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Three Coal Mine Ventilation Studies Using Sulfur Hexafluoride Tracer Gas

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Three Coal Mine Ventilation Studies Using Sulfur Hexafluoride Tracer Gas

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THREE COAL MINE VENTILATION STUDIES USING SULFUR HEXAFLUORIDE TRACER GAS

by

Robert P. Vinson[1] and Fred N. Kissell[2]

ABSTRACT

This report describes three coal mine ventilation studies by the Bureau of Mines in which sulfur hexafluoride (SF_6) was used as a tracer gas. One of these studies was conducted to determine air movement and leakage in a sealed area. Another was run to determine the ventilation efficiency of a bleeder system. Finally, a study was made of air leakage across permanent stoppings of parallel intake airways. These studies proved sulfur hexafluoride to be a useful addition to the equipment commonly used in coal mine ventilation analysis.

INTRODUCTION

Sulfur hexafluoride has been used to analyze ventilation in large buildings, for meteorological studies, in gas reservoir analysis, etc. (2, 4, 6).[3] It is an ideal gas for this type of work because it is odorless, colorless, chemically and thermally stable, and safe to breathe at high concentrations (7). In addition, sulfur hexafluoride can be detected at low concentrations by gas-solid chromatography using electron-capture detection (1, 9-10).

Recently, the Bureau of Mines has developed procedures for using SF_6 as a tracer gas for mine ventilation studies in cases where conventional equipment cannot be used (11-12). Except for some preliminary work, these studies were conducted in noncoal mines. Because coal mines have many different kinds of ventilation problems, particularly associated with ventilation of and/or leakage through abandoned areas, we felt it worthwhile to do a separate series of coal mine studies with SF_6.

This report discusses three tracer gas ventilation studies conducted in underground coal mines. The first study was conducted to investigate air movement and leakage in a sealed area. A second study was made to determine the effectiveness of a bleeder system. The third study was used to evaluate

[1] Physicist.
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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

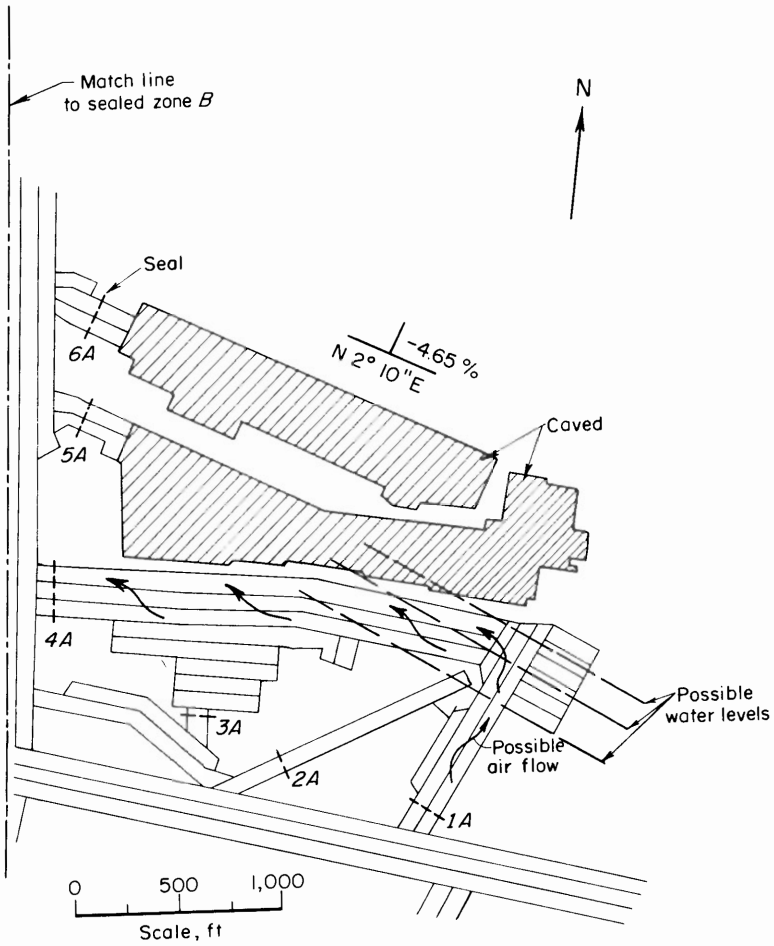

FIGURE 1. - Sealed zone A.

the sealing efficiency of a series of permanent stoppings between parallel intake airways.

FIRST STUDY: AIR MOVEMENT IN A SEALED AREA

This study was conducted in a mine working the B and C coal seams of the Somerset coalfield in western Colorado. Air leakage and air movement were investigated in a partially pillared sealed-off area, subdivided into zones A and B (figs. 1-2) by a four-entry heading. The coalbed in this region dips toward the northeast. Zone A is partially flooded (fig. 1), but the exact water level is unknown. Approximately 60 ft above zones A and B are old workings of C seam. These old workings are connected to the surface by a 10-in-diam borehole. An air shaft and two tunnels, which formerly gave access to the upper seam from the lower, have been sealed. These seals and the seals enclosing zones A and B were constructed of cemented concrete block that was then sprayed with urethane foam. Adjacent ribs and roof were also sprayed. A pipe with valve was inserted into each seal for gas sampling.

Air Movement--Zone A

Zone A contained a high concentration of carbon monoxide. Because of the self-heating nature of the coalbed, efforts were made to contain and reduce the CO to prevent leakage into the mine atmosphere. The carbon monoxide concentration was greatest on the east side behind the seals at location 1A (fig. 1). An "intake" air pressure differential was maintained across 1A seals. This means that the air pressure on the active mine side of the seal is greater than the air pressure on the sealed-zone side. This would tend to keep CO-contaminated air from migrating into the mine atmosphere in the immediate vicinity. Intake pressure was sustained by channeling high-pressure intake air directly across 1A seals.

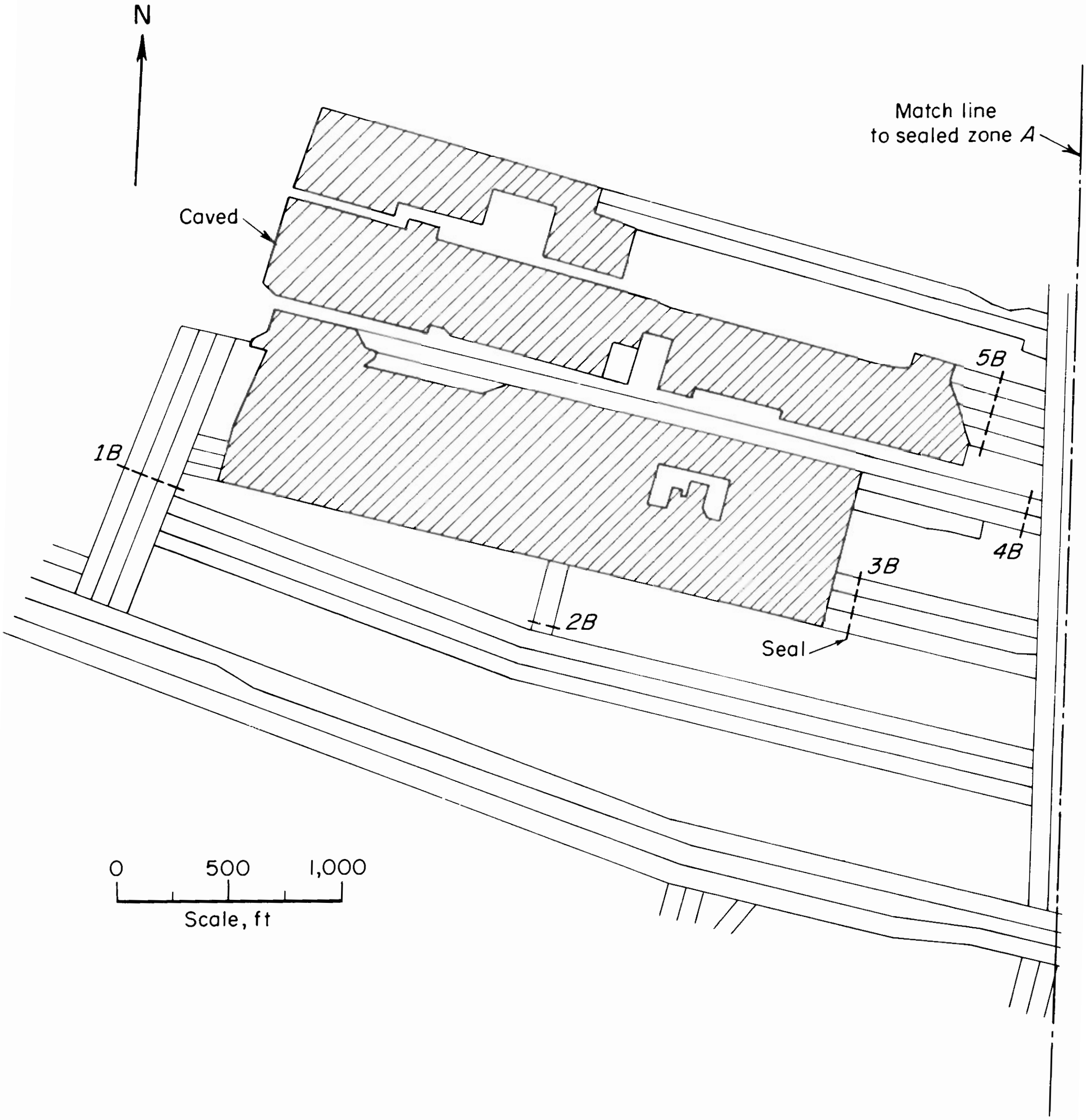

FIGURE 2. - Sealed zone B.

Normally, the other sealed locations were ventilated by lower pressure return air. This produced an "exhaust" pressure differential across these seals. This tended to pull air out of the sealed zone. The combination of exhausting and intaking pressure differentials would possibly pull CO-contaminated air from the east side to the west side of zone A. Normally, the oxygen in the sealed zone was depleted, but air movement would bring in fresh oxygen, which would react with the coal and produce fresh CO. An attempt was made to reduce the possible air movement at locations 2A and 3A by placing these seals on intake air pressure. This was done by building a second set of seals outby the first and connecting the air space between to intake air pressure by running tubing from an intake airway to the air space, as shown in figure 3 (3). These changes reduced the seal pressure differentials. Table 1 shows that exhaust pressures at 2A and 3A were lower than exhaust pressures at 4A, 5A, and 6A, which were not connected to intake air.

TABLE 1. - Air movement test in zone A, seal pressure in inches water gage

Day	Location							
	Right 1A	Center 1A	Left 1A	2A	3A	4A	5A	6A
0	I 0.06	X	I 0.06	Static	E 0.30	E 0.39	E 0.20	E 0.18
1	I 0.09	X	E 0.02	E 0.01	E 0.12	E 0.34	E 0.24	E 0.34
3	I 0.03	I 0.02	I 0.02	E 0.01	E 0.05	E 0.15	E 0.19	E 0.21
4	I 0.01	I 0.03	I 0.02	Static	E 0.14	E 0.31	E 0.36	E 0.34
8	I 0.09	I 0.07	I 0.07	Static	E 0.10	E 0.29	E 0.22	E 0.20
36	I 0.05	I 0.05	I 0.10	Static	I 0.02	E 0.12	E 0.10	E 0.15
70	I 0.07	X	I 0.04	E 0.01	Static	E 0.12	E 0.10	E 0.08

Static--No differential pressure.
I--Intaking pressure differential.
E--Exhausting pressure differential.
X--No pressure measurements taken.

Another factor relating to air movement within zone A was the position of the water level. If this level was maintained high enough, the entries behind 1A seals would be blocked off from the other sealed-off entries. This would prevent air movement in the sealed area, the input of fresh oxygen would be reduced, and high CO concentrations might be confined to the entries immediately behind seals at 1A. However, there was no definite way of knowing where the water level was, or whether in fact, it was blocking the entries behind 1A seals.

Tracer gas was used to determine if the flooding was blocking air in 1A and if not, whether the air was moving from east to west as shown in figure 1. For this purpose, 3.9 cu ft of SF_6 was injected through a pipe in the center seal of location 1A. Gas samples were then collected at various locations surrounding the enclosed area on day zero (the day SF_6 was injected) and 1, 3, 4, 8, 36, and 70 days after SF_6 injection. The sampling schedule was rather erratic because there were no established guidelines since this was the first test of this type. When SF_6 was detected, the location, date of sample, and measured concentration were plotted (fig. 4). Lines connecting the same location from day to day give the general history of the tracer gas at each measured location.

On day zero, SF_6 was detected only at the left and right seals of 1A, with the right seal showing its highest SF_6 concentration. In the following days, the SF_6 concentration declined as the gas moved away from the right seal.

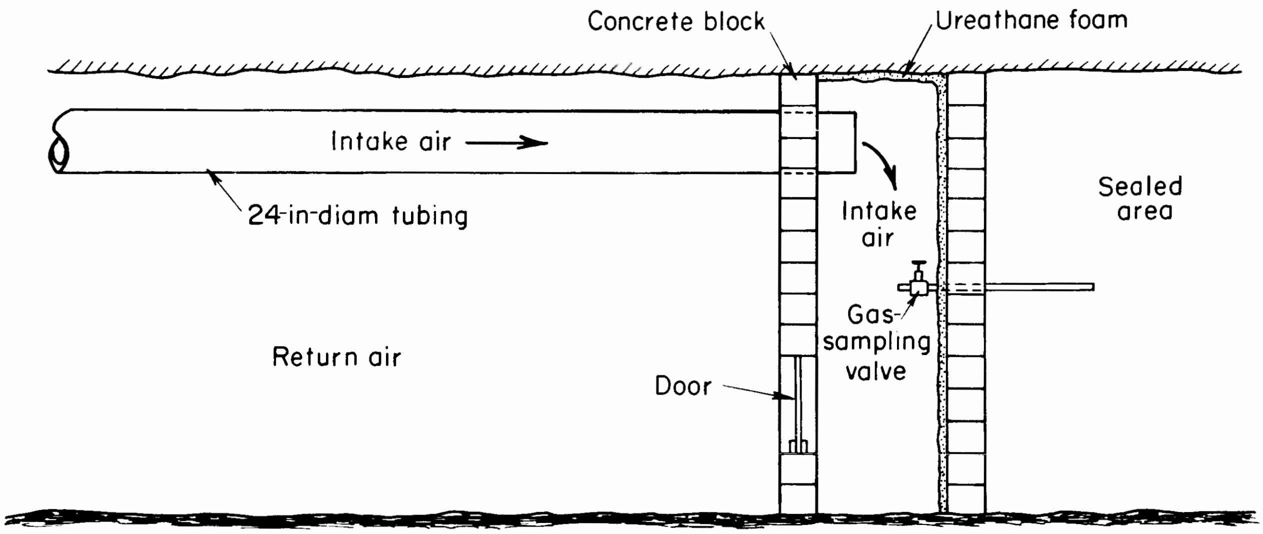

FIGURE 3. - Double seals.

Tracer gas concentrations at the left seal of 1A increased gradually until day 3, when the highest concentration was measured. This lag, with respect to the right seal, is probably due to the fact that the tracer had to travel approximately 150 ft and penetrate a stopping before reaching the left seal. However, the left seal attained a much higher concentration than the right, suggesting that the air was moving in a westerly direction. After the tracer reached peak concentration, it showed a constant decline.

Samples were first obtained from behind the center seal of 1A on day 3. Because this was where SF_6 was injected, the concentration was very high, almost 10,000 ppb. This seal showed the same rapid decline in SF_6 as the other seals at 1A.

The sequence in which SF_6 was first detected at locations 1A left to 4A is evidence that there was air movement behind the seals from east to west. The further west the seals were, the longer it took before SF_6 appeared (fig. 4). Only location 2A does not follow this sequence. This is probably because 2A is connected to the main body of sealed air by one entry (fig. 1). Also, the low exhaust pressures at 2A would tend to pull air at a much slower rate than other seals. The comparatively low SF_6 concentration is an indication that there was a weak connection to the main body of sealed air.

Arrival times of the peak concentration of SF_6 at locations 1A left through 4A follow the same sequence as the first appearance of tracer gas at each location. This would also indicate that the main body of SF_6 was slowly moving to the west side of zone A.

The last location at which SF_6 was measured was at the 5A seals. The area behind these seals is separated from the main zone of SF_6 injection by a 50-ft coal barrier. Tracer gas migrated through the coal and to the seal sometime between the 8th and 36th day.

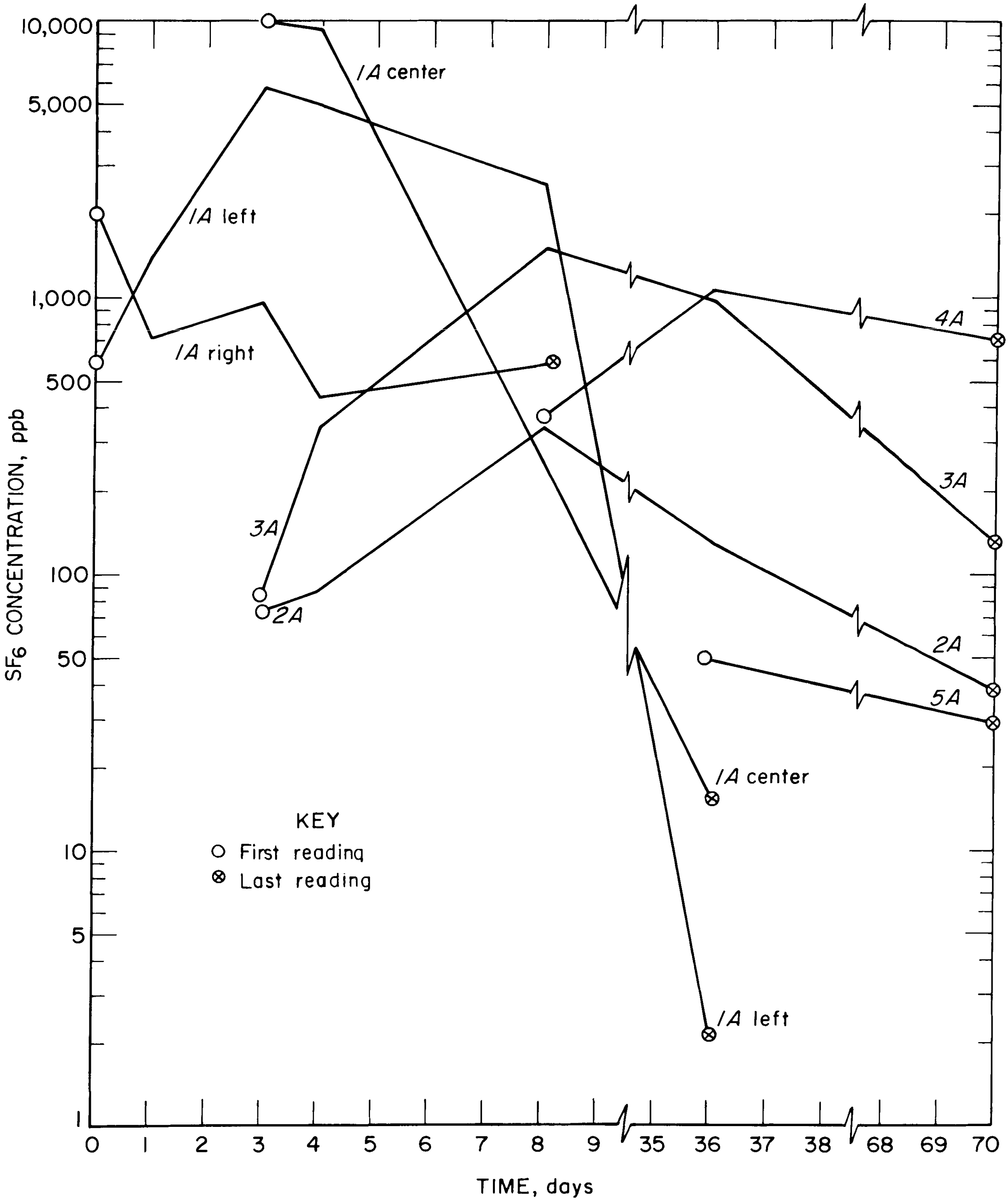

FIGURE 4. - Sulfur hexafluoride concentration as a function of time at each sampling location.

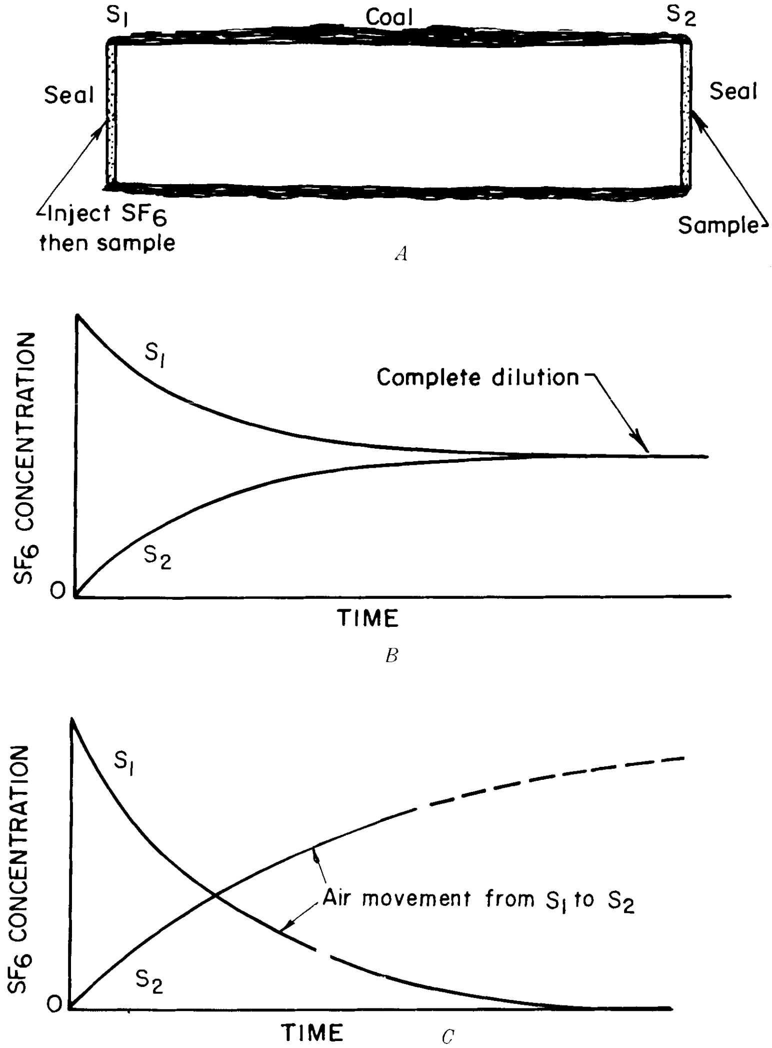

FIGURE 5. - Sulfur hexafluoride concentration in a simple enclosed area. *A*, Simple enclosed area; *B*, SF_6 concentration at S_1 and S_2 due to diffusion; *C*, SF_6 concentration at S_1 and S_2 due to air movement from S_1 to S_2.

The decline of SF_6 in the area of injection and the increase on the western side of zone A is positive evidence that air migrated from east to west behind the seals. If there were no air movement in zone A, the SF_6 would eventually diffuse equally throughout the sealed zone. For example, let us assume a simple enclosed area (fig. 5). If a volume of SF_6 is injected at S_1, it will diffuse until the SF_6 concentration at S_1 and S_2 are equal. Figure 5B illustrates how, with time, the S_1 and S_2 curves would meet at a single asymptote. If air moved from S_1 to S_2, the SF_6 concentrations would vary as shown in figure 5C. The S_1 curve would gradually decrease and cross the S_2 curve, which would gradually increase. This is essentially the case at the zone A sealed area.

The zone A study area contained approximately 3.56×10^6 cu ft of air space into which 3.92 cu ft of SF_6 was injected. If there was no air movement and the SF_6 dispersed evenly, the concentration would eventually be 1.1 ppm throughout the enclosed zone. This, however, was not the case. In figure 4, concentration curves 1A cross 2A, 3A, and 4A, in the same way as in figure 5C, indicating that air was moving from east to west, despite the reduced pressure differentials at 2A and 3A. It indicates also that the water level was not blocking off the region behind 1A from the rest of the sealed area. Fresh oxygen was still entering at 1A and generating CO.

Subsequent to these tracer gas tests, fresh water was piped into the zone to raise the level. This reduced the CO concentrations to a safe level, indicating that the raised water level had blocked air movement and reduced the oxygen influx.

Leakage From Upper Seam Into Zones A and B

The objective of this part of the study was to determine if air from the old workings of the upper seam was leaking into sealed zones A and B of the lower seam. There was reason to believe leakage was occurring. The upper seam was known to have methane gas. Methane was measured at seals 1B and 2B in the lower seam (zone B, fig. 2). To determine if there was air leakage between seams and if this was carrying the methane, SF_6 was injected into the upper seam through the surface borehole. Gas samples were then taken at seals enclosing zones A and B in the lower seam. These samples were then analyzed for SF_6, methane, and carbon monoxide. Air pressure differentials across the seals were also measured at each sampling location. A recording microbarograph located outside the mine was used to keep track of atmospheric pressure changes during the test period.

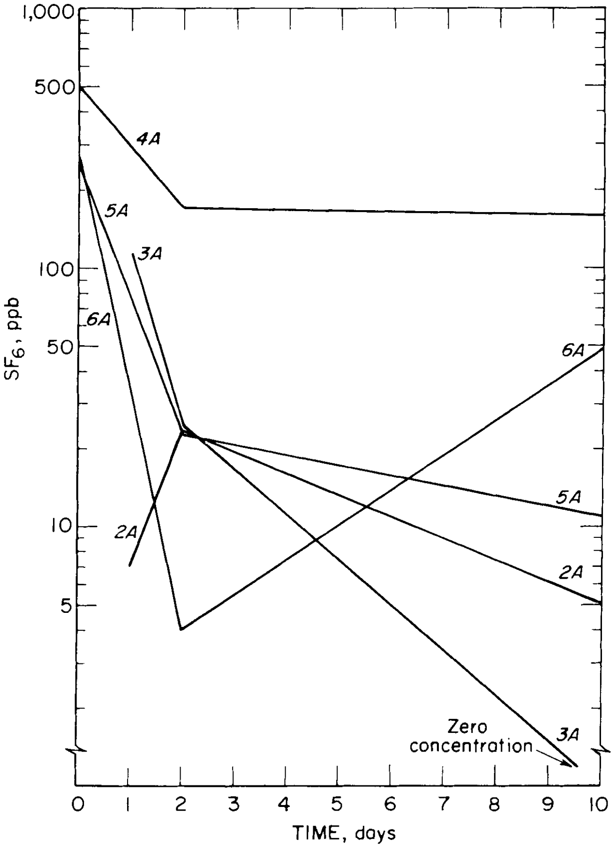

FIGURE 6. - Sulfur hexafluoride concentration as a function of time at sampling locations in zone A.

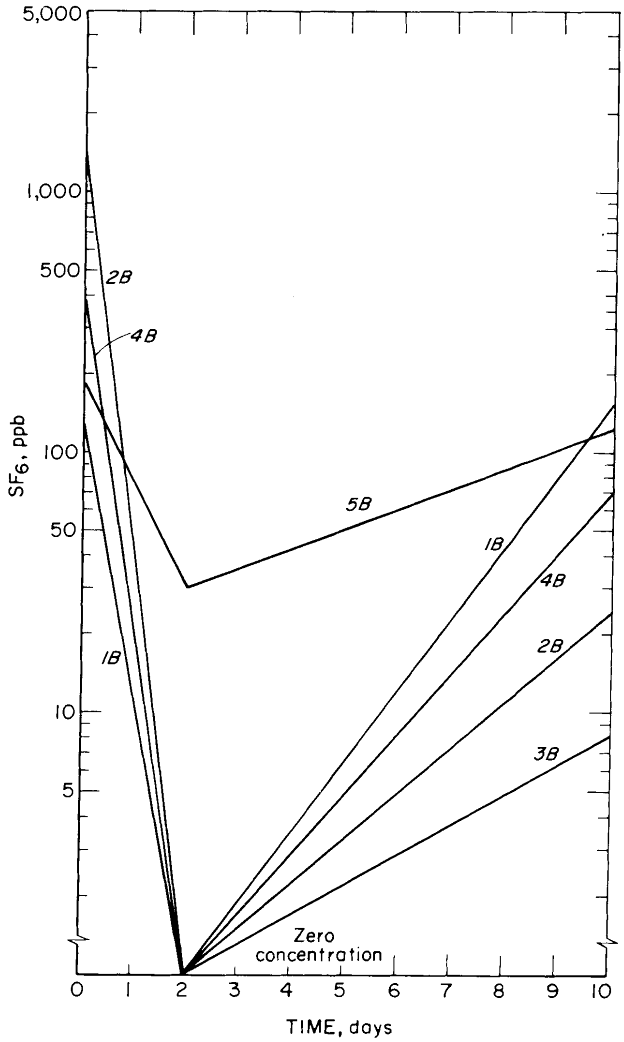

FIGURE 7. - Sulfur hexafluoride concentration as a function of time at sampling locations in zone B.

Within 3 hours after injection, SF_6 was detected at seven sampling locations showing that air from the upper seam was, in fact, leaking into both sealed zones A and B in the lower seam. Later, SF_6 appeared at three more locations.

The manner in which SF_6 varied at the seals is shown in figures 6 and 7. Most seals have a significant dip in concentration on day 2. On day 10, there was a rise in SF_6 concentration at five of the seals. This may be related to barometric pressure variations. As atmospheric pressure changes, there is a corresponding change in the mine air pressure. However, in the enclosed area, air pressure changes lag behind atmospheric changes. This in turn produces fluctuations in the pressure differentials across the seals. As the mine air pressure rises, the seals with exhaust pressure decrease and the seals with intake pressure increase. The opposite takes place with a drop in mine air pressure. Barometric pressure was dropping on days zero and 10, but was rising on day 2. Figures 8 and 9 show how the seal pressures varied during the test period. Seals 1B and 2B had unusually high exhaust pressures because they were in close proximity to one of the exhaust ventilating fans. With the exception of 4B, all seals having exhausting pressure showed a drop in pressure on day 2.

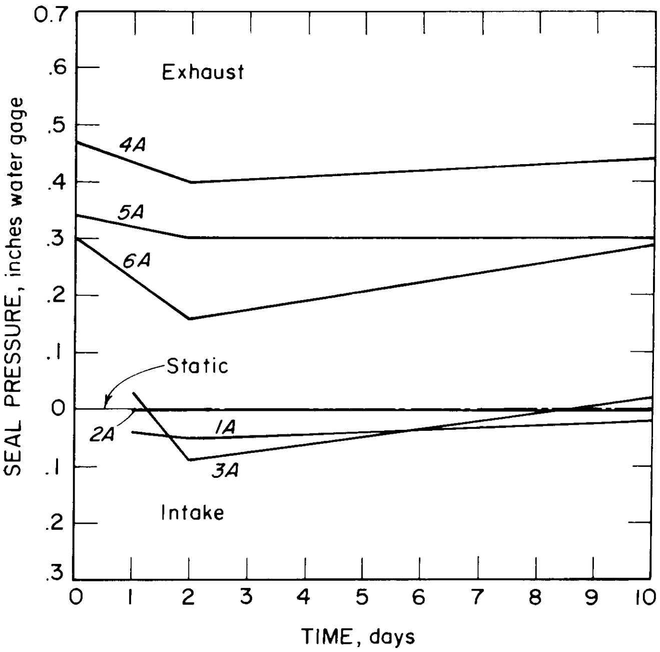

FIGURE 8. - Air pressure across seals as a function of time in zone A.

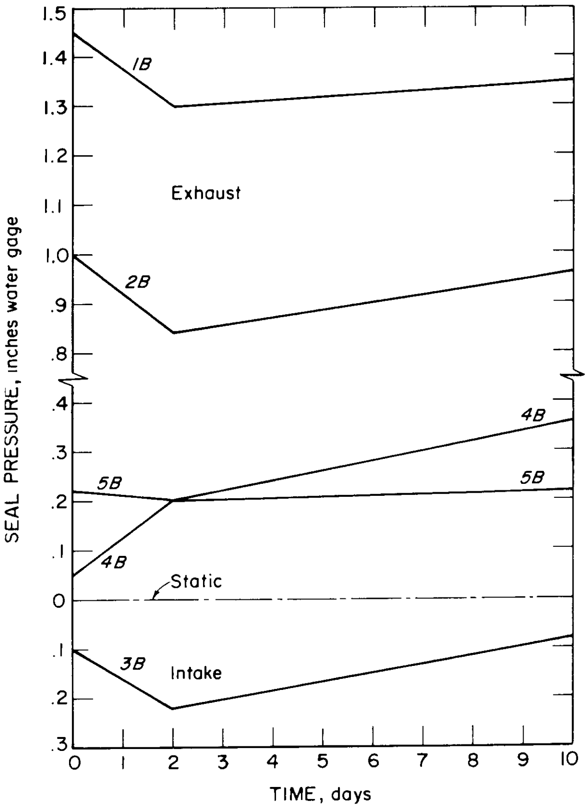

FIGURE 9. - Air pressure across seals as a function of time in zone B.

Pressure variation at seal 3A was most dramatic, changing from exhausting pressure to intaking pressure from day zero to day 2 and then back to an exhausting pressure on day 10. Seals with intaking pressures (1A and 3B) showed higher intaking pressures on day 2. These changes fit in with the barometric pressure rise on day 2. The only exception is 2A, which remained static because of its weak connection to the main body of sealed air.

Following injection into the borehole, tracer gas was detected at all seals with exhaust pressure differentials on day zero or day 1 (figs. 6 and 7). On day 2, the tracer declined or disappeared completely at these same seals following the barometric pressure rise. The relationship between seal pressure and SF_6 concentration was not so apparent on the 10th day. However, there was evidence to show that the relationship was still holding because there was an increase in SF_6 at four out of six seals that had higher exhaust pressures. This is another indication that air leakage across seals is influenced by atmospheric pressure changes.

Gas samples were also analyzed for CO and CH_4. The CO concentrations are shown in figures 10 and 11. Note that location 1A has by far the highest CO despite the fact that it was always intaking. This indicates that the CO source is close to the seals at this location because of the fresh air leaking in here.

Figure 12 shows CO versus CH_4 concentrations for all measurements on all seals. There seems to be little correlation aside from the fact that the very

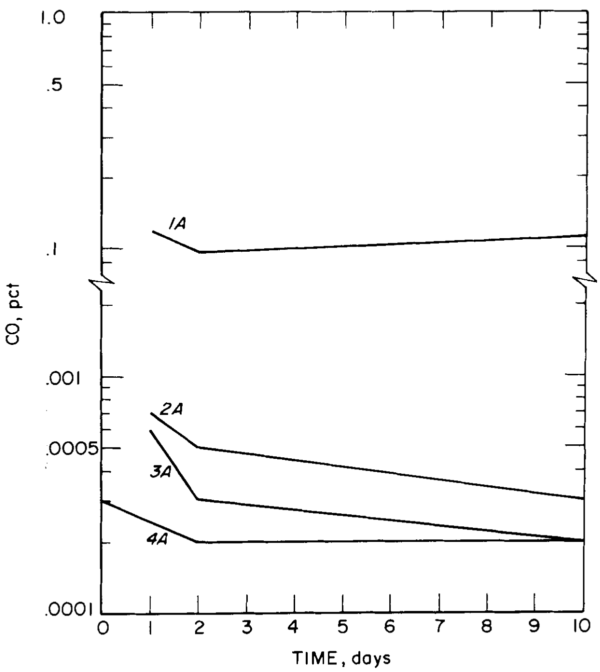

FIGURE 10. - Carbon monoxide concentration as a function of time in zone A.

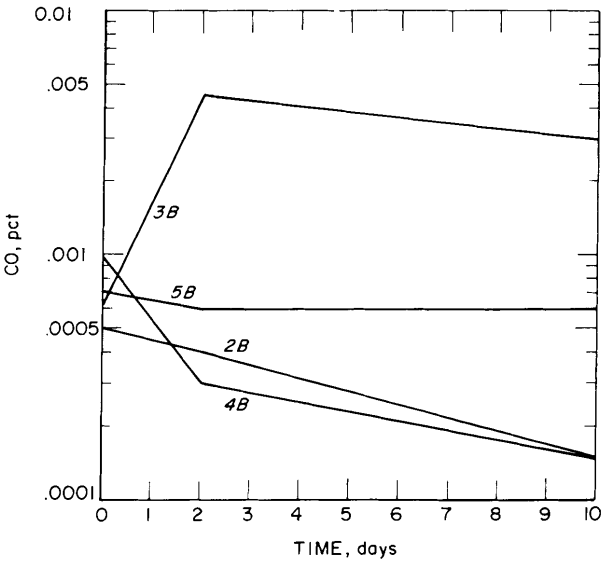

FIGURE 11. - Carbon monoxide concentration as a function of time in zone B.

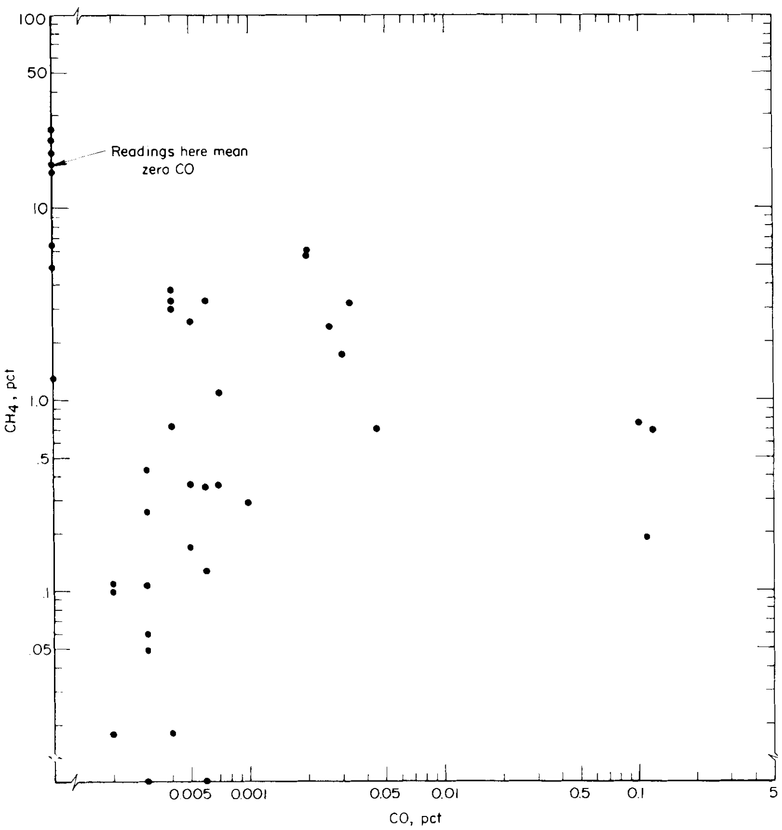

FIGURE 12. - Methane concentration as a function of CO concentration.

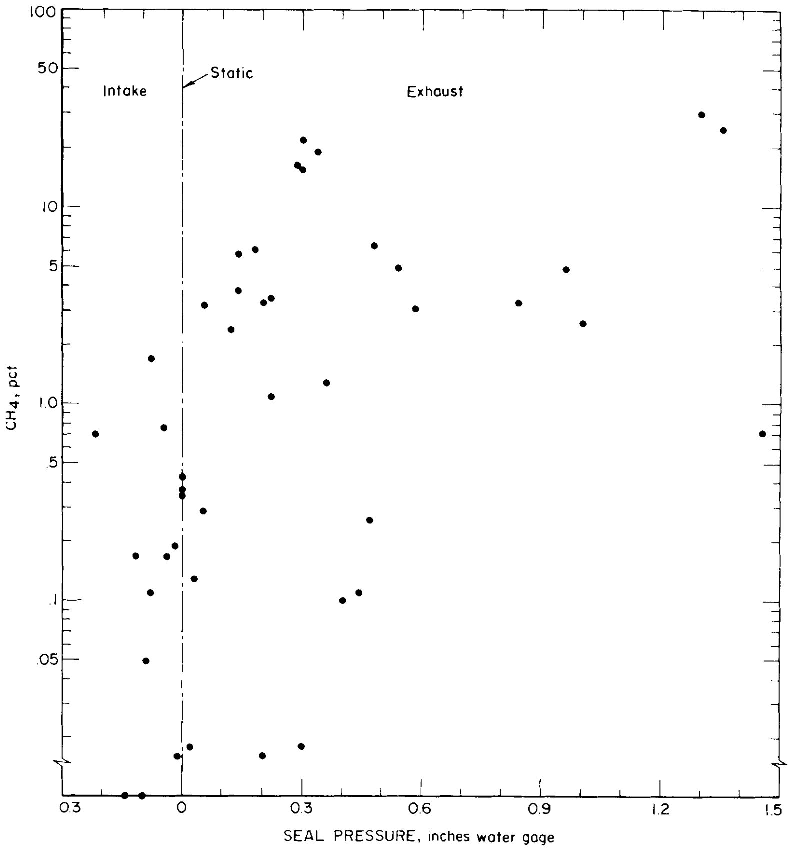

FIGURE 13. - Methane concentration as a function of seal pressure.

highest methane concentrations corresponded to zero CO concentrations. This confirms that CO and CH_4 originate in different locations.

Figures 13, 14, and 15 show CH_4, SF_6, and CO concentrations, respectively, versus seal pressure for all measurements on all seals. Figures 13 and 14 indicate that when the seals were exhausting, the CH_4 and SF_6 levels were generally higher than when the seals were intaking. However, in figure 15, CO levels are lower when the seals are exhausting, which lends strength to the notion that the SF_6 and CH_4 are not generated in the lower seam (this is certainly true for the SF_6), and that the CO comes from reactions with oxygen that leaks in through the lower seam seals when the seals are intaking.

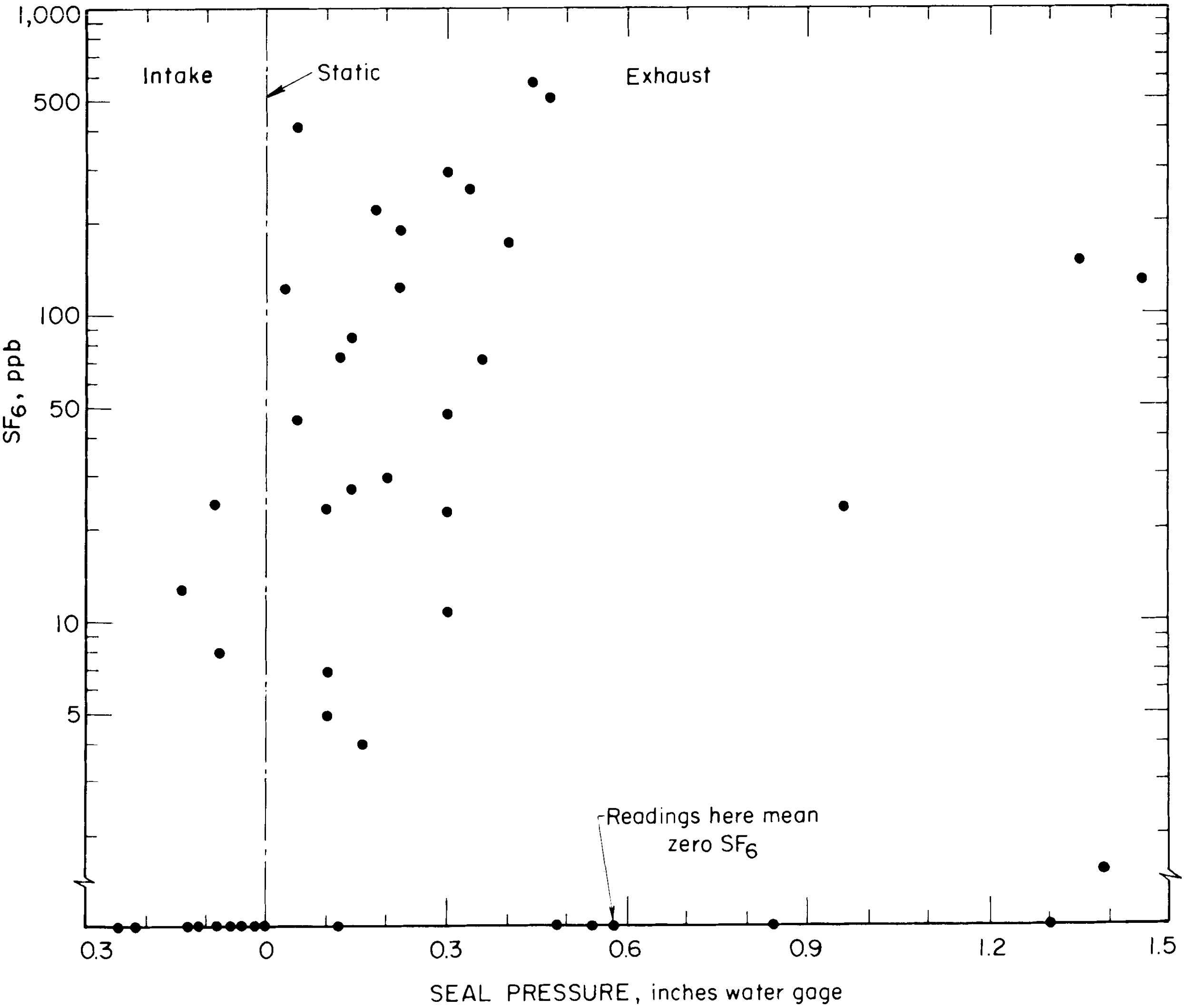

FIGURE 14. - Sulfur hexafluoride concentration as a function of seal pressure.

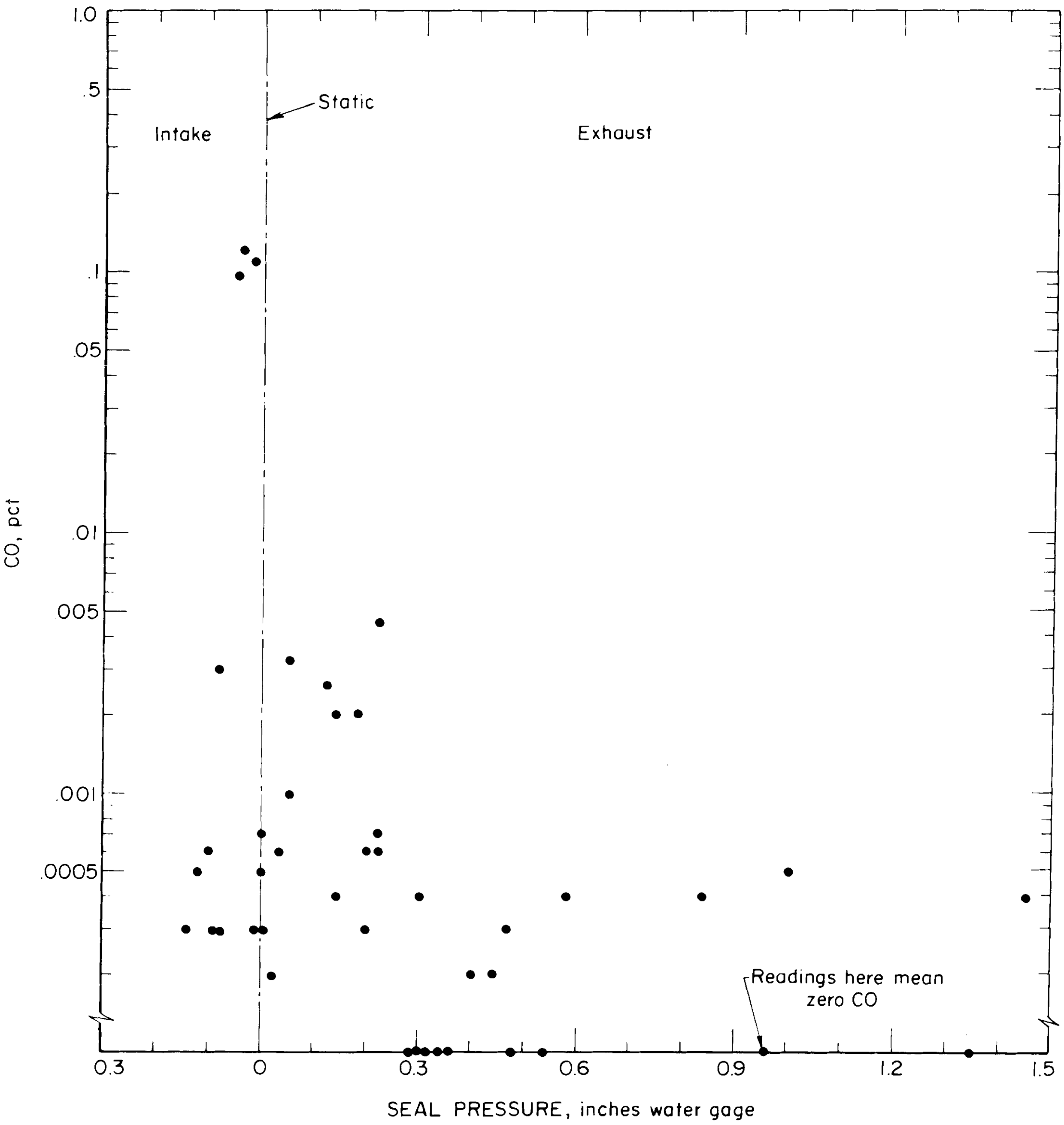

FIGURE 15. - Carbon monoxide concentration as a function of seal pressure.

SECOND STUDY: AIRFLOW TEST IN A PILLARED-AND-CAVED AREA

The methane content of the air emerging from a ventilated gob may not be a very good indicator of the methane content in the gob interior. It is easy to visualize gob ventilation air following some open path of least resistance which short-circuits around the gob edge and does a very poor job of ventilating the gob interior.

Short-circuit paths, if they do exist, should reduce the pressure drop across the gob. The air velocity along these paths would probably be relatively high, if they carry most of the air intended for the gob. The pressure drop across the gob can be measured in the conventional way using altimeters. However, the only way to measure air velocity within a gob is to use a tracer gas.

A ventilated gob investigated with SF_6 tracer gas is shown in figure 16. The mine is located in northern West Virginia and works the Pittsburgh coalbed. The section studied was advanced by the room-and-pillar method, and then immediately retreated and caved by mining the pillars. To trace the airflow, 1.6 cu ft of SF_6 was released at location A. Air samples were taken at 2-min intervals at location B, a regulator where the gob air emerged into a bleeder system. The air quantity passing through the gob measured at B was 4,050 cu ft/min. A conventional altimeter survey indicated that the pressure drop between A and B was 0.69 in w.g. The gob was about 1,200 ft long and 350 ft wide. The SF_6 tracer gas was detected at B, 60 min after it was released at A.

Since the tracer gas traveled only 1,200 ft in 60 min, the air velocity in the gob was relatively low (20 ft/min). This low velocity, coupled with a moderately high pressure drop of 0.69 in w.g., indicates that there was no major short-circuit path through the gob. This can be verified by the following example: Suppose the gob had a major short-circuit path that carried

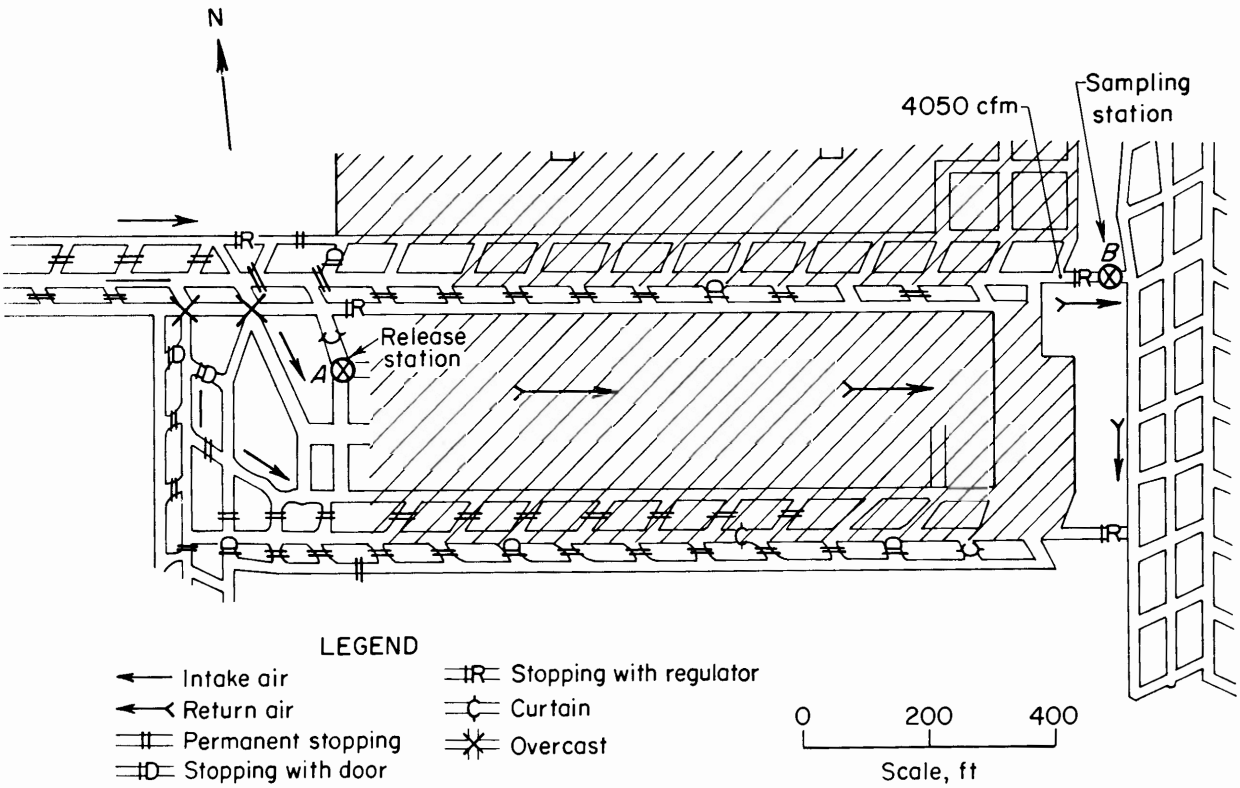

FIGURE 16. - Ventilated gob.

three-quarters of the gob air (3,000 cu ft/min). Suppose further that this path is a square passage 1,200 ft long and width D, and that it has a friction factor of 250 $\times$ 10^{10}. The Atkinson equation is as follows (5):

$$H_F = \frac{KPLV^2}{5.2A},$$

where H_F = friction loss, inches of water,

V = velocity, ft/min,

A = area, ft^2,

P = passage perimeter, ft,

K = friction factor for air of standard density (0.075 lb/ft^3),

and L = length, ft.

If the width is D, the perimeter is 4D and the area is D^2. If the Atkinson equation is solved simultaneously with the relation Q = AV, where Q is the air quantity in cubic feet per minute, then D $\cong$ 3 ft and V $\cong$ 300 ft/min. At this velocity, the SF_6 tracer would have traversed the gob in 4 min, but the actual time was 60 min. The same disparity between the calculated and actual velocities exists even with a tenfold increase in the friction factor or even assuming multiple short-circuit paths, each carrying smaller air quantities. From this, it may be inferred that an SF_6 arrival time of 60 min and a pressure drop of 0.69 in w.g. are not consistent with the concept of a few major passages around the gob edge. Thus, a different sort of approach is indicated.

A better solution might be to visualize the gob as having a permeable and an impermeable region and to estimate the relative size of the two regions as follows: If the SF_6 traveled 1,200 ft in 60 min, the air velocity was 20 ft/min. Since the air volume was 4,050 cu ft/min, the open area for flow was $\frac{Q}{V} = \frac{4,050}{20} \cong 200\ ft^2$. If this open area is in the permeable region, the size of that region can be calculated, based on an assumed void volume.

Miletich (8) has given void volumes (porosities) for longwall gobs in the Soviet Union. At a distance of 2,000 ft from the working face, typical values range is from 34% to 48%. If 40% is assumed, then the area of the permeable region is

$$\frac{200}{0.4} = 500\ ft^2.$$

Although these numbers are very approximate, they do indicate that no short-circuit path existed in this gob and that the permeable region occupied a fair percentage of the total cross-sectional area.

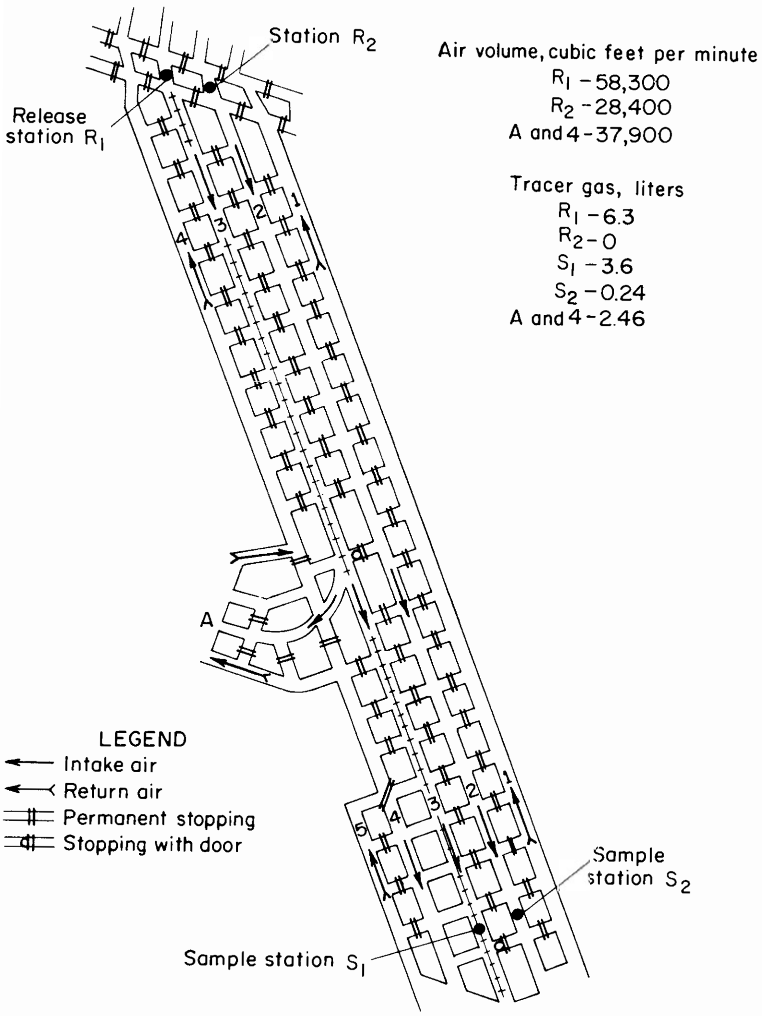

FIGURE 17. - Four-entry heading.

THIRD STUDY: STOPPING LEAKAGE

A mine working the C seam of the Somerset coalfield was the location of this study. The purpose was to determine the direction and amount of air leakage across a row of permanent stoppings separating two intake airways of a four-entry system. No pressure difference between these two intake airways could be detected with a manometer. Outside entries 1 and 4 were return airways (fig. 17). Tracer gas was released in entry 3 at station R_1 and gas samples were collected at S_1 and S_2, both 1,650 ft inby the release station. Approximately 6.3 liters was released and gas samples at S_1 and S_2 accounted for 3.6 and 0.24 liters, respectively (fig. 18). This was 61% of the amount released.

Unmeasured SF_6, 39% of the amount released, was diverted into two other entries at location A and entry 4. According to anemometer measurements, 44% of the intake air, and therefore 44% of the SF_6, should have been diverted. However, a difference of 5% between tracer gas and air measurements is not significant.

Measured air volume results also show that entry 2 lost 7,700 cu ft/min of air between the release and sampling stations, so the net leakage was from entry 2 into entry 3. Despite this, some air did leak the other way from entry 3 into entry 2 because the coal train traveling in and out of entry 3 created a temporary backflow into entry 2. This backflow forced $\frac{0.24}{6.3} = 3.8\%$ of the SF_6 from entry 3 into entry 2, even though the net flow was the other way.

The first 12 stoppings were constructed of cemented concrete block, and the last 8 were constructed of thin sheet metal on wooden frames. The sheet

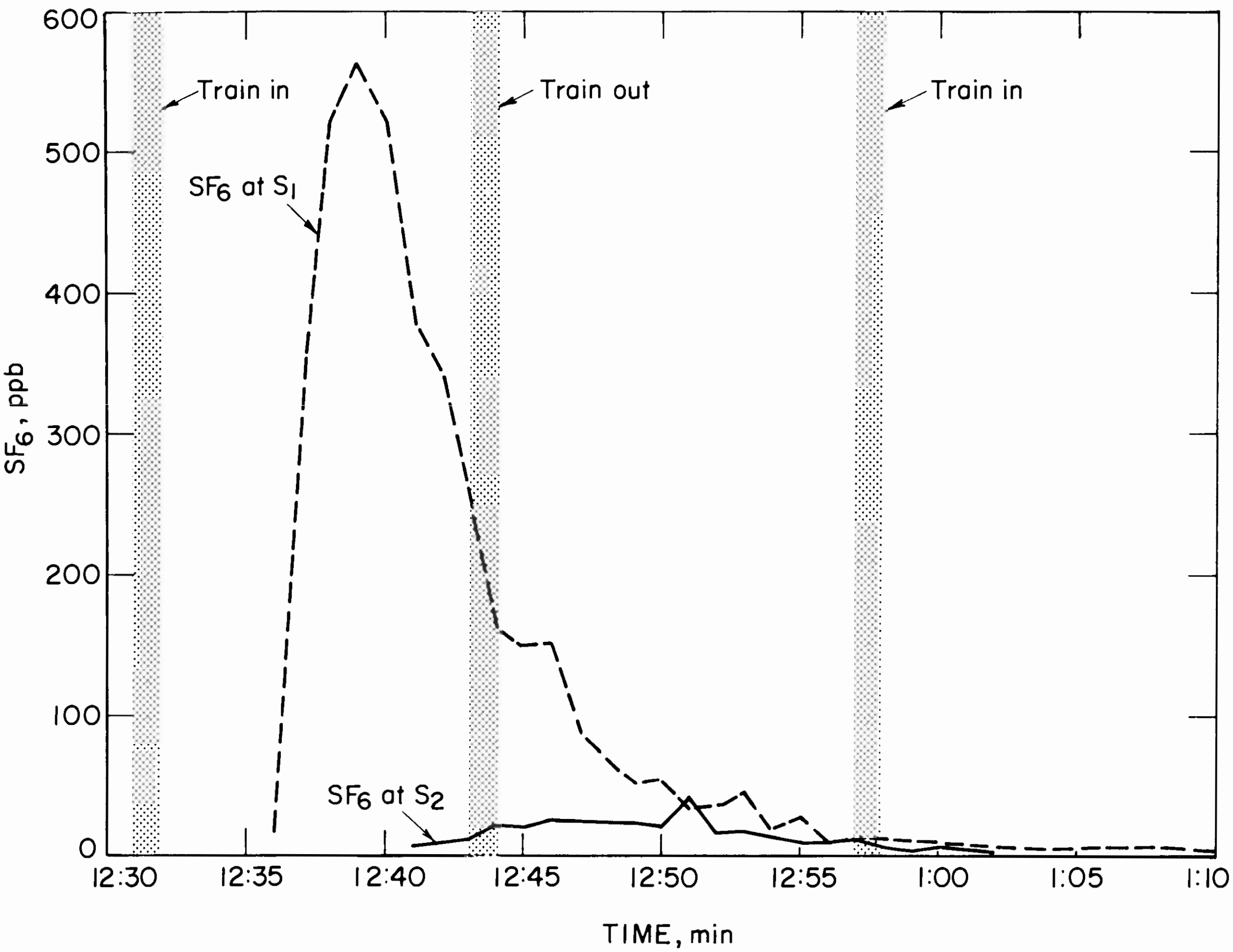

FIGURE 18. - Sulfur hexafluoride concentration at S_1 and S_2 as a function of time.

metal stoppings had leaks, and they flexed with the air pressure change caused by passage of the train. Thus, train movement caused a small amount of air leakage around the metal stoppings into the adjacent entry.

CONCLUSION

In the first study, SF_6 showed that air movement was taking place within a sealed area. The direction of this air movement was found by analyzing the SF_6 concentration curves at each sampled location. In the second part of this study, the tracer gas was used to confirm that air leakage was taking place from old workings of another seam. It was also found that atmospheric pressure changes strongly affect both seal leakage and the measured concentration of gas samples taken from short sample pipes cemented into seals.

The purpose of the second study was to determine if a pillared-and-caved area was being properly ventilated. By using tracer gas, it was possible to find the air velocity across the inaccessible area. With this information and an altimeter survey of the area, it was shown that the gob was properly ventilated and that there was no short-circuit path through the pillared-and-caved area.

A third study using SF_6 showed that pressure pulses caused by a moving train were causing a small reverse leakage from the intake airway with the train to the adjacent airway.

The successful use of SF_6 in these three studies indicates that SF_6 is potentially capable of helping to solve ventilation problems that do not respond to conventional methods of ventilation analysis. Its application should be considered when such problems are encountered.

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