RI 8843

Bureau of Mines Report of Investigations/1984

Use of a Sodium Silicate Gel Grout for Plugging Horizontal Methane-Drainage Holes

By David C. Oyler

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8843

Use of a Sodium Silicate Gel Grout for Plugging Horizontal Methane-Drainage Holes

By David C. Oyler

UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Oyler, David C

Use of a sodium silicate gel grout for plugging horizontal methane-drainage holes.

(Report of investigations ; 8843)

Supt. of Docs. no.: I 28.23:8843.

1. Coalbed methane drainage. 2. Grouting. 3. Sodium silicate. I. Title. II. Series: Report of investigations (United States. Bureau of Mines) ; 8843.

TN23.U43 [TN305] 622s [622'.8] 83-600297

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Bé	Baumé
cm	centimeter
cP	centipoise
ft	foot
ft^3/min	cubic foot per minute
gal	gallon
gal/min	gallon per minute
hr	hour
in	inch
kg	kilogram
kPa	kilopascal
lb	pound
lb/in^2g	pound per square inch, gauge
m	meter
m^3	cubic meter
m^3/hr	cubic meter per hour
m^3/min	cubic meter per minute
min	minute
mm	millimeter
pct	percent
vol pct	volume percent
wt pct	weight percent
yr	year

USE OF A SODIUM SILICATE GEL GROUT FOR PLUGGING HORIZONTAL METHANE-DRAINAGE HOLES

By David C. Oyler[1]

ABSTRACT

Methane-drainage holes must be completely filled by grout before mining to prevent the emission of large quantities of gas during mine-through, which would constitute an explosion hazard. In November 1980, seven horizontal holes at the multipurpose borehole, a small-diameter shaft drilled as a Bureau of Mines coalbed methane-drainage installation on the property of the Federal No. 2 Mine, Monongalia County, WV, were plugged using a sodium silicate gel grout. This report describes the grout mix and the use of the grout at the multipurpose borehole, and discusses the results observed upon mine-through of the holes in early 1981. Cost data for the sodium silicate grout are also presented.

[1]Mechanical engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Since the 1960's, the Bureau of Mines has been experimenting with the use of holes drilled horizontally in coalbeds to remove methane gas ahead of mining. As the technology and equipment used have become more sophisticated, the average length of the holes drilled and thus the average gas flow per hole (other factors, such as the depth of the coal seam, being equal) has increased.

There has been a concern as to the risk of mining into a horizontal hole that would bleed large quantities of methane (up to 8.5 m^3/min or 300 ft^3/min) directly onto the cutting head of a mining machine. Since this would greatly increase the probability of an ignition--a totally unacceptable risk--a means of plugging the methane-drainage holes before mine-through had to be developed.

In 1976, the first attempt was made to plug horizontal methane-drainage holes before they were mined through. These holes were located at the bottom of the Honey Run air shaft, on the property of the Federal No. 2 Mine.[2] The Honey Run holes were plugged[3] using a grout made from a mixture of cement, fly ash, and a fluidifier, known as Interaid,[4] of a type commonly used by grouting companies. All holes but one had 38-mm (1.5-in) diameter polyvinyl chloride (PVC) plastic pipe inserted in them; the longest hole (648 m or 2,126 ft) had a 25.4-mm (1-in) metal pipe in it.

To assure pumpability and to prevent premature set up of the grout, the grout designed was high in excess water, consisting of a sack of cement (42.6 kg or 94 lb) and a sack of fly ash (34 kg or 75 lb) added to each 0.057 m^3 (15 gal) of water used. Into this mix was added 1.1 kg (2.5 lb) of fluidifier. It was assumed that sufficient pumping times and pressures would allow the excess water to be squeezed into the fracture system of the coalbed and leave the holes full of solids. However, in most of the holes a layer of water, caused by the separation of excess water and solids in the grout, built up at the top of the hole. In the long hole at Honey Run, the grout was not pumped all the way around to the collar of the hole, which left sections of the hole unplugged. Also, some plugging of the grout lines still took place despite the precaution of using a thin, fluid grout.

Since the Honey Run shaft project, cement grouts with less excess water and larger percentages of fluidifier have been used with better results. The use of larger diameter (38-mm or 1.5-in) pipe has reduced the high friction losses that may have been a contributing factor to the poor plugging job done on the 648-m (2,126-ft) hole at Honey Run. Since 1977, 38-mm (1.5-in) PVC pipe has been used for plugging and in some cases this pipe has been installed immediately after drilling. However, there have been some doubts about the effectiveness of cement grouts. When the time came to begin planning to plug the seven horizontal methane drainage holes in the multipurpose borehole, a Bureau of Mines methane-drainage demonstration installation located in a specially drilled shaft on the property of the Eastern Associated Coal Corp. Federal No. 2 Mine (fig. 1),[5] the personnel of the Mine Safety and Health

[2]Fields, H. H., J. Cervik, and T. W. Goodman. Degasification and Production of Natural Gas From an Air Shaft in the Pittsburgh Coalbed. BuMines RI 8173, 1976, 23 pp.

[3]Aul, G. N., and J. Cervik. Grouting Horizontal Drainage Holes in Coalbeds. BuMines RI 8375, 1979, 16 pp.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

[5]Fields, H. H., S. Krickovic, A. Sainato, and M. G. Zabetakis. Degasification of Virgin Pittsburgh Coalbed Through a Large Borehole. BuMines RI 7800, 1973, 27 pp.

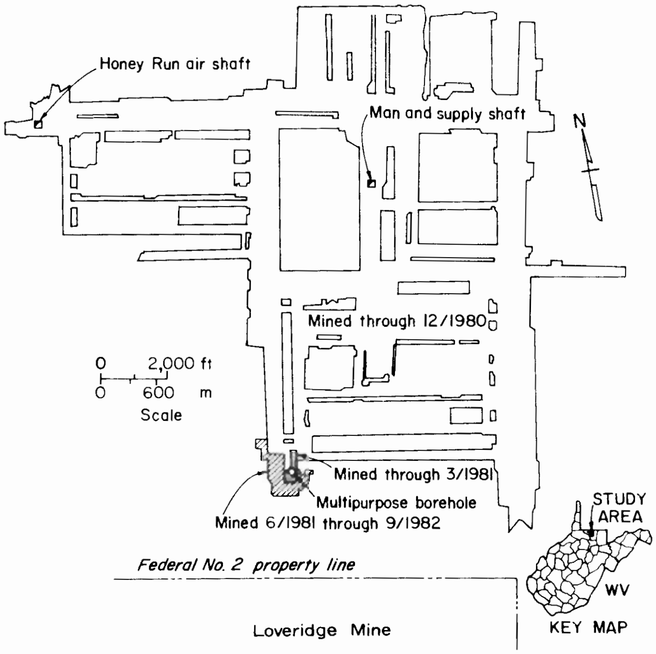

FIGURE 1. - Outline of Federal No. 2 Mine, 1980, and locations of the multipurpose borehole and Honey Run air shaft.

Administration (MSHA) District 3 office were in favor of considering other plugging methods, especially the use of sodium silicate grouts.

Between 1978 and 1980, Bureau personnel had experimented with sodium silicate-water mixtures in order to test their suitability as grouts. Mixes using sodium bicarbonate, calcium chloride, and formamide as setting agents had been tested, without success. None of the setting agents were found to give a permanently solid grout.

Information obtained from conversations with individuals in the chemical grouting industry confirmed the belief that the previously mentioned setting agents were not suited to producing a permanent grout. Because the Bureau did not have the expertise to develop a suitable setting agent, and since many grouting contractors appeared to have their own proprietary agents and grout mixes already available, it was decided in May 1980 to contract for the development of a grout suitable for plugging horizontal methane-drainage holes.

ACKNOWLEDGMENTS

The cooperation and efforts of the management and personnel of the Hayward Baker Co. Odenton, MD, and Eastern Associated Coal Corp. (Fairview, WV) Federal No. 2 Mine are greatly appreciated. In particular the efforts of Mr. John Veitch, resident engineer, and Mr. Frank Peduti, electrical engineer, Eastern Associated Coal Corp., and Mr. Robert Rubright of Hayward Baker Co. were invaluable. The author would also like to thank John Prichard, mechanic, Federal No. 2 Mine, for his help in flushing the horizontal holes.

GROUT DESIGN

In September 1980, a contract was awarded to Hayward Baker of Odenton, MD, for the development and emplacement, in the horizontal holes at the multipurpose borehole, of a sodium silicate grout. Hayward Baker had available a setting agent, and the major task of development was then to tailor the grout for use in horizontal methane-drainage holes.

Sodium silicate is a mixture of sodium oxide (Na_2O) and silicon dioxide (SiO_2) in various proportions ($Na_2O{:}xSiO_2$). It is a solid with a low solubility in hot or cold water, but it can be dissolved in saturated steam at 517 to 689 kPa (75 to 100 lb/in^2g). Although it can be purchased in many Na_2O-to-SiO_2 ratios, the most commonly used ratio is $Na_2O{:}3.22\ SiO_2$. This solid material is then commonly dissolved in steam to give a liquid of specific gravity 1.4 (11.67 lb/gal) and a viscosity of 206 cP.[6] This mixture, known variously as a 40 Bé, grade 40, or type N sodium silicate, was the material actually mixed with water in the grout tests and in the grouting operation.

[6]Diamond Shamrock Corp. (Cleveland, OH). Sodium Silicate Handbook. 1979, 55 pp.

The requirements for a grout for use in horizontal holes are--

1. A low shrinkage so that no void spaces will form as the grout sets.

2. A set time long enough to allow placement of the grout, generally from 1 to 8 hr, depending upon allowable pumping rates for the grout and hole length.

3. A low viscosity so that the grout can be pumped long distances (150 to 610 m or 500 to 2,000 ft are typical).

The material need not have a high compressive strength, but since sodium silicate gels have an inherently low strength this was also of concern.

There were two lines of development that could have been pursued. The development effort could have been concentrated on a low-solids grout that would be squeezed into the fracture system and seal there, but which would shrink in the hole; or a high-solids grout that would not shrink, but would probably not enter the fracture system as easily. The decision was made to concentrate upon low shrinkage grout.

It has been common practice in the grouting industry to add cement to the sodium silicate grout as the solid material to reduce shrinkage. However, the cement reduces the set time of the sodium silicate grout to minutes or even seconds. Since this created problems in grout placement, the use of cement as an additive to the grout was rejected. However, straight sodium silicate gels had too high a shrinkage so a compromise between a low-solids and zero-solids grout was made and mixes with various quantities of diatomaceous earth were tested.

The diatomaceous earth acted as a relatively low-cost filler. It had little effect upon the viscosity and density of the grout and it slightly increased the strength of the grout. The addition of diatomaceous earth also reduced the set time of the grout, but this effect was small enough that it was acceptable.

Figure 2 shows the effect of increasing quantities of diatomaceous earth on the shrinkage of a particular grout mix. The three samples shown in the photograph are all of the same mix used to grout the horizontal holes. Only the percentage of diatomaceous earth has been varied from sample to sample. Sample 4C has 2 pct, sample 5C, 6 pct, and sample 6C, 10 pct diatomaceous earth by weight.

The mix of sample 5C was the mix finally chosen for use in the horizontal holes. The composition of this grout, known as Geloc-4, is given in table 1. The organic reactant listed in the ingredients is the setting agent and is a proprietary material. The TX-100 is a surfactant (detergent) that allows an easier mixing of the water and the sodium silicate.

TABLE 1. - Composition of sodium silicate grout mix used to plug horizontal holes

Material	Mix design		Actual mix[1]	
	wt pct	vol pct	wt pct	vol pct
Sodium silicate[2].....	40	33.6	41.1±0.3	34.6±0.4
Water................	49.4	58.3	48.1± .2	56.8± .2
Diatomaceous earth...	6.0	3.4	5.8	[3]3.3
Organic reactant.....	4.5	4.7	4.9	5.2± .4
TX-100 surfactant....	.1	.1	.1	.1
Total..........	100.0	100.1	NAp	NAp

NAp Not applicable.
[1]Average for the 7 holes.
[2]Specific gravity 1.4; 40 Bé.
[3]Volume after being mixed in water.

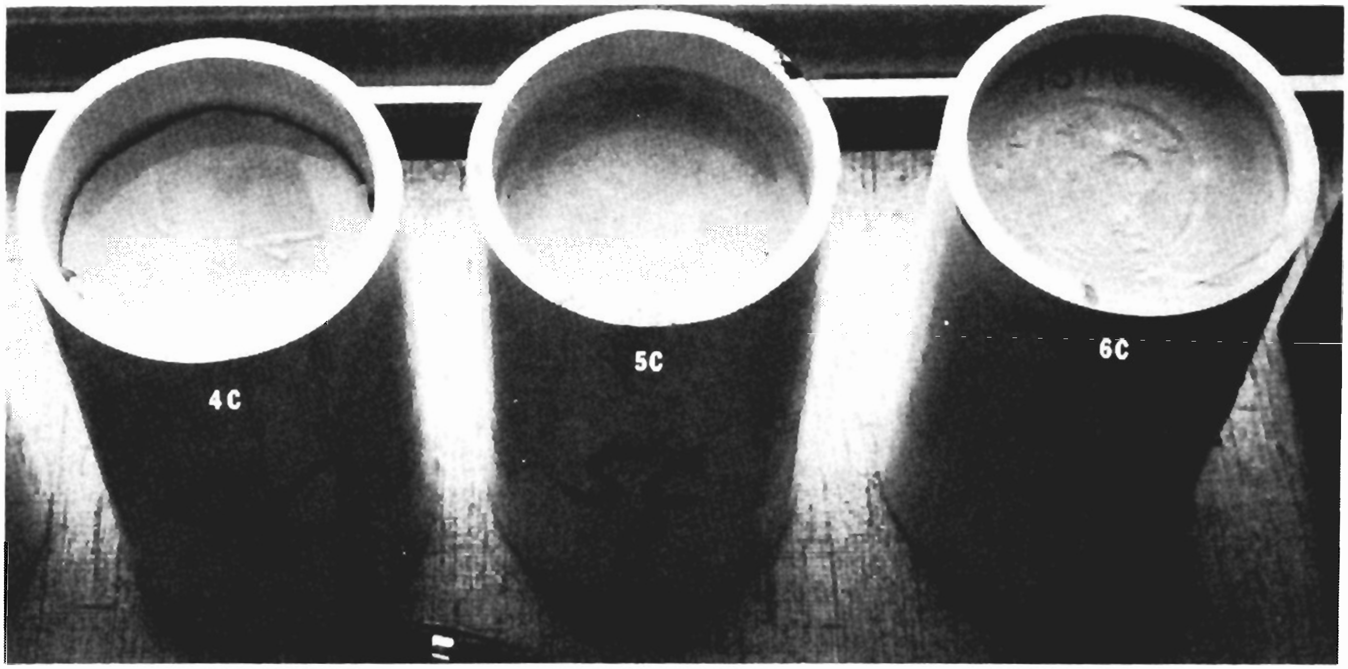

FIGURE 2. - Six-day-old Hayward Baker grout mixes with, from left to right, 2, 6, and 10 pct diatomaceous earth.

The grout design given in table 1 meets all of the requirements mentioned earlier. Its shrinkage is relatively small, a few percent at most, which allows it to adhere to the wall of a hole even after shrinking. It has a viscosity only slightly higher than that of water, making it easy to pump. As mixed in the laboratory its set time was about 30 min, which was marginal for the longest hole but sufficient for the rest. The actual setting time for the grout, when mixed at the jobsite, was about 1 hr, due to the reduced rate of the setting reaction under the cooler field conditions. The compressive strength of the grout was also quite high for sodium silicate mixtures, as can be seen from figure 3 where the grout easily supports the weight of a pencil placed in it.

GROUTING METHOD

It was initially planned to pour grout down one of the 102-mm (4-in) diameter steel lines originally used to pipe gas from the bottom of the shaft to the surface, to a high-pressure hose at the bottom of the shaft. A union would then be used to connect the hose to a grout header that was in turn connected to mechanical compression packers that were part of the gas piping system. High-pressure valves were to be used on each side of the union to allow the flow of grout to be shut off after a hole was filled. It was necessary to plan for the use of 12.7-mm (0.5-in) diameter grout pipe in the holes because the 32-mm (1.25-in) ID pipe of the packers (fig. 4) in the 76-mm (3-in) holes would not allow the passage of the coupling of any pipe larger than 12.7 mm (0.5 in).

This was a compromise from the 19-mm (0.75-in) pipe recommended by Hayward Baker. It meant that friction losses in the pipe while pumping grout at the planned rates of 3.6 to 4.5 m^3/hr (16-20 gal/min) would be very high. Had the use of a cement grout been planned, the friction losses would have been too high to allow the use of 12.7-mm (0.5-in) pipe. To decrease the friction losses, the direction of grout flow was changed from

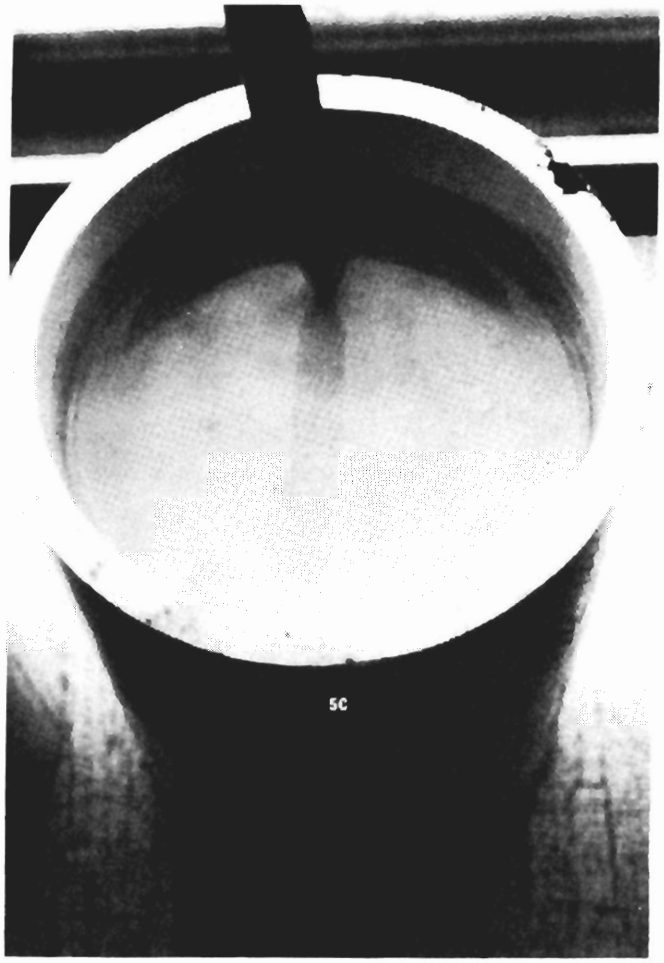

FIGURE 3. - Grout mix 5C with 6 pct diatomaceous earth, 6 days after mixing.

through the plastic and back through the annulus (between the pipe and the wall of the hole), to through the annulus and back out through the plastic pipe. With this procedure, even if the pressure began to rise as the grout entered the plastic, the hole itself would already be plugged. This method also had the advantage of putting the pipe collars in compression, rather than tension, thus decreasing the possibility of a joint separating during the operation.

The technique had the disadvantage that particles of coal or shale in the hole could plug the small-diameter pipe and prevent water, gas, and grout returns. To help prevent this, it was planned to flush each hole clean with water the day before grouting, by pumping water in the plastic pipe and out of the annulus.

A sketch of the grouting setup finally used is shown in figure 5, which also shows the compression packer used in the holes. Figures 6 and 7 show the underground grouting equipment setup to flush water from the number 2 hole. During the actual grouting operation, the high-pressure hose was connected to the side line as shown in figure 5, and the 12.7-mm (0.5-in) plastic pipe in the hole was the gas and water return line.

PLUGGING OPERATIONS

PREPARATION

Preparations for grouting the horizontal holes were begun early in September 1980. One of the two 102-mm (4-in) steel gas-flow lines from the bottom of the shaft to the surface was disconnected from the receiver tank underground, and from the 152-mm (6-in) gasline on the surface, to allow BQ wireline drill rod to be run inside it by personnel from the Federal No. 2 Mine. The drill (46-mm or 1.812-in ID) rod was used to carry the grout instead of the 102-mm (4-in) pipe, in order to decrease the amount of grout stored in the vertical line at any time. Had a smaller pipe been readily available, it would have been used rather than the BQ pipe.

During the week of September 29, 1980, 12.7-mm (0.5-in) ID schedule 40 PVC pipe was inserted into the horizontal holes. Although the holes had been drilled over 8 yr earlier (May-July 1972), the pipe was run into holes 1, 4, 6, and 8 with few difficulties (fig. 8). Some tight spots were encountered in hole 2, caused by loose coal in the hole at about 180 to 198 m (600-650 ft) from the collar of the hole. The pipe had to be worked through the tight areas by repeatedly pulling it out several meters and then shoving it back in forcefully. It was later discovered that this pipe had broken, five joints (15 m or 50 ft) from the far end, probably owing to the harsh treatment given it while working it to the back of the hole. Pipe counts while running

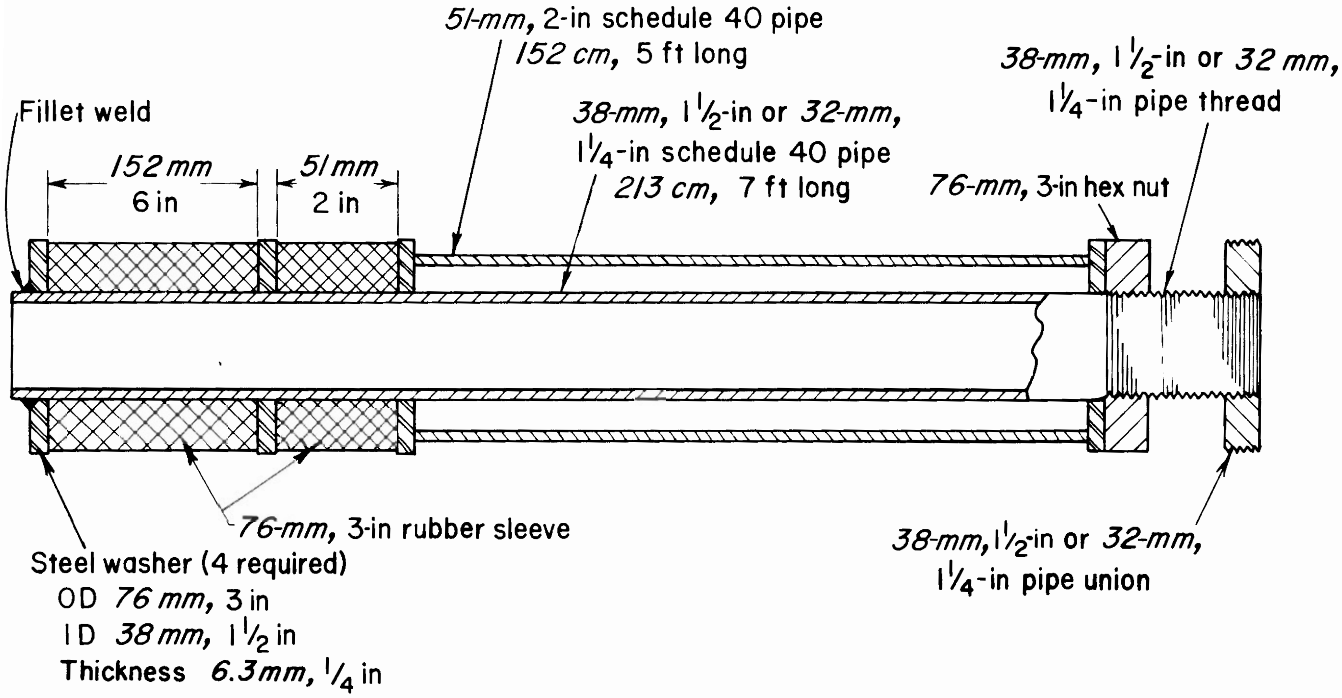

FIGURE 4. - Bureau-designed compression packer used to seal horizontal holes.

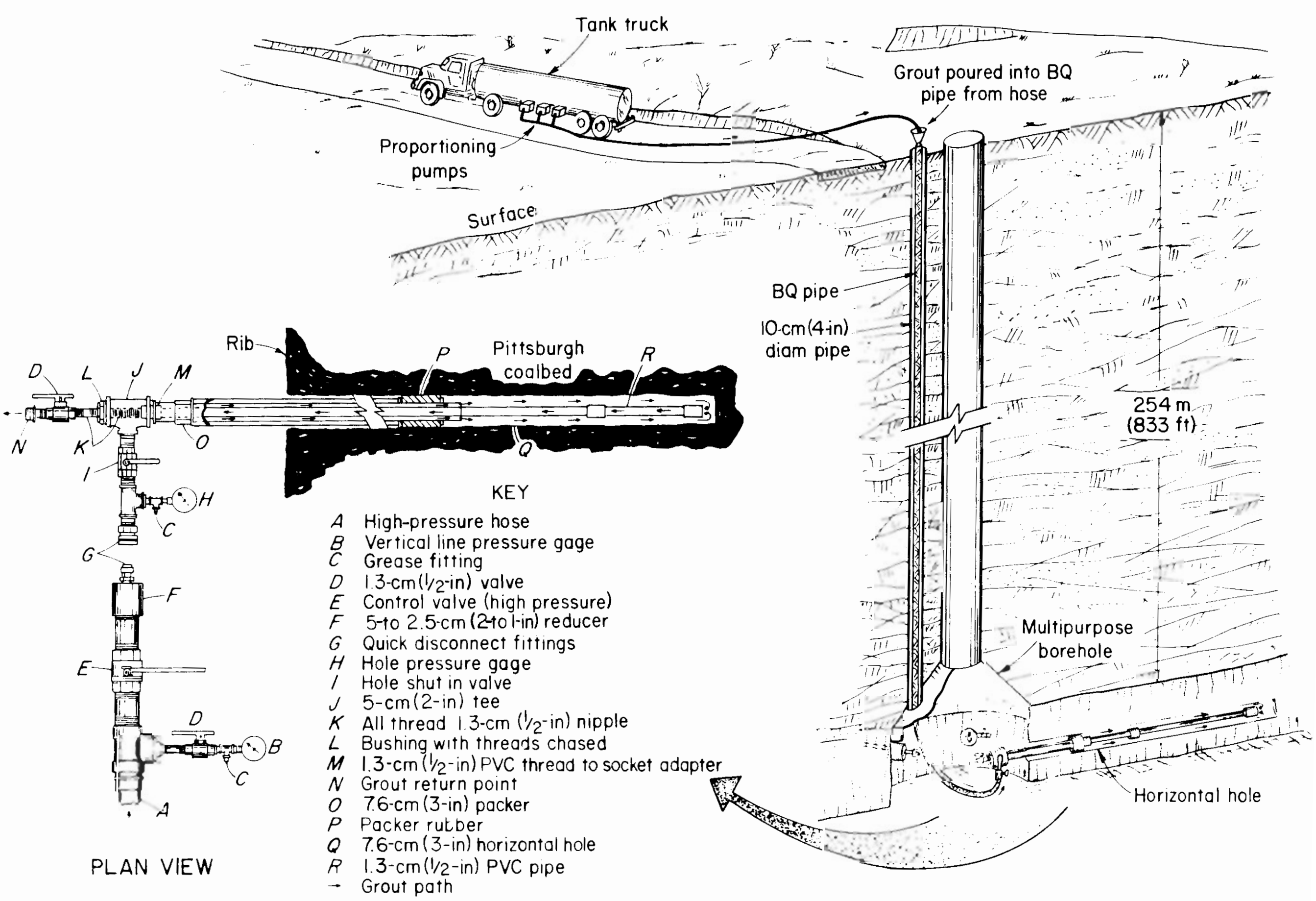

FIGURE 5. - Schematic of method used to plug horizontal holes.

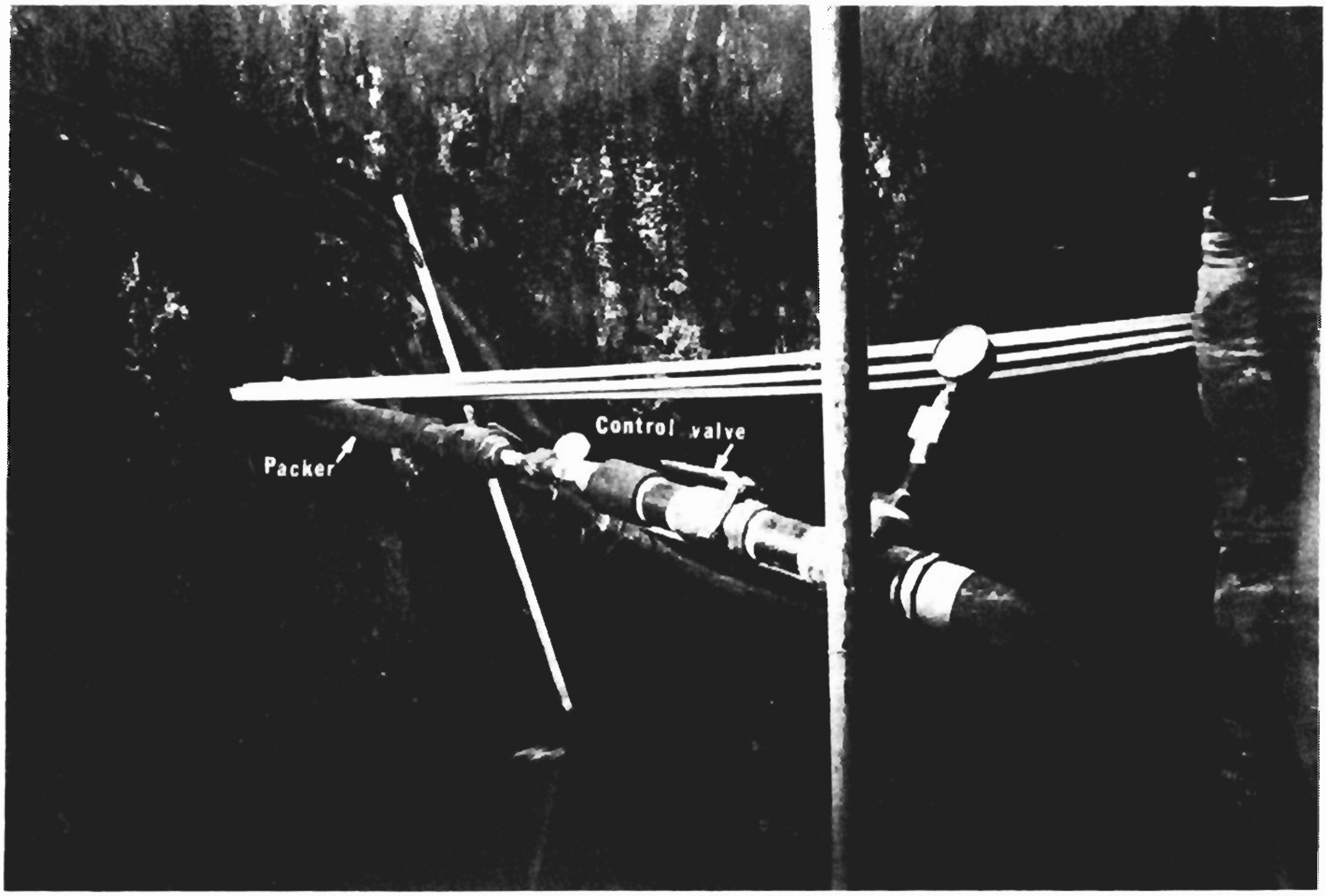

FIGURE 6. - Water flushing of hole 2.

the pipe also made it appear that the pipe in hole 7 had been separated, but when the pipe was removed from the hole later it was found to be intact and was re-inserted without difficulty. The greatest problems were encountered in inserting pipe in hole 5. In the initial attempts pipe could not be pushed past a depth of 47 m (155 ft).

In mid-October 1980, a crew with a hand-held air drill worked to clean out hole 5. The original records from 1972 indicated that the hole had been drilled into roof rock at 42 to 45 m (140-148 ft) and had been terminated at 47 m (155 ft). The hole had then been sidetracked at 21 to 34 m (70-110 ft). It appeared that the PVC pipe had entered the sidetrack. During the cleanout operation, the drill pipe followed the main hole and had no difficulty in reaching the end of the hole at 152 m (500 ft). The PVC pipe, however, still followed the sidetrack. To finally get the PVC pipe past the sidetrack, it was necessary to thread it through the drill pipe. After this was done, the PVC ran freely to the end of the hole. When hole 5 was mined through (fig. 8, locations L and M) it was found that the hole had actually been sidetracked twice, but since mining advanced only 29 m (94 ft) from the collar of the hole, it was not possible to confirm the lengths of the sidetracks or determine which sidetrack the PVC pipe had entered. In 1982 an area south of location L (fig. 8) was mined but hole 5 could not be found, possibly because it had been drilled in roof rock.

The final preparations for grouting were made on November 5 and 12. On November 5, hole 2 was flushed out with water by connecting a surface line to the BQ rod and using a hose to connect the BQ

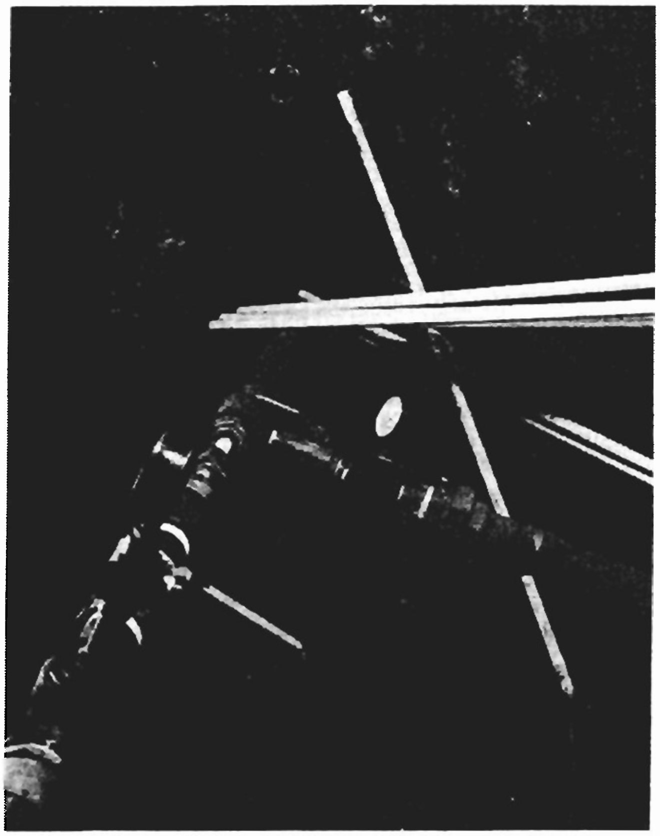

FIGURE 7. - Second view of hole 2 during flushing operation. Note 12.7-mm (0.5-in) PVC pipe in background.

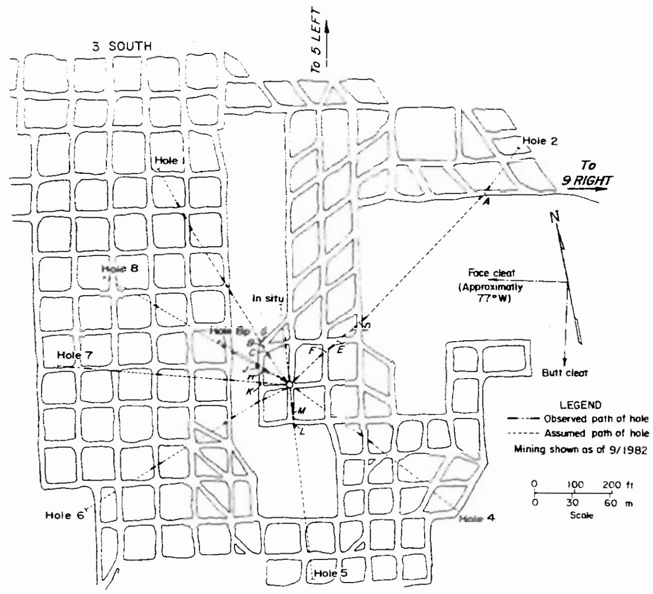

FIGURE 8. - Vicinity of multipurpose borehole showing locations of horizontal holes. Letters denote locations discussed in text.

rod to the 12.7-mm (0.5-in) PVC pipe underground (figs. 6 and 7). Water was then circulated in the hole through the 12.7-mm (0.5-in) PVC pipe and out the annulus of the hole, to the floor of the shaft.

Hole 2 was flushed on November 5 because of the five joints of pipe that had broken free. [This was determined by inspection of the hole in 9 Right (fig. 8, location A) where the hole had been mined through inadvertently in April 1980.] After the five broken joints had been removed, it was found that pipe could be pulled out but not pushed in. The hole was flushed on November 5 in an attempt to clean out broken coal, which was assumed to be wedging the pipe in the hole. The attempt was unsuccessful and hole 2 was later grouted with the back 15 m (50 ft) of hole having no pipe in it.

The problem with hole 2 also alerted Bureau personnel to the possibility of broken pipe in the other holes, and all of the other holes were checked by pushing the pipe all the way to the back of each hole, just before each was flushed with water. No broken pipe was found in any other hole.

The rest of the holes were flushed with water on November 12 in the same manner as hole 2 was flushed, with the exception that a 152-mm (6-in) vent tube was placed at the return line of each hole to carry gas coming from the holes to the shaft air exhaust line. All of the other six holes were flushed uneventfully and with little return of solid material, except hole 4.

In hole 4, which was producing between 60 and 80 pct of the gas being drained from the shaft in the last few months, large quantities of coal were seen in the form of dust and small lumps. In addition, flakes of calcite, similar to those seen in hole 2 when it was accidentally cut into in April 1980 (fig. 9), were observed in the returning water. [In hole

FIGURE 9. - Hole 2 after mine-through, April 10, 1980, showing calcite lining the lower half of the hole. Location A (fig. 8).

2, a thin layer of calcite had been seen coating the lower half of the hole. The layer was about 1 mm (1/16 in) thick, was nearly pure white, and had a pebbly appearance.] Hole 4 also required a much longer flushing time than the other holes because of the large quantities of coal particles in the hole.

GROUTING

The actual grouting operation was begun on November 13, 1980. First Hayward Baker's tank truck (fig. 10) was filled with a mixture of water and diatomaceous earth. This material could not be mixed more than 4 to 6 hr in advance of its use, or the diatomaceous earth would settle out in the tank, where it could not be remixed. Frozen hoses prevented the work of mixing from being completed until nearly noon, so only enough material was mixed to grout two holes.

Hayward Baker used a continuous mixing system for preparing its grout. This meant that as a given volume of grout entered the top of the BQ pipe, it had

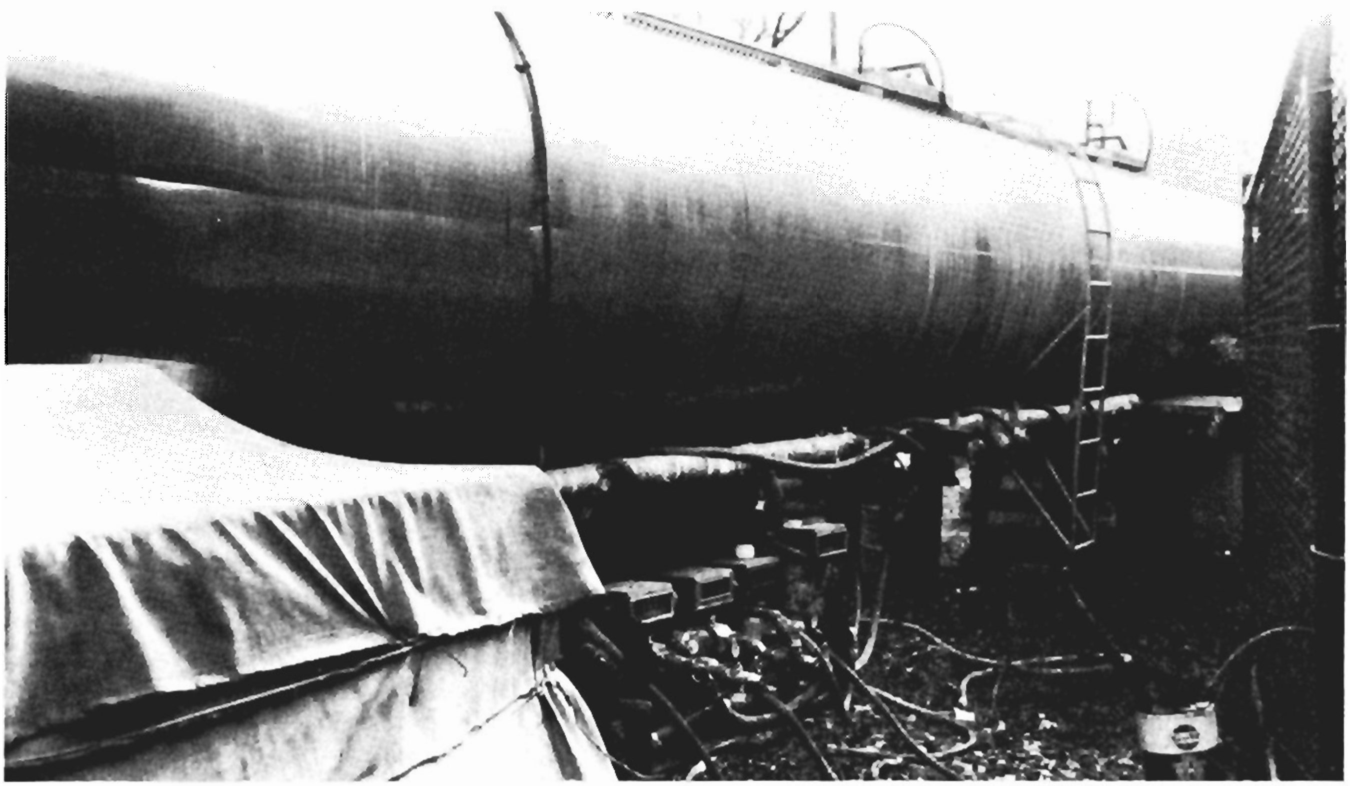

FIGURE 10. - Three-compartment tank truck at multipurpose borehole site.

nearly its entire set-up time to be pumped before gelling. This is different from batch mixing, where all of the grout would set at the same time and the last grout in the pipe would have only a few minutes left before setting. In effect, continuous mixing allows longer pumping times for grouts with short pumping lives before set up. In the grouting industry where cement-sodium silicate mixtures with set-up times measured in seconds are used, continuous mixing is absolutely necessary. However, continuous mixing also necessitates the use of several pumps and careful metering of the ingredients.

Figure 11 shows Hayward Baker's pumps and metering equipment. Four progressing cavity type pumps were used, two to pump the water-diatomaceous earth mixture, one to pump sodium silicate, and a fourth to pump the organic reactant. The TX-100 surfactant was mixed into the tank containing the water, and was pumped along with that component.

As the ingredients were pumped, they were mixed in hoses at the surface, and were then pumped through a single hose to the BQ pipe. The grout was then poured into the BQ, rather than pumped, so that if the rate of flow in the BQ became faster than the pumping rate of 3.6 m^3/hr (16 gal/min) the suction created would not pull the ingredients out of the pumps in incorrect proportions.

At the bottom of the shaft a high-pressure (4,100 kPa or 600 lb/in^2g) valve was used as a control valve to keep a constant height (and therefore constant pressure) column of grout in the vertical (BQ) pipe. A pressure of 1,030 kPa (150 lb/in^2g) was arbitrarily chosen as the desired pressure. Because the gauge used to monitor the pressure read 138 kPa (20 lb/in^2g) high, the actual pressures were less than the planned pressures. (All pressure values given in this report have been corrected to the pressures determined by a deadweight tester calibration

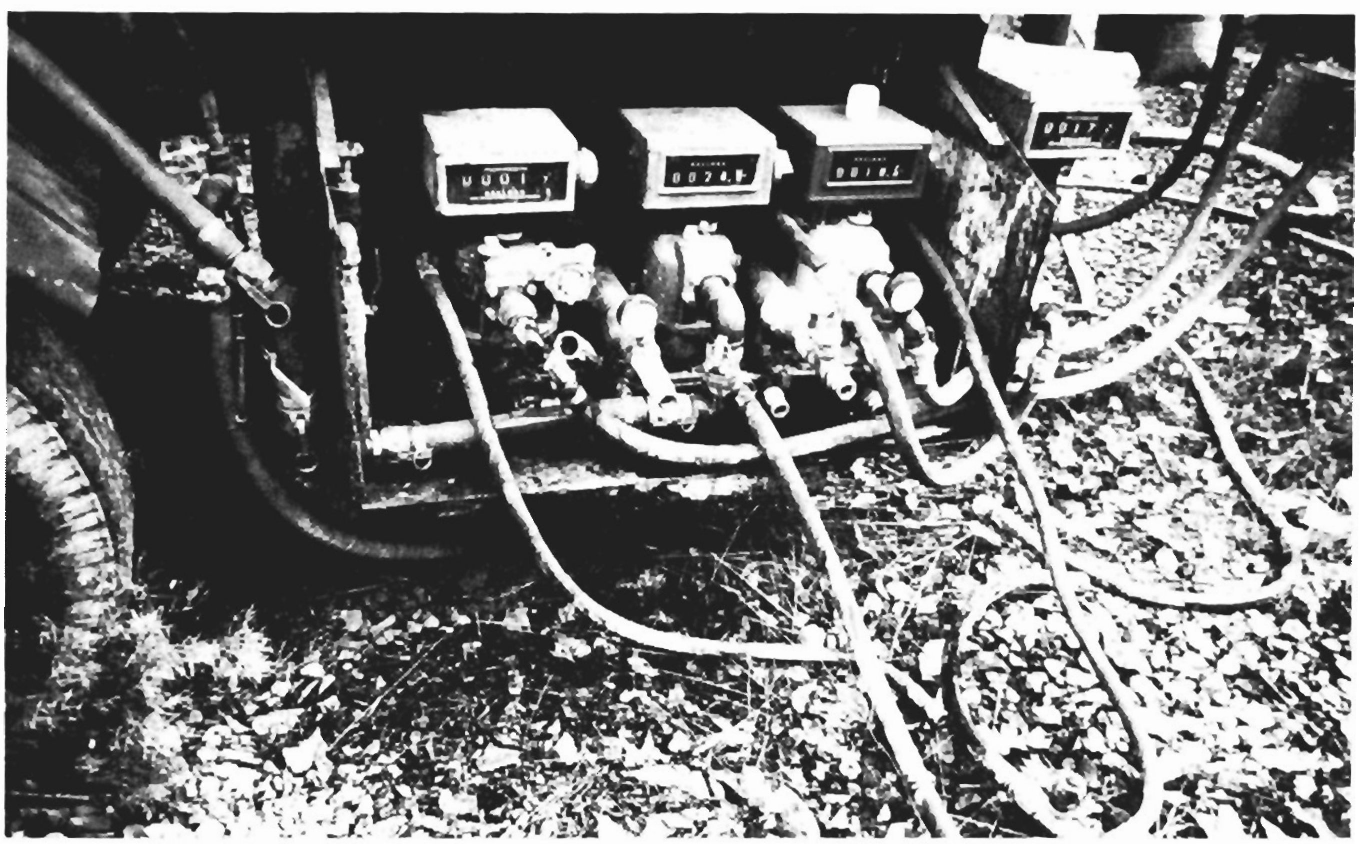

FIGURE 11. - Grout pumping and metering equipment.

of the gauge made after the project was completed.)

Figure 12 shows the pressure curves for each of the holes. Each graph shows two pressure curves. The upper curve shows the pressure at the bottom of the BQ pipe, and the lower curve shows the pressure in the hole and the pressure of the grout flowing in the hole. The grout entered the annulus of the hole from the side of the 51-mm (2-in) tee of the grout header (fig. 5), and then flowed along the length of the hole. At the same time the gas and water in the holes were forced to the back of the hole and then out by way of the 12.7-mm (0.5-in) PVC pipe.

Shortly before the grout entered the PVC pipe and began flowing back, the hole usually began to flow water without gas. The flowing pressure at that point was typically 70 to 100 kPa (10-15 lb/in^{2}g). It normally required about 15 min and an estimated grout volume just slightly higher than the calculated hole volume (table 2) to obtain grout returns. The time of grout returned is indicated in figure 12 by the circled X.

TABLE 2. - Horizontal hole grouting data

Hole	Length, m	Length, ft	Volume, m^3	Volume, gal	Grout return time, min	Estimated volume pumped to grout return[1], m^3	Estimated volume pumped to grout return[1], gal	Time, min: Grout pumping	Time, min: Hole open	Total grout volume used, m^3	Total grout volume used, gal	Ratio of pumped volume to estimated hole volume
1...	196.9	646	0.90	237	14	0.84	221	35	38	2.21	585	2.47
2...	228.6	750	1.04	275	18	1.08	284	41	45	2.68	707	2.57
4...	167.3	549	.76	202	17	1.01	268	32	32	1.84	485	2.40
5...	152.4	500	[2].76	202	14	.84	221	33	34	1.97	520	2.57
6...	187.8	616	.86	226	15	.89	236	27	36	1.59	419	1.85
7...	185.3	608	.84	223	19	1.13	299	45	47	2.57	678	3.04
8...	169.5	556	.77	204	17	1.01	268	40	82	2.62	693	3.40

[1]Assumes a grout pumping rate of 3.5±0.17 m^3/hr (15.75±0.75 gal/min) and ±0.5 min accuracy in determining the time of grout return.

[2]Includes a sidetrack assumed to be 15 m (50 ft) long.

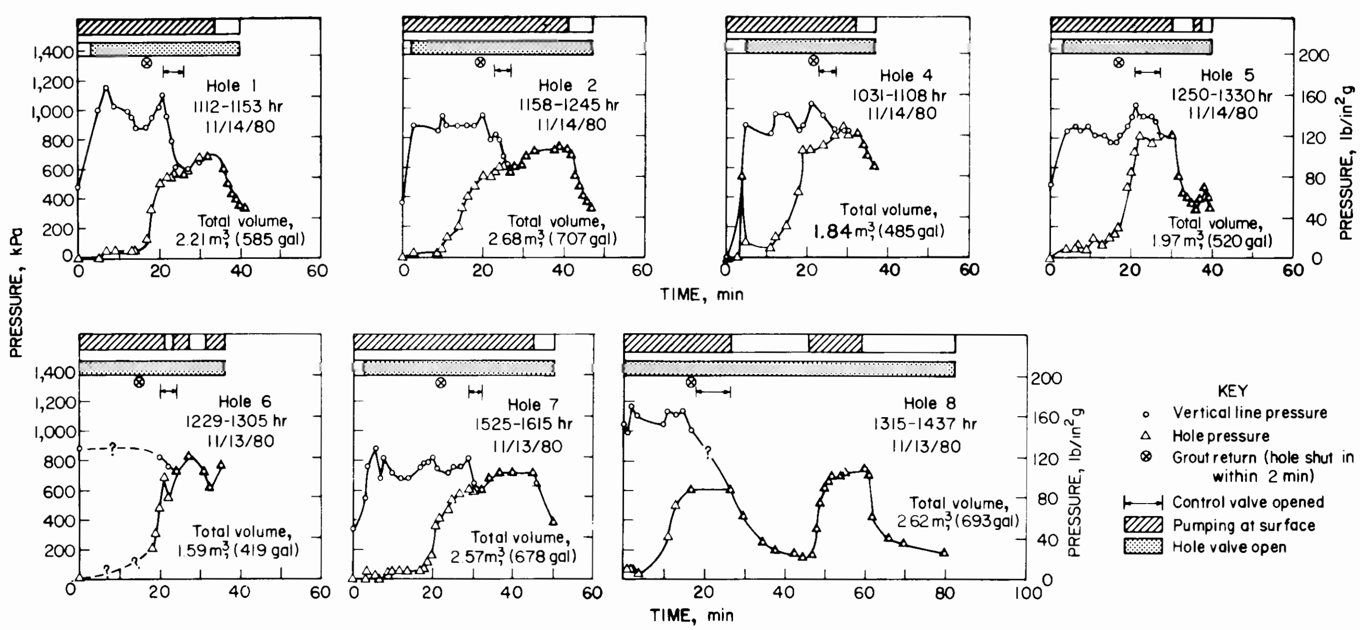

FIGURE 12. - Pressure curves and grouting records of horizontal holes. Activity times are expressed on the basis of a 24-hr clock.

As the grout returned through the much smaller 12.7-mm (0.5-in) PVC pipe, the hole pressure rapidly increased, primarily because of the pressure drop in the PVC pipe. Once the grout had returned, the control valve was gradually opened and the hole and vertical line pressures equalized. Grout was also poured on the floor of the borehole for 1 to 2 min after returns were obtained in order to remove any water-contaminated grout before the hole was shut in.

Pumping was usually continued until a grout volume of 2.5 times the calculated hole volume had been pumped. At that time, mixing of grout at the surface was discontinued and the grout remaining in the BQ pipe was allowed to flow into the hole until the hole pressure dropped to around 345 to 480 kPa (50-70 lb/in^{2}g). The hole was then shut in and preparations were made to move to the next hole. This technique evolved during the grouting operation, and it can be seen that the pressure-flow curves for holes 5, 6, 7, and 8 (fig. 12) do not match this description exactly.

Hole 6 was the first hole grouted. While grouting this hole it was found that no definite endpoint existed at which a hole would no longer accept grout, or at which the pumping pressure would rapidly increase. The grouting operation was shut down relatively early in hole 6, but because of the uncertainty in the condition of the grout in the holes, larger volumes were pumped into the other holes.

Grout was pumped into hole 8 in two separate stages because the initial diatomaceous earth-water mixture was used up and more had to be mixed in the surface tanks before more grout could be mixed and pumped. It should be noted that grout was still flowing into hole 8 under relatively low pressure (270 to 760 kPa or 40 to 110 lb/in^{2}g) at between 60 and 80 min elapsed time even though the set time of the grout was about 55 to 65 min. (This was partially because the grout mixing was done at temperatures just above freezing, which slowed the setting reaction.) Much of the previously set-up grout may have been either in the fracture system of the coalbed or coating the walls of the hole, but not blocking the hole. The continuous mixing method used may have allowed grout to be pumped in the hole long after the set-up time of the first grout pumped had passed. Recent work by Bader, and Krizek, and Baker[7] suggests that sodium silicate grouts may not completely set up as long as they are kept in motion. They report increases in set time, during pumping, of from 2 to 7 times as compared with samples not kept in motion.

Holes 6, 8, and 7 were grouted (in that order) on November 13. On November 14 the remaining four holes were completed and owing to the experience gained on the previous day, the methods used were much more uniform. Once all of the equipment and personnel were in place and ready, it was possible to grout a 150-m (500-ft) hole in about 30 min. The changeover to the next hole required about 5 min.

RESULTS

On November 19, shortly after the holes were grouted, a trip was made to the Federal No. 2 Mine to inspect hole 2 where it had been mined through in April 1980 (fig. 8, location A). A packer had been inserted to seal the hole just before the grouting operation was begun. When the valve on this packer was opened, the hole was found to have some pressure in it and some wet grout was forced out of the hole (fig. 13). With the valve shut, pressures of 41 kPa (6 lb/in^{2}g) built up in 10 min, but there was little flow of gas and no water flow from the hole.

Hole 1 was the first hole to be mined through (fig. 8, locations B and C),

[7] Bader, T. A, R. J. Krizek, and W. H. Baker. Injection and Distribution of Silicate Grout in Sand. Proceedings of the Conference on Grouting in Geotechnical Engineering. Am. Soc. Civil Eng., New York, 1982, pp. 540-563.

FIGURE 13. - Hole 2 five days after being grouted, location A (fig. 8). Note wet grout in the valve.

on February 5, 1981. Hole 2 was mined through (fig. 8, locations D, E, and F) in several locations between February 5 and 18.

Figures 14 and 15 are photographs of hole 1, taken on February 18, 1981, looking respectively away from and toward the shaft (fig. 8, locations B and C). The grout appeared to be in good condition, and no void spaces were noted in the hole. The condition of hole 2 in the locations where it was inspected was similar. At location G (fig. 8) grout was also observed in the fracture system of the coalbed about 0.6 m (2 ft) from hole 1. Figure 16 is a photograph of the grout in the cleat at that location. The white material in the center of the photo is a thin film of grout that had been pumped through the cleat system of the coalbed. The film could be identified as grout by its color[8] and the odor given to the grout by the setting agent. Indications of grout in the coal cleat were detected as far as 2.4 m (8 ft) from hole 1 and at a few feet from other holes. No attempt was made to determine the maximum extent of the migration of grout from the holes, so this distance is not necessarily a maximum.

Holes 7, 8, and 8P were mined through between February 18 and 24. They were inspected and photographed on March 3, 1981. (The shaft itself was mined into on February 25, 1981.) Holes 8 and 8P are shown together in figure 17 (location H), which was taken looking toward the shaft, and separately in closeups in figures 18 and 19. The holes are approximately 50 cm (20 in) apart at that point. They had started out roughly 23 cm (9 in apart), and both holes had voids in the grout in the upper part of the hole when the photographs were taken. However, when the outby rib was observed (location J) there appeared to be little or no void space in the grout there. There was also a film of water flowing from the outby sides of the holes, but no water flow from the inby sides. Hole 7 was inspected at location K (fig. 8), and the condition there was found to be similar to that of holes 8 and 8P.

The most important observation was that there was no gas flowing from any of the holes, on either rib. These observations indicate that, when wet (in unmined coal), the grout maintains its initial volume and acts as a seal to prevent gas flow. The grout does not appear to stop water flow, but this may actually be an

[8]Sodium silicate grouts are a milky white color, but the diatomaceous earth added to the grout made it a beige or tan color. Once exposed to air, the grout dries to an off-white color that makes it difficult to distinguish it from rock dust.

FIGURE 14. - Hole 1, view away from the borehole at location B (fig. 8).

FIGURE 15. - Hole 1, view toward the borehole at location C (fig. 8).

FIGURE 16. - Grout film in the coal cleat near hole 1.

advantage since the water flow appears to prevent the grout from drying out. As the grout dries, it becomes a chalky, low-density material which shrinks and loses its ability to prevent gas from flowing. However, the likely places for drying and shrinking to take place are in already isolated blocks of coal, which are also isolated from any appreciable methane flow.

Figures 17, 18, and 19 do not clearly show that holes 8 and 8P were filled with grout. The photographs do show at least a thin film of grout adhering to the entire circumference of both holes, which indicates that both were originally filled. Part of the void spaces in the holes were caused by crushing of the dry, brittle grout by a pick used to clean rock dust from the hole for photography. Crushing of the grout in the upper portions of the holes probably indicates that the grout in that part of the hole was low in density, possibly the last grout to solidify. However, on the outby rib the grout in holes 8 and 8P was solid, and no gas flow was observed.

It should also be noted that no grout was actually pumped into hole 8P. There had been no indication during tests made in 1972 that the two holes were directly connected, so any grout that had entered 8P had to migrate through 20 to 50 cm (8-20 in) of the coal's fracture system from hole 8. This indicates that the sodium silicate gel grout has a sufficiently low viscosity to be pumped through the coal cleat around short collapsed portions of horizontal holes. This would allow some holes to be plugged even when pipe could not be inserted to the total length of the hole.

All three remaining holes, 4, 5, and 6, were intercepted at least once before mining in the vicinity of the borehole was completed on March 26, 1981. All of the holes were inspected on April 7, 1981. In almost every case shrinkage of grout was noted on dry ribs. It also appeared that the volume of grout in the holes inspected on March 3 had decreased. On the virgin (and usually wet) rib, water flow was observed from all of the holes (fig. 8, locations B, D, J, K, and L). No gas flow was observed either from holes on the ribs on the isolated pillars or from holes on virgin ribs, even in places where gas and water could be seen and heard flowing from the rib itself.

FIGURE 17. - Holes 8 and 8P, location H (fig. 8), holes about 50-cm (20-in) apart.

FIGURE 18. - Hole 8, same location as figure 17.

FIGURE 19. - Hole 8P, same location as figure 17.

A final inspection of the holes was made on June 17, 1982, after mining had progressed sufficiently to cut through the far ends of most of the holes. During this inspection trip, each of holes 1, 6, 7, and 8 was located at least two points using mine spad and steel tape surveys. Hole 4 was found at only one location. Hole 5 could not be located in either of two anticipated locations, after passing through a 73-m (240-ft) barrier pillar. The June 1982 inspection confirmed the results of the 1981 inspections. Grout in the holes remained solid, without voids, and no gas flow was observed from the holes. Since most of the inspected portions of the holes were in pillars isolated by mining from virgin coal, no seepage of water was observed from the holes.

COSTS

On a unit volume basis, the contractor costs for placing the grout averaged $1,490 per cubic meter ($5.65 per gallon) in 1980 dollars. This includes the contractor's labor, equipment, and cost of the materials used. Table 3 gives the material costs. These costs were for an experimental procedure. If this type of grouting was done on a routine basis, it is possible that the unit cost could be reduced.

TABLE 3. - Grout costs[1]

Material	Unit cost	Amount
Sodium silicate, reactant, and surfactant....4,156.7 gal..	$1.50	$6,235.05
Diatomaceous earth 2,400 lb..	.175	441.00
Total material cost.	NAp	6,676.05
Overhead......15 pct..	NAp	1,001.41
Total...........	NAp	7,677.46

NAp Not applicable. [1]In 1980 dollars.

The material cost for the sodium silicate grout, not including overhead charges, was $425 per cubic meter ($1.61 per gallon). This compares to a cost for a cement grout (42 kg or 94 lb cement, 0.019 m^3 or 5 gal of water, and 0.91 kg or 2 lb of fluidifier) of $310 per cubic meter ($1.17 per gallon) (assuming $5.00 per sack of cement and $1.98 per kilogram of fluidifier).

This direct comparison is somewhat misleading, however, since the sodium silicate grout has a greater tendency to enter the coalbed. It may require two or three times as much sodium silicate as cement grout to fill a hole. Additional costs are also incurred with the use of sodium silicate for special services and equipment, not necessary in cement grouting, to mix and pump the grout.

Along with the contractor costs there were additional personnel costs for grouting preparations and for the actual grouting operation. Because a close accounting of this time was not kept and because some of the actual time was spent in what were essentially research activities, no attempt has been made to determine the actual hours. Instead, an estimate has been made of the number of hours required to perform a particular operation, under normal conditions, on a 150-m (500-ft) hole. These estimated times are as follows, in hours: Insertion of plastic pipe in a hole, 1.5 hr; assembly and hookup of a grout header, 1.0 hr; flushing of a hole with water, 1.0 hr; and grouting a hole, 1.0 hr. These times are based upon the use of a two- or three-person crew working underground (an engineer or supervisor and one or two laborers).

Since the work was also done from the bottom of a shaft, additional personnel had to be kept on surface at all times. These included the hoistman, a topman for safety, and a fireboss, who was occasionally used underground as an additional laborer when needed. Therefore, every hour worked on the holes required 2 or 3 employee-hours of labor by underground personnel and 3 employee-hours by surface personnel. It is possible that the size of the underground crew could be cut to two persons for all but the grouting operation, with only a slight loss of efficiency. The flushing operation was performed in 1 day by an engineer and the fireboss. The surface crew at that time consisted of the hoistman and a topman. However, during the grouting operation it is recommended that a three-person crew be used in order to avoid slowups and confusion.

DISCUSSION

Table 2 shows the total volumes of grout pumped into each hole and gives an estimate of the quantity of grout required to fill a hole. The total quantity pumped was determined by meters on Hayward Baker's pumps. Corrections were also made for grout stored in the vertical line or grout added from the vertical line. This value is probably accurate to ±0.04 m^3 (10 gal). The volume required to fill a hole was estimated from the time required to obtain grout returns and a steady pumping rate estimated by Hayward-Baker. The estimated pumping rate was 4.3 m^3/hr (15.75 gal/min). Again corrections were made for grout stored or left in the line during the period measured. The flow rate measured by Hayward Baker is probably accurate to ±5 pct, and the time measurement is accurate to within ±0.5 min.

The measured quantities of grout pumped, to the time of grout return, appear to have been close to the hole volumes except in the cases of holes 4, 7, and 8. In all cases the quantitites were larger than the estimated hole volumes. For each of holes 4, 7, and 8, the overruns were around 35 pct. It would have been reasonable to expect a higher overrun in the grout volume required to fill hole 8, since some grout could have flowed to hole 8P, but the overrun was no higher for that hole than for 4 or 7. This indicates that grout did not begin to migrate to hole 8P until the pressure in hole 8 began to rise. A 35-pct overrun, however, is not particularly high so it appears that the volumes of sodium silicate grout required to fill a hole can normally be expected to be close to the hole volume. This can probably be attributed to the low pressure actually required to pump the grout into a hole.

From the lower pressure curves in figure 12, it can be seen that the maximum pressures required were 100 kPa (15 lb/in^2g). Once the hole pressures reached 550 to 830 kPa (80-120 lb/in^2g), large quantities of grout began to enter the coalbed. In contrast, the pressure required to obtain returns of cement grouts in a 300-m (1,000-ft) hole are typically 600 to 900 kPa (90-130 lb/in^2g), and pressures up to 3,500 kPa (500 lb/in^2g) have been used in an attempt to force the excess water in the cement grouts into the coalbed. Sodium silicate grouts, because of their low viscosity, appear to require much lower pressures in order to fill a hole, and once pressures of 400 kPa (60 lb/in^2g) are reached, grout will begin to enter the coalbed.

Volumes of grout between 1.85 and 3.4 times the holes volume were pumped into the holes. The largest quantity was pumped into hole 8 and a large portion of this, 0.36 of the hole volume, went to fill hole 8P. As mentioned earlier the actual volumes required to obtain returns were never more than 1.35 times the hole volumes. In the case where only 1.85 times the hole volume was pumped, hole 6, the hole was still found to be full upon interception by mining. To insure that holes are filled, it appears that between 1.5 and 2.0 hole volumes of grout would typically be sufficient. The only question remaining is whether the grout in the hole or the grout in the cleat stops the flow of gas.[9] There was some evidence for both mechanisms, but the evidence was not convincing or strong for either. Because the hole must be filled in any case, there would only be a cost saving from reduced material costs if excess grout volumes over the hole volume were not required.

---

[9] Slobod, R. L., and E. J. Burcik. Method of Sealing Coal Against Methane Emission. U.S. Pat. 3,845,632, Nov. 5, 1974.

CONCLUSIONS

From the results of the plugging and mine through of the holes at the multipurpose borehole it can be seen that sodium silicate grouts can be very effective in plugging horizontal methane drainage holes. It also appears that sodium silicate can be pumped past blocked or partially collapsed portions of a hole to fill those areas that cements may not be able to enter. However, there are a number of problems and questions remaining in the use of this material:

1. The cost of the grout.

2. The cost of placement of the grout.

3. The short set-up times.

4. The proprietary nature of the material.

5. The lack of understanding of the grout's mode of action.

Although the cost estimates for portland cement and sodium silicate grouts given in this report are nearly equal, it should be remembered that the portland cement costs are inflated by the use of the large quantities of fluidifiers required to fill a long hole, which may not be needed in short holes. Also, as used in the multipurpose borehole, 2.5 times the estimated hole volume of sodium silicate grout was required, while probably no more than 1.5 times the estimated hole volume of cement would be required. Further research may show that less sodium silicate is required, but at present the probability of higher sodium silicate grout material costs must be a serious consideration.

The costs of placing the sodium silicate are also likely to be much higher. Sodium silicate must be pumped as separate components, in carefully measured quantities, before mixing. This requires the use of several accurate pumps and personnel trained in their use. Most mine personnel are also at least familiar with portland cements and their properties. It then requires more complicated equipment and greater expertise to use sodium silicate than cement, all resulting in higher costs.

Another major difficulty with sodium silicates is their short set-up times. The grout designed for this project had a nominal set-up time of 25 to 30 min in laboratory tests. The actual set-up time in the field was 55 to 65 min.

These short set-up times make it difficult to grout the 300- to 600-m (1,000- to 2,000-ft) long holes that are being more frequently drilled. Portland cements, on the other hand, can be designed with set-up times of 4 to 8 hr (although with their higher viscosities and consequently slower pumping rates, the advantage is not quite as great as at first glance). However, recent work cited earlier in this report indicates that sodium silicates may actually have very long set times while being pumped. If this is the case, then sodium silicates may actually have an advantage over cements in this respect.

At present the only sodium silicate that has been proven effective is the grout mix shown in table 1. The setting agent is a material proprietary to Hayward Baker. Although other companies may have equally effective grouts, only experiment and testing will determine which grouts are applicable. In the meantime a lack of competition or local availability may make the use of sodium silicates more expensive.

Finally, the lack of knowledge as to the true mode of action of the grout makes it necessary to use larger quantities of grout to insure that the operation is effective.