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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	L/mol	liter per mole
cfm/in, w.g.	cubic foot per minute per inch, water gauge	min	minute
fpm	foot per minute	mL	milliliter
ft	foot	mol	mole
ft^2	square foot	pct	percent
ft^3	cubic foot	ppm	part per million
g	gram	psi	pound per square inch
g/mol	gram per mole	st	short ton
h	hour	V dc	volt, direct current
in	inch	w.g.	water gauge
L	liter	yr	year

A SEAL BREACHING OPERATION IN QUINLAND COAL MINE: A CASE STUDY

By Diane M. Doyle-Coombs[1] and Randy Hansford[2]

ABSTRACT

In late July 1985, air samples from a sealed portion of the Quinland coal mine in West Virginia showed the presence of carbon monoxide (CO). Mine Safety and Health Administration (MSHA) personnel concluded that a fire was burning behind the seals. Since an imminent danger existed, the mine operator was given a closure order.

The gases behind the seals were monitored and almost 2 million ft^3 of carbon dioxide (CO_2) gas was pumped into the sealed area to stabilize the environment. Sixteen days after the closure order was issued, MSHA allowed the mine to return to production.

Approximately 1 yr later, mine management submitted a seal breaching request to MSHA in order to drive a set of entries to further develop the mine. The Bureau of Mines established a sampling strategy and monitored gases from behind the sealed area during the breaching operation until the atmosphere was safe. This report is an account of the seal breaching conducted by the mine, MSHA, and the Bureau. The logistics of this event, the sampling strategy, and the equations applied could be used by the mining industry in future breachings or mine recovery operations. Time to reenter the area was calculated by using the methane (CH_4) concentrations sampled at the discharge of the seals. Tracer gas was used to verify the ventilation flows through the area.

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INTRODUCTION

A goal of the coal industry is to maximize the amount of coal removed without compromising miners' health and safety. As a mine develops, portions of the mine are abandoned and mining moves to areas where coal production is feasible. To prevent explosive concentrations of gases in abandoned portions or gob areas, coal mine operators can (1) continue to ventilate them or (2) isolate them from the main mine ventilation system by sealing. To seal an abandoned area, operators construct substantial and incombustible seals of sufficient strength to prevent their rupture in the event of an explosion. The conditions encountered in underground coal mines make it difficult to construct a seal that is completely airtight; recent studies indicate a near perfect seal will leak 150 cfm/in, w.g. Seals do, however, greatly restrict the passage of air in and out of abandoned areas.

This report documents an investigation of an abandoned sealed area in a West Virginia coal mine. The atmosphere behind the seals was sampled on a regular basis. During one of the sampling cycles, peak concentrations of 2,800 ppm CO and 1,260 ppm hydrogen (H_2) were detected, leading MSHA to close the mine because of the implied danger. The atmosphere behind the seals was judged safe after CO_2 gas was injected into the abandoned area. A yr later, the seals needed to be breached in order to continue with extraction of the seam. The Bureau of Mines assisted in establishing a gas sampling strategy and in collecting gas samples until the air exiting the abandoned area had reached a CH_4 concentration of 1.5 pct. A tracer gas, sulfur hexafluoride (SF_6), was used to test the ventilation in the abandoned area after the seals were breached. The seals were safely breached, and within 95 h production at the mine was resumed.

BACKGROUND

Quinland Mine, an underground coal mine in southern West Virginia, was opened into the Cedar Grove coal seam in 1973. The coalbed locally averages 42 to 50 in thickness and the overburden ranges from 250 to 900 ft. The mine used room and pillar mining with six to seven entries (fig. 1). The parallel mains, submains, and panels were developed and interconnected at the termination point by bleeder entries. Barrier pillars ranging from 300 to 525 ft in width are maintained between mains, submains, and panels being developed. The mine is ventilated by two main fans operating parallel. One fan (339,000 cfm) ventilates the northern portion of the mine, while the other fan (212,000 cfm) ventilates the southern portion. CH_4 liberation at this operation is approximately 226,000 cfm in 24 h.

The mine developed from two mains (2 East Mains). Two parallel north mains were developed off the 2 east mains. Development of 1 North Mains began in May 1974; development of 2 North began in May 1977. The 1 and 2 North Mains are interconnected by bleeder entries. Last reported mining in 2 North Mains was on or about July 1982. A ventilation survey indicated that sealing off 1 and 2 North would result in more effective ventilation in the existing workings. In August 1984, two sets of seals were constructed in the 1 and 2 North entries (fig. 2). The 14 seals were constructed of solid concrete blocks, set on solid flooring and were not hitched into the ribs. The 16-in blocks were placed with the long axis of each block aligned parallel to the rib along the entry length, and laid skin to skin with mortared joints, producing an effective thickness of 16 in. Seals were faced with mortar, then the face and perimeter were coated with a fire-resistant rigid foam. A valved sampling pipe was placed in the center of the highest number 1 seal (left) of both panels to measure the pressure differential across the seals and to monitor the atmosphere in the sealed area. The sampling pipes terminated approximately 5 ft inby the seals. A water drainpipe and trap with a shutoff valve were installed in the lowest elevation, at the number 7 seal of each panel. Supplemental roof support, such as cribs and timbers, were used where needed in the 2 North area, because roof falls in the 2 North panel had occurred prior to sealing. The mine firebossed the seals during preshift and during the weekly ventilation inspection. During an inspection in April 1985, two of the seals in 1 North were outgassing around the perimeter and through the face of the seals. New seals were constructed outby the original number 3 and 6 seals in the same manner as the original seals.

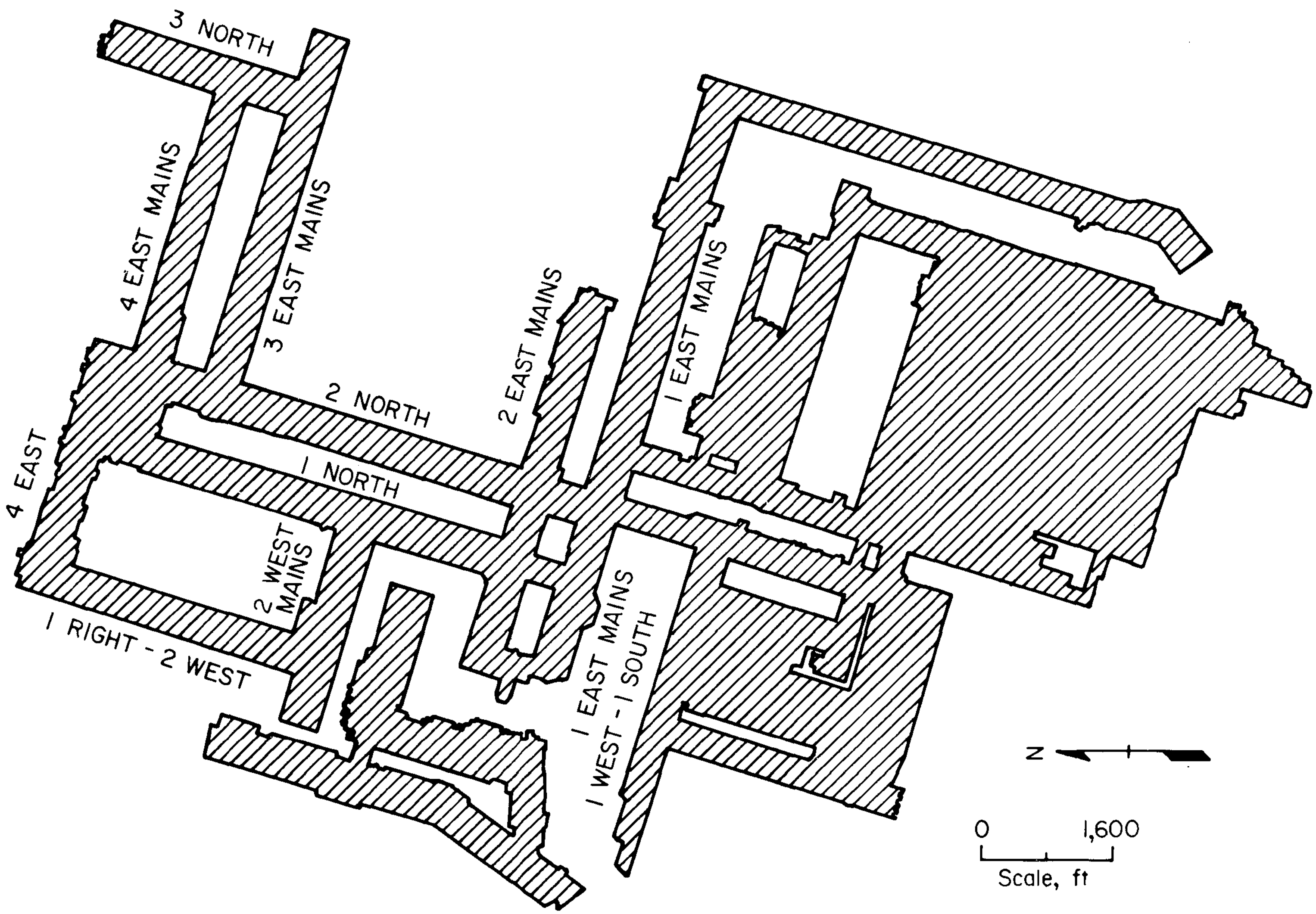

Figure 1.--Quinland Mine map.

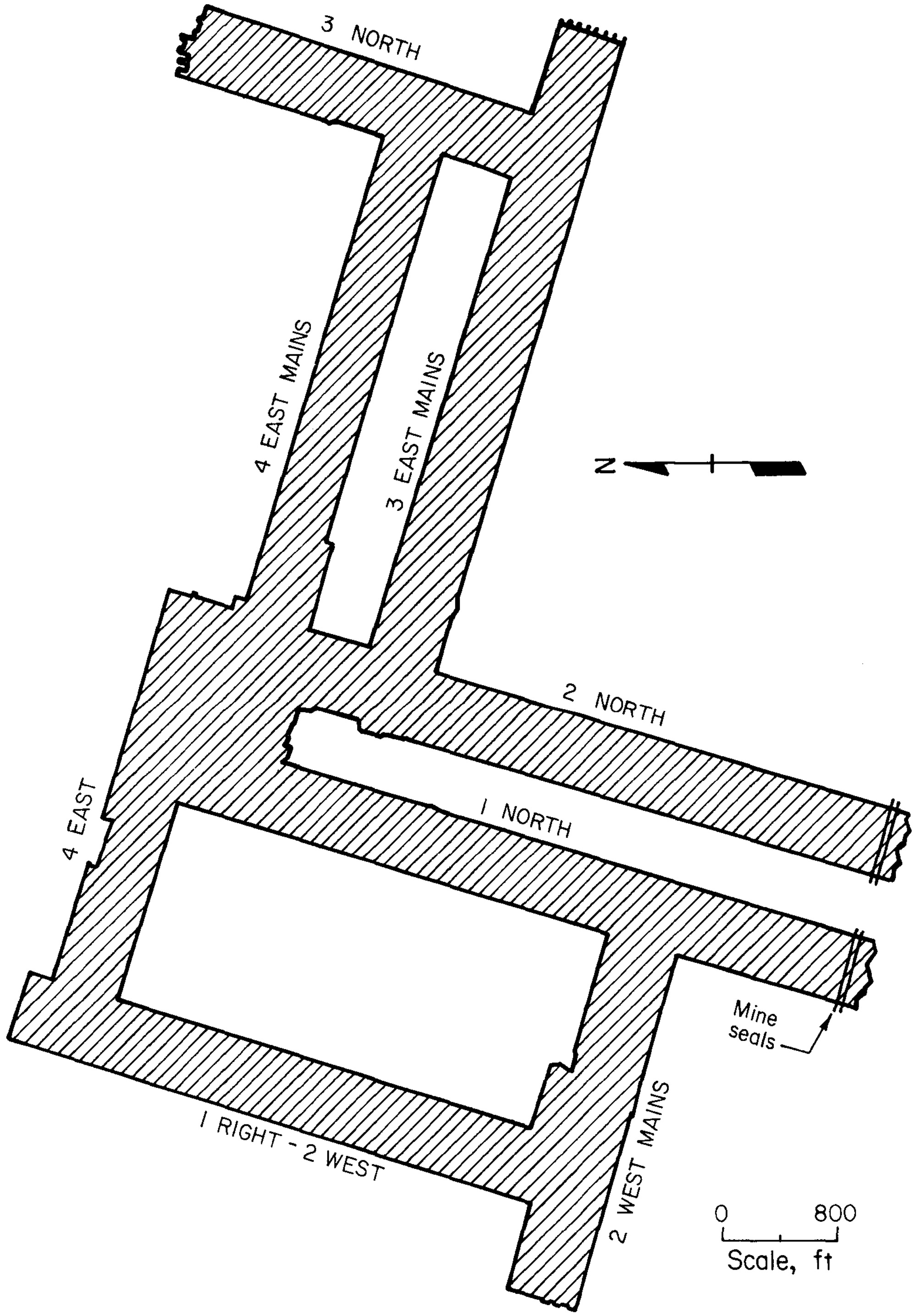

Figure 2.—Quinland Mine 1 and 2 North Main Seals.

DETECTION OF MINE FIRE

In addition to the regular inspections, MSHA inspectors examined the seals, assessed ventilation, and collected air samples from behind the 1 and 2 North seals. During one sampling cycle, MSHA reported the presence of CO and H_2 in 2 North. Table 1 shows the average concentrations of CO_2, oxygen (O_2), CH_4, CO, and H_2 reported in 1 and 2 North (*1*).[3]

The MSHA subdistrict manager requested that additional samples be collected at the 2 North location. Inspectors went underground to obtain bottle samples, visually inspect the seals, conduct smoke leakage tests, obtain hand-held sample readings at the seal face and outby the number 1 seal, take stain measurements, obtain pressure differentials across the seals, and take airflow readings. During the inspection of the 2 North seals, air was found to be leaking around the perimeter of the number 1 seal and at the water trap in number 7 seal. MSHA required mine management to remove miners from underground, and then issued an imminent danger order because of the elevated levels of CO (evidence of a fire) and the presence of H_2 in 2 North. The Jones-Trickett ratio (JTR) (*2*) was applied to the data to provide insight into what was on fire. The 2 North gas samples gave a JTR value of 0.53,which indicates CH_4 was the primary fuel for the fire.

Four boreholes (table 2) were drilled from the surface to the 2 North panel for atmospheric sampling (fig. 3). Each borehole was equipped with a three-tube bundle of sample tubing that extended through the borehole to near the top, middle, and bottom of the coalbed. This arrangement was initially used because air within a sealed area tends to stratify. After several hr of sampling, it was obvious that it was unnecessary to obtain gas readings at the three height locations; gas concentrations were the same at each height.

The number 4 borehole was sampled and gas concentrations, in pct, averaged: CO_2–0.8, O_2–18.7, CH_4–3.4, and CO–0.1. Underground, work crews collected bottle samples from the 2 North number 1 seal; gas concentrations, in pct, averaged: CO_2–0.9, O_2–17.8, CH_4–6.1, nitrogen (N_2)–76.41, CO–0.257, and H_2–0.076. These individual samples prompted mine management to submit a formal mine fire and sampling plan as an aid in dealing with the fire (appendix A). Decisions on the state of a fire are based on the changing composition of the mine air and not single samples (*3*).

Because the samples collected indicated the presence of an explosive mixture of gases behind the 2 North seals, MSHA prohibited regular visits to the underground sampling ports. To gain information on the environment behind the seals, a crew of workers was given permission to go underground and install a sampling tube from the number 1 seal of 2 North.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

Mine management proposed to MSHA that CO_2 gas be injected down a borehole. Thirty st (525,000 ft^3) of CO_2 gas, pumped down borehole 3, resulted in a nonexplosive atmosphere behind the 2 North seals. Miners were then permitted to go underground to assess the ventilation and to apply a cementitous (gunite) sealant to the surfaces. When the crew arrived at 2 North, members observed CO_2 leaking out of the seals. To reduce the leakage, they coated the seal face and ribs with gunite.

Forty-two st (735,000 ft^3) of CO_2 was then pumped through the number 3 borehole into the area behind the 2 North seals. Gas analyses indicated a steady improvement of the atmosphere behind the seals. The crew of miners returned underground to continue rehabilitating the seals. As a safety precaution, an additional 28 st of CO_2 was pumped down the number 3 borehole. A total of 98 st CO_2 (approximately 1,710,000 ft^3) was pumped into the area behind the 2 North seals to make the atmosphere nonexplosive.

Five days after the initial injection of CO_2 in the number 3 borehole, bottle samples collected at the number 2 borehole had gas concentrations below the explosive range (table 3). The continuous gas monitoring station

TABLE 1. - Average gas concentrations behind seals, percent

	1 North	2 North
CO_2	1.30	0.91
O_2	12.35	18.62
CH_4	19.07	2.13
CO	0	.268
H_2	0	.12
Higher hydrocarbons	Trace	Trace

TABLE 2. - Borehole descriptions

Borehole	Diameter, in	Depth, ft	Entry location in 2 North seals	Distance from 2 North seal, ft
1	6	261	6	2,900
2	6	269	3	3,050
3	6	176	1	3,075
4	2	685	4	310

TABLE 3. - Gas concentrations in number 2 borehole of 2 North after injection of 98 st of CO_2, percent

Location	Borehole 2
CO_2	9.38
O_2	11.08
N_2[1]	62.32
CH_4	18.19
CO	.0298
H_2	NA

NA Not analyzed.

[1]The percentage of N_2 was determined by subtracting the sum of the reported values from 100.00. This valve is nitrogen plus argon.

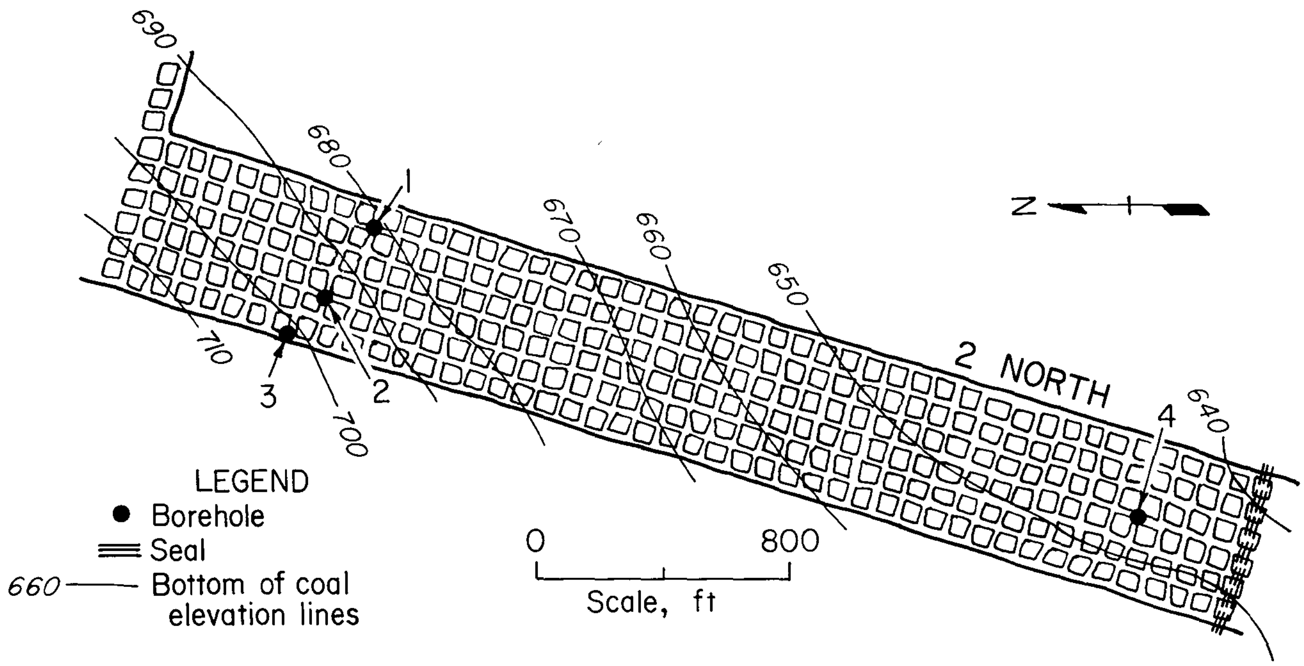

Figure 3.—Borehole locations in 2 North.

samples collected immediately behind the 2 North seals were considered stable. The data indicated the original fire behind the seals was not burning, and CH_4 concentration in the atmosphere at the boreholes was due to the holes being at a higher elevation than the seals, therefore the CH_4 was displaced by CO_2.

The closure order was terminated because a nonexplosive atmosphere now existed behind the seals. After mine management submitted a completion plan to MSHA (appendix B), the mine was reopened.

SEAL BREACHING

Approximately 1 yr after the start of the fire, mine management submitted a plan to MSHA to open the seals in 1 and 2 North Mains for the purpose of driving a set of mains off the number 7 entry in 2 North (*3*). The mine had attempted to develop a set of mains off of 2 North, but was unable to continue advancing because of geologic conditions that created roof control problems (fig. 4). For future development of the mine, it was necessary to break into the sealed area, establish ventilation, and begin driving a set of entries from the number 7 entry in 2 North. The Bureau was requested to establish a gas sampling strategy to be used during the seal-breaching operation, and to conduct a tracer gas test to evaluate the ventilation in the abandoned area.

Two 3/8-in-ID tube bundles were extended from the seals at 1 and 2 North to an outside monitoring station. One tube bundle was for 1 North and the other was for 2 North. The outside monitoring station was equipped with a portable gas chromatograph, sampling pumps used to draw samples from behind the seals to the surface, calibration gas, evacuated sample tubes, detector stain tubes, and hand-held gas detecting instruments. This continuous monitoring station made it unnecessary for individuals to go underground to obtain air samples. If the continuous monitoring station failed, an alternative plan would have been followed (appendix C).

A known concentration of calibration gas was inserted at the tube end to test for leakage and accuracy. Before taking a sample, it was necessary to draw the atmosphere through the tubing for a period not less than three times that required for one air exchange (*4*). Once started, sampling pumps operated continuously, ensuring an uninterrupted air exchange.

Some site preparation was done prior to the seal breaching. Mine phone communications were established between both seal locations and the surface. An air compressor was located in 2 North with the air lines extending to the 1 and 2 North seal areas. Gunite on the number 1 seals of both 1 and 2 North was removed from a 48- by 48-in area using jackhammers with standard hardened steel bits. Wing curtains were installed within 10 ft of each of the seals to provide ventilation to sweep away any noxious or toxic gases emitted from behind the seals when they were opened. Temporary ventilation controls were installed in 2 East to facilitate a 0.5-in, w.g. drop between 1 and 2 North, so that air would enter 2 North and exit

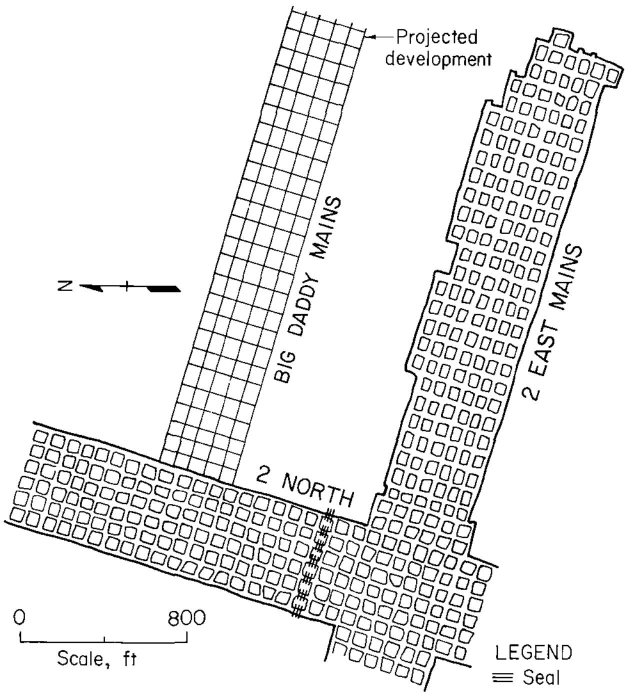

Figure 4.—Projected mine development.

1 North (fig. 5). An air volume of 35,000 cfm was measured at the junction of 1 North and 2 East. It was calculated that a 10-ft^2 opening would be needed to ensure a flow of 20,000 cfm through the sealed area.

For a period of 24 h prior to the seal breaching, gas concentrations behind 1 and 2 North seals were collected via the sampling tube for background information. As a calibration check, bottle samples were also collected. The pressure differential across the seals prior to breakthrough and the average gas concentrations behind the seals collected for this 24 h period are shown in table 4.

On the first day of miners annual vacation, Saturday, July 26, 1986, at 11:00 a.m. the number 1 seals in both 1 and 2 North Mains were breached. Only personnel required for the seal breaking were permitted underground. Seals were breached by a certified mine foreman/fireboss who performed all tests prescribed by law. Two persons trained in mine rescue procedures were present at the seals with mine rescue apparatus. All electrical power inby the intersection of 2 North and 2 East was shut off. Phone communication to the surface was established. Ventilation measurements were taken at the 1 North-2 East intersection to ensure that an air quantity of 35,000 cfm of air was available. Hand-held gas readings, evacuated tube samples, and bottle samples were collected as a calibration check for the outside monitoring station. The work sequence was to breach the number 1 seal of 1 North, then advance to 2 North and breach the number 1 seal of 2 North. If during the seal breaching, either mine fan failed, all persons underground would return to the surface and all electrical power would be deenergized.

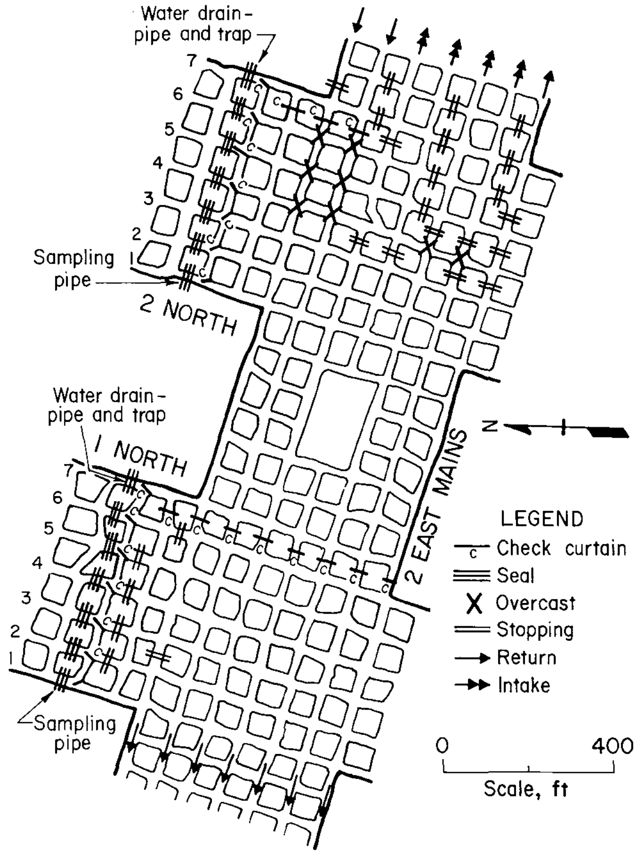

Figure 5.—Temporary ventilation controls in 2 East.

Table 4. - Average gas concentrations behind seals, percent, and pressure differential across seals prior to breakthrough

	1 North	2 North
CO_2	3.22	1.37
O_2	6.15	13.5
N_2[1]	56.29	63.45
CH_4	31.11	19.89
Other gases	3.23	1.79
CO	0	0
C_2H_6	.0008	.0006
Pressure differential .... in, w.g. . .	+0.8	-0.37

[1]Nitrogen plus argon.

To eliminate sparking, brass tools were used to break the seals. The number 1 seal of 1 North was breached with a 4- by 2.5-ft opening. After the crew arrived at the 2 North seals and communication was established to the outside, the number 1 seal of 2 North was also breached with a 4- by 2.5-ft opening. The air reading was taken to ensure that a minimum of 20,000 cfm was entering the 2 North seal opening. One individual, using breathing apparatus, then went back to the 1 North opening to obtain measurements of pressure drop across the opening (0.1 in, w.g.), air volume (22,500 cfm), and concentrations of O_2, (3.7 pct), CO, (0 ppm), and CH_4 (>5 pct). After

30 min, SF_6 was released at the opening of the 2 North seal. All persons then exited the mine. Power was restored inby 2 East-2 North intersection.

Gas concentrations were continuously recorded. The air volume contained in the abandoned area was calculated by mine engineers in an attempt to determine how long it would take for the return air out of the 1 North seal to reach a CH_4 concentration of 1.5 pct. CH_4 was the gas that was used to assess the ventilation inby the seals. No one was certain of the entry and roof conditions that existed inby the seals. Mine maps showed conditions prior to sealing, but how the abandoned area had been affected by the fire was unknown. The open volume behind the 1 and 2 North seals was estimated as 26,676,000 ft^3 (appendix D) with a ventilating airflow of 22,500 cfm entering the 2 North seal and exiting 1 North. It was assumed that the air in 1 and 2 North had a known CH_4 concentration of 31 pct and that generation of CH_4 had ceased.

Depending on the equation applied, purge times were calculated as 20 h, 60 h (*4*), 120 h (*5*), and 138 h (*6*) (appendix E). The CH_4 concentration declines as clean air is substituted for contaminated air. A dilution time of 20 h would result from plug flow in which the volume of contaminated air contained behind the seals is completely flushed out as an air exchange is made. This is an ideal situation and assumes that all the contaminated gas is displaced without mixing with the air. The dilution time of 60 h is based on dilution equations presented by Hartman (*4*), and is used to determine the time that elapses before a certain concentration is reached. The purge time of 120 h uses dilution equations commonly used in industrial ventilation (*5*). This situation often arises when confined spaces need to be ventilated to permit safe reentry after contamination, and implies that the volume of air required to reduce the concentration of the contaminant is proportional to the contaminated volume space. A dilution time of 138 h assumes that a space has an initial concentration and air is continuously fed into the space; then the diluted concentration at any time will follow a logarithmic decay curve (*7*).

Forty-nine hr after the seals were breached, the CH_4 concentration of air exiting 1 North had only dropped to 4.8 pct, and mine management decided to speed up the dilution time. The openings in the number 1 seals of 1 and 2 North were enlarged to 20 ft^2, allowing 31,000 cfm of air to enter the 2 North mains and return through the 1 North opening. Routine air sampling of the atmosphere in the number 1 and 2 North Mains continued. After the air volume was increased for 2 h, the CH_4 concentration climbed to 6 pct; within 3 h after this surge, the CH_4 concentration dropped to 4 pct. The CH_4 concentration reached 1.5 pct at the 1 North seal, 95 h after breaching. Appropriate inspections were made and the mine went back into production on Wednesday, July 30, 1986 at 12:30 p.m.

Redoing the calculations originally used for estimating the time for CH_4 to reach 1.5 pct and accounting for the increase in airflow after 49 h, the previous calculated dilution times are recalculated as 14 h, 54 h (*4*), 107 h (*5*), and 117 h (*6*) (appendix F). The industrial ventilation equation used to calculate the purge time required to safely enter a confined space (107 h) gave the closest approximation of the actual dilution time (95 h).

USING TRACER GAS TO UNDERSTAND AIR MIGRATION PATTERNS THROUGH ABANDONED AREA

SF_6 was used as an aid to understanding the migration patterns through the sealed area. SF_6 is colorless, odorless, chemically and thermally stable, and can easily be introduced into an airstream (*7-8*). SF_6 is contained in metal pressurized cylinders, which are pressured to 300 psi, equivalent to approximately 1.5 ft^3 of gas at atmospheric pressure. Since SF_6 does not occur naturally in the environment, background concentrations are no problem. SF_6 samples are collected in evacuated 10- or 20-mL test tubes. Samples are returned to the laboratory, where 0.1 mL of the sample is drawn with a syringe and injected into an electron capture gas chromatograph for analysis.

Thirty minutes after the 2 North seals were breached, a known volume of SF_6, 30.0 L, was released into the airstream at 2 North. The mass of SF_6 recovered in the return air exiting 1 North was determined to be 28.1 L, which is nearly equivalent to the amount released. An example of this recovery calculation is presented in appendix G.

Figure 6 shows a concentration curve for SF_6 exhausting from the 1 North opening as a function of time. SF_6 was released in an airstream having an air velocity of 2,258 fpm, which created adequate mixing of SF_6 at that location. SF_6 was first detected exiting at 1 North 10.8 h after it was released in 2 North, and SF_6 continued to exist at the sampling location in the 1 North seals for a period of 90.8 h after release, at which time sampling ended. The straight-line path for air from 2 North to 1 North is 12,000 ft. This travel length divided by SF_6 arrival time gives an air velocity of 18.7 fpm.

Assuming different stopping conditions behind the seals, different average velocities could have been calculated. In one assumed case, there are two connected entries inby the breached seal that are separated from the other five entries by a stopping line. Equivalent entries are used to account for the crosscut space between these two parallel entries. Assuming that all stoppings through this area offer quality construction and minimum leakage, the velocity through these two entries would be 82.3 fpm (appendix H). In the second assumed case, all seven entries are functioning as aircourses with normal mine leakage at each of the stoppings. Since it is assumed that each entry is an aircourse, there is no migration of air into crosscuts and crosscut space is not taken into consideration. The

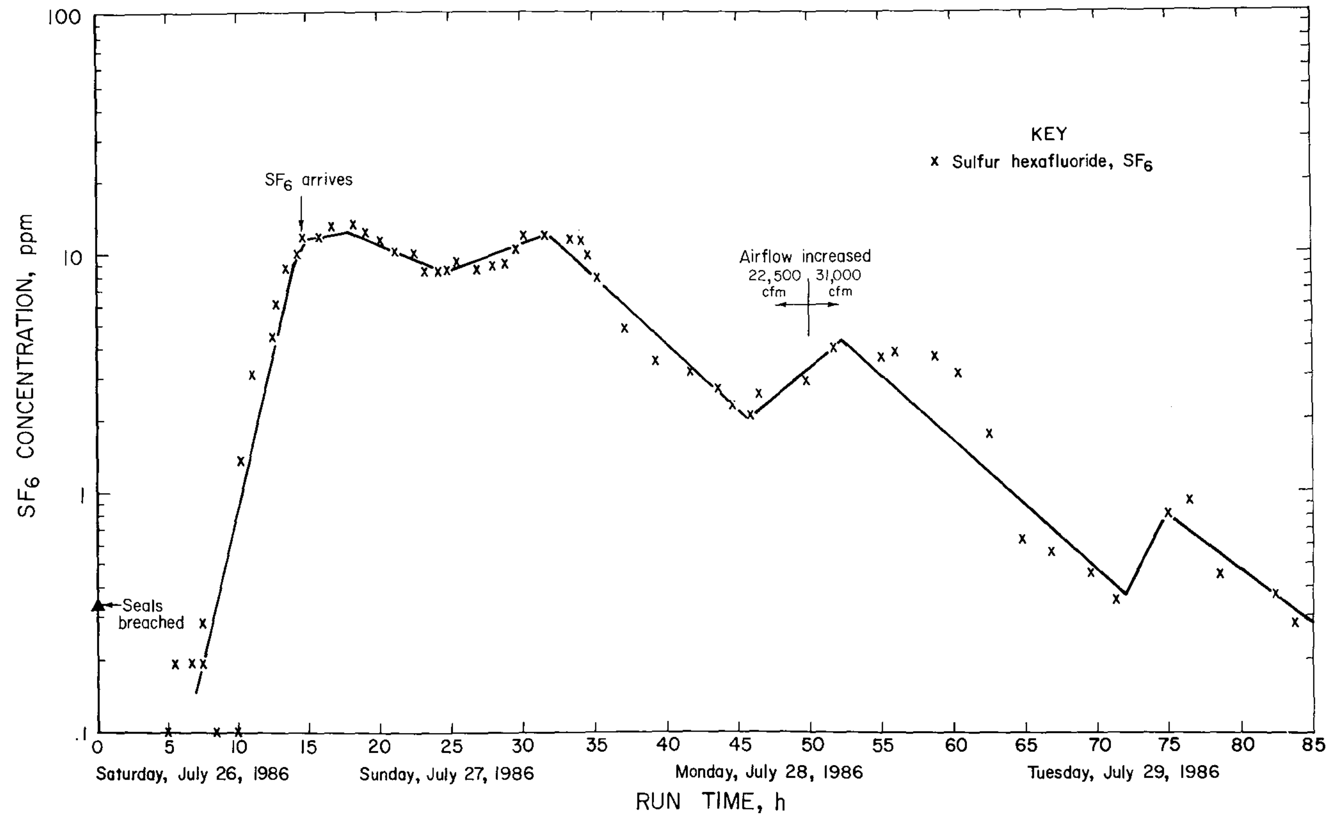

Figure 6.—SF_6 concentration in 1 North.

velocity through these entries becomes 32.1 fpm. In the third assumed case, the stopping lines are not intact because of the fire or because of roof falls. In this situation, once again, equivalent entries should be used to determine the average velocity through the total volume, which becomes 19.7 fpm. After an investigation inby the seals, some stoppings between entries were found to have been destroyed because of the shock wave created by forces of the explosion or fire (*2*). In this situation, the use of equivalent entries to calculate the velocity of the area behind the seals (19.7 fpm) closely approximates the travel velocity of SF_6 (18.7 fpm).

Figure 7 shows CH_4 levels plotted as a function of time. The concentration of CH_4 exiting the 1 North seal remained relatively constant for a period of 12.3 h, before beginning to decrease. The arrival time of SF_6 at the 1 North opening was 10.8 h, which is relatively close to the 12.3-h initial decrease time of CH_4. After 12.3 h CH_4 concentration was found to decay exponentially, but with a change in slope after 43.5 h; this change in slope is attributed to eddy zones (*9*) that could cause problems in data interpretation. The ventilating area behind the seals had zones of CH_4 laden air, well and poorly mixed with fresh air. After 43.5 h, CH_4 concentration reached a constant slope. Use of the initial slope as a means to predict a time when CH_4 would have reached 1.5 pct would have resulted in an incorrect prediction.

Tracer gas can be used as a tool to understand the conditions inby a set of seals, should future openings in other abandoned areas be necessary. The tracer gas, in conjunction with CH_4, provides insight to the conditions inby the seals. The CO_2 decay curve could have been used in the same manner as the CH_4 concentration information. Concentrations of the other gases were not high enough to be used to interpret trends.

The SF_6 decay curve (fig. 6) and the CH_4 decay curve (fig. 7) do not have the same slope. The concentration of CH_4 that existed inby the seals was distributed through all entries and crosscuts. As fresh air passed through the section, CH_4 was continuously diffusing from other entries into the main flow stream. The SF_6 was injected into the moving airstream and did not get coursed to all the back entries behind the seals. The SF_6 decay curve indicates that different flow paths exist behind the seals.

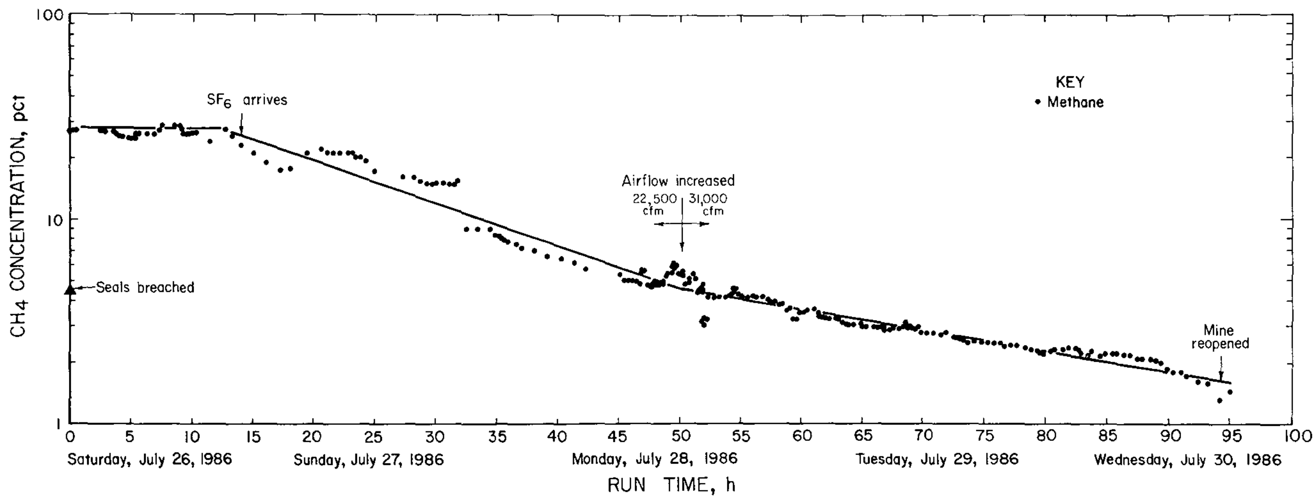

Figure 7.—1 North CH_4 decay curve.

PREDICTING GAS CONCENTRATIONS

From the time the seals were breached until CH_4 levels reached 1.5 pct the following gases were continuously sampled: CO, CO_2, O_2, and CH_4. N_2 level was determined by subtracting the sum of the reported values from 100.00. Because the critical gas was CH_4, the portable gas chromatograph only sampled for CH_4. Evacuated bottle samples were collected for analysis of other gases by a laboratory gas chromatograph. Bottle samples were collected continuously for 24 h before and during breaching of the seals and until the CH_4 exiting the 1 North seal reached 1.5 pct. The concentrations of CO_2, CO, O_2, and N_2 as a function of time are shown in figure 8.

When using gas concentrations as indicators of existing conditions, it is important to look at long-term trends, as opposed to single numbers. The Bureau's continuous monitoring system made on-site data interpretation possible. To predict trends, semilogarithmic graph paper was used to plot instantaneous CH_4 gas concentrations versus time data (fig. 6). Three days after the seals were opened, the CH_4 concentration exiting the 1 North opening was less than 5 pct and CO concentration was 0 ppm. Because these concentrations indicated an explosion was not possible, mine management requested that a ventilation change be made. The 1 and 2 North seal openings were enlarged to 20 ft^2, allowing 31,000 cfm of air to enter the 2 North mains and return through the 1 North opening. Two hours after the air volume was increased, the CH_4 concentration rose to 6 pct. Within 3 h after this CH_4 surge, the concentration approached 4 pct. After realizing that there were different slopes for CH_4 decay, the Bureau was able to collect data and extrapolate a time when CH_4 would reach 1.5 pct. The change in slope occurred before an increase in air volume was made. Using the data plotted on semilogarithmic paper when CH_4 would reach 1.5 pct, it was estimated that it would occur 99 h after the seals were breached and ventilation was established.

In reality, the concentration of CH_4 reached 1.5 pct in 95 h, a 4.2-pct difference from the predicted value, which indicates that sampled gas data can be effectively used to extrapolate future gas concentrations. After a trend has been established and is well defined, one can mathematically derive the time for a gas concentration to reach a certain level using appropriate equations.

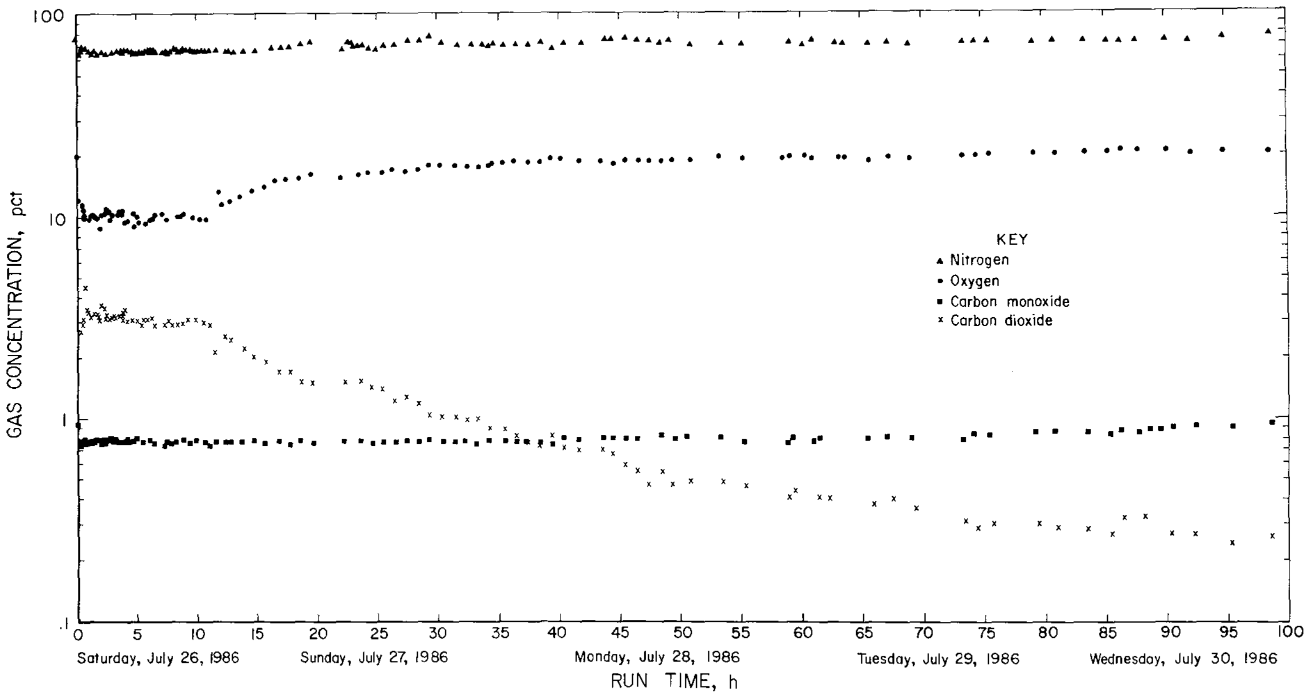

Figure 8.—Concentration in 1 North—CO_2, O_2, N_2, and CO.

DISCUSSION

Gases considered typical of those from a fire were detected behind a sealed area in a producing coal mine, which caused MSHA to require the mine operator to take actions to remedy the situation immediately. When the analytical results of air samples collected from the sealed area were incorporated into the JTR, the results showed that CH_4 was the probable fuel. Boreholes were drilled into the sealed area to collect air samples to interpret what was occurring. Because the activity occurring in the sealed area was stable, and nothing supported a belief that the fire might be spreading, mine management's goal was to create a nonexplosive atmosphere behind the seals and return the mine to production status. Because CO_2 gas seeks an area of low elevation, it was pumped down a borehole and traveled to the low elevation sampling area established behind the seals. This created a nonexplosive atmosphere in the sealed area, and the mine was returned to production. Approximately 1 yr later, mine management submitted a plan to MSHA to breach the seals. The Bureau was requested to establish a sampling strategy, study airflow migration in the area using a tracer gas, and monitor the atmosphere in the abandoned area until the return air contained less than 1.5 pct CH_4.

No one was certain of the airflow patterns that existed inby the seals. Mine maps showed ventilation controls and known falls, but how the abandoned area was affected by the fire was unknown. Purge times were estimated using different equations. On the assumption that CH_4 generation had ceased behind the seals and using an estimated volume, the industrial ventilation equation provided the closest approximation to the actual time in which CH_4 reached 1.5 pct. SF_6 tracer gas was used to determine the air migration patterns through the abandoned area. In this situation, SF_6 was used to determine the velocity of air through the sealed area and to understand the CH_4 rate of decay from the 1 North exit. CH_4 exiting the sealed area followed a logarithmic decay curve but with a change in slope. This phenomenon is due to eddy zones that exist in mines. CO_2 could have been used in the same manner; the other gases (O_2, CO, and N_2) were not sufficient to use in establishing a trend for use in understanding the eddy zones within the sealed area.

For proper decisionmaking throughout a mine fire (or other events that are atypical of a mine's daily routine, such as seal breaching), it is essential to have reliable gas sampling information. Computations, diagrams and common sense are used as aides in understanding and interpreting the situation. Repeated gas sampling of an environment permits forecasting trends and evaluating the effectiveness of a change. During the seal breaching operation, a change was made approximately 2 days after the seals were opened. When CH_4 concentration exiting the return opening was below the lower explosive limit (5 pct) mine management, wanting to expedite the dilution process, arranged to go underground to enlarge the seal openings to permit 40 pct more air through this section. The CH_4 concentration 1 North return air reached 1.5 pct 46 h after the airflow through the area was increased. Because gas samples were continuously collected, analyzed, and plotted, it was possible to evaluate how effective a change was on the return atmosphere. Data interpreters should be aware that abrupt changes can occur, therefore, continuous, long-term data must be used to understand and evaluate changes.

SUMMARY

After an investigation, it was determined that an explosion had occurred behind the sealed area of the Quinland Mine (*10*). The fire situation caused the mine to be placed under a closure order. After 98 st of CO_2 was pumped into the sealed area, the atmosphere behind the seals was considered stable and the mine returned to full production.

Approximately 1 yr later, mine management submitted a request to breach the seals. The Bureau was requested to establish a sampling strategy and monitor the atmosphere in the abandoned area until the return air contained less than 1.5 pct CH_4. Continuously monitoring the CH_4 gas and plotting the results, showed that after 49 h CH_4 concentration exiting the abandoned area was below the explosive range. The seal openings were increased to allow an airflow of 31,000 cfm to enter the area. Within 46 h after the airflow change, CH_4 concentration exiting the opening reached 1.5 pct. The continuous sampling of return gases and their proper interpretation allowed safe decisions to be made on the ventilation air in the abandoned area. Tracer gas was used to aid in understanding flow paths through the area. In future operations, SF_6 can help to solve ventilation analysis problems that do not respond to conventional methods analysis; its application should be considered when such problems are encountered. Other mine operators have used modified techniques before breaching seals. This procedure requires that the area adjacent to the seals be inerted with N_2 (this involves an airlock with a set of temporary stoppings built out by the seals). The recovery team using brass tools and under breathing apparatus would breach the seals. With this method, an inert atmosphere was assumed on both sides of the seals (high CH_4 on one side and high N_2 on the other).

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APPENDIX A.–MINE FIRE SAMPLING PLAN

Samples of the atmosphere behind seals in 1 and 2 North off 2 East Mains are to be taken in accordance with the procedures given below. The person taking samples should report any sampling that deviates from one or more of these procedures; i.e., the person should record the sample number and manner by which it deviates, and that record should be made part of the analysis and should be noted in the remarks column of the computer printout of gas-sample data.

Procedures

A. Three lines of 1/4-in-ID, semirigid sampling tubing in a closed bundle extend from the surface through each borehole into 2 North. One tube (floor) will be 1 ft above the bottom (a point that might be above as well as on the floor); a second tube (midheight) will be 2 ft above the bottom; a third tube (roof) will be 3 ft above the bottom.

1. Each tube shall be labeled by borehole and location. For example, 1-F is the floor tube on borehole 1.

B. Samples shall be taken *ONLY* when a magnahelic or other pressure differential gauge indicates NO NEGATIVE pressure on the tube for which a sample is intended to be drawn.

1. The pressure reading shall be recorded.

C. At least two samples complying with B above shall be taken at least once every 4 h from each sampling tube (3 tubes by 4 boreholes by 2 = 24 samples).

1. Each sample shall be labeled by date, time, location, and sample number.

D. A sample shall be taken *ONLY* after the atmosphere is drawn through the sampling tube for a period of not less than 1 min using the 12-V dc pump.

E. Each sample shall be analyzed using a gas chromatograph that has been calibrated that day using a standard traceable to National Bureau of Standards.

1. The chromatograph operator shall reanalyze CO in samples containing more than 10 pct CH_4 plus higher hydrocarbons.

F. The results of each sample shall be reported to mine management's authorized representative.

1. The data shall be entered into the computer.
2. The data shall be reported by
   - Borehole.
   - Location.
   - Date.
   - Time.
   - Hydrogen (H_2), percent.
   - Carbon monoxide (CO), percent.
   - Oxygen (O_2), percent.
   - Methane (CH_4), percent.
   - Other hydrocarbons (C_xH_x), percent.
   - Nitrogen (N_2) plus argon, percent.
   - Carbon dioxide (CO_2), percent.

Jones-Trickett ratio (JTR): $JTR = [(CO_2 + 0.75\ CO) - (0.25\ H_2 + 0.25\ C_xH_x)]/(0.265\ N_2 - O_2)$.

Fuel (F): When JTR is less than 0.4 F = None; JTR = 0.4-0.54, F= CH_4; JTR = 0.55-0.8, F = coal or CH_4; JTR = 0.8-1.0, F = Coal; JTR = 1.0-1.6, F = wood; JTR is greater than 1.6, F = bad sample.

Effective combustible (EC): $EC = CH_4 + C_xH_x + 1.25\ H_2 + 0.4\ CO$.

Explosibility (Ex): $Ex = EC(O_2/MAO)$ where maximum allowable oxygen, $MAO = 5 + 7\ \dfrac{(CH_4 + C_xH_x)}{CH_4 + C_xH_x + CO}$.

Relative intensity (RI): RI + $\left(1 - 3.8 \ \frac{O_2}{N_2} \ \frac{(CO \times 100)}{(0.265\ N_2 - O_2)}\right)$.

CO_2 - Blackdamp = (R/3.777 + 0.01 R + 0.01 S),

where R = $CO_2/(0.265\ N_2\text{-}O_2)$

and S = $CO/(0.265\ N_2\text{-}O_2)$.

Remarks

G. The fire is out when all samples taken in six consecutive sampling periods show F = none or O_2 less than 12 pct and RI is decreasing.

NOTE: A fire in which CH_4 is the principal fuel produces little or no carbon residue such as soots, cokes, or charcoals. CO, after a fire is extinguished, disappears by

1. Reventilation, and
2. Absorption by carbon residue primarily, coal secondarily.

Therefore, unless 2 North is reventilated or the fire consumed considerable coal, one should expect CO to decrease at a slow rate. CO, therefore, should not be used as a critical factor in decisionmaking, unless the CO concentration is rising.

APPENDIX B.–COMPLETION PLAN

1. Remove any temporary ventilation controls.

2. Conduct preshift examination of the entire mine.

3. Complete the work of applying gunite to the number 1 and 2 North seals, and to the roof and coal ribs of the blocks of coal containing the seals.

4. Grout number 1 and 4 boreholes.

5. Maintain number 2 and 3 boreholes for sampling and for pumping additional CO_2 if needed.

6. Return the mine to production status within 5 days.

7. Collect bottle samples daily at 2 North seal and number 2 borehole until CH_4 concentration is greater than 16.0 pct and O_2 is less than 10 pct, and then sample once a week. Continue collecting air samples at number 4 borehole until notified by MSHA to discontinue.

APPENDIX C.–MSHA APPROVED PLAN FOR MINE UNSEALING IF CONTINUOUS MONITORING SYSTEM FAILED

After 24 h, three certified personnel shall reenter the mine and check permanent checkpoints, A and B. (fig. C-1). Should the air contain less than 1 pct CH_4 and less than 0.5 pct CO_2 in the immediate return, the complete mine shall be firebossed and normal work carried out. These established checkpoints (A and B) will be checked weekly and recorded.

Because of the existing ventilation controls in this section, the entire area inby 1 North and 2 North is being ventilated, because stoppings and falls direct air in the entries and gas concentrations can be safely evaluated at these established points. After the area has been flushed, the remaining seals in 2 North Mains shall be removed. The 2 North Mains shall then be rehabilitated and permanent checkpoint B moved inby Big Daddy Mains.

Should bottle samples taken from checkpoint A or B indicate a rekindling of the fire, the area should be resealed CO_2 injected in borehole 2 or 3. A certain amount of CO is still known to exist in the sealed regions because it shows up periodically in MSHA bottle samples. A certain amount is expected to be flushed out. Should a steady increase in CO (and possibly H_2) indicate a rekindling, the area should be immediately sealed. Should the area not be flushed, an on-site meeting will be conducted to determine what secondary procedures can be implemented to expedite the flushing of the seal regions–such as enlarging the opening in the 2 North seal and/or adding additional restrictions across the 1 East Mains returns to force more air into the seals. Bottle samples shall be taken daily for 2 weeks and sent to MSHA's Mt. Hope, WV, Laboratory. The evaluation checkpoints A and B shall be used solely in evaluating the entire sealed region. A determination shall be made at a later date as to whether these two points are sufficient (long term), or one of two of the following options will have to be instituted.

1. Rehabilitate 1 North to establish a bleeder checkpoint and rehabilitate 2 North Mains inby Big Daddy Mains to establish the water level in 3 East and 4 East as well as bleeder check points.

2. 1 North shall be resealed at its present location, and 2 North shall be resealed inby Big Daddy Mains.

After the seals have been broken and the area is bleeding normally, the power shall be reenergized and the 1 North and 2 North areas be flushed 24 h prior to checking the newly established permanent checkpoints at 1 North and 2 North Mains.

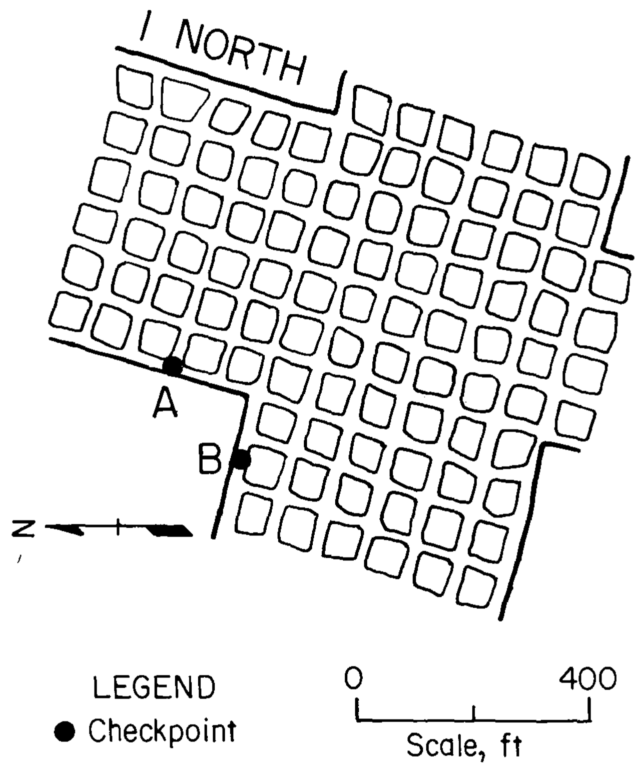

Figure C-1.–Location of checkpoints.

APPENDIX D.–VOLUME CALCULATION BEHIND SEALED AREA

Total length of airway: 23,400 ft

Average seam height: 5 ft

Average seam width: 20 ft

Equivalent entries:	Number of entries	= 7
	Number of crosscuts	= 6
	Crosscuts	= 75 ft centers
	Entries	= 55 ft centers
	7 + [6 (55/75)]	= 11.4
	Volume	= 23,400 ft × 5 ft × 20 ft × 11.4 = 26,676,000 ft^3

APPENDIX E.–CALCULATIONS OF PURGE TIMES

Plug flow: Assume that fresh air displaces ambient gas without mixing.

$$\frac{\text{Volume}}{\text{Airflow}}$$

Hartman (*4*):[1]

$$\log_{10} \frac{Q_g - Qx}{Q_g - Qx_0} = \frac{t}{2.303} \; \frac{Q}{Y},$$

where $Y = 26{,}676{,}000 \text{ ft}^3$,

$Q = 22{,}500$ cfm,

t = time, min,

$Q_g = 0$,

$x = 31$ pct,

$x_0 = 1.5$ pct,

and time = 3,591 min = 60 h.

Guffey (*5*):

$$t = [R(M)/Q] \; \ln (C_1/C_t)$$

where $R = 26{,}676{,}000 \text{ ft}^3$,

$C_1 = 31$ pct,

M = mixing factor = 2,

$C_t = 1.5$ pct,

$G = 0$ cfm,

$Q = 22{,}500$ cfm,

and time = 7,181 min = 120 h.

Mateer (*6*):

Dilution follows a logarithmic decay curve:

Time = 8,274 min = 138 h.

[1]Italic numbers in parentheses refer to items in the list of references preceding appendix A.

APPENDIX F.–CALCULATIONS OF PURGE TIME AFTER INCREASE IN AIR VOLUME

Plug flow: Assume that fresh air displaces ambient gas without mixing.

$$\frac{\text{Volume}}{\text{Airflow}}$$

Hartman (*4*):[1]

$$\log_{10} \frac{Q_g - Qx}{Q_g - Qx_0} = \frac{t}{2.303} \frac{Q}{Y}$$

Y	= 26,676,000 ft^3,	Y	= 26,676,000 ft^3,
Q	= 22,500 cfm,	Q	= 31,000 cfm,
t	= time, min,	t	= time, min,
Q_g	= 0,	Q_g	= 0,
x	= 31 pct,	x	= 4.8 pct,
x_0	= 4.8 pct,	x_0	= 1.5 pct,
$time_1$	= 2,212 min,	$time_2$	= 1,001 min,

$$\text{Total time} = time_1 + time_2 = 3{,}213 \text{ min} = 54 \text{ h.}$$

Guffey (*5*):

$$t = [R(M)/Q] \ \ln (C_1/C_t)$$

R	= 26,676,000 ft^3,	R	= 26,676,000 ft^3,
C_1	= 31 pct,	C_1	= 4.8 pct,
M	= mixing factor = 2,	M	= mixing factor = 2,
C_t	= 4.8 pct,	C_t	= 1.5 pct,
G	= 0 cfm,	G	= 0 cfm,
Q	= 22,500 cfm,	Q	= 31,000 cfm,
$time_1$	= 4,423 min,	$time_2$	= 2,002 min,

$$\text{Total time} = time_1 + time_2 = 6{,}425 \text{ min} = 107 \text{ h}$$

Mateer (*6*):

Dilution follows a logarithmic decay curve. During the fourth air exchange the airflow was increased from 22,500 to 31,000 cfm.

$$\text{Time} = 6{,}999 \text{ min} = 117 \text{ h.}$$

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[1]Italic numbers in parentheses refer to items in the list of references preceding appendix A.

APPENDIX G.–TRACER GAS RELEASED AT 2 NORTH AND RECOVERED AT 1 NORTH

A known volume of SF_6 was released in the opening of 2 North. The mass of the released gas was determined using the change in mass of the pressurized cylinder.

Mass of SF_6 released = 195.5 g per molecular weight of SF_6 = 146.1 g/mol

$$\text{Moles of } SF_6 \text{ released} = \frac{195.5 \text{ g}}{146.1 \text{ g/mol}} = 1.34 \text{ mol}$$

$$\text{Volume per mol} = 22.4 \text{ L}$$

$$1.34 \text{ mol} \times 22.4 \text{ L/mol} = 29.9 \text{ L} = \text{volume of } SF_6 \text{ released.}$$

The mass of SF_6 recovered at 1 North was determined by adding all the SF_6 that was recovered at 1 North and dividing that by the number of samples in which a measurable quantity of SF_6 was present. The average concentration of SF_6 for the sampling period of 5,445 min was equal to 0.00809 ppm. Knowing the average concentration, the airflow volume exiting 1 North, and the sampling time, one is able to calculate the amount that was recovered:

$$0.00809 \times 10\text{E-}6 \text{ ft}^3 \text{ } SF_6/\text{ft}^3 \text{ air} \times 22{,}580 \text{ cfm} \times 5{,}445 \text{ min} \times 28.2 \text{ L/ft}^3 = 28.1 \text{ L} = \text{volume of } SF_6 \text{ recovered.}$$

The SF_6 volume recovered is nearly equivalent to the amount released.

APPENDIX H.–VELOCITY CALCULATIONS INBY SEALS

Case 1: Behind the number 1 opening in 2 North were two interconnected entries separated from other entries by a stopping line. Assume no leakage.

Air volume: 22,500 cfm

Equivalent entries: 2 + 1(55/75) = 2.73

Entry width: 20 ft

Entry height: 5 ft

$$\text{Velocity} = 22{,}500 \text{ cfm} / (2.73 \times 20 \text{ ft} \times 5 \text{ ft}) = 82.3 \text{ fpm}$$

Case 2: Normal leakage exists in all stopping inby the seals.

Air volume: 22,500 cfm

Entries: 7

Entry width: 20 ft

Entry height: 5 ft

$$\text{Velocity} = 22{,}500 \text{ cfm} / (7 \times 20 \text{ ft} \times 5 \text{ ft}) = 32.1 \text{ fpm}$$

Case 3: The stoppings inby the seals are not intact-destroyed. Equivalent entries are used to account for the space in the crosscuts.

Air volume: 22,500 cfm

Equivalent entries: 7 + 6(55/75) = 11.4

Entry width: 20 ft

Entry height: 5 ft

$$\text{Velocity} = 22{,}500 \text{ cfm} / (11.4 \times 20 \text{ ft} \times 5 \text{ ft}) = 19.7 \text{ fpm.}$$

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