# THE USE OF NITROGEN-ENHANCED FOAM AT THE PINNACLE MINE FIRE

***By***

**A. C. Smith[1], T. P. Mucho[2], M. A. Trevits[1], and M. Cummins[3]**

*[1]National Institute for Occupational Safety and Health*
*Pittsburgh, PA*

*[2]Thomas P. Mucho & Associates, Inc.*
*Washington, PA*

*[3]Cummins Industries, Inc.*
*Burleson, TX*

# THE USE OF NITROGEN-ENHANCED FOAM AT THE PINNACLE MINE FIRE

**A. C. Smith[1], T. P. Mucho[2], M. A. Trevits[1], and M. Cummins[3]**

*[1]National Institute for Occupational Safety and Health*
*Pittsburgh, PA*

*[2]Thomas P. Mucho & Associates, Inc.*
*Washington, PA*

*[3]Cummins Industries, Inc.*
*Burleson, TX*

**ABSTRACT**

This paper evaluates the effectiveness of remotely applied nitrogen-enhanced foam to aid in efforts to isolate and suppress a mine fire. The foam, in combination with a remotely-installed cementitious mine seal and a novel borehole pressure sampling methodology to determine the location of the suspected ignition source, was used to help control ventilation and inert the area surrounding the suspected ignition source by isolating it from oxygen. This allowed mine rescue teams to safely enter the mine, seal the area, and begin recovery operations to successfully return the mine to full production.

## INTRODUCTION

The Pinnacle Mine fire suppression and recovery efforts demonstrated the use of several innovative technologies to isolate, control, and extinguish mine fires. It is believed that the methods used to monitor the pressure at boreholes near the fire area to determine the location of the source of the fire resulted in the first real-time capturing of mine explosion data. This data was used to determine the most probable location of the fire so that suppression efforts could be directed to that area. The GAG[1] jet engine was used to lower oxygen concentrations in the mine. This particular application was a much larger test of the engine's abilities than previously demonstrated which introduced several new variables into its operational viability. The use of remotely-installed cementitious seals, successfully used at the West Elk (CO) mine fire to isolate the fire area, also presented new operational variables. At the Pinnacle Mine, located near Pineville, WV, the process had to be modified to create a much faster material set-up time. Finally, nitrogen-enhanced high expansion foam was remotely injected into the fire area from the surface, and was used not only as a suppression agent, but was also used to create a gas barrier along the tailgate of the panel to control ventilation so that inerting efforts could be confined to the active gob. This fire presented new conditions and parameters to the successful use of each of these technologies, and the technologies are evolving as they are applied to each new challenge. Researchers at the National Institute for Occupational Safety and Health (NIOSH) are partnering with the users of these technologies and analyzing the results from these events to aid in their development and application to improve the health and safety of miners, fire fighters, and mine rescue and recovery teams.

This paper focuses on the use of the nitrogen-enhanced fire-fighting foam to aid in the suppression of the fire and the isolation of the fire area. The state of the mine fire prior to the foam injection as indicated by gas samples taken through boreholes located in the longwall district will be described. The effectiveness of the foam to isolate the fire area will be evaluated based on gas readings in and around the active panel where the location of the fire was believed to be located, after foam injection into the mine.

---

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

## OVERVIEW OF MINE FIRE AND USE OF GAG ENGINE

Between August 31 and September 7, 2003, a series of explosions occurred in the active longwall district of the Pinnacle Mine, located near Pineville, WV. A schematic of the mine is shown in figure 1. Carbon monoxide readings in the bleeder entries of the active longwall district indicated that there was a small but active fire at an unknown location. The operator began drilling holes into the longwall gateroads to detect the heat source. The company decided to use the Phoenix First Response GAG jet engine in an attempt to inert the longwall district and extinguish the fire.

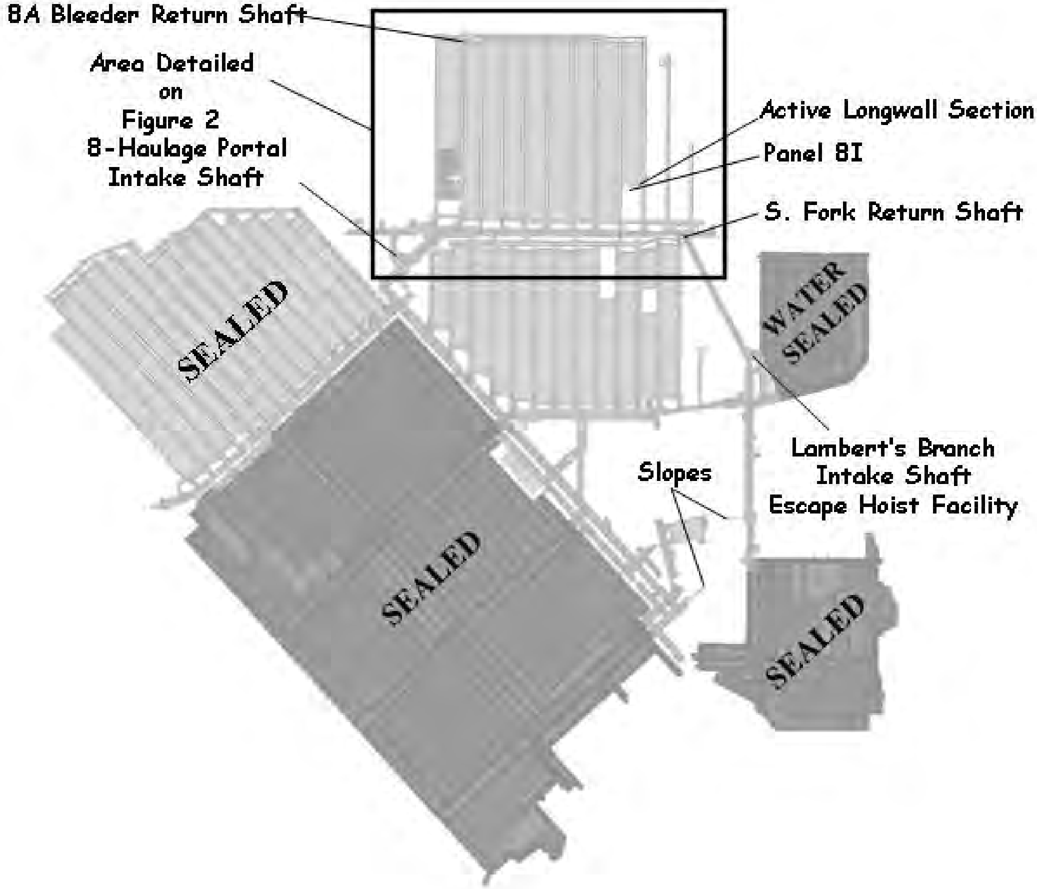


**Figure 1. Schematic of the Pinnacle Mine.**

Figure 2 shows the oxygen, carbon monoxide, methane, and hydrogen concentrations at various locations in the longwall district on September 30, 2003, just prior to the start-up of the GAG engine. In general, the oxygen concentrations were near ambient in the gateroad entries, with the exception of the location inby the tailgate entry, where concentrations as low as 12 pct were indicated. Oxygen concentrations in the caved areas ranged from 9.3 immediately behind the active face near the tailgate, to 17.3 pct in panel G. Carbon monoxide concentrations were generally low in gateroads and bleeder entries, with the highest readings observed inby the tailgate entry. Hydrogen concentrations were elevated inby the tailgate entry and caved area surrounding the tailgate entry, ranging from 0 to 89 ppm. Finally, the methane concentrations were unremarkable, being highest in the caved areas and low in the gateroads and bleeder entries.

The GAG engine was installed on the longwall district's bleeder fan, located at the back end of panel B, to push inert gas across the gob area. The GAG engine is based on a Soviet designed agricultural jet engine which consumes oxygen and aviation fuel and exhausts combustion gases, primarily carbon dioxide and water. Depending on the stoichiometry of the fuel/air mixture, traces of carbon monoxide and hydrogen can be generated. Injection of

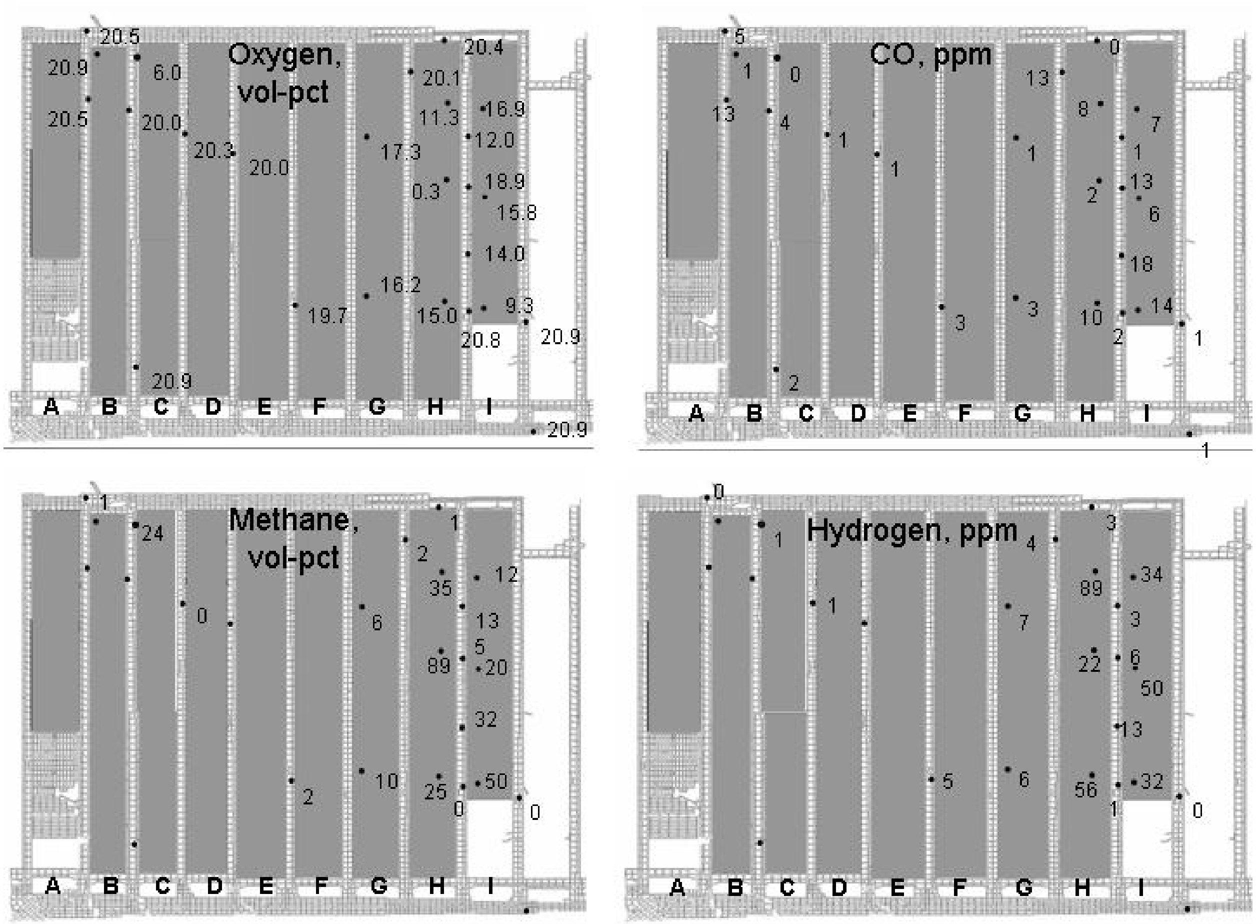


**Figure 2. Gas concentrations at various locations in longwall district 8 on September 30, 2003.**

**Figure 3. GAG engine installation.**

engine gases was started on October 1. A photograph of the GAG engine installation is shown in figure 3. By October 6, the inert gases from the GAG engine appeared to be approaching the area behind the active longwall face. Figure 4 shows the oxygen, hydrogen, and carbon monoxide concentrations on October 6. Oxygen concentrations were observed to be dropping, while hydrogen and carbon monoxide concentrations, which are by-products of the engine, increased. At the bleeder fan shaft, the oxygen concentration was 2.1 pct, the carbon monoxide concentration was over 5000 ppm, and the hydrogen concentration was over 4000 ppm. The concentrations of these gases in the bleeder entry at the top of the H panel were 3.8 pct and 4185 and 3465 ppm, respectively, indicating that the engine gases had filled the bleeder entries. The engine gases appeared to be moving through the tailgate entry between panel H and panel I, but had clearly not reached the area directly inby the tailgate, where the oxygen concentration was 19.8 pct, the carbon monoxide concentration was 20 ppm, and the hydrogen concentration was 6 ppm. The gases appeared to be infiltrating panel I, as evidenced by the increased hydrogen concentrations at the two locations in the caved area near the top of the panel.

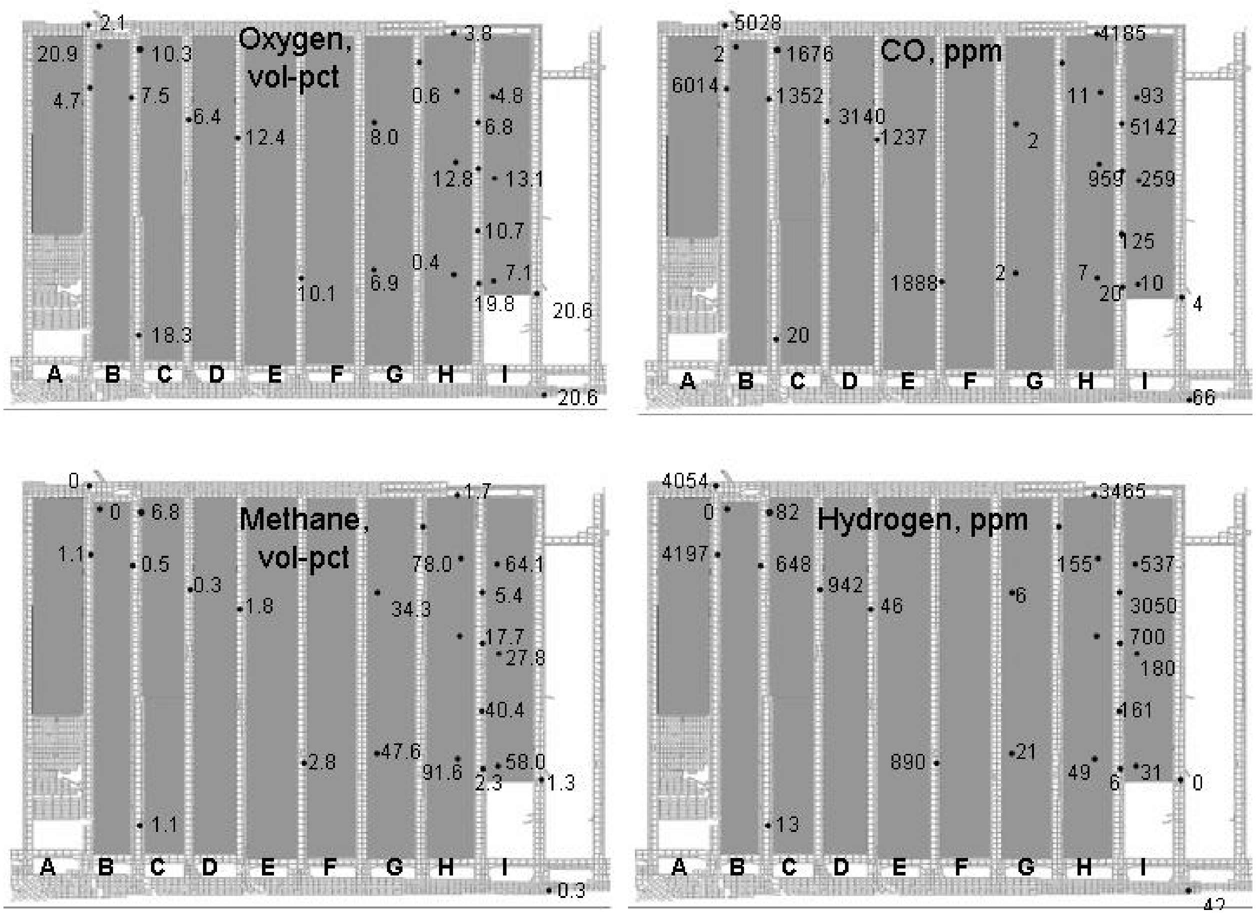


**Figure 4. Gas concentrations at various locations in longwall district 8 on October 6, 2003.**

Prior to the GAG engine start-up, NIOSH was asked to provide technical assistance in locating the fire source. It was hypothesized that as the inert gas from the GAG engine pushed through the gob, there was a possibility that explosive mixtures of methane and oxygen could be pushed through the fire zone, causing an explosion. NIOSH developed and implemented a plan to instrument five boreholes near the active longwall panel with sensitive pressure monitoring devices that could detect an explosion if it occurred and be used to determine the point source of the explosion using triangulation techniques. A pressure sensor borehole installation is seen in figure 5. On October 8, these pressure sensors measured pressure increases attributed to a possible gas ignition or explosion. It is believed that, this was the first real-time capturing of mine explosion data during an actual mine fire. The determination of the location of this event was much more difficult than envisioned because it appeared that the pathway to the nearest boreholes may have been mostly or entirely through the gob itself. This introduced several unknown variables into the calculations due to the lack of data on the travel of pressure waves through gobs. The data was analyzed using three empirical methods based on 1) the arrival times of peak pressures, 2) the magnitude of the peak pressures, and 3) the difference of arrival time between peak one and two at each location. All three methods showed the most probable location of the source of the explosion to be in caved area of the active longwall panel, just inby the face. The results of these analyses are shown in figure 6.

**Figure 5. A pressure sensor mounted on top of borehole. Polyurethane foam was used to seal the borehole.**

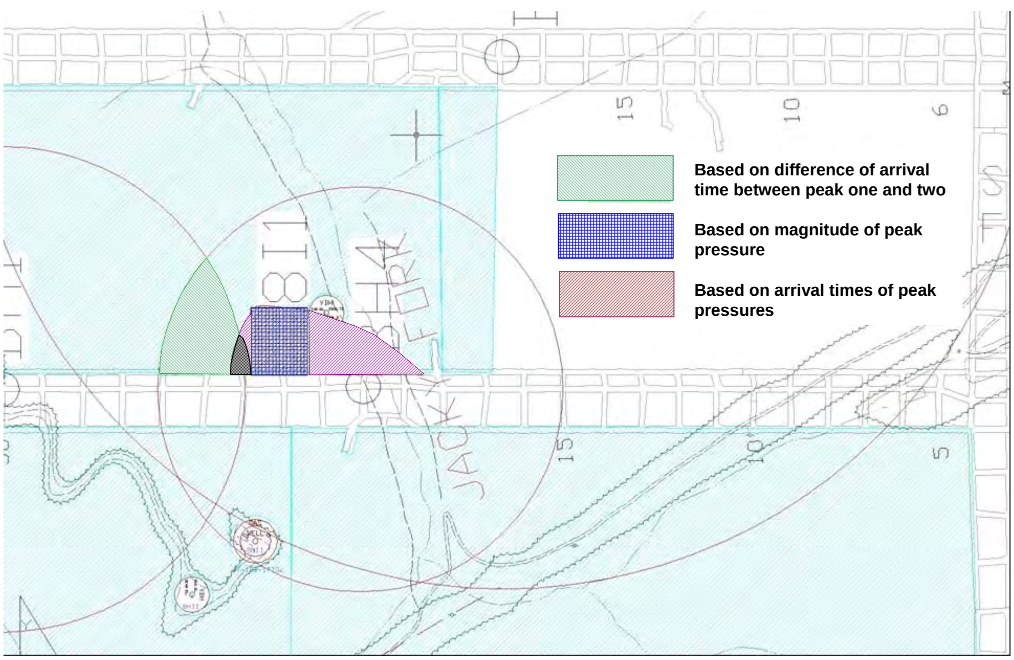


**Figure 6. Probability spaces of ignition source on October 7, 2003, based on three triangulation methods.**

On October 14, a second pressure excursion was detected by the pressure sensors. This event was a much slower and longer lasting event. To determine the source of this event, a fourth method was used based on the arrival time of the leading edge of the pressure wave. This method is similar to the first method, used previously, based on the arrival time of the pressure peak. However, because of the slower nature of this event, it is believed that the leading edge approach is more related to the location of the initiation of the event. We believe that the peak approach relates more to the center of the event. The results of these analyses are shown in figure 7. Again, it appeared that the location of the source of the event was in the caved area of the active panel, and that the pathway to the nearest boreholes was mostly or entirely through the gob itself. The GAG engine ran until October 19 in an attempt to maintain inert gases in the area behind the active longwall panel. On October 19, ventilation was re-established in parts of the mine and the monitoring of fire gases continued.

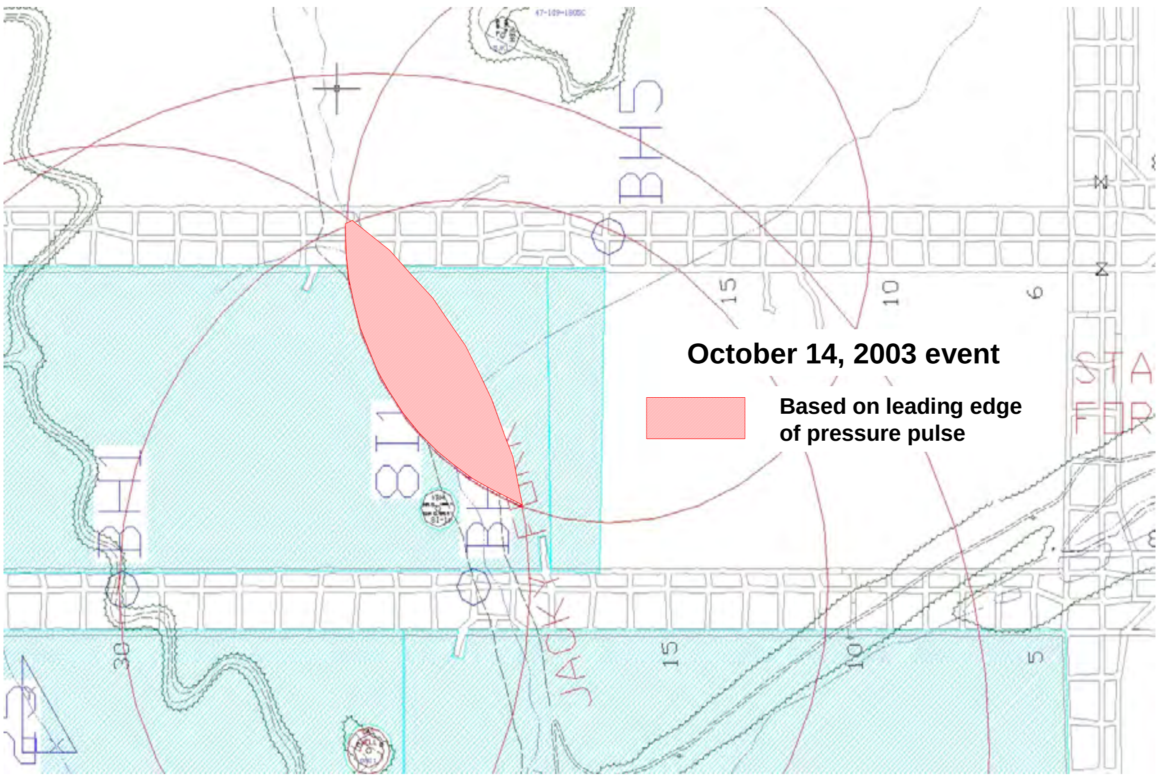


**Figure 7. Probability space of location of ignition source on October 14, 2003 based on leading edge triangulation method.**

The mine operators continued to ventilate the longwall district into January 2004. Gas sampling data on the state of the fire was inconclusive because of the continued presence of hydrogen and carbon monoxide in samples near the active longwall panel, since these gases are byproducts of both the GAG engine and an active coal fire. In early January, all fans and gob vent boreholes were shut down in an attempt to determine if a fire or heating was on-going. Low levels of CO were measured, supporting the possibility that a fire still existed.

## Localized Inerting Plan

Based on gas sampling data and the pressure monitoring data from the October events, which indicated that a possible fire or ignition source still existed in panel I, a localized inerting plan was designed to isolate panel I. This would be accomplished by placing a remotely-installed cementitious seal in the tailgate entry inby the longwall face and injecting nitrogen-enhanced foam through a borehole directly inby the remote seal. It was hypothesized that the dip of the mine away from the seal would allow the foam to flow into and fill the tailgate entries between panels H and I. At the same time, nitrogen gas was to be injected into other boreholes in the tailgate entries inby the longwall face. The nitrogen-enhanced foam would be used to create an inert gas barrier along the tailgate of the panel so that inerting efforts could be confined to the active gob. Figure 8 shows the oxygen, carbon monoxide, hydrogen, and methane concentrations in panels H and I on January 26, 2004, just prior to the implementation of the inerting plan. It appeared that most remaining gateroad entries were being well ventilated, with oxygen concentrations near ambient levels, and little carbon monoxide, hydrogen, and methane. The back end of the tailgate entry of Panel I showed decreased oxygen concentrations and elevated levels of hydrogen and methane. Samples from the caved areas in panel I also showed decrease oxygen levels and high hydrogen and methane concentrations.

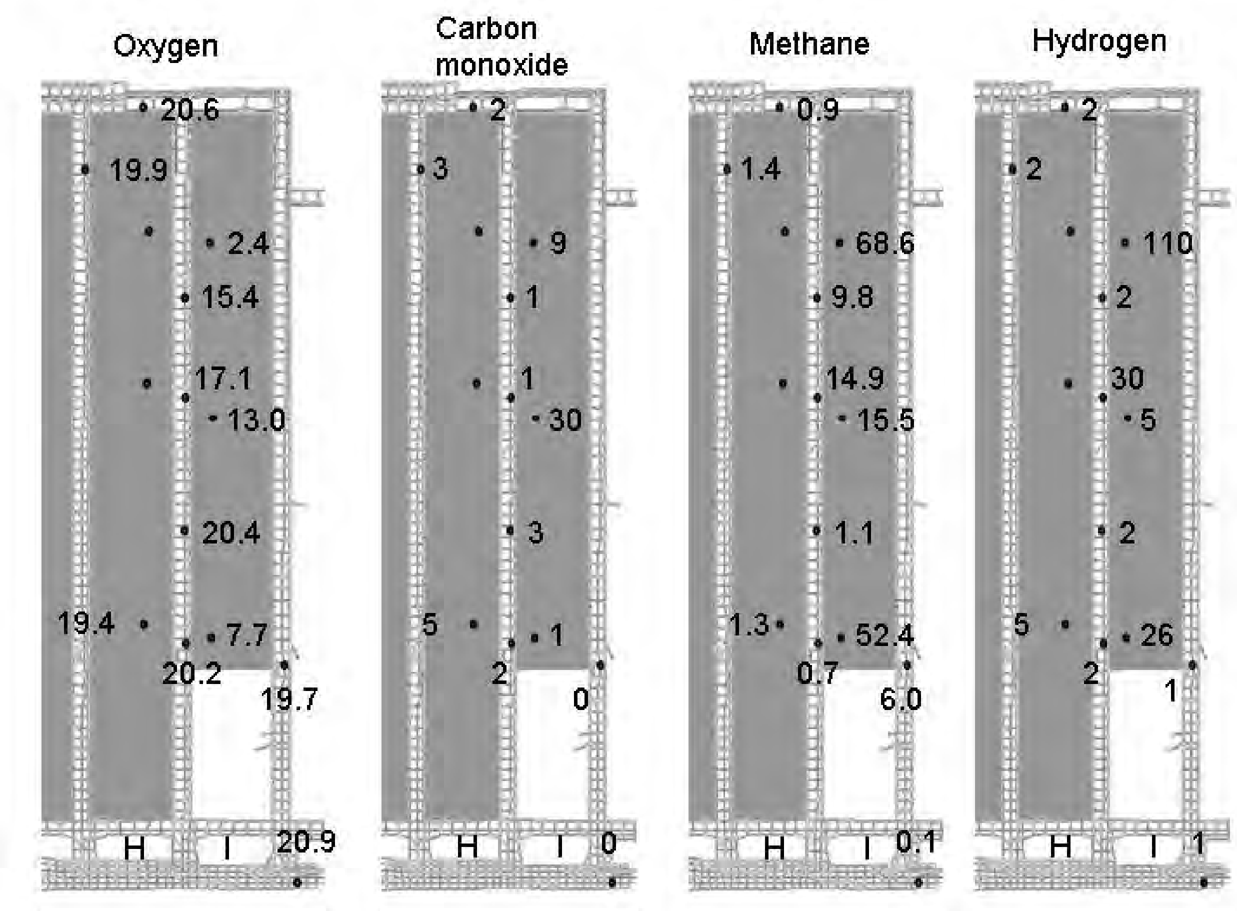


**Figure 8. Gas concentrations for panels 8H and 8I on January 26, 2004.**

## REMOTE SEAL INSTALLATION

On January 30, 2004, a borehole was completed to the coal seam and cased to the surface with 5-in pipe for injection of the mine seal material. Figure 9 shows a photo of some of the equipment used to deploy the remote seal. A video inspection of the mine seal borehole from an observation borehole located about 30 ft away showed that the hole was located in the approximate center of the mine void and that the casing was placed about 12 in into the mine opening. The video camera probe is shown in figure 10. A length of 2-3/8-in-diam tubing with a jet mixing tool on the end was then placed into the mine seal borehole. The tubing and mixing tool extended down into the casing and was hung about 1 ft above the bottom of the casing to form a downhole mixing chamber. The mine seal design called for the injection of a two-part mixture of materials. The first part of the mixture consisted of a 50 pct cement/50 pct fly ash (by volume) mixture blended to a density of 15.3 lb/gal. This mixture was designed to be pumped through the annular space between the tubing and the borehole casing. The second part of the mixture design involved the injection of an activator (an accelerator composed of an epoxy-resin compound) through the tubing string of pipe. The activator fluid would then exit the bottom of the tubing through a jet nozzle that sprays the fluid into the cement slurry. The two components are then mixed at the bottom of the casing in the mixing chamber and the blended mix is pumped into the mine opening to form the seal. The pumping strategy assumed that the blended mix would flow into the mine opening at a putty-like consistency. It was thought that the seal material would be pumped into the mine opening at such a high rate that the material would form a mound with a depression in the middle. As pumping continued, the mound would grow outward toward the rib areas of the mine void. The ridges of the mound would then extend to the mine roof and would ultimately facilitate mine roof-to-floor closure. Pumping was terminated when all of the seal material on site has been placed into the borehole. In all, about 128 $yd^3$ of material was pumped into the mine void.

**Figure 9. Surface operation for remote seal deployment.**

**Figure 10. Remote video camera probe inserted into borehole near remote seal installation.**

Video scans made from the observation borehole 30 ft away showed that seal material had flowed to the observation borehole and had filled to the mine roof. Voids in the seal material were observed along the rib areas near the observation borehole. It was impossible to view the condition of the mine seal near the injection borehole because the seal material near the observation borehole obscured the camera. Based on injection pressure readings during installation, and mine pressure readings across the seal, it appeared that the seal did not form a full seal. Additional seal material was pumped into the seal injection borehole the next day and it appeared that the mine void around the seal had been closed off based on operational parameters of the seal installation. Attempts to view and inspect the remote seal directly when mine rescue teams entered the mine were not possible because of a large roof fall outby the seal.

## NITROGEN-FOAM INJECTION

On January 29, 2004, nitrogen-enhanced foam injection began in the tailgate entry at a borehole located approximately 1200 ft inby the proposed remote seal location. The borehole installation is shown in figure 11. The remote seal was installed on January 30. Upon completion of the seal, the nitrogen-enhanced foam was also injected into a borehole just inby the seal. The foam was batch mixed at 1 or 2 pct in four 21,000 gallon frac tanks and pumped into the mine using a 750 cubic feet per minute nitrogen membrane separation plant, shown in figure 12.


**Figure 11. Borehole installation for nitrogen-enhanced foam injection.**

**Figure 12. Nitrogen membrane separation plant.**

The foam was pumped at an average rate of about 1,500 gallons per minute for nine days, ending on February 7. In total, about 18 million gallons of foam was pumped into the mine. Initially, the foam stability was about 3 hours, which it was believed would allow the foaming agent to penetrate into the caved area to possibly suppress the fire source. A polymer was then added to the foam mixture to increase its stability. Surface tests indicated that this increased the stability of the foam to about 8 hours.

To evaluate the effectiveness of the foam to fill the entry and create a barrier to gas movement, gas sampling data from four boreholes located in the tailgate entry inby the longwall face were analyzed. Plots of the oxygen, nitrogen, and methane concentrations at these locations are shown in figures 13-16. Figure 13 shows the gas concentrations from Jan 14 to February 7 at a borehole just inby the location of the remotely-installed seal. Prior to foam injection, the oxygen concentration was steady at about 20.4 pct, the nitrogen was at 78 pct, and the methane was approximately 1 pct. Foam injection started on January 29 and the seal was installed on January 30. Gas samples after the foam injection indicate that the oxygen level dropped to about 6 pct, while the nitrogen concentration increased to about 93 pct. However, there were many fluctuations in the gas samples over the next 8 days indicating that the seal installation did not totally seal the entry. The increase in methane and decrease in oxygen after February 6 indicates that the location was isolated from the mine air at that point and the gas levels were a reflection of gases from the caved area migrating to this sampling location.

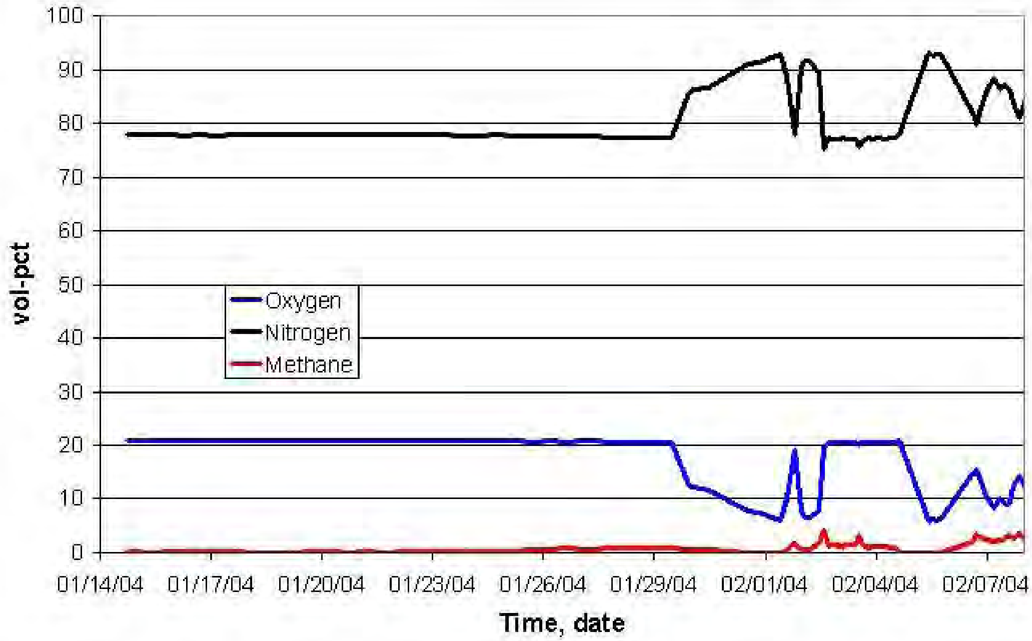


**Figure 13. Gas concentrations from Jan 14 to February 7 at a borehole just inby the location of the remotely-installed seal.**

Figure 14 shows the gas data for the foam injection location, approximately 1200 feet inby the remote seal. The decrease in nitrogen and oxygen and increase in methane on January 29 indicates that initially this location was isolated from the main mine air and was affected by gases from the caved area. After February 1, the oxygen and methane levels fell and the nitrogen level increased to 94 pct, indicating that this location was probably filled with foam, isolating it from the mine air and the caved area.

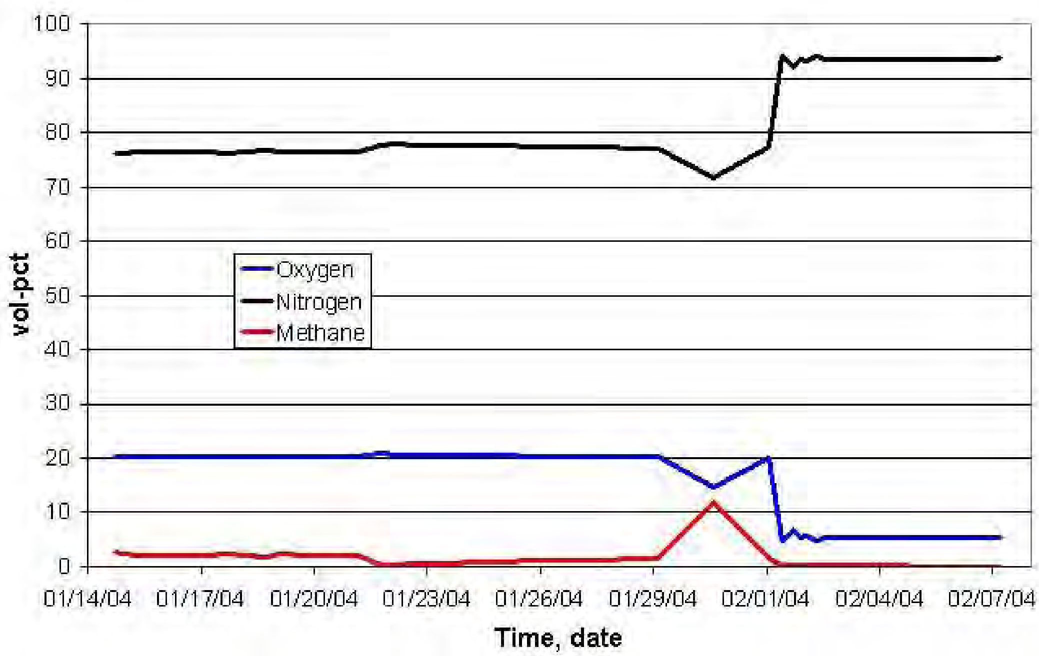


**Figure 14. Gas concentrations for the foam injection location, approximately 1200 feet inby the remote seal.**

Figure 15 shows the gas data from a borehole located about 1000 feet inby the foam injection hole and about 2200 feet inby the remote seal. Prior to the foam injection, the oxygen concentration was fairly stable at about 17 pct, the nitrogen concentration was about 67 pct, and the methane concentration was about 16 pct. This indicates that the location was being influenced mostly by mine air, with some effect from the methane emissions from the caved area. There is some evidence based on data, not shown, that this hole was drilled into a rib near the tailgate entry, further muddling the interpretation of data from this hole. After the foam injection, the methane fell to about 1 pct for about 4 days before rising back to its previous level. On February 7, it fell again along with the oxygen concentration, while the nitrogen concentration increased to about 85 pct. This indicates that initially, the foam had an effect on the location to isolate it temporarily from the caved area gases but not from the mine air. On February 7, it appears that the location experienced the effect of the nitrogen from the foam. It is possible that the foam plug reached this location at this time.

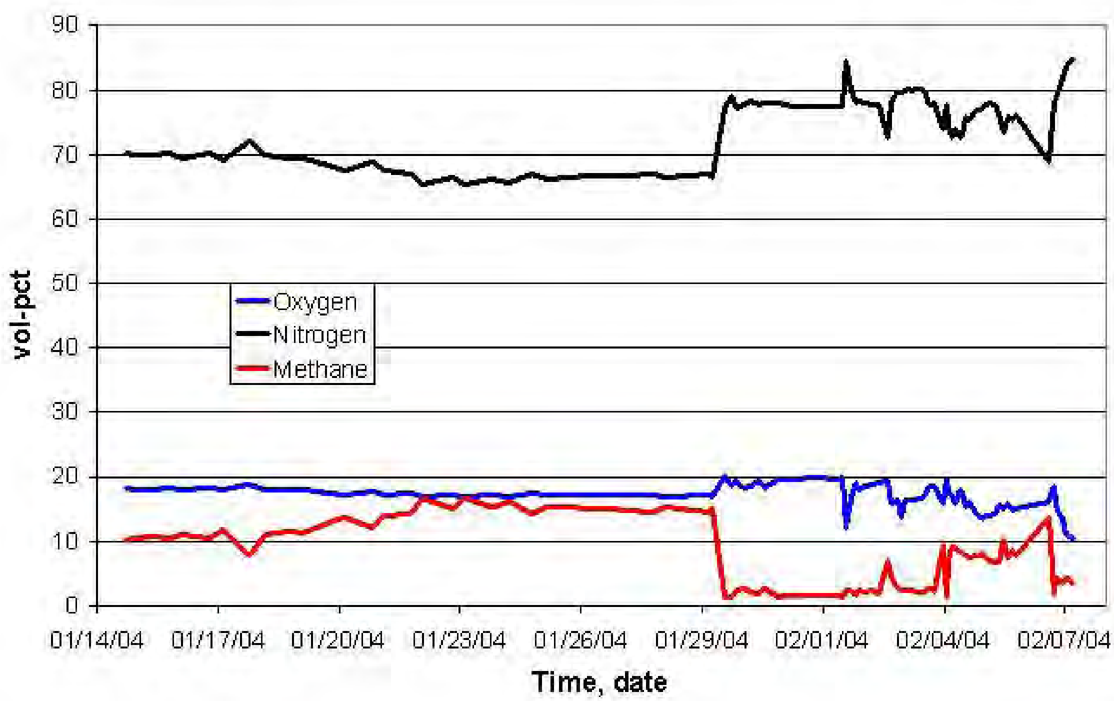


**Figure 15. Gas concentrations from borehole located about 1000 feet inby the foam injection hole and about 2200 feet inby the remote seal.**

Gas data from a borehole located approximately 2000 feet inby the foam injection hole and about 3200 inby the remote seal is shown in figure 16. Prior to the remote seal installation and foam injection, the data indicates that this location was being influenced mostly by gas from the caved area, based on the low oxygen and nitrogen concentrations and high methane levels. Ambient air contains about 21 pct oxygen and 78 pct nitrogen. After the foam injection, the nitrogen concentration increased, but so did the oxygen concentration, indicating that the location was now isolated from the caved area, but at the same time a pathway to mine air had opened. It is possible that since this location is down dip and relatively far away from the foam injection point, that the foam had plugged the entry at some point down dip from this location and stopped moving up dip. At this distance from the longwall face, the entry would be expected to be nearly closed. At the same time, runoff water from the foam degradation may have cleared small pathways for air movement between this location and the bleeder entries. Looking at the data from the three holes together, it appears that the foam probably plugged the entry near the injection hole, and the combination of the foam and the remotely-installed seal restricted air movement to a good degree at the seal, as evidenced by the decrease in oxygen concentration to about 6 pct at that location.

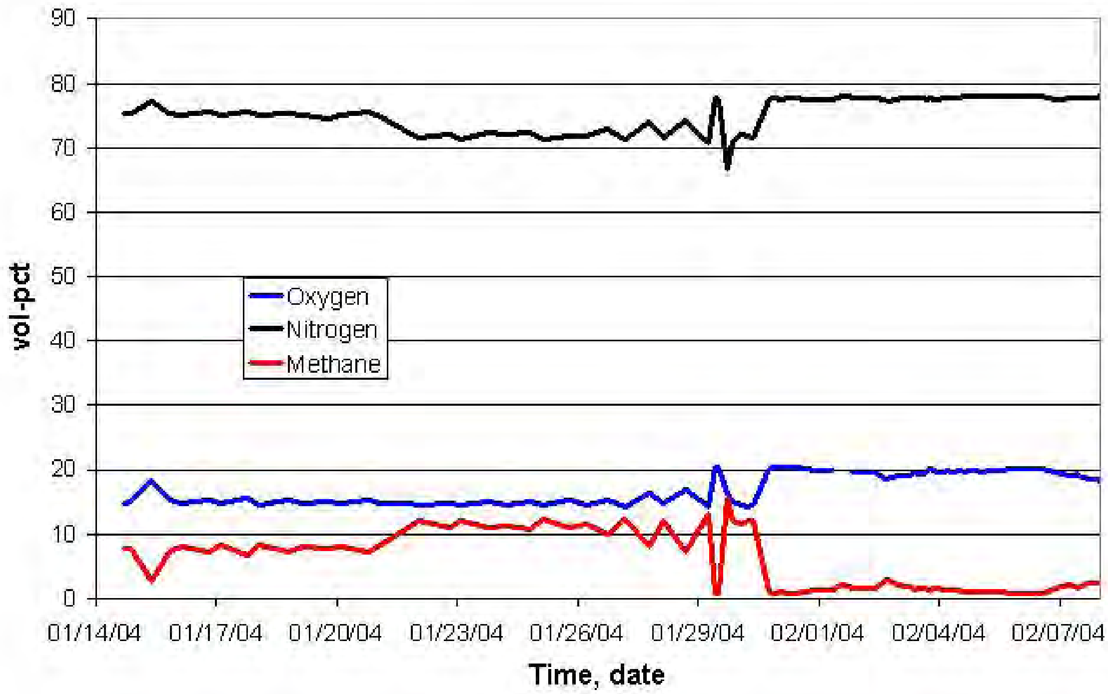


**Figure 16. Gas concentrations from borehole located approximately 2000 feet inby the foam injection hole and about 3200 inby the remote seal.**

The real effectiveness of the seal and foam injection to isolate the suspected fire area from the main mine air to suppress the fire can be seen by analyzing the data from two sampling locations in the caved area nearest the tailgate entry. Figure 17 shows the gas concentrations at a location behind the longwall face near the tailgate entries approximately the same distance inby the face as the first borehole, shown in figure 13. The second location, seen in figure 18, is also in the caved area near the tailgate entries, about 1000 feet inby the previously mentioned sampling hole. Prior to the remote seal installation and foam injection, these locations were being influenced by the mine air migrating from the tailgate entries. The oxygen concentration at the location shown in figure 17 fluctuates around 10 pct, while the nitrogen concentration is between 40 and 60 pct. The methane concentration fluctuated between 20 and 60 pct. These values indicate that the location was seeing mine air that was being diluted by methane emissions in the caved area. The other location, shown in figure 18, appears to be mostly mine air, with a huge increase in methane on January 28. This indicates that the location probably has a substantial pathway to the tailgate entry and is consequently made up of mine air, but is very near the boundary of caved area gas zone.

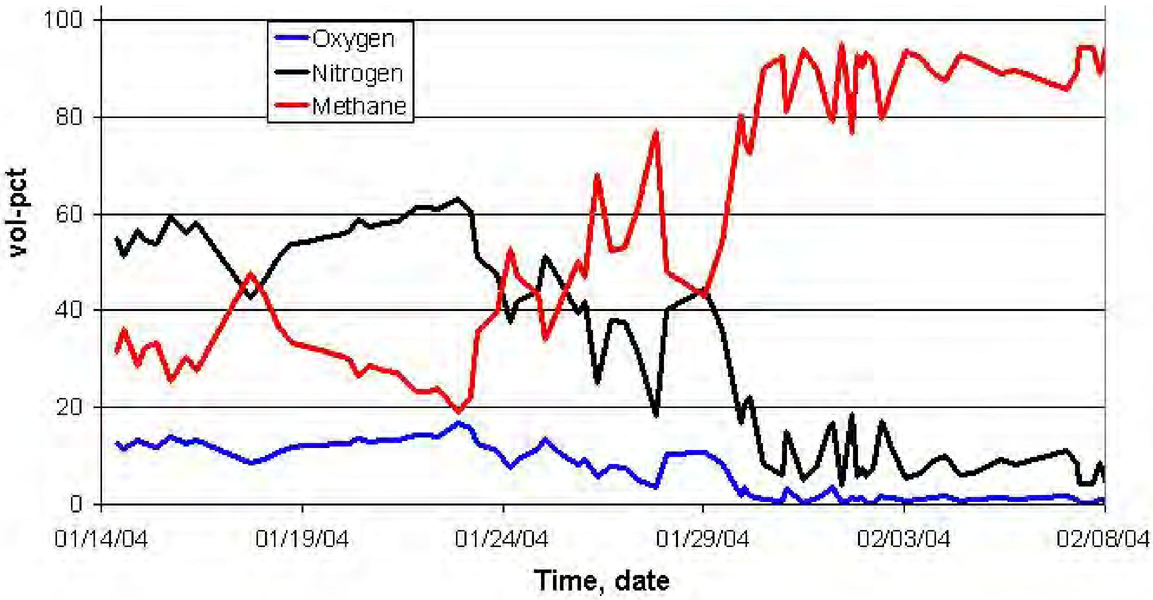


**Figure 17. Gas concentrations at a location behind the longwall face near the tailgate entries.**

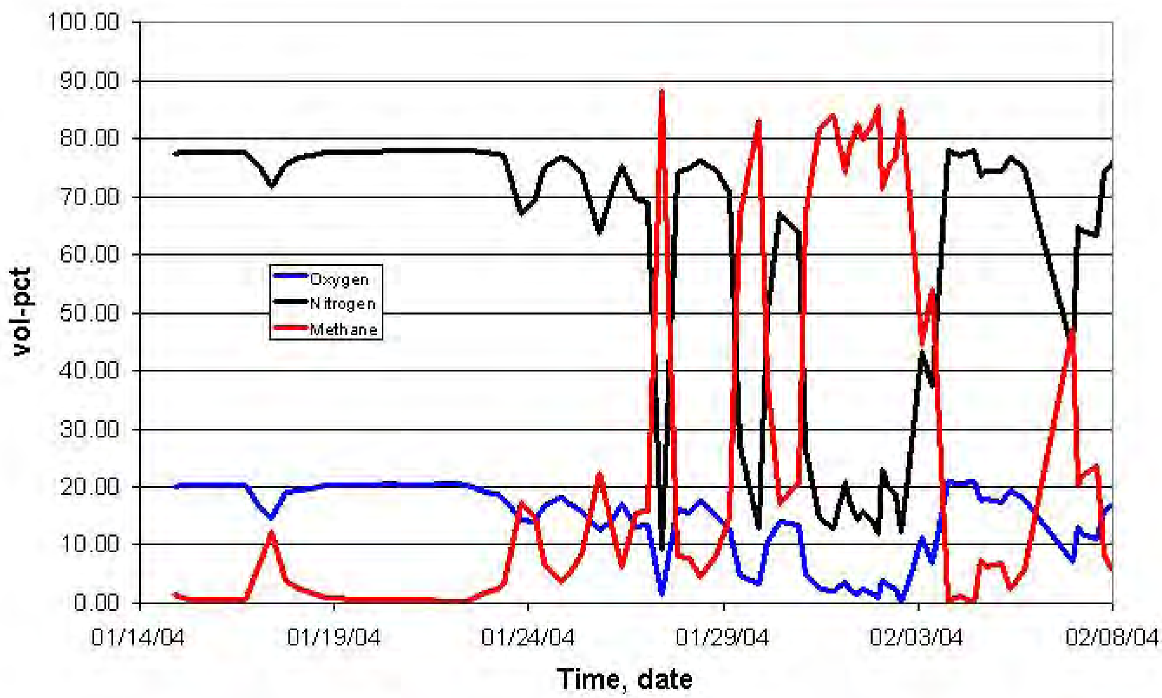


**Figure 18. Gas concentrations from borehole in the caved area near the tailgate entries.**

It appears that the first location experiences the effect of the remote seal and foam injection. The oxygen and nitrogen concentrations drop to very low levels and the methane increases to almost 100 pct. This indicates that this location was not seeing gases from the foam or nitrogen injection, but is now being isolated from the mine air. The location further inby experiences this effect sporadically, meaning that the pathways to the mine air are being affected periodically, as evidenced by the sharp drops in the nitrogen concentration and concurrent spikes in the methane concentration. This also reinforces the idea that the foam plug did not reach this area of the tailgate entry. The most likely path to mine air from this location would be via the tailgate entry. If the entry where these pathways exist were filled with nitrogen-foam, the nitrogen concentration would increase above 78 pct and the oxygen concentration would not rise to 20 pct, as it did on February 4.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge Ronnie Marcum, Paul Hafera, Doug Williams, and others at PinnOak Resources, John Urosek and the Mine Safety and Health Administration Technology Support group, and William Diamond, Fred Garcia, Craig Compton, Richard Thomas, Michael Meighen, Gerald Morrow, Michael Sapko, Kenneth Cashdollar, David Dwyer, Cindy Hollerich, John Marshall, and Marcia Harris at NIOSH for their assistance in conducting this research and helpful suggestions on the manuscript.

## SUMMARY

In summary, it appears that the combination of the remotely-installed seal and nitrogen-enhanced foam injection in the tailgate entry was able to isolate an area from the seal to approximately the location of the third borehole in the tailgate, about 2200 inby the seal. There are many uncertainties in this analysis, however, since no visual observations were possible. Data indicates that the foam plug extended 2200 feet inby the remote seal, but it is not known if the foam was able to fill the void area mentioned from floor to roof. It is impossible to discern if the increased nitrogen and decreased oxygen concentrations at the third borehole inby the seal were a result of the foam plug maintaining itself for that distance or if the gas concentrations were merely the result of gases emanating from the foam as it degraded. Finally, it is not known if the foam was able to penetrate the caved area and what role it played in the suppression of the suspected fire. However, it does appear that the foam was effective in isolating the front end of the panel I caved area. Further research is recommended under controlled conditions, where observation of the foam is possible, to continue to evaluate the performance of remotely-injected foam into mine entries to control and suppress mine fires.

On February 7, 2004, recovery teams re-entered the mine to begin erecting temporary seals around the longwall. In April, the mine was given permission to restart their continuous miner sections, and on May 19, 2004, the mine restarted the longwall.