations were suspended in the early evening on January 6, 2005 and a total of 3,000,000 gallons, 3,000,000 gallons and 1,600,000 gallons of foam were pumped into boreholes V2, V4 and V13 respectively.

Mine Atmosphere Monitoring

Figures 17-20 shows representative gas monitoring information for boreholes V6, V8, the A-Intake Shaft and the Slope as provided by MSHA (2, 7). As expected, just after the mine was sealed and monitoring was initiated, the initial value for carbon monoxide concentration in the mine atmosphere was high at all locations except the 3-A Intake Shaft located far away from the fire zone. Injection of liquid nitrogen began at the Slope on the morning of December 28th and that afternoon at borehole V1.

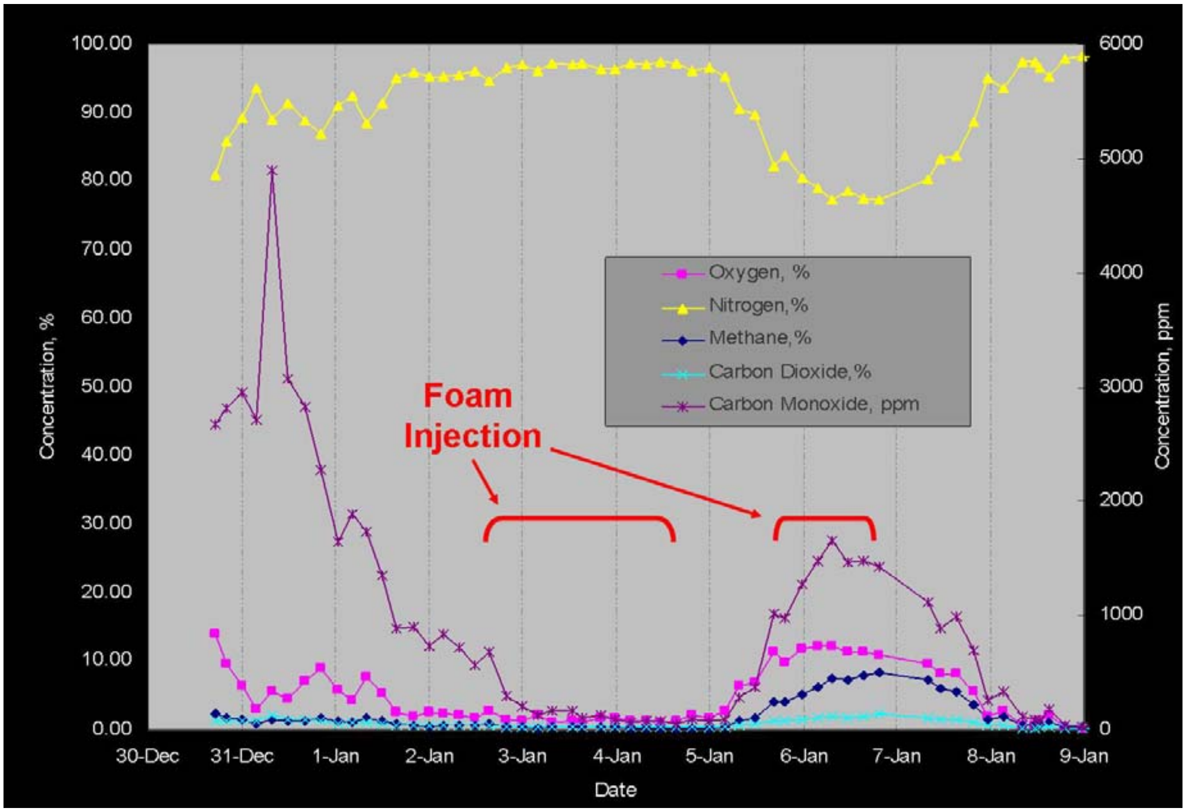

Figure 17. Mine atmosphere monitoring data for borehole V6.

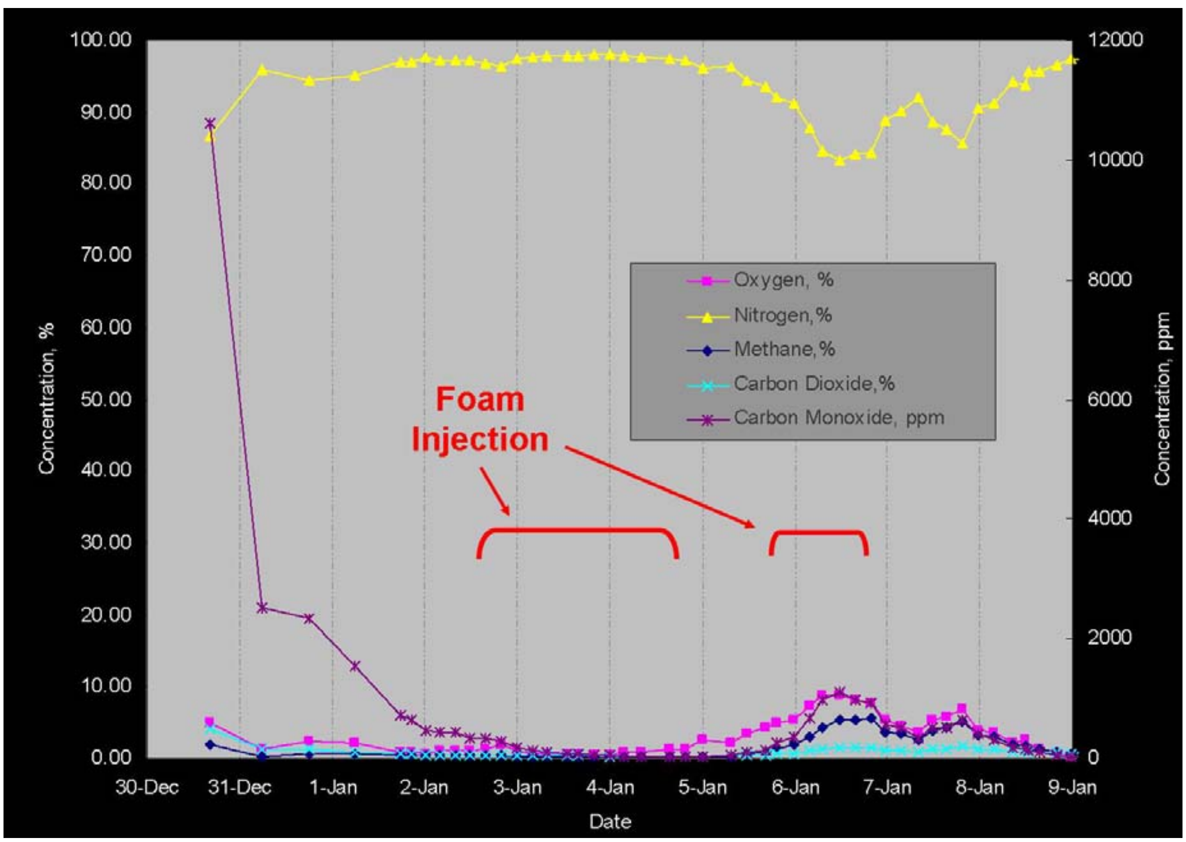

Figure 18. Mine atmosphere monitoring data for borehole V8.

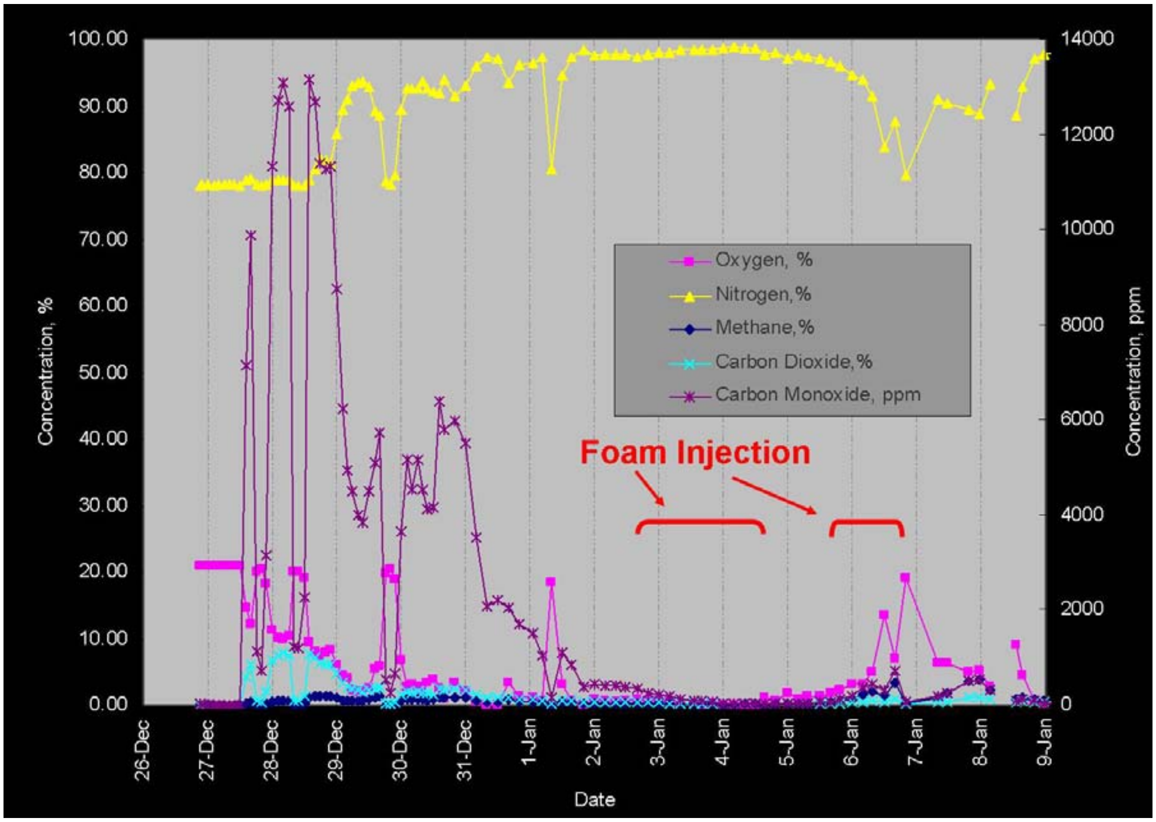

Figure 19. Mine atmosphere monitoring data for the A-Intake Shaft.

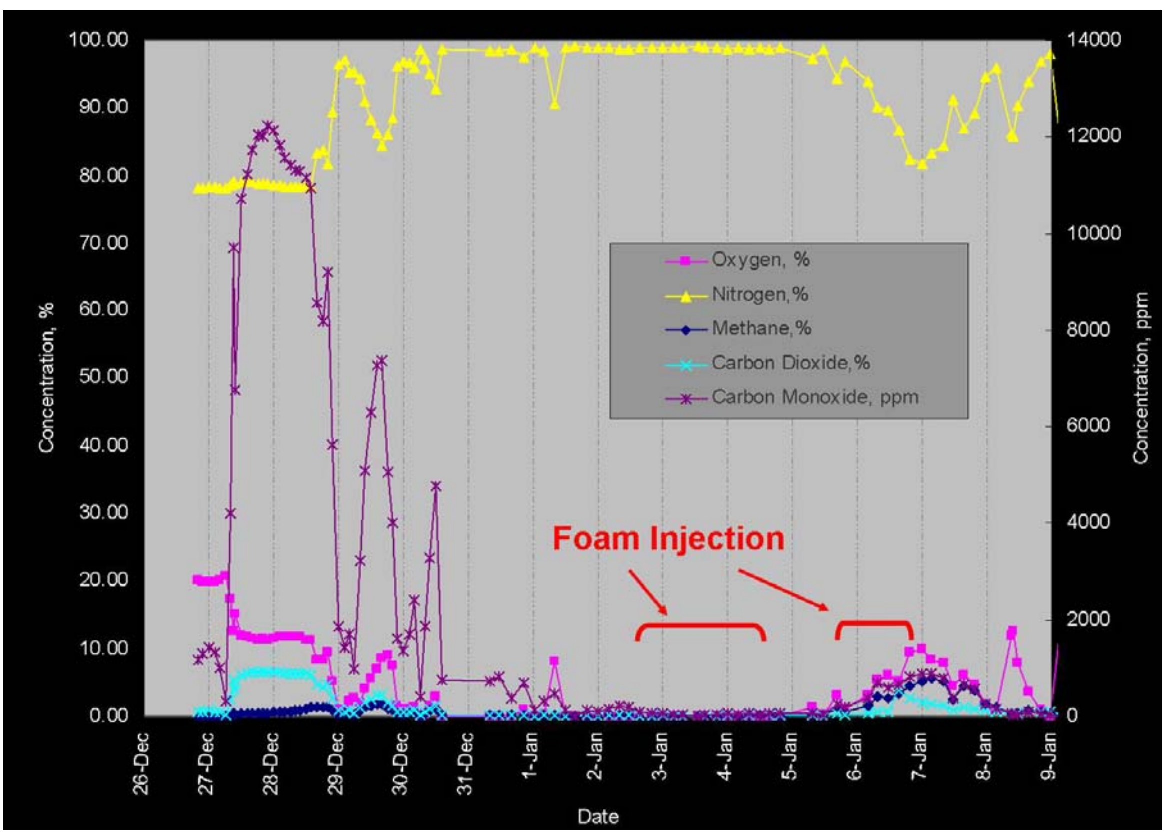

Figure 20. Mine atmosphere monitoring data for the Slope.

From the monitoring data, it appears that shaft and slope sealing operation and the injection of liquid nitrogen had a positive effect on the fire as the values for carbon monoxide concentration declined dramatically and the concentration of nitrogen increased well above normal levels (approximately 78%). It should be noted that the large variations in carbon monoxide and carbon dioxide concentrations observed in the early stages of monitoring the mine atmosphere are due to air contamination in the gas samples. In all likelihood the carbon monoxide levels in the mine stayed at high levels as shown in the data from the Slope (figure 20) until liquid nitrogen was injected into the mine void. On December 31, 2004, liquid nitrogen injection was initiated at borehole V9 and nitrogen levels at the observation boreholes continued to increase and the concentration of all other gases decreased.

On January 5, 2005, the concentration of nitrogen gas in the mine atmosphere began to decrease with a concomitant increase in the concentration of all other gases. This condition continued and a peak was observed late on January 6, 2005. The reason behind this change can be attributed to the following factors.

- There was a decrease in barometric pressure (see figure 21). It is a known phenomenon that a mine will outgas during periods of lower barometric pressure and an increase in the concentration of methane, carbon dioxide, etc along with a decrease in nitrogen gas concentration is commonly observed.
- Delivery of nitrogen to the mine site (and hence injection into the mine void) was not regular and there was a lull in the delivery schedule (note the change in the cumulative volume curves for the Slope and borehole V9 in figures 7-9).
- Injection of nitrogen gas was terminated at borehole V1 in the late morning of January 6, 2005 and injection of carbon dioxide was attempted in the early afternoon. Unfortunately, the borehole was lost due to a downhole accumulation of ice. The borehole was rendered unusable for the duration of the mine fire suppression work.
- Injection of nitrogen-generated foam at boreholes V2 and V4 was interrupted beginning early on January 4, 2005 and continued until the evening of January 5, 2005. It should be noted that when the Hellfighter™ system was not being used, nitrogen gas from the membrane plants was diverted and was injected into boreholes V11 and V13.
- Nitrogen gas injection at the Slope was terminated late in the afternoon on January 5, 2005.
- It is possible that the mine fire was not completely extinguished or a "hot-spot" existed and began to flare-up given the changing mine atmosphere conditions.

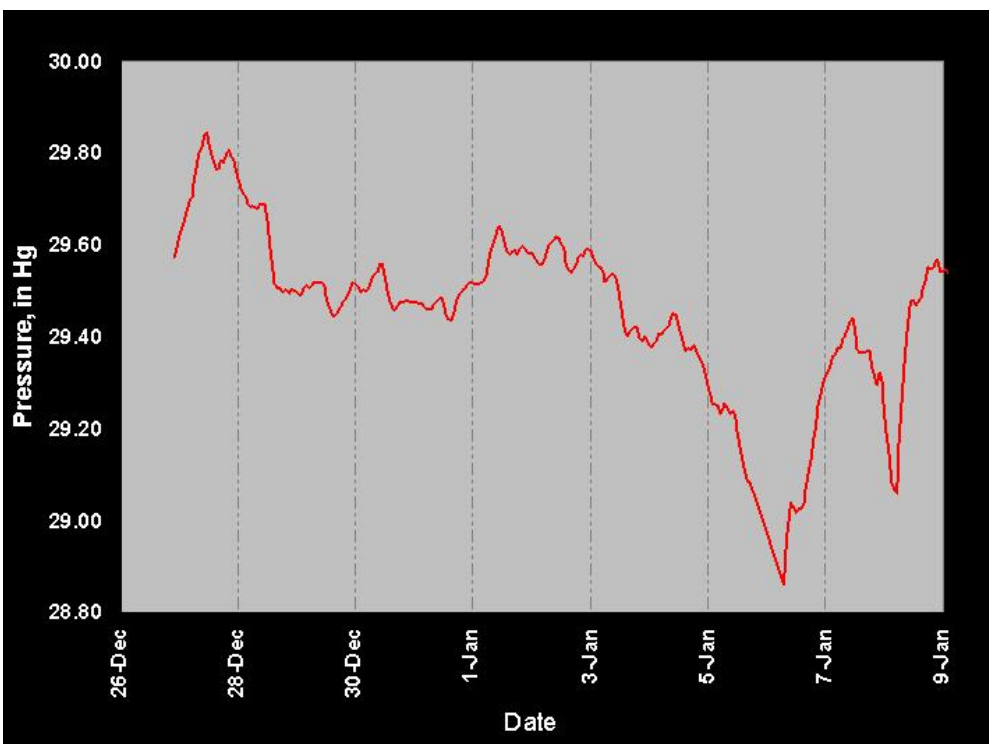

Figure 21. Plot of barometric pressure during the time of the mine fire.

The decision to reenter the mine and begin recovery efforts on the morning of January 8, 2005 was based upon the ability to maintain an inert atmosphere, thereby removing the risk of an explosion or expansion of the fire. Throughout the recovery efforts the mine atmosphere continued to be monitored and nitrogen continued to be injected into the mine to maintain an inert atmosphere in and around the fire area. Ventilation of the mine could not be reestablished until the fire area was completely separated from the rest of the mine atmosphere by permanent barriers. In effect, suppression of the fire amounted to controlling the mine atmosphere and this effort continued throughout the mine recovery phase. By February 21, 2005, mining operations were restarted (10).

SUMMARY AND CONCLUSIONS

Late on December 25, 2004, a fire, of unknown origin, was discovered near the bottom of the slope area at the mine. After detecting the fire, the mine operator took immediate actions to fight and control the fire but was unsuccessful. On December 26, 2004, it was deemed that conditions in the mine were too dangerous to directly suppress the fire and the mine was evacuated. The mine operator immediately began working with MSHA and OMSL officials to develop a plan to seal the mine and fight the fire remotely using nitrogen gas and nitrogen gas-enhanced foam. By the afternoon of December 26, 2004, temporary seals had been installed on the slope and the three shafts at the mine to limit the inflow of oxygen to the fire zone. A short time later, the B-Return shaft was permanently sealed when it was discovered that it was leaking air. Several monitoring stations (using boreholes and the existing shafts and slope) were set-up around the fire zone measure the changing conditions in the mine. On December 28, 2004, injection of liquid nitrogen was initiated at the Slope, the A-Intake shaft and in two nearby boreholes. An analysis of the gas monitoring data indicates that the sealing of the mine and the injection of nitrogen served to control the spread and growth of the fire.

On January 2, 2005, the injection of nitrogen gas-enhanced foam began at two holes thought to be very close to the fire area. The injection of gas-enhanced foam continued on an intermittent basis due to the periodic failure of the mine's water system. When the water system was down, it was not possible to produce foam, so nitrogen gas from the membrane plant was injected directly into the boreholes. When the gas-enhanced foam system was operating, it served to supplement the liquid nitrogen injection activities.

On January 4, 2005, the mine operator requested a temporary halt in gas-enhanced foam injection and the gas produced by the membrane plant was diverted to boreholes located near the B-Return Shaft. The mine operator requested the halt to evaluate the mine fire conditions and to conduct video surveys of the mine void. On January 5, 2005, the concentration of nitrogen gas in the mine atmosphere began to decrease with a concomitant increase in the concentration of all other gases. The reasons for the increase can be attributed to one or all of the following: a decrease in barometric pressure, a lull in the delivery of liquid nitrogen, halt of gas-enhanced foam injection, loss of injection borehole V1, and termination of liquid nitrogen at the Slope. When the results of the changing conditions in the mine atmosphere were observed, gas-enhanced foam injection work was immediately resumed along with a more regularized delivery schedule of liquid nitrogen through the creation of a waiting queue on the mine site. Nitrogen gas concentration decreased to the lowest level (and the increase in all other gases were at the highest levels) on January 6, 2005. The nitrogen gas concentration increased significantly after that time when injection of inert gas and foam resumed. On January 7, 2005, the mine fire was deemed successfully suppressed and work focused on reentry and safe ventilation of the mine workings. The Excel No. 3 Mine was reentered the morning of January 8, 2005 and permanent underground seals were installed to completely contain and isolate the area of the mine affected by the fire. The decision to reenter the mine and begin recovery efforts on the morning of January 8, 2005 was based upon the ability to maintain an inert atmosphere, thereby removing the risk of an explosion or expansion of the fire. Throughout the recovery efforts the mine atmosphere continued to be monitored and nitrogen continued to be injected into the mine to maintain an inert atmosphere in and around the fire area. Ventilation of the mine could not be reestablished until the fire area was completely separated from the rest of the mine atmosphere by permanent barriers. In effect, suppression of the fire amounted to controlling the mine atmosphere and this effort continued throughout the mine recovery phase. By February 21, 2005, mining operations were restarted.

In conclusion, all of the components used to remotely fight the fire at the Excel No. 3 Mine played significant roles. The quick action of the mine operator to seal the shaft and slope areas served to preclude the further inflow of oxygen to feed the fire. Injection of liquid nitrogen undoubtedly helped control and reduce the growth of the fire. Finally, the injection of gas-enhanced foam added to the suppression of the mine fire and provided the mine operator with the flexibility of injecting nitrogen gas at borehole sites that could not accessed by the liquid nitrogen tanker trucks.

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