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Sulfur Hexafluoride as a Mine Ventilation Research Tool—Recent Field Applications

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UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

SULFUR HEXAFLUORIDE AS A MINE VENTILATION RESEARCH TOOL—RECENT FIELD APPLICATIONS

By Robert J. Timko [1] and Edward D. Thimons [2]

ABSTRACT

Sulfur hexafluoride (SF_6) is an odorless, colorless, nontoxic gas that has found acceptance as a tracer gas in research on ventilation patterns, measurement of air leak rates, respirable dust reductions due to bagging hood modifications, and the study of airflows relating to gob boreholes. Following a short review of the SF_6 sampling technique, this report describes recent Bureau of Mines projects in which SF_6 was used successfully as a tracer gas, enabling researchers to acquire representative data quickly and inexpensively.

INTRODUCTION

Analyzing mine air ventilation patterns can be tedious, time-consuming work. Smoke tubes can give only rough approximations of airflow direction and velocity. Anemometers are capable of accurately measuring air velocities, but large-scale mine airflows can only be derived through approximations. On the other hand, with tracer gas, not only can the airflow patterns throughout the mine be determined, but average air velocities can be accurately measured over substantial distances.

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BACKGROUND

The Bureau of Mines has been using sulfur hexafluoride (SF_6) tracer gas in ventilation measurement work for several years. SF_6 is colorless, odorless, chemically and thermally stable, and can easily be dispensed in air (5).[3] In testing by the Bureau, SF_6 was contained in metal, high-pressure bottles that hold approximately 42.5 L (1-1/2 ft^3) of gas. It is released simply by opening a valve on the bottle (fig. 1). The mass of SF_6 released is equal to the weight loss of the bottle.

The volume of gas released is determined by the equation:

$$V = nR \tag{1}$$

where V = volume of SF_6 released,

n = moles of SF_6 released,

and R = volume per mole (22.4 L).

This is a simplified version of the formula used initially (4): $PV = nRT$.

Since $n = \Delta M/M$

where ΔM = weight loss of bottle, in grams,

and M = molecular weight of SF_6,

equation (1) becomes

$$V = \Delta M\ R/M \tag{2}$$

And since

$$R = 22.4 \text{ L/mole}$$

$$M = 146.07 \text{ g/mole}$$

the equation is reduced to

$$V = 0.15\ \Delta M \tag{3}$$

Determining the volume of SF_6 released becomes important when comparing the quantity released to that recovered.

SF_6 is sampled by inserting a 90% air evacuated, 10-ml Vacutainer[4] test-tube into a plastic plunger, similar to a device used to extract blood for clinical testing. Inside the plunger is a hypodermic needle, which punctures a rubber bladder at one end of the test tube. As the bladder is punctured (fig. 2), ambient air enters the test tube and the sample is complete. Withdrawing the test tube from the plunger reseals the rubber bladder, preventing the sample from escaping. Samples are taken at predetermined intervals, and the test tubes can be marked with any information pertinent to the sampling procedure. Samples are brought back to the laboratory, where 0.1 ml of the sample is withdrawn with a syringe and injected into a gas chromatograph for SF_6 analysis.

Data reduction is done in two separate steps. First, SF_6 concentration is plotted with respect to time for each sampling position. The maximum SF_6 concentration and dispersion rate immediately become evident. Second, the total quantity of tracer gas recovered is determined as (1)

$$QSF_6 = Q_{air} \int c\,dt$$

where QSF_6 = SF_6 volume recovered,

Q_{air} = Volumetric airflow rate,

and c = Instantaneous SF_6 concentration at time t.

Knowing V, the volume of SF_6 released, the percent tracer gas recovered can be calculated:

$$Q'SF_6 = \frac{QSF_6}{V}(100)$$

where $Q'SF_6$ = percent SF_6 recovered.

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

[4]Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

FIGURE 1. - Releasing SF_6 for ventilation analysis.

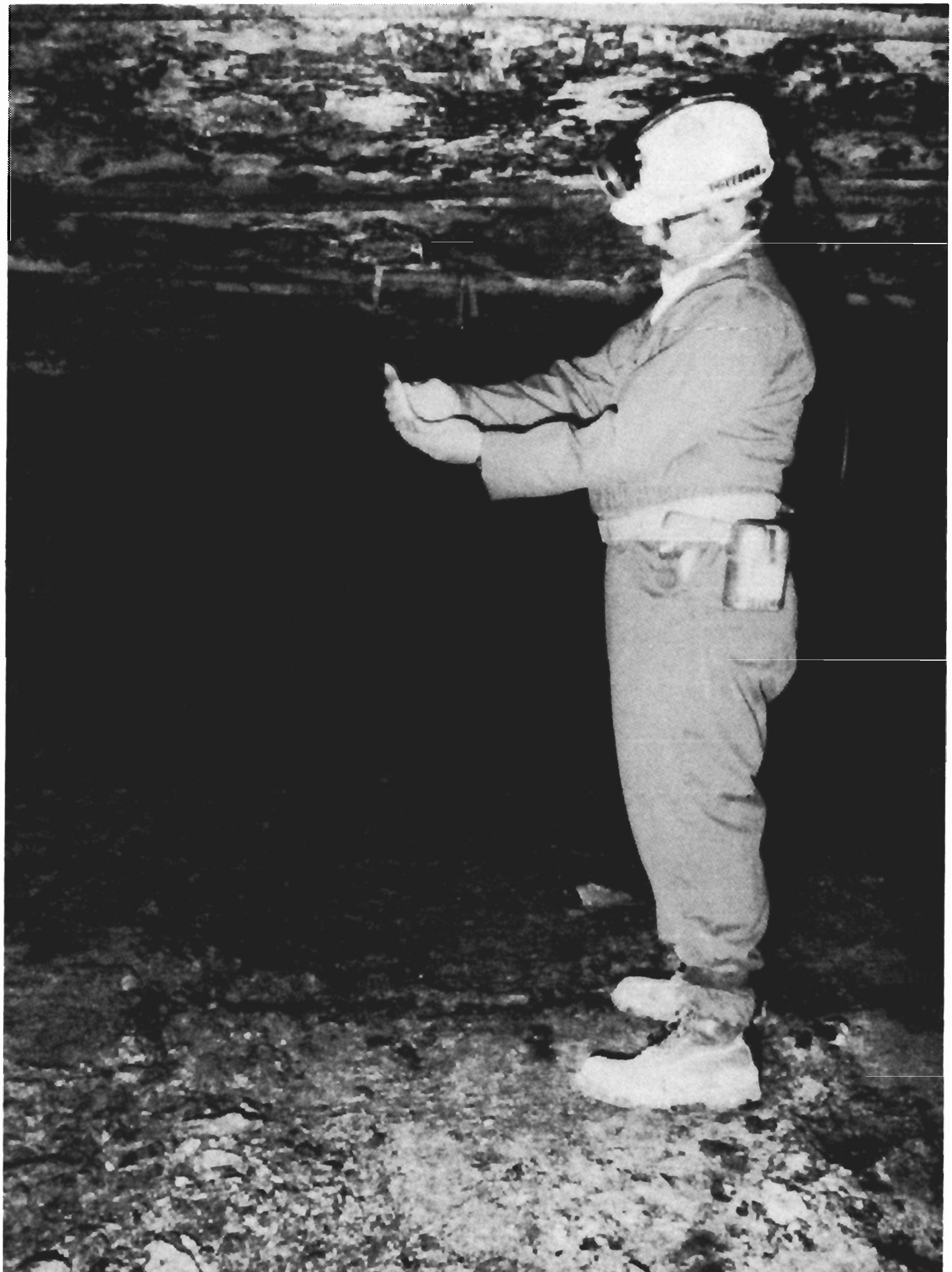

FIGURE 2. - Taking samples of mine atmosphere to determine SF_6 content.

SF_6 tracer gas is being increasingly accepted by the mining industry as a viable mine ventilation analysis tool. S-Cubed (formerly Systems Science and Software) of La Jolla, Calif., now commercially performs ventilation research using SF_6 tracer gas. Several ventilation research projects recently completed by the Bureau illustrate the many diversified applications of SF_6 that are possible.

SF_6 IN VENTILATION RESEARCH

Limestone Mine Ventilation

SF_6 was used to study existing ventilation patterns (fig. 3*A*) in a gassy underground limestone mine where ventilation is provided by a positive-pressure fan blowing air down a shaft on the western side of the mine (fig. 3*B*). According to the mine ventilation plan, the air splits at the 600 level with air heading eastward and westward at the 600 level and vertically to the 960 level, the only active working level in the mine. Air moving westward at the 600 level travels vertically downward through the stopes. The air ventilating the 600 east level flows through a booster fan, vertically down through the old east side workings to the 960 east level, then westward to the main shaft. The ventilation air reaching the 960 west level is boosted to the face with an auxiliary fan, then exhausted eastward through the 960 main drift to the main shaft.

In the initial test series (Test Group 1), SF_6 was released at the 960 west advancing face for the first test and the closest active stope for the second. As a check, oil of wintergreen was released with the SF_6. If ventilation patterns were as predicted, all odor associated with the oil of wintergreen would exhaust through the 960 west main drift to the main shaft. However, miners told of smelling the odor throughout the day on the 600 level.

Further evidence that the ventilation patterns were not as predicted was the small amount of SF_6 recovered at three sampling positions on the 960 level. The amount of SF_6 released was known. When the results from each position were graphed, the total amount recovered was less than 20% of the SF_6 released. These irregularities were reported to mine personnel. They replied that several openings from the 960 level to the 600 level were found and sealed.

In two later tests (Test Group 2), ventilation patterns were examined in more detail. SF_6 was again released at the 960 main drift west advancing face for the first test and at the closest working stope for the second. Sampling points were on the 600 level as well as on the 960 level.

Results showed that no SF_6 was found on the 600 level west of the conveyor belt. However, SF_6 was being carried up the beltway, meaning that exhaust air was recirculating up the conveyor and into the 600 level. To alleviate this recirculation problem, airflow changes around the beltway were needed.

Coal Mine Face Ventilation

Adequate face ventilation to remove hazardous dust and gases is important in mining. A simple method was needed to measure face ventilation without exposing mine personnel to more hazardous types of tracer gases. The Bureau of Mines developed an easy, rapid SF_6 technique for making face measurements. With this method, called the face ventilation measurement method (FVM) (8), a small quantity of SF_6 is released at the start of the mining cycle just behind the continuous miner drum on the operator side, opposite the line curtain. SF_6 samples are then taken at specific time intervals from behind the line curtain in the return. After data reduction in the laboratory, two graphs are generated: (1) depletion of SF_6 with respect to time, and from this (2) a cumulative percentage of SF_6 depleted with respect to time. The basic premise of this technique is that the faster the depletion, the better the ventilation.

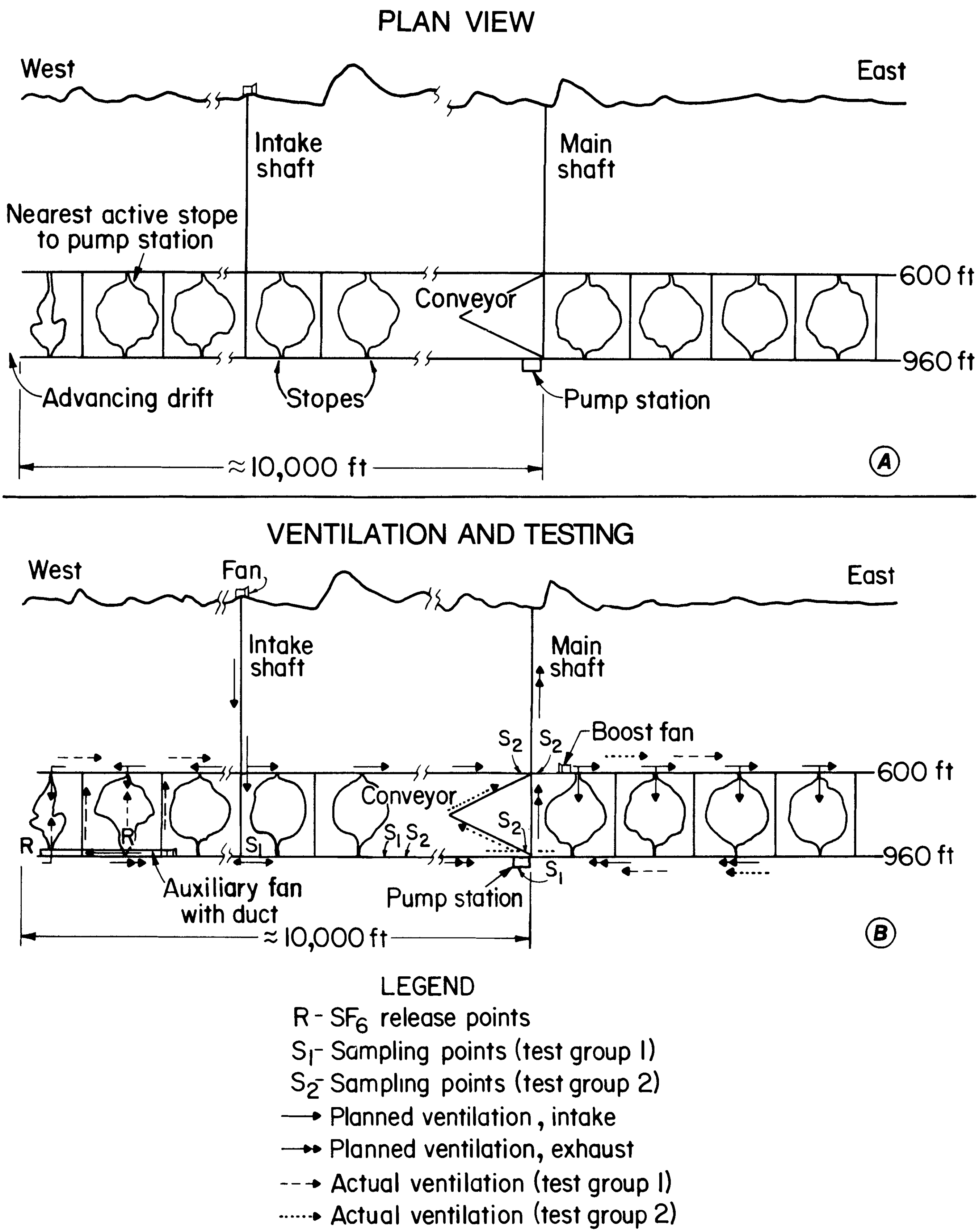

FIGURE 3. - Limestone mine. *A*, plan view; *B*, ventilation plan and SF_6 experiments.

Using the FVM method it is graphically shown that keeping curtain-to-face distances within 10 ft is essential to good face ventilation (fig. 4). This supports the Mine Safety and Health Administration (MSHA) requirement that the inby side of the line curtain be within 10 ft of the working face (7).

In another project the FVM method was used to demonstrate the effectiveness of equipping a continuous miner with a spray fan ventilation system, consisting of a series of water sprays strategically located so as to sweep mine ventilation air over the entire face and direct it to the return.

The FVM method was also used to evaluate the efficiency of a dual-scrubber system on a continuous miner and compare its effectiveness with that of conventional ventilation. SF_6 testing enabled a quick determination of optimal curtain-to-face distances and face ventilation velocities for machines equipped with the dual scrubber configuration.

Jet Fan Effectiveness

Underground mines circulate large quantities of ventilation air to dilute and remove hazardous gases. For certain areas, such as dead headings, where distribution of fresh air is inadequate, the Bureau examined the use of auxiliary ventilation provided by placing different fans in airways or work areas, without bulkheads or tubing on the fans. This type of ventilation is called impulse or jet ventilation (3).

SF_6 was used to evaluate the effectiveness of various jet fans and their positions in dead headings. Position L2 (fig. 5) was selected because Krause (2) suggests that better ventilation can be expected if a jet expands in fresh air. However, underground experiments with SF_6 and smoke tubes proved position L2 to be greatly inferior to position L1.

The superiority of SF_6 over smoke tubes became obvious when attempting to examine the effectiveness of the jet fan in dead headings. It was found that air from a jet fan can purge beyond the penetration distance measured with a smoke tube. In fact, effective ventilation occurred at twice the distance that the jet was detected with smoke tubes.

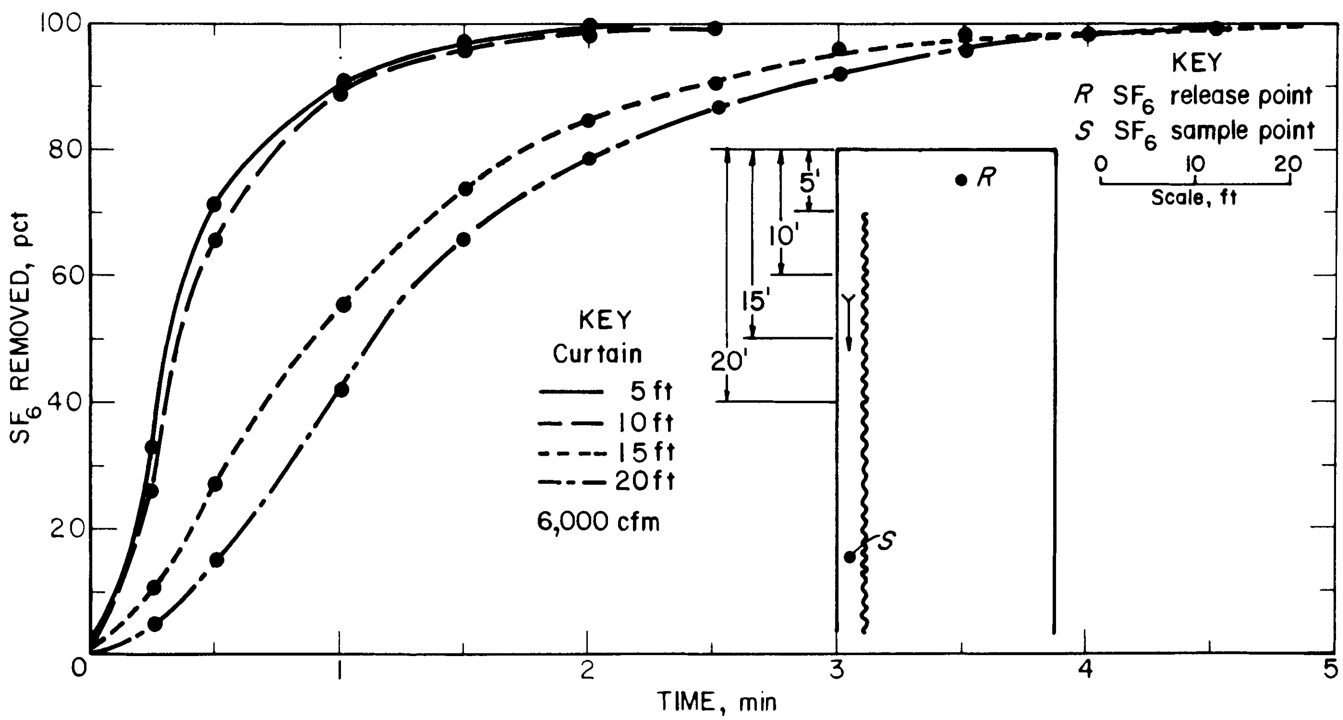

FIGURE 4. - Ventilation effects of various curtain distances from the face.

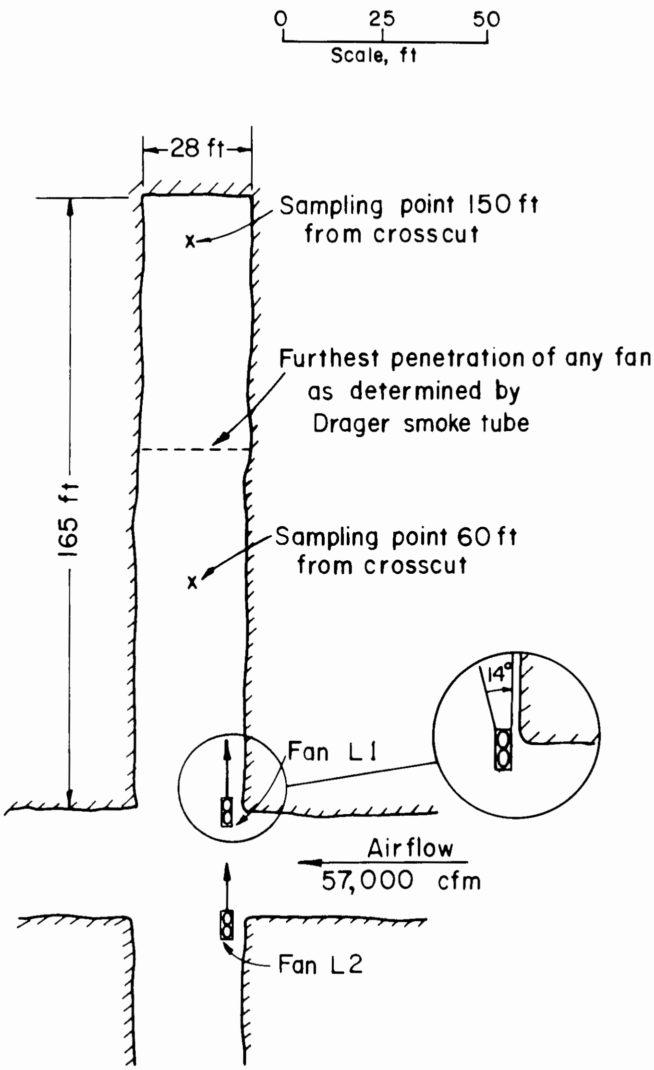

FIGURE 5. - Fan comparison in a dead heading.

Air Leakage Across Stoppings

SF_6 is used to measure air leakage through and around permanent concrete block stoppings in coal mines. Two different methods are used, depending upon the location of the stopping with respect to the ventilation fans.

For the SF_6 technique to work, a pressure differential is created across the stopping. For stoppings with less than 1-in-wg pressure differential, (1) a parachute is anchored by fastening its lines to roof bolts on the intake side of the stopping, and (2) a fan forces air behind the parachute, inflates it against the floor, roof, and ribs of the crosscut and creates a positive pressure on the stopping (fig. 6). The pressure differential forces air through any imperfections in the stopping and depletes the SF_6 in the known volume.

When pressure differentials of greater than 1 in wg exist across the stopping, the parachute and fan are not needed. The natural driving force of the ventilation air is great enough to send air through any imperfections in the stopping.

A quantity of SF_6 tracer gas is released into a known volume on the return, or low-pressure, side of the stopping.

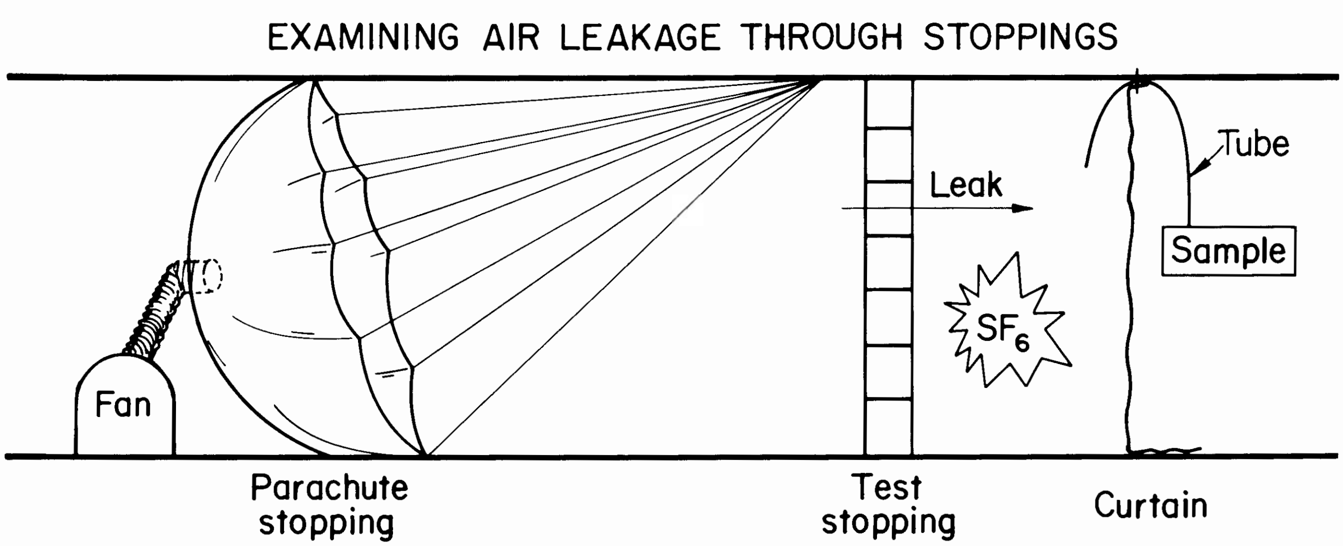

FIGURE 6. - Stopping air leakage test setup.

The volume is predetermined by hanging brattice curtain completely across the crosscut, some distance from the stopping, and multiplying this distance by the width and height of the crosscut.

One end of a rubber sampling tube is draped over the brattice into the volume, with the other end connected to a personal sampling pump. At predetermined intervals, the pump is removed from the sampling line and an SF_6 sample is taken. When reducing the data, an SF_6 depletion curve is drawn and stopping leak rates obtained (fig. 7). The leak rate is given by

$$Q = \frac{\ln (C_1/C_2)}{T_1-T_2} (-V)$$

where Q = air leak rate (CFM)

C_1 = SF_6 concentration (PPB) at time T_1

C_2 = SF_6 concentration (PPB) at time T_2

V = stopping to brattice curtain volume (ft^3).

In both cases, low air leak rates on various types of stoppings could be measured. SF_6 analysis provided an accurate and repeatable means of determining leak

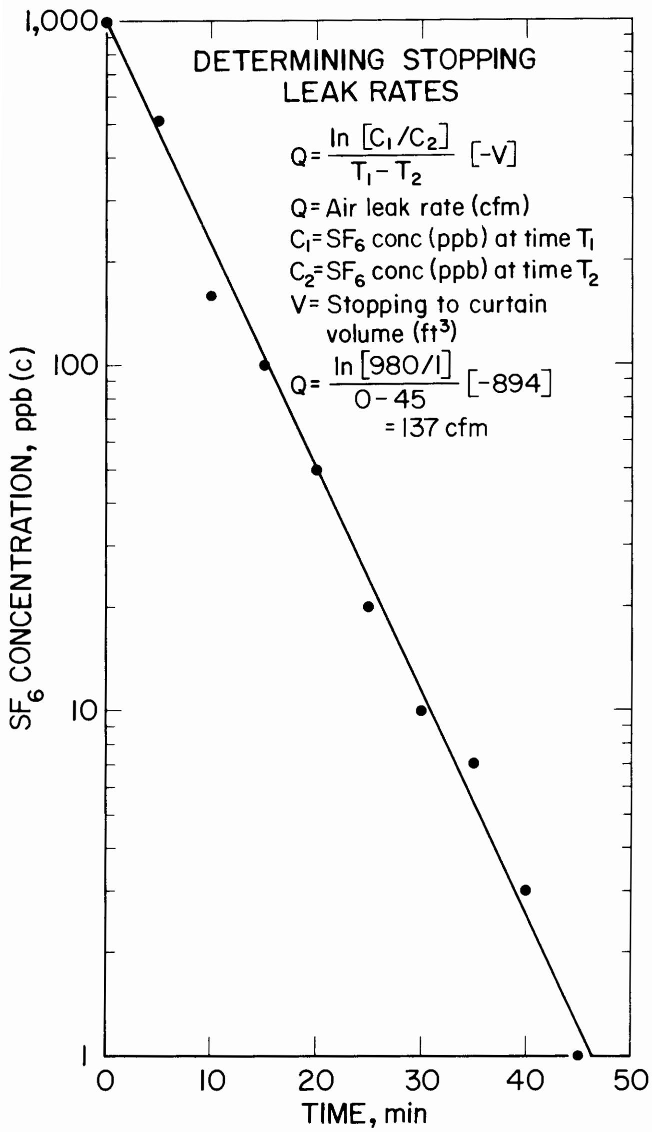

FIGURE 7. - Calculating stopping leak rates.

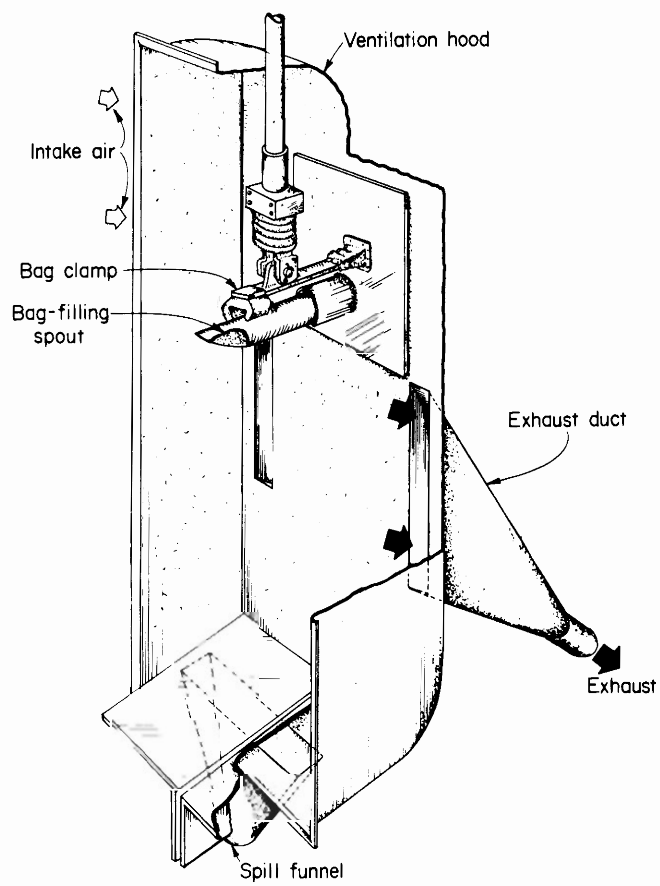

FIGURE 8. - Bagging hood enclosure.

rates through and around permanent concrete block stoppings.

Bagging-Machine Hood Enclosure

Machines that bag sand, flour, and other granular bulk products generate considerable quantities of dust. A hooded enclosure, developed by the Bureau, reduces the amount of dust escaping from the bagger (fig. 8) (6). SF_6 tracer gas was used to quantitatively determine how effective this method of dust reduction is at three facilities where hoods had been installed (9). For this purpose SF_6 was released within a hood during bagging and nonbagging cycles. Samples were taken periodically at various points around the outside of the hoods. If the enclosures operated as designed, no SF_6 would be detected in the samples.

At the first facility the bagging hoods were enclosed in a plywood room, ventilated through a network of grills in the roof. SF_6 was detected at various points around the hood during bagging and nonbagging cycles. Upon reviewing the data, it became apparent that SF_6 release into the room was due to improper ventilation. Air jets, used for makeup air, were directed at the hoods, causing turbulent air and permitting gas to escape.

At the second facility, the hooded baggers were again located in a room with exhaust and makeup ventilation systems. However, only a small amount of SF_6 was detected here, probably because of a lack of air jets forcing air from the hoods. Any SF_6 detected escaped through holes in the hood provided for the bagger nozzles.

At the third facility, the bagging hoods were not enclosed in a room. An exhaust ventilation system was used to remove air from the bagging hoods. No SF_6 was detected at any sampling point. Smoke-tube tests visually confirmed these results.

At all three facilities SF_6 tests on bagging hood enclosures enabled research personnel to determine the effectiveness of the enclosures. After analyzing the results, recommendations to vary airflows or modify the apparatus could be made.

Coal Mine Boreholes

SF_6 was used in three borehole experiments at two different coal mines to determine the tightness of the gob and if ventilation air was diluting methane liberated in the gob. In each case, a longwall panel had advanced beyond the gob borehole location. If a gob was tightly caved, SF_6 would be detected in the return air but not at the gob borehole. In essence, the ventilation air would sweep the gob but not penetrate it to any extent. Conversely, if the gob was loosely caved SF_6 would be detected not only in the returns underground but also on the surface at the gob boreholes.

At the first mine, SF_6 was injected into an exhausting mine entry borehole (R), where a negative pressure fan pulled air from the mine (fig. 9). The fan was stopped, the borehole was capped, and an SF_6 bottle was connected to a tapped fitting on the mine side of the shutoff valve. Approximately 42.5 L (1-1/2 ft^3) of SF_6 was then released into the entry borehole. Sampling was begun at a gob borehole approximately 1 km (0.62 mi) from the release point and underground in the return nearly 1.65 km (1 mi) away. Sampling at the surface lasted for 6 hr; underground for 5 hr. No SF_6 was ever detected on the surface at the gob borehole. SF_6 concentration in the return peaked less than 3-1/2 hr after tracer gas release. Unfortunately, sampling underground did not last long enough to determine the total amount of gas passing the sampling point.

A second coal mine requested an SF_6 tracer gas study for a borehole (fig. 10) recently drilled above a longwall gob. The seam depth was approximately 275 m (900 ft). At about 180 m (600 ft) a void was encountered and drilling stopped. Methane began exhausting from the borehole and pressure increased, indicating some type of outgassing. It was not known at this time if the void extended

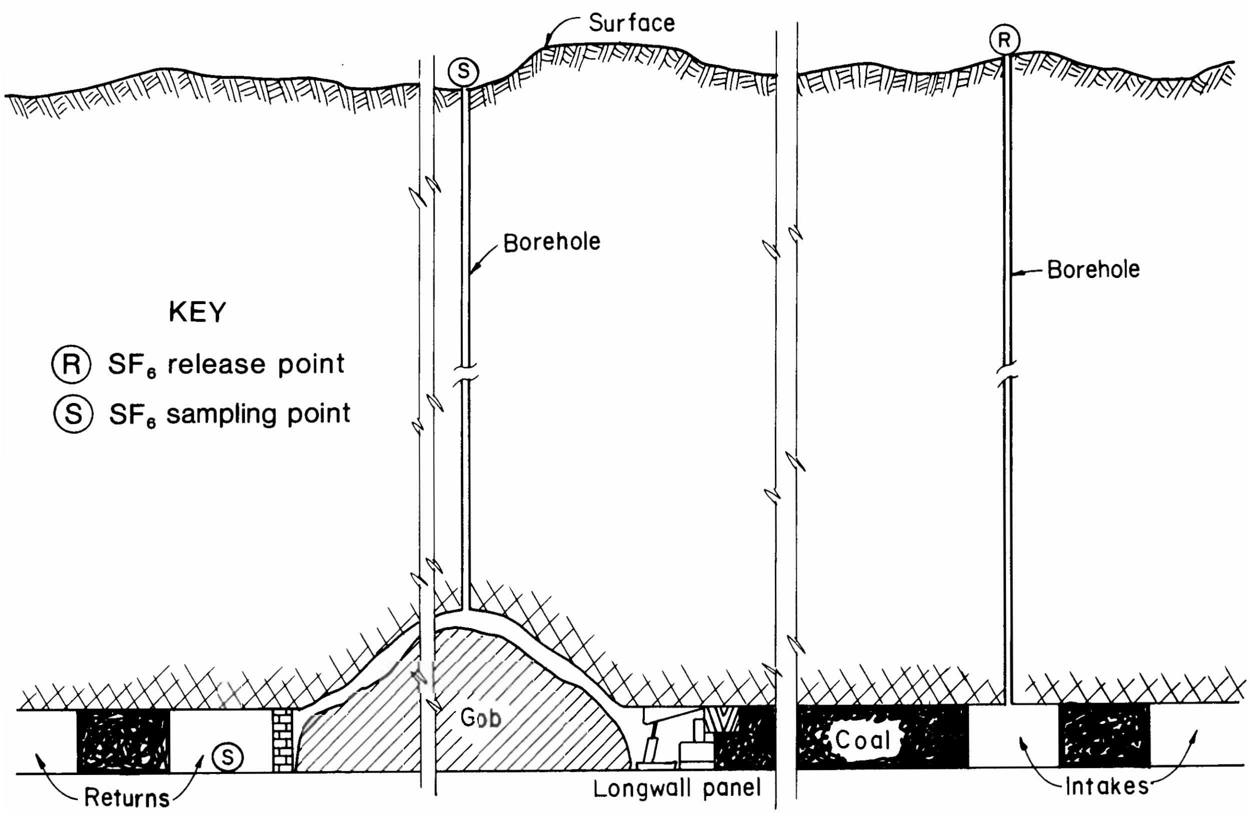

FIGURE 9. - First borehole examination.

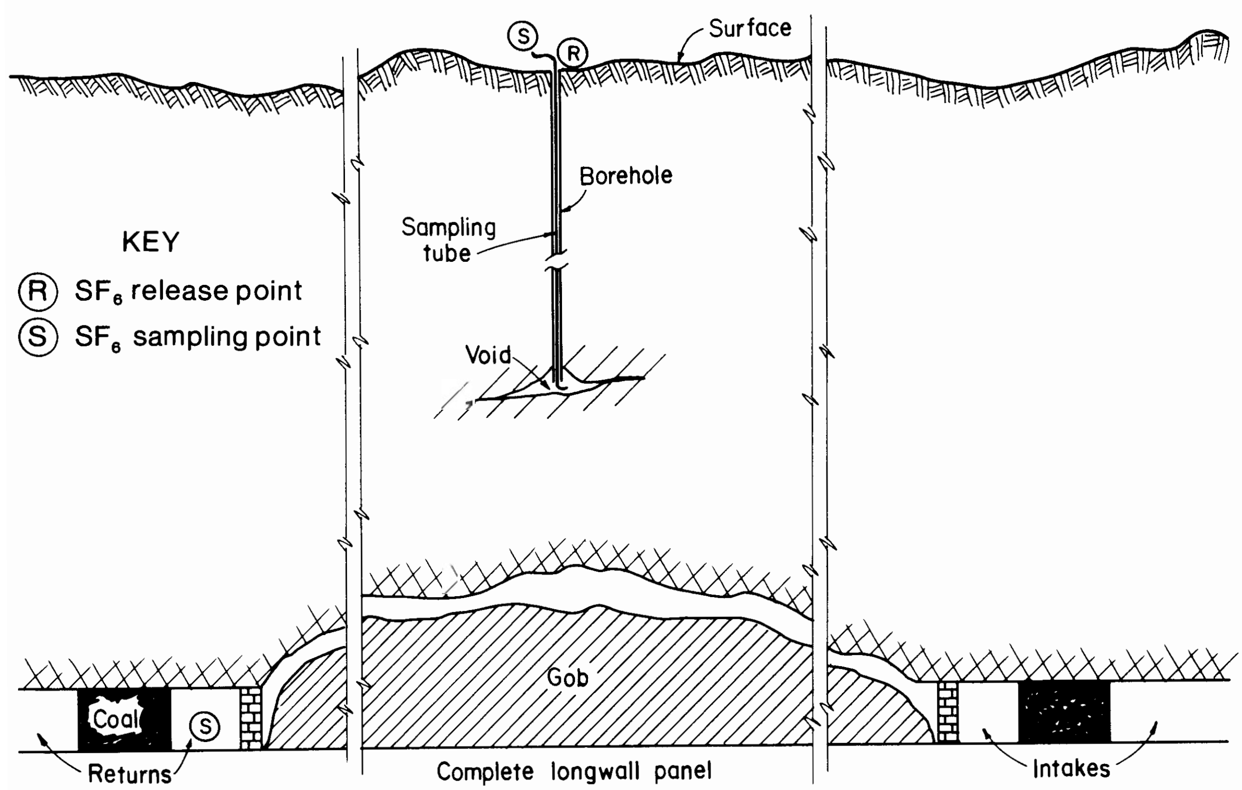

FIGURE 10. - Second borehole examination.

into the gob. At first researchers wanted to release SF_6 underground and sample at several locations underground and on the surface at the borehole, but because the gas could not be released near the borehole underground, SF_6 was again released on the surface and forced down the borehole.

Prior to capping the borehole, a 180-m (600-ft) length of 6.4-mm (1/4-in) plastic tubing was extended down the hole to sample the void from the surface. A personal sampling pump operating at a flowrate of 2 L/min was used to pull air from the void through the tubing.

Next, 69.4 L (2.45 ft^3) of SF_6 was released through a tap into the borehole. This was followed by more than 11,300 L (400 ft^3) of nitrogen, forcing the SF_6 down the borehole. Actual sampling was begun just before release of SF_6, so that a good baseline could be obtained. Sampling lasted 24 hr at the surface, 72 hr underground.

SF_6 was detected only in the void at the bottom of the borehole. No tracer gas was ever detected underground. After sampling for 3 days and finding no SF_6, it was apparent that the borehole was not connected to the mine. A complete hydrocarbon analysis at the borehole showed more than 95% methane being emitted. Additionally, borehole pressure continually increased to 27.3 cm (10.75 in) wg after only 24 hr.

The void size was estimated by determining the volume of SF_6 released into the borehole and assuming that this volume contained a 100% concentration of SF_6. The average SF_6 concentration for the 24-hr period appears to be near 1.5%. The volume of the void can be calculated approximately:

Mass of SF_6 released = 452.6 g molecular weight of SF_6 = 146.1 g/mole

$$\text{Moles of } SF_6 \text{ released} = \frac{452.6\text{g}}{146.1 \text{ g/mole}} = 3.10 \text{ moles}$$

$$\text{Volume/mole} = 22.4 \text{ L}$$

$$3.10 \text{ moles} \times 22.4 \text{ L/mole} = 69.44 \text{ L} = \text{volume of } SF_6 \text{ released}$$

$$\text{Approximate } SF_6 \text{ concentration for sampling period} = 1.5\%$$

$$\text{Approximate void volume} = \frac{69.44 \text{ L}}{1.5} \times 100 = 4{,}629.33 \text{ L } (163.47 \text{ ft}^3)$$

In tests on another borehole (fig. 11), SF_6 was released underground near the longwall face but not in the face ventilation airstream. It was hoped that the SF_6 would sweep the gob as well as penetrate the gob, with SF_6 being detected on the surface at the borehole as well as in the returns. Sampling took place at five positions underground and one position on the surface at the borehole. Each underground location was sampled for 17 hr and the surface for 24 hr.

SF_6 was released behind brattice curtains that separated main ventilation air from gob bleeder air. The top of the borehole was approximately 460 m (1,500 ft) from the release point. In slightly more than 2 hr the SF_6 concentration peaked at the borehole. No SF_6 was detected in the immediate longwall face return, but it was detected at various times in different bleeder evaluation points, depending upon distance from the release point.

In all cases SF_6 proved to be an excellent tool to measure underground ventilation. The sampling tubes can also be examined in a gas chromatograph for total

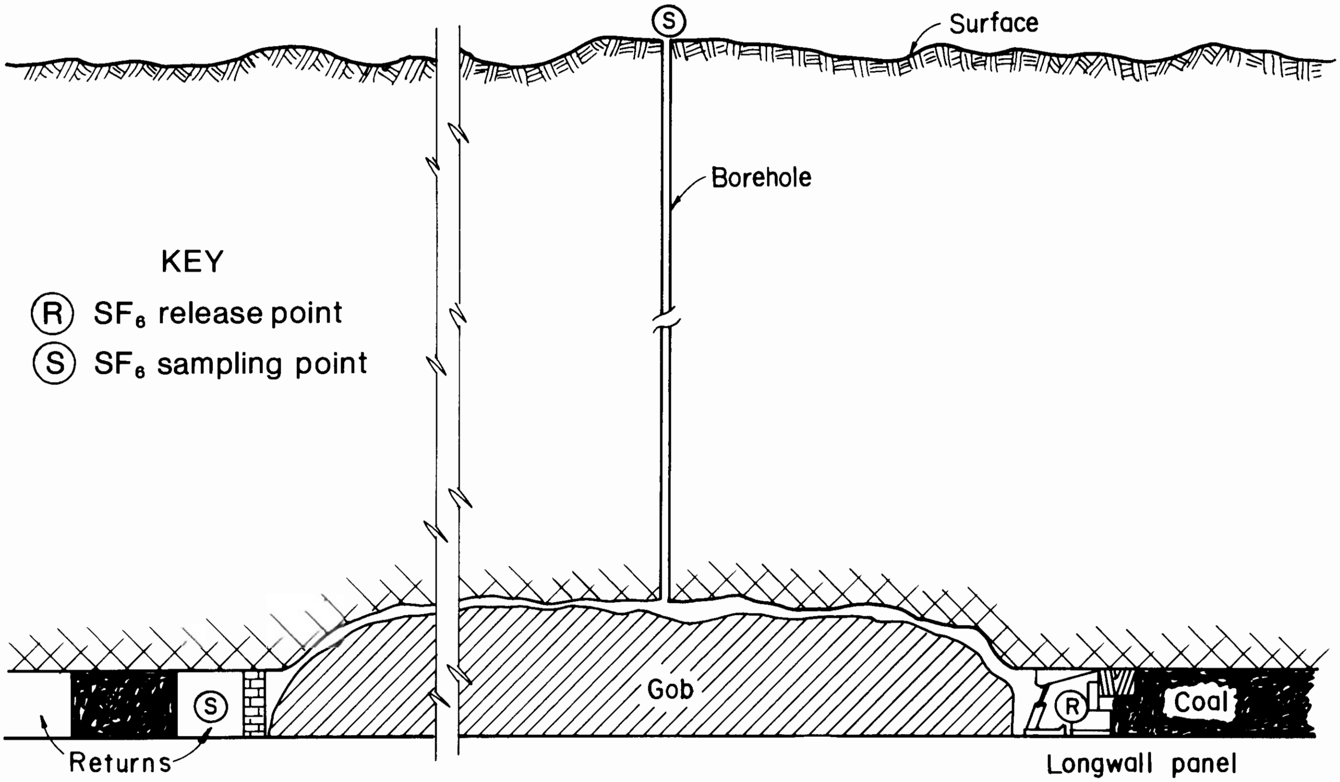

FIGURE 11. - Third borehole examination.

hydrocarbons. This was done for the third borehole experiment and showed conclusively that the hydrocarbons in the return air increased as the distance of the sampling points from the SF_6 release point increased. Detection of SF_6 in the borehole showed that ventilation air was entering the gob.

OTHER SF_6 WORK

Oil Shale Mine

S-Cubed of LaJolla, Calif., performed several SF_6 experiments at an oil shale mine in Colorado that uses a modified in-situ method of burning to extract oil from shale. The material is rubblized and dumped into large underground voids that become retorts when burning is begun. During burning, the retort has a negative pressure imposed on it by exhaust fans. If a fan fails, burning can cause the retort to become positively pressurized before one-way ventilation valves can prevent outgassing into the mine. A primary concern during outgassing is the amount of hydrogen sulfide (H_2S) released into the mine workings. To quantitatively determine H_2S concentrations in the mine, enough SF_6 was released into the underground retorts to produce a known concentration at a known pressure. Samples were taken at various positions throughout the mine. The quantity of ventilation air in the mine was known. If SF_6 was detected in the mine, a lead rate from the retort, and thus the concentration of SF_6 in the mine at that particular sampling point, could be determined.

Samples taken from over 100 positions throughout the mine showed that SF_6 concentrations, simulating H_2S, were well within MSHA requirements.

Lead-Zinc-Silver Mine

Tracer gas tests were completed in a lead-zinc-silver mine (fig. 12) to

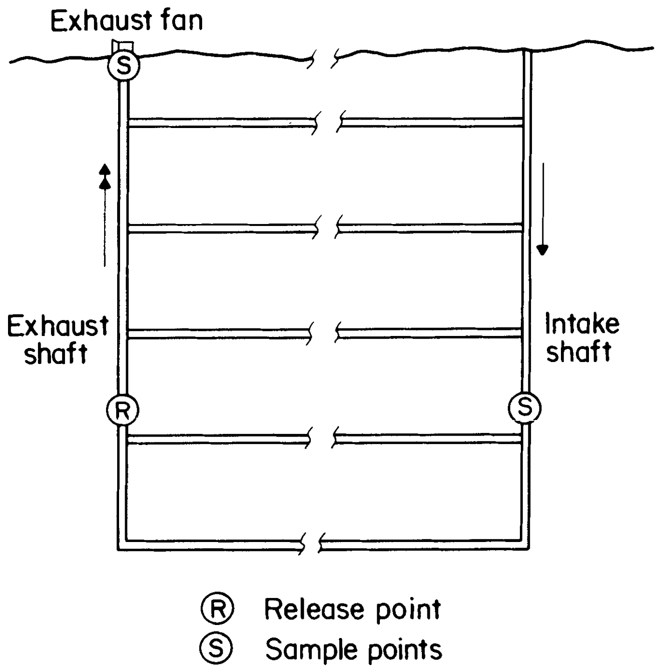

FIGURE 12. - Lead-zinc-silver mine ventilation schematic.

determine if ventilation air was short-circuiting from the exhaust back into intake air. The intake and exhaust are two separate shafts with workings at various levels between the shafts. It was feared that air was passing through old workings on upper levels and entering the intake shaft, rather than exhausting to the atmosphere. If this was the case, the integrity of the intake shaft as an escape route would be lost.

SF_6 was released about one-third of the way up the exhaust shaft. Sampling took place at the exhaust fan and about two-thirds of the way down the intake shaft. None of the intake air samples contained SF_6; at the fan SF_6 was detected for approximately 20 minutes. The data clearly showed that no ventilation air is short-circuiting between exhaust and intake shafts.

Coal Mine Fire

A fire occurred in a coal mine gob, requiring that the gob be sealed. Although it was not known whether air was still leaking through the gob seals, it was suspected that some seals were not airtight. In an attempt to determine approximate airflow into the gob and ventilation patterns, SF_6 was released behind a seal considered not airtight, and samples were taken at a seal on the opposite side of the gob. Both seals had sampling probes, so that release and sampling of SF_6 in the gob presented no problem. The dispersal time for the SF_6 was determined by taking samples behind the seal at which the SF_6 was released. If there was little or no leakage, SF_6 would disperse very slowly. Additionally, the gas should not arrive at the other seal for several hours.

In fact, SF_6 concentrations at the release point dropped rapidly. Within 45 min the gas was detected at the second seal. This gave a rough estimate of airflow patterns and qualitatively showed that air was leaking through seals, making it possible for management to take appropriate action to further reduce or eliminate leakage through the seals to the burning gob.

SUMMARY

The uses for sulfur hexafluoride (SF_6) as a tracer gas are becoming more numerous as researchers more fully understand its potential. This colorless, odorless, nontoxic gas is easily dispensed in air. Sampling is done by inserting 10-ml, 90% evacuated Vacutainer test tubes into a plastic plunger containing a hypodermic needle. The needle punctures a rubber bladder on one end of the evacuated tube, permitting an ambient air sample to enter the tube. When the needle is withdrawn, the bladder reseals itself and can be returned to the lab, where 0.1 ml of the sample is withdrawn and injected into a gas chromatograph. After determining the amount of SF_6 in the sample, the only other task is to reduce the data to tabular or graphic form.

The tremendous benefit of SF_6 is the ability to use it in ventilation problems that are difficult to accomplish with typical airflow instruments. The uses described in this report are only samples of what can be done. S-Cubed of La Jolla, Calif., has seen the potential of SF_6 and is commercially performing ventilation research using SF_6. The future will see many more diversified uses for SF_6 in studying unique mine ventilation problems.

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