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TECHNICAL REPORT
FOR
EXTINGUISHING COAL MINE FIRES
BY REMOTE SEALING

Volume II

By

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SUMMARY

The objective of this program was to develop a system to extinguish coal mine fires by remote sealing of the underground passageways. The system developed had to be versatile enough to function under a wide range of operating conditions, including large variations in passageway geometry, depth of mine, water conditions, both in the mine and at the surface, and rubble in the mine passage. The system developed had to include instrumentation for the remote probing of the passageway prior to sealing, a system for sealing the mine passages, and instrumentation for remote monitoring of the quality of the seal during and after construction.

These objectives were successfully achieved during this program. The remote mine sealing capability of the system was satisfactorily demonstrated in a field test conducted at the Eastern Associated Coal Corporation Federal No. 1 Mine in Grant Town, West Virginia.

The remote sealing consists of:

(1) A sonar initial probing system which can operate satisfactorily even in the presence of dense smoke. The system is capable of determining both the local passageway geometry, identifying the presence of cribs and other obstructions, and the position of the borehole in the mine passage.

(2) A mine sealing material system which utilizes fly ash for making the complete seal or as a bulk filler in conjunction with a urethane, froth foam, seal topping system. The choice of using fly ash alone or fly ash with foam topping depends on a number of factors, such as quality of seal desired, time available per seal, depth of borehole, passageway geometry, and water holding requirement. The fly ash-foam seal is a better seal, capable of sealing against a higher water head than fly ash alone. The fly ash sealing

system uses a high velocity technique for injecting fly ash into the mine. This method results in the development of a large crater in the fly ash pile and causes the seal to form first at the ribs and, subsequently, to move in towards the borehole. The presence of the crater eliminates the chance of premature plugging of the borehole and provides a receptacle for the froth foam used to top off the seal.

The froth foam system uses a downhole, static mixing head designed to provide uniform mixing of the foam components.

(3) An acoustic seal checking system which is capable of monitoring the continuous development of the seal during seal construction and providing a sensitive indication of the quality of the completed seal. The system senses the decay in strength of an acoustic signal passing through the sealed passage as a measure of the quality of the seal.

Figure 1 illustrates the operation of the complete remote mine sealing system developed in this program. The system is shown in various phases of operation at three different sealing locations. A total of 3 boreholes per seal are required, one for sealing and one on either side of the seal for seal checking. The boreholes must be cased and grouted to prevent borehole water flow into the mine passage being sealed.

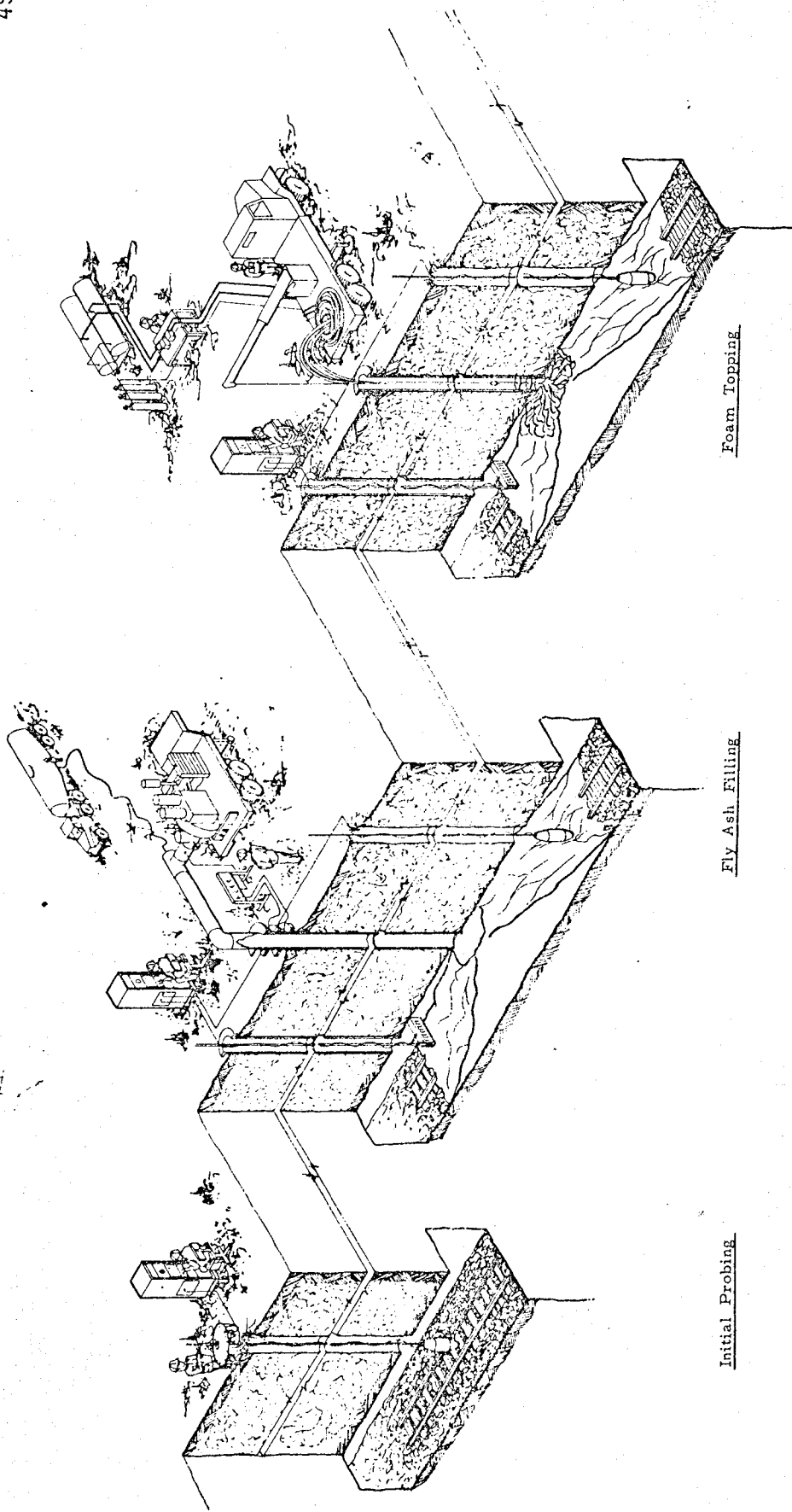
The various stages in the operation of the remote sealing system are:

- (1) Drill, case and grout boreholes.
- (2) Probe passageway through main sealing borehole.
Retrieve system after completion of probing.

- (3) Deploy acoustic seal checking system.
- (4) Deliver fly ash through main borehole using high air flow delivery system.
- (5) Monitor seal development and terminate fly ash pour either after completion of bulk filling or complete fly ash seal.
- (6) Deploy downhole froth-foam system to top bulk filled fly ash pile.
- (7) Complete foam topping while monitoring seal completion with the acoustic seal checker.
- (8) Retrieve froth foam system and acoustic seal checker.

At the first location, the primary borehole has been drilled, and the sonar probe has been lowered into the mine passage. The sonar probe is used to scan the passageway, in order to determine local passageway geometry, position of the borehole, cribs, rubble piles, or other obstructions. The display on the surface indicates the distance of a target in any desired direction, as determined by the compass markings on the rotary table at the surface. The probing information is used to establish the operating conditions of the fly ash delivery system. The system has a range of 20 feet.

The second sealing location shows the acoustic seal checking system deployed through the two seal checking boreholes. The system consists of a line array of speakers on one side of the seal and a microphone on the other. As the seal develops, the strength of the signal received at the microphone reduces. This reduction in sound level is a direct measure of the percentage of the mine passage area



Remote Mine Sealing System
Figure 1

blocked by the seal. The electronic signal processing system includes a pulse-gating technique to eliminate the effect of sound traveling through parallel passageways to reach the microphone.

The fly ash pumping system utilizes the blower contained on the fly ash truck plus an auxiliary, diesel-driven blower, which provides ten times the air flow available from the truck. The truck pumps fly ash through a standard 4" hose to a special mixing nozzle, which injects the fly ash into the high-flow air stream from the auxiliary blower and, thence, through an 8" pipe to the borehole. Instruments monitor the air flow rate, fly ash flow rate, and pressure at critical points in the system. This high flow rate system causes the fly ash to form a large crater in the mine passage, permitting the seal to form at the ribs first and then work back towards the borehole. The crater also provides a receptacle for the froth foam used to top off the seal. Typical air flow rates lie in the range of 2500 to 4000 scfm, depending on passage geometry.

The froth foam topping system is shown in use at the third sealing location, with the seal-checking system being used to verify that a 100 percent seal has been formed. The two components of the foam are stored in the large cylindrical tanks and pumped separately to the remote mixing head, which is lowered by a truck-mounted crane. Instruments monitor the system pressures and flow rates.

Field testing of the system was conducted at the Eastern Associated Coal Company Federal Number 1 Mine in Grant Town, West Virginia. Three 100 percent seals were remotely constructed in passages 370 feet underground, each under different conditions. The first two seals were placed in straight passages, one with a 5 foot roof and the other with a ten foot roof. Both of these seals were topped off using the froth foam system. The third underground location was a 4-way intersection with a 12 foot roof. The 100 percent seal at this location was constructed entirely of fly ash. In

addition to building the seals and verifying the accuracy of the instrumentation which had been developed, tests were conducted to determine the maximum fly ash pumping rates achievable, the effect of borehole water flow, and the effect of borehole depths greater than 370 feet.

From the results of the field test program, it was possible to assess the capabilities of the system over a wide range of operating conditions. Realistic estimates could be made of the operating times required for the remote seal emplacement depending on the conditions encountered at the site. The following is typical of the information available concerning the time required for the separate operations in the system:

Time Required for Complete Sealing Operation

100 foot deep passage; 1 drill rig	50 hours
100 foot deep passage; 2 drill rigs	40 hours
400 foot deep passage; 1 drill rig	100 hours
400 foot deep passage; 2 drill rigs	75 hours
1500 foot deep passage; 3 drill rigs	140 hours

Tables and charts are provided to aid the prospective user of the system in determining the personnel, equipment, and total time required for the complete operation of remote seal emplacement as a function of the conditions encountered at the site.

The overall development effort which led to the satisfactory field demonstration of the remote sealing system was conducted in three phases:

- (1) Phase I, determination and evaluation of applicable equipment, material, and techniques

- (2) Phase II, laboratory and experimental testing of promising system components.
- (3) Phase III, demonstration of the complete system at Eastern Associated Coal Corp. Federal No. 1 Mine.

During Phase I previous remote sealing experience was reviewed and evaluated. This included a survey of methods for sealing acid mine drainage and for controlling subsidence. Equipment and techniques that could possibly be used for probing passageways and for checking seals were investigated. Material and material-delivery techniques for seal construction were studied. Finally, new system and equipment concepts were conceived and evaluated. The conclusions and results of this phase were as follows:

- (1) No existing equipment or techniques appeared suitable for remote probing of a smoke-filled mine passage. Methods using acoustic energy appeared to have the most promise for adaptation.
- (2) A concept was generated for an acoustic remote probing system. It would operate much like sonar, measuring distance by measuring the travel time of a reflected acoustic pulse.
- (3) Four material systems were selected for Phase II evaluation:
 - (a) Grouted aggregate base,* fly ash or fly ash-cement mixture bulk filler.

* To accommodate running water in the passage.

- (b) Same as (a) with a urethane foam topping.
 - (c) Grouted aggregate base, * light expansive concrete bulk filler.
 - (d) Grouted aggregate base, * self-supporting thick slurry filler.
- (4) No existing equipment or techniques appeared suitable for checking the integrity of the completed seals.
- (5) A concept for a seal checker was generated. It would employ an acoustic source on one side of the seal and a receiver on the other. Seal completeness would be indicated by measuring the decrease in acoustic transmission.

During Phase II both the probing and seal checking systems were designed, fabricated, and tested in the FMA laboratory and at the Bureau Experimental Mine at Bruceton. Deployment systems and a rigid tube system for remote manipulation of the acoustic probing system were also fabricated.

A 1/40 and a 1/4 scale mine passage were constructed, extensive tests of the four material systems were completed. These included the effects of water flow, borehole position, rubble, and passage slope. Tests of the foam were conducted full scale in a simulated passageway. The results of this effort were as follows:

- (1) A new method of creating good, airtight, fly ash seals was developed, a method which overcomes many of the problems previously experienced with fly ash systems

* To accommodate running water in the passage.

(borehole plugging, excessive material consumption, incomplete sealing at the roof-rib corners).

This method utilizes much higher air velocities and lower mass densities than previous work. Analytical relations to predict the air flow required as a function of passage size were developed.

- (2) The fly ash systems were selected for demonstration. Fly ash alone can satisfactorily seal mine passages with flow rates up to 10 gpm. A grouted gravel bed and a fly ash-cement mixture of approximately 16 percent cement is required to seal higher flows and to hold static water heads.

Eastern Associated Coal Corporation provided facilities and invaluable assistance for the full-scale demonstration tests. Three seals were attempted and were successfully completed - two straight passages and a large four-way intersection. A series of borehole flow tests were also run. The results of this test program are as follows:

- (1) The acoustic probing system could accurately map objects and the passage geometry at distances up to 20 feet from the unit.
- (2) Both the fly ash and the fly ash-foam systems were successfully demonstrated. The high velocity cratering technique was used, proving that the fly ash sealing technique could be satisfactorily modeled in the laboratory.
- (3) The acoustic seal checking system provides an accurate indication of the sealed passage area. It is relatively insensitive to passage irregularities and sealant materials.

RECOMMENDATIONS FOR FURTHER WORK

Based on the development effort and full-scale tests conducted during this program, a number of technical areas for future research and development have been identified. Further work in these areas would help to improve the reliability, speed of operation and efficiency of the remote sealing system. Recommendations for future work are summarized as follows:

1. Development of an Inert Gas Generator

For the sake of expediency in conducting the field test program, fresh air was used as the fluidizing medium for the fly ash. However, in an actual mine fire application the use of fresh air is likely to be prohibited. An inert gas, such as nitrogen, carbon dioxide or air containing less than 8 percent oxygen would be required. Using combustion as a means of reducing the oxygen content of air appears to be an attractive solution to the generation of the high flow rates of gas required (2500 to 5000 scfm).

Such an inert gas generator would serve a dual purpose for the overall fire extinguishing operation. First, it would provide the inert gas for fluidizing the fly ash. Second, it could be used for inerting the fire area after the seals had been placed, thereby reducing the time required to extinguish the fire.

It is recommended that the Bureau undertake a program to develop a field-operable, inert gas generator to satisfy these two requirements.

2. Development of a Field-Operable Sonar Initial Probing System

A first stage prototype of a sonar initial probing system was developed during this present program. The results obtained with

this prototype show the design concept to have great promise for a variety of applications. Presently, the unit can be used to obtain certain vital information about the passage being sealed even when the atmosphere in the mine is smoky and visual methods such as video or photographic techniques cannot be used. In addition, if the capabilities of the unit were extended, the sonar probing technique would likely prove to be extremely valuable in a number of other vital applications, for example, as a probing system for use in post-disaster and survival work.

The system, as presently designed, is a first prototype and as such requires improvements in the areas of electronic design of the transducer and deployment down the hole. A development effort to accomplish these improvements would consist essentially of two parts:

- (a) Improved transducer and electronics design to increase directionality and range of the sonar system to 50 feet and greater.
- (b) Design and development of an improved deployment system to permit lowering the equipment on a cable and remote manipulation of the transducer. The system would be designed to replace the pole lowering system developed during this program which is slow in operation and limited in depth capability. The increased capability and simplicity of operation offered by such a system would make it adaptable to a much wider range of possible disaster situations.

This additional design effort would result in the development of a reliable, easy to use, field-operable, sonar initial probing system ready for use in a mine-fire disaster.

3. Development of an Improved, Field-Operable, Acoustic Seal Checking System

The acoustic seal checking system developed in this program is a new, and extremely promising piece of equipment for the remote evaluation of the quality of seals in mine passages. The field tests conducted during this program have shown it to be a very sensitive indicator of seal tightness.

The use of this concept and the equipment developed in this program is not necessarily unique to the remote mine sealing program, and, with further development, could be used to evaluate:

- (a) The effectiveness of all stoppings
- (b) The effectiveness of all bulkheads
- (c) The degree of compactness of a gob
- (d) The adequacy of a bleeder system.

The system developed in the present program is a first prototype. The field test results have shown that the system is capable of much simplification and miniaturization. The mechanical pole lowering system developed during this program was considered to be satisfactory for the type of field tests conducted, however, the design would hinder its use in a disaster situation and would be marginal at larger depths. Thus we recommend the following two part program to refine and develop an improved, field-operable, acoustic seal checking system which could be used in a wide variety of disaster situations:

- (a) Redesign of the acoustic source and electronics, to reduce size by redesigning the source configuration,

increase sensitivity, simplify electronics and controls, and achieve certification by the U.S. Bureau of Mines for use in coal mines.

- (b) Design and development of an improved deployment system to permit lowering the equipment on a cable and remote manipulation of the acoustic source. This system would be similar in many respects to the sonar probing deployment system and could be designed to be interchangeable with the latter.

4. Development and Demonstration of Field Equipment to Remotely Seal a Mine Passage in the Presence of Water Flows up to 50 gpm

Field tests of the fly-ash-froth-foam mine sealing system developed during this program have demonstrated the system's effectiveness in making air-tight seals. In addition, to these field tests, limited laboratory tests conducted during this program have shown that the system should be capable of providing an air-tight seal in the presence of stagnant water alone. However, the tests also showed that fly ash alone has limited water sealing capabilities and that the ability of fly ash to seal a running water flow rate in the passage, greater than 10 gpm, is questionable.

These system limitations can be overcome with the use of a controlled-setting fly-ash-cement mixture to make the seal water-tight, and a gravel-grout system to seal against running water. Successful laboratory tests of these techniques were conducted during this program. It is recommended that the development of these sealing techniques be continued into the design and delivery of a field operable mine sealing system capable of making air and water-tight seals with passage water flow rates of up to 50 gpm. Such a development effort would require:

- (a) Development of an optimum fly-ash-cement mixture and a suitable method for mixing and injecting the mixture down the borehole.
- (b) Design and development of a field useable, gravel-grout system.
- (c) Field tests to demonstrate the capability of remotely building an air and water-tight seal in a passage having a running water flow rate up to 50 gpm.

5. Demonstration of the Remote Sealing System to Extinguish a Controlled Coal Mine Fire

As a final demonstration of the effectiveness of the Remote Sealing System, it is recommended that the total improved system be used to make a number of air- and water-tight seals remotely in a coal mine. Preferably, this demonstration could be designed to extinguish an actual coal mine fire started under controlled conditions. It may be possible to utilize the Bureau's Experimental Mine at Bruceton, Pennsylvania for this demonstration.

The demonstration program would be designed to show the effectiveness of the improved sonar initial probing system, the improved acoustic seal checking system, the inert gas generator, the fly ash-cement mixture, the gravel-grout system and the froth-foam system.

6. Availability of Field Useable, Remote Mine Sealing Systems

In order to ensure a rapid, response capability for fighting coal mine fire disasters, it is recommended that the Bureau maintain complete remote sealing systems at one or more strategic Bureau locations. These systems should include all the hardware required

to perform the remote sealing operations in the particular district's coal mines. All the hardware would be designed for rapid deployment in the field.

The system hardware would include:

1. The inert-gas generator
2. Initial probing system
3. Acoustic seal checking system
4. Gravel-grout system
5. Froth-foam system
6. Fly ash plumbing and flow instrumentation
7. Miscellaneous hardware
8. Operations Manual



1. Introduction

This document represents Part II of our final report on the development of a "Remote Sealing System for Extinguishing Coal Mine Fires." It is a technical report which summarizes the results of system development and field demonstration. Part I of this two-part final report is an Operator's Manual for the application of the Remote Sealing System to a coal mine fire.

1.1 Background

When coal mine fires go out of control and can no longer be fought directly, the standard fire fighting technique is to construct air-tight seals in the mine passages leading to the fire area so that the oxygen supply to the fire is cut off. Ultimately, it is desirable to isolate the fire zone in such a way that normal operations can resume in the remainder of the mine.

The construction of seals in the mine causes the atmosphere to pass through a toxic and explosive phase. Explosions, if they occur, are not only hazardous to the men working at the sealing operation, but can also undo much of the sealing work which has already been accomplished. Sealing of passageways surrounding the fire zone from within the mine is extremely difficult and dangerous. Methods for direct sealing are detailed in "Control of Mine Fires".^{(1)*} An alternative to this approach is the technique of remote sealing. This involves drilling boreholes which intersect the mine passages at the locations where the desired seals are to be constructed. The seals are then constructed by pouring material down the borehole and filling a segment of the passage from bottom to top. During this operation, there are no personnel in the mine, all operations taking place on the ground surface.

* Numbers in parentheses refer to references listed in the Bibliography.

During the past ten years several efforts have been made to develop technology for remote sealing both by the United States Bureau of Mines and by the coal mining industry. These previous attempts at surface mine sealing through boreholes have met with limited success in certain cases and complete failure at a recent disaster emergency involving two men trapped underground.

The first effort to isolate an active fire was made in a large mine located in northern West Virginia that had been sealed over twelve months and had experienced explosions when previous reopening attempts had been made.⁽²⁾ This attempt was made as a result of the Bureau of Mines' experimental work, which included testing of urea formaldehyde foam, urethane foam, inflatable balloons, pneumatic injection of rock wool, and caving by blasting.⁽³⁾ Rock wool was pumped into the sealing boundary of a large mine through six-inch boreholes with air pumped from the area to balance the impounded atmosphere and gases. The resultant seals were rated 80 percent effective; however, they did impede the air flow into the sealed area when a limited air split was introduced. The final result of this effort was that mine recovery was expedited. Observed comment was that rock wool material is not an ideal sealing material, since it is affected by water, and its angle of repose makes a good roof seal very difficult.

At a different mine in northern West Virginia, remote sealing of a fire area was attempted between April and June, 1968. Conditions were unusual in that the sealing attempt was made two years after a serious fire occurred in October, 1965. The mine had been recovered and was in production; however, the fire area had not been completely sealed in that samples indicated a dormant fire. One side of the area had not been effectively sealed because of massive falls and roof cavities.

A total of six boreholes were drilled, five of which

entered caved areas. The depth of the boreholes ranged from 500 to 600 feet. A total of 925 tons of fly ash was used with the open hole taking 524 tons. Difficulties were experienced with holes lacking adequate clearance over fallen material. Material packed in the borehole and required drilling. Six seals were made and the attempt was considered successful.

A disappointing attempt was made to seal an active fire at a mine in Pennsylvania in March, 1971, in which two workers were trapped. The rapid spread of the fire combined with the proximity of massive gob areas made direct fighting efforts very dangerous. Numerous boreholes were driven into the mine, and efforts to construct effective seals utilizing fly ash, crushed stone, cement concrete, and other combinations of materials were attempted with limited success. The purpose of these seals was to form a barrier dam that would isolate the fire and permit flooding the fire area. Difficulty was experienced with material flowing away from the desired location and clogging the borehole.

The most recent major work by the U. S. Bureau of Mines⁽⁴⁾ indicated that fly ash showed great promise as a bulk sealing material. In addition, the report of this work concluded with comments concerning the necessity of obtaining "information on the conditions of the void. . . before a filling operation" and then using a secondary borehole for monitoring of the seal during the remote placement.

1.2 Objective

The objective of this program was to develop within 9 months a system for remotely sealing coal mine passages from the surface. The seals must be air- and water-tight and be capable of withstanding a 15-ft pressure head for at least one year. The specific objectives of this development effort were:

- (1) To determine the methods, materials and equipment that may be combined to yield the "best" system for remote sealing. Materials containing 18 percent or more of organic matter shall not be considered, except as a last resort.
- (2) To develop methods for probing the passageway to be sealed, so as to determine the configuration, dimensions, and slope of passageway and restrictions, and cavities within that passageway prior to construction of seals.
- (3) Develop methods for monitoring the air-and water-tightness of the seal after its construction.
- (4) Demonstrate the effectiveness of the initial probing, mine sealing, and seal checking systems in both simulated and actual mine passageways. The latter are to be 400 or more feet below the ground. These seals will be constructed in dry-mine working conditions and will be checked for air-tightness only.
- (5) Develop and demonstrate, in the laboratory only, the effectiveness of building seals with mine passage water flow and subsequently retaining the equivalent of a 15-ft water head.

The critical parameters of interest are:

- (1) Dimensional Requirements
 - a. Passageway - 13 to 20 feet in width, 4 to 7 feet in height

- b. Roof - Irregular with a cavity
up to 6 cubic feet
- c. Intersection - Same as passageway
- d. Slope (either passageway or roof) -
Up to 5° from level

(2) Emplacement Condition Requirements

- a. Passageway Water Flow - Up to
50 gpm
- b. Borehole Water Flow - Up to 50 gpm
- c. Rubble - Up to 70 percent of
passage volume

(3) Operational Condition Requirements

- a. Air Flow - Air-Tight
- b. Water Flow - Water-Tight
- c. Stability - Able to withstand
a 15-ft pressure head for at
least one year

1.3 Scope of Effort

The overall remote sealing system included the following
three systems:

- a. Initial Probing System

- b. Mine Sealing System
- c. Seal Checking System

The development and testing effort was broken up into three phases:

1. Phase I consisted of the preliminary generation and evaluation of concepts for probing, sealing and seal checking systems. This phase included a comprehensive state-of-the-art survey of specific and allied technology pertinent to the development effort. From this preliminary evaluation came a number of promising concepts for further development and laboratory evaluation. At this stage more than one promising concept was selected for each of the three subsystems. Sections 2, 3, and 4 summarize the results of this preliminary evaluation for the probing, mine sealing, and seal checking systems, respectively.
2. Phase II included preliminary laboratory evaluation of the promising concepts selected in Phase I, and the identification of the best method for each of the three subsystems. Further development of these best methods included a comprehensive laboratory investigation using a quarter-scale simulated mine passage and leading to the design and fabrication of prototypes for field demonstration. Prototype equipment for the initial probing and seal checking system were completely assembled in this phase and transported to the field.

The actual mine sealant systems were designed in this phase but assembled at the field site itself in the following phase.

Sections 5, 6 and 7 summarize the laboratory testing and prototype development efforts for the initial probing, mine sealing and seal checking systems, respectively. Appendices A through E contain the necessary technical supporting information.

3. Phase III consisted of field testing the system in an actual coal mine. The Federal No. 1 mine of the Eastern Associated Coal Corporation at Grant Town, West Virginia, was selected as the test site. The system was demonstrated by making 3 seals, one in a simulated low-roof straight passage, the second in a straight passage, and the third in a four-way intersection. Fly ash and froth foam were the two materials used.

The overall field test program is described in Section 8. A summary of the system capabilities is provided in Section 9.

2. Preliminary Study - Initial Probing

2.1 Introduction

Initial probing of the mine passage is required prior to the emplacement of the sealant material or deployment of the seal checker system. Factors which are of interest in sealing and checking include:

- a. size and condition of the mine passage
- b. location of the borehole with respect to the ribs
- c. the presence of water flows
- d. the proximity to an intersection

The importance of each of these factors depends strongly on the sealant material. Because the sealant material had not been selected at the time of the initial probing study, a broad survey of probing techniques was conducted. The capabilities and limitations of each technique as they applied to probing through the borehole were identified.

To facilitate this comparative evaluation, Table I was prepared which lists all passage conditions which might affect the emplacement of sealant material in the passage. The most satisfactory techniques for observing each condition of interest are listed together with the effects of the observation on the sealing operation.

Table II summarizes the environmental conditions likely to be encountered in the passage being probed and the physical

TABLE I

INITIAL PROBING

This chart is an attempt at listing all possible conditions which we might wish to detect; it should not be assumed that we must detect each item listed.

<u>SITUATION TO BE "OBSERVED"</u>	<u>BEST METHODS OF OBSERVATION</u> (in order of effectiveness)	<u>REACTION TO OBSERVATION</u>
1. Rubble in passageway/slate fall	video/radar/tactile	i Full cave in will necessitate relocation? ii Affects deployment of seal-check probes iii Eliminates high α of repose sealants?
Smoldering rubble	video/I.R. detector	Relocate?
2. Size of passageway	equally good: video (with yardstick ref.) radar tactile	Affects amount of sealant required
3. Proximity to intersection and condition of pre-existing stoppings	video/radar/tactile video only	i Affects amount of sealant required ii Helps define borehole location with respect to mine maps
4. Location of borehold (in passageway)	equally good: video radar tactile	i Affects deployment of seal-check probes ii Affects distribution technique (for sealant) iii Severe cases (on rib edge maybe?) may require borehold modification or re-location
5. Proximity to fire	I.R. detector/video	i Define fire location - if fire is seen ii Relocate if too close - if fire is seen iii Demonstrate to rescue teams that fire is very distant or else out. (if fire (or smoke) is not seen)
6. Contour/shape/texture of passage	video	i Relocate if geometry is too severe ii Determine necessity of pre-spray of foam, for example iii Will affect the use of directed sealant
7. Slope of passageway mine maps	to be determined independently from mine maps	i Affects qty. of sealant required ii Indicates direction of water flow iii Affects use of directed sealant (i.e. want to throw up hill)
8. Presence of dead men	video	Relocate to avoid burying bodies?
9. Waterflow in passage	sonics/video	i Put down a dam ii Change consistency of sealant material?
in borehole		Case the hole

TABLE II
ENVIRONMENTAL CONDITIONS

Temperature	50° to 60°F in a normal working mine; higher temperatures must be considered in the event the probe is near the fire location
Humidity	100 percent R.H., also could be foggy
Atmosphere	The mine atmosphere might be equivalent to normal air. Must consider possibilities of extremely high methane content (up to 76 percent) plus CO and CO ₂ contents sub- stantially higher than normal air. Dense smoke may be present. The potentially explosive atmosphere will require explosion proof instrumentation.
Remote Operation	Display and/or manual controls will be located up to 1500 feet away from the sensor.
Physical Size	Sensor should be capable of being lowered through 6-inch diameter cased borehole. Reevaluation of system constraints will be required if a superior sensor is identified whose size prevents deployment through 6" borehole.
Deployment	Considerable jostling of instrumentation may be expected during descent into borehole. For convenience and simplicity it would be advantageous if probe could be lowered on a cable.

limitations imposed on the probing equipment by the borehole deployment requirements and the passage geometry.

Preliminary evaluation of the requirements of Table I and Table II indicated that:

- (1) The presence of dense smoke is the most severe environmental constraint on probing system performance.
- (2) Some of the information desired from the initial probing system is available from mine maps which frequently contain slope data, in addition to passage width and roof height.

Dense smoke is not likely to be present in all the mine passageways to be sealed. Accordingly, probing systems were conceived and evaluated for both clear and smoky environments. The availability of mine maps and their use in initial probing were also surveyed. The results of this preliminary evaluation are described in the following sections.

2.2 Utilization of Mine Maps for Passage Details

Coal mine operating companies are required to maintain current mine maps which yield such information as bottom elevation data, passage location, passage width, intersection location, and general layout. The specific requirements for maintaining mine maps are listed in the Coal Mine Health and Safety Act, Underground Coal Mines Sub-part M751200, Federal Register November 20, 1970. Prior to passage of this law, practically all major coal mine companies had maintained level surveys and entered such data on their mine maps. This has been done as company policy for drainage control, to tie in surface

and underground elevations for possible shaft and borehole locations, and also to consider cover and surface irregularities in the mine plan. These kinds of data are sufficient to determine mine passage slope.

An example of the usefulness and accuracy of company-compiled mine maps is the work of the U. S. B. M. Ventilation Group in using the pressure survey technique based upon air column calculations. Such determinations necessitate accurate underground elevation data. During the past 15 years since this technique has been used to evaluate mine ventilation systems, more than 150 surveys have been completed. These surveys were made using the information available on existing maps with seldom the need for special data. In most cases, certainly over 90 percent, adequate base elevation information was available.

Further, an estimate of the passage slope can be established from the general pitch of the coal bed, drainage patterns, and transportation grades. Except for local irregularities, the slope of the coal bed in bituminous coal mines is generally constant. In only a few mines in Eastern Pennsylvania and in the Far West will geologic disorders change this.

From these considerations it would appear that for most mines an adequate estimate of passageway slope can be obtained from data available on mine maps and would not require special probing.

2.3 Probing Systems

Techniques which may be employed to obtain detailed information for use in conjunction with the mine maps may be classified into two categories: tactile systems which employ

mechanical contact between the probe and the mine passageways or objects, and remote systems which use energy in some part of the electromagnetic spectrum to yield the desired information. Tactile systems include the use of arms or feelers, while remote systems encompass visible and infrared video, radar, and sonar. Table III lists the types of systems considered and comments about their relative performance capabilities.

2.3.1 Tactile Systems

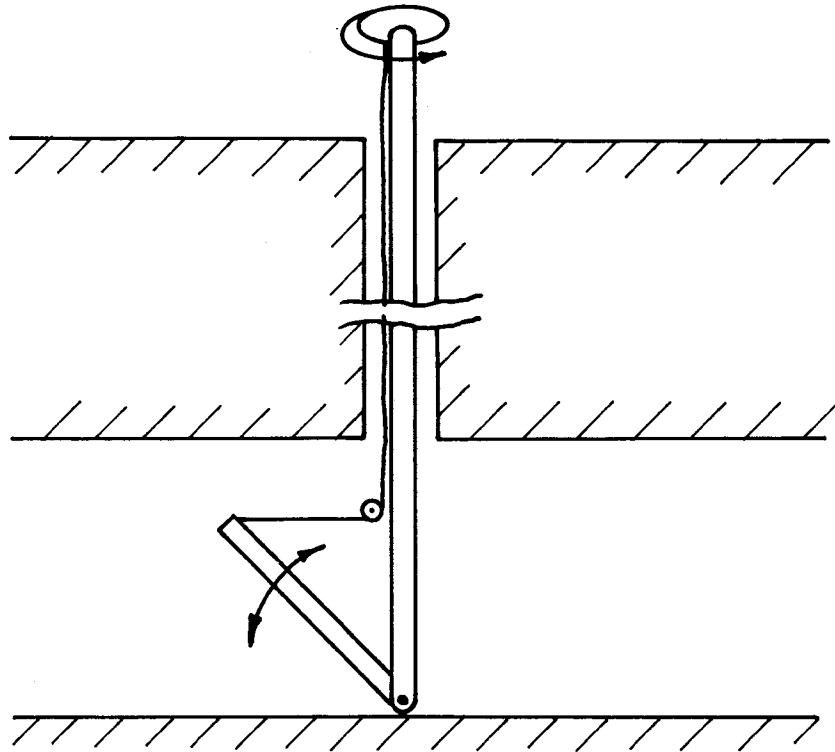
A tactile system constitutes the simplest and most positive form of probing system. It consists of a feeler arm which is lowered down the borehole into the mine passage and can detect the presence of an object by contact. In its simplest form, the tactile system shown in Figure 2 (a) consists of a boom hinged to the end of a pole lowered down the borehole. The boom is designed to swing down under its own weight and is held in position by a rope running back up to the surface. The operator rotates the pole to a desired compass heading and allows the boom to swing down. The location of an object may then be determined by the compass heading of the pole and the distance that the boom travelled before contact. This system has a serious limitation in that the length of the boom and, hence, its probing distance is limited to the height of the passage. A device of this nature was used successfully by the Eastern Associated Coal Company in 1963 during the remote sealing operation at the Federal Number 1 Coal Mine.

Numerous modifications to this design are possible to extend range and accuracy. The hinged boom can be telescoped to provide for remote extension and retraction as shown in Figure 2 (b). The rotation can also be accomplished remotely with a small electric motor and an electronic readout at the surface to indicate angular position. A system of this nature is sure to provide some useful information as to location of the borehole,

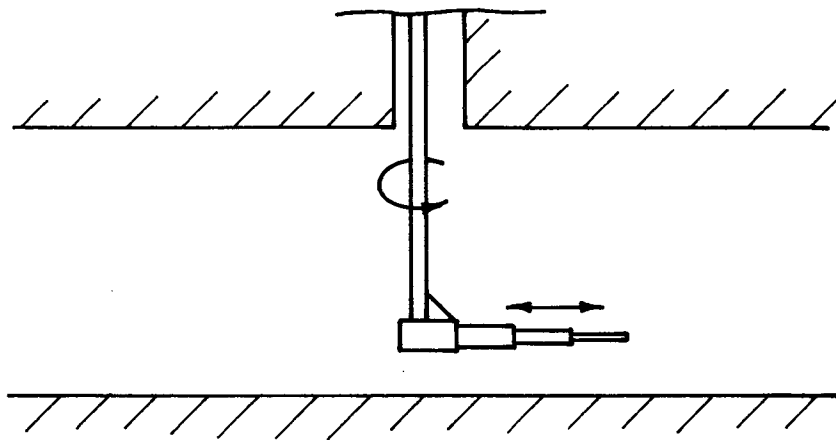
TABLE III

INITIAL PROBING SYSTEMS

Sensing Device	Wavelength	References	Probability of Success	Risk Level (Measure of Complexity or development effort required)
Video	(.3 to .7 μ)	Penn-Drilling G. E. Instrument Technology, Inc. Bureau of Mines Army Engineering Corps Eastern Coal	100 percent	Low
For Smoky Environment w/Infra-red source and I.R. sensitive vidicon	(up to 1.2 μ)	Singer Corp. Aerosol Technology Consultants Reference Texts	Extend range of visible light by 50 percent	Low
Physically separate light source and camera		MIT EE Dept. Reference Texts	Simple Testing Required	Medium
Use scanning light source		Colorado Video	Testing required	Medium/High
Clean-air flow to displace/dilute smoke				Medium
Range Gating		Raytheon MIT EE Dept.	Reliability problems?	High
Infra-Red Imaging	(up to 15 μ)	Barnes AGA Inc. Polaroid Eastman Kodak Remote Sensing Div. of Willow Run Labs Ft. Belvoir Night Vision Lab.	Testing required to determine information obtainable from system	Low
Radar	(.1 to 10 cm)	Raytheon Norden	70 percent - some question as to resolution obtainable	High
Sonar	(.1 cm and up)	Raytheon Seismographic Services Corp. Dowel Co. Bendix Corp.	Question of resolution and directionality Must interpret signals to minimize random noise and multiple reflections	High
Tactile		Hunter Spring Spar Aerospace Eastern Coal	100 percent chance of getting at least some useful information from a tactile system	



(a) Swinging Boom - Tactile System



(b) Telescoping Boom - Tactile System

Tactile Systems

Figure 2

height of passageway, and local passageway geometry (including location of obstructions) under the most severe environmental conditions. Accordingly, a simple tactile system was recommended as a necessary back up to the more elaborate remote probing systems to be discussed later.

2.3.2 Optical Viewing Systems

An optical viewing system would consist of a camera and light source remotely deployed in the mine passageway. The design of this unit must provide for remote manipulation so that the camera may be pointed in any desired direction. In a clear atmosphere, such a system would be capable of obtaining all the information considered necessary for the implementation of the subsequent sealing operation.

However, in a smoky environment, the capability of the optical system will be severely limited. The degree of detail of the information to be obtained will depend on the characteristics of the smoke, such as density and particle size. It is more than likely that conditions will exist where no visible information can be obtained. Thus, an optical viewing system by itself is not sufficient. A back-up system for smoky environments would be required.

There are two basic camera designs which can be utilized: still cameras and closed circuit television (CCTV). Both of these techniques have been used in the past with varying degrees of success in a clear environment. In order to extend their performance range in a smoky environment, methods to extend the transmission of visible light in a smoky environment were conceived and evaluated, as discussed in Section 3.3.2.3.

2.3.2.1 Still Cameras

A still camera offers the advantages of relative simplicity and a hard-copy picture which can be used to measure distances and size objects. The major disadvantage is the necessity of extracting the unit from the borehole to obtain the pictures. With any unit other than a Polaroid* camera, additional delay is created by the processing time.

The Pennsylvania Drilling Company⁽⁵⁾ has been using a still camera in remote underground studies for a number of years. The unit is packaged with a self-contained light source. Controls are provided to index the camera rotation in 30° increments to scan a full 360° around the passageway; separate instrumentation records the compass reading of the initial camera position. Using two pictures of the same scene taken at different camera elevations, Pennsylvania Drilling can triangulate to accurately determine the distance of objects from the camera.

2.3.2.2 Closed Circuit Television Systems (CCTV)

While more complex than a still camera, CCTV has the capability of providing continuous and instantaneous pictures. The Industrial Hazards and Communications Division of the Bureau of Mines⁽⁶⁾ currently has a CCTV unit under development. A detailed evaluation of the camera capabilities was conducted at a meeting with Bureau personnel and subsequent exploratory tests in the Bureau's Experimental Coal Mine at Bruceton, Pennsylvania. For the initial probing application, the major shortcoming of this unit was found to be the lack of a light level adequate to properly observe the coal ribs, which have very low reflectivity if they are not covered with a heavy application of rock dust.

* Trade Name.

CCTV has also been used in related areas requiring remote operation in adverse environmental conditions. Applications include examination of nuclear reactors⁽⁷⁾ and underground sewer lines.⁽⁸⁾

Development of a suitable CCTV system would involve identification of a low-light-level unit⁽⁹⁾ and the design of the housing and controls needed for remotely positioning the unit. A significant amount of the required effort would have duplicated work already being done by the Bureau. It was, therefore, recommended that Foster-Miller Associates not develop any CCTV hardware but consider the possibility of using the system under development by the Bureau. Accordingly, FMA maintained an active interest in this area, including close contact with the effort being conducted by the Bureau.

2.3.2.3 Modifications to Improve the Transmission of Visible Light

(1) Range-Gating

The major problem caused by smoke is the "back-scatter" of light: some light going from the source bounces off the smoke particles and back to the camera, obscuring whatever light image is returning from the target. One technique of filtering out this back-scattered light is range-gating, a technique borrowed from radar and used with some success in underwater optics.⁽¹⁰⁾ In this system, short pulses of light are sent out from the source. The camera optics are then gated so that the only signals processed are those corresponding to the light returning from a set range. For example, if the light pulse is 10 nanoseconds (nsec.) long and the optics are turned on for 10 nsec., then the light received, 50 nsec. after the pulse ends, will be only that which is reflected from a range of 30 to 35 feet away from the camera. Range-gating, therefore, allows one to look at a slice of

space some set distance away from the receiver, ignoring all light scattered by the environment in front of this slice. A system such as this, which responds in nanoseconds, requires complex circuitry and the use of a laser as the pulsed light source.

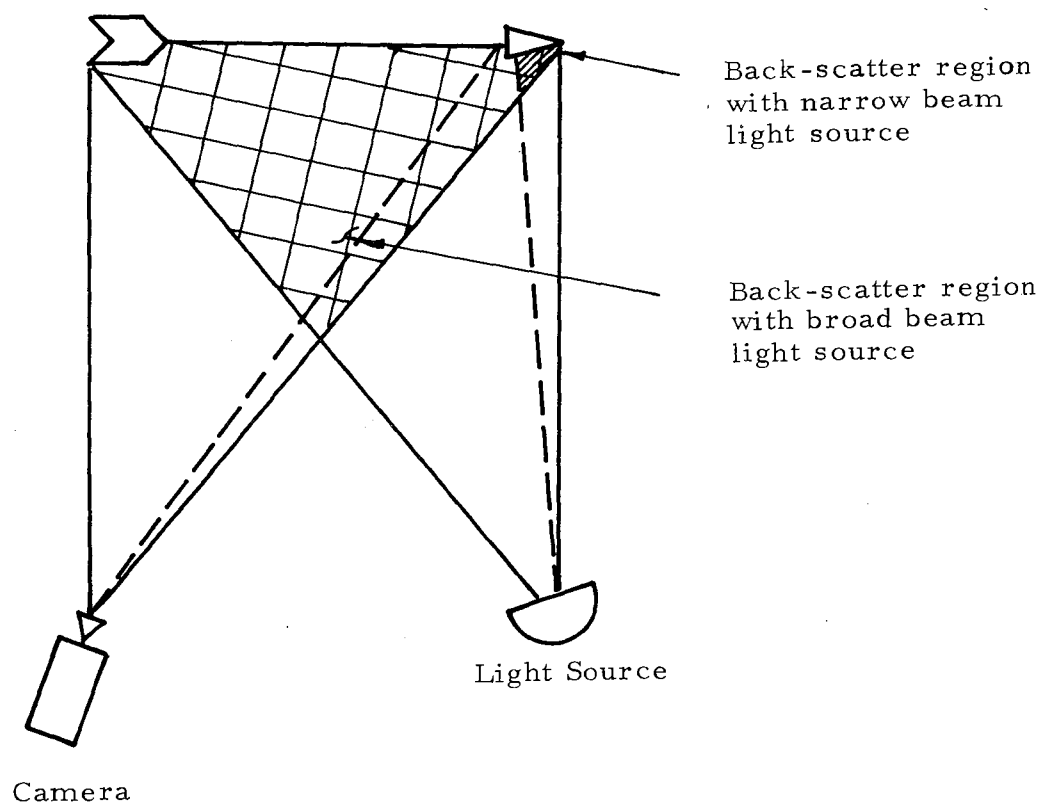
(2) Scanning Techniques; Remote Light Sources

Instead of filtering out back-scattered light by time, it is also possible to use distance: the further apart the light source and receiver are placed, the less back-scatter will be "seen" by the receiver. In Figure 3 the shaded area represents the region in which back-scattered light affects the camera image. In addition, the beam spread of the light sources affects the amount of back-scatter. Again referring to the figure, note that the image of the tail of the arrow will have a minimum of light-scatter in front of it, while the head will be obscured. However, if a narrow beam of light is used, as shown by the dotted line, back-scatter is greatly reduced in that region. The camera and light source must then be focused to the same range, and the target mechanically scanned to make up a total picture. The state-of-the-art review failed to turn up any development in this area.

(3) Removing the Smoke

If it is not possible to optically penetrate the smoke, then an alternative is to displace or dilute the smoke with clean air. Fluid dynamics analysis indicates that there are two possible methods for implementation of this concept.

If the smoke were perfectly stagnant and fresh gas of equal density were introduced, then the smoke would be directly displaced. Calculations show that, with



Effect of Back-scattered Light

Figure 3

2000 CFM (requiring 250 HP to push the flow through a 4" I. D. pipe 1000 feet long), it will take about 10 minutes to clear a passage for a distance of at least 20 feet in each direction. At this time the smoke concentration would be 5 percent of the initial concentration.

If airflow in the passageway exceeds 10 feet/minute, the only satisfactory approach is the use of large diameter air jets which could clear a narrow path. For example, a 2-foot-diameter clean-air jet with 800 feet/minute velocity could penetrate at least 20 feet. At that distance, smoke concentration on the jet axis would be 10 percent, while concentration around the 2-foot-diameter would be 25 percent. Such a jet could utilize a 4-inch-diameter pipe with a 2-foot-diameter "wind sock" deployed at the end to form the jet. Such a configuration would require 2500 CFM, or about 300 HP.

Implementation of any of these three modifications would involve considerable development with accompanying risk. Little, if any, work has been done in any of these three fields (with the possible exception of range-gating in underwater applications which also would be the most complex), so that the potential pitfalls are virtually unknown. For these reasons further development along these lines could not be recommended.

2.3.3 Longer Wavelength Viewing Systems

Vision is obscured in smoke because light is absorbed or scattered by the individual particles which make up the smoke. For the type of smoke most likely to be encountered in a coal mine fire, the average diameter of the suspended smoke particles will be in the range 0.2 - 0.3 μ .⁽¹¹⁾ The coefficient of extinction of the light increases with increasing size of the suspended

particles, reaching a maximum value when the particle diameter exceeds $2/3$ the wavelength of the light being transmitted.⁽¹²⁾ An acceptable system, therefore, is one that transmits a wavelength substantially longer than the smoke particle size. In the ensuing sections, such systems are discussed. With the single exception of infrared imaging, each system requires the use of a sender, such as a light source in the case of conventional photography, and a receiver to pick up the reflected signal, such as a camera in conventional photography.

2.3.3.1 Extending the Wavelength of Conventional Camera Systems

Because of the sensitivity obtainable with state-of-the-art camera systems, the practical upper limit on wavelength is $.95\mu$ for photographic film and 1.2μ for CCTV.⁽¹³⁾ Calculations indicate that using a light source of 1.2μ wavelength with the appropriate CCTV camera would essentially double the "optical" range. In other words, if a target were barely visible at 10 feet using visible light, it could be discerned 20 feet away with the 1.2μ system. However, this also means that, if the smoke were thick enough to limit the visible light range to 2 feet, which is not an unreasonable assumption, the improved system could see only 4 feet. For this reason it did not seem worthwhile to pursue this approach any further.

2.3.3.2 Infrared Imaging

To utilize infrared wavelengths longer than 1.2μ , the receiver would have to be sensitive to radiant energy (heat) emitted from the target rather than reflected by it. This is the only system considered which does not have a sender as well as a receiver. Units of this nature are sensitive up to approximately 15μ . The basic unit consists of an infrared detector

coupled to an optical scanner. An actual picture is produced on the TV-style monitor, the intensity of the image being a function of the temperature and emmissivity of the object being viewed.

A number of companies manufacture infrared imagers of varying size, quality, and price.⁽¹⁴⁾ In general, the units cost upward of \$20,000 and would have to be redesigned to provide a package which is explosion proof, capable of remote operation, and small enough to lower down a 6"- or 8"-diameter borehole. Preliminary field testing would also be required to determine the amount of information obtainable from an IR scan of a mine passage as well as the ability of the unit to penetrate dense smoke. The purchase of an infrared imaging unit was not recommended.

2.3.3.3 Radar

The typical wavelength range for radar transmission is .001 to .1 meter; transmission through smoke would, therefore, be no problem at all. Although this concept would not provide direct imaging, it would provide a direct readout of target bearing and range.

Major modifications from conventional designs would include providing a range of 2 feet to 100 feet, instead of the conventional 100 feet to infinity, and packaging a transmitter-receiver dish (antenna) small enough to transport down a borehole. Some commercial applications have successfully reduced the radar concept to a hand-held battery-operated unit;⁽¹⁵⁾ however, the major problem is the tradeoff between the dish-size and resolution. For example, an 8-inch dish might provide a resolution of 2 feet at a range of 10 feet, while a 4-inch dish could not resolve less than 4 feet. An application of this technology, where resolution is

relatively unimportant, is being developed for use in the guidance system of an operator-less mine-rescue vehicle.⁽¹⁶⁾

Development of a radar system appeared feasible; however, the complexity of the system precluded further work in this area for the initial probing application.

2.3.3.4 Sonar

Sonar, or acoustic ranging in air, is actually similar to radar; characteristic wavelengths are about the same. However, sound travels one million times slower in air than does an electromagnetic signal; this characteristic can make the electronic circuitry for sonar considerably simpler than radar. One disadvantage of the sonar system is that ultrasonic sound attenuates rapidly in air; however, this is not a major disadvantage if ranges greater than 50 feet are not needed.

Instrumentation is currently available which permits lowering of a 3-1/2-inch diameter probe into an underground cavern full of water; this probe can then provide enough data to construct an entire 3-D map of the cavern.⁽¹⁷⁾ The Seismagraphic Services Corp. has attempted to extend this concept for use in air without success. In other applications, however, ultrasonic transducers have been utilized in air to provide some useful information, including sensory aids for the blind.⁽¹⁸⁾ The Liberty Mutual Insurance Company has developed a system originally designed to indicate the presence of an obstruction behind a truck as it is backing up. This design incorporates a direct readout which indicates range of the obstruction up to a maximum of 6 or 8 feet.

2.4 Preliminary Evaluation

When the mine atmosphere is clear, a CCTV system provides major advantages over any of the other systems previously described. Only minor modifications would be required to package the camera in a small, explosion proof housing. The monitor would then display a complete, instantaneous picture of the mine passageway. Furthermore, this visual display could be easily interpreted by any operator with virtually no training required. However, in the event that dense smoke is encountered, the CCTV system would be completely useless.

In the absence of a useful television picture, a tactile probe could provide some useful information about passageway geometry in the immediate vicinity of the borehole. This technique would utilize simple mechanical linkages, thereby minimizing complexity and the associated development costs.

A simplified sonar system would function in much the same manner as a telescoping tactile probe, except that ultrasonic sound would replace the extendable feeler arm in determining range. It was, therefore, determined to proceed with the development of the sonar probe, with the design goal of a 30 foot range. To keep the total development effort as uncomplicated as possible, the probe would be lowered on a string of rigid pipe, which could be hand-rotated from the surface to permit the probe to scan a full 360° around the passageway. It was not anticipated that this device would provide a total "picture" of a mine passage; rather, the design goal would be to fill the void between the limited data obtainable with a simple, mechanical tactile probe and the complete picture offered by a conventional CCTV camera in a clear atmosphere.

3. Preliminary Evaluation of Mine Sealing Techniques

As the first stage in the development of a technique for the remote sealing of mines, a state-of-the-art survey of various mine sealing techniques was conducted. This was expanded to include a review of different materials offering some potential for use as a mine sealant. Techniques for the remote placement of materials for other applications were evaluated, and system concepts for distributing remotely placed materials were developed.

This preliminary review led to the development of a functional description of a general mine sealing technique to meet the specified conditions. Various potential system configurations were synthesized. These were subjected to a preliminary evaluation based on estimated confidence in system performance, development risk, cost, and sealing time. Based on this preliminary evaluation, promising mine-sealing techniques were selected for further development.

This section presents a review of the following:

- (a) Techniques for constructing permanent seals from within a mine.
- (b) State of the art in remote sealing for mine fire control.
- (c) Techniques for remote placement of materials for other applications.
- (d) Systems for distributing remotely placed material.
- (e) Materials for mine sealing.
- (f) Synthesis of remote mine sealing concepts.

- (g) Preliminary evaluation of promising remote mine sealing techniques.

3.1 Review of Techniques for Constructing Permanent Seals from within a Mine

In American coal mining practice such seals have typically been built from cement block, lumber, brattice cloth, tile, or brick.⁽¹⁹⁾ Because of urgency, immediate availability frequently dictates the material to be used. British and German mining engineers have traditionally used sandbags, although recent advances have been made in the use of concrete or gypsum based materials for monolithic stoppings.⁽²⁰⁾ In the case of explosion-proof stoppings the amount of material required is a function of its strength.⁽²¹⁾

The monolithic-type structures made from cements and gypsum (plasters) are a considerable advance over the previous methods.⁽²²⁾ Once retaining forms are built, material can be continuously pumped between the forms with a minimum amount of labor. Gypsum, in particular, can have a controlled quick set so that material at the bottom is setting while the upper layers are being poured. The principal problem in this method is transporting the material to the site of the stopping. Pumping a rapid setting material is a problem where pumping distances are too great. The alternative, as employed in German experiments,⁽²⁰⁾ is to have the active ingredients mixed at a nozzle at the point of delivery.

The problems of material delivery and of handling fast-setting materials also arise in remote sealing operations. The principal advantage of constructing seals from within the mine is the ability to construct containment bulkheads.

3.2 Remote Sealing for Mine Fire Control

Remote sealing through a borehole is a relatively recent

technique. The principal problems in a remote-sealing operation are lack of knowledge of mine passage conditions, delivery of material down a borehole, correct distribution of material in the mine passage, and the ability to check the effectiveness of the resulting seal.

In the United States, rock wool and fly ash have been the principal materials used for remote sealing.⁽¹⁹⁾ At present it is generally felt that the fly ash injection technique is the most effective. It has been employed as a fire control technique in a number of coal mine fires, and reports have always indicated some level of success. The fly ash technique has problems when there is a large amount of rubble under the borehole, and when there is borehole or passage water flow.⁽²³⁾ In addition, the low repose angle of fly ash results in the need for extremely large quantities of materials. These considerations have stimulated a search for alternate remote-sealing techniques.

Most remote-sealing research has been conducted by the U. S. Bureau of Mines and by individual coal mine companies in the U. S. Experiments have been conducted with rock wool, sand, aggregate, urea formaldehyde foam, urethane foam, balloons, and caving by blasting. The following results were reported.^(24, 25)

(a) Pneumatic Pumping of Rock Wool - The normal repose angle of rock wool prevented it from sealing the passage corners when it was injected directly. More successful seals were developed with a moveable placement spout.

(b) Pneumatically Pumped Sand - Sand pumped under pressures less than 30 psig formed a truncated cone whose top did not seal the entire mine roof. Higher pressures up to 90 psig forced the sand to redistribute and form a broader based cone.

(c) Water Flushed Crushed Limestone - Crushed

limestone formed a conical pile to the borehole when flushed in with water. Additional flushing caused the pile to spread, and the borehole plugged when 98 percent of the passage cross section had been blocked.

(d) Urea Formaldehyde - Remote injection of urea formaldehyde was successful in forming seals remotely. The principal problems in this technique were the clogging of the nozzle during filling and the ultimate shrinkage and degradation of material after the seal was formed. As with fast setting materials, the mixing and spray nozzle had to be deployed at the bottom of the borehole.

(e) Balloons - A method of sealing by inflating a large plastic bag was tested. Although the bag conformed well with the shape of the passage, the additional pressure required caused it to eventually fail at a seam.

(f) Caving by Blasting - A mine passage was sealed by blast induced cave-ins. The resulting seal appeared to be tight. Such a technique would only be applicable in abandoned mines and then where potential subsidence is not a problem.

3.3 Review of Remote Material Placement Techniques Used for Other Applications

There are applications of remote material placement techniques other than for fighting coal mine fires. These include water pollution control, control of subsidence, filling underground nuclear test cavities, and filling abandoned sewage systems.

3.3.1 Mine Drainage Pollution Control

Acid water in mines which drain into rivers causes a pollution problem, and hence, efforts have been made to seal these mines against water flow. The problem is similar to that for fire control, except that the absence of fire allows for

construction to take place at the seal location. Frequently, however, the inaccessibility of abandoned mines will force these operations to be carried out remotely through a borehole.

The Haliburton Company under contract by the Federal Water Quality Administration has conducted an extensive project in this area.⁽²⁶⁾ They have developed a special stiff, fast-setting grout which will form bulkheads that will stand up under their own weight as placed. This grout eliminates the need for a form. The self-supporting slurry consisted of cement, water, bentonite, and sodium silicate. The final rapid-setting slurry was delivered to the bulkhead site as two inactive slurries - a bentonite - sodium silicate slurry and a neat cement slurry. These two slurries were mixed at a mixing head, which then sprayed the resulting slurry against the walls of the mine passage.

The mixing head was not deployed vertically through a borehole. Rather, it was mounted on pipes which entered horizontally through the drift mine opening. In addition, proper placement of the slurry involved rotating the mixing head about the pipe while the material was being placed. Application through a borehole would require a remote, mobile mixing head. Although the self-supporting slurry is a very promising concept, the implementation of this particular system through a borehole would be complex and, no doubt, unreliable.

The Pennsylvania Department of Environmental Resources has been involved in similar water pollution work. Their efforts have been mainly concerned with remote operations through boreholes. Their remote techniques use crushed stone and fly ash with cement additive. In one case, seven holes were drilled per seal.⁽²⁷⁾ Three holes were drilled across the width of a passage, and stones were dropped to form a bulkhead. Distribution of the stone was aided by an air lance. This type of bulkhead was formed

in two locations in the passage, and the region between was filled with a fly ash-cement slurry. The resulting seal has exhibited some leakage but is considered to be satisfactory. The mines sealed by this technique were only 25 to 30 feet below the surface, and hence, the seven boreholes could be rapidly and accurately drilled. The accuracy and time element become a severe problem when considering 400-foot deep boreholes. Even at the shallow depths, the above technique requires one normal work week per seal. ⁽²⁸⁾

A second method, used primarily to raise the water table, was to first drop gravel, then distribute it with air pressure, and finally drop in a dry mixture of cement and fly ash. This operation is currently going on in Meyersdale, Pa. ⁽²⁸⁾

3.3.2 Control of Subsidence over Abandoned Mines

Serious problems have occurred as the result of the subsidence of the ground surface above abandoned coal mines. Many abandoned mines underlie urban and residential areas, and subsidence has resulted in considerable property damage. Techniques have been developed for remote backfilling or otherwise supporting the mine void roofs so that future subsidence can be controlled.

In one such instance in Rock Springs, Wyoming, the Dowell Company developed a technique for back filling with a sand slurry. ⁽²⁹⁾ The slurry would enter the mine void through a borehole at high velocity, and subsequent reduction in velocity would cause the sand to settle out and form a doughnut-shaped mound. The technique was intended for distribution of sand through a 500 - 1500 foot radius. A demonstration test of this method at Rock Springs showed that a large area was backfilled, but the desired doughnut-shaped distribution was prevented by obstructions.

Another technique for controlling subsidence

above abandoned mines calls for the remote construction of pillars to support mine roofs.^(30, 31) This was accomplished through a borehole by first dropping aggregate and forming a truncated cone, and then grouting the aggregate with a cement - fly ash mixture. Consideration must be given to the action of acidic mine water on the concrete pillar.

3.3.3 Filling of Underground Cavities Associated with Nuclear Tests

Underground cavities associated with underground nuclear tests have been filled with highly fluid grouts with pea gravel as aggregate.⁽³²⁾ The grout was delivered by gravity fall through a borehole, and then deflected at the bottom to aid in placement. The high terminal velocity of the free-falling material caused considerable wear on downhole deflectors, and these deflectors had to be replaced several times during a single filling operation.

3.3.4 Filling Abandoned Sewer Lines

A Metro Subway construction program in Washington, D. C. required the filling of an 8-foot diameter abandoned underground sewer line in a dense downtown area.⁽³³⁾ Access to the sewer line was through a series of 4-inch cased holes. These were filled to refusal by dry fly ash.

3.4 Review of Systems for Distributing Remotely Placed Material

As indicated earlier, the remote placement of material to create an air-tight seal in a mine passage, which is unconfined in two directions, presents a formidable problem. Either the sealant material is ideal; i. e., it flows freely away from the borehole a fixed distance and then sets and builds up, or some distribution method is used to place material in a desired way. The

distribution systems which have been used to date are described below. Some distribution concepts are depicted in Figure 4.

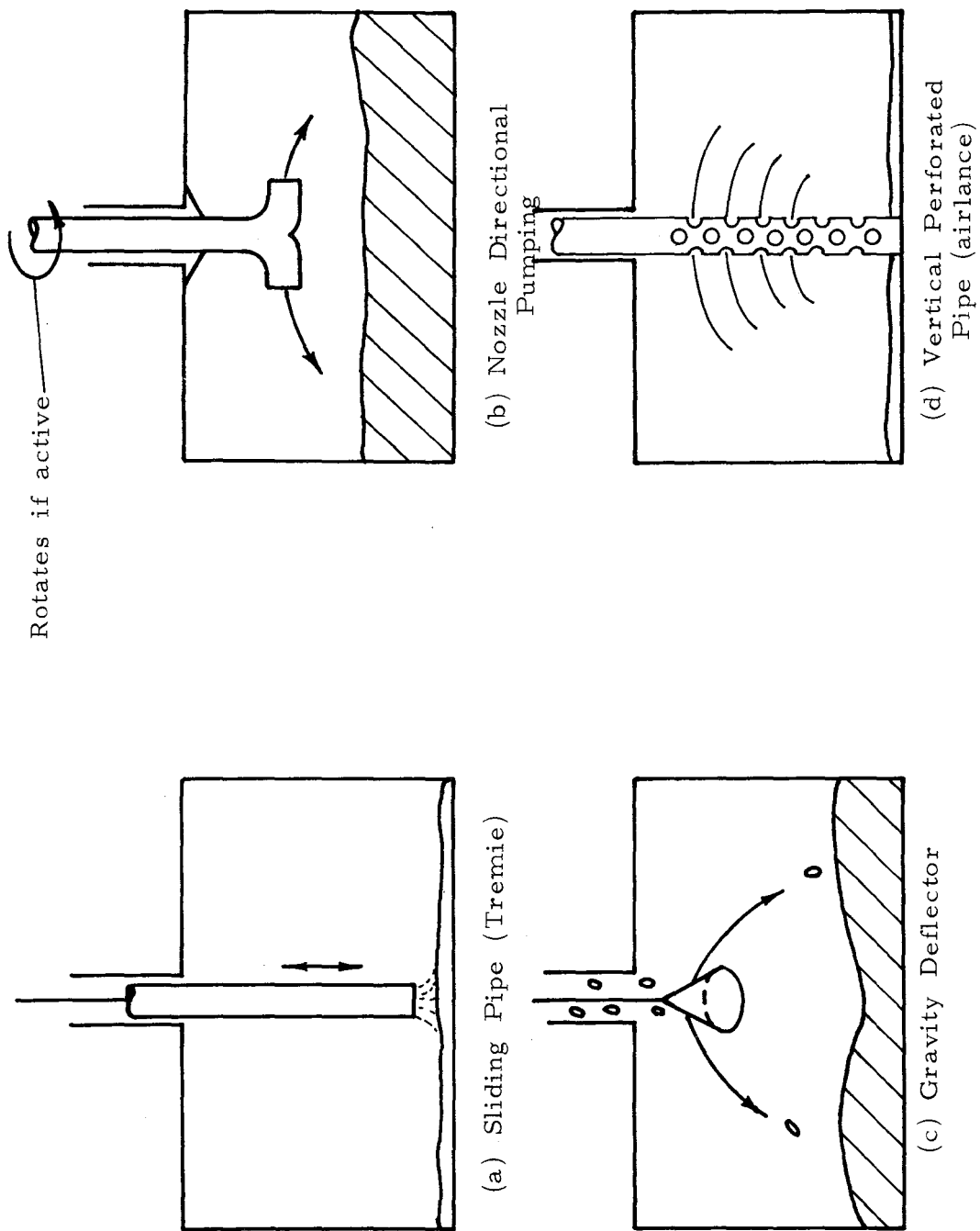
3.4.1 Sliding Pipe or Tremie

The sliding pipe or Tremie shown in Figure 4 (a) is used to aid in distribution of dry material. The pipe is lowered to the bottom of the passage so that the jet effect against the floor helps to spread the material. As the pile builds up, the pipe is moved up always maintaining a close spacing with the pile to maximize the effect of jetting.

3.4.2 Directed Nozzle

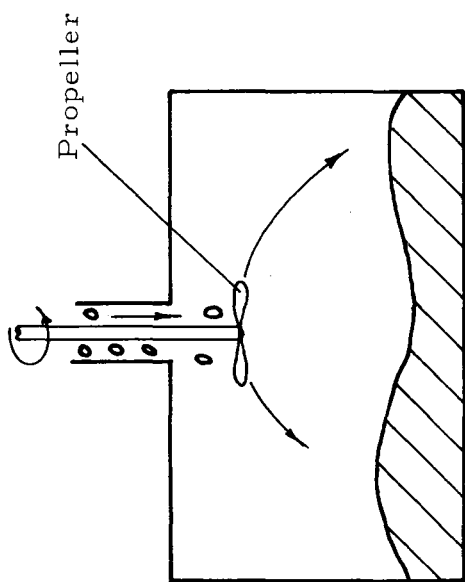
The Bureau of Mines has used a directed nozzle for the pneumatic placement of rock wool seals.⁽²⁴⁾ The nozzle, which is essentially a pipe elbowed at about 120°, is lowered into the mine passage through a borehole, pointed down the passage axis, and rotated about the borehole axis 35° either way to form a uniform seal. This technique implies a knowledge of the position of the nozzle with respect to passage axis. This was not a problem for the 72-foot borehole used in the above study but may become so for deep boreholes. Figure 4 (b) shows an alternative double-ended nozzle.

In building bulkheads for mine water pollution control, the Haliburton Company placed cement slurry inside a mine drift opening from outside of the opening.⁽²⁶⁾ The placement was done remotely through a horizontal pipe with a nozzle mounted at the end. The nozzle included a pipe elbow followed by a deflecting nozzle. The net effect was the placement of material perpendicular to the horizontal pipe, placing material along the walls, floor and ceiling of the passage as the pipe was rotated. A complete seal was constructed in this manner.

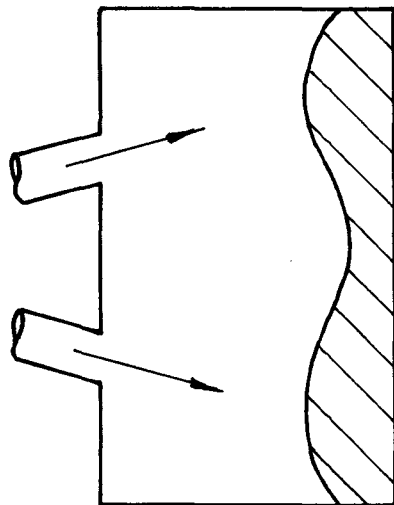


Sealant Distribution Systems

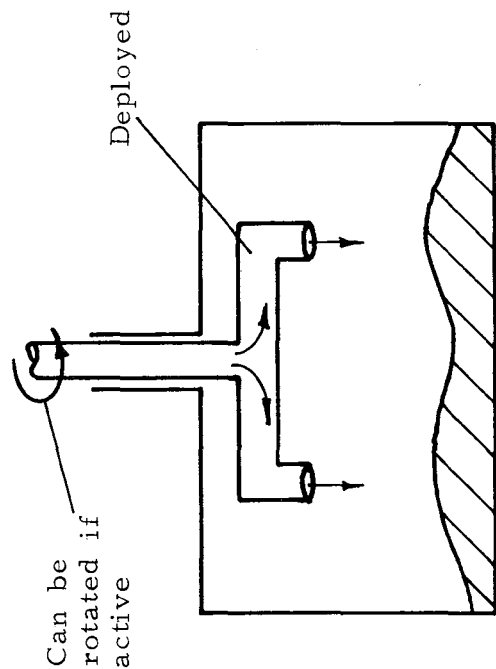
Figure 4



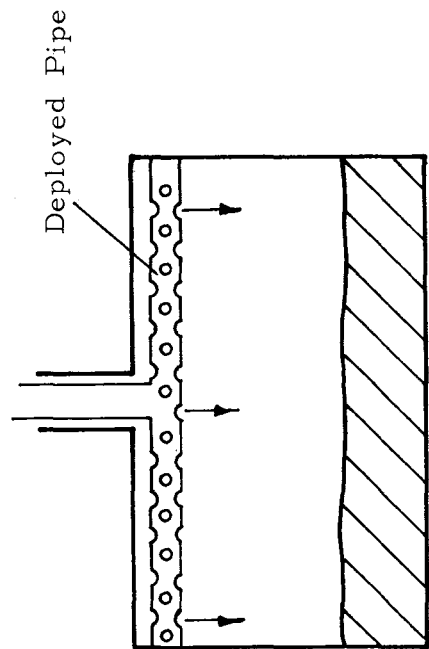
(e) Mechanical Slinger



(f) Multiple Point Source



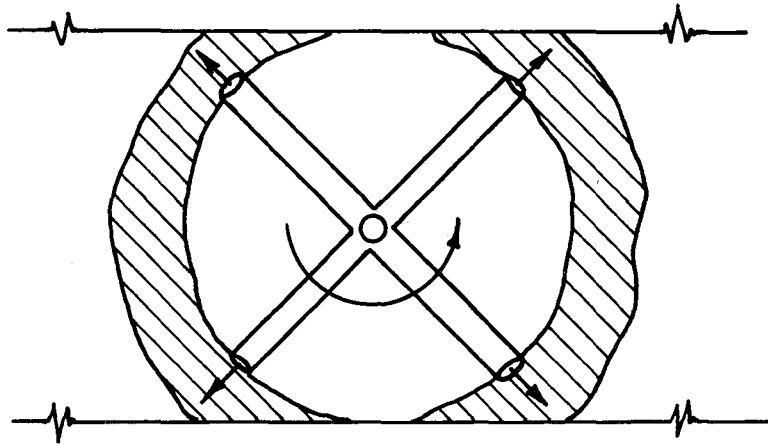
(g) Active Multiple Point Source



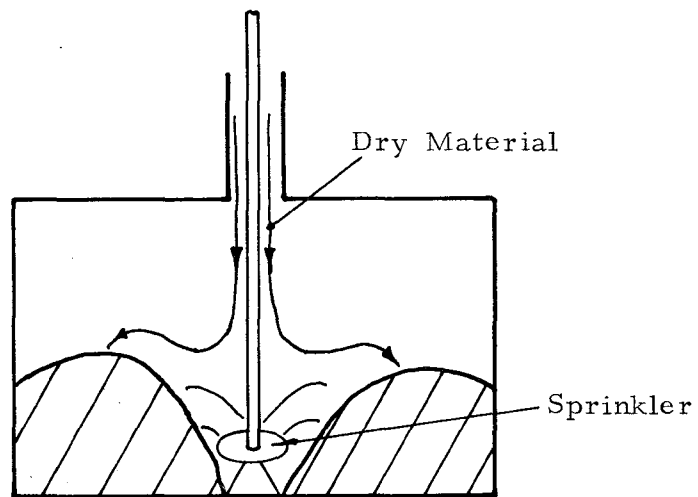
(h) Line Source - Perforated Pipe

Material Distribution Systems

Figure 4 (cont.)



(i) Circumferential Line Source -- Top View



(k) Sprinkler

Sealant Distribution Systems

Figure 4 (cont.)

3.4.3 Deflectors

Deflectors have been used in nuclear test cavity filling work described earlier. They were used in the placing of free falling pea gravel concrete. The principal problem was excessive wear. The deflector concept is currently being considered for aggregate placement in mine sealing work. In addition to wear, the principal problems with such a device are remote deployment and breaking of the aggregate upon impact. A possible deflecting device is shown in Figure 4 (c).

3.4.4 Distribution by Air Pressure

An aggregate material when dropped through a borehole will form a conical pile with an angle equal to the repose angle of material. As this is not a desirable distribution, techniques have been developed to redistribute the aggregate with air pressure as shown in Figure 4 (d).

An air line within the borehole has been used to redistribute already placed aggregate. The Layne Corporation has used this technique for spreading crushed 1-inch stone for drainage control work as discussed in Section 3.3.1. The air is delivered through a 1-1/4-inch I. D. pipe, which has a perforated end buried in the stone pile. The air pressure is applied periodically after a certain amount of stone is dropped. The result is a truncated cone of aggregate.

The Bureau of Mines succeeded in spreading a truncated cone of sand into a coal mine passage seal by inserting a 1-inch I. D. pipe and pumping air at 120 cfm and 90 psi pressure.

3.4.5 Water Flushing of Aggregate Material

Water flushing implies the use of water as the medium for transporting an aggregate material into the mine passage. The water aggregate particles to be carried by water are generally a function of particle size. A slurry of fly ash will remain a slurry for a long period of time after it enters the mine passage. As the particle size increases, the particles settle out of the slurry much sooner (i.e., a larger water velocity is required to keep the particles in the slurry). The control of particle settling as a function of water velocity is the principle underlying the Dowell Method described earlier ⁽²⁹⁾ and could conceivably be applied to other situations where controlled placement of aggregate is desired. It has been suggested ⁽³⁴⁾ that 1-inch aggregate can be flushed into a mine passage to construct aggregate retaining walls on either side of a borehole. Water flushing of aggregate enhances the spread of material in the passage, increases the potential aggregate flow rates (300 cu. yds/hr at 50 percent solids), and reduces the possibility of borehole plugging. ⁽³⁴⁾ The flow properties are enhanced by using a sonic pump. This kind of technology has been applied to the problem of dredging which is opposite to the problem of mine sealing. The major difficulty with this system is the water supply requirement which may be difficult to meet at the site of a remote sealing operation.

The water flushing of crushed limestone, as tested by the Bureau of Mines, did not deliver material at sufficient rates to form a continuous slurry, and hence, the above conditions were not achieved.

3.4.6 Mechanical Flingers

An alternative for placing material is a mechanical flinger which will throw the material away from the borehole. Such devices have been used to solve a number of packing

problems, including the loading of ships, railroad cars, and tank trucks. One type of system developed for the above applications uses a high speed belt which accelerates particles in the required directions. Another type of flinger is illustrated in Figure 4 (e).

3.4.7 Multiple Point Source

Multiple point source configurations shown in Figures 4 (f) and (g) will aid in spreading the pile. Two cones or a large truncated cone would result. The method shown in Figure 4 (f) would require angle drilling, which is difficult and expensive. The system shown in Figure 4 (g) would require downhole deployment of the two point distributor.

3.4.8 Line Source

In this concept, a perforated pipe is deployed along the top of the passage from rib to rib as shown in Figure 4 (h). This would eliminate the problem of conical piling under a single borehole and would provide a uniform distribution system for slurries, as well as for dry particulate materials. The principal problems would be deployment and the high risk of clogging of the holes. A similar concept for a circumferential line source is shown in Figure 4 (i) where the cross deployed down the borehole is rotated to form a doughnut-shaped pile, which will keep the borehole clear of material.

3.4.9 Sprinkler

In this concept, shown in Figure 4 (j), a water sprinkler system is deployed down the borehole. The sprinkler wets the dry fly ash pouring down the hole causing it to agglomerate and settle into a doughnut shaped pile having a high angle of repose.

3.4.10 Inflated Balloon Distributor

One means for distributing aggregate would involve the placing of a balloon on the bottom of the passage, connected to an air line which extends to the top of the borehole. Aggregate dropped by gravity fall would be distributed to the sides of the passage by periodically inflating the balloon, which would move the aggregate on top of it to the sides of the passage. The balloon material would have to be strong enough to resist the abrasion and impact endured in this process.

3.5 Review of Materials for Mine Sealing

Potential materials for remote sealing of mines have been alluded to in the previous sections. This section reviews materials which are potential candidates for application as mine sealing materials.

3.5.1 Fly Ash

Fly ash is readily available in regions where pulverized coal is used as fuel for power plants. It costs about \$4 - \$5 per ton (60-80 lbs/ft³) for delivery when donated by a nearby power plant. Typical chemical composition,

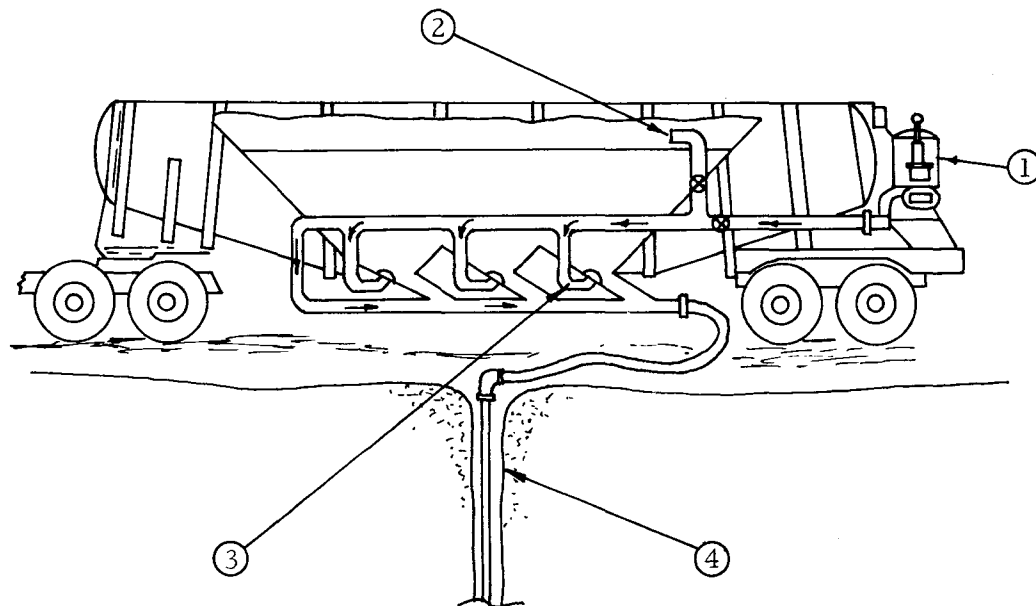
SiO ₂	- 30 - 60 percent
Al ₂ O ₃	- 15 - 30 percent
Carbon	- up to 30 percent
CaO	- 1 - 7 percent
MgO, SO ₃	- small quantities

3.5.1.1 Dry Fly Ash

Fly ash is generally supplied in a 20-ton pneumatic bulk hauler. A typical delivery system is shown in Figure 5.⁽³⁵⁾ An air compressor, either mounted on the truck (1) or supplied separately, is used to pressurize the fly ash tank (2), loosen the fly ash for the gravity feeder (3), and transport the fly ash to the borehole (4). The proportions of gas and fly ash range from 300 cu. ft. of gas per ton of fly ash using air⁽³⁵⁾ to 1,000 cu. ft. of gas per ton of fly ash using nitrogen.⁽²³⁾ Fly ash can be delivered from the truck at an average rate of 1 ton per minute. The fly ash is pumped at 12 psi for the bulk of the filling operation. As the fly ash pile approaches the roof, the supply pressure must be increased to break up and redistribute the conical fly ash pile building up below the borehole. Good seals are claimed to have been made using this technique. A detailed description of the fly ash sealing mechanism is not available. The only available information relates to amount of material delivered to the hole, pump pressure, ultimate refusal of material, and view of final seal.⁽³⁶⁾

The fly ash seal absorbs water and in two to three weeks becomes hard. In the past the fly ash system has exhibited the following drawbacks.

- (a) large quantities of material required.
- (b) passage and borehole water flow will reduce the effectiveness of the technique.
- (c) premature plugging when there is a large amount of rubble under the borehole.



Typical Fly Ash Bulk Hauler

Figure 5

3.5.1.2 Fly Ash Slurry

Fly ash slurries have been used with a typical composition of 25 percent by weight of water.⁽³⁶⁾ It has been found that some holes which would not take dry fly ash would take fly ash slurry,⁽³⁷⁾ probably because of excessive rubble.

Preparation of the slurry requires a slurry tank and some control over the thickness. In practice, it has been injected using a Moyno* slurry pump with a 100 psi capacity. It has been injected under pressure through a plastic hose extending down to the mine shaft, as well as by free fall. Tests have shown⁽³⁶⁾ that the slurry penetrates rubble piles which dry fly ash merely coats.

3.5.2 Cementitious Materials

The above title embraces a broad technology of materials, all of which contain cement as the basic ingredient. These materials are referred to as Concrete, Cement Slurry, Mortar, Grout, Shotcrete, Gunite, etc. They can take on a number of properties depending upon the relative amounts of air, water aggregate, and chemical admixtures present in the mix. The variety of available properties makes this category of materials attractive for mine sealing materials. Material costs range from \$15 to \$30 per cubic yard. Reference (38) presents a general review of the properties of cementitious materials, and much of the information below is summarized from this reference.

Cementitious materials for mine sealing operations can be characterized in terms of density, plastic flow, set time, and final strength. The term "set" describes the initial stiffening of the cement paste, such that it changes from a fluid to a rigid state, with the strength of a few psi. Set usually occurs within hours, whereas final strength is achieved after several days.

* Trade Name.

3.5.2.1 Structural Concrete

Ordinary structural concrete is a mixture of water, cement, sand, and coarse aggregate. A typical mix would have the following properties: proportions by weight of 0.5:1:2:4 of the above components, respectively; material cost of about \$20 per cubic yard; a density of 150 lbs/ft³; a set time of two to three hours; and a final compression strength of about 5000 psi. Concrete can be pumped up to 1500 ft horizontally or 140 ft vertically using special purpose concrete pumps. When pumped, concrete flows as a cylindrical plug, lubricated at the pipe walls by a thin layer of cement paste.⁽³⁹⁾ The lubricating quality of this layer is a function of mix design.

The two principal problems confronting the use of concrete in mine sealing are pumping down a borehole and ability to build up vertically in the passageway. There has been very little experience in pumping concrete down long distances. Preliminary calculations indicate that gravity flow of concrete down a 4-inch I. D. pipe, without any pressure applied at the top, would produce a flow of about 30 cu. yds/hr., about equal to the capacity of a concrete pump. The main problem in downflow of concrete is the segregation of coarse aggregate. Segregation causes an increase in friction and can lead to plugging of the pipe.

The vertical pileup of concrete in the mine passage is analogous to the slump test. The slump test essentially measures the ratio of the gravity load of concrete to the plastic flow properties. Because slump tests are done with the same dimension slump cone, relative slumps yield relative flow properties. If the same concrete were tested with a larger slump cone, the percentage of slump would increase due to the increase in the ratio of the gravity force to the plastic flow resistance. Considering the filling of the mine passage to be a large scale slump test, it is not likely that the concrete will form a pile reaching the mine roof.

The problem of passage pileup can be approached by considering the following alternatives.

- (a) Provide a retaining structure for concrete.
- (b) Decrease the density while maintaining similar plastic properties.
- (c) Increase plastic stiffness.
- (d) Control set time so that material at the bottom of the pipe is strengthening as the pile is being formed.
- (e) Use a material which expands after being placed.
- (f) Use an instantaneously setting material which can be sprayed in place.

Items (b) through (e) above have led to a search for different types of cementitious materials, and these are described below.

3.5.2.2 Haliburton Slurry

In an effort to construct bulkheads which required no forms, and which had a high angle of repose, the Haliburton Company tested a number of slurries for the required viscosity and setting characteristics.⁽²⁶⁾ The slurry selected was discussed in Section 3.3.1.

3.5.2.3 Concrete with Lightweight Aggregate

In many structural applications, considerable savings can result from reduction of dead load and of weight of material to be handled. For these applications, the typical aggregates of crushed stone and gravel are replaced by hollow, cellular, or porous aggregates. Typical lightweight aggregates include fly ash, vermiculite, perlite, clay and shale, all expanded by some type of heat treatment. Resulting concretes have a density range between 30 and 90 lbs/ft³. (40)

One severe problem in the use of lightweight aggregate is pumping. The aggregate is highly porous; a mix which seems sufficiently fluid before pumping will stiffen while being pumped due to absorption of water by the aggregate. To avoid this problem, the American Concrete Institute (ACI) recommends the soaking of lightweight aggregate in water for 24 hours before it is mixed and pumped.

3.5.2.4 Aerated Concrete

An alternative means of developing lightweight concrete has been the use of a cellular structure of air bubbles to replace the lightweight aggregate. The air bubbles are formed by either a chemical reaction in the wet, placed concrete or by introducing a stable foam in the mortar when mixed. The mortars used are typically fine sand and cement, but other siliceous materials, such as fly ash, can be used in place of sand.

Aeration by chemical reaction can be accomplished by addition of aluminum powder. The reaction of the cement paste with the aluminum powder results in the formation of hydrogen, which causes the paste to expand and develop a cellular structure. This type of concrete is generally used for prefabricated

structural elements, where the reaction and curing can be factory controlled.

Aeration by the introduction of a preformed stable foam is generally used for the in-place casting of roof decks and walls. A foaming agent is diluted with water and then mixed with air at a pressure nozzle to form a foam that has the consistency of shaving cream. This is then introduced to the mortar (sometimes at the mixer, sometimes at a blending head) to produce a lightweight paste with small stable bubbles. Such paste has been pumped to 1000' horizontally and 250-feet vertically up. ⁽⁴¹⁾

The preformed, foam-aerated concrete is particularly attractive for mine sealing, as it can be continuously produced on the site with a minimum amount of materials. Continuous foam generating, mixing, and pumping units are commercially available.

3.5.2.5 Rapid Setting Cements and Admixtures

There are numerous ways of controlling the setting time of a cement mix with setting times varying from a few seconds to 1 or 2 hours. Rapid set can be achieved by using special purpose cements or by the addition of known chemicals or proprietary admixtures.

Two special cements manufactured in the United States are Huron Regulated Set Portland Cement* and Atlas Lumnite.* The Huron Reg Set* is similar in composition to ordinary Type I Portland cement. The main difference is that the basic chemicals are compounded in a different way so that the reaction rates are changed. Reg Set* cement will set in 5 to 10 minutes. This can be retarded by the addition of citric acid or by replacing

* Trade Names.

the cement with filler such as fly ash.⁽⁴²⁾ Reg Set* cement has been mixed with preformed foam to make lightweight, fast setting, insulation.⁽⁴³⁾ It currently sells for \$2.25 a sack, F. O. B. Alpen, Michigan.

Atlas Lumnite Cement is a calcium aluminate cement developed primarily for refractory purposes and for resistance to sulfate attack. By itself, it has a slower setting time than ordinary Portland Cement. When mixed with small quantities of Portland Cement, or vice versa, a flash set develops within a few minutes.⁽⁴⁴⁾ Lumnite cement costs approximately \$6.75 per sack delivered.

One problem which must be considered with these special cements is availability. Each of these cements are manufactured in only one place in the country (Huron in Michigan, Lumnite in Indiana). Since they are special-purpose products, it may be difficult to obtain a desired quantity on short notice.

Sodium silicate (water glass) forms a gel-like set within seconds of mixing with cement. Because of the rapidity of set, it has to be mixed and placed simultaneously. It has been used both in developing self-supporting bulkheads by Haliburton and in developing instant spray barriers for containment of dangerous liquid spills.⁽⁴⁵⁾ The cost ranges between \$2 - \$3/ gallon.

Calcium Chloride is also used to accelerate setting, as are numerous commercial admixtures such as Sikaset*, Darex Set Accelerator*, etc. Because the performance of such additives can not be predetermined, it is standard procedure to develop a number of control mixes and to determine the most desirable compositions through trial and error.

* Trade Names.

In all of the above-mentioned techniques for accelerating the set of cement, water temperature and water cement ratio have an influence on setting time. Hence all compositions specified for a given set must be with reference to these two factors.

3.5.2.6 Shotcrete

Shotcrete refers to pneumatically placed mortar or concrete. Pneumatically placed mortar is also referred to as Gunit. In the "wet-mix" process, water, cement, and aggregate are first mixed and then pumped under pressure through a nozzle. In the "dry-mix" process, the dry materials and water are mixed at the nozzle. (46)

Concrete applied by shotcreting tends to build up on the surface where it is applied, including walls and ceilings. It is a desirable technique for directional placement of concrete and may have application to remote sealing of mines. (47)

3.5.2.7 Expansive Concrete

Certain chemicals, when added to a cement mix, will form a gas and cause an expansion of the wet material. Aluminum powder, alluded to with reference to aerated concrete, is one such chemical. When added 5 percent by weight of cement to a small amount of cement mix in a container, the mix rapidly expands, heat evolves, and the resulting hardened mass is about two to three times the volume of the original. If placed in a large quantity, the expansion will reduce due to the excess weight of material. Aluminum powder sells for \$.50 a lb. Apart from aluminum powder there are commercial expansive admixtures, such as Intracrete* and Intraplast N.* These, however, are primarily for counteracting normal shrinkage and for chemical prestressing.

* Trade Names.

The use of an expansive cement is an attractive approach to the problem of making a final seal across the mine roof.

3.5.3 Other Hydraulically Setting Materials

In addition to cements, there are other materials commonly used in construction which set and harden after mixing with water. Gypsum plaster has a setting time between 10 minutes and an hour. It has a major limitation in that it is always soluble in water, even after hardening. Another possible material is a lime-fly ash mix. This combination is very similar to Portland cement in chemical composition. It is cheaper than cement but has a longer setting time.⁽⁴⁸⁾ It has been used as a grout for soil stabilization.

3.5.4 Urethane Foam

Urethane foam is formed by combining a resin with an isocyanate. The foaming reaction does not begin until these two components are mixed and mixing takes place at a mixing head. The foam component can be delivered at 700 lbs/min and expand to 30 times its original volume, producing a rigid foam with density as low as 2 lbs/cu. ft.

Urethane foam is flammable. Its flammability can be retarded in a number of ways, but it must be considered flammable. Were it not flammable, urethane foam would be an ideal sealant material. When poured into place, its viscosity increases with time as it hardens and expands. It can also be applied in a pre-foamed state, somewhat like shaving cream. The viscosity, as well as expansion and hardening times can be easily adjusted. The time for beginning of the chemical reaction, called the "cream time", is usually less than one minute. Longer cream times would produce less expansive foams.

The outlet conditions of the foam mixing head can be controlled by the pressure on the inlet tanks. Mixing head pressures range from 10 psi (low pressure head) to 100 psi (high pressure head).

Typically, low-density urethane foam costs \$.60 to \$1.50 per cubic foot. Some of the possible uses of urethane foam in the sealing of mines are listed below:

1. As bulk sealing material
 - a. The resin component can be combined with a filler (fly ash) to reduce cost and flammability. This can be applied either by pouring or spraying through a mixing head in the mine shaft.
 - b. Foam pellets - The two foam components can be mixed into a sealed capsule. A number of these capsules can be dropped into the mine shaft. The expanding components will cause the capsules to break, distributing foam throughout the shaft (rather like popcorn). (49)
2. As final seal
 - a. Foam can be sprayed across the mine roof to create a final seal between the bulk material and the mine roof.
 - b. Liquid foam can be poured on top of a pile of porous bulk material, which absorbs the liquid and rises as a mass to form the final seal.

3.5.5 Asphalt Emulsions⁽⁵⁰⁾

Asphalt is organic and, hence, flammable. A sufficient amount of filler will reduce the total organic content and, thus, make this material more applicable to mine sealing. Asphalt emulsions, for example, contain from 40 to 70 percent asphalt with asphalt particle sizes from 2 to 10 μ . An emulsion of asphalt in water is much more fluid than asphalt alone. It requires an emulsifying agent, which can be anionic or cationic depending upon the nature of the surface to which the asphalt will be applied. These agents are added in quantities up to 3 percent by volume depending on the rate of "break" desired, "break" being defined as the dispersed asphalt beginning to precipitate. This break time can be varied from a few minutes to 3 to 4 hours.

Asphalt emulsions can be delivered already prepared in tank trucks. They are generally used for roads and road repair and, hence, should be easily available.⁽⁴⁸⁾ The emulsion is usually applied as a layer on an existing aggregate base. As such, it can be used in mine applications to fill a preplaced aggregate pile. It can also be mixed with aggregate before it is poured. In this case, break time must be controlled so that it does not break in the borehole.

3.5.6 AM-9⁽⁵¹⁾

AM-9 is a chemical grout developed by American Cyanamid. It has been used as a grout for stopping water flow, which may be applicable to mine sealing work where there is a passage water flow to be stopped. AM-9 is a powder, which, when mixed with water, retains the viscosity of water until it begins to

gel. Gel times can range from a few seconds to two hours depending on composition and temperature. By itself, AM-9 forms a clear, jelly-like mass. It can be mixed, for example, with 9 parts of fly ash without reducing its effectiveness. In this ratio, the fly ash-AM-9 mixture would cost approximately \$6.00 to \$8.00/cu. ft.

3.5.7 Sand and Coarse Aggregate

It was mentioned earlier that sand and coarse aggregates by themselves have had some application in mine sealing work, both experimentally and in practice. It might be possible to form a full seal remotely with sand; however, the complete development of a fool-proof distribution system would be required. Damp sand may be difficult to pump pneumatically, and dried sand may be required.

Coarse aggregate is too porous to form a complete seal. It can, however, provide a form for subsequent grouting. It can also be used for building bulkheads and for slowing down and redistributing passage water flow.

3.6 Synthesis and Evaluation of Mine Sealant Material Systems

The process of synthesis of various mine sealant material systems was based on the development of a functional description of the mine sealing process, followed by the development of concepts to fulfill these functions. These concepts were then synthesized into total mine sealant material systems.

3.6.1 Functional Description of Mine Sealing

The overall function of the mine-sealing process is to remotely fill the passage through one or more boreholes and build an air-tight and water-tight seal under the environmental conditions specified in Section 2.1. To fulfill this requirement, the mine-sealing process may be classified into the following three functions:

- a. Initial Preparation of Mine Passage
- b. Bulk Filling of Mine Passage
- c. Final Sealing of Mine Passage

The function of the initial preparation subsystem is to prepare the mine passage to receive and hold the bulk filler. For example, laying a bed of coarse aggregate to build a dam against water flow, when it is present, or building two bulkheads to hold the filler material poured into the confined space. It is likely that the material system required for initial preparation will be quite different from that of the bulk filler or final seal.

The function of the bulk filling subsystem is to fill the bulk of the passage area with the minimum amount of material and in the shortest possible time while producing a surface geometry suitable for receiving and retaining the final sealant material.

Further, it should distribute the material in such a way that the borehole or material entry point into the mine passage is kept clear of the bulk filler material to facilitate subsequent completion of the final sealing operation. It is quite likely that the same material may be used for the bulk filler and the final seal, but the distribution systems may be different because of conflicting requirements.

The function of the final sealing subsystem is to make an air-tight seal by filling the air space between the bulk filler and the mine roof surface. Most mine roof surfaces can be quite rough with roof falls leaving pockets which may be difficult to seal. The final sealant should be fluid enough to fill these spaces before plugging the borehole. An expanding material, such as foam, would be desirable. However, flammability considerations dictate that its quantity be kept to a minimum.

3.6.2 Development of Concepts

By definition all material systems consist of two parts: a material having the desired characteristics and a distribution system to place the material in the desired configuration. From the reviews of candidate materials and distribution systems described in the previous sections, it is obvious that a large number of material systems combinations can be developed to satisfy the functional requirements of the three subsystems: initial preparation; bulk filling; and final sealing. In such a case it would be extremely difficult to objectively evaluate the relative performance of these system combinations. Instead, Foster-Miller preferred to conduct the development on a functional basis.

General material and distribution characteristics were defined to fulfill each of the three functional requirements. Particular materials and distribution methods satisfying these characteristics were selected. Table IV shows the functional

TABLE IV
FUNCTIONAL DEVELOPMENT OF MINE SEALANT MATERIAL SYSTEMS

	Function	Desired Material Characteristics	Possible Materials	Distribution Systems	Performance Capability	Cost	Development Risk
1. Preparation of Mine Passage	1. Stopping water flow during filling	(a) Consolidation under water	1. Fast setting concrete or shotcrete 2. Chemical grouts (e.g. AM-9 and fly ash)	Special, directional, pressurized mixing nozzles for liquids or slurries	Good, proven practice	High	Reasonably low
		(b) Heavy, coarse, unrodable	Extremely coarse gravel impregnated with filler during bulk filling operation	Vertical or directed point source, downstream (mechanical slinger or gravity fall deflectors)	Good - wear problem	Low	Low
	2. Providing retaining structure for bulk filler	(a) High angle of repose	1. Gravel or sand	Directed distribution, into and out of borehole	Good - wear of distributor likely problem	Low	Moderate
		(b) Special retaining structures	2. Wet fly ash - cement mixture 3. Sprayed fast-set slurry 1. Inflatable structures - (gas-filled balloons) 2. Bags filled with filler materials	Directed pneumatic nozzle distribution as water sprinkler with controlled spatial distribution Special directed deployment systems Dropped through borehole	Unknown Good Good Fair	Low Moderate High Moderate	High Moderate Extremely High Moderate
2. Bulk filling of Mine Passage	3. Coat walls, roof and floor to smooth crevices and cavities	(a) Adhesive material	Gunned concrete	Highly directional and controllable - pressurized mixing nozzle	Good	?	High
		(b) Expanding material	Expanding foam	Highly directional and controllable - pressurized mixing nozzle	Good	?	High
	Block the major portion of the passage cross section and provide large area for final seal	(a) Low angle of repose - setting ability with moisture	1. Fly ash - cement mixture } dry 2. Vibrant sand	1. Undirected vertical point source 2. Line source	Excellent, good flat top	Low	Low
		(b) High angle of repose	1. Sand } dry 2. Rock wool	1. Directed point source - mechanical 2. Line source - pneumatic	Good - but more angular flat top	Low	Medium
3. Final Seal	(c) Time setting after limited flow with good set strength		1. Lightweight concrete } slurry 2. Fly ash concrete	1. Vertical point source 2. Directed point source 3. Line source	Good	Low	Low
			3. Filled foam 4. Asphalt emulsion } slurry 5. Asphalt concrete	same	Poor	Low	Moderate
	Positively fill space between bulk material and passage roof	(a) Fluid, expanding material	1. Expanding, aluminum cement grout 2. Urethane foam - pour, spray stream	1. Point source - directed 2. Line source	Fair	Moderate	Moderate
		(b) Low angle of repose fluidized dry solids	1. Flyash - expanding cement mixture 2. Use heavy displacing material Cement slurry	1. Directed point source } High pressure redistribution 2. Line source	Good	Low	Low
		(c) Fluid material, forced into place under pressure		1. Vertical flow from borehole	Good	Low	Low


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development of mine sealant material and distribution systems, with a preliminary estimate of the performance to be expected, the relative cost and the development risk. These concepts consisted of the building blocks for the synthesis of a number of different mine sealant material systems.

3.6.3 Synthesis of System Concepts

Table V summarizes some of the more promising material and distribution systems synthesized to satisfy the functional requirements outlined in Table IV. The table also includes preliminary estimates of probability of success, development cost, development effort required, material cost, time for making a seal, and on-site equipment required.

The effect of multiple boreholes on the design and performance of these systems was considered. Multiple boreholes would facilitate to some extent the distribution of coarse, high-angle-of-repose materials. In particular, multiple boreholes might make it easier to make bulkheads of coarse aggregate (System C of Table V). However, the magnitude of performance improvement with multiple boreholes does not appear at this time to justify the inclusion of a multiple borehole sealing system.

Based on this evaluation a number of promising systems were selected for further development.

3.7 Selection of Material Systems for Further Development

From Table V the following systems were selected for further development:

System A	Aggregate, Fly Ash System

System Designation	Scaling Phase	Material	Distribu Metho	On Site Equipment	Material Cost	Required Probing Information
A	1	Aggregate	Deflector, flange		Agg. \$ 100	Presence of water in passage, location of borehole from passage axis (and intersection), borehole water flow.
	2	Fly Ash (dry)	Vertical fall	Aggregate pump, fluidizing tank.	Fly ash \$2200	
	3	Fly Ash (dry)	Redistribution un		\$2300	
B	1	Aggregate	Deflector, flange		Agg. \$ 100	Presence of water in passage, location of borehole from passage axis (and intersection), borehole water flow.
	2	Fly Ash (dry)	Vertical fall	Aggregate pump, fluidizing tank, foam components and regulators.	Fly ash \$2100	
	3	Liquid foam	Mixing nozzle		Foam \$ 250 \$2450	
C	1	Aggregate	Deflector, flange		Agg. \$1600	Location of borehole, intersections, dimensions of passage, location of obstructions, rubble.
	2	Light, expansive concrete	Vertical fall	Aggregate pump, concrete mixer and pump.	Conc. \$2400	
	3	Light, expansive concrete	Vertical fall		\$4000	
D	1	Sand	Perforated line	and Pump	Sand \$ 900	Location of borehole from passage axis, passage dimensions, rubble.
	2	Sand	Perforated line			
	3	Sand	Perforated line			
E	1	Dry fly Ash and AM9	Perforated line	etering of AM9, y ash fluidizing imp.	AM9 \$ 850	Location of borehole from passage axis, passage dimensions, rubble, borehole water.
	2	Dry Fly Ash	Perforated line		Fly ash \$2200	
	3	Dry Fly Ash	Perforated line		\$3050	
F	1	Aggregate	Deflector, flange		Agg. \$ 100	Location of borehole from passage axis, passage dimensions, existence of water flow.
	2	Thick concrete slurry	Vertical fall	Aggregate pump, concrete mixer and pump.	Slurry \$4800	
	3	Thick concrete slurry	Redistribution un		\$4900	
G	1	Quick set concrete	Variable height	one, mixer and imp, metering active components	Slurry \$4800	Passage dimensions, proximity to intersections.
	2	Quick set concrete	Variable height			
	3	Expansive concrete	Variable height			
H	1	Fly Ash and AM9 (dry)	Vertical fall	etering of AM9, y ash fluidizing imp.	AM9 \$ 850	Presence of water, dimensions of passage, intersections, borehole water.
	2	Fly Ash (dry)	Vertical fall		Fly ash \$2200	
	3	Fly Ash (dry)	Pressure redistrib		\$3050	
I	1	Fly Ash and AM9 (dry)	Vertical fall	etering of AM9, y ash fluidizing unk, foam mixing equipment.	AM9 \$ 850	Presence (and amount) of water flow, passage dimensions, intersections, borehole water.
	2	Fly Ash (dry)	Vertical fall		Fly ash \$2100	
	3	Liquid foam	Mixing head		Foam \$ 250 \$3200	

A

B

System B	Aggregate, Fly Ash, Urethane Foam System
System C	Aggregate Bulkhead, Light Expansive Concrete System
System D	Aggregate, Self-Supporting Thick Slurry System

The first two are essentially dry material systems, while the latter two are water-based, self-setting, slurry systems. The dry fly-ash based systems are simple with a good probability of success at low to medium development cost. The major problems with these systems are associated with borehole and passage water-flow. The introduction of high volumes of air as the carrier may also be available in a fire situation. In this instance, air must be replaced by an inert gas. System A uses fly ash as both the bulk filler and the final sealant. System B uses fly ash as the bulk filler and urethane foam as the final sealant. System B is expected to produce a better seal than System A but requires the use of foam, which may be considered an undesirable material in a working mine due to its flammability.

The self-setting slurry systems are likely to offer a number of advantages, in particular a possible low sensitivity to water flow. In addition, they avoid the problem of admission of air into the fire zone in the mine. System C requires the building of bulkheads to retain the slurry, while System F uses a self-supporting setting material by itself without any bulkheads.

To build a seal in the presence of mine passage waterflow, all systems require that a bed of aggregate be first deposited on the mine floor to act as a retainer for the bulk filler or special grouting material.

The other systems were eliminated as either having too high a development risk or not offering any significant performance advantages over the ones selected.

4. Preliminary Study - Remote Seal Checker

4.1 Introduction

Determination of the completeness of each individual seal at the time of its emplacement is essential for an effective remote sealing system. A satisfactory seal checking technique should provide a signal which:

- (1) indicates percentage completion as the seal is emplaced
- (2) provides a definite indication of a complete seal
- (3) indicates the size of the unsealed area if a complete seal is not feasible

This information is required to establish the need for additional seal material, the need for additional seals, and the risk likely involved in entering the mine. In many situations it is as important to know the quality of a seal as it is to build an effective one. It is likely that with repeated use the remote sealing technique developed by Foster-Miller Associates will be sufficiently reliable and predictable to preclude the seal checking requirement. It is recommended, however, that each seal be checked during construction to insure its completeness and increase the level of confidence so necessary in reopening the mine.

4.2 Description of General Problem

Several characteristics of remote mine seals are important in considering techniques for evaluating the effectiveness of these seals. These include:

- (1) large area blockage
- (2) long sealed perimeter
- (3) thick barrier
- (4) low pressure differential
- (5) unpredictable direction for pressure differential
- (6) voids possible at positions other than roof
- (7) flanking entries may short circuit seal

The cross sectional area of the passages to be blocked by the seal might range from less than 50 square feet to over 150 square feet. The perimeter of this area, where leakage is most likely to occur, may then range from 30 feet to nearly 60 feet in length. The barrier itself is thick: 15 feet at roof level and nearly 100 feet at the floor. The pressure differential across the seal can vary both in magnitude and direction, complicating checking techniques which rely on mass transfer across the seal in a preferred direction.

Holes through the seal might occur at the ribs or floor level due to irregularities in the surface. The probability of this is low, however, with the roof-seal interface providing the obvious place for discontinuities to occur. For most seal materials the corners where roof and rib meet is the critical area. Knowing the most likely location for discontinuities is important for seal checking, affecting the checking device itself and its most satisfactory deployment location.

Flanking paths along passages parallel to the one being sealed, as well as through cracks in the rock and coal, short-circuit the seal being constructed until the final seal has been emplaced. It is important to insure completeness of each seal immediately after it is formed, in the presence of these large flanking paths, to eliminate the expense and time consumed in returning to boreholes to "top off" a seal. To permit checking of individual seals, the checking system must distinguish between paths through and paths around the seal.

4.3 Limitations of Conventional Seal Checking Techniques

Conventional techniques for determining the effectiveness of a seal monitor the actual flow past the seal and, thus, may be considered "direct" approaches. Among these are:

- (1) trace elements - add on one side of the seal and monitor on the other
- (2) volumetric change - monitor the increase or decrease in fluid volume on one side of the barrier
- (3) bubble test - coat the barrier with an impervious but flexible layer and search for bubbles in the layer
- (4) passive acoustic - detect acoustic energy of the escaping fluid

Starting with the last method, we note that acoustic techniques are being used to detect both air and water leaks. Air or gas escaping through an orifice produces sonic energy primarily in the 30 to 50 kHz band.⁽⁵²⁾ A variety of ultrasonic equipment is

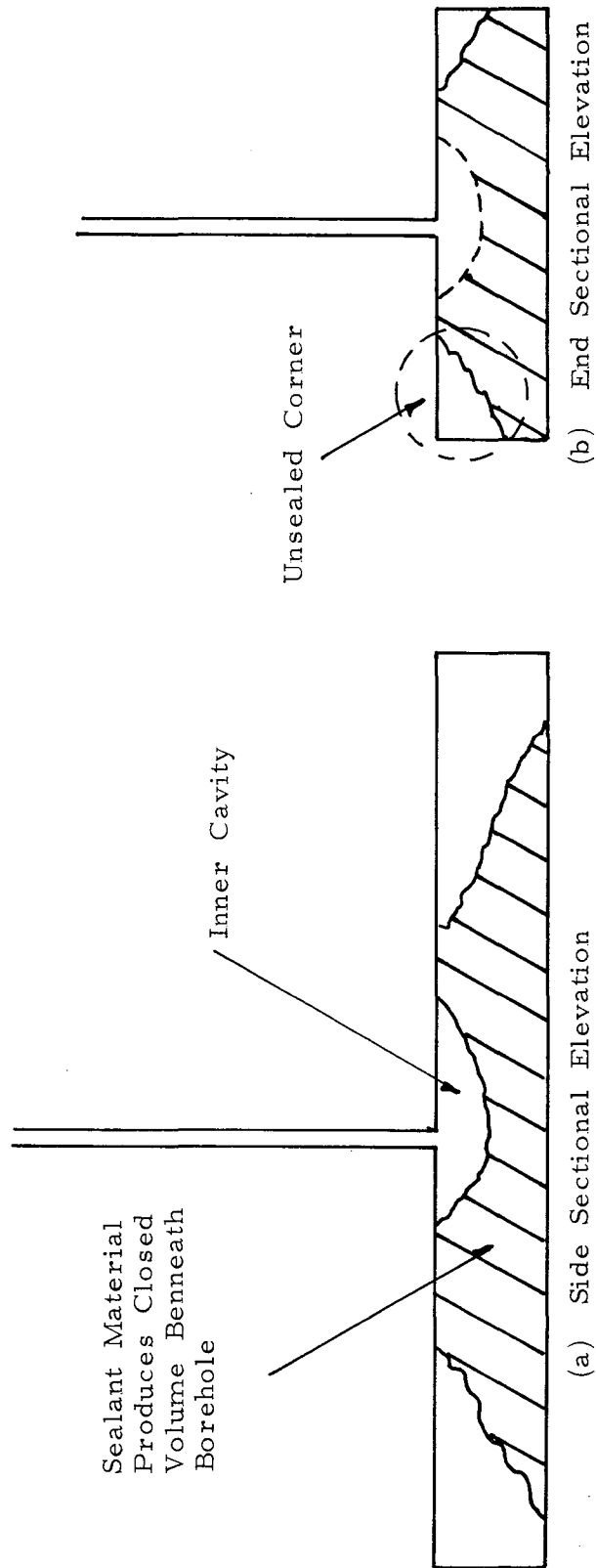
available to detect such signals. It is used, for instance, to detect leaks in pressurized telephone cables, tires, ducts, and other pressurized systems. It does not appear, however, that this equipment is suitable for detecting flow across the seals under consideration. The pressure drop across the barrier is typically so low that flow through a sizeable opening is unlikely to generate sufficient energy.⁽⁵³⁾ Similarly, flow through a porous boundary of this type will also fail to generate readily detectable signals. For these reasons we do not anticipate that high-frequency acoustic phenomena will be of use in detecting air-tightness of the boundary.

Much lower frequency acoustic techniques are also used to detect the flow of water in soil. However, we feel that the background noise (flow of water against the barrier, flow in other passageways) makes this method unusable.

Coating the barrier with an impervious layer and looking for the formation of bubbles is a classic leak detection technique but is obviously unsuitable for remote seal checking.

The seepage flow through a barrier such as a dam is usually detected by measuring the water that collects either in a trench on its downstream side, in an interior tunnel, or in an interior probe hole. All appear unsuited for the application under consideration.

The reverse of this method - measuring the decrease of material in a closed volume - might be used under certain circumstances. It is obviously impractical to use either side of the sealed passageway as neither is likely to be a closed volume. However, if the seal were constructed by distributing the material first against the passageway corners and at a distance from the entering borehole as shown in Figure 6, it would be possible to pressurize the inner



Potential Difficulty with Closed Volume Seal Checker System

Figure 6

cavity with either air or water and determine if it were tight by measuring the loss in pressure or water. Unfortunately, such a test would only determine if the barrier were tight and not if the passage-way seal was. Figure 6 illustrates how such a test might give an erroneous result.

Evaluation of seal effectiveness through the use of trace elements is hampered by the parallel paths that exist through adjacent passages and cracks in the rock and coal. Distinguishing between trace elements which diffuse through the seal and those which diffuse through the available parallel paths is not practical.

4.4 Unconventional Seal Checker Approaches Considered

The alternatives to conventional seal checking techniques investigated during this program may be divided into two categories differing from the "direct" techniques presented previously. These categories may be defined as "indirect" and "internal".

4.4.1 Indirect Seal Checking System

"Indirect" seal checking techniques are those which monitor the transmission through the "seal" of energy that is artificially introduced on one side of the seal. This class of techniques requires a sender and a receiver on opposite sides of the seal. The presence of flanking passages connecting opposite sides of the seal adversely affects these systems by providing short-circuit paths for the energy to follow. Attenuation along the paths or pulse gating techniques must be relied on to eliminate the portion of the signal which reaches the "sealed" area via the flanking path. Indirect approaches considered in detail include active acoustics and active optics.

4.4.1.1 Active Acoustics

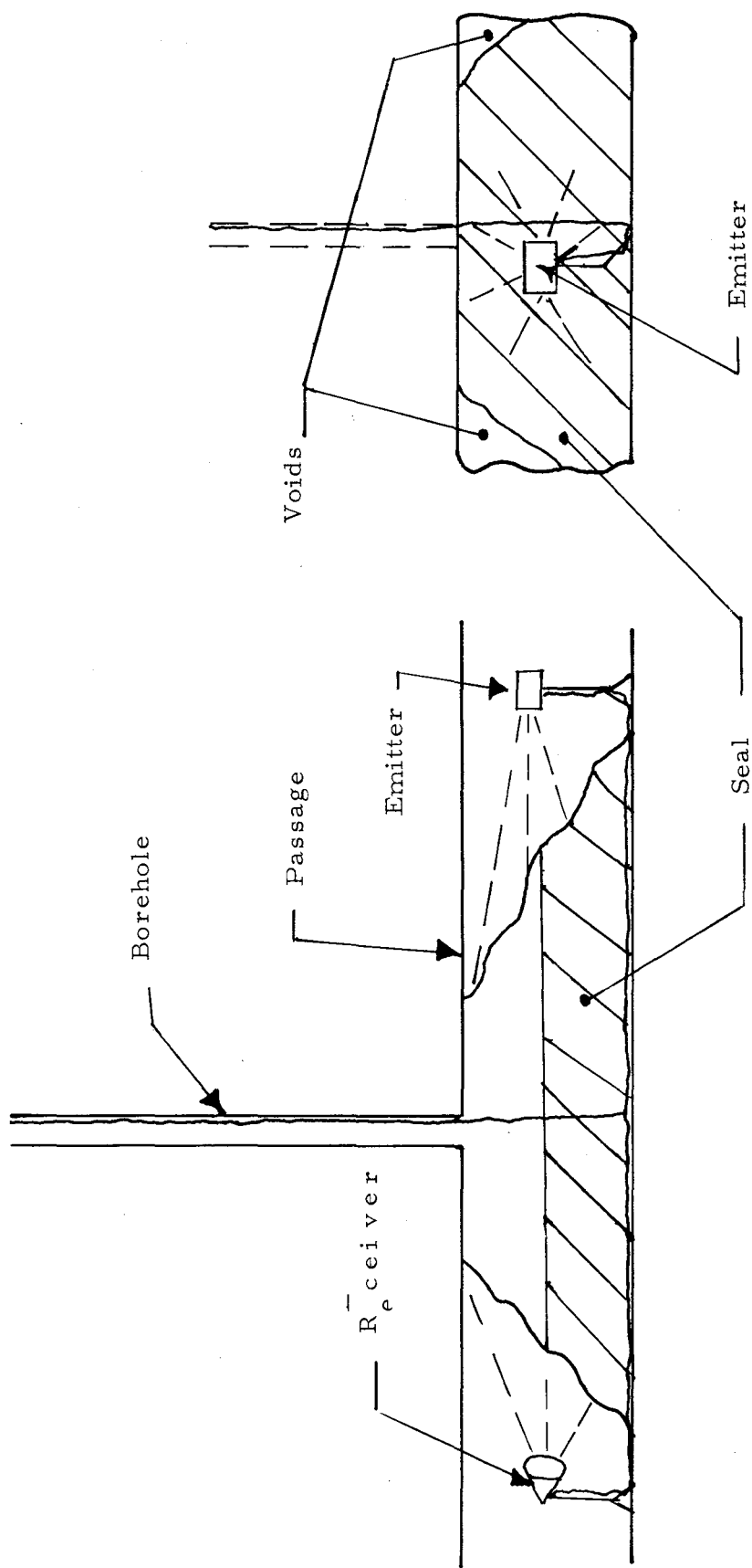
A powerful acoustic source and sensitive receiver may be employed to determine the completeness of a seal. Using the arrangement of Figure 7 , the emission of a fixed acoustic power in a controlled frequency range will produce a fixed sound energy level at the microphone on the other side of the region to be sealed.

As the barrier is erected between the acoustic sender and receiver, the sound energy level at the receiver is reduced in a predictable manner. The frequency range may be selected to minimize the attenuation of the signal along the passage and maximize the ability of the energy to penetrate "holes" in the seal. A pulse gating system may be included to distinguish between the energy transmitted through the sealed region and that transmitted along the flanking paths.

4.4.1.2 Active Optics

A high intensity light source and sensitive receiver may be employed to check a seal as shown schematically in Figure 7 . The high intensity light will penetrate typical "holes" in a seal. Extremely sensitive photo diodes are available at low cost that will sense the light passing through the "holes". Attenuation in the mine atmosphere will be sufficient to eliminate the undesirable flanking path effects.

Limitations of the optical approach are two-fold. Smoke in the passage will seriously degrade the performance of an optical system. Distinguishing between a small hole in a seal in a clear passage and a large hole in a smoke filled passage would be extremely difficult. An infrared source could provide more satisfactory penetration of smoke, but the range is increased by only a factor of two over that with visible light.



Schematic of Active Optical or Acoustic System

Figure 7

The other limitation of energy in the visual spectrum is the high degree of directionality associated with the energy. The ability of this energy to penetrate an irregular passage through a highly absorptive material is limited.

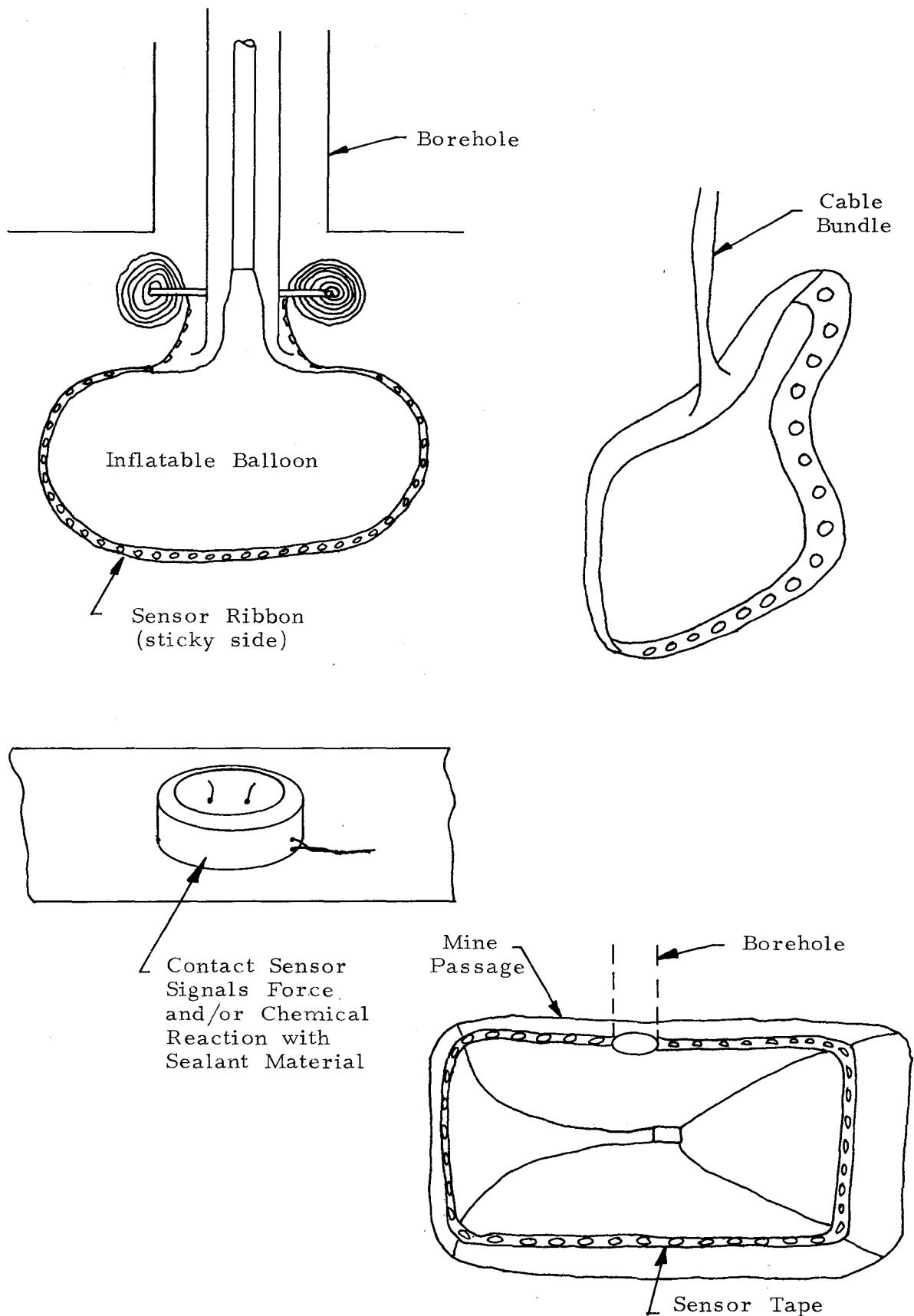
4.4.2 Internal Seal Checking Systems

"Internal" seal checking techniques employ a system of "probes" located along the seal-passage interface to insure that the seal material has been deposited at a series of adjacent points. This method does not guarantee a complete seal, but rather that the material has reached particular locations such as across the roof or a specified distance along the passage. The confidence placed in the output from these devices depends strongly on the physical properties of the sealant materials.

Flanking paths do not compromise the performance of the internal seal checking concepts, but deployment of these in a semi-continuous string presents a formidable challenge to the designer. Details of the deployment schemes are presented with the concepts discussed.

4.4.2.1 Discrete Sealant Material Sensors

Discrete sensors placed around the periphery of the intended seal location as shown in Figure 8 and activated by contact with the seal material could provide a signal proportional to the length of periphery covered by the seal material. The sensor elements could be activated by the electrically conducting properties of the seal material, the force generated by the seal material, a chemical reaction with the seal, or the blocking of an orifice through which air was passing.



Discrete Seal Sensors

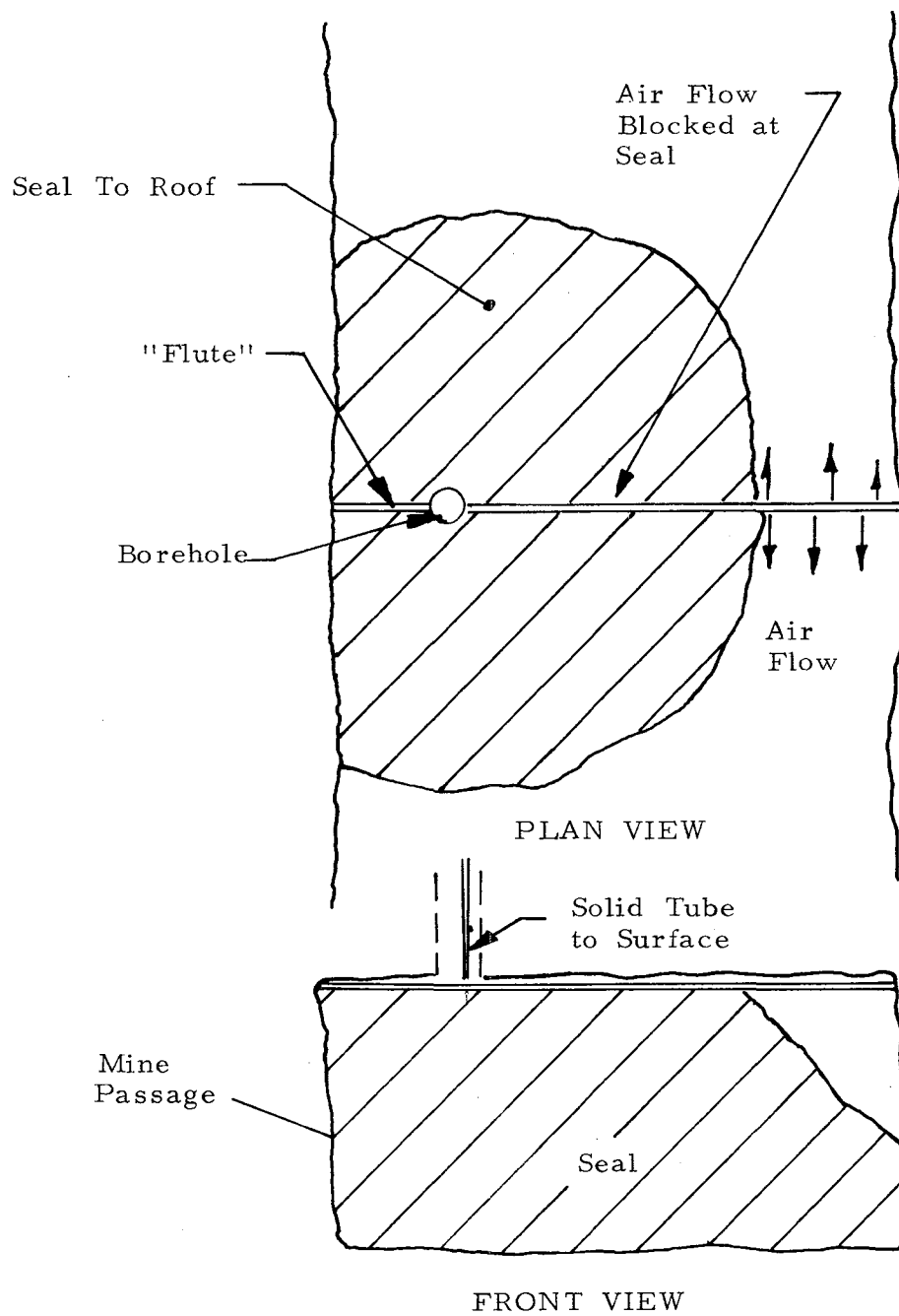
Figure 8

Independent of the details of sensor activation, the deployment of this seal checking concept as shown in Figure 9 is an extremely difficult task. The sensors must be supported near to, or in contact with, the ribs and roof of the passage to insure reliable indications of sealing. Accomplishing this for the range of passage sizes considered and the irregularity likely to be encountered would require an extremely sophisticated system.

4.4.2.2 "Flute" Seal Checker

The "Flute" concept employs a hollow tube which is deployed completely across the mine passage prior to the formation of the seal, as shown in Figure 9. Pressurization of this tube at low levels will produce air flow from the holes spaced along the length of the tube. As sealant material reaches the roof level, the holes become plugged, and flow through the tube decreases in proportion to the number of holes plugged. This decrease in flow indicates the completeness of the seal at the roof level. Complete blockage of the air flow would occur only when the seal was complete.

This concept relies on the fact that voids are far more likely at the roof than at intermediate locations or near the floor. The technique is deductive in that one assumes that a barrier which bridges at the roof level is an effective seal. This reasoning may be carried further to generate a checker which senses the presence of material only in the last place likely to be filled, the corners between the rib and the roof. The validity of these concepts will depend heavily on the characteristics of the sealant material and distribution technique selected. As with the other concepts, the deployment of the sensors is the most difficult task.



"Flute" Seal Checking System Deployed in Mine Passageway

Figure 9

4.5 Preliminary Evaluation

The review and evaluation of conventional and non-conventional techniques for establishing the effectiveness of remotely emplaced mine seals indicated that the most promising technique employs the active acoustic concept. This technique would provide the resolution to distinguish leakage paths of less than 1 percent of the total seal area. The sender and receiver are relatively simple, inexpensive devices which are reliable and consume minimal power.

The energy at low audio frequencies is sufficiently omnidirectional to penetrate torturous "holes" through seals, while attenuation at these frequencies will eliminate much of the flanking problem. A pulse gating system will eliminate the remainder of the signal which arrives via the longer flanking path.

The active optical approach was eliminated because of the "line of sight" behavior associated with energy in the visual spectrum. The signal which penetrated a torturous path would be considerably weaker than one penetrating through a straight path of the same cross-sectional area. This would create several problems in calibration of the system.

The "internal" concepts were eliminated because of the deductive nature of the conclusions drawn from the output and the practical problems associated with deployment of the sensor systems. The variety of the passage geometries and the irregularity of the surfaces require an extremely sophisticated deployment system. This was ruled out in favor of the simple deployment system of the acoustic checker system.

5. Development of Initial Probing System

5.1 Introduction

The preliminary evaluation of a variety of potential methods for initial probing showed that the optical system using closed circuit television (CCTV) and the sonar, or acoustic ranging, system were the most promising. The former is capable of providing a visual display of the mine passages in a clear, non-smoky environment, and the latter is capable of providing a map of the spatial location of the coal surfaces making up the entries, as well as objects, such as cribs, mining machines, etc., in the passages in both smoky and non-smoky environments. The sonar system used in conjunction with the CCTV in a clear environment can greatly assist in resolving the spatial distribution of objects seen on the TV screen. Further, in a smoky environment the interpretation of the sonar information could be facilitated if some visual information were also available.

CCTV systems exist but require some modifications to suit this particular application. The Industrial Hazards and Communications Division of the Bureau has an ongoing program for the development of such a CCTV system. Rather than duplicate this effort in developing a CCTV system, it was decided to evaluate the possibility of utilizing their system for initial probing, while continuing with the development of a system which would work in any environment, including the presence of dense smoke.

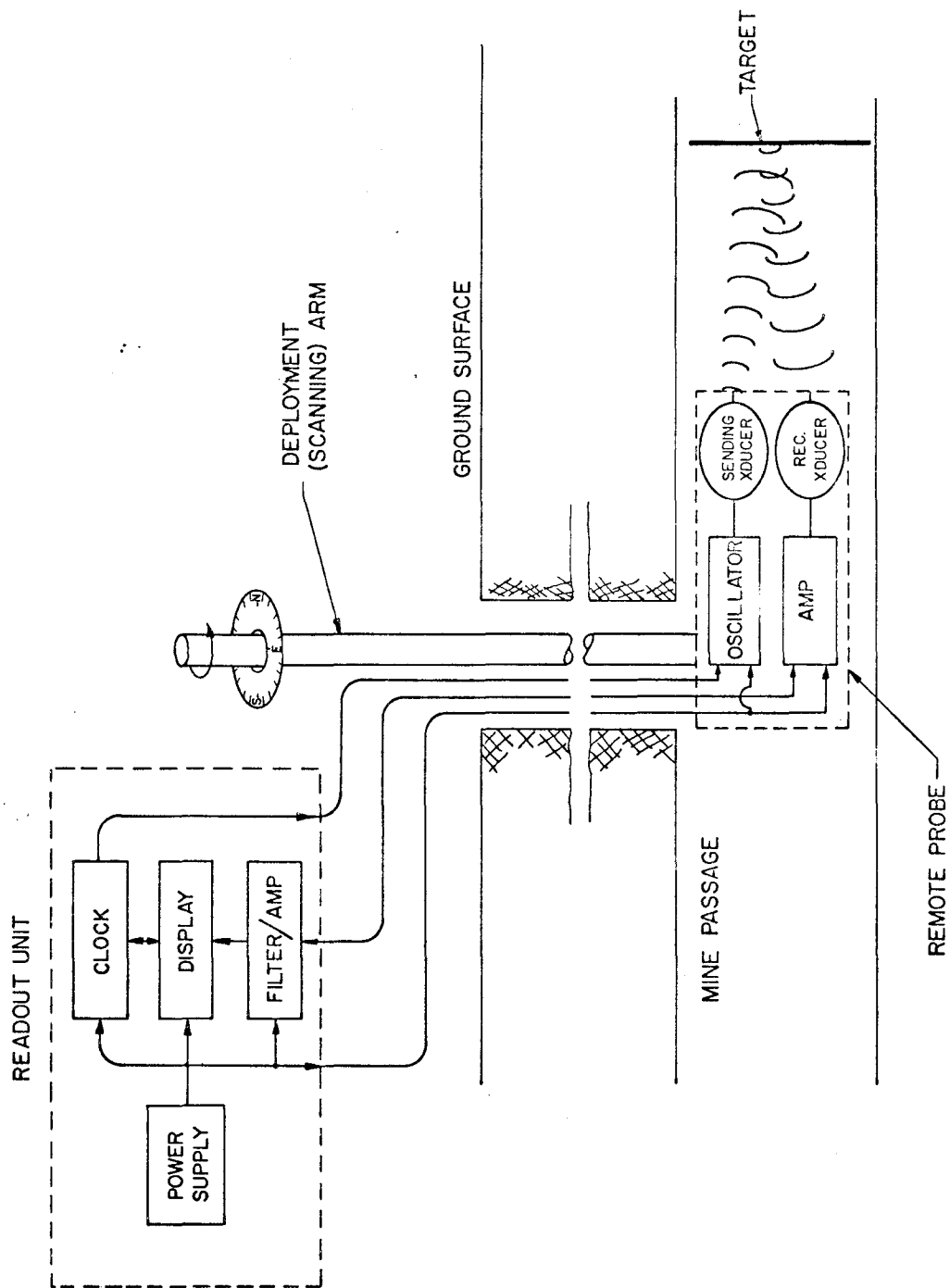
The concept of using sonar for the initial probing of mine passages represents the application of new technology requiring development. The results of such a development effort undertaken during the course of this program are described in the following sections.

5.2 Description of the Concept

The sonar probing concept is shown schematically in Figure 10. It consists of three major components:

- (1) The sonar probe containing the sending and receiving transducers and electronics for signal processing,
- (2) The information readout or display unit, and
- (3) The mechanical deployment and scanning system to orient the probe in the required direction.

The information readout unit serves two functions: it provides the display indicating the distance to the target in front of the remote probe and it contains the necessary power and synchronizing circuits to actuate the probe. In operation, the synchronizing circuit transmits a pulse to the probe through the connector cable. This pulse is used to trigger the frequency generator (oscillator) in the probe head, producing a burst of sound by the emitting transducer. The sound travels outward to the target, where some of it is reflected and returns to the probe. The receiving transducer picks up this reflected sound and converts it to an electrical signal. The signal is amplified and transmitted through the connector cable back to the readout unit. At this point, the received signal is filtered and further amplified. Because the electrical signals travel virtually instantaneously, the time lapse from transmission of the synchronizing pulse until the reception of the amplified return signal depends only upon the time required for the sound to travel from the sending transducer, bounce off the target, and return to the receiving transducer. A light then flashes on the display at a



Sonar System Block Diagram

Figure 10

position corresponding to the distance from the remote probe to the target as shown in Figure 11.

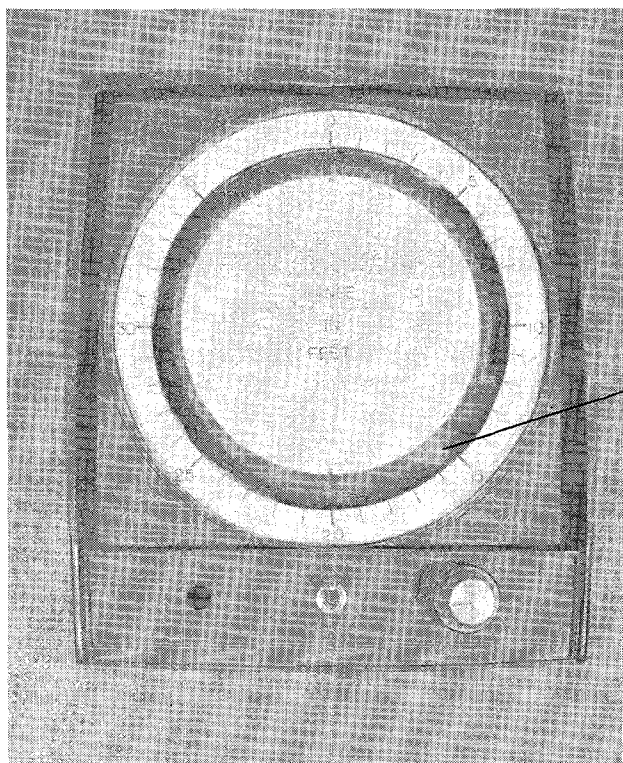
The remote sonar probe and its associated electronics are mounted in an aluminum housing as shown in Figure 12. Figure 13 illustrates the internal packaging of the transducers and electronics in the probe housing. The probe is lowered down the borehole into the mine passage at the end of a string of aluminum pipe. The pipe is suspended at the top of the borehole by a rotary table which can be rotated in the azimuth circle, and thus provides the direction scanning for the probe.

Conceptually, the operation of the sonar probing device is simple. The instrument is placed in the mine passageway and oriented in a known direction or compass bearing. The read-out unit displays the distance to the nearest object in front of the probe. In terms of the information received and the manner of operating the unit, the device is similar to a tactile probe: a tactile probe would telescope out horizontally until it hit an object. At this point the range of a target in one direction is known and the device is then rotated to a new compass heading where a new range is determined. Plotting the data obtained in a complete 360° sweep (in increments) produces a "map" of the area. The sonar device works in an identical manner, except that sound pulses are used instead of the telescoping arm.

5.3 Description of System Components

5.3.1 Electronic Circuit

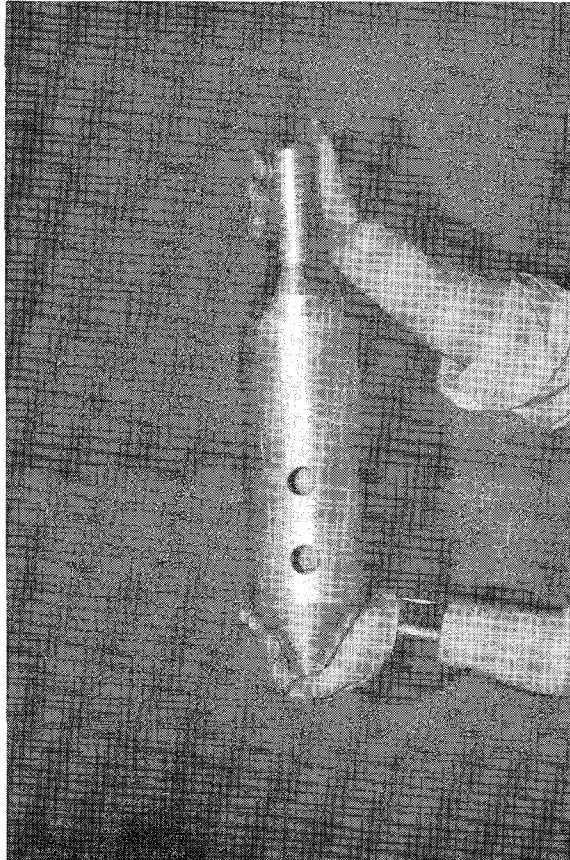
A schematic of the sonar system electronics is shown in Figure 14.



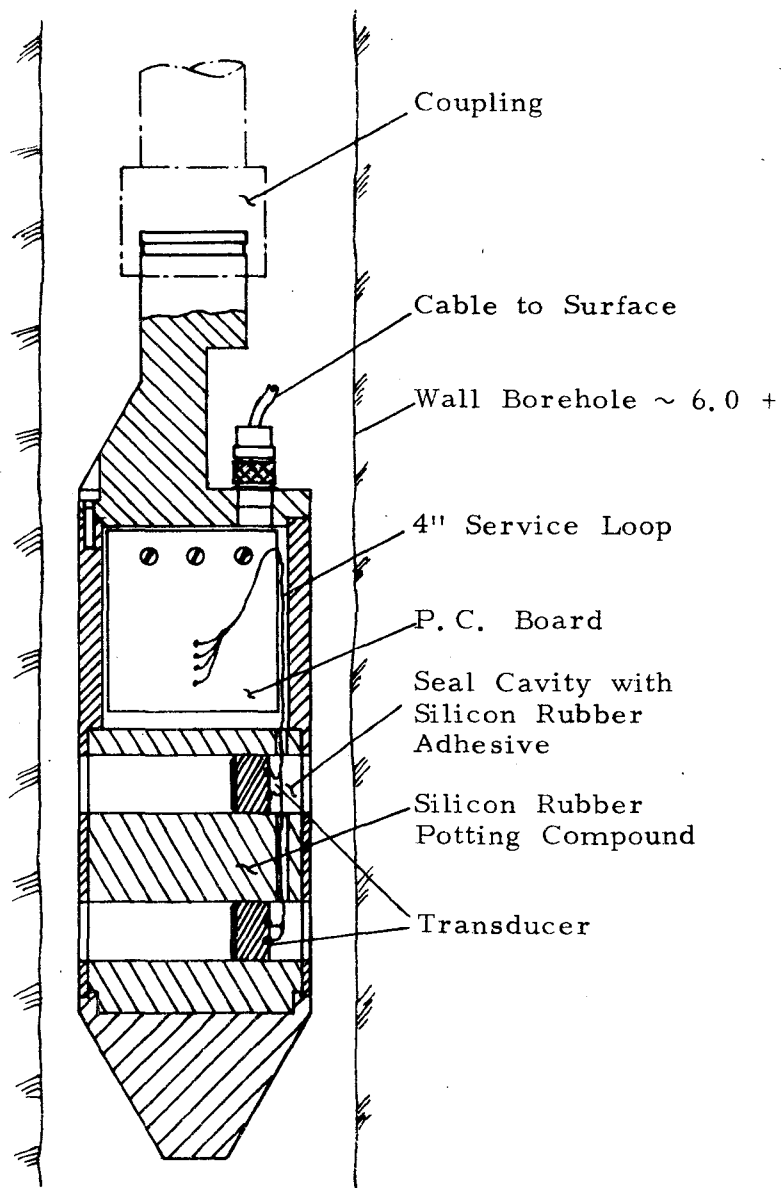
Flashing
Light

Sonar Display, with Flashing Light Indicating a Target at 15 feet

Figure 11



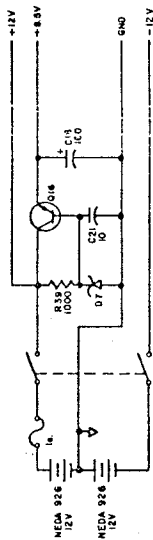
Sonar Housing
Figure 12



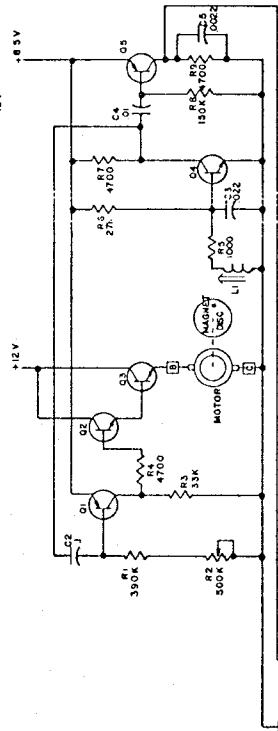
Cross Section of Sonar Housing

Figure 13

POWER SUPPLY (HEATHKIT)

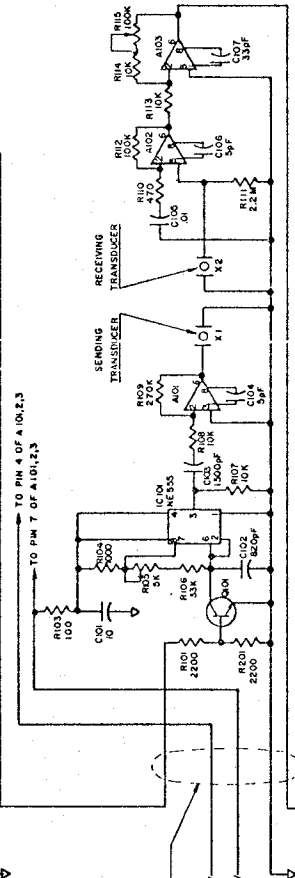


TIMING CIRCUIT (HEATHKIT)

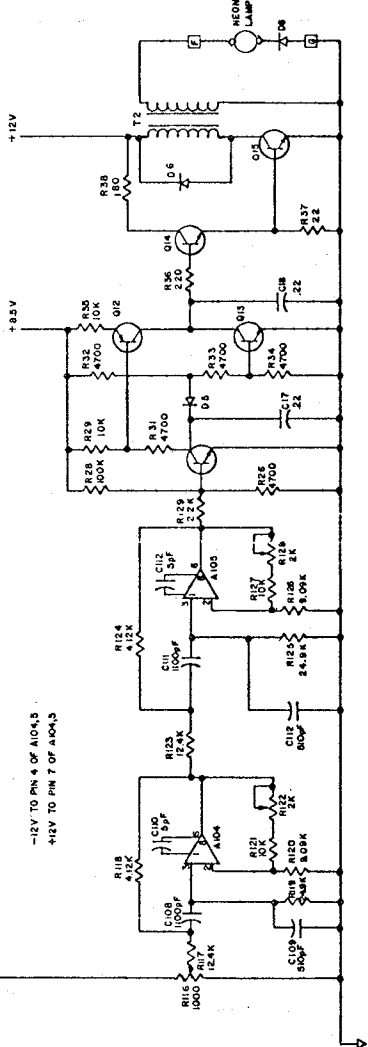


REMOTE PROBING HEAD

5 CONDUCTOR CABLE #20 WIRE
CAN BE UP TO 1000 FEET
LONG UNSHIELDED



PROCESSING FILTERS & (HEATHKIT) DISPLAY



Schematic of Sonar System Electronics
Figure 14

The readout unit consists of a Heathkit Model No. MI-1030 Depth Sounder display, modified for this application. The timing circuit portion of the unit generates a 1 millisecond pulse once every 36 milliseconds. This synchronizing pulse is transmitted through the cable to the remote probe. The return signal from the probe is attenuated by a variable resistor on the readout unit. This control, the only adjustment readily accessible to the operator, is used to provide just enough gain to see the primary reflection, so that secondary reflections and random noise are minimized for the operator.

The unit also contains two bandpass filters which amplify signals of the same frequency as the remote probe and attenuate any stray frequencies. The display portion of the readout unit incorporates a conventional neon light indicator, which is in widespread use throughout the marine pleasure-craft industry. Distance to the target is indicated on the circular dial by a light flashing next to the appropriate scale division. Figure 11 shows the display indicating a target at a range of 15 feet.

The remote probing head contains two ultrasonic transducers, discussed in Section 5.3.2, and the associated electronic circuitry. This circuitry is contained on a single printed circuit card, 2" x 3" in size. On this card are the transmitting oscillator and two receiving amplifiers. Turned on by the synchronizing pulse, the oscillator drives the sending transducer at a frequency of 23 KHz and an amplitude of 24 volts peak-to-peak. The two receiving amplifiers process the signal generated by the receiving transducer and relay the amplified signal back up the cable to the readout unit. The gain of the second amplifier is controlled by a variable resistor on the printed circuit card and may be adjusted to compensate for different lengths of cable.

Power for the entire sonar system is supplied by two dry-cell 12 volt batteries, N. E. D. A. code number 926, such as Eveready* No. 732 or Burgess* No. TW2. These batteries are enclosed within the readout unit.

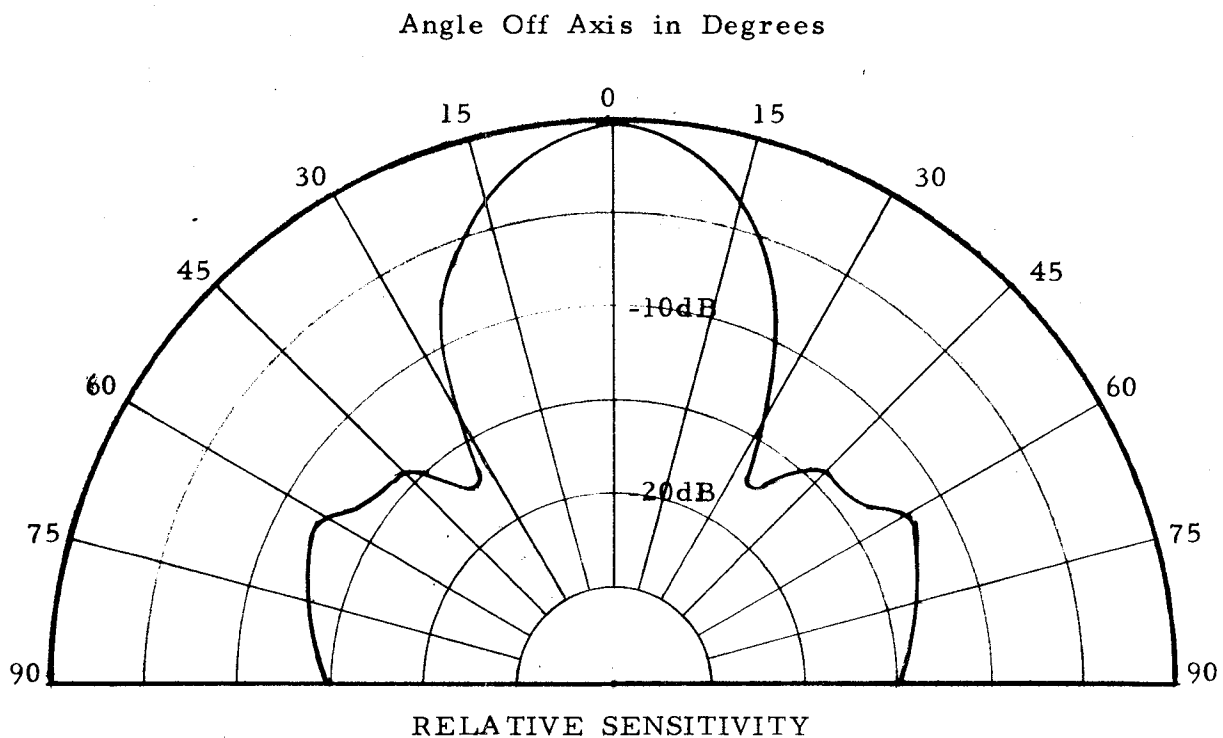
5.3.2 Transducer

The transducers used are Model TR89B manufactured by the Massa Corporation, Hingham, Massachusetts. For this application, the units were specified to have a natural frequency of 23 to 23.5 KHz. They are readily available; similar models are currently used in large quantities for the remote control units of television sets. The same transducer can function as either a sender or a receiver. The unit is small in size, 1-inch diameter x 1/2-inch thick and draws very little power, 35 milliwatts at a duty cycle of 3 percent for an average power consumption of about 1 milliwatt.

The major disadvantage of this unit is in its directionability, which is not as good as desired. As shown in Figure 15, the directional radiation pattern does not drop below -15 db for the entire forward direction of the transducer, $\pm 90^\circ$ off axis. Calculations using classical acoustic theory indicate that this performance is typical of a transducer of this size and frequency.

In practical terms, the import of this behavior is that the transducer is not only "looking" straight ahead but will also be sensitive to targets which are significantly off axis of the transducer. The problem is most acute when distant objects in a direct line become obscured by closer objects off to the side, as discussed in more detail in Section 5.4.2.

* Trade Name.



Directional Radiation Pattern at 23 KHZ
Massa Corp. Model TR89B Transducer

Figure 15

5.3.3 Permissibility Investigation

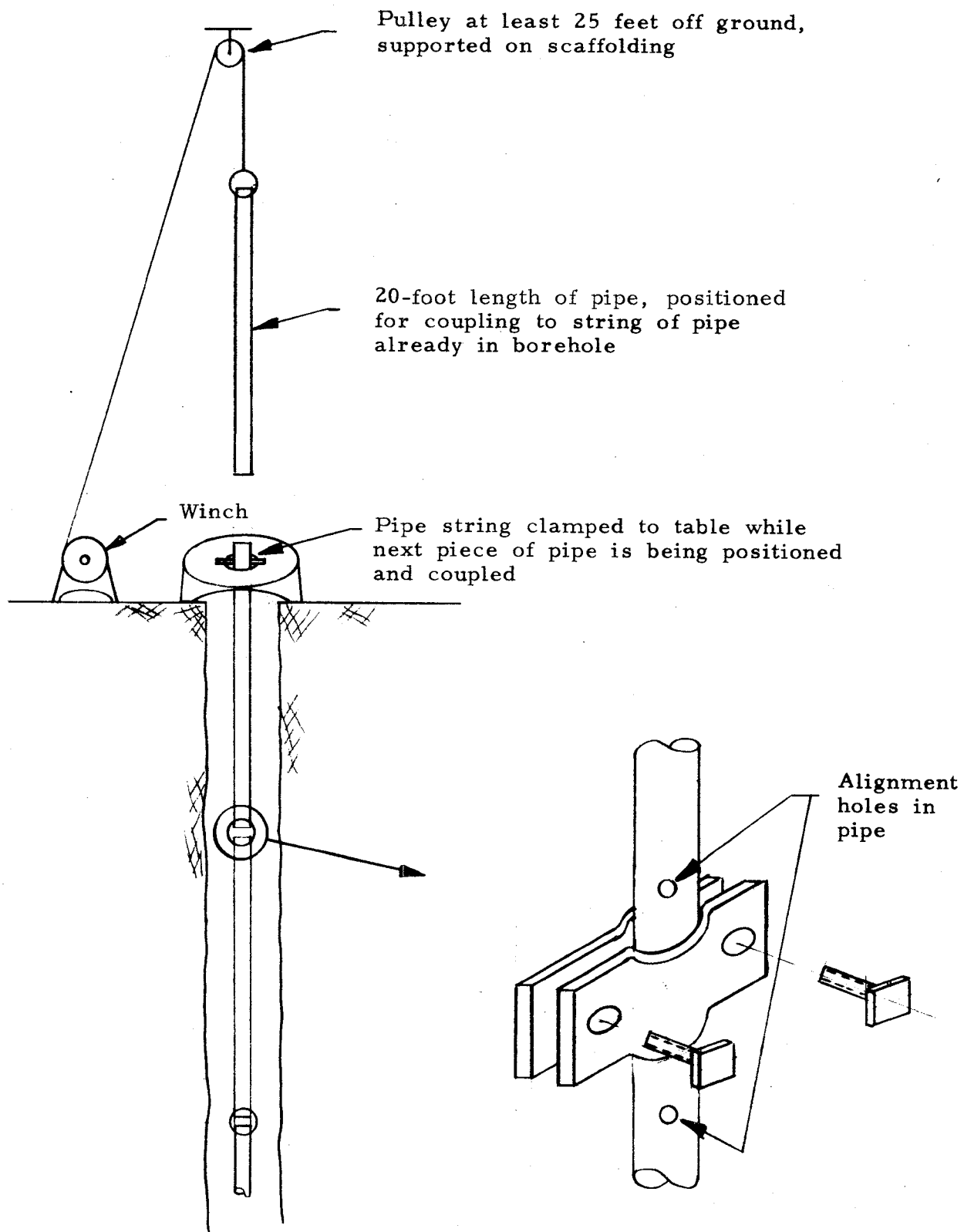
The Approval and Testing Group of the U.S. Bureau of Mines was approached for permissibility certification of the sonar device. Preliminary designs were submitted to the Bureau; however, it was not practical to proceed with formal certification until the prototype design was thoroughly established and field tested. Based upon discussions with the Approval and Testing personnel and the prototype schematics presented, Permit No. 193 was issued by the Director of the Bureau for the use and testing of the device at the test site at Federal No. 1 mine. It is expected that certification of the final design could now proceed without complication.

5.3.4 Sonar Probe Housing and Deployment System

A cross-section assembly drawing of the sonar probe housing is shown in Figure 13. The 4" diameter aluminum housing contains the two transducers and a printed circuit card. The top of the housing can be removed to provide access to the electronics. The lower portion of the housing is filled with silicon rubber, which is used to support the transducers and minimize direct acoustical coupling between the sender and the receiver. The groove on the top of the housing is used to connect to the 1-1/2-inch diameter aluminum pipe which holds the housing. An alignment hole is provided on both the housing and pipe to ensure proper orientation of the sonar probe with respect to the rotary table on the surface.

The probe lowering system consists of 20-foot sections of 1-1/2-inch aluminum pipe connected together with Victaulic* couplings as shown in Figure 16. To ensure proper orientation between the probe and the rotary table, the pipe sections were provided with alignment holes, so that pipe connections

* Trade Name.



Close-Up Sketch of Pipe-Coupling

Figure 16

could be made and the probe lowered without affecting the relative orientation. The procedure for lowering the probe is virtually identical to the standard technique used for lowering drill pipe. It is described in detail in Section 8.3.3.

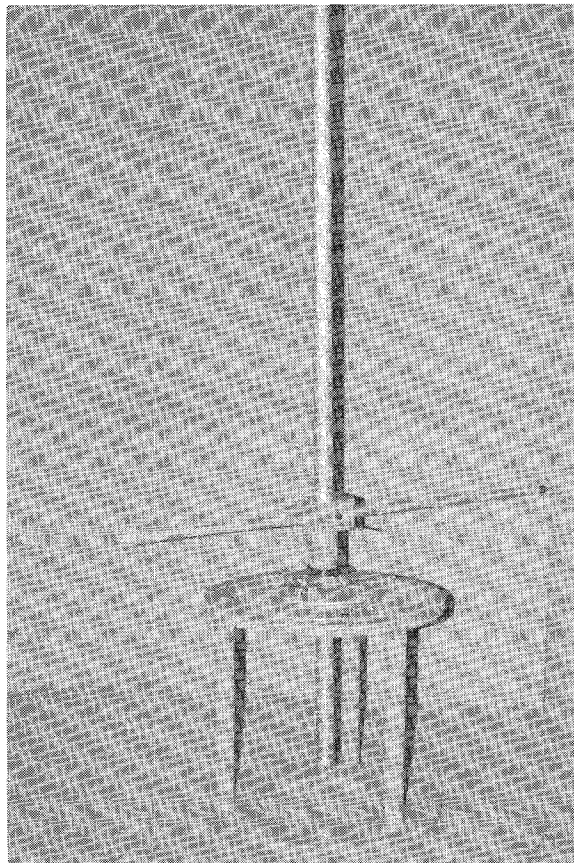
At the ground surface the pipe string is clamped to a rotary table. The table contains a 360° azimuth circle with a pointer which can be used to read the direction of the probe. The table has to be aligned with magnetic North prior to sonar probing of the passageway. Figure 17 shows a photograph of the rotary table.

The rigid pipe probe lowering and scanning system was selected over a cable-hung and servo-controlled down-hole scanning system in the interests of simplicity of design and reliability of operation. The rigid pipe system is slower and more cumbersome to deploy than a winch-operated, cable-hung system. However, the latter requires a remotely-controlled, probe-scanning system, the development of which was considered to be beyond the scope of this development effort. It is an item recommended for future development to reduce time of operation and increase ease of deployment.

5.4 Preliminary Testing

5.4.1 Testing at Foster-Miller Laboratory

Preliminary testing of the prototype sonar probe was conducted in the Foster-Miller laboratory facilities. These tests verified that the device could accurately determine the range of targets at distances up to thirty feet. It was also evident that reflections could be received from targets which were



Rotary Table Used in Sonar Probe Deployment

Figure 17

displaced as much as 30° from the axis of the transducers. However, for a realistic evaluation of the unit's capabilities, further tests were conducted in an actual mine environment.

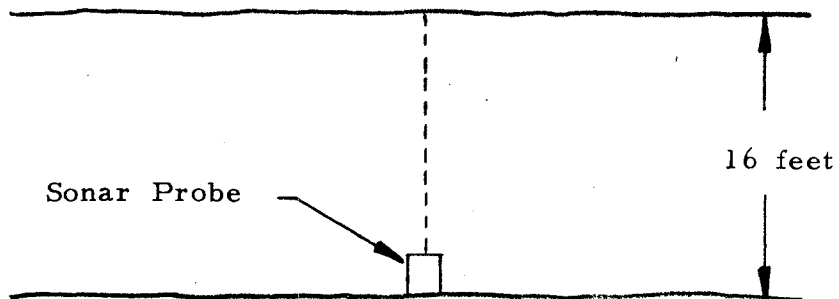
5.4.2 Investigations at the U.S. Bureau of Mines Experimental Mine

The first field testing of the prototype electronic design was carried out at the USBM Experimental Mine in Bruceton, Pa. For this testing the entire system was carried inside the mine. In this manner, the operator could read the display unit while also observing the same scene that the sonar transducers were "seeing". This experience provided much insight into how the sonar system would react to a wide variety of conditions.

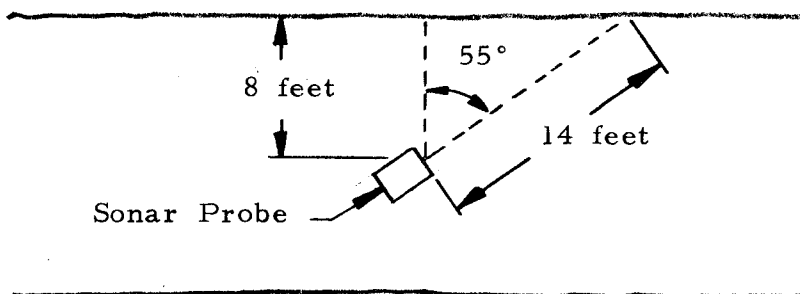
It was found that when looking directly at a coal rib with the axis of the transducer perpendicular to the rib, the readout was clear and accurate with no secondary reflections. This was true even with the probe placed next to one rib and looking 16 feet across the passage to the other rib, as shown in Figure 18 (a).

A second test evaluated the data obtainable from the readout unit when the probe was oriented in the middle of the passage but at an angle to the coal rib as shown in Figure 18 (b). It was found that a reflection of the rib could be obtained at an angle up to 55° from perpendicular, indicating a target distance of 14-feet. However, a secondary reflection was also evidenced, corresponding to the perpendicular distance from the probe to the rib of 8-feet.

As in the laboratory testing, it was found that the prototype sonar system could "see" at least 30 feet. However, due to the broad cone of sound emitted, objects in the thirty-foot range could be obscured by reflections from targets closer to the probe, even though these closer targets were not in the direct line



(a) Plan View of Passageway, Test No. 1



(b) Plan View of Passageway, Test No. 2

Figure 18

of sight. In one test, shown in Figure 19 (a), the probe was placed 30 feet from a coal face and 5 feet off the ground. In front of the face was a piece of mining machinery. Roof bolts in the passage were supporting several large pieces of steel channel, running perpendicular to the axis of the transducer. It was found that when the gain of the instrument was sufficiently increased to "see" the coal face, reflections could also be seen from the mining machine and the steel channel roof supports, as shown in Figure 19 (b).

The following conclusions were drawn from the tests performed:

- (1) Range of the device is at least 30 feet.
- (2) Lack of sufficient directionability in the transducers at times can cause ambiguous or misleading readings.
- (3) The surface of a coal rib is sufficiently rough to provide reflections of incident sound waves even when the axis of the sending transducer is 45° from perpendicular to the rib.
- (4) Mining machinery can be detected on the display.

In summary, the results of this testing indicated that the sonar probe would be a valuable tool for use in the remote "mapping" of local passageway geometry. However, considerable care would have to be taken by the operator in evaluating and interpreting the data received.

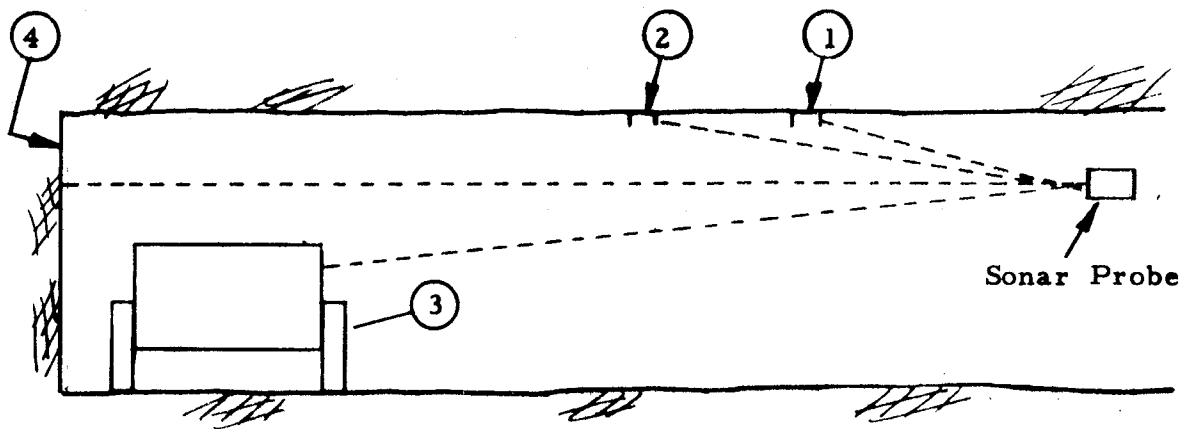


Figure 19 (a)

Longitudinal Cross Section of Blind Passageway

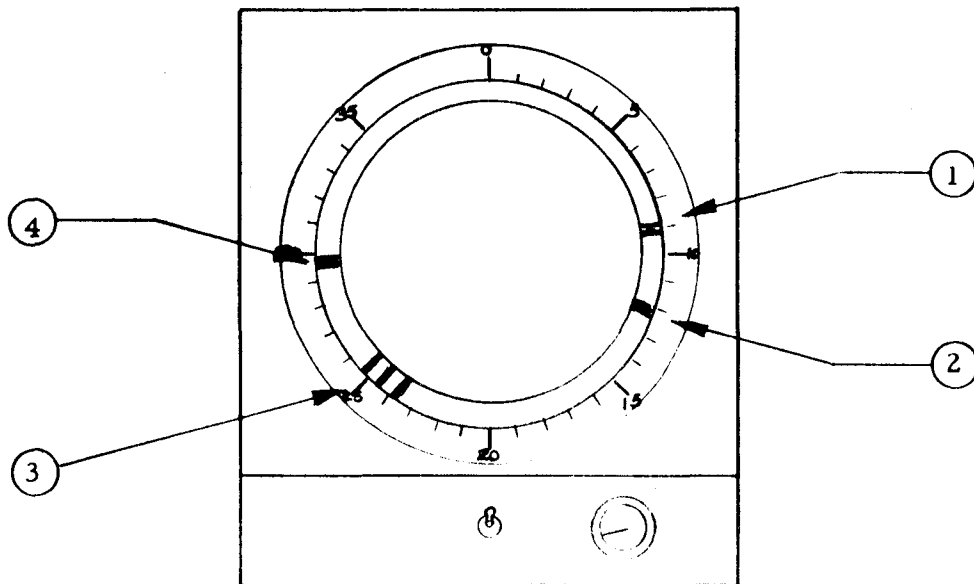


Figure 19 (b)

Simulated Display, Showing Simultaneous Reflections
from Targets Identified in Figure (a) Above

6. Development of Mine Sealant Material Systems

6.1 Introduction

The preliminary evaluation of material systems described in Section 3 led to the selection of the following four promising systems for further development:

System A: Aggregate, Fly Ash System

System B: Aggregate, Fly Ash, Urethane
Foam System

System C: Aggregate, Bulkhead, Light
Expansive Concrete

System D: Aggregate, Self-Supporting
Thick Slurry

Preliminary laboratory tests indicated that the building of effective bulkheads from one borehole would be extremely difficult. Two extra boreholes would be required adding to the overall cost of the system and making the system less attractive. Tests with light expansive concrete showed that bulkheads would be required, the material would not support itself. As a result, further development of this system was terminated.

Foam concrete was selected as the most suitable material to be developed into a self-supporting, rapid-setting slurry. A laboratory investigation of its use for mine sealing was conducted during this program; the results are summarized in Section 6.5 and details of the laboratory program are presented in Appendix B.

The development of the fly ash mine-sealing technique and the urethane foam seal topping process are described in detail in this section. The basic development of the fly ash seal technique is for a mine with no water flow. Modification of this technique to make a water-tight seal in the presence of water flow required the development of a gravel-grout technique for initial water holding and bulk filling with a fly ash cement mixture to retain water. The laboratory development of this technique is also described in this section.

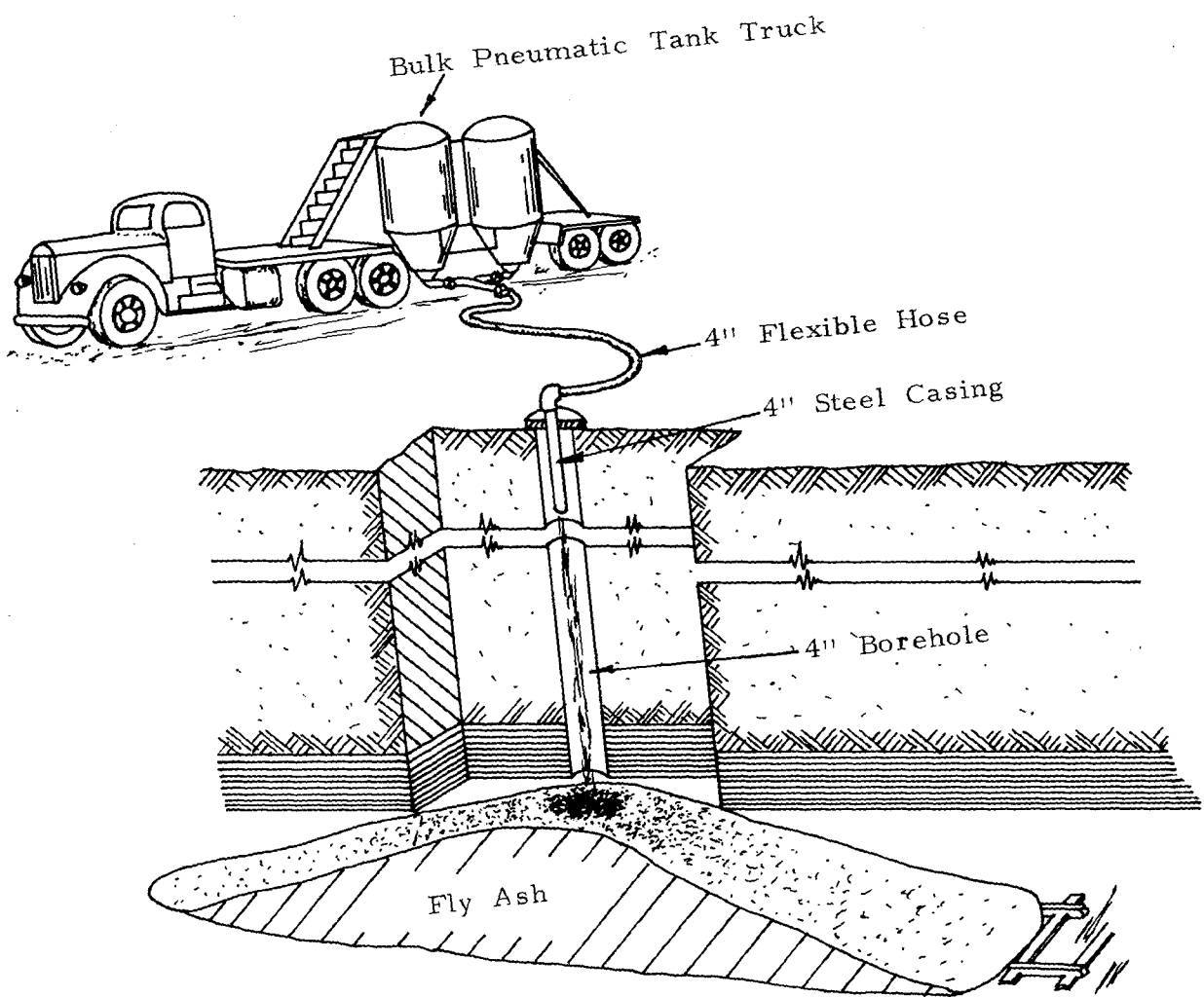
The laboratory tests consisted essentially of studying the process of sealing mine passages using a quarter-scale mine-passage geometry. Some preliminary tests were done with a 1/40-scale mine-passage model. The foam-topping tests were done in a full scale mine passage mockup as scaling of this expanding, time-setting material was not possible.

6.2 Development of Fly Ash Mine Sealing Technique

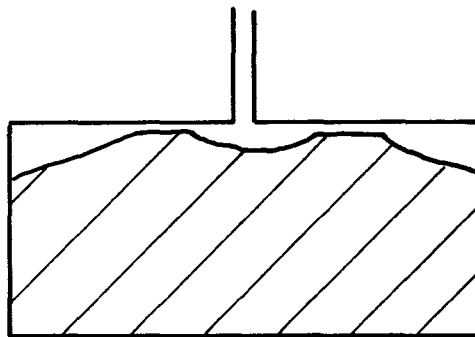
6.2.1 General Description of Fly Ash Sealing

The systems being evaluated for mine sealing using fly ash envisage its use either as a total seal or as a bulk filler to be topped with urethane foam as the final seal. In either case the fly ash material must be distributed through the borehole in a manner which produces a pile that is capable of both filling the passage corners and providing a geometry suitable for foam topping. The technique must avoid flow conditions which are likely to lead to premature plugging of the borehole.

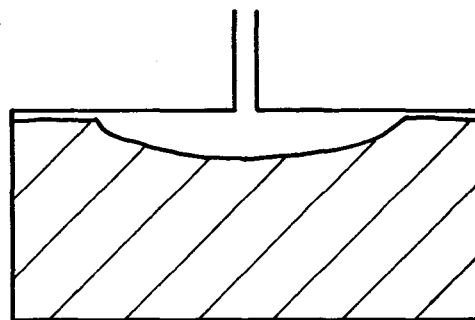
As described in Section 3.6.1.1 of this report, fly ash is generally supplied to the mine site in a bulk hauler and discharged in a fluidized state using the air supply integral with the bulk hauler. Previous tests using fly ash for mine sealing, ⁽⁵⁴⁾ as well as present day operations of sealing fires in abandoned coal mines ⁽⁵⁵⁾, utilize the system shown in Figure 20 where the fly ash truck discharges the fly ash into the borehole using only the air supply available on the truck for fluidization and pumping. Typical discharge rate from these trucks is approximately 1 ton of fly ash per minute at an air flow rate of 300 to 350 cfm resulting in a solids loading of approximately 50 pounds of solids per pound of air. This is 'dense phase flow' of fluidized fly ash and as such is sensitive to choking and plugging in long lines. This phenomena is described in Appendix A, Borehole Flow of Fluidized Fly Ash. For high solids loading and low air flow rates, a conical pile is formed directly beneath the borehole. This can cause premature plugging of the borehole. In addition the corners of the passage remain open because of the shape of the pile and consequently a good seal is not possible. This is shown schematically in Figure 21a.



Conventional Technique for Pneumatic Injection of Fly Ash⁽⁴⁾
Figure 20



(a) Small Crater



(b) Large Crater

Possible Seal Cross Sections

Figure 21

At low solids loadings with high air flow rates, the solids are distributed in a different manner. The air jet produces a large crater under the hole and pushes the fly ash to the sides of the passage so the corners are sealed first. This technique fills from the outer edges inward, producing excellent sealing geometries. Figure 21b shows the formation of a fly ash seal with high air flow rates. The seals are broad and flat containing craters which aid the foam topping procedure.

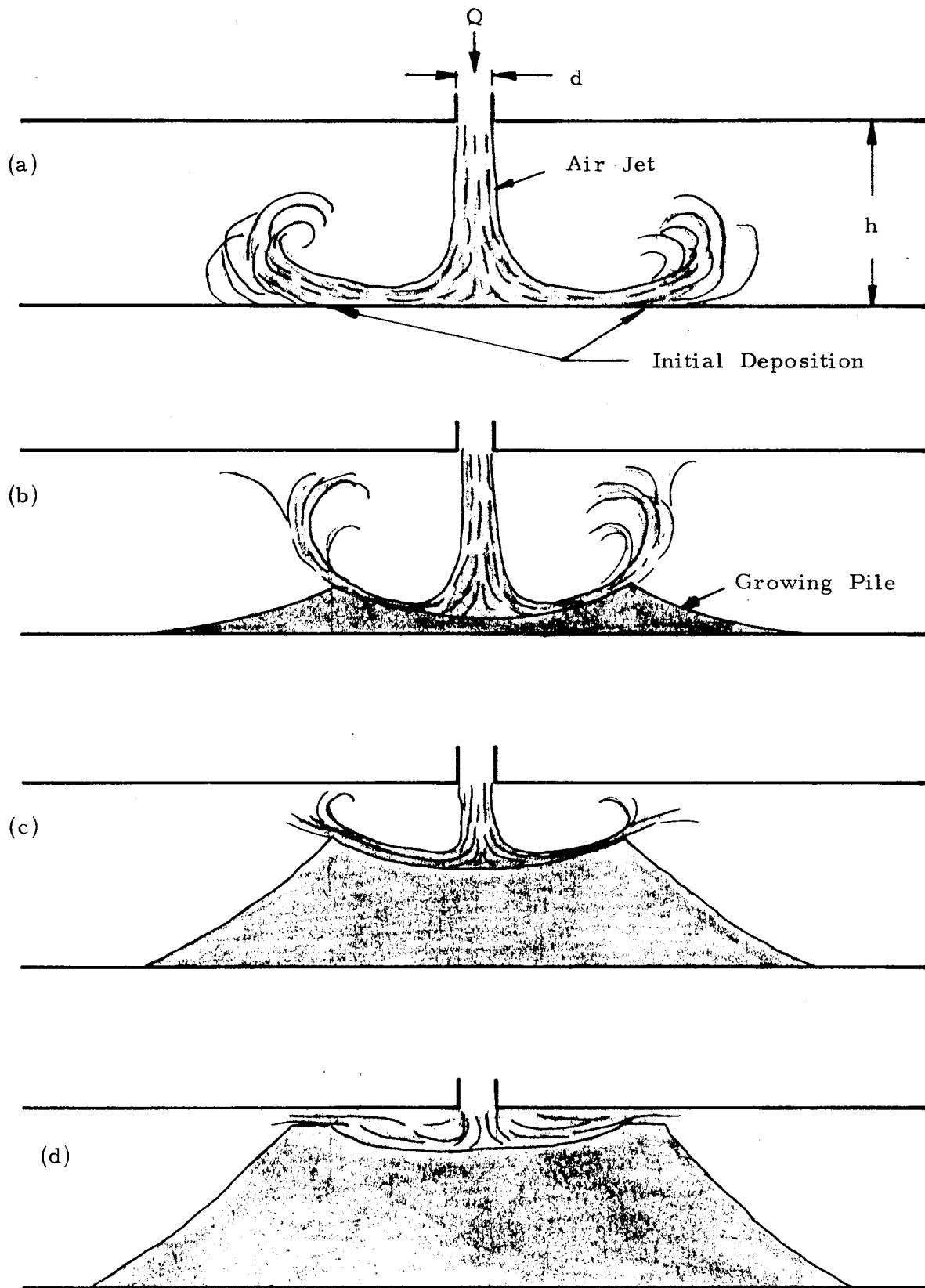
Rubble piles beneath the borehole strongly interfere with the formation of the pile from the dense phase and result in premature plugging. With high air flow the crater spreads beyond the rubble and the effect on the overall geometry is small.

The theoretical description of the physical phenomena associated with the flow and deposition of fly ash during the development of a complete fly ash seal is extremely complicated. Consequently, a laboratory test program was conducted to develop a physical understanding of fly ash sealing for a variety of mine sealing conditions. Based on these test results, suitable sealing relationships were developed from which the design air flow rate can be selected for any different mine sealing operation.

This section describes the results of the laboratory development of mine sealing techniques using fly ash in the absence of water. The effect of water flows on mine sealing is described in Section 6.3.

6.2.2 Development of Scaling Relationships for Fly Ash Sealing of Mine Passages

A similitude analysis of fly ash sealing is presented in Appendix C. The analysis is based on the physical model of fly ash sealing shown schematically in Figure 22. This



Formation of Fly Ash Seal

Figure 22

figure shows the air flow pattern at different stages of the seal and the resulting fly ash deposition.

Deposition is defined by the settling velocity of the fly ash particles and the magnitude and direction of the air velocity in the neighborhood of the borehole. Fly ash consists of a spectrum of particle sizes having settling velocities in the range of 0.1 to 5 ft/sec. The small particles will be carried further away from the borehole while the coarser ones will be deposited near the borehole. The nature of air-borne fly ash deposition is very similar to the deposition of water-borne sand the particles remain in suspension until the velocity of the medium becomes low enough to allow the settling of the particle to dominate.

Referring to Figure 22 it can be seen that the initial air flow field defines the beginnings of a crater-like formation, Figure 22 (a). The formation of the crater changes the air flow pattern by making it conform to the already deposited contour. This process tends to smooth out passage irregularities and results in the formation of a reproducible, symmetric pattern, following the mold of the initial crater, Figure 22 (b) and (c). The final stages of the seal are governed by the flow of air between the crater crest and the passage roof, Figure 22 (d). This results in the flattening of the crater crest and the spreading of the flanking slopes of the seal.

The model of Appendix C assumes that this basic seal formation can be simulated for different mine passage geometries and scales by adjusting the air flow rate. The development of this air flow rate scale factor is described in Appendix C. The results show that for similitude the air flow rate must be scaled by the passage width to $5/2$ power i. e.,

$$\text{Air flow rate} \propto (\text{Passage Width})^{5/2}$$

Accordingly, 80 cfm at 1/4-scale is equivalent to 2500 cfm at full-scale.

6.2.3 Purpose of Laboratory Test Program

The purpose of the test program was to observe the development of a fly ash seal in a passage and to analyze its dependence on

- (a) Passage geometry
- (b) Air flow rate
- (c) Solids flow rate
- (d) Borehole diameter
- (e) Borehole location
- (f) Presence of rubble piles

The program was conducted in two phases. The first phase of testing utilized a 1/40-scale table top model of a mine passage. This served to illustrate some of the basic phenomena and determine the range of parameters to be considered in the subsequent 1/4-scale model testing. The second phase involved an extensive test program utilizing a 1/4-scale model of a mine passage where the effect of the specified parameters on mine sealing was investigated. These tests provided a realistic picture of the development of the fly ash seal and the necessary confidence to scale this phenomenon for an actual mine.

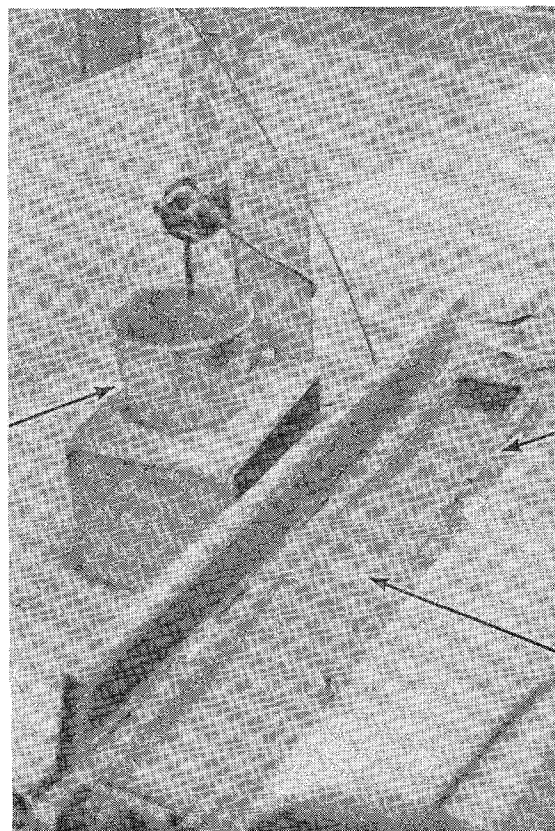
6.2.4 Description of 1/40 Scale Laboratory Tests

The table top, 1/40th scale mine passage model and fly ash air feeding system is shown in Figure 23. The fly ash in the bucket was delivered into an air line with a motor mounted screw feeder. The air was obtained from a shop compressor, and the flow rate monitored with an air flow meter measuring a range from 0 to 1.3 scfm.

Figure 23 also shows the resulting seal configuration for an air flow rate of .65 scfm. Figures 24 , 25 , 26 and 27 show configurations for other flow rates. The principal observations from these tests are the following:

- (a) A seal formed by air-borne fly ash is accompanied by the formation of a crater, the diameter of which increases with increased air flow rate.
- (b) When the seal is almost complete, the air escapes from the borehole through thin channels in the fly ash. The channels increase in size with higher air flows.
- (c) The slope of the seal is maximum at the crater rim (about 20°) and gradually tapers off at the extremes.
- (d) When the seal meets the roof, it begins to spread as a flat-topped pile out radially from the borehole.

Fly Ash
Feeder

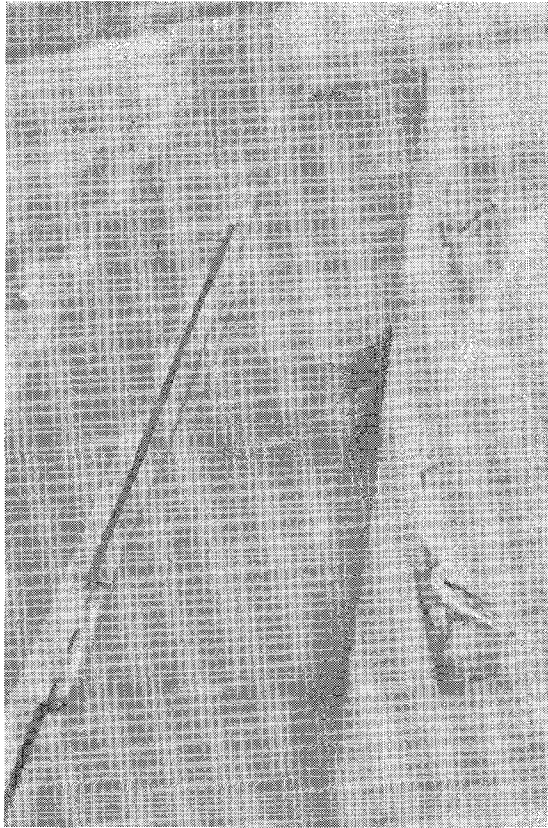


Simulated
Mine
Passage

Fly Ash Seal
With Crater

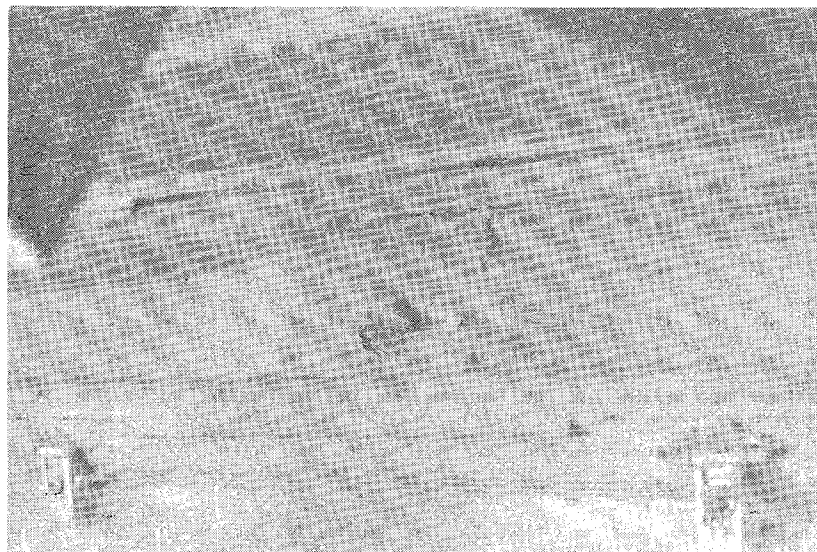
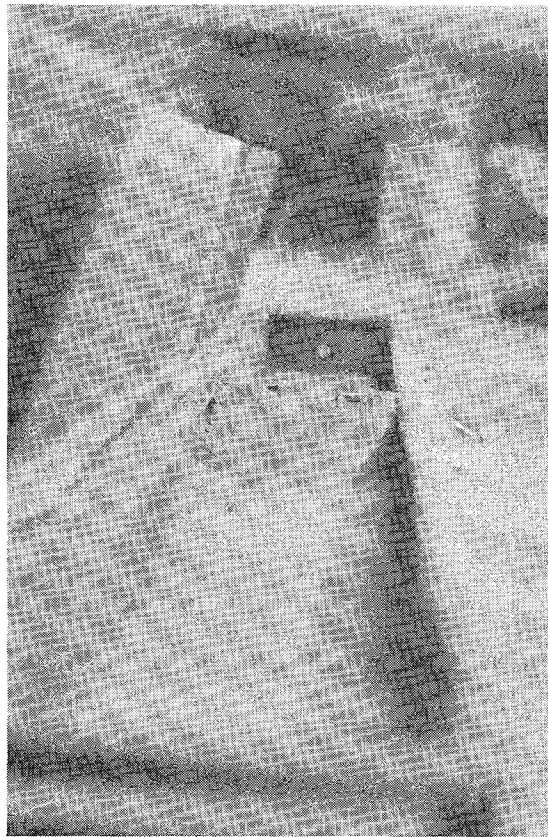
1/40 Scale Fly Ash Test Facility

Figure 23



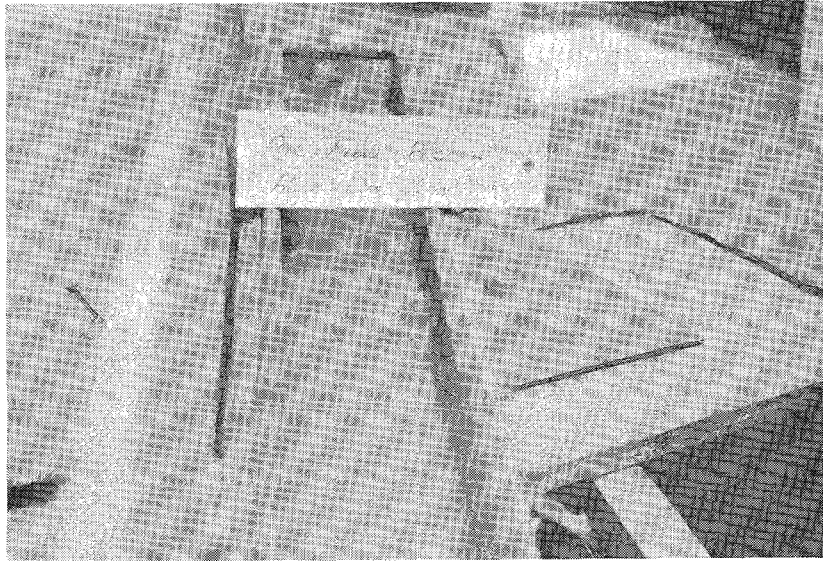
1/40 Scale Seal Configuration at .4 scfm

Figure 24

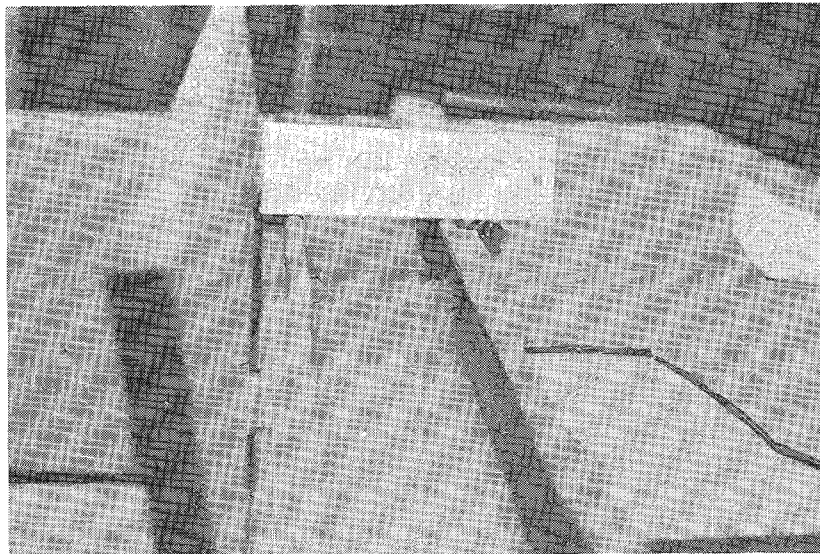


1/40 Scale - Roofed Seal at .4 scfm

Figure 25



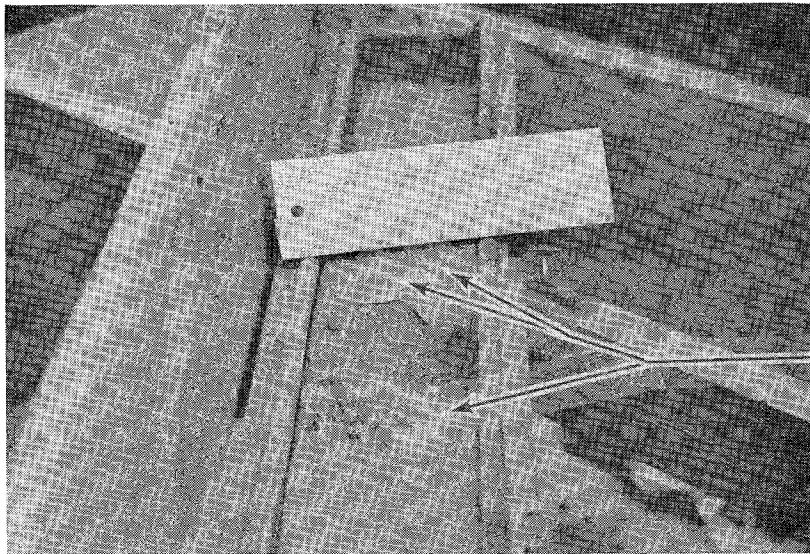
(a) Hole at Side



(b) Hole in Center

1/40 Scale Seal Configuration at .13 scfm

Figure 26



Formation
of Air
Channels

1/40 Scale - Final Sealing at .4 scfm
Borehole at Side of Passage

Figure 27

6.2.5 Description of Fly Ash Distribution Tests with 1/4-Scale Mine Passage Facility

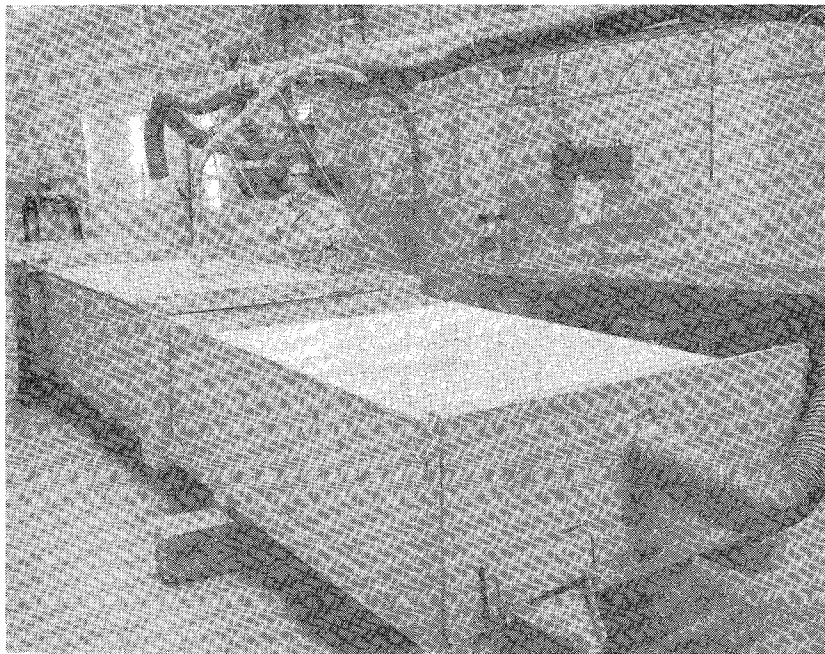
6.2.5.1 Description of Facility

Figure 28 shows the 1/4-scale simulated mine passage. It consists of a plywood box 25-feet long x 4-feet wide x 1-1/2-feet high, representing an actual mine passage approximately 6-feet high and 16-feet wide. The center of the box has a removable lid for periodic observation of the developing seal. The fly ash was exhausted at both ends to the outside atmosphere through 6-inch diameter Flexhaust* hoses.

The box is provided with Lucite* panels for flow visualization. However, fly ash deposits on the Lucite* make any meaningful flow visualization practically impossible. The panels did allow for some visibility of the fly ash cloud, demonstrating the considerable fluid turbulence accompanying seal formation. The spillway at the near end of the box was opened for water flow tests in Section 6.3.

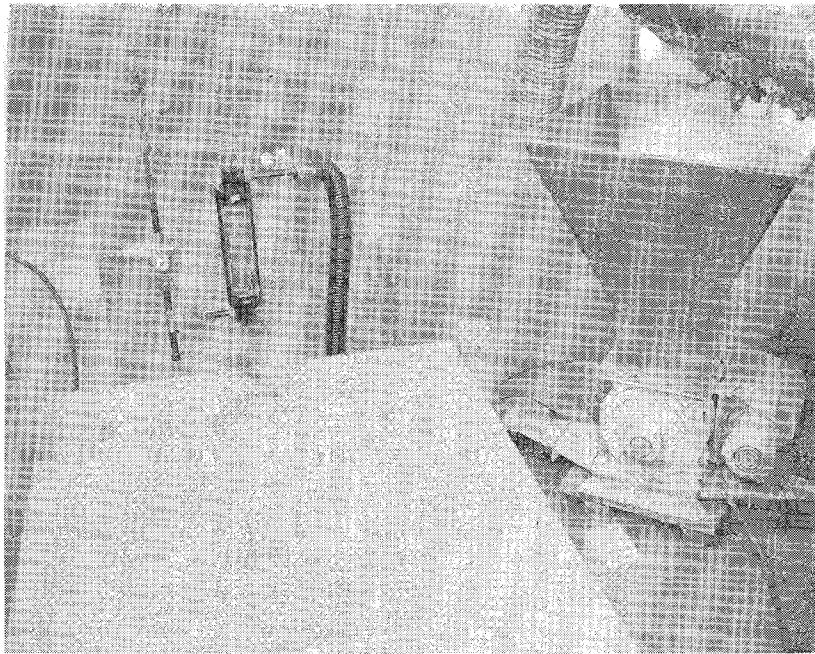
The components of the air - fly ash delivery system are shown in Figure 29. The principal component of this system is the rotary air lock solids feeder commonly used for the pneumatic transport of granular solids. Fly ash in the hopper falls by gravity into the rotating vanes of the airlock where it is fluidized with air and transported into the simulated passage through a 2-inch I.D. flexible hose. The vanes of the airlock are at extremely close tolerances to the walls of the cylinder in which they are turning, so that the air does not escape back into the hopper. The air flow into the system was measured by the air flowmeter shown in the figure. Based on the scaling of the 1/40-scale model results, the meter range was selected to be 100 scfm maximum.

* Trade Names.

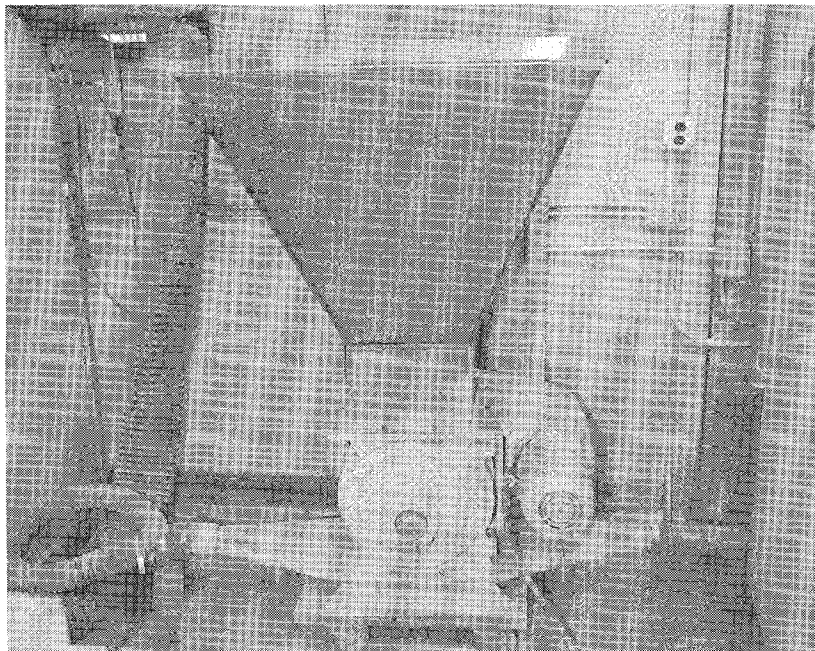


Simulated Mine Passage - 1/4 Scale

Figure 28



(a) Fly Ash Pneumatic Delivery System



(b) Rotary Airlock with Hopper

Air Fly Ash Delivery System

Figure 29

A pressure regulator placed before the flow meter kept the supply pressure at or below 10 psi. Air was supplied by a 200 scfm, 100 psi compressor, located externally to the laboratory.

The tap into the end of the simulated passage shown in Figure 29 (a) is for the introduction of water. Water flow was measured by the water flow meter, shown on the left in Figure 30. This meter measured flows from 0 to 10 gpm.

6.2.5.2 Test Program

The test program included the following range of parameters:

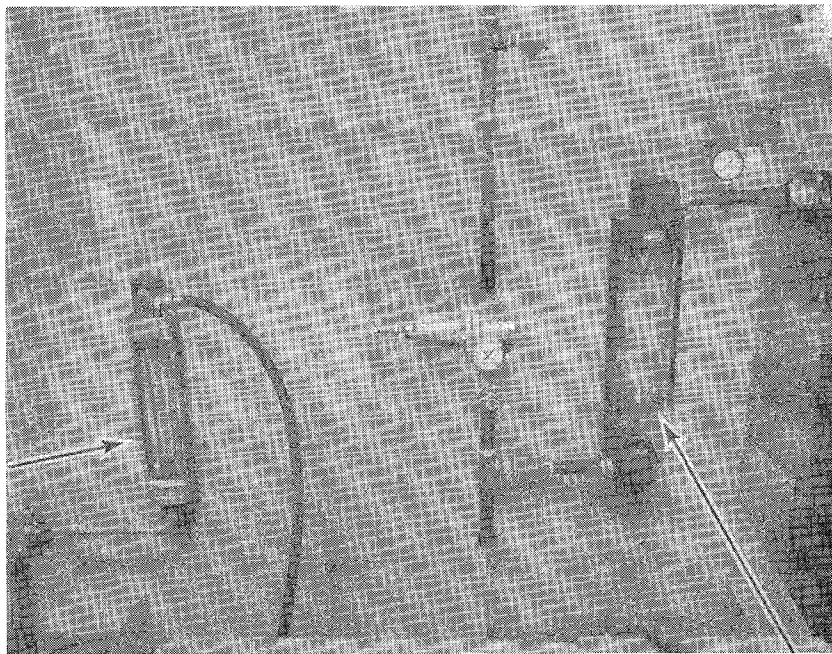
(1) Air Flow Rate - Tests were conducted primarily at 40 and 80 scfm. It was found that these flow rates defined two basic behavioral regimes in terms of crater formation.

(2) Fly Ash Flow Rate - The air lock, which was an off-the-shelf-item, was modified by filling the vanes with urethane foam to produce a fly ash flow rate of approximately 25 lbs/minute.

(3) Passage Cross Section - The interior of the simulated passage was filled with foam boards to alter the cross section dimensions. Passage width was varied from 3 to 4 feet, and passage height varied from 3/4 to 1 1/2-feet.

(4) Nozzle (borehole) Diameter - The outlet diameter of the pipe delivering fly ash into the simulated passage was varied from 1-1/8-inch to 1-1/2-inches. This was to determine if the use of a restricted high velocity nozzle (for a given air flow) would produce a more favorable seal geometry.

Air
Flow Meter



Water Flow
Meter

Measurement of Air and Water Flows

Figure 30

(5) Passage Tilt - A test was conducted with the simulated passage at a 4° tilt. For all other tests the passage was horizontal.

(6) Seal at an Intersection - Tests were conducted at a simulated 3-way intersection to determine the applicability of the seal technique to this configuration.

(7) Rubble Pile - A pile of gravel was preplaced under the fly ash inlet hole to investigate the influence of a rubble pile on the fly ash seal geometry.

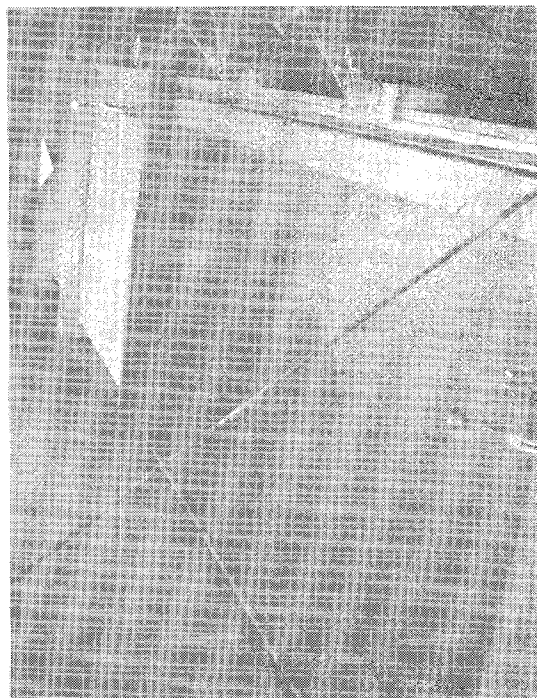
6.2.5.3 Results of 1/4-Scale Fly Ash Distribution Tests

1. Effect of Air Flow Rate

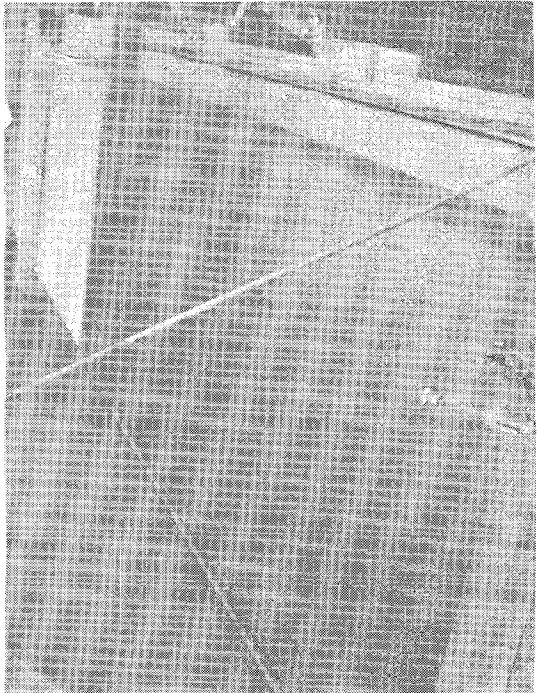
Figures 31 and 32 show the sequential seal formation for air flow rates of 40 and 80 scfm respectively. Typically, the lower flow rate produced a small crater which converged to a flat-topped cone. Continued pumping beyond this point caused the top to spread, but plugging occurred before the passage corners were filled. The higher flow rate produced a larger crater, which developed a flat rim when it reached the roof. This rim then spread in thickness, creating a ring-like seal which included the passage corners. As long as the flow was maintained at 80 scfm, plugging did not occur. Continued pumping of fly ash at this flow rate caused further spreading of the flat rim. Finally, the air flow was gradually reduced, filling up the crater and finally plugging at 20 scfm. Figure 32 (d) shows the result of this procedure.

2. Effect of Passage Depth

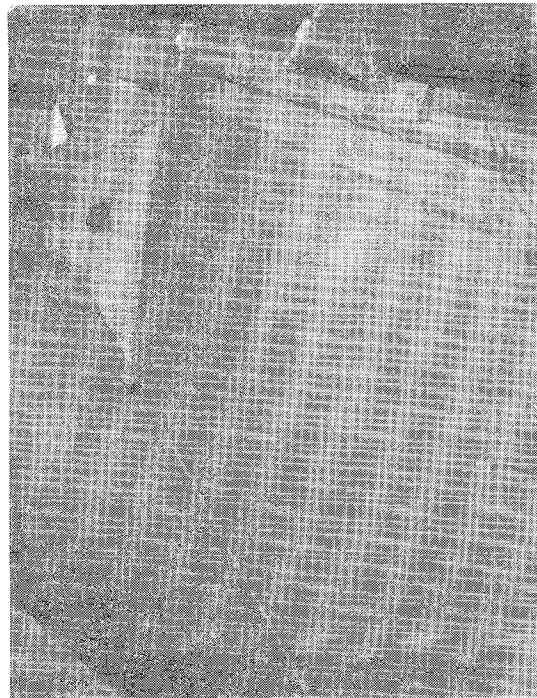
Figure 33 illustrates two



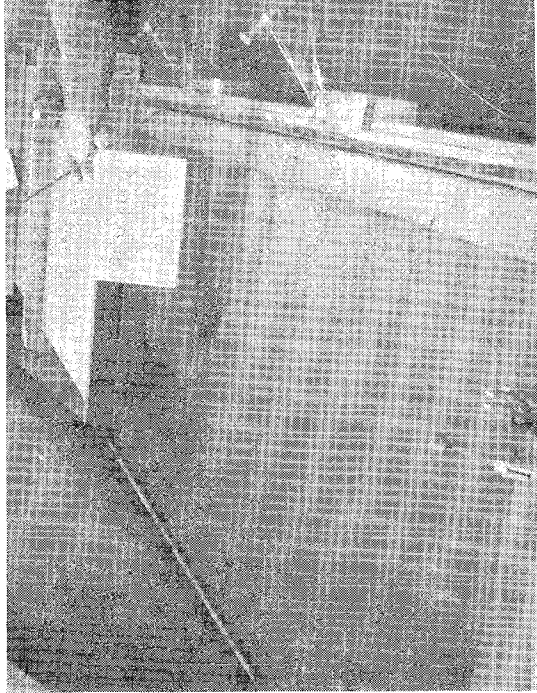
(a)



(b)

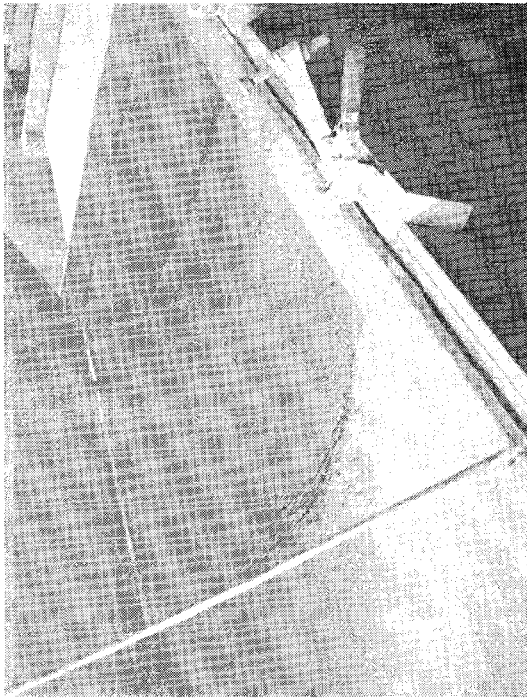


(c)

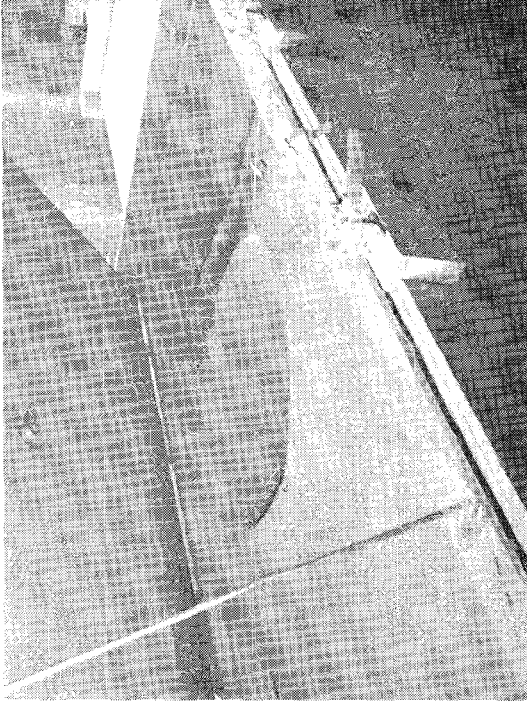


(d)

$\frac{1}{4}$ Scale
Fly Ash Seal, 40 scfm
Figure 31



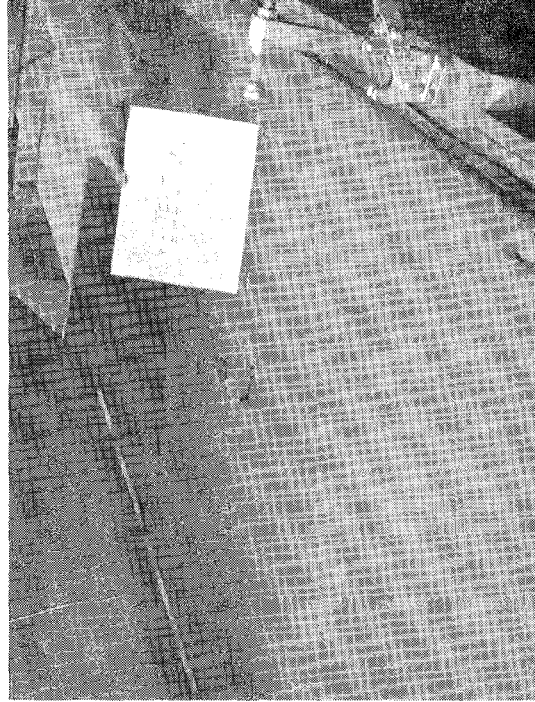
(a)



(b)

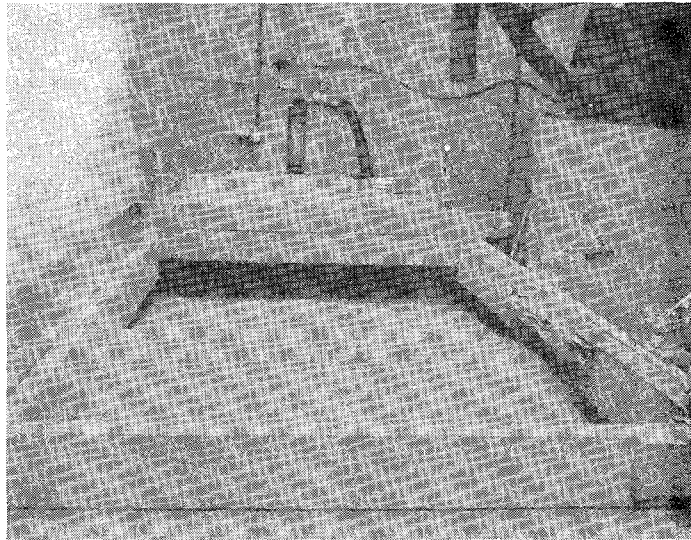


(c)



(d)

$\frac{1}{4}$ Scale
Fly Ash Seal at 80 scfm
Figure 32



(a) Depth = 9"



(b) Depth = 15"

Effect of Passage Depth: Passage Width 3 1/2'

Figure 33

identical tests at 80 scfm, the only difference being the passage depth. The results show two completely different types of craters. Figure 33 (a), for the shallower passage shows a circular flat-topped crater similar to those of Figures 31 and 32. Figure 33 (b), however shows an elliptical crater with peaks at the passage walls. The deeper passage produces a more favorable seal geometry.

3. Effect of Borehole Location

Tests similar to that shown in Figure 31 were conducted with the entry hole at the side of the passage, and in the neighborhood of an intersection. Figures 34 and 35 show the results of these tests. As can be seen, the diameter and shape of the crater is relatively unaffected by the location of the borehole. These photo sequences also indicate the ability of the seal rim to spread to a thickness of approximately one crater diameter. Figure 34 (c) shows the spreading of the seal to the opposite corner of the passage, and Figure 34 (d) shows the final seal which resulted from gradually cutting down the air flow from 80 to 20 scfm. Note the air channels in Figures 34 (c) and 34 (d). These are produced by the escape of the inlet air between the fly ash pile and the passage roof.

4. Influence of Passage Tilt

The 1/4-scale passage was propped up at one end to produce a 4° slope. Figure 36 shows the seal which developed under these conditions. The arrows in the figure indicate the direction of downward slope.

The most interesting observation was that the slope of the seal flanks with respect to the passage was the same as for a level passage. Also of interest is the



(a)



(b)



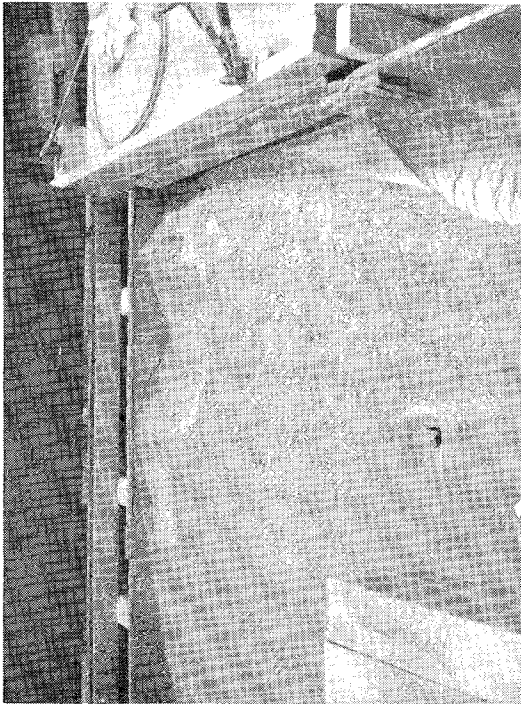
(c)



(d)

Seal at 80 scfm, Hole at Side, Passage 1' x 3'

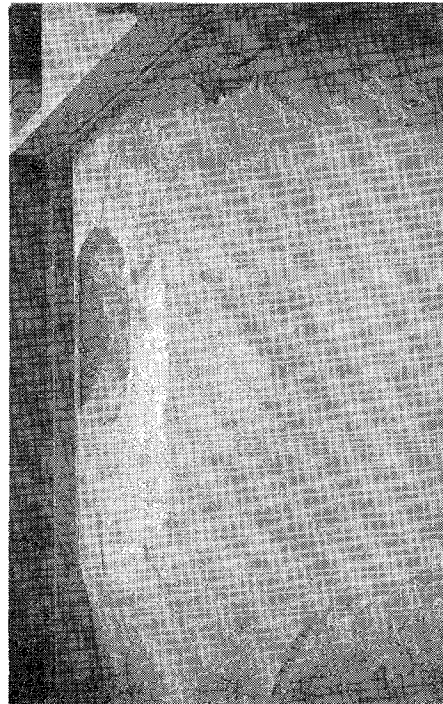
Figure 34



(a)



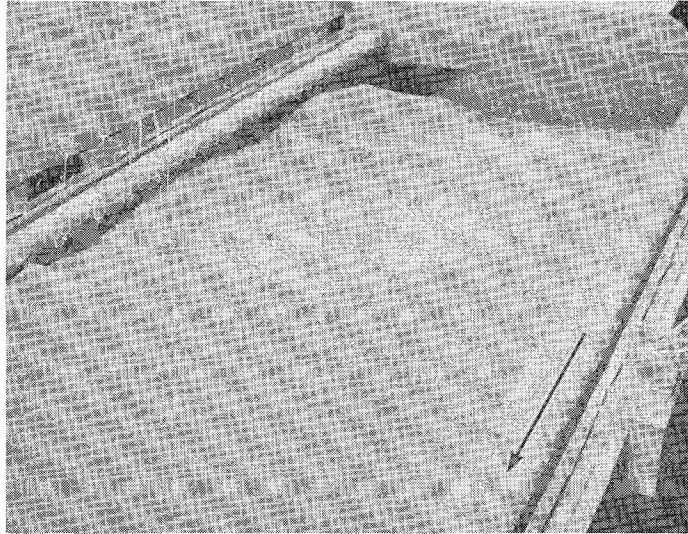
(b)



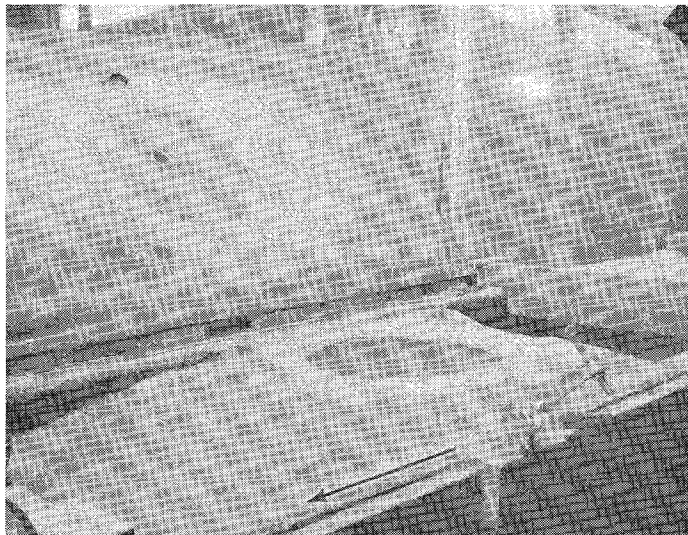
(c)

1/4 Scale Seal at 3-Way Intersection

Figure 35



(a)



(b)

Fly Ash in Passage Tilted 4°

Figure 36

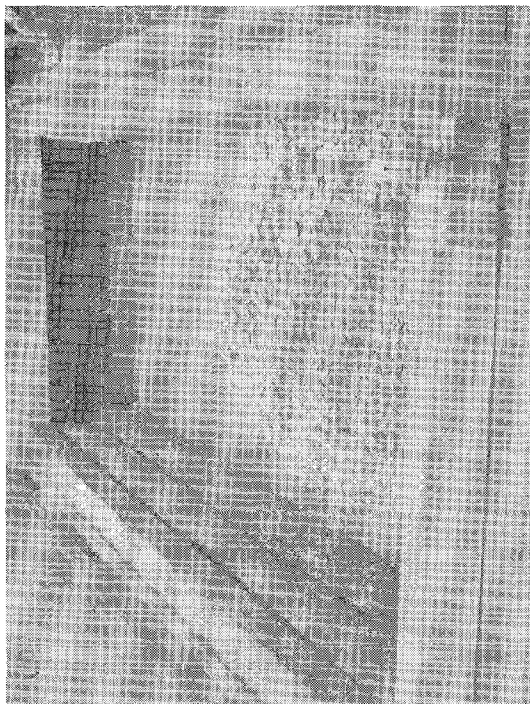
shift of the crater center upstream of the borehole, as can be seen in the roof imprint of Figure 36 (b). One procedural drawback of this test was that the inlet pipe tilted along with the passage, an occurrence which would not be representative of a vertical borehole. The small angle, however, may not be significant.

5. Influence of Rubble Pile

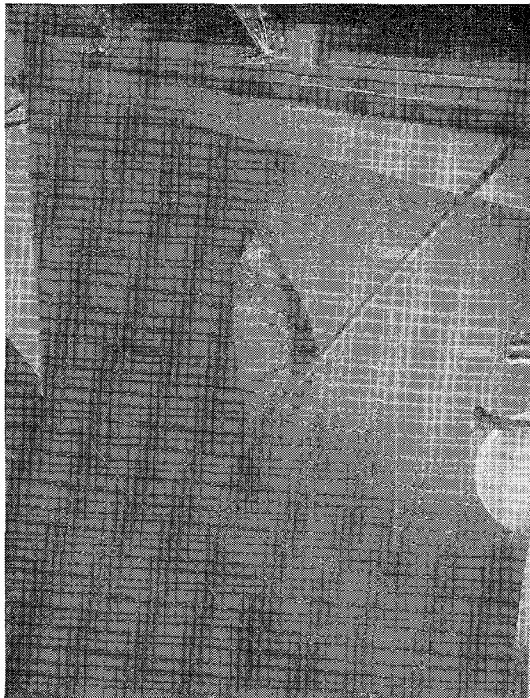
A pile of 1/2-inch gravel, 12-inches high, was placed in the 18-inch high passage to represent a pile of rubble or gob, as shown in Figure 37 (a). Fly ash was then delivered at 80 scfm. The resulting crater formation is shown in Figures 37 (b) and 37 (c). The air force turned out to be strong enough to form a crater in the gravel as well as in the fly ash. Although this result was not considered to be representative for mine rubble, it was felt that the presence of rigid rubble would serve to spread the fly ash, and hence would not have a detrimental effect on the fly ash seal. The test was not repeated.

6. Use of a Deflector

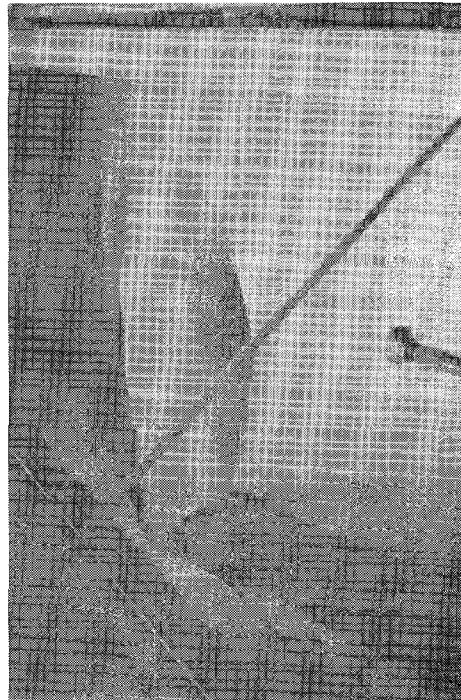
It was anticipated during the lab program that the 80 scfm results would require about 4000 scfm in the field test at Federal No. 1 mine since the passages were about 20-feet in width. In order to reduce the air flow requirement, tests were conducted with a deflector at the end of the nozzle. The deflector was designed to assist the fly ash distribution so that good distribution could be obtained at a lower air flow rate than that required for cratering. Figure 38 shows the deflection device tested. The deflector is disc placed 1/2-inch to 1-inch beyond the fly ash outlet pipe. It was assumed that the deflector would be deployed through the borehole, and hence it was the same diameter as the outlet pipe.



(a)



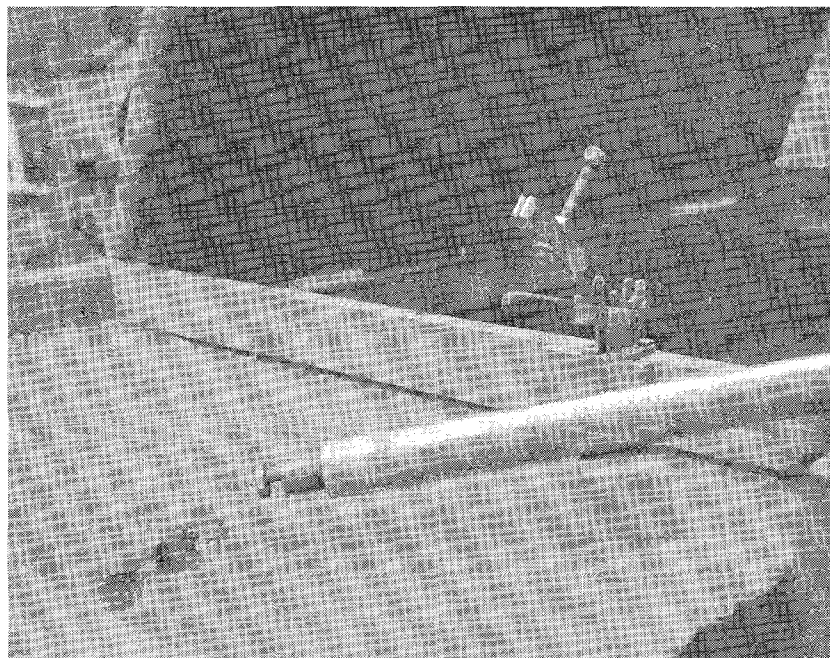
(b)



(c)

Seal With Rubble Pile

Figure 37



Fly Ash Deflection Device

Figure 38

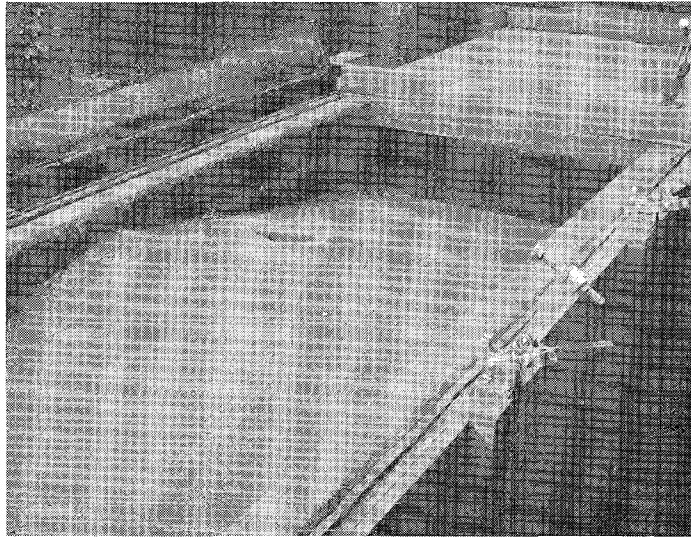
Figures 39 (a) and (b) show the developing and final seal respectively for a flow rate of 40 scfm. Note the improvement in final seal over the 40 scfm result shown in Figure 31 without the deflector. The improvement, however, was not sufficient to guarantee a complete seal, as can be seen on the left hand side of Figure 39 (b). No further development work on this concept was performed.

6.2.6 Discussion of Results

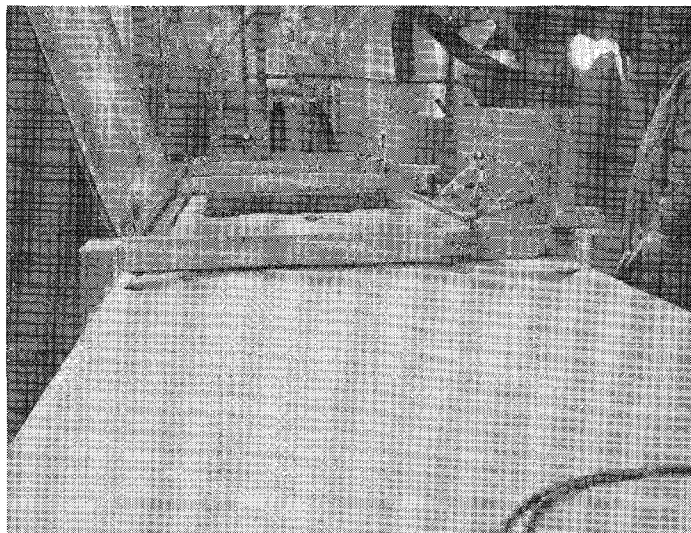
6.2.6.1 General Features of Seal

The 1/4 scale fly ash program indicated that the critical parameter defining the quality of the seal is the air flow rate. Low air flow rates, similar to those used in previous fly ash sealing techniques, produce a conical fly ash pile, which roofs and then spreads laterally away from the borehole until plugging occurs. The higher the air flow, the more spreading occurs before plugging. High air flows produce a crater, whose rim roofs and then spreads as shown in Figure 32. The greater the air flow, the wider the crater. If the crater is as wide as the passage, as shown in Figure 33 (b), the seal is formed in the most desirable manner, i.e., from the corners inward. If the crater is smaller than the passage width, Figure 34 (b), the roofed rim will spread to the corners, Figure 34 (c). The larger air channels which result at the higher air flows make premature plugging unlikely. The cratered seal with air channels can be filled in by a gradual reduction in air flow, as shown in Figures 32 (d), 34 (d).

The following observations were made regarding the relationship of crater size and shape to passage height and borehole diameter.



(a)



(b)

Development of Seal with Deflector at 40 scfm

Figure 39

(a) For a given air flow rate a lower height to width ratio results in a smaller crater, Figure 33 .

(b) A uniform increase in the length scale of the model, including borehole diameter, changed the crater rim shape from a well defined plane circle, Figure 32 (b) to an ellipse with raised corners, Figure 33 (b). As will be discussed later, the phenomena described above were also observed in full scale field tests.

In our opinion these two different types of craters are the result of different physical phenomena. The initial crater shape is dependent on the jet velocity and is thus independent of the passage width. The subsequent fly ash seal development is dependent on the air flow rate and the air flow distribution in the passage thus making it strongly dependent on passage dimensions.

All of the laboratory tests conducted at 80 scfm produced seal configurations which were considered to be acceptable for the full scale test program. Plugging never occurred at this flow rate, and, as far as could be seen, the roofed portion of the seal could be extended indefinitely. It seems reasonable to expect, however, that a seal width would be reached when plugging occurs, and that this width increases with increasing flow rate. In the case of 80 scfm, this limit was never reached.

6.2.6.2 Slope Angle of Fly Ash Seal

The flanking slopes of the seal were concave upward with maximum slope at the crater rim. All test observations indicated that the slope of the fly ash depended on the settling of particles and not on a natural angle of repose. This is particularly evident in the results for the tilted passage.

Cohesiveness in the fly ash permitted angles of up to 70° to form on the inside of the crater. Such slopes would eventually topple due to disturbances. It was found, however, that the maximum stable slope obtainable was between 16° and 20° , and this range was typical for the side slopes of the developing fly ash pile. Once the fly ash roofs, the roofed portion begins to spread and the air-fly ash mixture jets out of channels in the roofed portion. This results in a settling pattern which tends to flatten the flanking slopes.

6.2.6.3 Volume of Material

The total amount of material required increased considerably in the final increments of the sealing process. For example, the pile shown in Figure 32 (b) (90 percent seal) required 3 hoppers of fly ash. Three more hoppers were required to achieve 99 percent seal, Figure 32 (c). Thus, the volume of fly ash for making a 99 percent seal was essentially double that required to make a 90 percent seal where the air flow rate is kept essentially unchanged. There is no noticeable increase in air pressure as this portion of the seal is being made. Hence without this feedback it is not possible to know without any external instrumentation the quality of seal achieved. Thus estimates of fly ash quantities for achieving a 99 percent plus fly ash seal would have to be on the conservative side.

Two possible methods can be used to reduce total fly ash volume and time for sealing:

- (1) Suitable control of air flow rate to make the final seal. After achieving the 90 percent seal the

air flow rate would be decreased at a gradual but controlled rate to make the final seal. To make this system effective would require continuous and good feedback information on the rate of buildup of the fly ash seal.

(2) The use of an expanding frothed foam topping on the 90 percent seal presents an attractive alternative to doubling the amount of fly ash. Cost and time trade-offs for using foam versus fly ash are presented later in Section 9.

6.2.6.4 Scaling

The phenomena observed in the 1/40-scale model were reproduced at 1/4-scale by scaling the volume flow rate of air by the width of the passage to the 5/2 power. The ability to make such an extrapolation increased the confidence that similar correlation would occur with a full-scale mine passage.

6.2.7 Conclusions

The conclusions of the laboratory program to test the distribution and seal formation of air-borne fly ash can be summarized as follows.

- (a) The fly ash forms a crater whose diameter can be made to reach the passage width by supplying a large volume of air.
- (b) Under the above conditions, a 100-percent fly ash seal can be consistently formed without the possibility of premature plugging.

- (c) The cratering phenomenon can be scaled by a factor of 10, implying that the 1/4-scale results will be applicable to a full-sized mine passage.
- (d) The slope of the fly ash pile with respect to the passage depends on the settling distribution of particles and is unchanged when the passage is tilted. Typically the fly ash pile had a 16° slope with a maximum stable slope of about 20°.
- (e) For a given passage width and air flow, a shallower passage results in a smaller crater.

6.3 Construction of a Fly Ash Seal in Water Flow and Subsequent Retention of Water Backfill

6.3.1 General Description

The development effort for fly ash sealing was devoted to the construction of a seal in a dry mine passage. The presence of flowing water in the passage presents additional problems which are treated in this section.

The source of water flow in a mine can be from natural drainage of the water in the overlying strata or from water that is being introduced artificially for the purpose of fire control. In either case, the two problems concerning the development of a seal are:

- (a) Can a seal be built in the presence of running water ?
- (b) Once built, can this seal retain the back-filled head of water ?

Item (b) is particularly important when inundation of the sealed area with water is being used as a fire-fighting technique.

The logic of the test program to be described can be summarized as follows:

- (a) Determine what limitations the fly ash seal technique has in terms of water flow and water retention.

- (b) Develop and test improved techniques for enhancing this capability.

6.3.2 Placement of Fly Ash Seal in Flowing Water

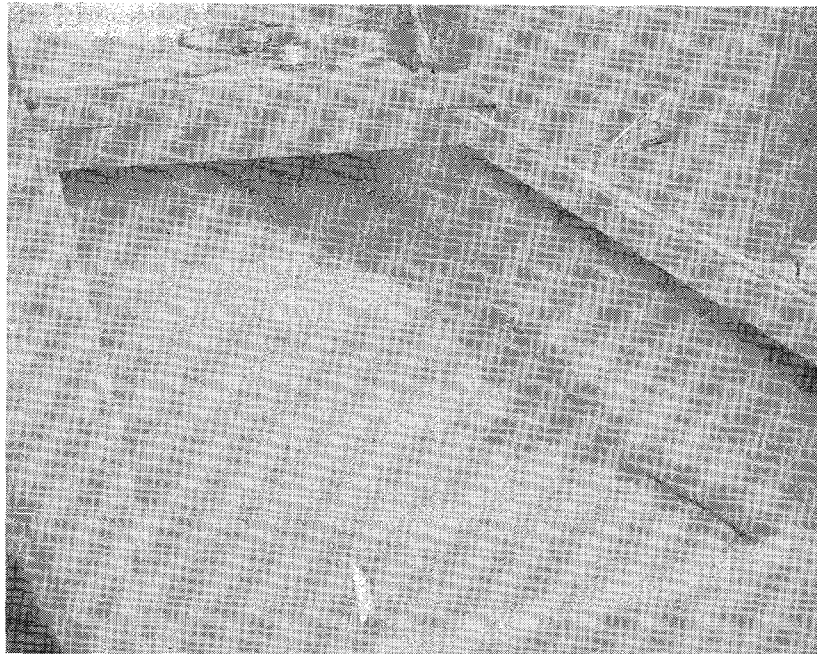
This test was conducted in the 1/4-scale test facility described earlier. It was assumed that the ability of the fly ash to stop the water flow is dependent upon the water flow rate, Q , and the rate of fly ash pumping per unit width of passage, F/w . Scaling was accomplished by maintaining the following relationship:

$$\left[\frac{Q}{F/w} \right]_{\text{lab}} = \left[\frac{Q}{F/w} \right]_{\text{full scale}}$$

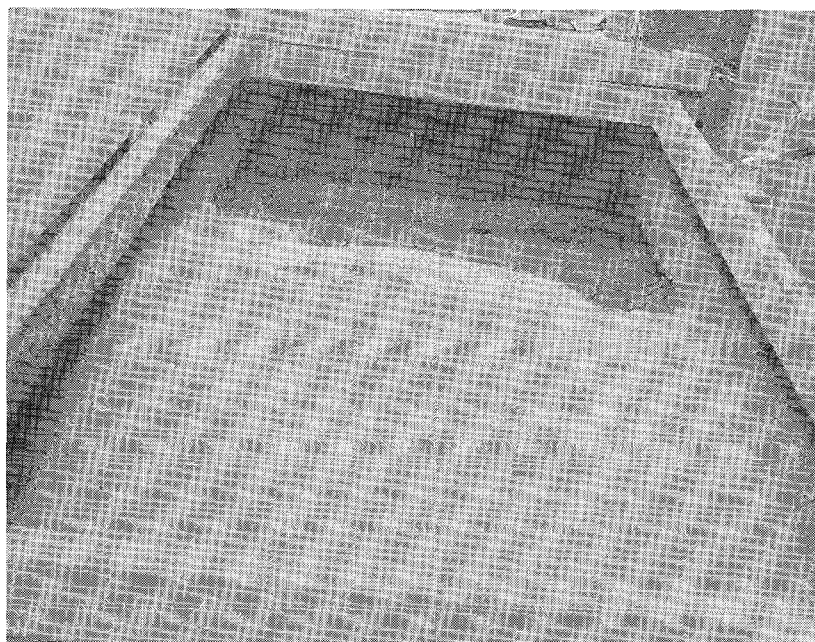
The laboratory values were $w = 4$ feet and $F = 1$ ton/hour.

Our first test was conducted at 1 gpm, and the sequential results are shown in Figure 40. Figure 40(a) shows the water channeling its way through the fly ash. Between the times of Figure 40(a) and 40(b), the fly ash pile caved into this channel, stopping the water flow completely, as shown in Figure 40(b). Based on the scaling law, it was concluded that in a 20-foot-wide passage, fly ash pumped at 40 tons/hour could form an effective seal against a water flow rate of 8 gpm.

The second test was conducted at 5 gpm, and the results are shown in the sequence of photos of Figure 41. The initial water flow, shown in (a) becomes channeled in the same way as it was in the 1 gpm test (b). Subsequent filling caused occasional blockages of this channel, but the backed-up water always managed to break through, and the channel became deeper (c). Finally, the seal bridged over the channel and the water continued flowing under the seal (d). It was felt that beyond this point, the water could not be stopped, and the test was terminated. We concluded that at sufficiently high water flows (approximately 40 to 50 gpm), the fly ash sealing technique could not stop the water flow, and alternative techniques would have to be developed to handle this range.

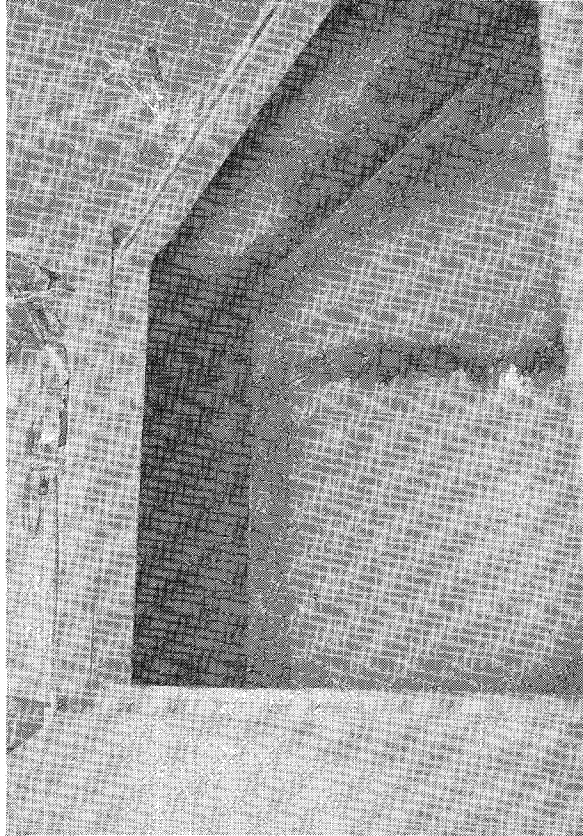


(a) Water Initially Channeling

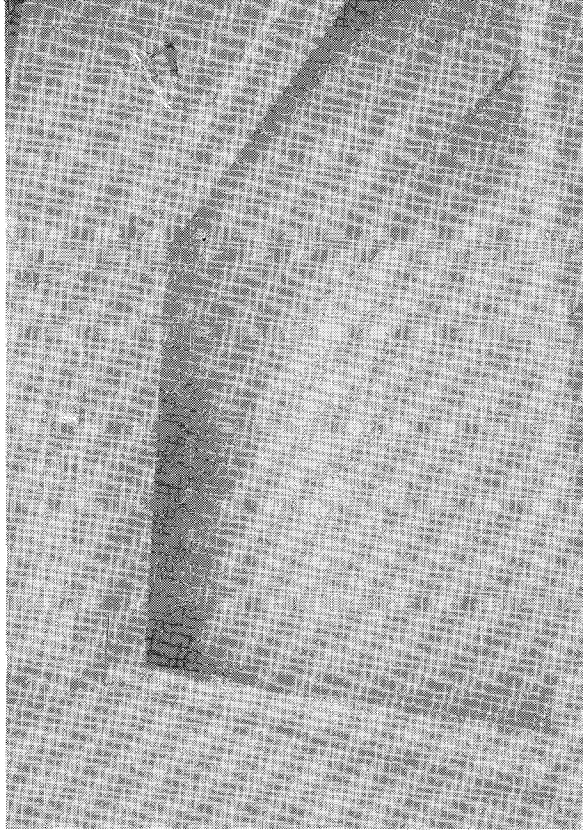


(b) Water Flow Stopped

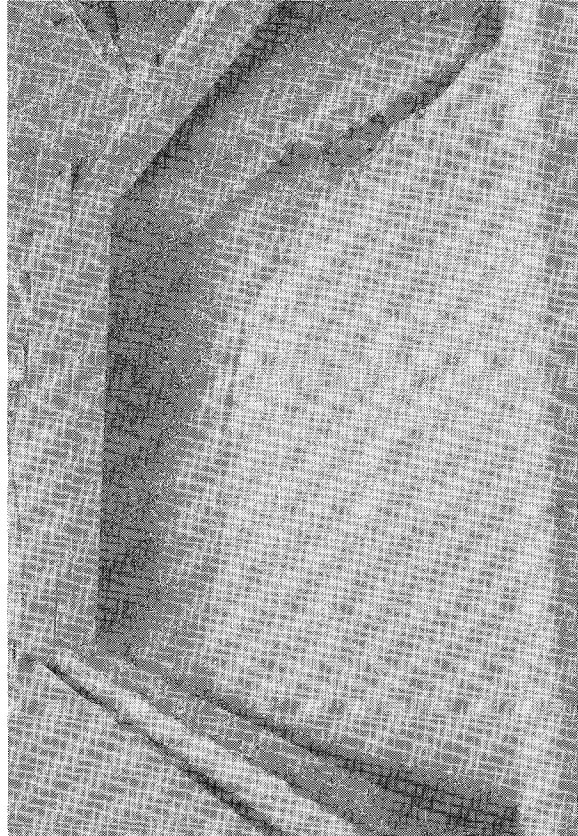
1/4 Scale Test
Fly Ash Placement in Water Flow at 1 gpm
Figure 40



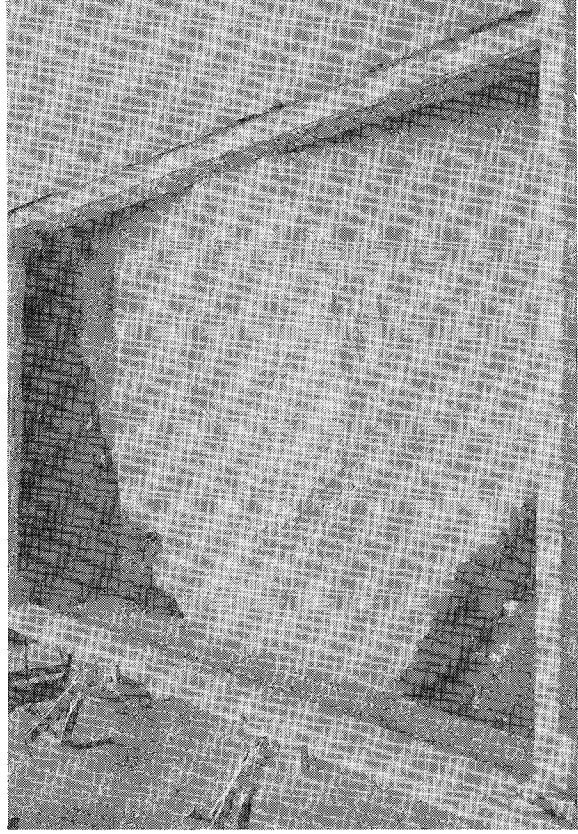
(a)



(b)



(c)



(d)

Placement of Fly Ash in Water Flow at 5 gpm; 1/4 Scale Test

Figure 41

6.3.3 Gravel Grout System for Sealing Against High Water Flows in the Mine

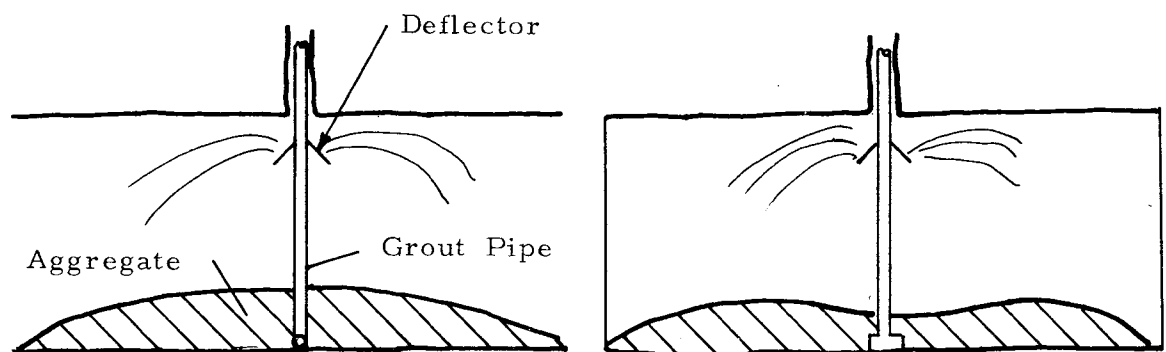
6.3.3.1 Concept Description

One can consider the construction of a seal in a heavy water flow as the remote construction of a dam. As with a dam, the water must be diverted while the structure is being built in such a way that the diversion can be closed off when the structure is completed. The following technique was conceptualized for a remote mine seal.

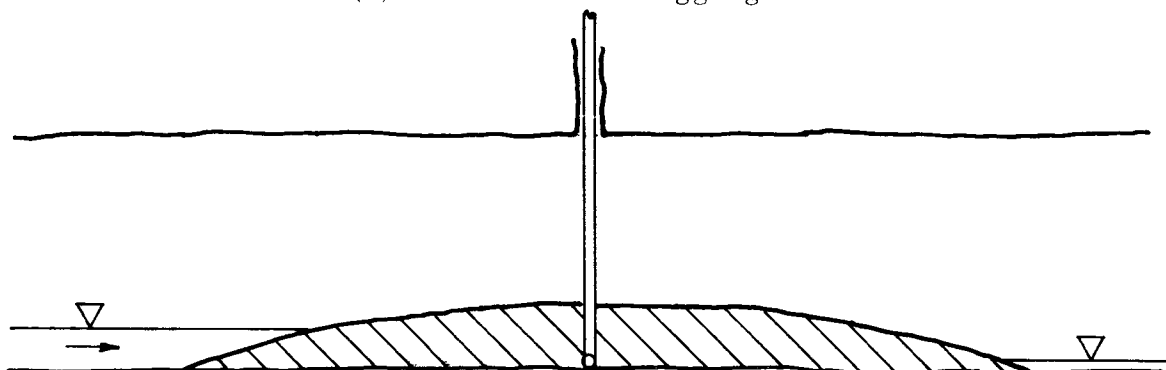
Gravel is first introduced into the passage through the borehole either by gravity or with pneumatic assistance. It is spread uniformly across the passage floor with a deflector, which is deployed on a pipe, as shown in Figure 42(a). The placed gravel, which covers the open end of the pipe, smooths out the water flow across the passage width and creates a backup of water as shown in Figure 42(b). The fly ash is then pneumatically delivered on top of the gravel through an adjacent hole, Figure 42(c). During the seal formation, the water continues to run through the gravel below the fly ash. When the fly ash seal is completed, grout is pumped into the gravel through the preplaced pipe the gravel becomes plugged, and a water-tight seal results.

Some of the specific problem areas which must be considered in the development of this technique are:

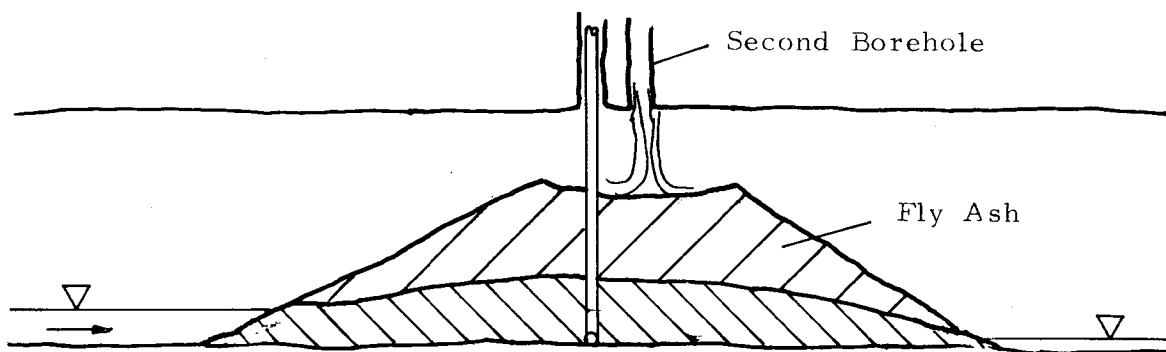
- (a) Distribution of gravel
- (b) Choice of gravel size
- (c) Optimum design of grout



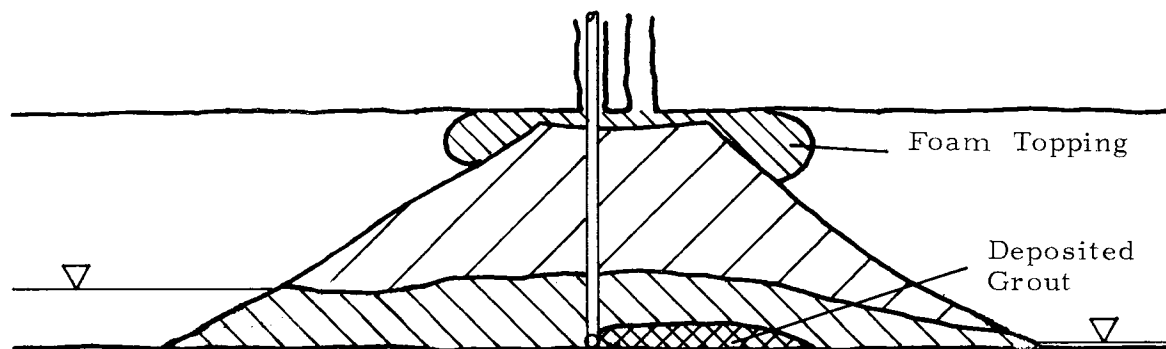
(a) Placement of Aggregate



(b) Steady State Water Backup Through Aggregate



(c) Placement of Fly Ash Seal



(d) Final Grouting of the Aggregate

Gravel-Grout System - Sequence of Events

Figure 42

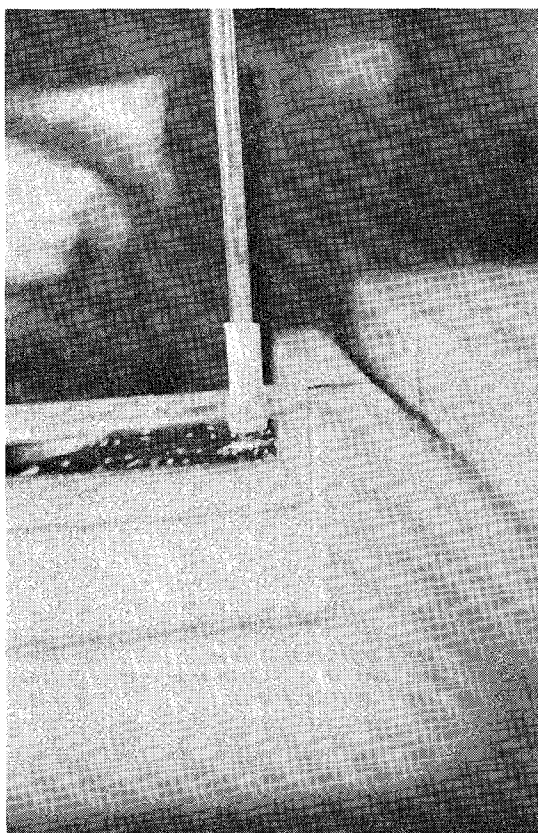
- (d) Distribution of grout in the gravel
- (e) Plugging of gravel by pneumatically placed fly ash
- (f) Development of a deployable deflector - grouting system.

As part of our laboratory program, we investigated item (a) and then proceeded directly to a small-scale simulation of the complete system.

6.3.3.2 Gravel Distribution Tests

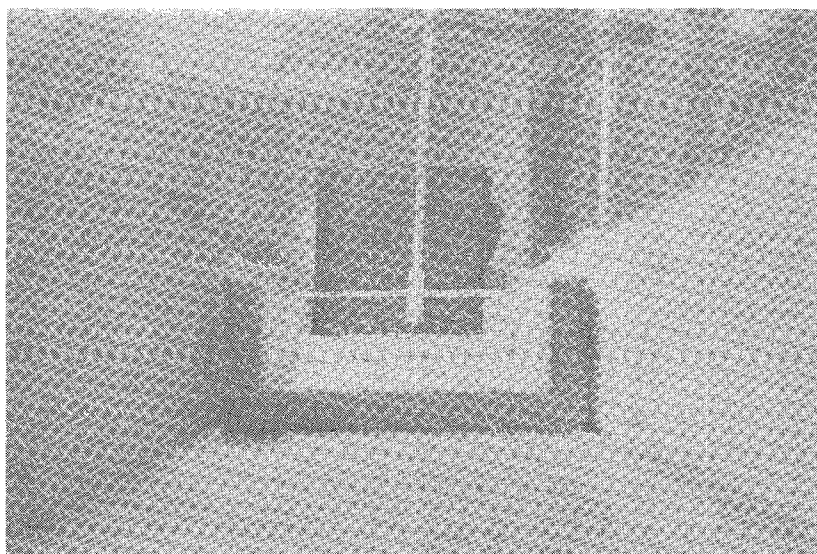
In order to develop a feel for the deflection characteristics of gravel, initial tests were conducted in a small table top trough, 2-inches high and 5-inches wide. Uniform Ottawa sand, about .03-inch in diameter, was used to represent the gravel. It was found through scaling considerations (described in Appendix C) that the trajectory of such a sand grain at terminal velocity in this size passage is geometrically similar to that of a 1-inch stone at terminal velocity in a full scale mine passage. The sand grains were delivered from a funnel into a 4-foot glass tube with 1/4-inch inside diameter. The tube entered the simulated passage as shown in Figure 43. A number of different deflector shapes were considered, as well as locations at the center and side of the passage. The deflector shown in Figure 44 is an inverted circular dish located at the side of the passage.

The two most promising deflector shapes were the inverted circular dish and the folded plate. Figure 44 shows the sand pile development for center mounted dish and folded-plate deflector. Note that both deflectors produce a uniform pile across the passage width.

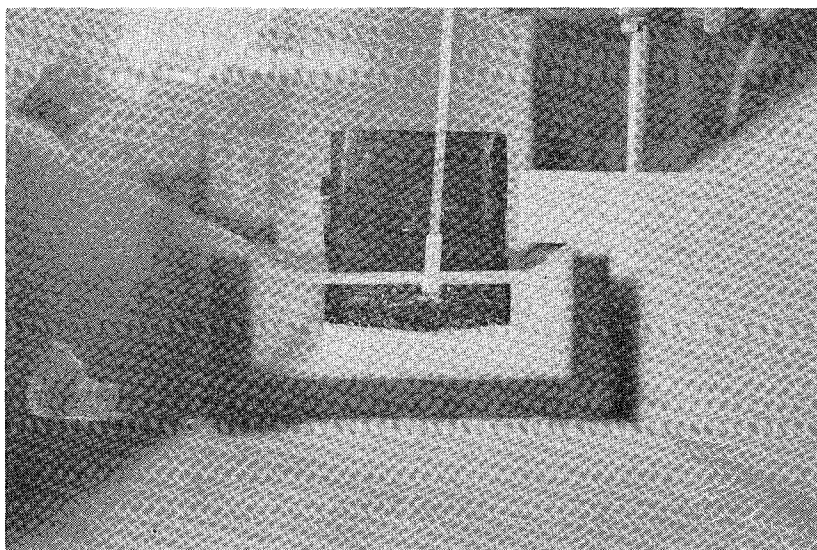


Simulated Borehole - Deflector Arrangement

Figure 43



(a) Inverted Circular Dish



(b) Folded Plate

Center Mounted Deflector

Figure 44

The capability to pile gravel across the passage from an off-center borehole is illustrated in Figure 45a. The pile is actually higher at the far end, indicating that the deflector angle could be increased.

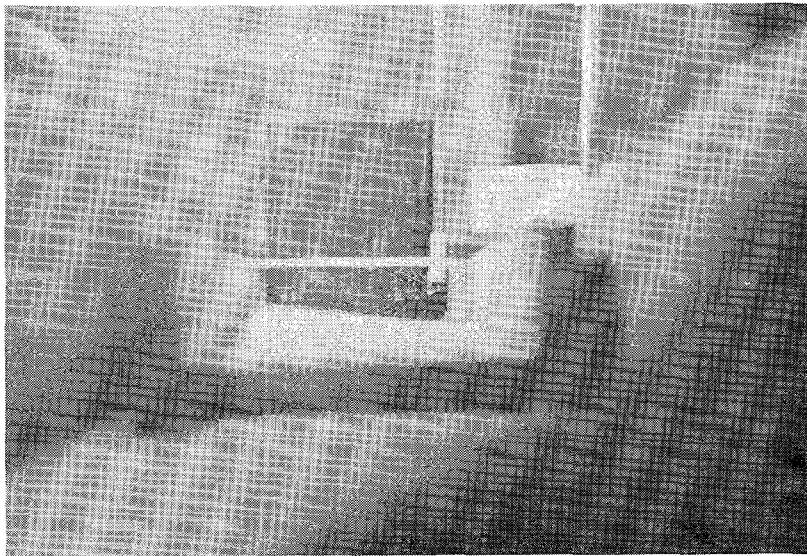
The possibility of increasing the deflection velocity by delivering the gravel with an air velocity is demonstrated in Figure 45b. The high-speed sand particles produced a more random motion and a more uniform pile in the process.

One subsequent gravel distribution test was conducted in the quarter scale facility. 1/2-inch crushed stone was dropped down a 12-foot tube on to the deflector shown in Figure 46. The test results verify the ability to form a uniform gravel pile across a passage width.

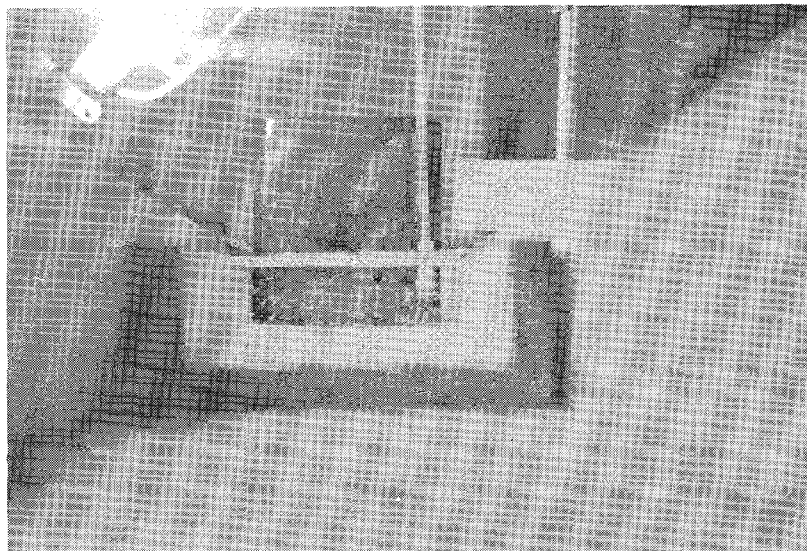
The conclusion from the above test program was that aggregate could be spread across the width of a passage in the desired manner for the gravel grout technique by using a deflector.

6.3.3.3 Water Flow Through Aggregate

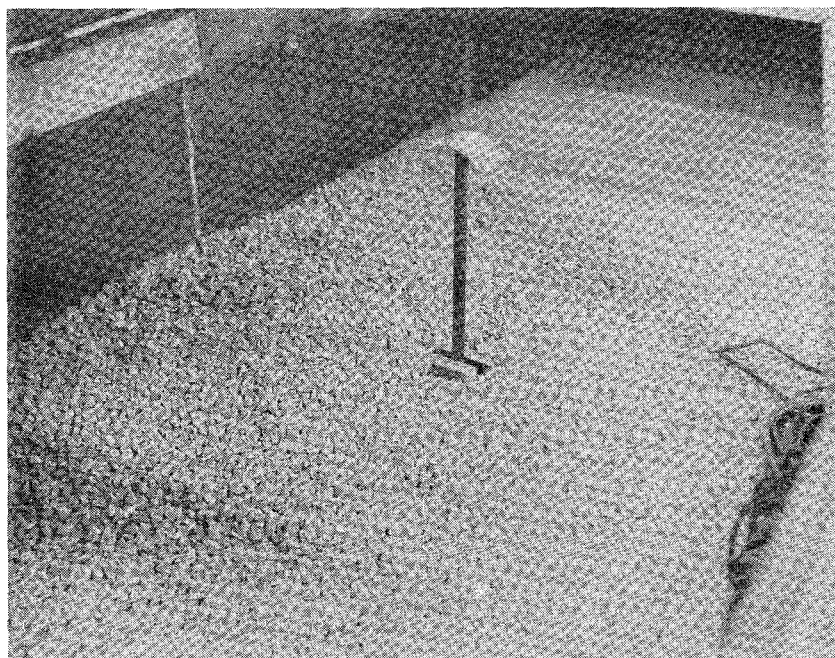
The resistance of the placed aggregate to water flow produces a head differential and a rise of water on the upstream side of the aggregate pile. Initially there was concern about the height of this backup, in particular, maintaining it below the top of the gravel. Further consideration of the actual mine conditions indicated that after a certain height is reached, the water flow into the passage in question will backup into other areas and continued increases in height will not occur until the entire sealed area is being backfilled. This initial height will depend on the passage slope, passage length, aggregate size and water flow rate.



Tilted Plate Deflector for Off-Center Borehole
Gravity Fall of Aggregate
Figure 45a



Tilted Plate Deflector. Gravity Fall of Aggregate
With Pneumatic Assistance
Figure 45b



Deflection of 1/2" Crushed Stone in the 1/4 Scale Passage

Figure 46

Water flow through a porous aggregate bed is shown in Figure 47. The demonstration was conducted in a Lucite* tank, 1-foot wide, 1-1/2-feet high and 15-feet long. The photo shows a bed of 1/2-inch crushed stone, 4-inches high and 4-feet long, with a water flow of 5 gpm. The black line on the side of the tank indicates the water height profile through the aggregate. The test was used to demonstrate the influence of placed aggregate on water flow.

6.3.3.4 Small Scale Simulation of Complete Gravel Grout Technique

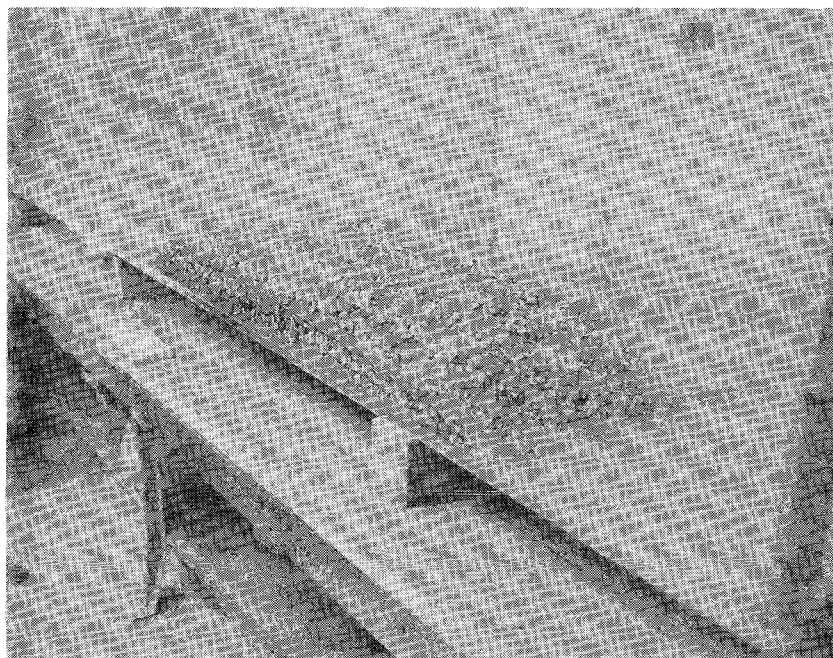
The complete gravel grout technique was demonstrated in the Lucite* tank. The set-up is shown in Figure 48. A bed of gravel was preplaced in the tank which was at a 2° slope. The tank was then covered air tight with controlled ventilation for pneumatic injection of the fly ash-cement mix. (The use of cement is discussed in the next section in reference to retention of water head). A grout pipe was buried in the gravel, and connected by hose to a Moyno pump. Water was pumped into the top of the tank at the far end of Figure 48a through a water flowmeter to measure the flow. After passing through the aggregate the water fell into the tank at the far end of Figure 48 (b) and was pumped down the drain.

The test was designed to investigate two potential techniques.

(a) Plugging of aggregate with pneumatically placed fly ash cement mixture as the grout. It was thought that the pneumatically-placed fly ash cement mixture would fall into the water upstream and be carried into the gravel bed. This would eventually plug the gravel.

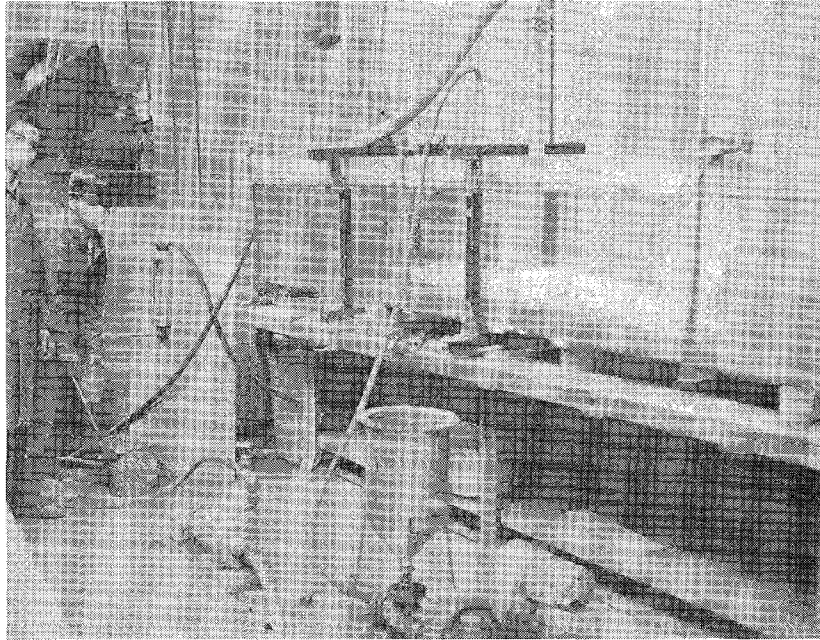
(b) Plugging of aggregate with injected grout.

* Trade Name.

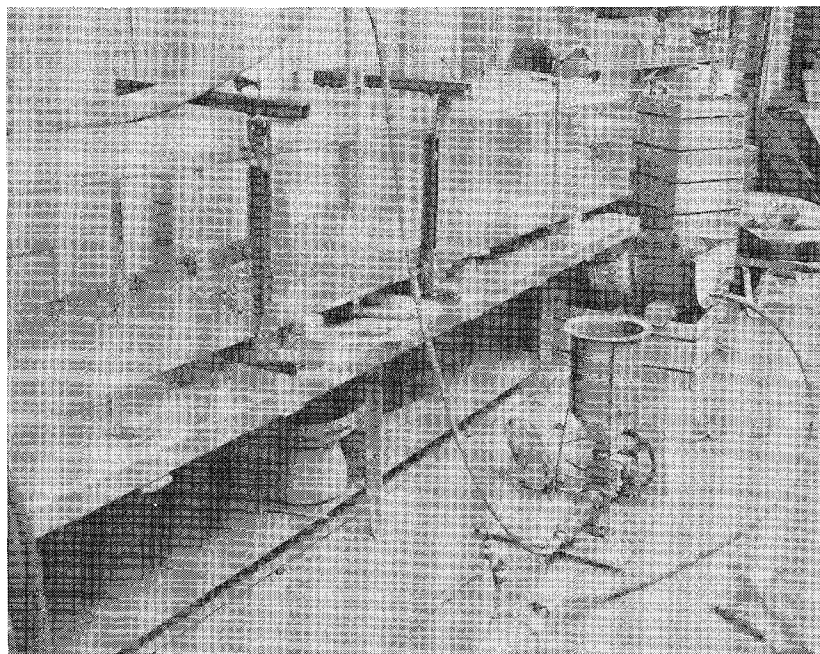


Water Flow Through Porous Aggregate Bed

Figure 47



(a)



(b)

Small Scale Gravel Grout Experimental Setup

Figure 48

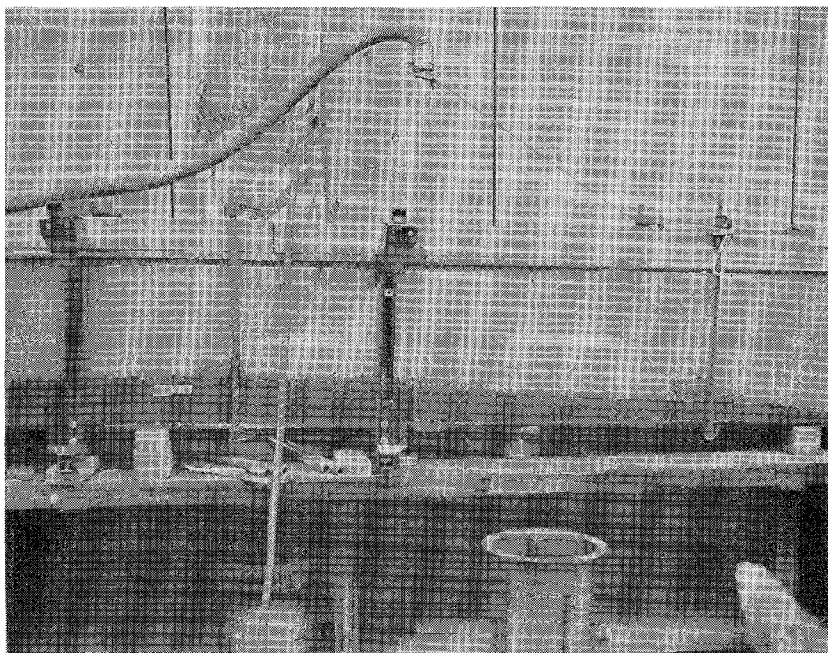
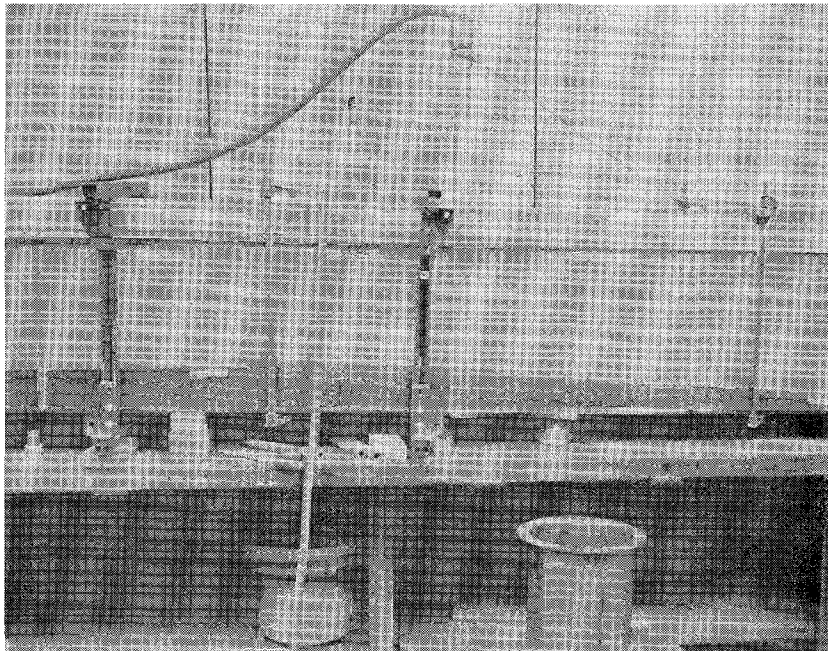
If technique (a) did not work, the gravel would be grouted directly after the fly ash seal had been completed.

The test was initiated at 5 gpm and was conducted at a constant head of backup water; i. e., it was assumed that the gravel had caused the water to back up into other passages so that any further rise in water height during the sealing process would be negligible. The adjustments of water flow rate required to maintain constant head were monitored throughout the test.

Figure 49 shows the fly ash-cement pile developing during the water flow. Some of the fly ash-cement did fall into the upstream water and some plugging of the gravel occurred. The water flow rate was decreased from 5 gpm to 2 gpm at the completion of the fly ash seal. The water flow had not completely stopped, and therefore grout had to be injected into the aggregate.

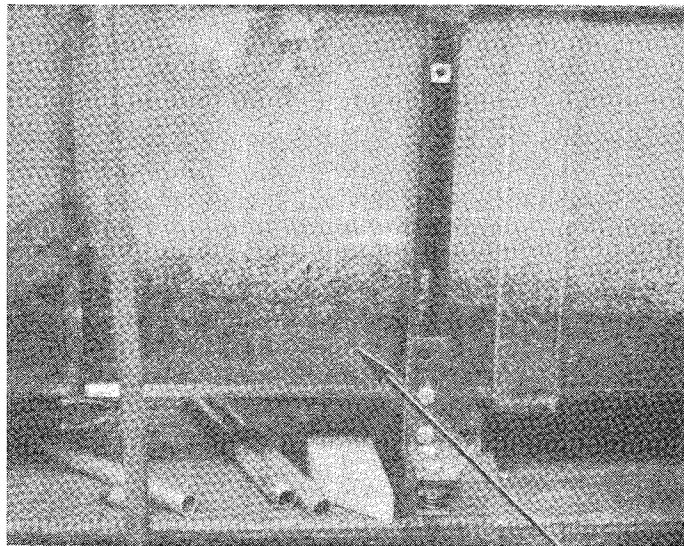
A slurry of 55 percent fly ash and 45 percent water by weight, with 12 percent Huron Regulated Set Portland Cement by weight of fly ash was used for the grouting. Earlier tests showed that the addition of this amount of Huron cement would result in a set in about 10 minutes, thus preventing erosion after deposition in the gravel.

Figure 50 shows the grout deposition in the aggregate bed. In Figure 50 (a) the deposited slurry has plugged half the height of the gravel bed. Figure 50 (b) shows complete plugging - the deposited slurry has connected with the pneumatically placed fly ash to form a complete seal against water flow. Figure 51 shows the configuration after the complete water seal. Note the rising water level (the tape was the original level).



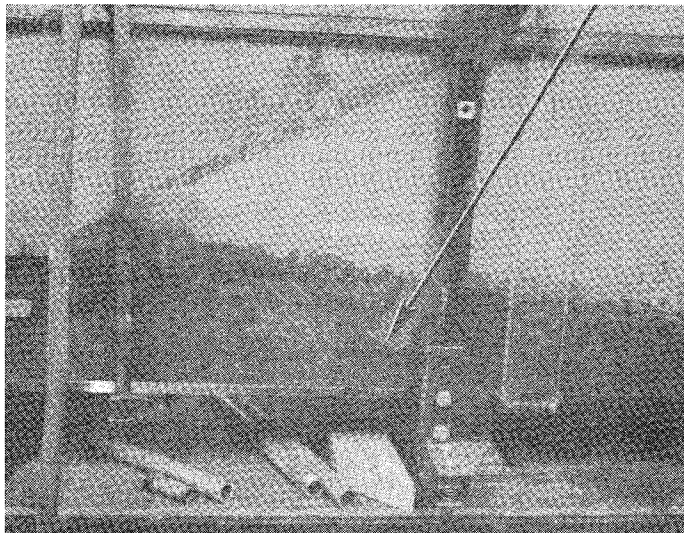
Water Flow Through Aggregate Bed
During Pneumatic Injection of Fly Ash

Figure 49



(a)

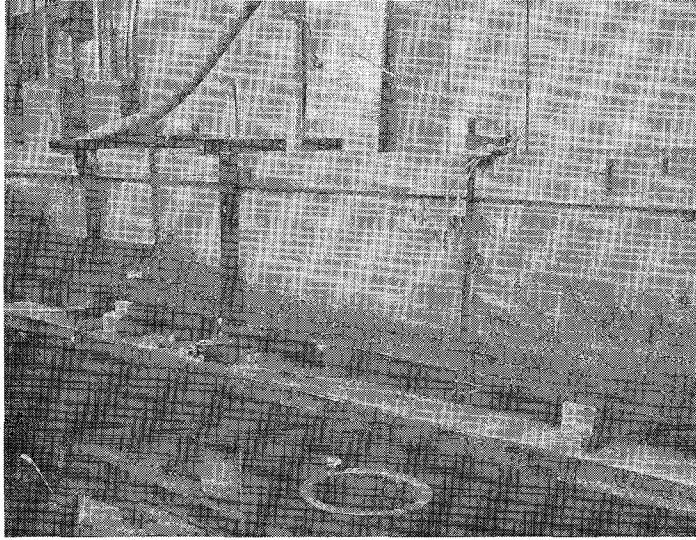
Deposited Grout



(b)

Deposition of Grout in the Aggregate Bed

Figure 50



Final Water Seal

Figure 51

6.3.4 Support of Backed Up Water Head

In certain fire situations rapid extinguishment can be achieved by inundation of the sealed fire area with water. In such cases, the fly ash seal must act as a dam, supporting a head which may be more than twice the passage height. A laboratory program was conducted to test the behavior of a fly ash seal when completely backfilled with water.

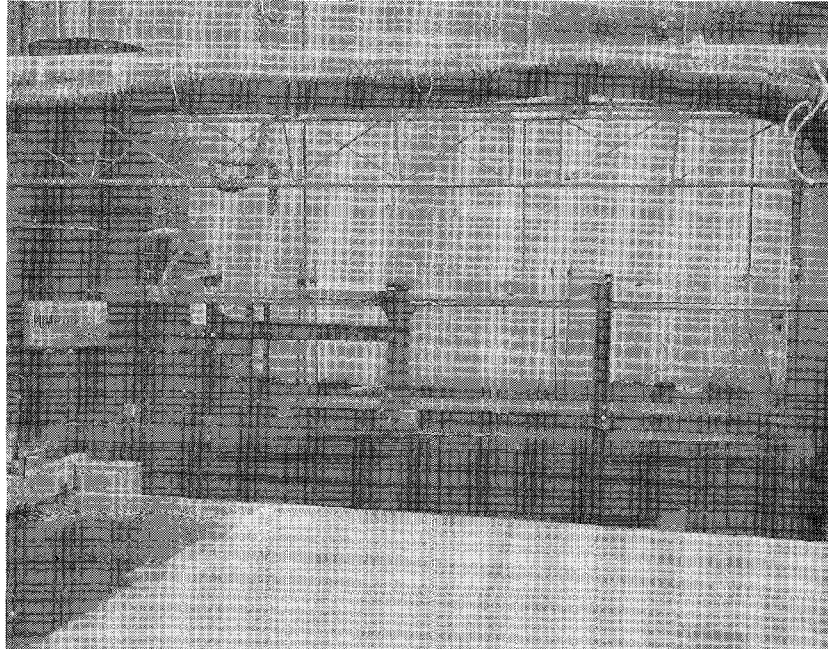
It was assumed that the strength of the seal would be proportional to its length, and therefore the ratio of water head to seal length could characterize the effectiveness of a seal against water head. Consequently, it was felt that a scaled model with the ratio of water head to seal length the same as the field requirements, would be a representative test.

The test facility was the Lucite* tank discussed earlier, modified for the development of upstream water pressure. Figure 52 shows the test arrangement. The water was supplied from a reservoir in the upper barrel on the left, so that when the seal had been completely backfilled, an additional 3-feet of head could be supplied.

6.3.4.1 First Test - Fly Ash Seal

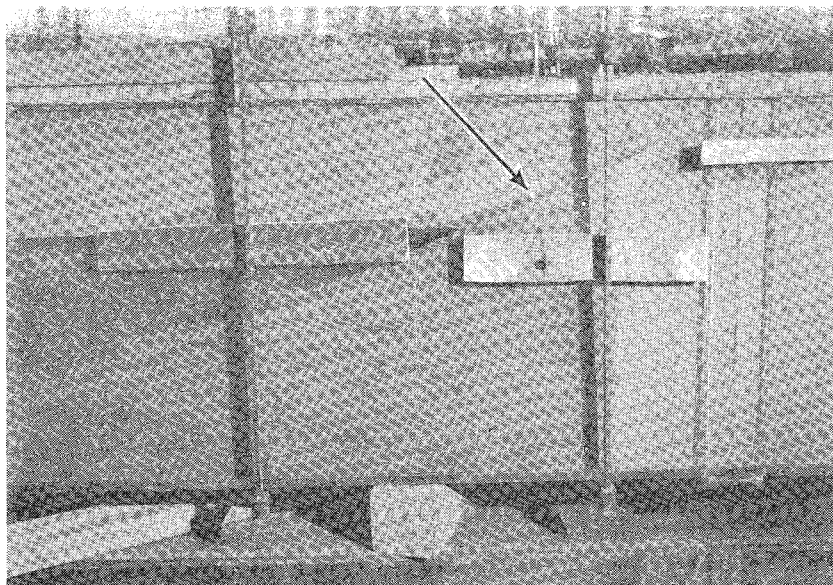
Figure 53 shows the results of the first test. The backfilling of the seal took about 3 hours. It was initially thought that seal failure would take place by piping: i.e., particle erosion at the downstream toe of the seal due to pore water pressure. This did not turn out to be the case; failure occurred by sloughing. The water-soaked fly ash decreased in volume and caused fracture and collapse of local areas in the fly ash. Figure 53 (a) shows the development of many small channels. As the water continues to soak through the seal, additional fissures develop and link up

* Trade Name.

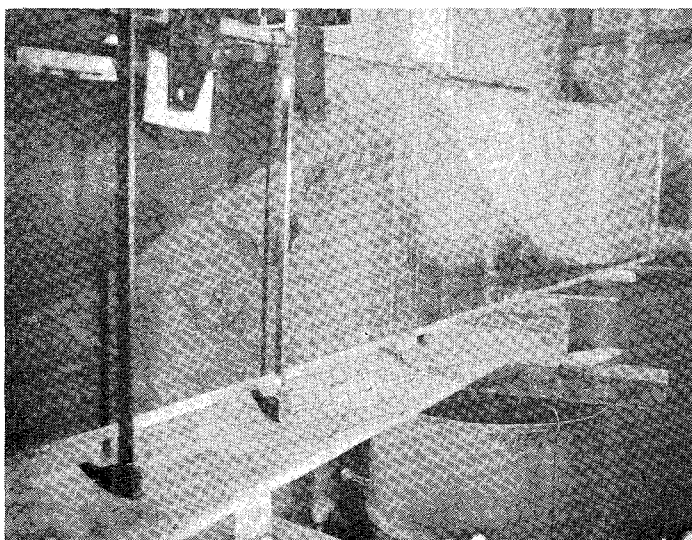


Test Facility for Water Head Development

Figure



(a) Development of Fissures
Note Advancing Capillary Water (Arrow)



(b) Subsequent Failure of Seal

Fly Ash Seal Subjected to Rapid Water Backfill

Figure 53

until a continuous channel from end to end develops. This failure is shown in Figure 53 (b).

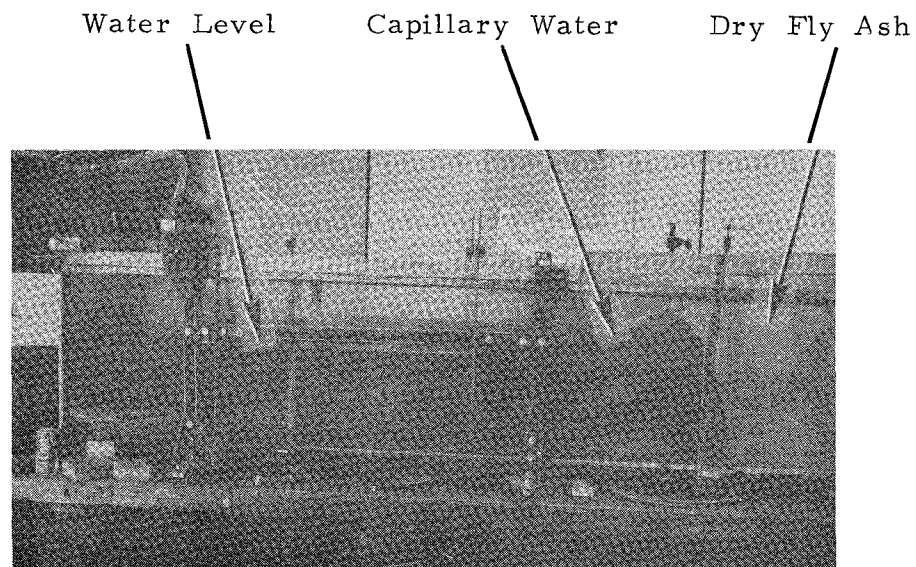
Further consideration of actual mine conditions indicated that the rate of head development should occur over a period of days rather than hours. In addition, it was felt that the addition of dry cement to the fly ash, coupled with the slow water height development, would allow the seal material to set before it developed failures. These two considerations defined the conditions of the second tests.

6.3.4.2 Second Test - Fly Ash- Huron Cement Seal

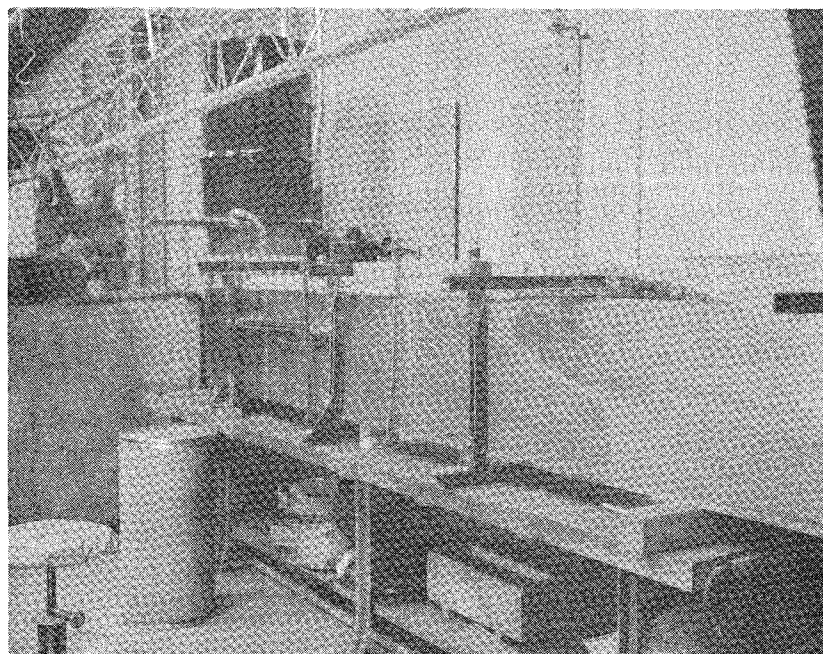
It was observed in Figure 54 (a) of test 1 that a front of capillary water advanced above the rising water level in the tank. The addition of cement to the fly ash would cause the capillary zone to harden before it was covered by the advancing water level, thus preventing material collapse and subsequent seal failure.

Tests were conducted to determine the influence of capillary water on a number of different fly ash cement mixes. It was found that a mixture of 6 parts fly ash and 1 part Huron Regulated Set Portland Cement would develop a noticeable set between 10 and 30 minutes after absorbing capillary water. For the second test, the seal consisted of a pneumatically placed mixture of 6 parts fly ash and 1 part Huron cement. The input water was adjusted so that back-filling would take about 3 days.

Figure 54 (a) shows the water backup about half the height of the seal. Note that no fissures or channels are formed in the seal. Figure 54 (b) shows complete back-filling of the seal. The seal is completely intact, and most



(a)



(b)

Fly Ash-Cement Seal - Slow Water Backfill

Figure 54

of the upstream portion of the seal has hardened. Capillary water has permeated almost the entire length of the seal, hardening the fly ash cement mixture in the process.

An additional water head of 2-feet above the Lucite* tank was supplied through the reservoir. A small amount of leakage between the fly ash seal and the roof developed in a region where there was not a perfect seal. No other damage to the seal occurred.

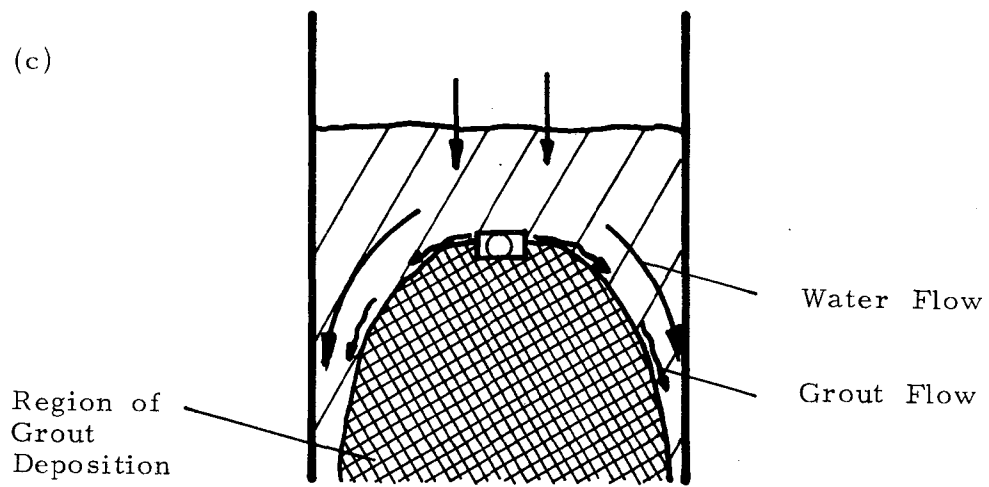
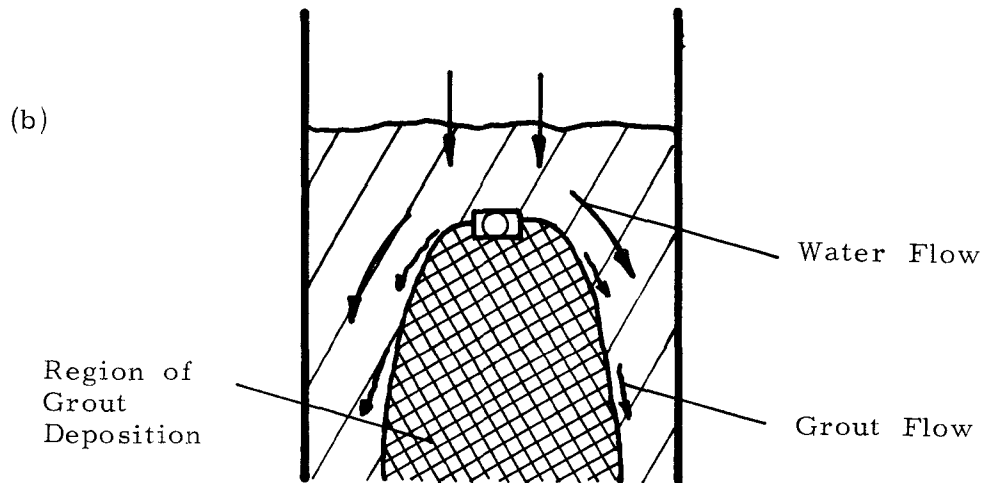
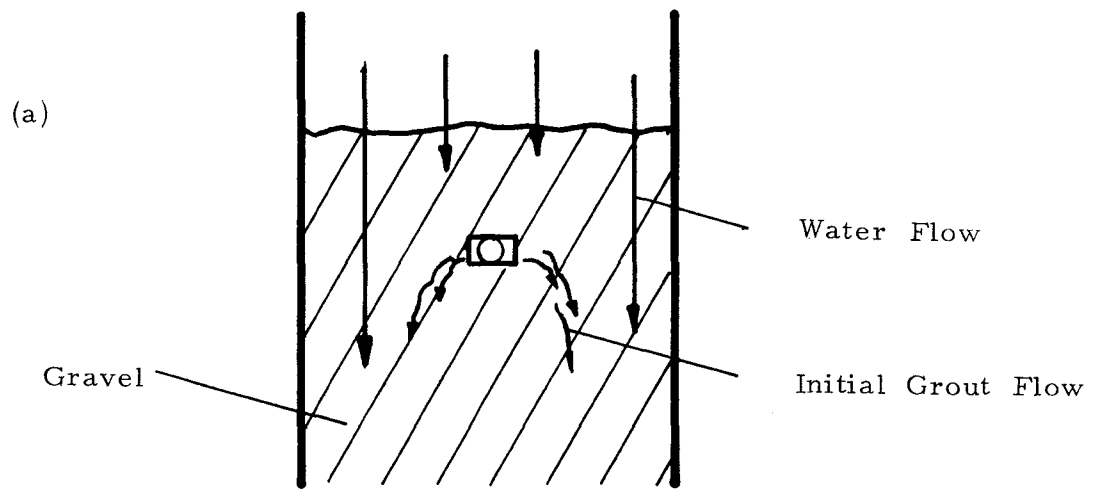
6.3.4.3 Conclusions and Discussion of Field Application

The laboratory results presented in the previous section indicate that the proposed gravel grout system combined with a fly ash-cement seal can be placed in running water and can support the resulting water backfill. It was also shown that for limited water flows of less than 10 gpm, the gravel grout technique is not necessary and the fly ash or fly ash-cement combination alone is sufficient to stop the water flow.

The distribution of the grout in the gravel in a full passage from a point source has not been demonstrated, but Figure 55 indicates how this would occur. The initial grout flow would not reach the sides of the passage. Once the grout has deposited in the center of the passage, however, the water flow is diverted to the sides and along with it the grout flow. Eventually, the entire passage width will be grouted. It is possible, however, to enhance the lateral distribution with a flop out grout pipe.

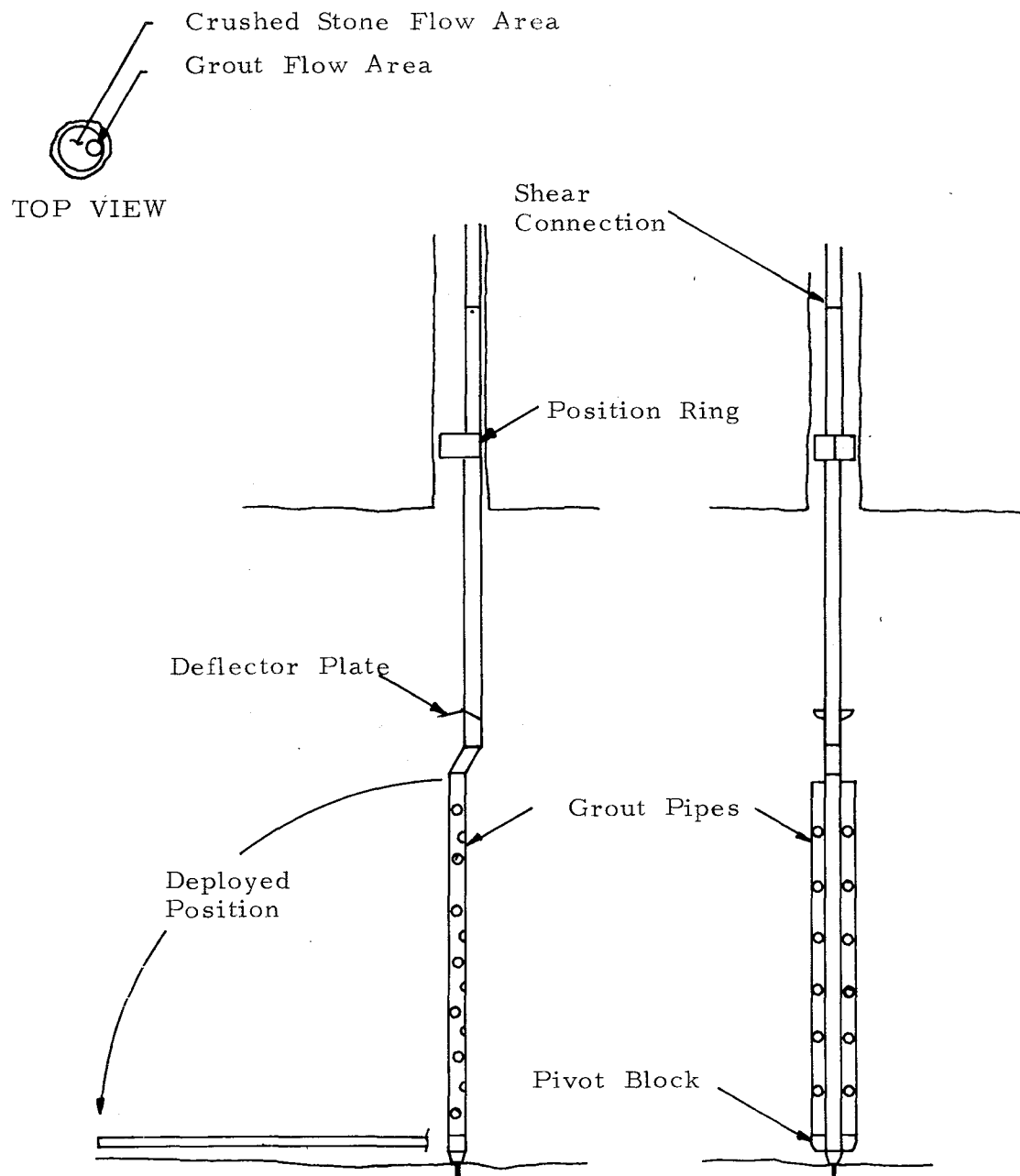
One possible deflector-grout arrangement is shown in Figure 56. Here the aggregate deflector is mounted on the grout pipe, and the grout pipe can be deployed laterally.

* Trade Name.



Sequential Flow and Deposition of Grout - Plan View

Figure 55



Expendable Deflector and Grout Pipe System

Figure 56

The mixing of fly ash and cement can occur after each has been pumped from a bulk truck. The two components can be mixed at a "Y" connection, and the quantity of cement controlled with a solids flowmeter.

The complete sealing procedure, as tested, is a 2-borehole operation. It may be possible to use only one borehole, but consideration must be given to the influence of the grouting pipe and deflector on the fly ash flow. An alternative possibility is to use one of the seal-checker holes for deployment of the grout pipe.

6.4 Development of Polyurethane Froth-Foam Mine Sealant Topping System

6.4.1 Use of Foam as a Topping Material

The use of urethane foam as a topping material for a bulk seal filled with fly ash offers a number of advantages:

- (a) It is an expanding material which flows under pressure thus allowing it to fill corners and cavities and result in a good seal.
- (b) As discussed in Section 6.2, the use of foam to make the seal can result in a significant reduction in the volume of fly ash and possibly reduce the time required to make the total 100 percent air tight seal.
- (c) The foam can provide increased resistance to holding a water head. Foam, unlike fly ash, will not be eroded by flowing water.

The major disadvantage with foam is its flammability and susceptibility to spontaneous combustion due to improper mixing, particularly in large pours. Consequently, the use of foam has been restricted to topping of a fly ash seal where foam quantity can be minimized.

The foaming system selected must ensure proper mixing at all times in order to minimize the risk of spontaneous

combustion. Two possible methods exist for mixing foam. In one method, the two components of the foam are mixed at the surface and the mixture pumped down the borehole through a hose. The foam must have a long setting time in order to minimize the risk of setting and plugging the line; nevertheless, such a risk will always exist. Further, after the completion of every foam pour, either the lines would have to be purged with solvent immediately in order to permit reuse or they would have to be discarded. The amount of solvent required to purge 400 to 1500 feet of hose would be substantial.

In the second method the foam components are pumped from the surface in separate lines and mixed downhole. The successful application of this method has been limited by the availability of a high performance, compact, simple, and reliable mixing head which can be deployed down a 6-inch diameter borehole.

In recent years a new technology has been developed for mixing the two components of a foam system which substantially reduces the disadvantages outlined in the preceding paragraph. This technique uses what is commonly referred to as a "froth foam", as opposed to a pourable foam. For a froth-foam system, pressurized fluorocarbon gas is dissolved in the A and B components of the foam during manufacture and the two components are stored under pressure. In operation, the A and B components are separately pumped to the mixing head, where they join and then pass through a static mixer such as a Kenics* mixer. When the two components enter the mixer they are released from pressure, causing the dissolved gas to boil and froth up the liquid foam. This frothing action continues as the material flows through the static mixer. The frothing action ensures good mixing and the flash boiling of the fluorocarbon absorbs heat and minimizes the temperature rise of the foaming chemical reaction. After the

* Trade Name

material leaves the mixer, subsequent expansion occurs through chemical reaction of the mixed components just as in a pourable foam.

The use of a static mixing head with no moving parts makes it possible to design a simple, compact and reliable downhole mixing head which can be deployed down a 6-inch diameter borehole.

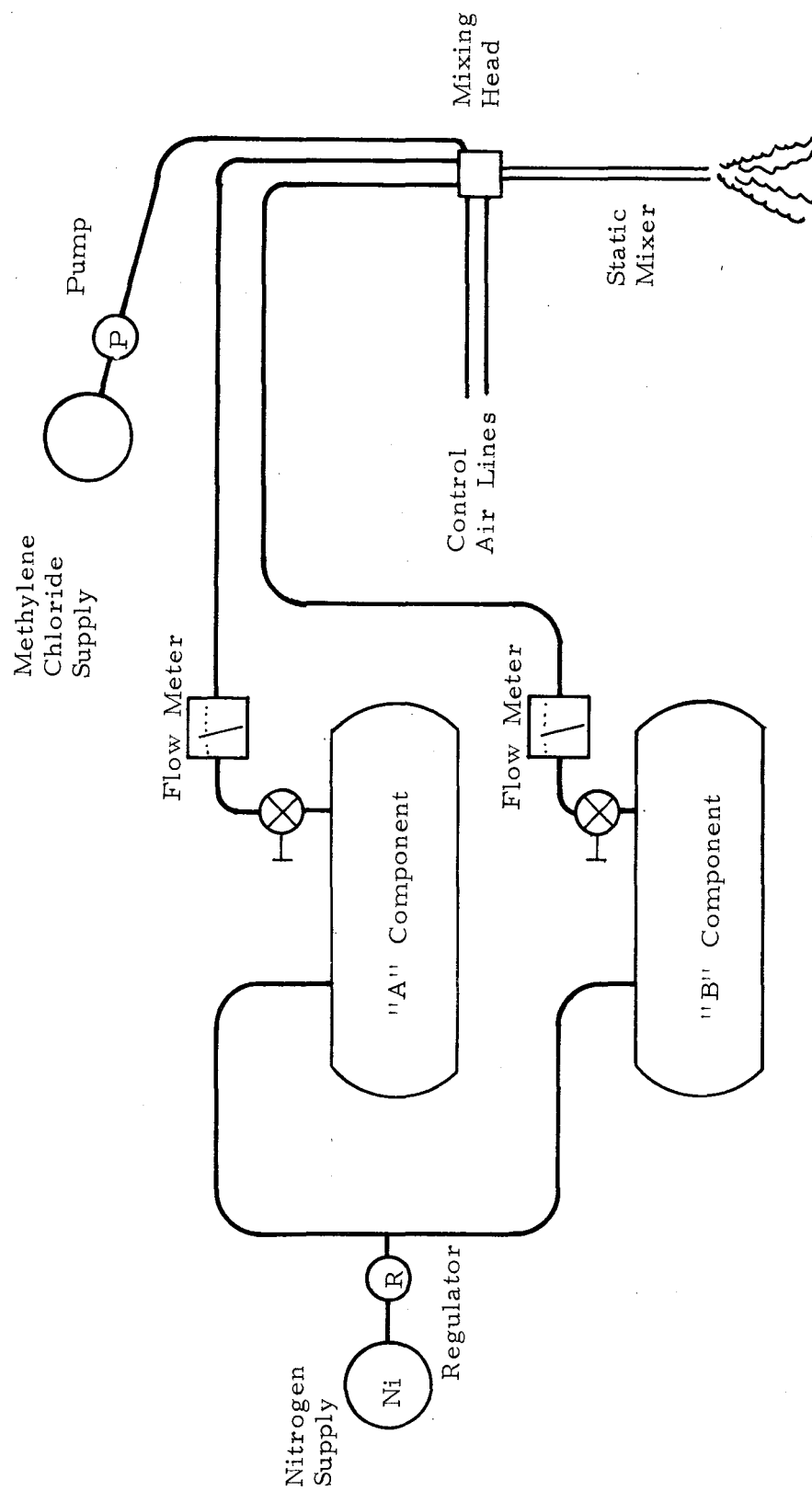
6.4.2 Description of Froth Foam System

The froth-foam system developed by Geologic Associates, Franklin, Tennessee, for underground pressure grouting was selected as the most suitable for our application. This system was developed by Geologic Associates in conjunction with Murphy Pacific, a marine salvage firm in California which had developed a froth foam system to raise sunken ships.

The froth-foam system is shown schematically in Figure 57. The A and B components are stored in two large trailer-mounted tanks, as shown in Figure 58a. The driving force to pump the material is provided by a bottled nitrogen supply set by a regulator to about 150 psi. The flow rates of the two components are indicated by flow meters and are manually adjusted by regulators mounted on the tanks.

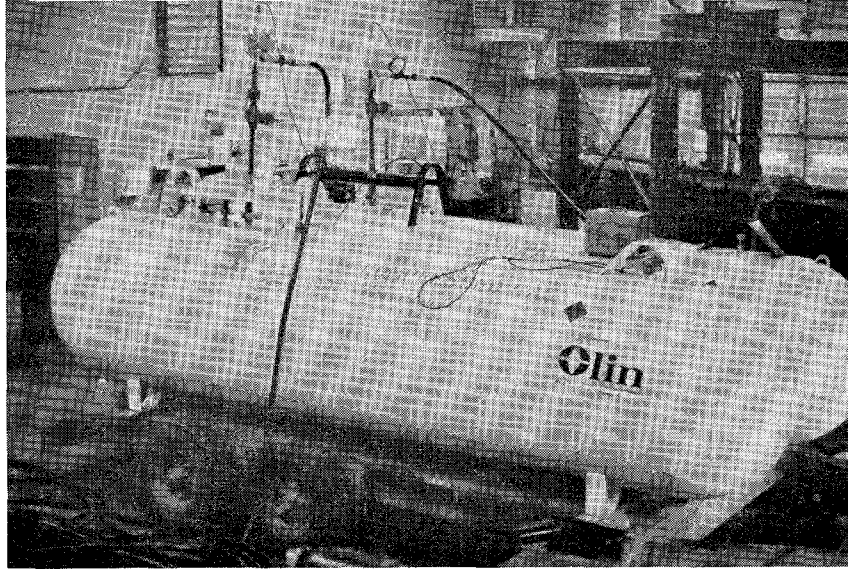
From the regulators the material flows through one-inch diameter Synflex* plastic hose to the mixing head. Valves at the mixing head turn the flow on and off. These valves are controlled by two airlines (1/4 diameter plastic hose) from the operator's station. A fifth line permits methylene chloride solvent to be pumped to the mixing head to purge the static mixer after the foam pour has been concluded or in the case of a premature test absorption. The mixing head is shown in Figure 58b.

* Trade Name.



Schematic of Experimental Foam System, Used for Gallery Testing

Figure 57



Foam Tanks used in Preliminary Testing

Figure 58 (a)



Mixing Head and Static
Mixer Used in
Preliminary Testing

Figure 58 (b)

6.4.3 Testing of Froth-Foam System

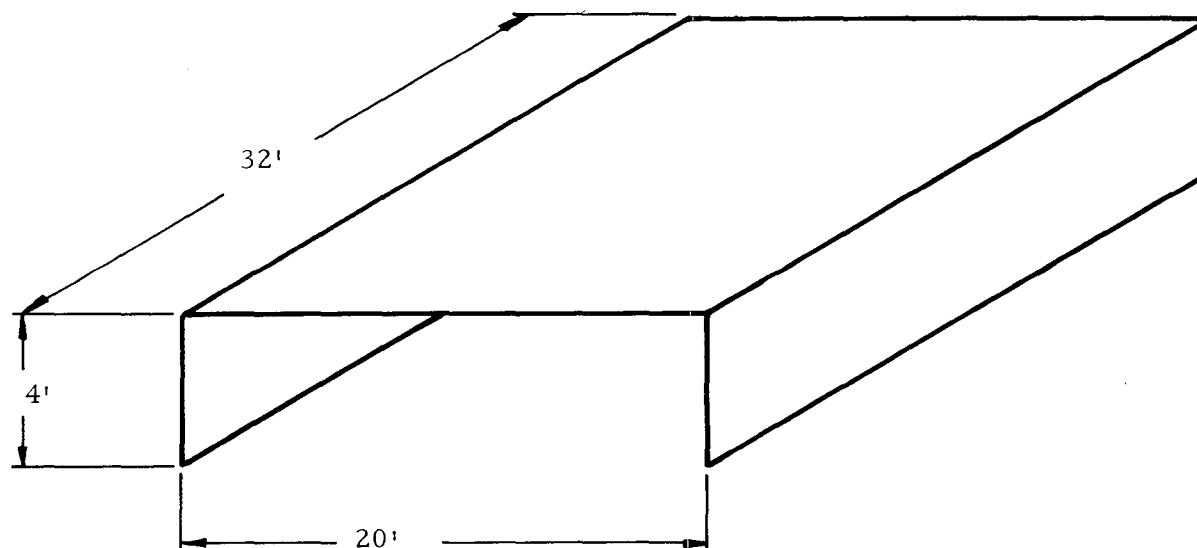
6.4.3.1 General Test Plan

Because of the non-Newtonian characteristics of foam, it was decided that meaningful small-scale testing would be difficult and that a full-scale test would be required to satisfactorily determine the effectiveness of froth-foam as a topping-off material. Arrangements were therefore made with Geological Associates to construct on their premises a full-scale gallery to simulate a section of the mine passageway. The gallery was built 32-feet long, 20-feet wide and 4 feet high as shown in Figure 59. The two ends were left open so that the foam could travel unimpeded along the axis of the simulated passageway. Sand was placed inside the gallery to simulate the fly ash bulk seal to be topped.

Two tests were conducted with different sand pile configurations and centered and off-centered boreholes. Both the tests were conducted with a polyurethane foam at a flow rate of 50 lbs per minute. The isocyanate portion of the formulation was a TDI prepolymer prepared with a pentaerythritol-based polyol. The polyol portion of the formulation was a blend of pentaerythritol-based polyol and an alpha-methyl-glucoside-based polyol. Both foam components had about 10 percent of fluorocarbon 12 and 22 blended into them.

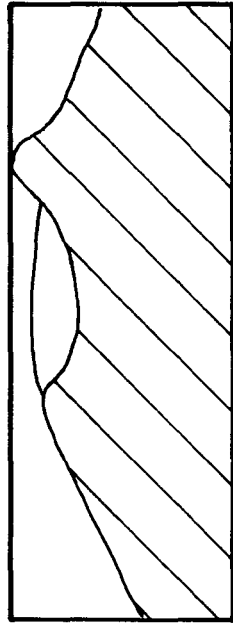
6.4.3.2 First Test - Centered Borehole

For the first test, the borehole was centered in the gallery, and the sand was arranged as shown schematically in Figure 60, a photograph of which is shown in Figure 62a. The progress of the seal can be traced using Figure 61



Gallery Used for Foam Testing in Franklin, Tennessee

Figure 59



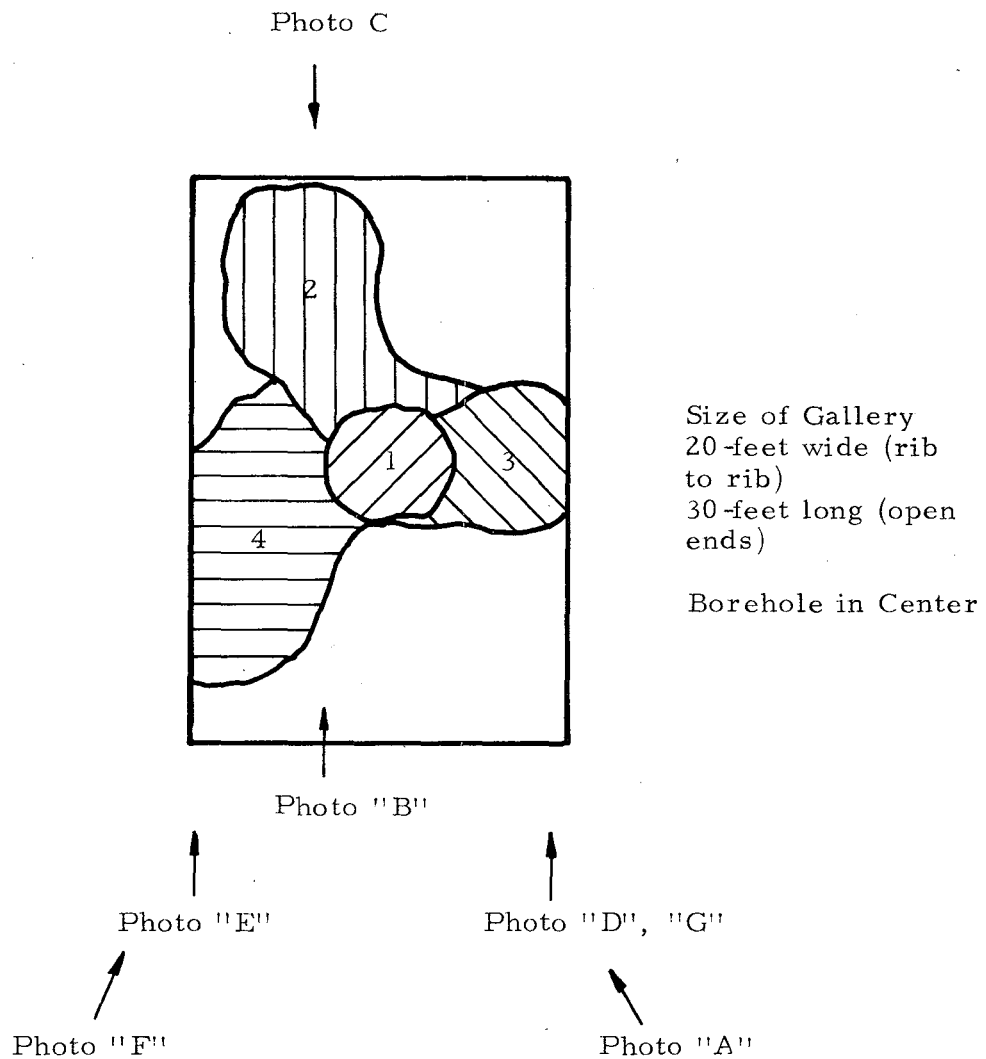
Width-wise cross-section
across middle of gallery



Length-wise cross-section
down center of gallery

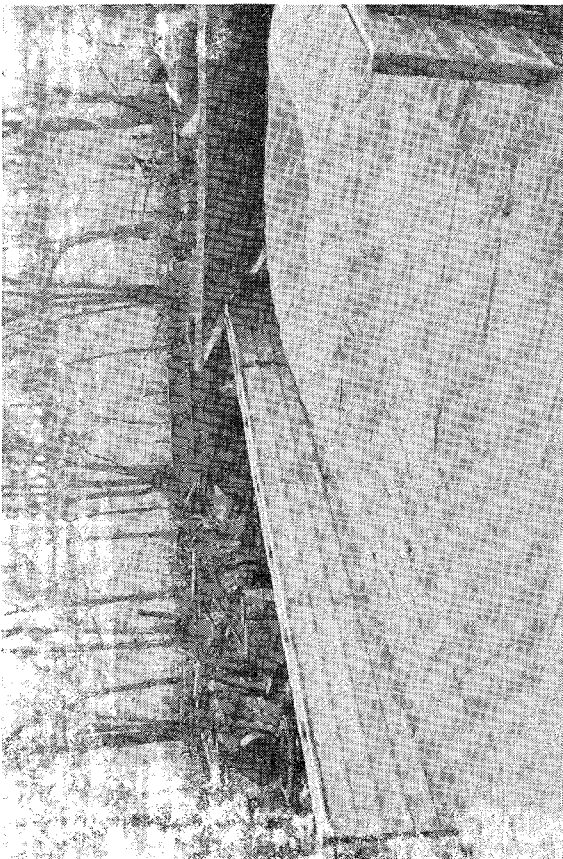
Test 1, Cross-Sectional Views of Sand Pile, Simulating Fly Ash Seal

Figure 60

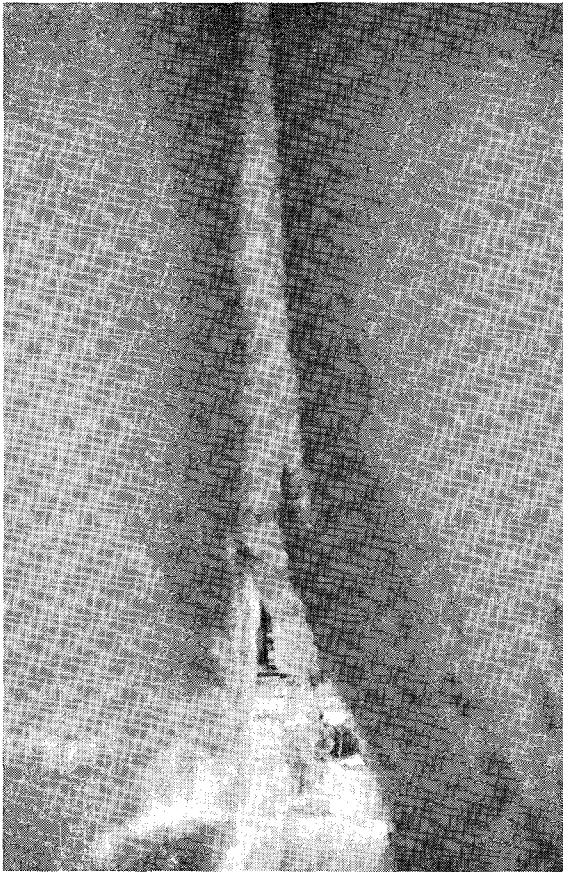


Simplified Plan View of Test Gallery Showing Section of Seal
in the Order They Were Formed (Test 1). Arrows Indicate Camera
Locations for Respective Photographs "A" thru "G"

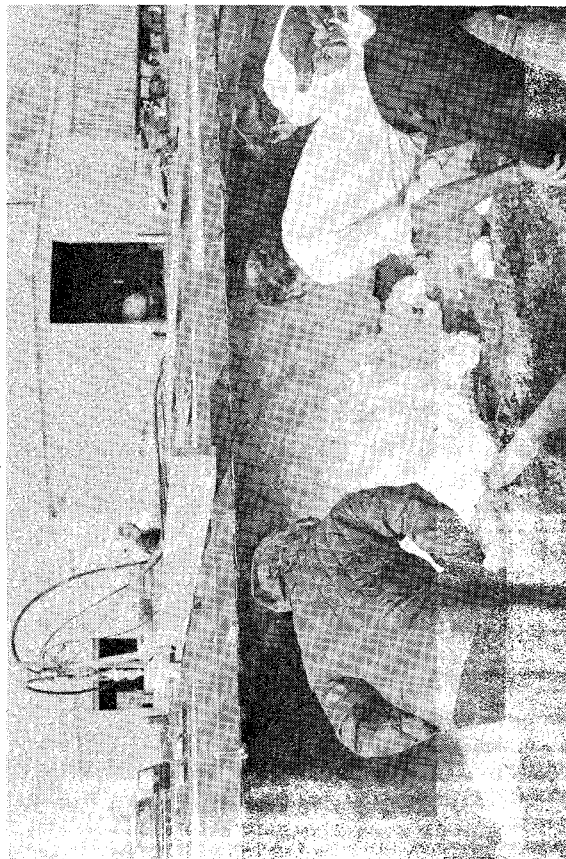
Figure 61



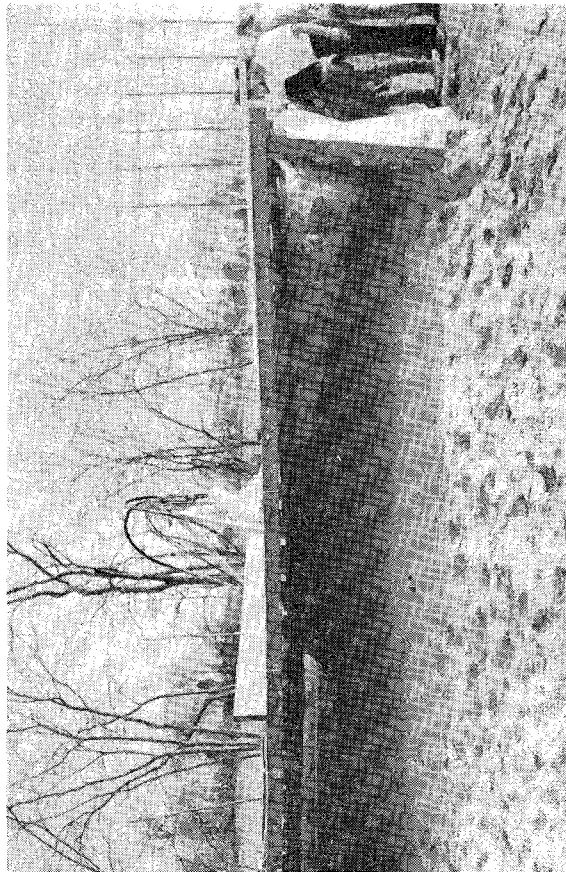
(a)



(b)



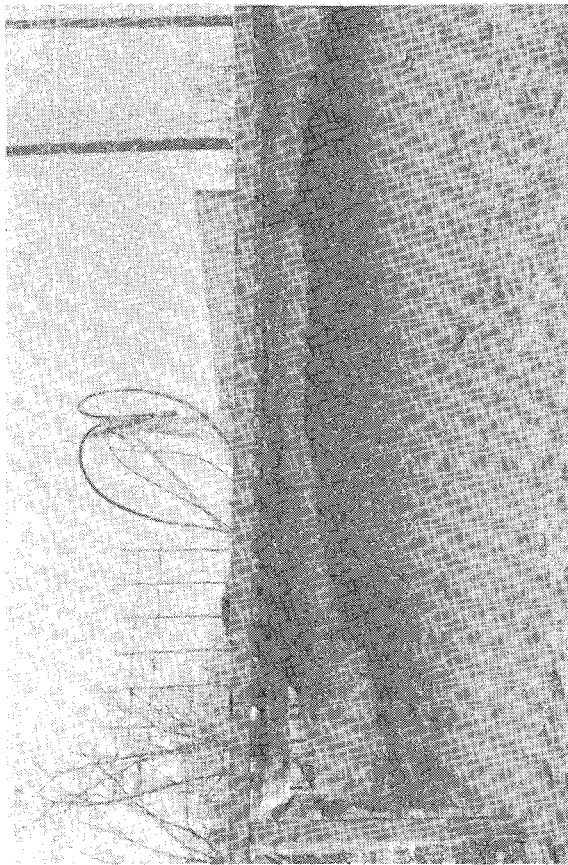
(c)



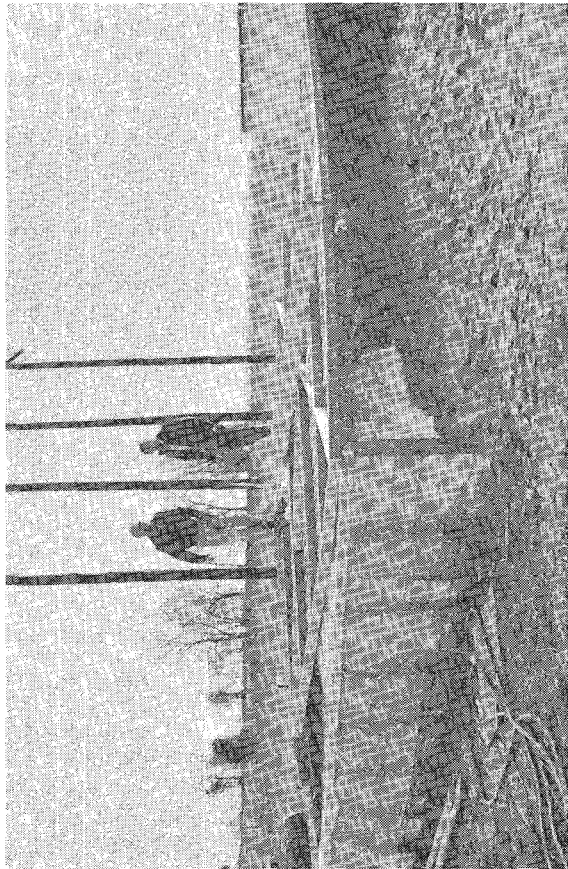
(d)

Foam Sealing in Gallery, Test No. 1

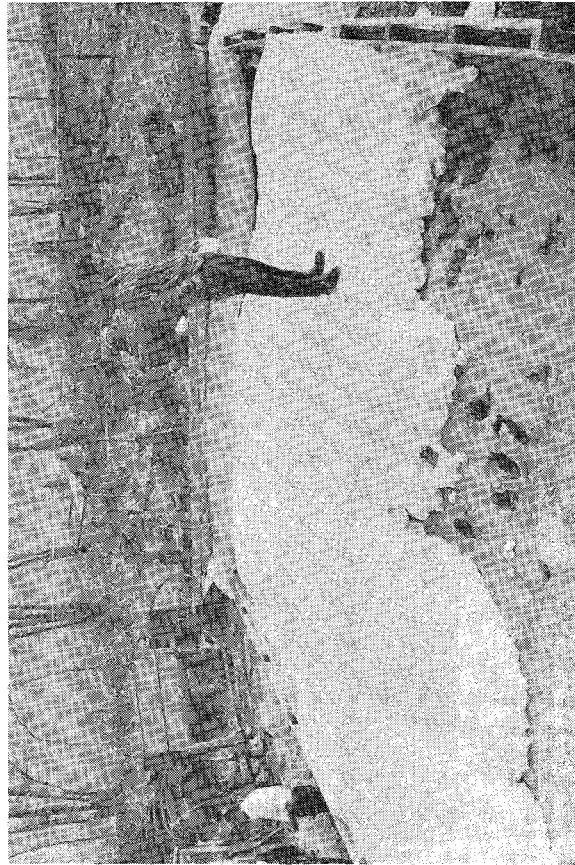
Figure 62



(e)



(f)



(g)

Foam Sealing in Gallery, Test No. 1

Figure 62 (cont.)

and photographs 'a' through 'g' of Figure 62 . Figure 62 (g) shows a plan view of the foam distribution with a roof of the gallery removed. During foaming, the foam material did not spread uniformly over the sand pile, but rather flowed in the form of a channel, 4-to 6-feet wide. The channel flow would continue until increased flow resistance due to foam expansion and increasing tackiness resulted in stoppage. The foam in this channel would continue to expand and bridge the roof developing into a type of foam segment shown in Figure 61c. Further flow would then channelize in the direction of least flow resistance, leading to the formation of another foam segment. This process would continue until the area was sealed.

Figure 61 shows a sketch of the foam segments of the completed seal. The segments have been numbered sequentially as they developed. The initial flow of foam filled the crater in the middle of the sand pile and flowed out radially in all directions until segment 1 had developed into an 8-foot diameter circle. The foam then channelized to form segment 2, flowing for about 8 minutes down this channel, stopping, and setting just at the end of the gallery. Further foaming led to the development of segments 3 and 4 and the development of a complete seal within 25 minutes from the start of the test. Further foam flow seemed to be confined to the center of the gallery, where it began lifting the roof as shown in Figure 62 (f). The foam flow was stopped 30 minutes after the test started. At a foam flow rate of 50 lbs per minute this represented 1500 lbs of foam.

After the test, the roof was removed verifying that a total seal had indeed been created. The final seal with the roof removed is shown in Figure 62 (g); the ripples on the surface of the foam were caused by the foam's following the contour of the corrugated metal roof.

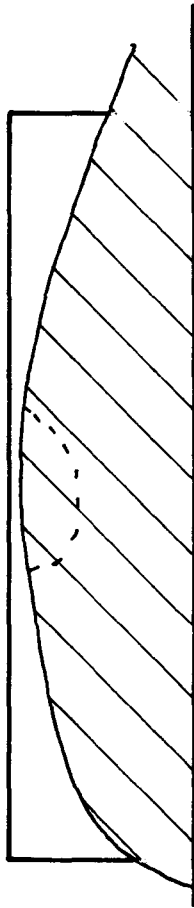
The operator of the system, who was monitoring the pressure and flow rates, indicated that at no time did the readings give any indication as to when the total seal had been formed; the flow of foam was stopped only because it could be visually verified that the seal was complete and that further flow was lifting the roof.

6.4.3.3 Second Test - Off-Center Borehole

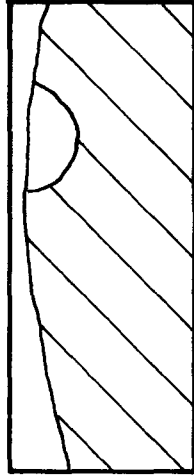
Several parameters were changed for the second test. The roof was bolted to the two side walls to prevent the foam from lifting it up. The geometry of the sandpile was changed to provide a much lower angle of repose, as shown in Figure 63 and photograph 65 (a). The borehole location and accompanying crater were also relocated, putting them 5 feet from the side wall instead of on the gallery centerline.

The foam seal development is shown in Figures 64 and 65. Once again flow channeling and segment development were observed. The initial flow of foam again filled the crater and then proceeded radially outward in all directions. The wall close to the borehole was sealed up to the roof in less than 5 minutes after the test start and before the foam had begun to channel in one direction. Once again the channelized foam flow stopped just at the edge of the gallery.

Segments 1, 2, 3 and 4 constitute a complete seal which was achieved in 20 minutes with 1000 lbs of foam. No bowing of the roof was observed at this time. Segment 5 developed subsequently and represents another 8 minutes of foaming. Some bowing of the roof and leakage in the gallery wall were observed during the development of segment 5. Foam flow was stopped 31 minutes after test start. As in the first test, the stopping time was arbitrary with no indication from the control equipment as to when a total seal had been formed.



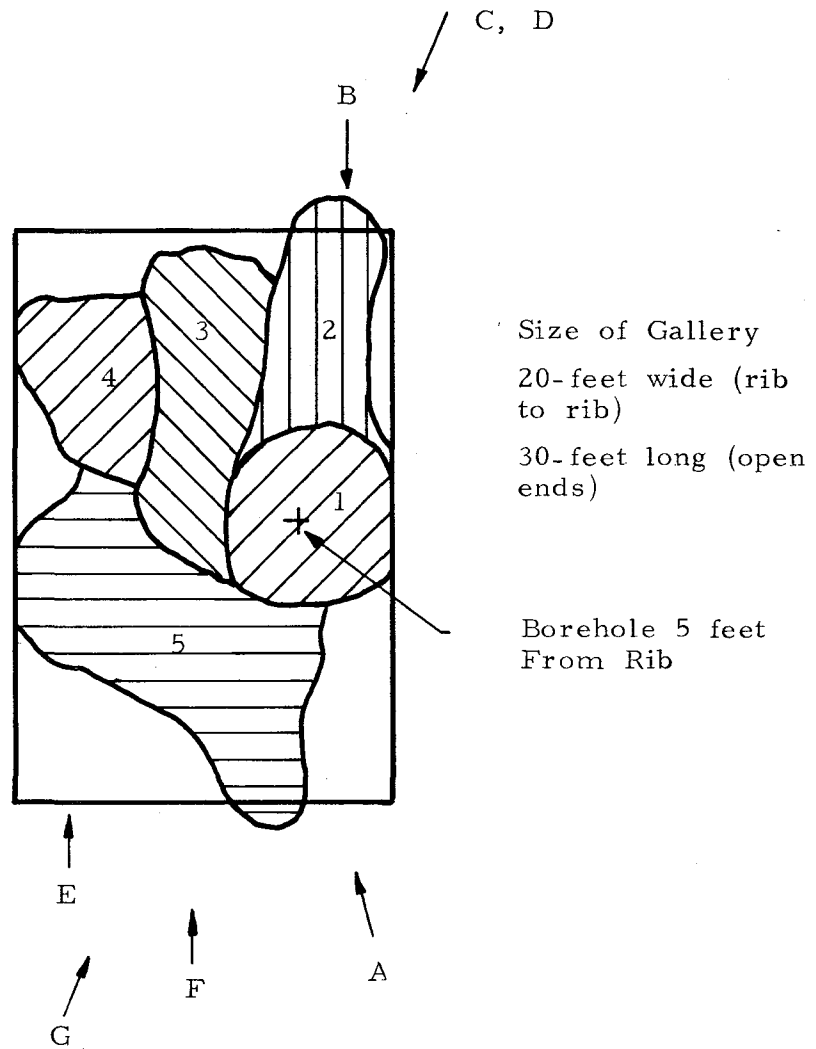
Lengthwise cross-section
down center of gallery



Width-wise cross-section
across middle of gallery

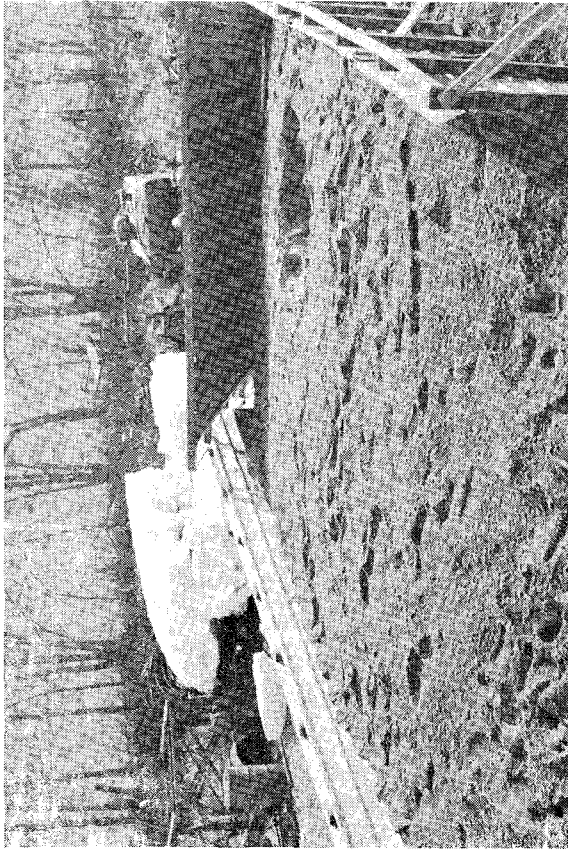
Test 2, Cross-Sectional Views of Sand Pile, Simulating Fly Ash Seal

Figure 63

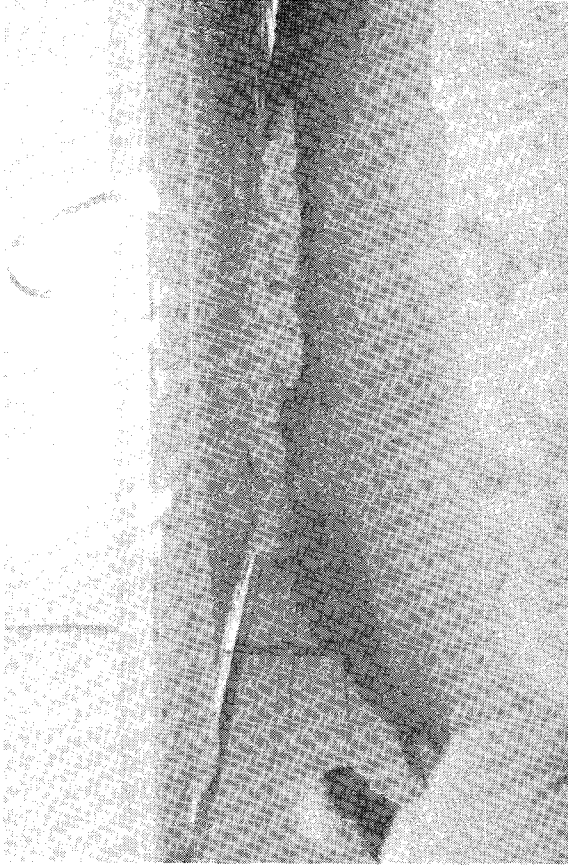


Simplified Plan View of Test Gallery Showing Section of Seal in the Order They Were Formed (Test 2). Arrows Indicate Camera Locations for Respective Photographs "A" thru "G"

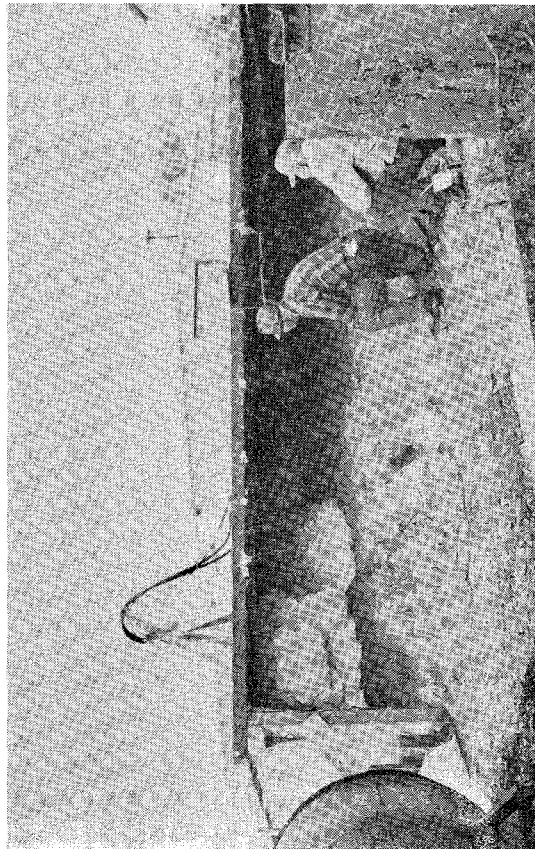
Figure 64



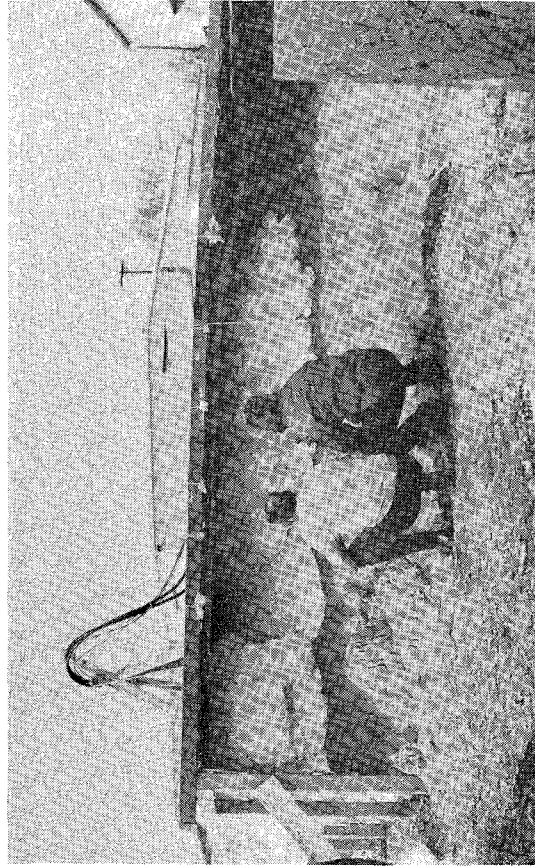
(a)



(b)



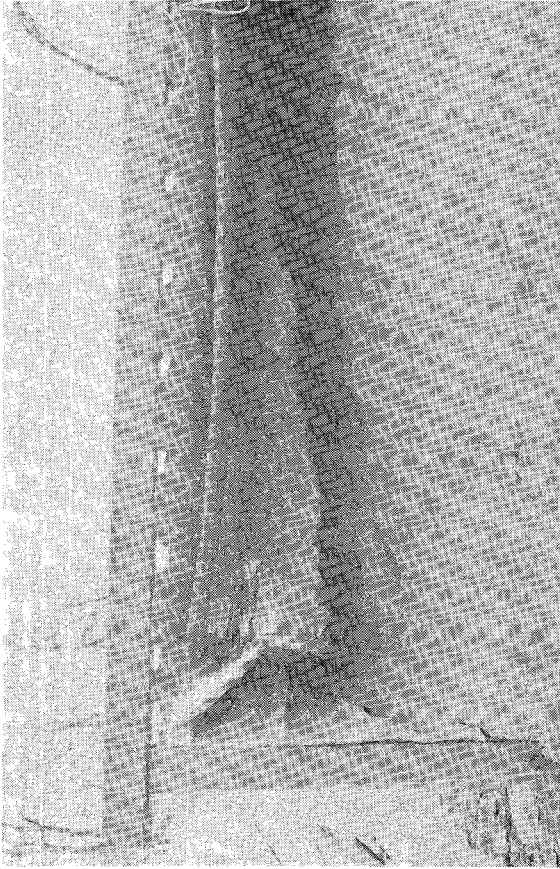
(c)



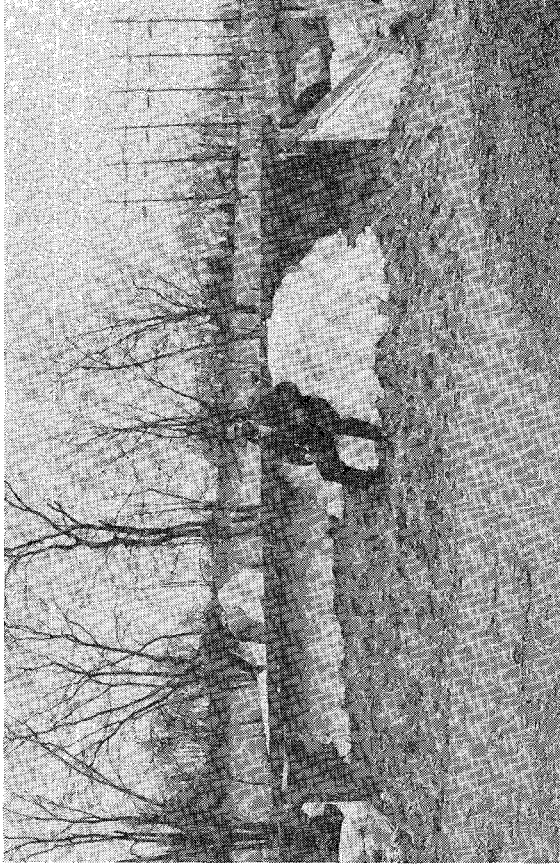
(d)

Foam Sealing in Gallery, Test No. 2

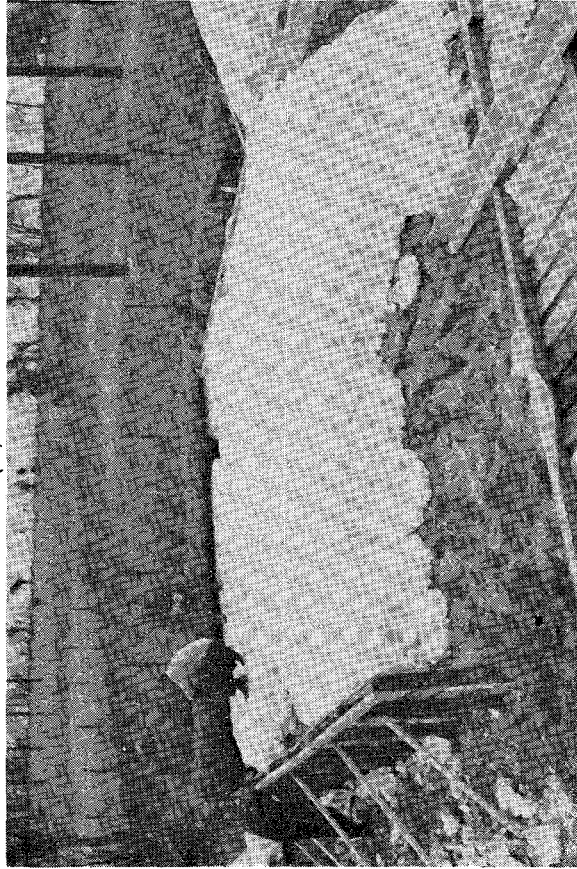
Figure 65



(e)



(f)



(g)

Foam Sealing in Gallery, Test No. 2

Figure 65 (cont.)

The final seal with the roof removed is seen in Figure 65 (g). Examination of the seal provided strong evidence that the foam had been able to fill in segment 5 by pushing up the roof and flowing over previously placed material.

6.4.4 Results and Conclusions

In general, the results of the foam test were most encouraging. In two tests utilizing very different bulk-filler geometries and borehole locations, the foam was able to form 100 percent seals. In addition, the seals were quite solid (the average thickness of both seals was at least 15 feet) and were placed under significant pressure, as witnessed by the lifting and lowering of the roof.

The presence of a crater in the bulk-filler provides an excellent receptacle for the uniform filling of foam. In both cases, flow channeling did not start until after the crater had been filled. Channeling results in nonuniform foam distribution and increased material usage. To minimize both, the bulk fill should be formed with a shallow but large-diameter crater preferably extending to the passage walls.

There are, however, some potential drawbacks to this foam system. It is evidently impossible to determine from the foam system monitoring equipment when a complete seal has been formed. This means that the system will either have to be run for a predetermined length of time, or else the seal-checking system must be used to monitor the foam seal as it is placed to indicate when the last gap has been bridged.

There is also some concern over the validity of the test results because of the compliance in the gallery roof. Short of an actual mine demonstration, there appears to be no

reasonable method of being 100 percent sure that bowing of the test roof did not enable the foam to flow over itself to permit channelling in a new direction after the primary flow stopped. However, reasonable engineering judgement of the test observers was that the major lifting of the roof occurred after a 100 percent seal had been formed. Furthermore, it is anticipated that the proposed bulk material, pneumatically-injected fly ash, will be compressible enough to provide much of the compliance, which the roof provided in the test program, if this were indeed a factor.

Noxious fumes were strongly in evidence in the test program due to the TDI component of the foam. While not a factor in an actual sealing program in a mine abandoned because of fire, these fumes might be a nuisance in the working mine to be used for testing. It was therefore recommended that MDI or PAPI be substituted for TDI during the test program.

Finally, the hazards of foam flammability still remain. The frothed foam mixes extremely well, minimizing the hazards of spontaneous combustion. However, the set foam used in these tests will burn in the presence of an open flame. New formulations, now being made available, may well significantly reduce this hazard. Furthermore, the use of foam only as a topping means that the exposed foam area is very small when compared to its total mass.

In summary, the success of the full-scale testing indicated that the foam topping system could be used in the Grant Town testing program with reasonable expectation that a 100 percent seal would be formed.

6.5 Development of the Foam-Concrete Slurry Mine Sealing Technique

During the laboratory testing and evaluation phase of the program, the possibility of making a seal with some type of slurry was given serious consideration. Particular attention was given to the development of a controlled-set slurry, which would build itself up in a pile as poured to form a seal. Appendix B describes the laboratory program in greater detail. The basic results of this program are described below.

It was concluded that the use of foam (aerated) concrete would be the most economical and efficient slurry for mine sealing. Several commercial and chemical additives were tested for rapid setting capabilities, and two mixes were found to be most effective for controlled setting -- one with CaCl_2 additive in cement and one with NaHCO_3 additive in a fly ash-cement mix.

These two mixes were tested for ability to support their own weight at heights up to 6-feet, and the NaHCO_3 mix was found to be the most effective, piling up at a maximum angle of 45° . This same mix was then tested in a 1/4-scale simulation of a full seal. It was found that the slurry developed radial failures, as opposed to failing under gravity. These failures caused excessive spreading of the seal. It was determined that this slurry as demonstrated would be unsuitable for mine sealing. Modifications to the slurry system were considered, including the addition of clay for improved cohesion, and the use of a spray to minimize radial pressure. Time limitations, however, forced the discontinuation of the slurry program.

6.6 Conclusions

The results of this laboratory development effort have led to the following conclusions:

- (1) Good, air-tight seals can be made with fly ash alone using the high velocity cratering technique at a flow rate of 80 scfm in the quarter-scale mine facility.
- (2) A scaling relationship has been derived from which the air flow rate required for any mine passage geometry can be computed. The air flow rate in scfm is proportional to (mine passage width)^{5/2}.
- (3) The fly ash cratering technique is an effective method for bulk filling of the mine passage for subsequent seal topping with foam.
- (4) Polyurethane froth foam is an effective final sealant. The mixing head for the froth-foam system uses a static mixer which is simple, compact and reliable. With minor modifications the available system can be used for deployment down a 400-foot, 6-inch diameter borehole.
- (5) Fly ash alone can satisfactorily seal a mine passage containing pools of stagnant water and mine passage water flows of up to 5 to 10 gpm. Higher water flow rates up to 50 gpm cannot be sealed using water alone. A special system is required.

- (6) The special system for sealing with a high mine passage water flow rate and subsequently retaining a 15-foot water head would consist of:
- (a) Downhole aggregate distributor to lay an aggregate bed on the passage floor.
 - (b) Grout pipe deployed in the gravel bed.
 - (c) Bulk sealer using a fly ash-cement mixture containing 16 percent of fast setting cement.
 - (d) Froth-foam final seal.

The performance of such a system was demonstrated on a small scale in the laboratory.

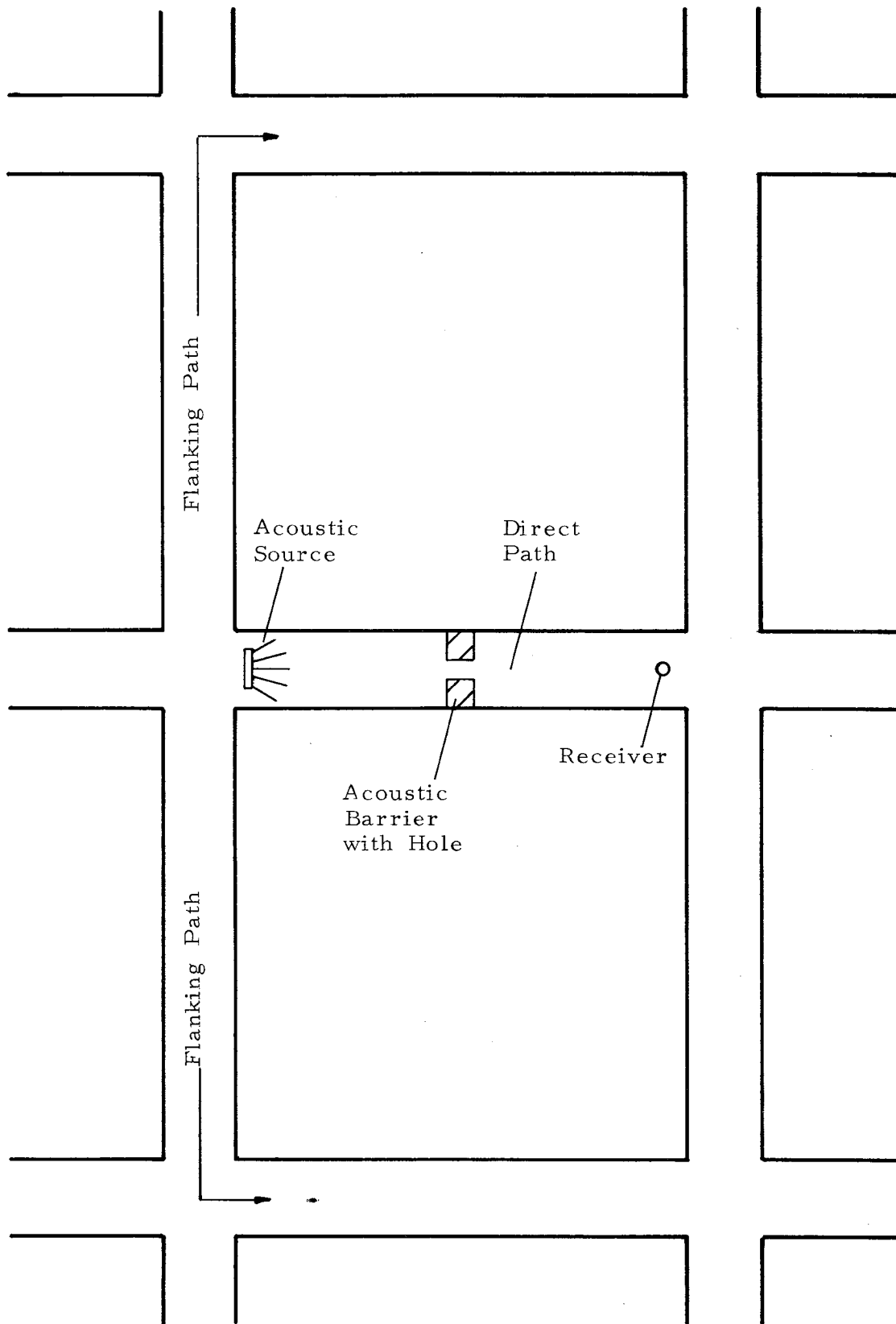
7. Development of Acoustic Seal Checking System

The acoustic approach was shown in Section 4 of this report to be the most promising concept for checking the seals. This section describes the development of this concept into a working hardware system to be used later in the field test program. This development effort included:

- (1) Theoretical analysis of the acoustic behavior in the mine using acoustic modeling techniques.
- (2) Experimental determination of acoustic patterns in mine passages.
- (3) Refinement of the theoretical model.
- (4) Verification of final theoretical predictions in the quarter-scale laboratory model of a mine passage and seal.
- (5) Development of system specifications.
- (6) Development of the Acoustic Prototype Seal Checking System.

7.1 Analysis of the Acoustic Seal Checker Concept

The acoustic seal checker concept is based on a model which combines corridor acoustics and hole transmission theory. The idealized model for the mine sealing application is shown schematically in Figure 66. A high intensity acoustic source is located in a corridor at a position adjacent to the location to be sealed. The acoustic signal transmitted through the seal is monitored by a microphone pick-up placed on the opposite side.



Idealized Model for Acoustic Seal Checker Analysis

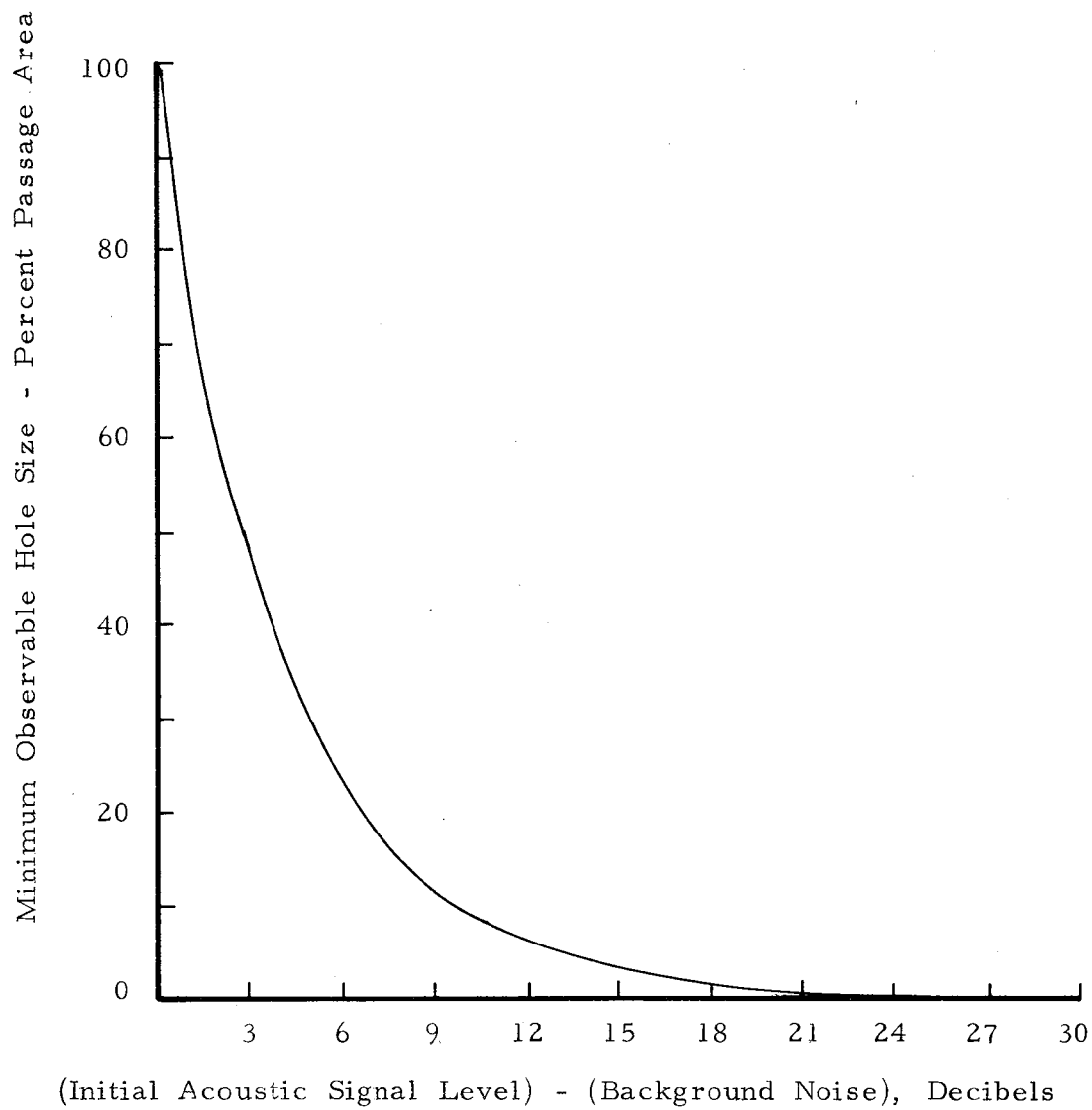
Figure 66

The model also accounts for the effect of flanking paths with a variety of three-and four-way intersections.

The analysis was designed to determine the intensity of the acoustic energy which arrives at the monitoring location via both the direct and flanking paths. Variation in these levels with hole size, frequency, material properties, flanking path length, and hole shape were considered. The details of this analysis are presented in Appendix D.

From the results of this analysis the following conclusions are drawn:

- (1) The level of the acoustic signal reaching the monitoring point directly from the source will decrease 3 decibels each time the cross sectional area of the opening in the seal is halved.
- (2) Two factors affect the size of the hole which may be perceived - the level of background noise and the length of the flanking paths. In the absence of flanking paths, limits on the observable hole size may be determined from Figure 67 by knowing the original cross-sectional area of the passage, the background noise level, and the original sound level at the microphone.
- (3) A directional source may be employed to favorably apportion the acoustic energy which travels the direct path, thus increasing the hole sensitivity and reducing the interference from flanking paths.



Minimum Hole Size Observable with Acoustic Seal Checker

Figure 67

- (4) Flanking path interference may be completely eliminated through a pulse gating system which pulses the sound source intermittently and then gates the receiving system to listen only during the period when sound arrives along the direct path.

For typical mine sealing situations the direct distance between the sender and the receiver is expected to be of the order of 50 to 80 feet and the flanking path length 150 to 240 feet. Thus, approximately a 100 to 160 millisecond delay is to be expected between the arrival of the direct and indirect signals at the microphone. The listening gate would be designed to be smaller than this delay so that the microphone always listens to the direct signal only.

Thus, the acoustic energy from the flanking path can be excluded and the system made independent of flanking path length at the price of greater system complexity. With the pulse gating system the observable hole size depends only on the intensity of the sound source and background noise.

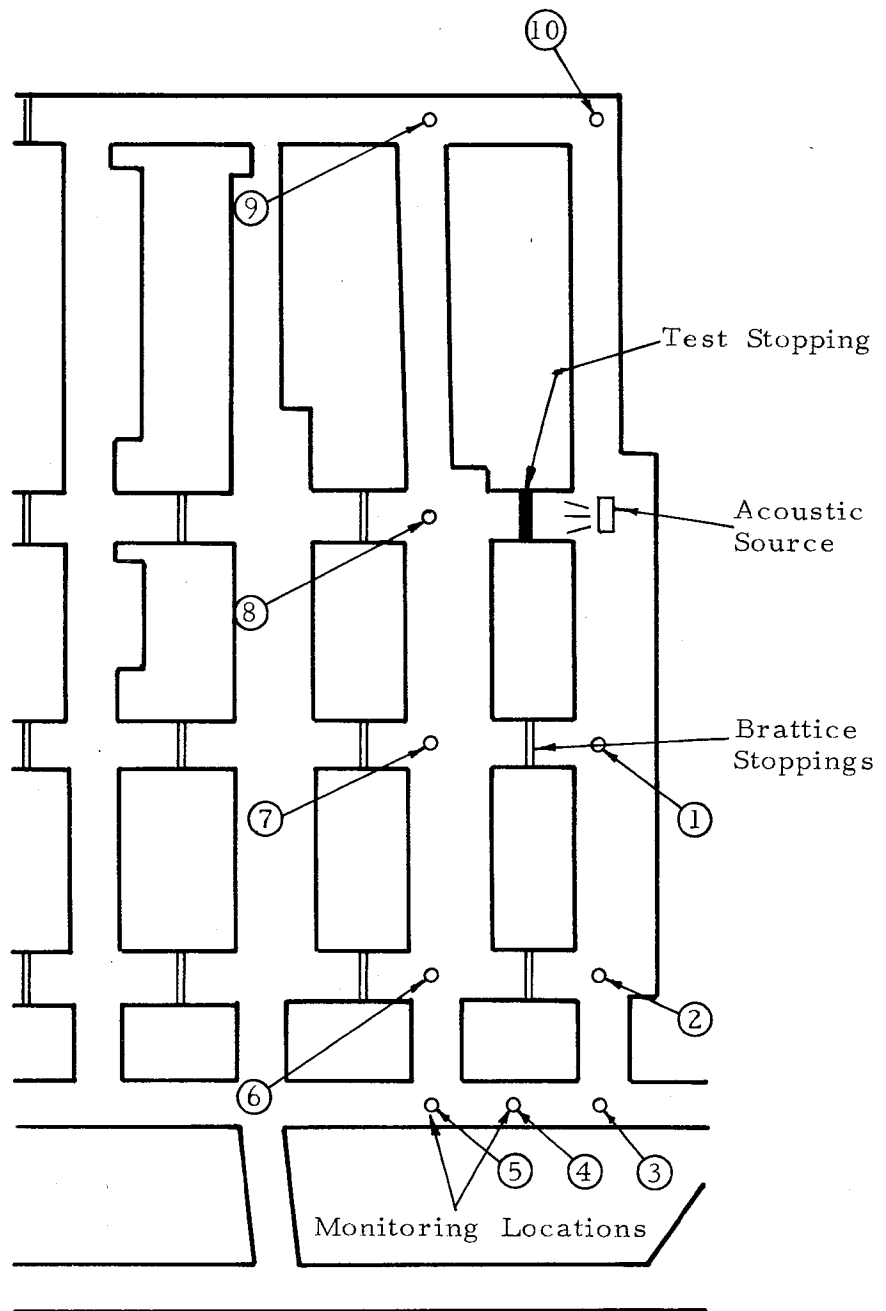
7.2 Experimental Verification of Theory

In order to verify the corridor model and the hole transmission theory, a preliminary experimental program was undertaken at the U.S. Bureau of Mines Experimental Mine at Bruceton, Pennsylvania. The purposes of this program were:

- (1) to verify the validity of applying the corridor model of acoustic behavior to a coal mine situation
- (2) to establish the validity of the hole transmission theory for holes in stoppings in the mine
- (3) to determine the most satisfactory frequency range for the seal checking application
- (4) to determine absorption coefficients for the corridor model. Attenuation along the corridor may be predicted based on this coefficient.

A signal generator, power amplifier and powerful driver were employed to produce a high intensity acoustic signal over a wide range of frequencies. A soundproof stopping was constructed of wood, wire mesh and sodium silicate foam by U. S. Bureau of Mines personnel. It was located in a crosscut between two entries in a typical location for a seal. The layout of the mine in the vicinity of the stopping is shown in Figure 68 with the monitoring points indicated. Photographs describing the experimental program are presented in Figure 69 .

Using pure tones at frequencies ranging from 250 kHz to 16 kHz the sound pressure level was measured at all ten locations shown on Figure 68 . These tests were run with a full stopping and then with holes of increasing size cut through the stopping. The tests generated a series of sound pressure level profiles in the passages near the stopping. These profiles for the several frequencies and several hole sizes provide the information required to evaluate the general theory and permit prediction of the acoustic behavior in other mine locations.

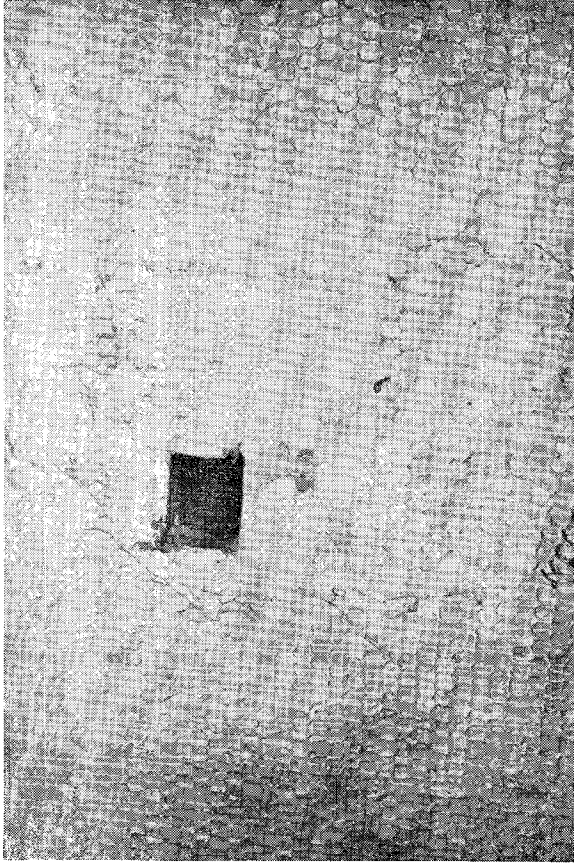


Layout of Mine for Theory Verification Tests

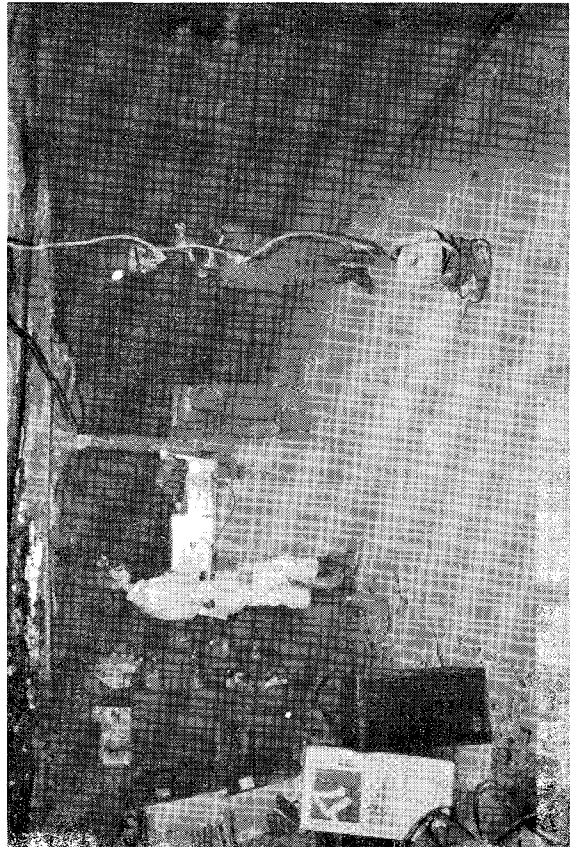
Figure 68



(a)



(b)



(c)

- (a) Acoustic Source Directed at Test Stopping
- (b) Hole in Test Stopping
- (c) Sound Level Data Collection

Acoustic Test Program at Experimental Mine

Figure 69

Based on the results of this experimental evaluation, the feasibility of the acoustic technique for determining seal completeness was verified. It was shown that direct field estimates for transmission through a hole in the stopping adequately predict the noise level beyond the stopping. Conversely, the intensity of the sound beyond the stopping can be used to determine the size of the hole.

A factor of 0.275 db/foot was established for the attenuation along the corridor in the far field. Although the numerical value of the attenuation could vary for passages of different sizes, the general approach of using an empirical attenuation factor together with a factor for geometric connections to predict flanking behavior was verified.

Broad band noise from 500 kHz to 4000 kHz was found to be the most satisfactory frequency range. This frequency range represents a compromise. It is sufficiently high to allow some directionality from the source yet low enough to take advantage of a relatively uniform field in the passage beyond the seal. Broad band noise was selected over a pure tone in order to eliminate the nodes and antinodes which occur at positions along the corridor when a pure tone is employed.

Based on the results of this experimental program, a laboratory version of the proposed seal checker was constructed and installed in the quarter-scale model mine passage to permit monitoring the actual emplacement of a seal.

7.3 Laboratory Verification of Theory

The experimental program described in the previous section determined typical absorption coefficients for mine passages. It also verified that corridor acoustics and hole transmission theory

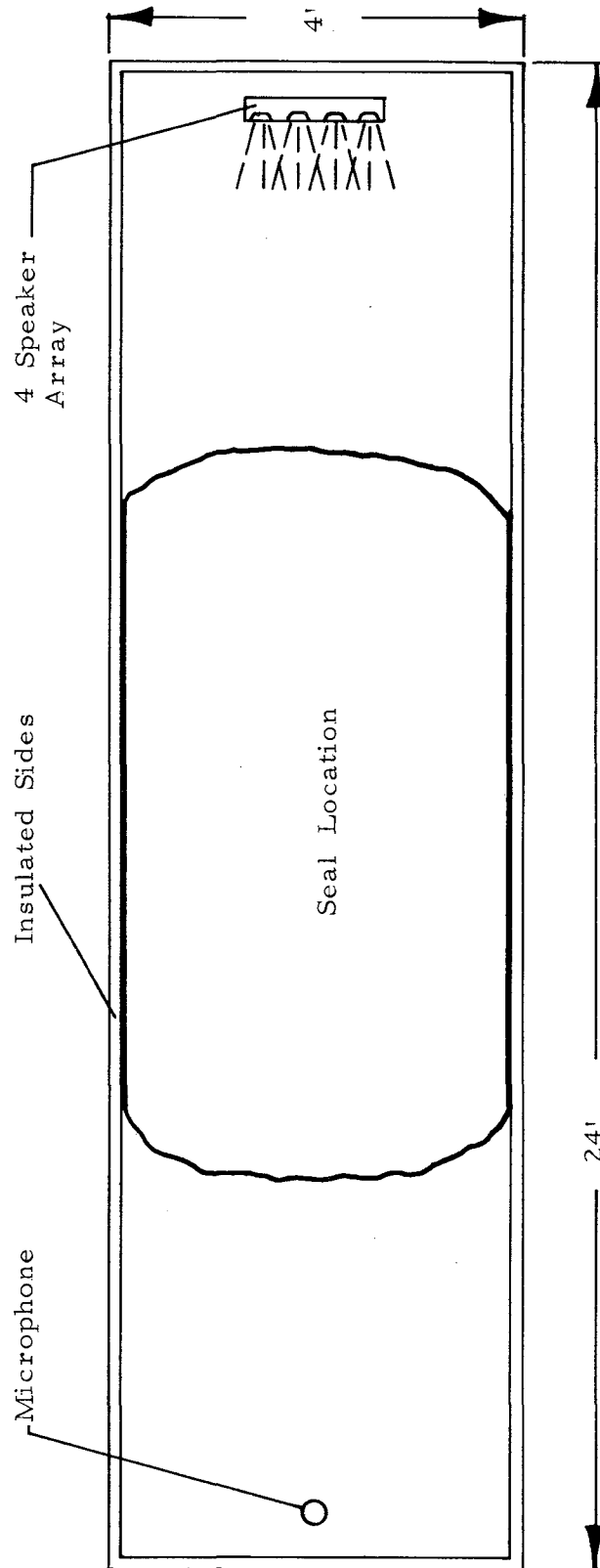
can satisfactorily predict acoustic behavior in the mine. The "holes" in the soundproof stopping in the experimental mine did not necessarily simulate the leakage paths to be expected in the case of a full-scale passage seal. While actual leakage paths are long relative to their other dimensions due to the thickness of the seal, those of the simulated stopping were extremely short. The acoustic properties of the material from which the stopping was constructed also differ markedly from those of fly ash. To determine the effect of the passage geometry and material properties on the acoustic behavior, a series of tests were performed using the quarter-scale model mine passage in the Foster-Miller Laboratory.

7.3.1 Laboratory Facility

The laboratory tests employed the quarter-scale model mine passage described in Section 6.2.5.1. For the acoustic seal checker tests the model was modified by the addition of three layers of 1/2-inch Desoban* insulation board to all the interior surfaces of the passage. Insulation of the passage in this manner reduced the external noise transmission through the walls and thus reduced the ambient noise level in the passage. In addition, the insulation board reduced the sound transmitted along the box from one end to the other. Thus, the acoustic energy was not easily conducted through the walls along the sides of the seal.

Four speakers were installed in a row at one end of the passage and directed toward the other end. A sensitive ceramic microphone was inserted through the roof of the passage at the opposite end. The relative positions are shown on Figure 70. Polyethylene sheet of 1 mil thickness protected the speaker cones and microphone from excessive accumulations of fly ash without degrading the performance of the system.

* Trade Name.



Top View of Soundproof 1/4-Scale Mine Passage for Acoustic Tests

Figure 70

The TDL Pseudo-Random Noise Generator* and a power amplifier were used to drive the speakers. Because no flanking paths were available and flanking path characteristics had been established in the actual mine, the pulse gating was not included in these tests. The tests were run with a continuous acoustic signal. The sound intensity as sensed by the General Radio microphone was monitored using a General Radio Type 1561 Precision Sound Level Meter.*

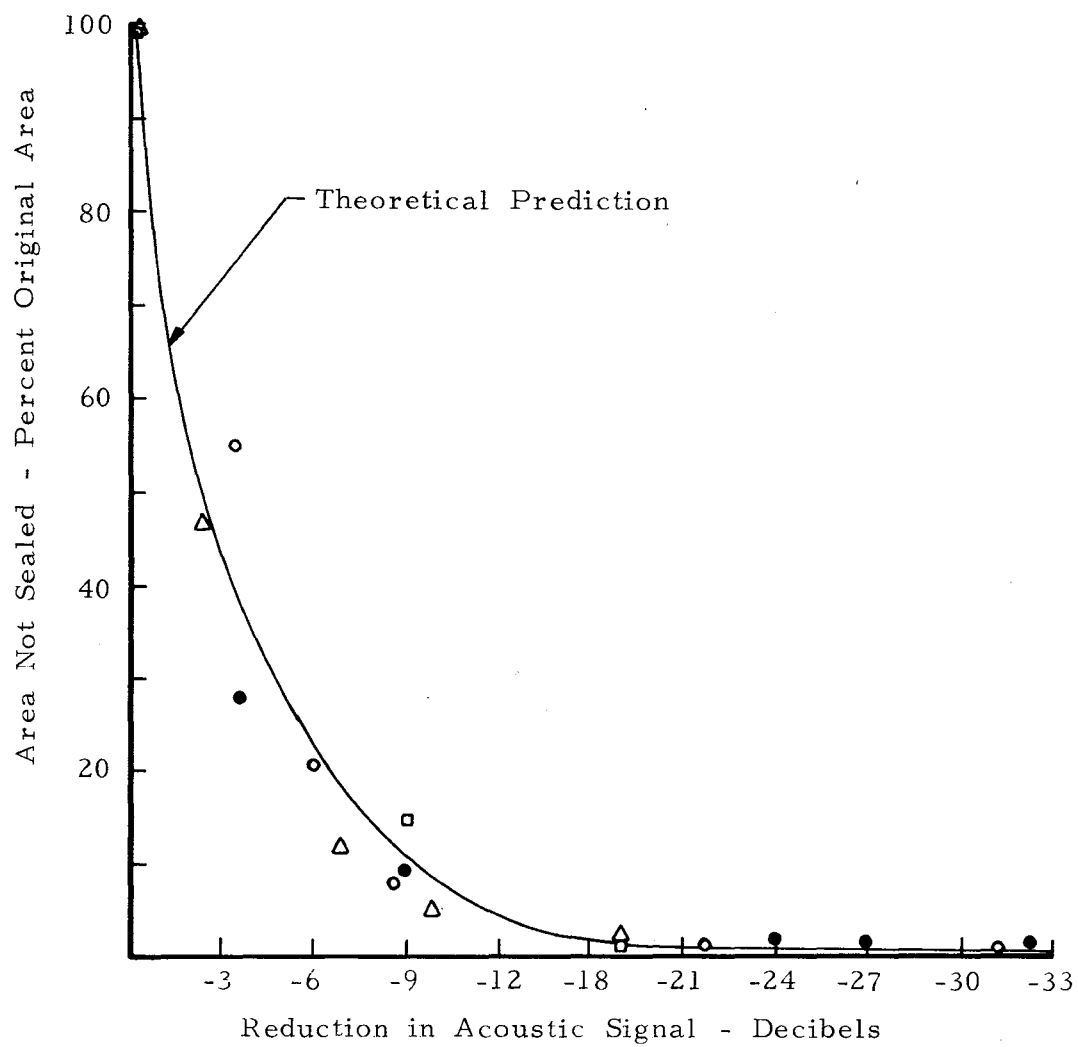
7.3.2 Procedure and Results

The acoustic seal checker laboratory tests were run in conjunction with several fly ash seal pouring tests. The procedure and equipment for pumping fly ash was as described in Section 6.2.5.2 except that interruptions in the pouring routine were more frequent to accommodate seal checker readings and visual observation of the seal.

A total of four fly ash seals were poured and monitored using the acoustic checker. The pumping parameters were varied to achieve a wide range of seal configurations and leakage path geometries. The leakage path varied from that of a triangular cross section in the upper corners to very thin slits along the roof of the passage. In all cases the pouring was continued until the seals were considered complete based on visual inspection. Seal checker readings after the seals appeared complete never indicated more than 0.1 percent area open. The failure of the checker to indicate a complete seal (by indicating only ambient noise levels in the presence of speaker inputs) was attributed to some leakage along the floor and roof of the passage.

The results of the four tests are summarized in Figure 71. The theoretical prediction of sound level reduction with area blockage is indicated clearly. The data points indicate

* Trade Name.



Summary of 1/4-Scale Test Program for Acoustic Seal Checker

Figure 71

the values actually obtained during the tests. The agreement between theoretical prediction and experimentally-obtained results is excellent. The spread in the data includes both experimental error and a wide range of seal geometries. Note how the results all converge at the critical time when the seal nears completion.

This experimental program indicated that the performance of the seal checking system was relatively insensitive to the geometry of the leakage paths and the material properties of the seal.

7.4 Prototype Seal Checker Design

7.4.1 Design Background

The theoretical predictions and experimental verification described in the preceeding sections resulted in a set of design specifications for the acoustic characteristics of the seal checker system. These characteristics coupled with the physical characteristics of the mine passages dictate many aspects of the system design. These desirable characteristics are summarized and discussed as follows:

- (1) The entire acoustic seal checker system must be deployable from the surface through 6-inch-diameter boreholes.
- (2) The total vertical clearance required under the borehole should be reduced as much as possible to prevent malfunction because of accumulated debris or rubble under the borehole.

- (3) A frequency range of 500 to 4000 kHz is most satisfactory for the mine seal application.
- (4) A directional source is desirable to improve the sensitivity of the system in the presence of flanking path interference and improve the efficiency of the acoustic input system.
- (5) A pulse gating circuit for the speaker-microphone system is desirable to completely eliminate the effect of flanking path interference. The pulse gating circuit must be adjustable to accommodate a wide range of direct paths and flanking paths.
- (6) Having eliminated the effect of flanking paths, the sensitivity of the acoustic approach is directly related to acoustic power generated at the acoustic source. This demands high electrical power into the speakers as well as efficient speakers.

Satisfactory and reliable system operation was considered essential to the success of the field test program. Consequently the system was overdesigned.

- (1) All potentially desirable features were included in the design. The relative merits of the several features were to be evaluated during the field test program.

- (2) Excess capacity was built into each feature to maximize confidence in the final results.
- (3) A simple yet reliable deployment system was utilized, essentially the same as for the initial probing system.

Field testing of the system in an operating coal mine required that the system be designed for intrinsic safety. This requirement imposed a limitation on input power resulting in a reduction in system sensitivity. It also increased the complexity of the deployment system. Such a limitation would not exist in an actual application of the system. Thus increased system sensitivity and a simplified deployment system could be achieved.

7.4.2 General System Description

The acoustic seal checker system is composed of several major subsystems. These include:

- (1) signal generator system
- (2) power amplifier
- (3) high power linear acoustic array
- (4) microphone and preamplifier
- (5) signal processing module
- (6) speaker and microphone deployment subsystems.

The operational relationship of these subsystems is presented graphically on Figure 72. The details of construction and operation of each subsystem are presented in the following sections.

7.4.3 Signal Generator Subsystem

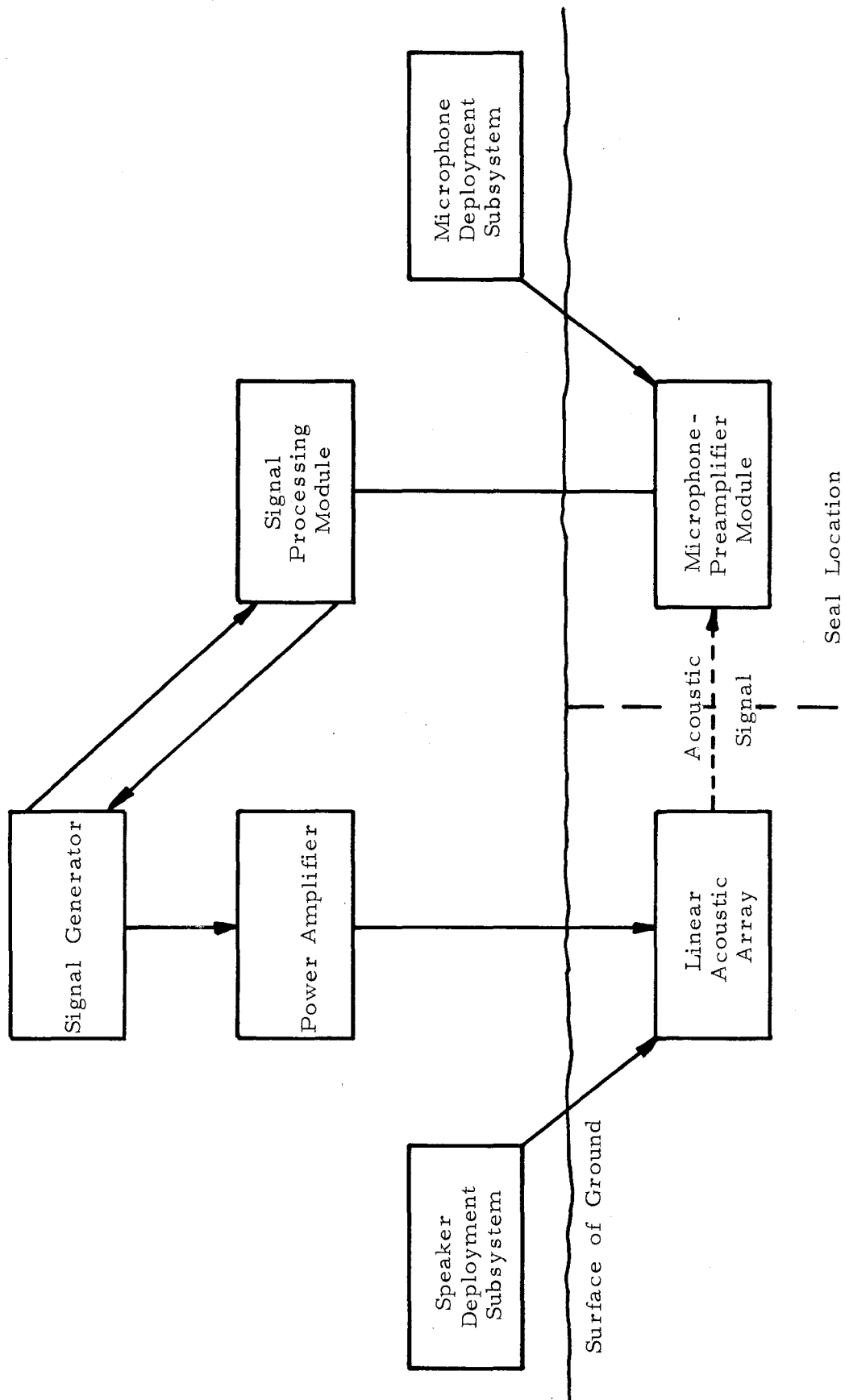
As determined in the preliminary investigation, the most desirable acoustic signal for the seal checking application is pulsed, broad band noise in the 500 kHz to 4000 kHz frequency range. Pulsing the input permits gating the received signal to eliminate flanking path interference. The frequency range described is sufficiently high to allow some source directionality, yet low enough to take advantage of a relatively uniform field in the passage beyond the seal. The broad band feature eliminates the nodes associated with pure tone transmission down a corridor.

A Model 108 Pseudo-random Noise Generator from Testronic Development Laboratory* in LasCruces, New Mexico was easily modified to produce the desired signal. It is capable of producing bursts of 200, 300 or 500 millisecond duration as well as continuous noise. The Model 108 generates a pseudo-random binary sequence when driven by the internal crystal-controlled clock. This sequence is then low-pass filtered to produce a continuous noise waveform with a near-Gaussian amplitude distribution. For our application, a high pass filter was added to limit the frequency band to the 500 to 400 kHz.

7.4.4 Power Amplifier

A Bose 1801 Solid State Dual Channel Power Amplifier* was selected to amplify the output of the random noise generator. This amplifier was selected for its rugged construction,

* Trade Name.



Operational Block Diagram - Acoustic Seal Checker

Figure 72

adaptable circuitry, and potentially high output power with no distortion in the frequency range of interest. Only one channel of the amplifier was used for the test program, but both could be employed to produce higher sound levels for applications where intrinsic safety considerations do not limit the speaker input power.

7.4.5 Linear Acoustic Array

The output from the power amplifier was fed into a bank of eight powerful speakers. For this application we selected Bose 901* midrange drivers because of their small size, high power levels, rugged construction, reliability and acceptable frequency range.

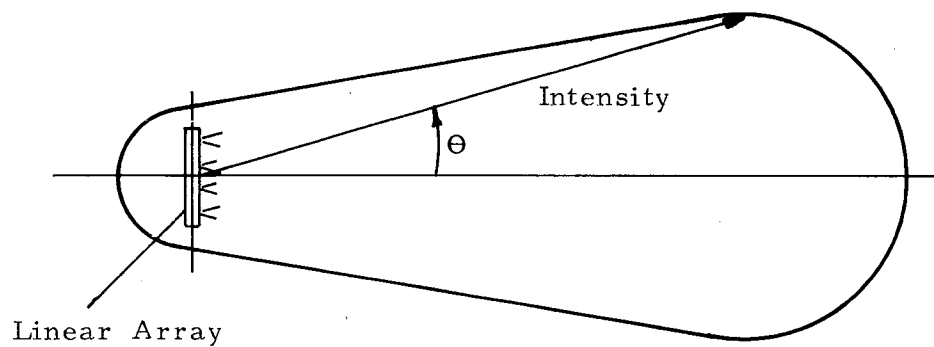
The drivers were mounted side by side in a 5-1/2-inch diameter cylindrical module approximately 4-feet in length. This speaker arrangement allows deployment through a 6-inch borehole and results in a directional sound source.

Prior to actual installation each speaker cone was waterproofed. One mil polyethylene sheet was stretched loosely over the face of the array to afford additional protection against foreign objects. Loose coverings of this sort do not degrade speaker performance. A photograph of the linear array is presented in Figure 73a.

The linear acoustic array approximated by this system possesses directional properties which may be employed to advantage to improve sensitivity and reduce the effect of flanking paths. A linear array produces an acoustic field like that shown in Figure 73b. The magnitude of the directionality is

* Trade Name.

(a) Photograph of Linear Acoustic Array



(b) Acoustic Field of Linear Array

Linear Acoustic Array

Figure 73

determined by the L/d of the source. The module must be oriented horizontally in the passage to take advantage of the directionality.

The eight drivers were wired in series-parallel with an additional eight ohm resistor as shown in Figure 74 to produce an equivalent eight ohm load for the amplifier. In order to meet intrinsic safety requirements, the series-parallel connections were made at the amplifier. Completely isolated circuits from the amplifier fed each individual speaker through 500 feet of cable. This required an 18 conductor 14 gage cable to avoid excessive voltage drop in the 500 feet of cable. This isolation of the speaker leads would not be required for the final seal checker system since intrinsic safety is not a consideration in a mine fire situation.

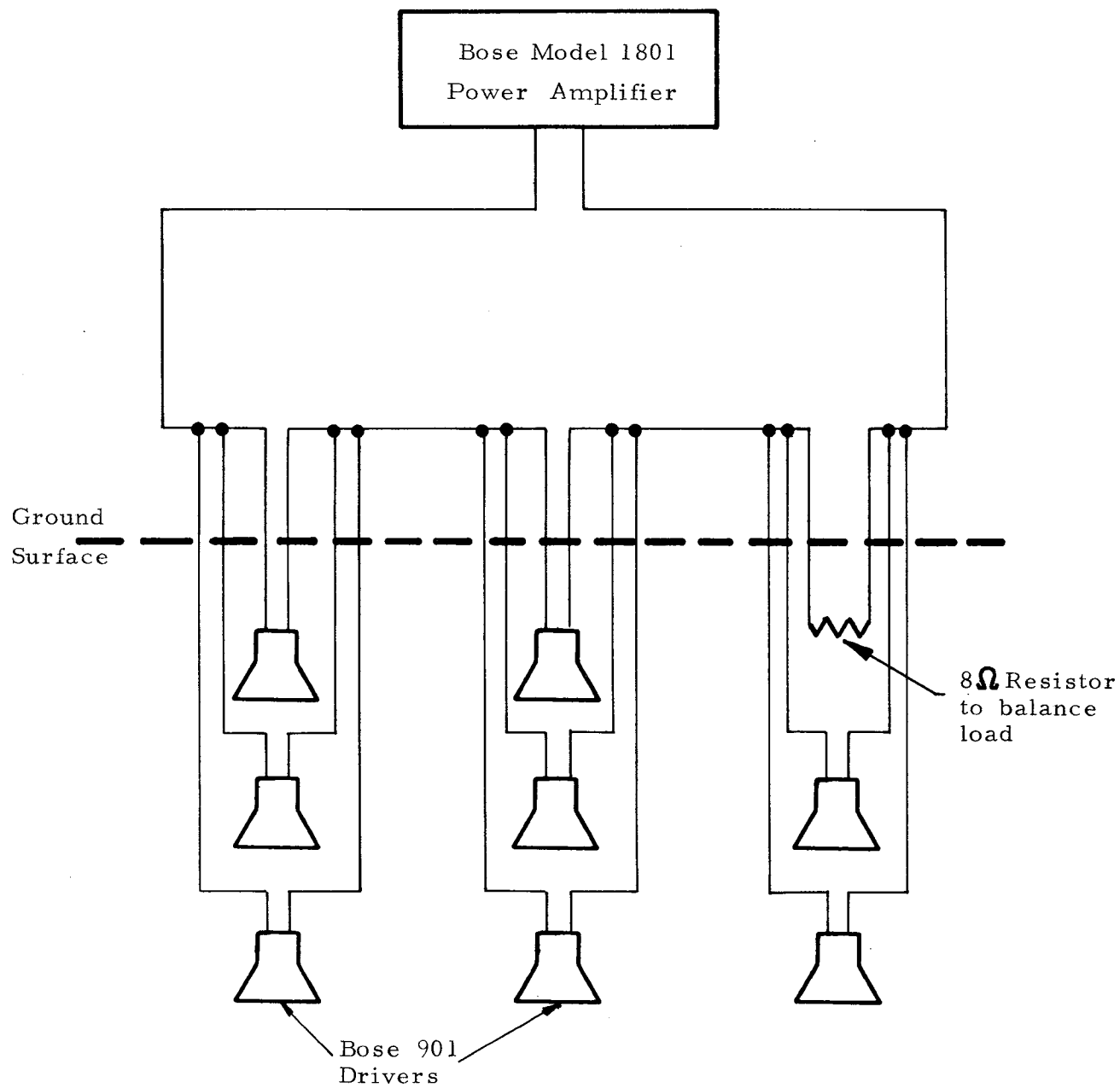
7.4.6 Microphone-Preamplifier Module

A General Radio* Type 1560-9570 Microphone and Type 1560-P40 Preamplifier were selected to monitor the acoustic signal from the linear array.

A ceramic microphone was selected because of its ruggedness, stability and reliability. The low impedance results in low preamplifier noise and high sensitivity as well as contributing to good performance under conditions of relatively high humidity. In addition, the ceramic units are self-generating devices and therefore require no polarizing voltage.

The 1560-P40 Preamplifier is a low noise amplifier designed to couple a microphone to a coaxial cable without voltage loss or with a voltage gain of 10 to 1. The preamplifier is required for this application because of the long length of lead from microphone to amplifier. Boosting the signal ahead of the cable improves the signal to noise ratio at the amplifier end of the cable.

* Trade Name.



Series - Parallel Speaker Array

Figure 74

Connections to the preamplifier were made through a three-terminal microphone connector at the output end of the preamplifier. Two pins carry the amplifier output while the third carries the power to the circuit. The power required by the preamplifier is 15 to 25 volts at 1 to 2 milliamperes. This power is supplied by the circuit of the sound level meter employed as part of the signal processing module and described in the following sections.

The microphone and preamplifier were rigidly mounted in a rugged housing. The housing shown in Figure 75 provides mechanical protection during the lowering operation. Compliant "bumpers" cushion impacts with the borehole to prevent mechanical shocks from being transmitted through the housing to the microphone. Electrical insulation was provided between the microphone-preamp and the housing to eliminate the possibility of unintentional grounds.

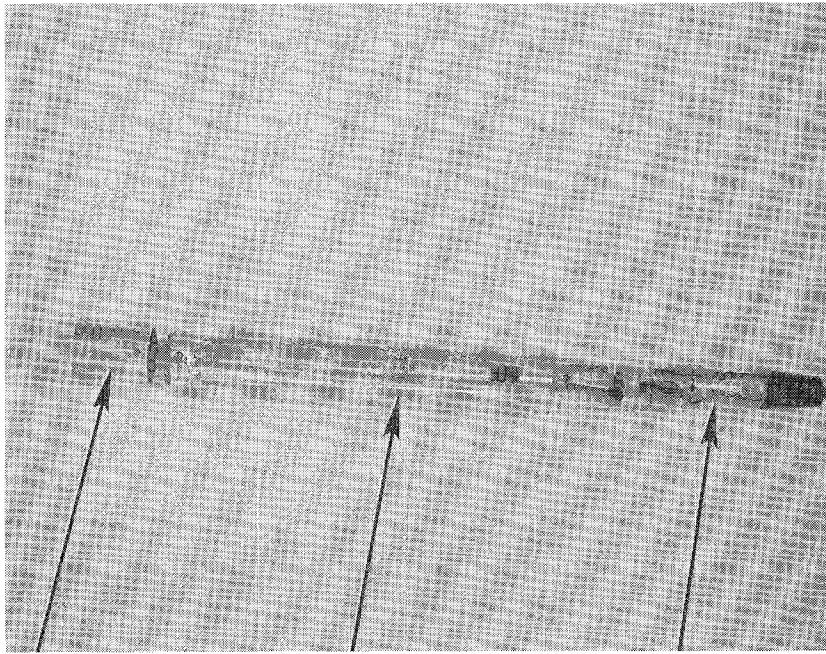
Moisture and fly ash protection was supplied without any decrease in sensitivity by using a 1 mil polyethylene sheet to cover the opening in the housing through which the microphone monitors the signal.

7.4.7 Signal Processing Module

The signal processing module includes the electronics required to convert the microphone-preamplifier output into a meaningful indication of the extent the passage is blocked.

An operational diagram of the electronics is presented in Figure 76. From the microphone preamplifier the signal enters a General Radio Type 1561 Precision Sound Level Meter.* This meter amplifies the signal and provides an indication of the instantaneous sound level at the microphone. The

* Trade Name.

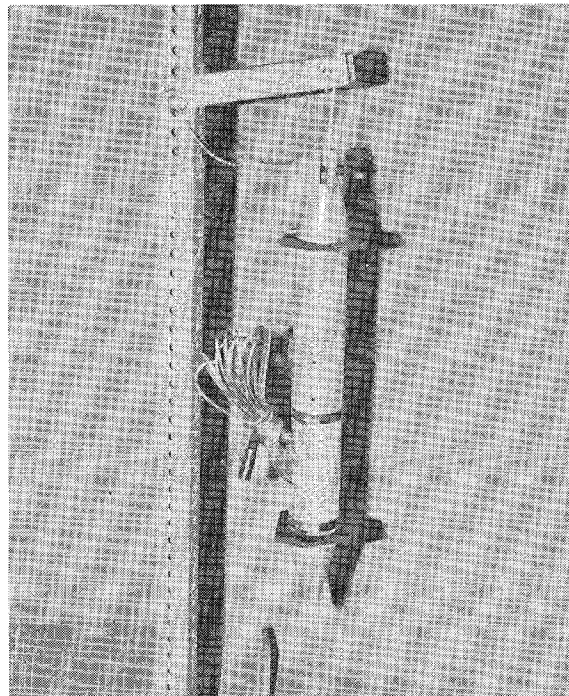


Microphone

Preamplifier

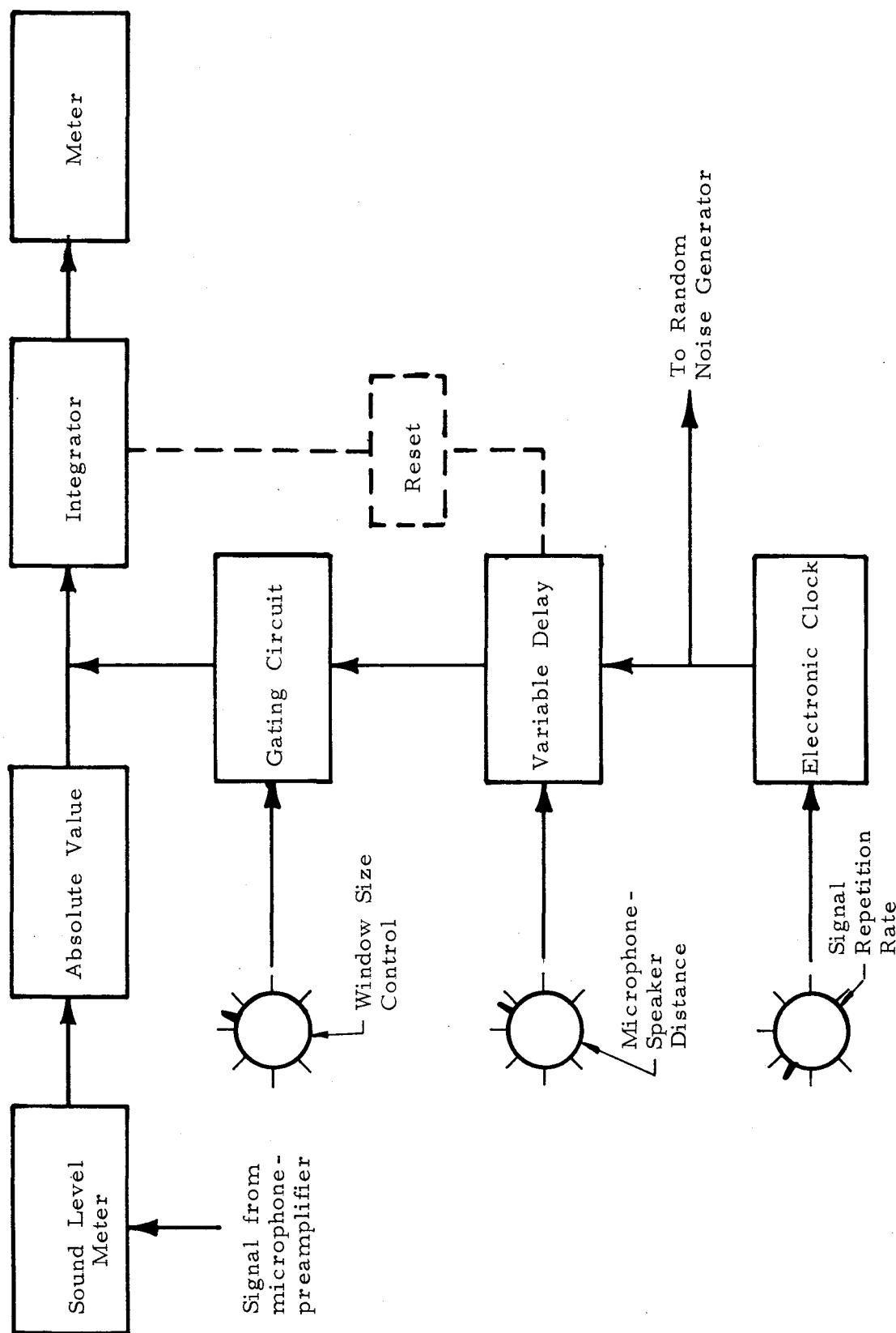
Cable Connector

(a) Microphone and Preamplifier



(b) Microphone Preamplifier Module

Figure 75



Operational Diagram of Signal Processing Electronics

Figure 76

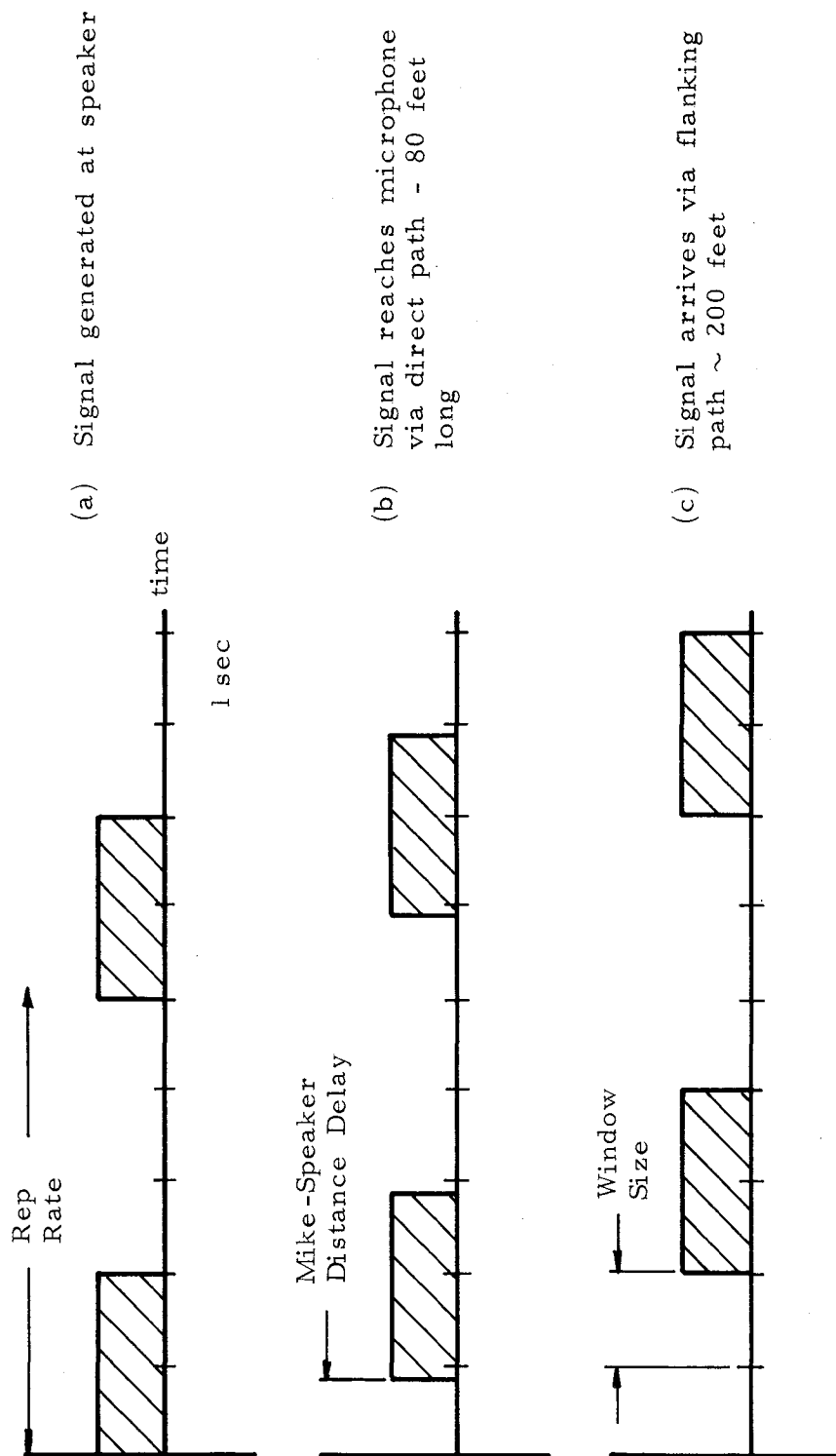
meter scale ranges from 30 decibels to 150 decibels in 1 decibel increments.

The signal from the sound level meter is monitored for only an extremely short portion of the cycle. The rate at which the speakers are pulsed is adjustable. It is driven from an electronic clock and adjusted manually by a "rep" rate control knob. The clock triggers the random noise generator and the electronic circuit simultaneously. The microphone samples continuously but an adjustable delay delays the recording of the signal for a period of time determined by the setting on the mike-speaker distance control. This delay prevents the microphone from "listening" before the signal from the speakers reaches the microphone location.

The length of time during which the signal is monitored depends on the "window size" selected. The window size selected should reflect the difference in length between the direct path and shortest flanking path. This control closes the "gate" prior to the arrival of sound via the flanking path. Thus only the signal along the direct path is integrated, averaged and shown on the meter. The operation of the pulse gating circuit is shown in Figure 77 .

Averaging and coupling circuits within the processing module produce accurate indications of the instantaneous sound intensity at the microphone regardless of the window size or repetition rate selected.

An additional circuit monitors the output of the power amplifier. This insures that any variation in signal from the sound level meter is attributable to the downhole phenomena, not a malfunction of the random noise generator or the power amplifier.



Diagrammatic Representation of Pulse-Gating Variables

Figure 77

The signal processing module is rack-mounted. This provides convenient access for testing or modification and permits combining all seal checking and sonar probe electronics in a single cabinet shown in Figure 78 .

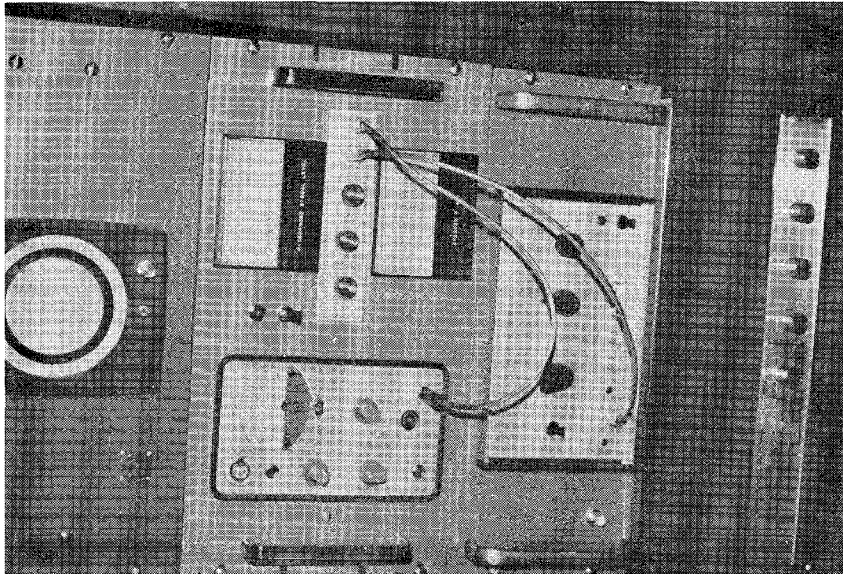
7.4.8 Downhole Support Systems

Both the linear acoustic array and the microphone module require downhole support systems to lower them into the passage, deploy them in the optimum position and support them during the seal checker test. The support systems selected for the test program employed standard or slightly modified components. Simplicity and reliability were favored.

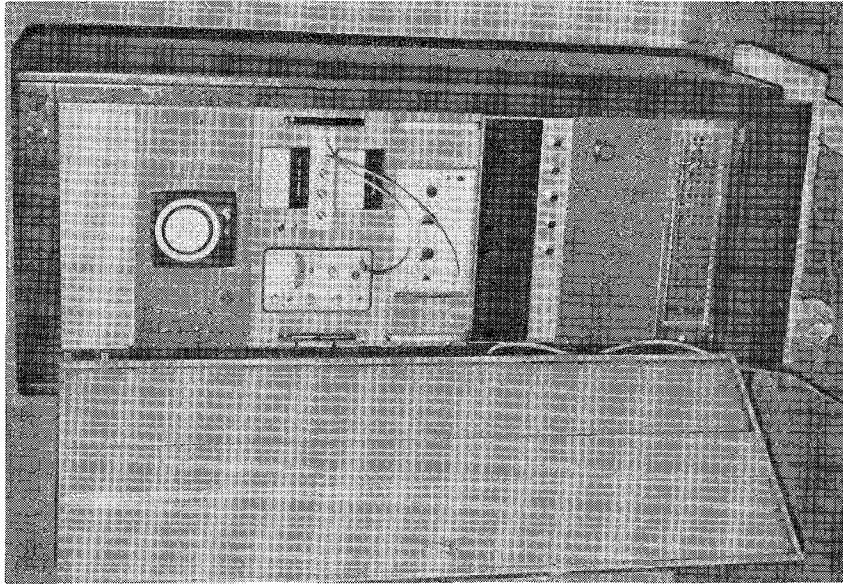
The downhole support system for the microphone module is required to produce motion in only the vertical direction to position the microphone at the proper height in the passage. In addition to vertical motion the linear acoustic array requires rotation around the borehole axis to a known position. The downhole support system for the acoustic array must provide a torsionally rigid link between the surface and the array to provide feedback indicating the absolute orientation of the speaker module. The requirements of the sonar probe downhole support system are almost identical to those of the acoustic array. One system was developed for use with the sonar probe and the acoustic array. A different, less complex system was used for the microphone module. The hardware and procedure employed in lowering, deploying and supporting these devices are presented in the following sections.

7.4.8.1 Microphone-Preamplifier Support System

The downhole support system for the microphone module employed standard components entirely. An electric winch with a maximum capacity of 1000 pounds lowered the



(a) Signal Processing Module



(b) Electronics Cabinet for Sonar Probe and Acoustic Checker

Electronics Components

Figure 78

microphone module on 500 feet of 1/8-inch standard steel aircraft cable. The cable, attached directly to the top end of the microphone module, passed over a pulley at the top of the borehole and around the drum on the winch.

The lowering operation consisted simply of operating the electric winch to allow the weight of the module to draw the cable down the borehole. To avoid heavy mechanical loadings on the cable to the microphone, it was secured with clamps to the steel cable at intervals of 20 feet.

7.4.8.2 Linear Acoustic Array Support System

The optimum positioning of the linear acoustic array in the passage employs several definable subsystems - a horizontal deployment subsystem, a torsionally rigid pipe stack and a load-carrying lowering system. The hardware components and the procedure will be described in the following sections.

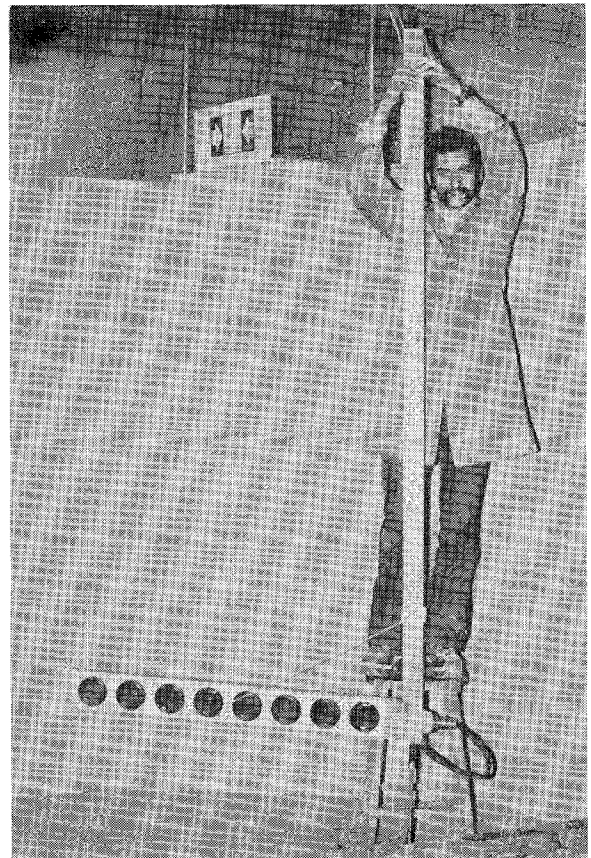
7.4.8.2.1 Support System Hardware

The linear acoustic array is oriented vertically as it is lowered through the borehole. A horizontal deployment subsystem locks the array in the vertical position while in the borehole, then automatically deploys the linear array horizontally upon contact of the foot with the floor of the mine passage. The photographs of Figure 79 show the array in both orientations.



(a) Linear Acoustic Array
in "Cocked" Position for
Lowering Through Borehole

(b) Linear Array Deployed
Horizontally



Linear Acoustic Array Deployment

Figure 79

The cylinder pivoted on the support arm contains a compression spring and an air cushion to provide both the force required to deploy the linear array initially and the damping required to decelerate it slowly as it approaches the horizontal position. When the array is "cocked" in the vertical position, the compression spring is preloaded in such a way as to kick out the array to one side when the locking pin is withdrawn by contact of the foot with the floor of the passage. The side selected for deployment depends on the location of the borehole with respect to the ribs of the passage as determined by the preliminary probing. The side chosen would eliminate any possible interference with the ribs and insure positioning of the array near the center of the passage.

The support arm bolts directly to the end of a torsionally rigid tube stack. The aluminum tubes are 2 inches in diameter and 20 feet in length. Special grooves near the tube ends permit the use of Victaulic* couplings to connect the tubes in a torsionally rigid manner. The pair of holes in each end are used to provide support and alignment during the lowering operation. The alignment tool is used during the installation of the couplings to maintain the correct orientation of the pipes from one end of the stack to the other. This provides an absolute reference point if desired. A complete description of the lowering system may be found in Section 8.3.3.

* Trade Name.

8. Field Demonstration of the Remote Mine Sealing System in a Coal Mine

8.1 Selection of Field Test Site

Eastern Associated Coal Corporation (EACC) offered its Federal No. 1 coal mine in Grant Town, West Virginia as the site for field testing of the remote sealing system. The choice of Federal No. 1 mine was particularly appropriate as the first attempt at fire control by remote sealing was done in this mine in 1963. EACC provided the men and equipment required for much of the initial preparation. Considerable assistance, advice, and background on coal mining technology was given by Mr. William Laird, Vice President for Research and Development, EACC, and by Mr. Lawrence Jackson, Resident Engineer at the Federal No. 1 mine.

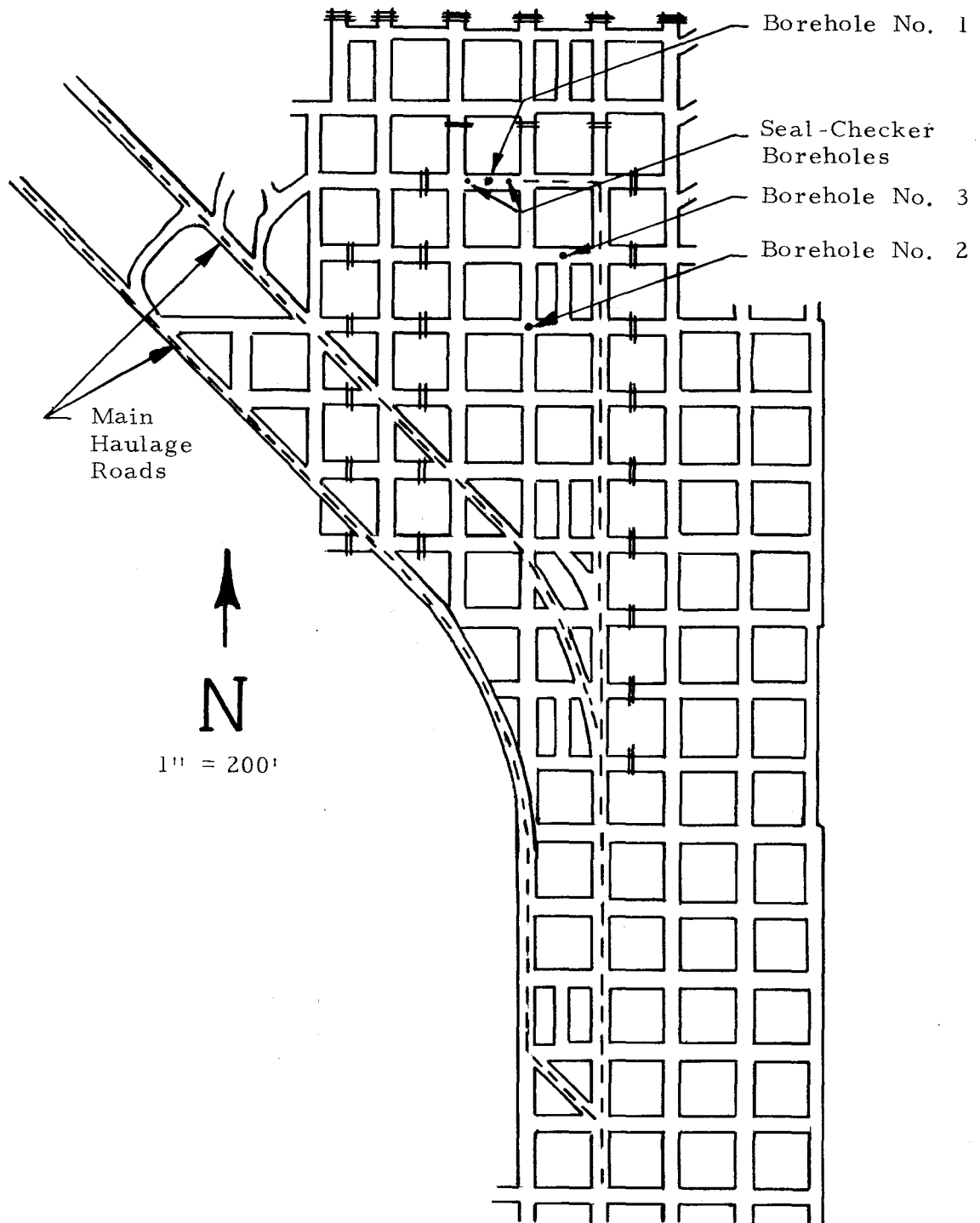
District 3 USBM office, the West Virginia Bureau of Mines, the Technical Support Group of the USBM, and Local 4047 of the United Mine Workers of America also cooperated.

8.2 Preparation of Field Test Site

8.2.1 Underground Site Preparation

The underground site chosen for the field testing was in a non-working portion of the mine within a few hundred feet of the main haulage road, as shown in Figure 80. Known as "Seven Switch," this area was a 20 minute walk or 5 minute "jeep" trip from the man-trip shaft. Ten years having passed since this area was actively worked, considerable effort was required for gob clearing, roof bolting, rock dusting, and rejuvenating the track from the haulage road to the test area.

Three primary borehole locations were chosen for the test program. Borehole No. 1 was in a straight passageway



Underground Demonstration Area

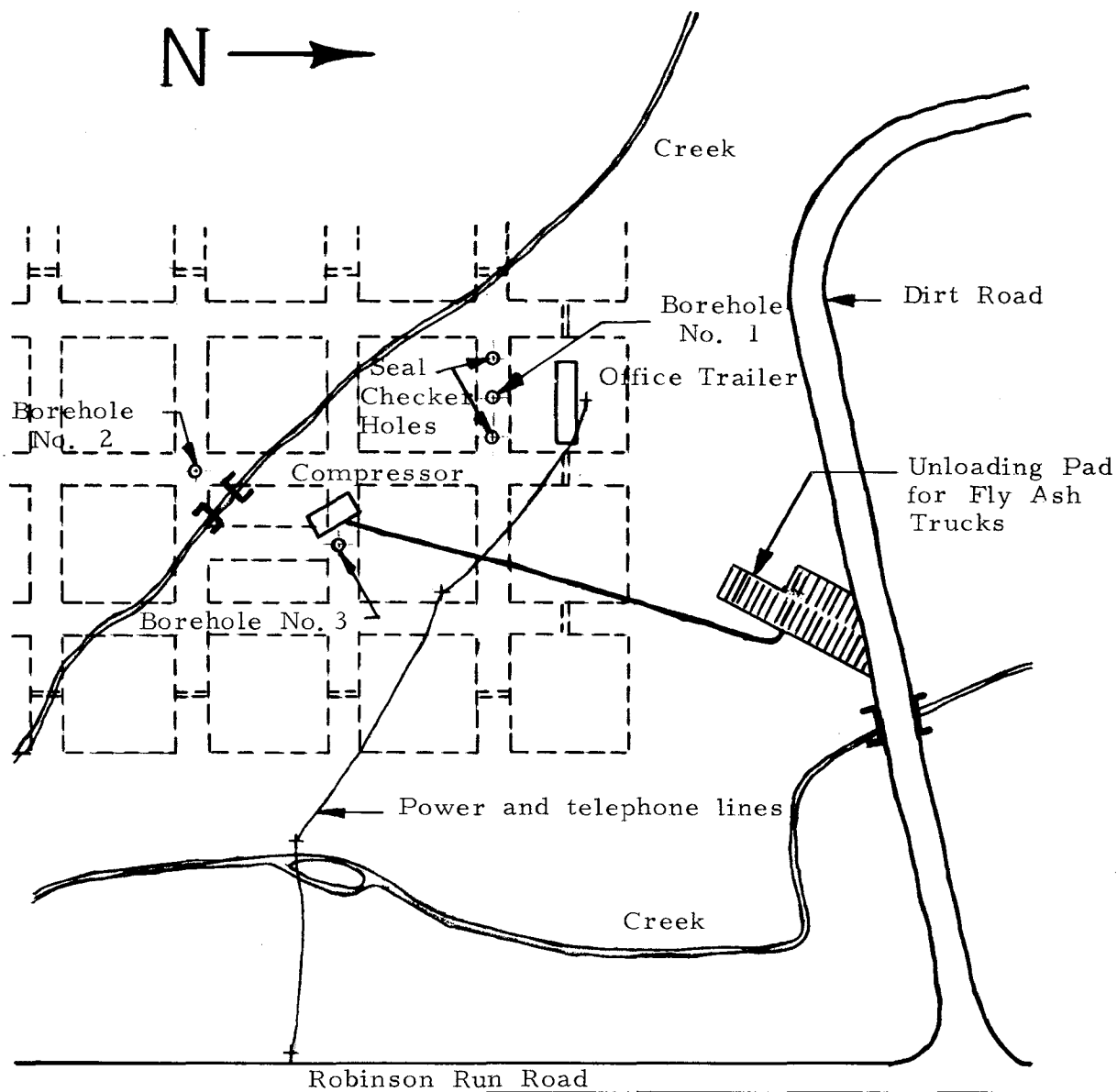
Figure 80

with an average roof height of 10 feet. Borehole No. 2 was at a 4-way intersection of 12 feet average height. Borehole No. 3, at a 3-way intersection, was used for pilot trials by constructing a false roof and side walls to simulate a straight passage with a 5-foot roof.

8.2.2. Surface Site Preparation

The surface site above the mine was located on flat ground close to the main road, as shown in Figure 81. Frequent rainstorms and several snow falls kept the field in quagmire condition and required special preparations to be made for vehicle passage across the test site. The single most important factor in assuring smooth operation of the entire system is providing ready access to the site. In this instance, the dirt road and bridge were upgraded to accommodate the many fly ash trucks required. To avoid the major effort required to extend the road across the field to each of the boreholes, a 4-inch fly ash line was extended from the blower to the wooden ramp. The fly ash trucks parked on the ramp for off-loading. In dry weather they could drive into the field to turn around. During foul weather, the field condition precluded this. It was then necessary for the trucks to back up the wooden ramp and up the dirt road to the main road. A Bucyrus-Erie TW18 bulldozer was available on site full-time to push or pull an occasional vehicle.

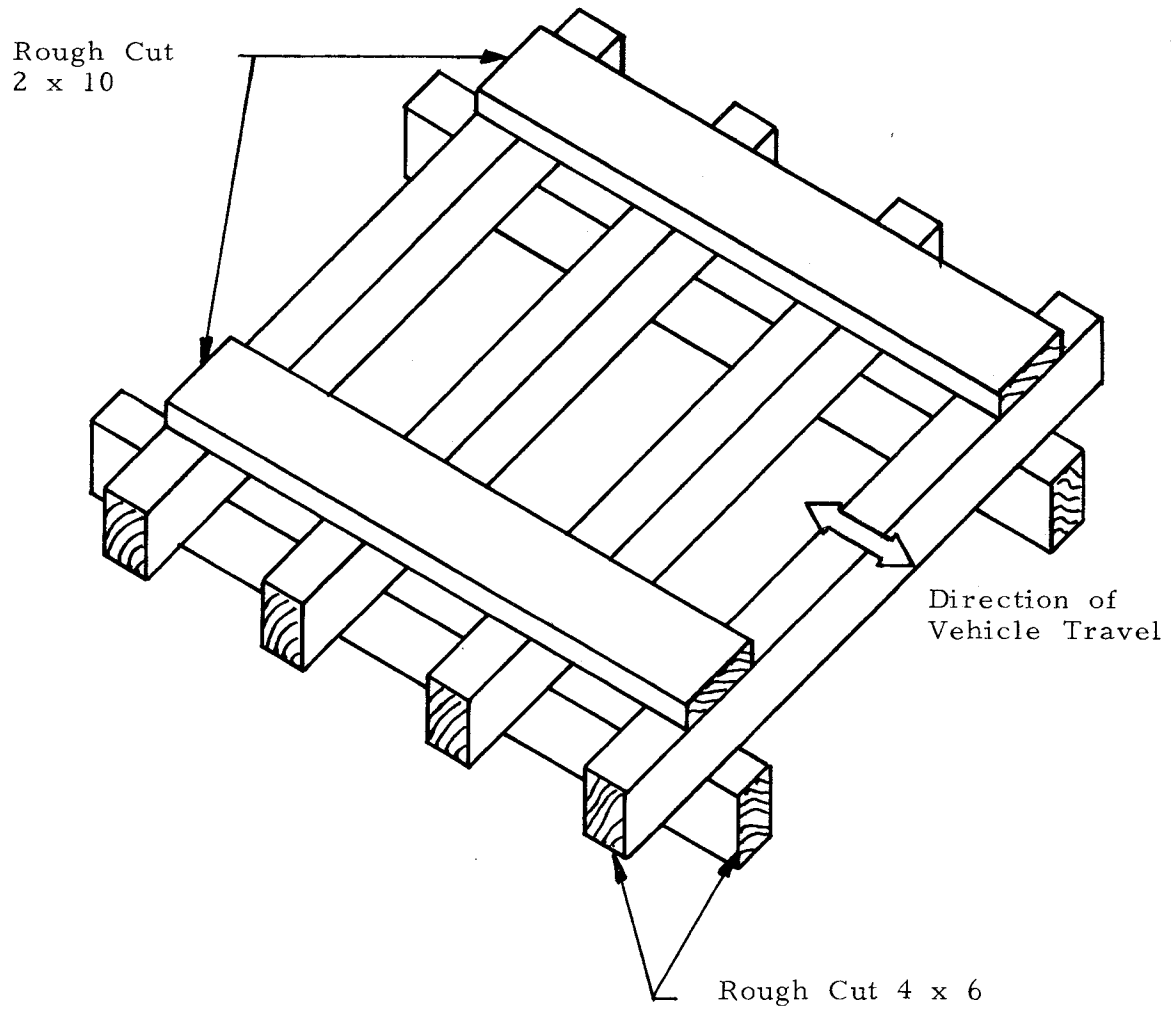
The wooden ramp, which effectively extended the dirt road 100 feet into the field, was of "corduroy" construction. As shown in Figure 82, the corduroy road was constructed by spiking timbers across the underboards. This road-building technique is simple and reasonably inexpensive. The 14-foot lengths of rough cut 4 x 6 are the standard timbers often used in mines for roof support. Other techniques of road-building in a virgin field were considered. The use of gravel was rejected because of its tendency to sink into the soggy ground and the difficulty of recovering the field for agricultural purposes. Aircraft landing mats, while effective, are extremely expensive.



Dotted lines show underground mine layout

Location of Surface Equipment

Figure 81



Section of Corduroy Road
Figure 82

8.2.3 Survey of Borehole Locations

After the borehole locations were chosen, an underground survey was conducted to check the data available from old mine maps. Using this information, the surface site was surveyed to spot the exact drilling locations. This work was facilitated by locating two iron pins recorded in the log of an earlier surface survey. The surface locations for the boreholes were closed out (checked) to an accuracy of one part in 20,000.

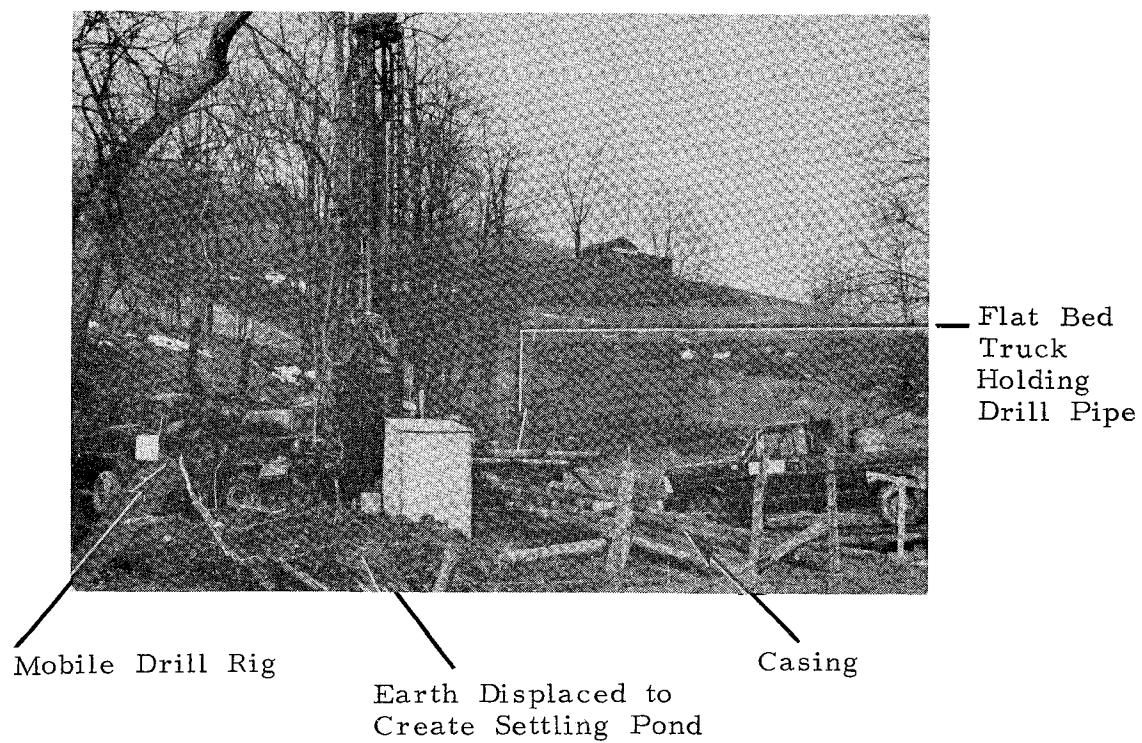
8.2.4 Borehole Drilling

The contractor chosen for the drilling operation was Floyd S. Marts and Sons. The No. 1 borehole was drilled first, followed by the seal-checker holes, so that work could commence on the sealing operations while the remaining holes were still being drilled. In planning the surface site preparation, ample working room had to be supplied so that all of the required equipment could be placed in close proximity to the borehole, as shown in Figure 83. A list of the required equipment is given in Appendix E. The sequence of operations for drilling a hole was as follows:

- a. Position the drill-rig over the surveyed location.
- b. Using a transit, plumb the drill-rig.
- c. If needed, bulldoze a crater to use as a settling pond for the discharged water laden with cuttings.

- d. Drill a 12-inch hole 20- feet deep, reaching the bed rock.
- e. Pull the drill and install a 20-foot length of 10-inch casing.
- f. Drill a 10-inch hole to a depth of 80-feet.
- g. Pull the drill pipe and install and grout 80-feet of 8-inch casing.
- h. Drill an 8-inch hole through to the mine passage.
- i. Pull the drill pipe and install 6-inch casing the length of the hole. Grout in place.

The drilling operation employed standard procedures; the technique chosen for casing the hole was the most expeditious for the conditions at this site. A single length of 10-inch casing was used to prevent the top soil from collapsing into the hole as it was being drilled. The 8-inch casing was used to shut off the surface water. The actual length of the 8-inch cased section of the hole varied according to the water conditions found at each location. Even with more than 100 feet of this surface casing shutting out surface water, approximately 10 to 20 GPM of water was found to be entering the mine from fissures in the bedrock when the drill broke through into the passageway.



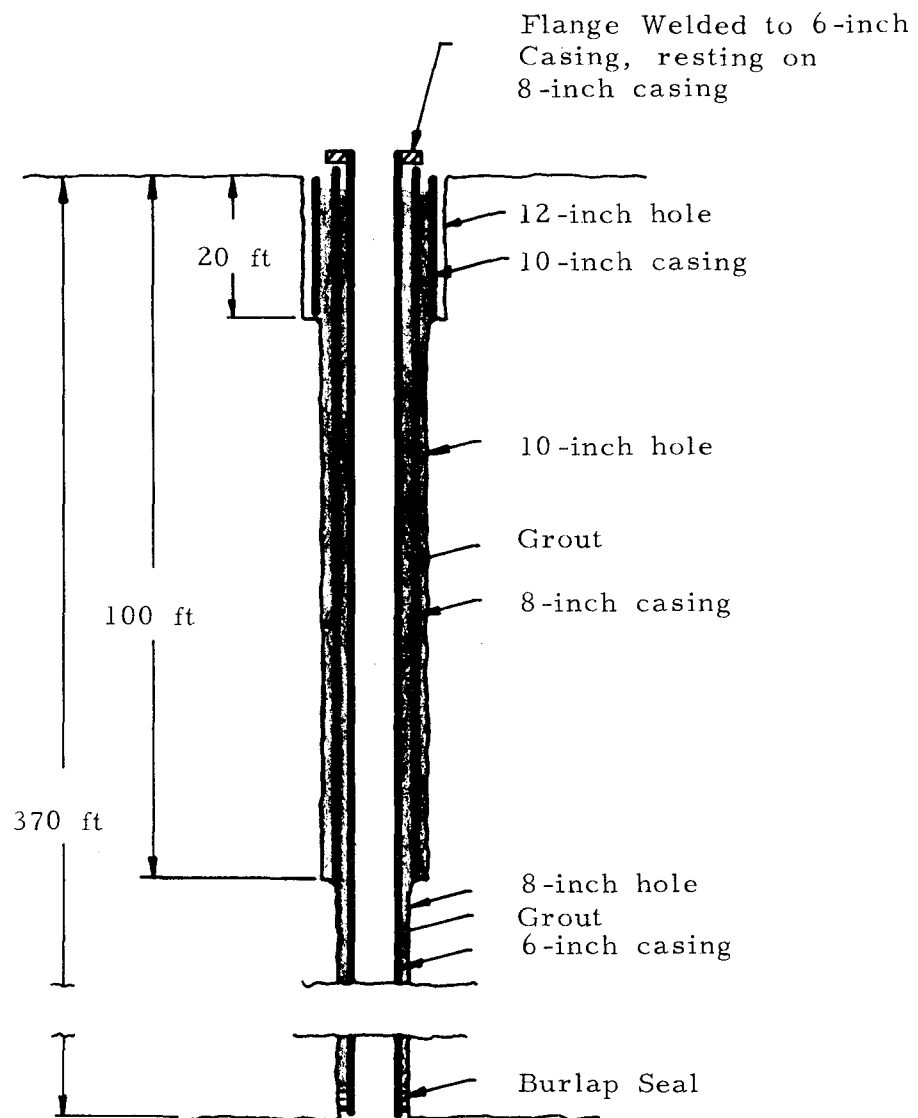
Drilling Operation, Showing Major Equipment Required

Figure 83

To stop this flow into the mine the entire length of 6-inch casing was grouted by gravity flow. In an emergency situation, a good procedure for grouting is to stop the drilling approximately 10 feet before breaking into the passageway. Pull the string of 8-inch drill pipe and put the 6-inch casing in place. Pour grout down the inside of the casing. Fill the casing with water under high pressure, approximately 1 psi per foot of hole, to force the grout out the end of the casing and back up the borehole between the casing and the wall of the borehole, as shown in Figure 85. A thorough job can be assured by observing the grout oozing from the annular hole between the casing and the borehole wall. After the grout is set, a 6-inch drill is lowered down through the casing to drill through the last ten feet into the mine. This method is expensive and time consuming. It is a standard procedure, however, where a dry hole is necessary.

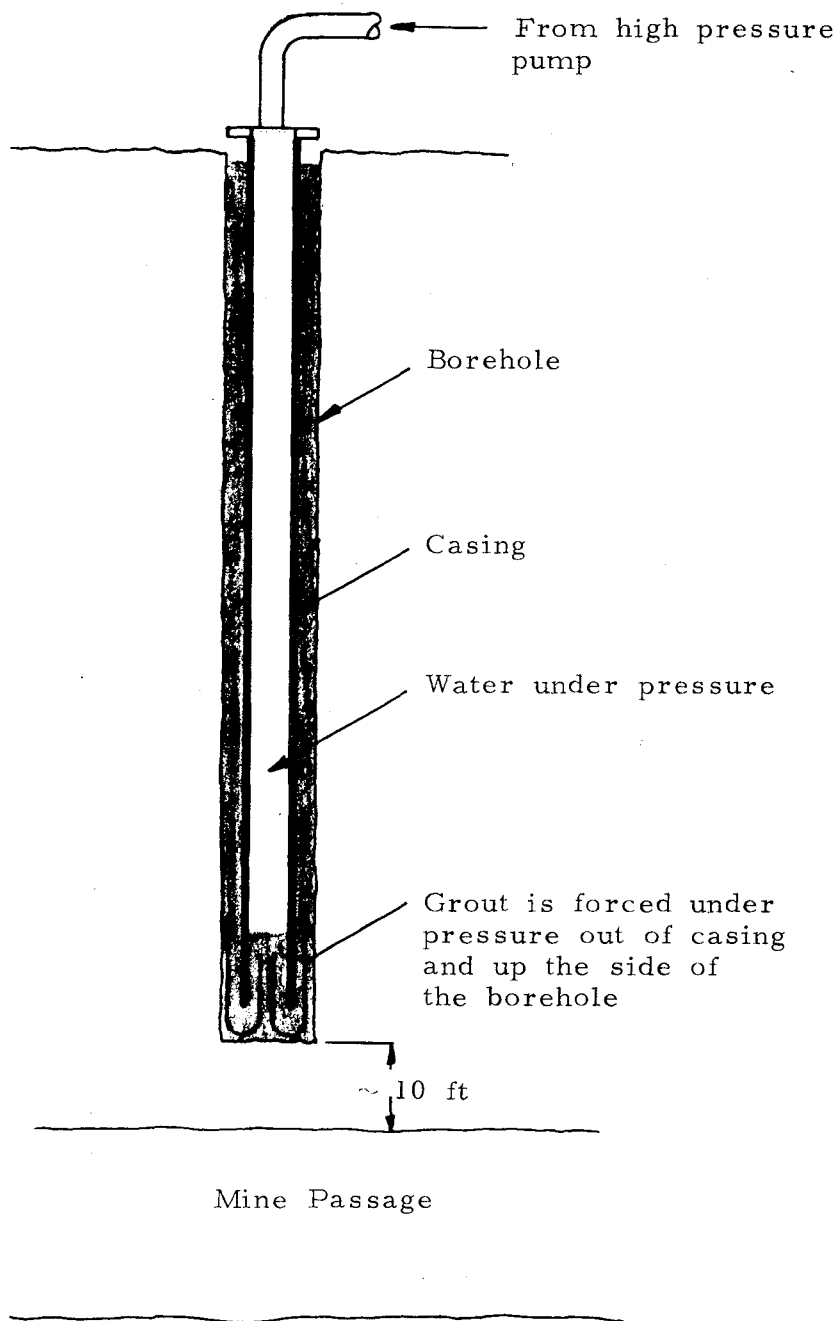
8.3 Field Evaluation of Sonar Probe

Final field testing of the prototype sonar system, including all deployment hardware, was done in the Federal No. 1 mine. The support hardware and deployment equipment performed well and the sonar probe produced an underground map which was consistent with actual passageway geometry. The equipment required for deployment and operation of the sonar system is listed in Appendix E.



Cross Section of Finished Borehole

Figure 84



Cross Section of Borehole Showing Alternative Grouting Technique

Figure 85

8.3.1 Assembly of Scaffolding-Towers

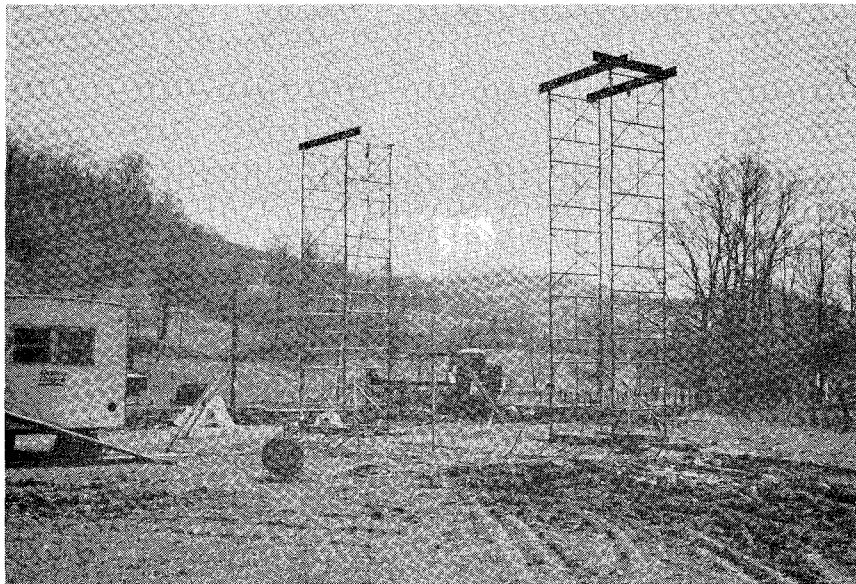
To permit the handling of the 20-foot poles used for the sonar deployment, it was necessary to position a pulley 25 feet above ground level. A tower constructed of standard industrial scaffolding was used for this purpose. The cuttings from the drilling operation were smoothed and leveled to form a suitable base and a wooden frame was built to serve as the foundation. Two men were able to erect the 5 sections of scaffolding in two hours. The pulley was mounted on I beams atop the structure, and guy-wires were used to steady the entire assembly. A completed tower is shown in Figure 86.

8.3.2 Lowering the Sonar Probe

The remote sonar housing was deployed on the end of the pipe string mentioned in Section 5.3.4. The pipe string was raised and lowered with a 1000-pound-capacity electric winch. The 5/16-inch diameter cable from the winch passed over the pulley atop the tower and back to the ground, providing a lifting height of 25 feet.

The sonar housing was coupled to the first section of pipe and lowered into the hole. Additional sections of pipe were then added in the following sequence of operations.

- a. Raise new section of pipe above the end of the pipe protruding from the borehole (Figure 87).



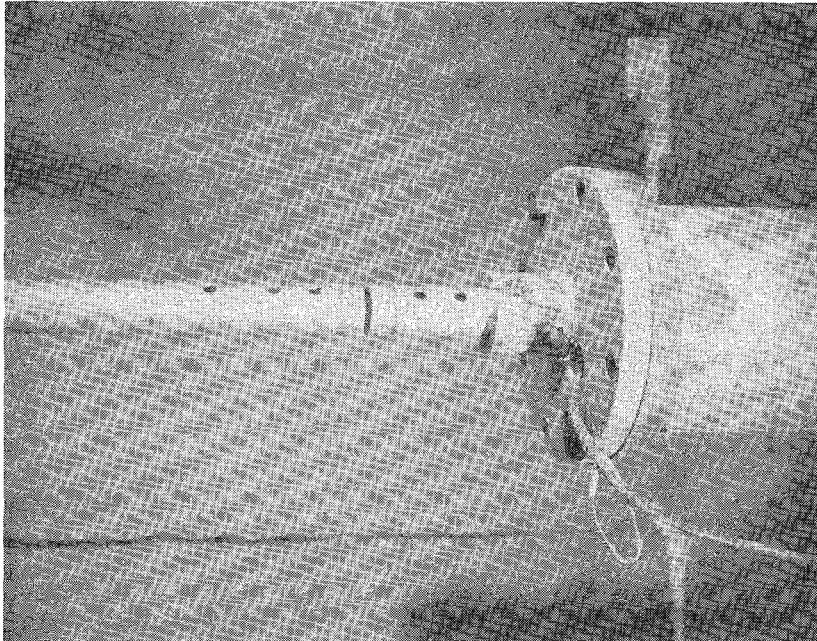
Scaffolding Towers used in Deployment
of Sonar Probe and Acoustic Seal-Checker

Figure 86

- b. Insert the alignment tool into the alignment holes in the two pieces of pipe (Figure 88).
- c. Insert the electrical cable hanger in the Victaulic* coupling. (Figure 89).
- d. Install the Victaulic* coupling to clamp the two pieces of pipe together (Figure 90).
- e. Remote the alignment tool from the pipe sections.
- f. Raise the pipe string enough to remove the holding pin (Figure 91).
- g. Open the split flange (Figure 92).
- h. Lower the pipe stack approximately 20 feet. (Figure 93.)
- i. Close the split flange. (Figure 94).
- j. Insert the holding pin in the pipe section and lower the pipe string until the pin supports the weight and the winch cable goes slack. (Figure 95).
- k. Remove the end cap from the pipe and attach to a new section of pipe.

Three men assembled and lowered 370 feet of pipe in this manner in 2-1/2 hours.

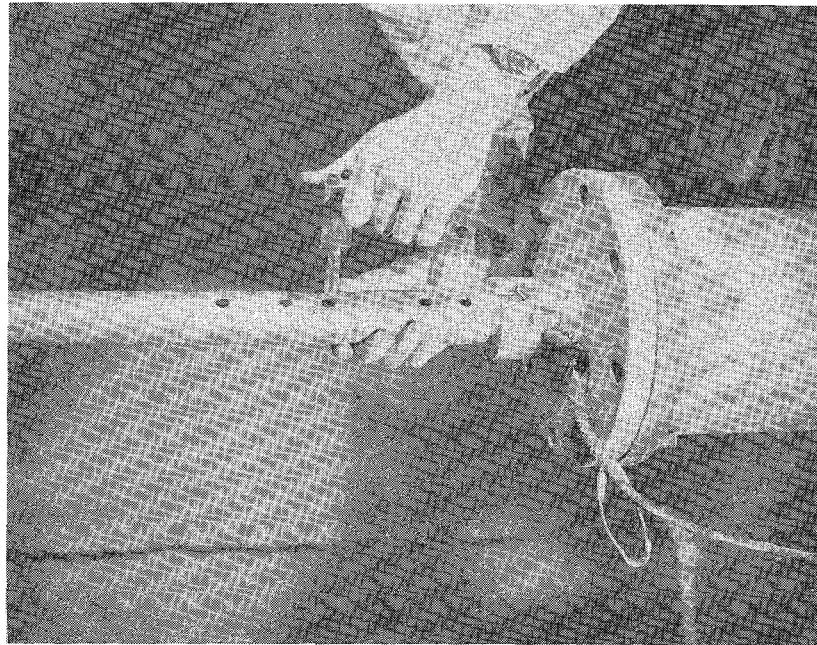
* Trade Name



New Pipe Section in Position

Above Borehole

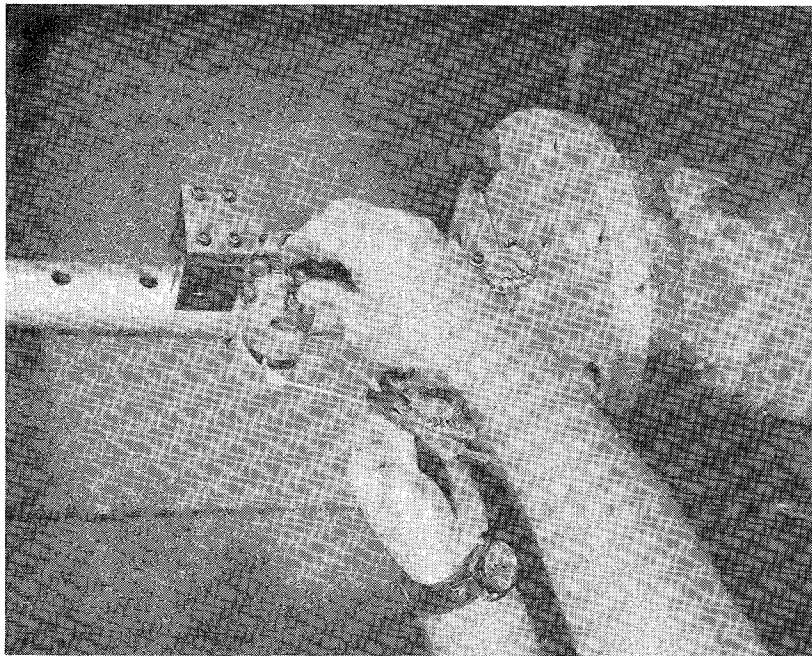
Figure 87



Aligning Pipe Section with

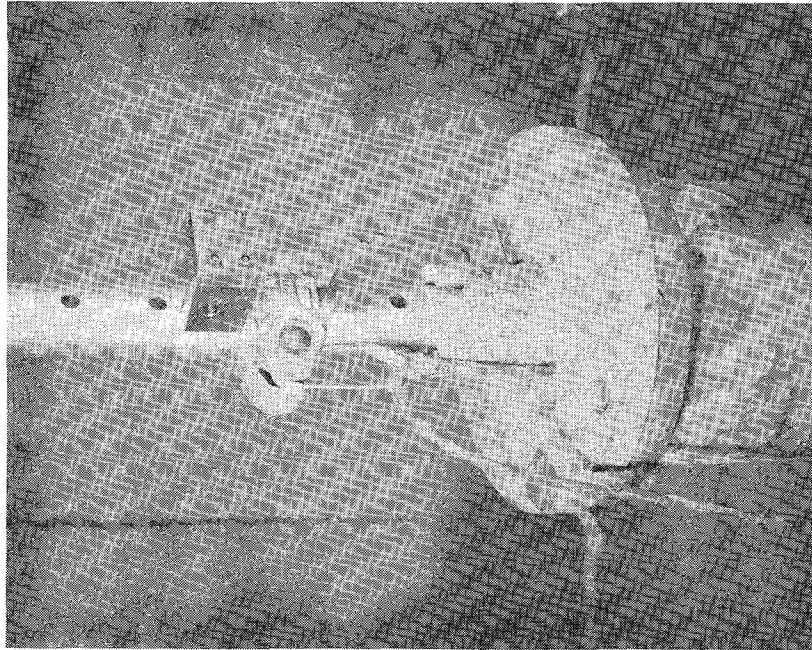
Special Tool

Figure 88



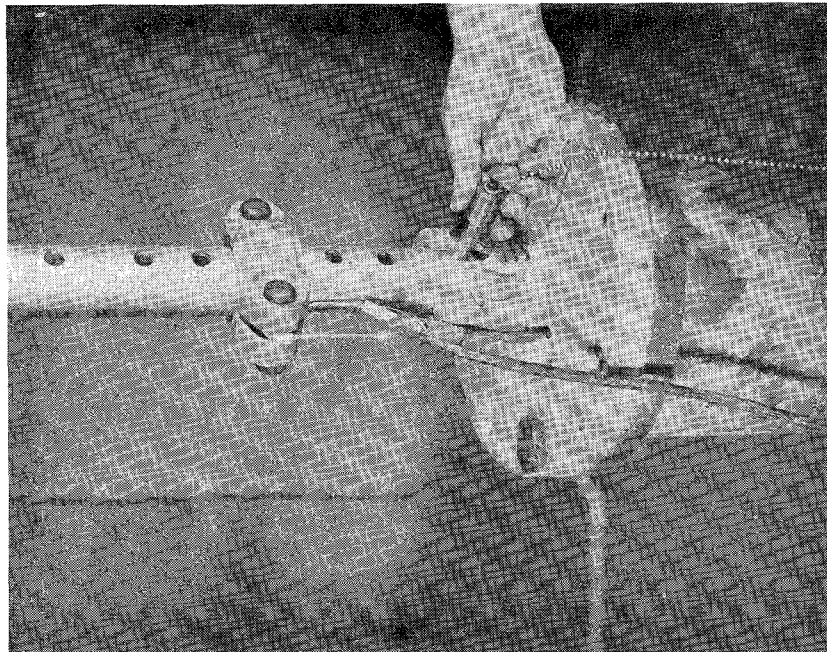
Installation of Electrical Cable Hanger

Figure 89



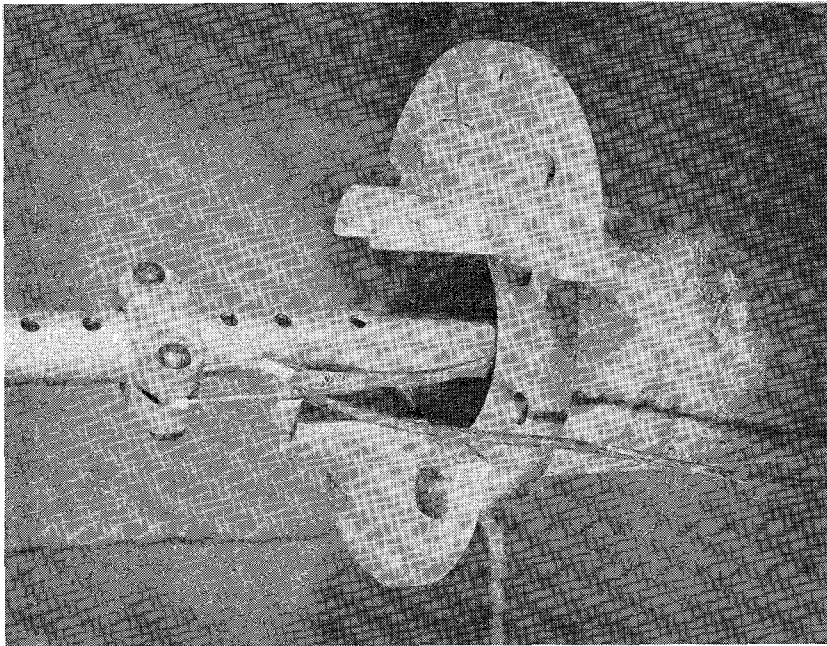
Assembled Pipe Coupling

Figure 90



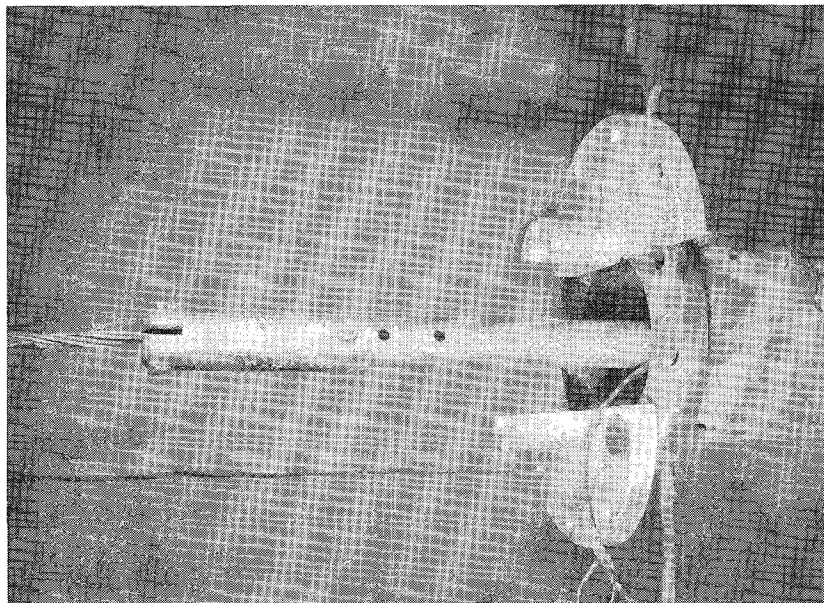
Removal Of Holding Pin

Figure 91



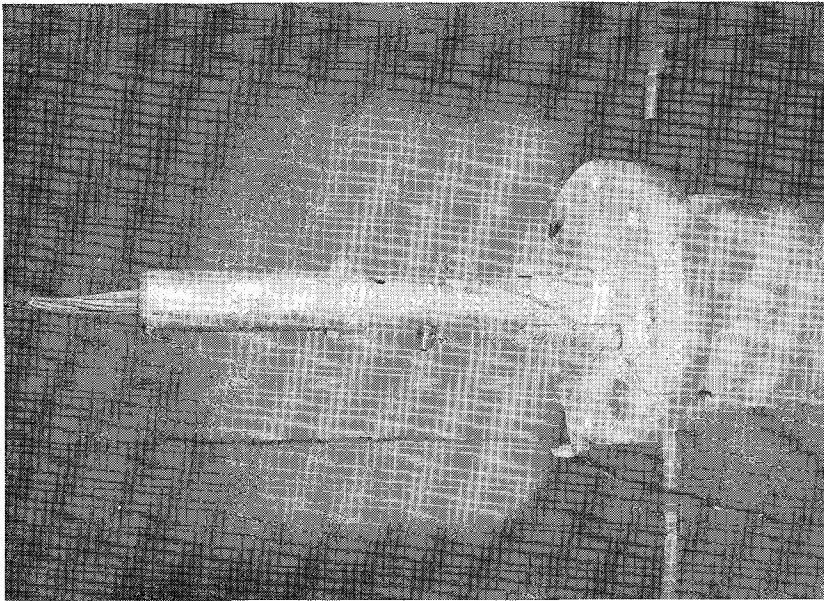
Split Flange in Open Position

Figure 92



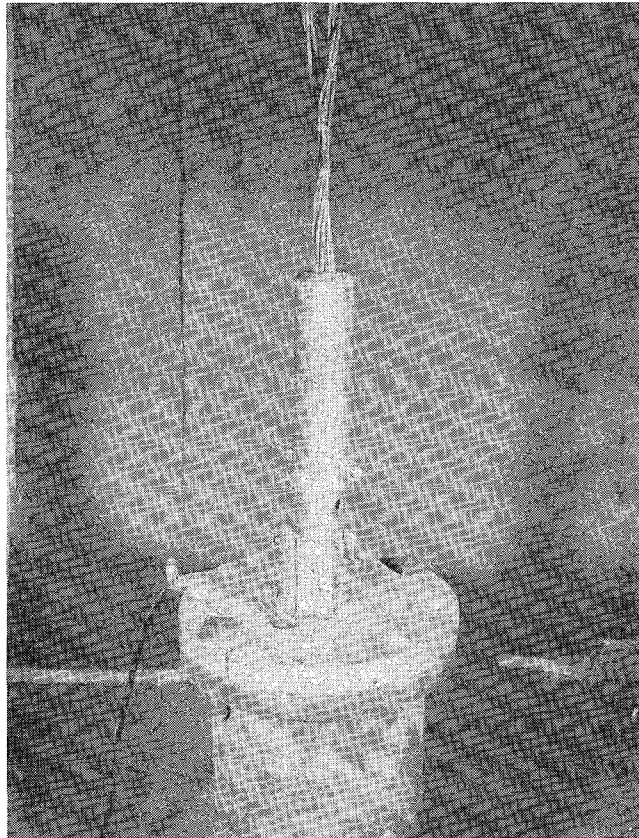
New Pipe Section Lowered 20 feet into Hole

Figure 93



Split Flange in Closed Position

Figure 94



Pipe Section with Holding Pin Resting on Split Flange

Figure 95

This procedure was repeated until the remote probe was within one pipe length of being in the passageway. Before connecting the last length of pipe, the rotary table was placed over the borehole and the last piece of pipe was guided through the bearing in the table. When the probe was positioned at the desired height in the passageway, the pointer block was clamped to the pipe just above the rotary table with the pointer oriented with the alignment holes at the end of the pipe. With this block resting on the self-aligning bearing in the rotary table, the entire pipe string is supported by the rotary table. The compass rose on the rotary table may then be aligned with magnetic North. The entire 370-foot string of pipe, with the remote probe mounted on the end, may be oriented along any desired compass heading with only a few inch pounds of torque required. The completed rotary table assembly is shown in Figure 96.

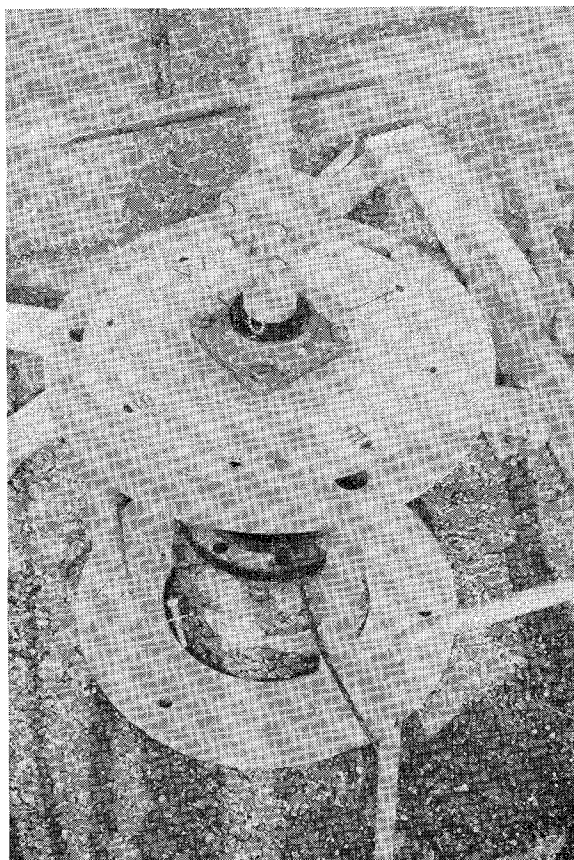
The deviation of the actual underground heading of the sonar probe from the indicated heading on the rotary table compass rose was less than 10 degrees.

8.3.3 General Sonar Operation

Once the remote probe was located in the passageway, the sonar system was ready for operation. Range readings were taken in 30° increments of the azimuth circle. Polar graph paper was used to record target distances at each heading. After this preliminary data had been gathered, the sonar unit could be redirected to areas of concern for more detailed evaluation.

8.3.4 Straight Passage Probing - Borehole No. 1

As discussed previously, the initial data consisted of target ranges in 30° increments around the azimuth circle. From this preliminary scan, the major highlights of the passage were evident, including the perpendicular distance to both ribs.



Completed Rotary Table Assembly

Figure 96

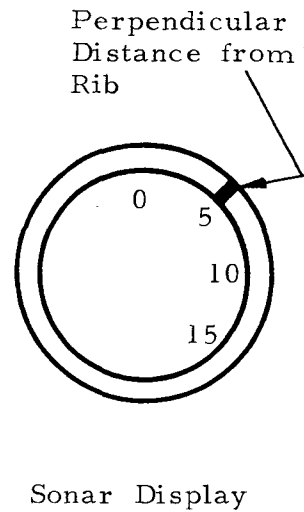
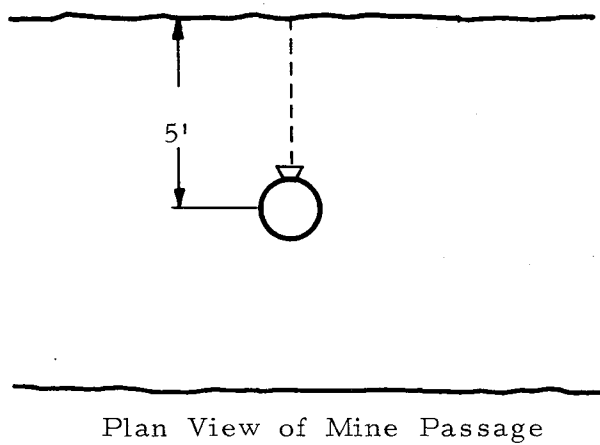
For more detail additional readings were taken at increments less than 30° . Figure 97 shows a plan view of the passageway. Superimposed on this map are the data points obtained with the sonor probe.

At close range interpretation of the data as presented on the screen frequently requires differentiation between two images. A brief description of this is in order. With the transducer directed perpendicular to a rib, one clear signal indicates the exact distance to the rib as shown in Figure 98 (a). As rotation of the probe directs the transducer at a skewed angle, double images occur. One image comes from the reflection directly in front of the transducer and the other from the reflection of the section of rib perpendicular to the transducer, as shown in Figure 98 (b). A focused beam to produce a single sharp signal is not practical within the size limitations of the probe. Understanding of the phenomenon and familiarity with the operation of the probe permit accurate determination of passage characteristics even at close range in a matter of minutes.

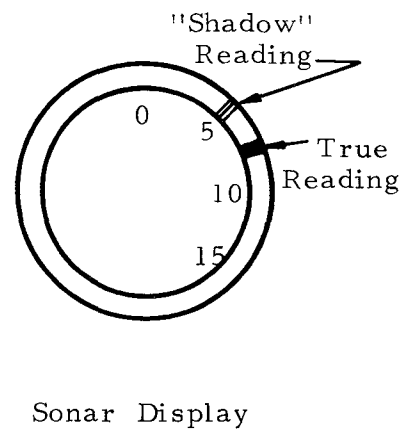
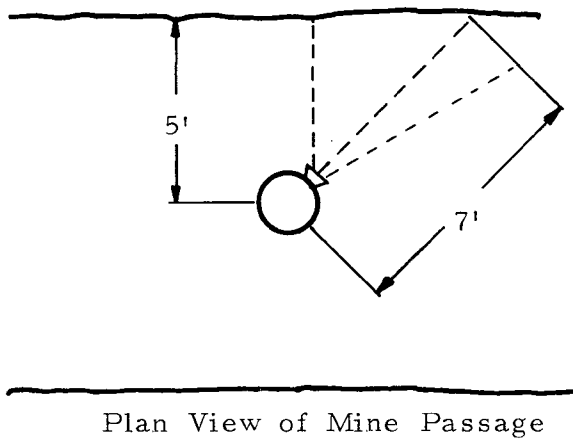
For this passageway, data were taken with the probe 4 feet and 6 feet off the floor. Height of the passageway varied from 8 to 10 feet.

8.3.5 Four-Way Intersection Probing-Borehole No. 2

The procedure for the sonor mapping of this area was the same as for the straight passage, with two major differences. First, the passageway was sufficiently high (12 feet in most places) that there was little acoustic reflection from the roof. Secondly, the targets were far enough from the probe so that small irregularities in the area could not be detected. It



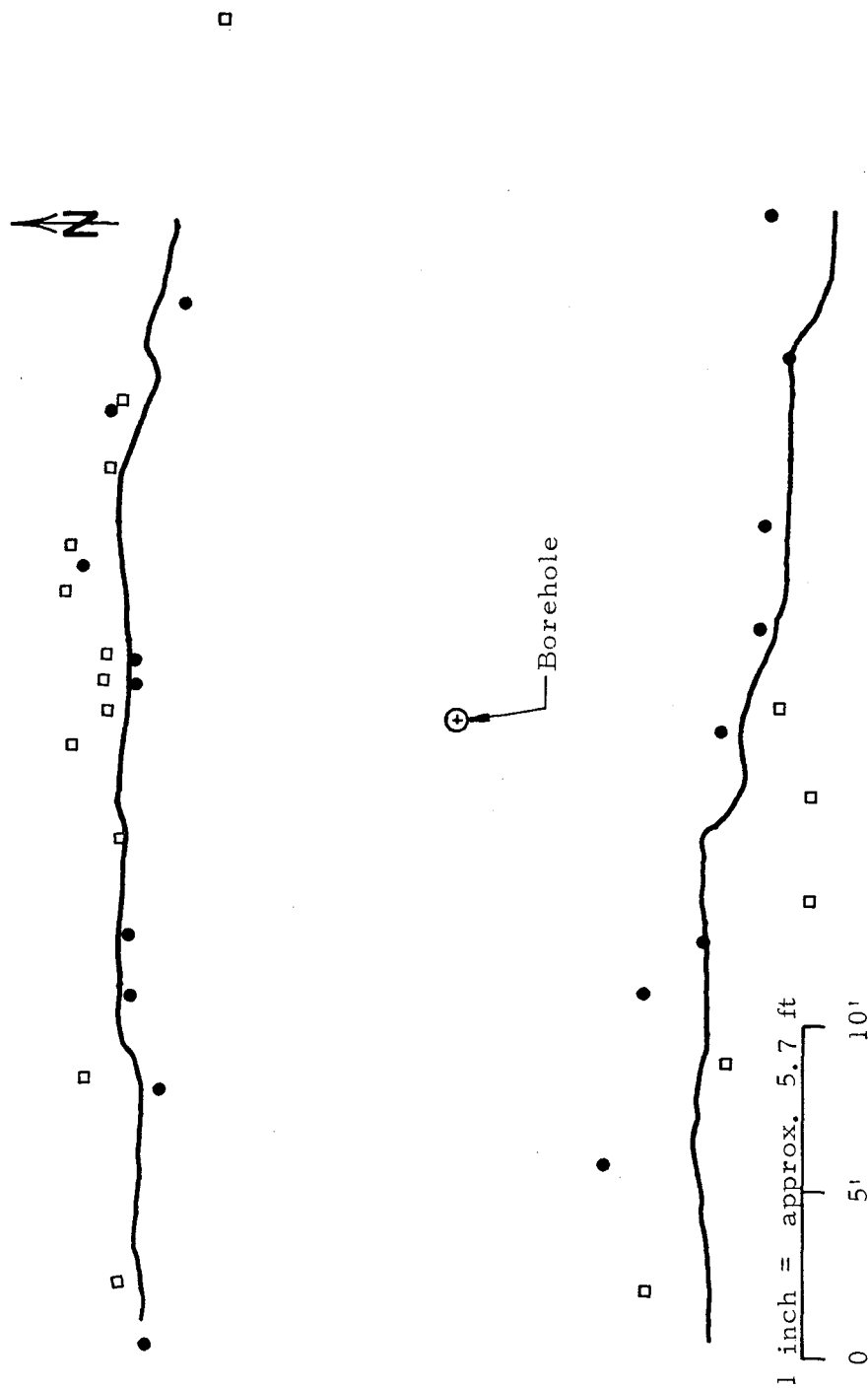
(a) Perpendicular Operation



(b) Skewed Operation

Actual Mine Conditions and Respective Readings of Sonar Display

Figure 97



Solid lines represent actual passageway geometry

- Sonar display data points, probe 6 feet from floor
- Sonar display data points, probe 4 feet from floor

Plan View of Straight Passage with Sonar Data Points

Figure 98

was found that in this case a single sweep with the sonar (again at 30° increments) provided enough information to "map" the area. Of particular interest were the 4 cribs in the intersections. These supports produced a consistent and distinct display on the sonar readout - a "double reflection". A portion of the sound wave bounces off the front crib blocks while some of the sound continues through the crib and reflects off the rear blocks. This behavior produces a very sharp image on the display, which shows as two distinct targets, one three feet behind the other.

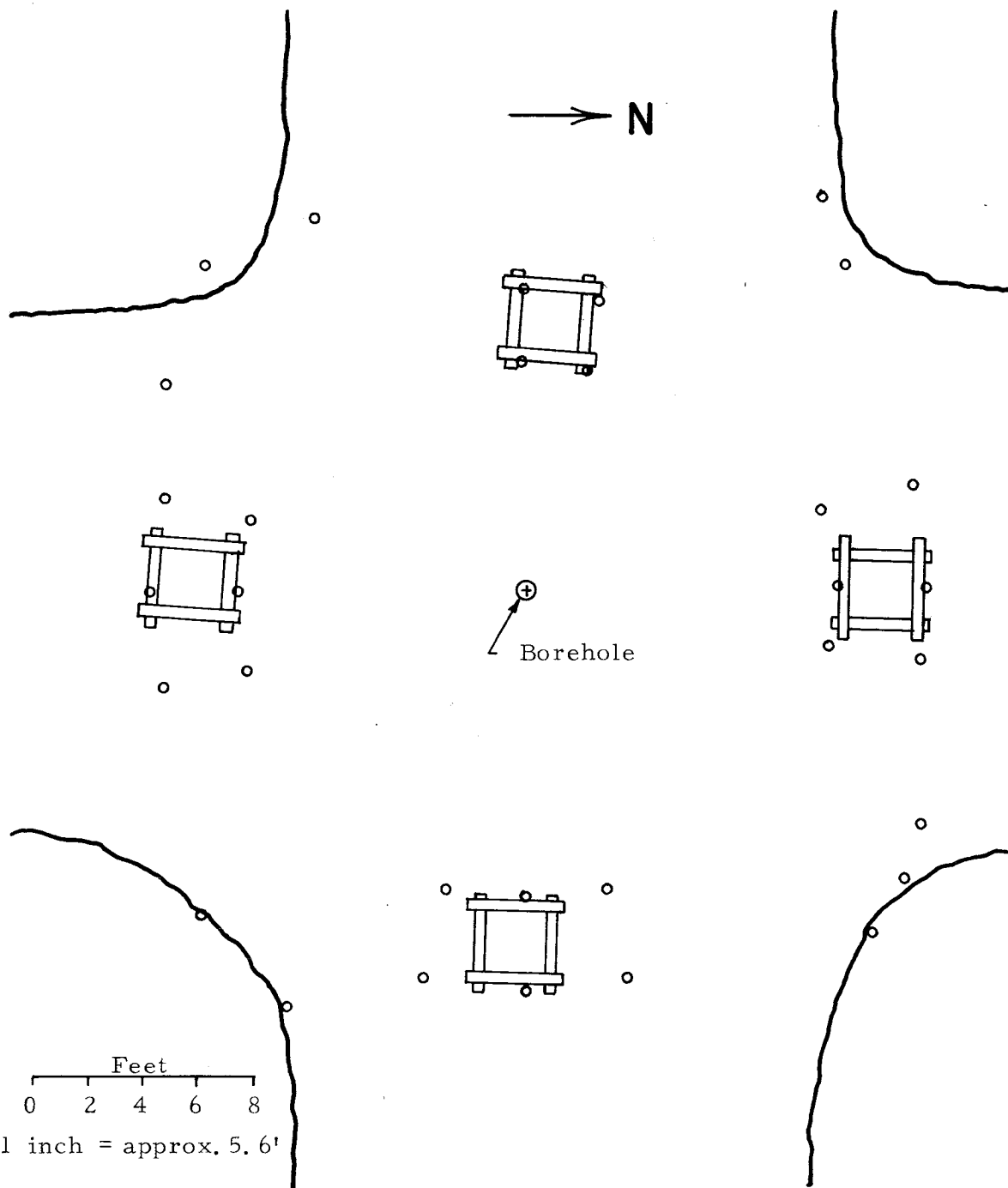
Figure 99 shows a plan view of the actual mine passage (including the cribs) with the sonar data points superimposed.

8.3.6 Conclusions and Recommendations

8.3.6.1 Capabilities of Prototype Design

The sonar probing system has been successfully tested and has demonstrated the capability to produce enough data to map out a small area in an underground passageway. The useful range of the device in an actual underground environment is approximately 20 feet. This means that the unit can determine the position of a borehole relative to both ribs of the entry or the corners of a coal pillar if the borehole is in an intersection. The unit can also detect mining machinery and can identify a crib and determine its range. Because of the multiple reflections created by the broad-beamed transducers, a trained operator is required to interpret the data.

The technique used for lowering the probe into the passage is simple and effective. The rigid pipe string provides positive support and an accurate means of controlling the rotational position of the probe.



Solid lines represent actual passageway geometry, including locations of 4 cribs
 • indicates data points from sonar probing device

Plan View of 4-way Passage with Sonar Data Points

Figure 99

8.3.6.2 Recommendations for Further Development

As indicated in previous sections, the single major short-coming of the sonar probe is the lack of strong directionality. The proper modifications to "focus" the beam of the transducer would significantly reduce the time required to obtain data. In addition, it would be possible to produce more accurate, detailed maps. Finally, it would simplify the interpretation required and permit a man to operate the system with only a few minutes of instruction.

The deployment system, while simple and effective in its current form, would also benefit from a new development program. Currently, approximately 8 man hours are required to erect the 25-foot tower required and an additional 6 man hours needed to assemble and lower the 400-foot pipe string. The total effort to place the remote probe in the passageway could be reduced to 2 man hours if a winch were used to cable-lower the probe. If a cable is used, there will be no mechanical control of the rotational position of the probe. Therefore, a sensor will be needed to determine position and a remote actuator must provide control of this position. These must be chosen for best possible reliability and repeatability; modifications will undoubtedly be required to make them compatible with the rest of the system. Size of the units will also be important as they must fit in the remote probe housing.

8.4 Field Evaluation of Fly Ash Mine Sealing System

8.4.1 Design Considerations in the Development of the Fly Ash Mine Sealing System

The laboratory program described in Section 6.2 showed that effective fly ash seals can be made using the high velocity cratering method. This requires that fly ash be introduced into the mine passage at a high enough velocity and flow rate so that local jet action leads to the formation of a large diameter, shallow crater immediately below the borehole. Fly ash fills the corners of the passage, leading to the development of a fly ash pile which builds up inwards from the side walls rather than outwards from the borehole. The borehole is maintained free of fly ash and the possibility of premature plugging of the borehole prior to completion of the seal is eliminated.

Based on the 80 scfm air flow rate required to develop fly ash seals in the laboratory with the 1/4-scale mine passage facility, it was found that an air flow rate in the range of 2000 to 5000 scfm would be required for a full-scale mine passage. Fly ash is normally supplied by fly ash bulk delivery trucks which pneumatically pump fly ash at air flow rates typically in the 300 to 500 scfm range. Consequently the prototype system required a high flow-rate air supply to mix with the truck delivered fly ash before delivery into the borehole. Horizontal transport of fly ash beyond the mixing point at these high flow rates requires that the pipe size be carefully selected. The pipe size must be large enough to prevent aerodynamic choking due to compressibility effects resulting in excessive pressure losses but small enough so that adequate velocity is maintained for the pneumatic transport of fly ash without deposition.

From the theoretical analysis of borehole flow of fluidized fly ash developed in Appendix A, the maximum pressure at the top of the borehole was calculated to be about 5 psi. This, coupled with pressure losses expected in the surface piping system, indicated that the blower be capable of generating approximately 10 psi of air pressure.

For the pneumatic transport of fly ash or any granular material, a positive displacement type of blower or compressor is to be preferred. For this type of a unit, the air-flow rate is relatively independent of system pressure, so that small changes in pressure due to local plugging do not cause a decrease in flow rate. Such a decrease could aggravate the local condition leading to further fly ash deposition due to reduced flow rate and ultimately to plugging of the line.

The prototype system was to be instrumented so that the behavior of the fly ash delivery system could be monitored over a wide range of air and fly ash flow rates.

The layout of the field test site described in Section 8.2 was such that the fly ash truck had to be parked about 300 feet from the borehole locations where the blower was located. The truck was required to pump the fly ash through 300-feet of 4-inch diameter flexible hose, normally used for pumping fly ash, to the blower where it was mixed with the auxiliary air supplied by the blower. An ejector system was designed to mix the high pressure, high flow-rate auxiliary air with the low pressure, low flow-rate fly ash. With such a system, mixing occurred without the addition of a significant back pressure to the fly ash discharge or a reduction in the fly ash delivery rate from the truck.

8.4.2 Description of the Fly Ash Mine Sealing System

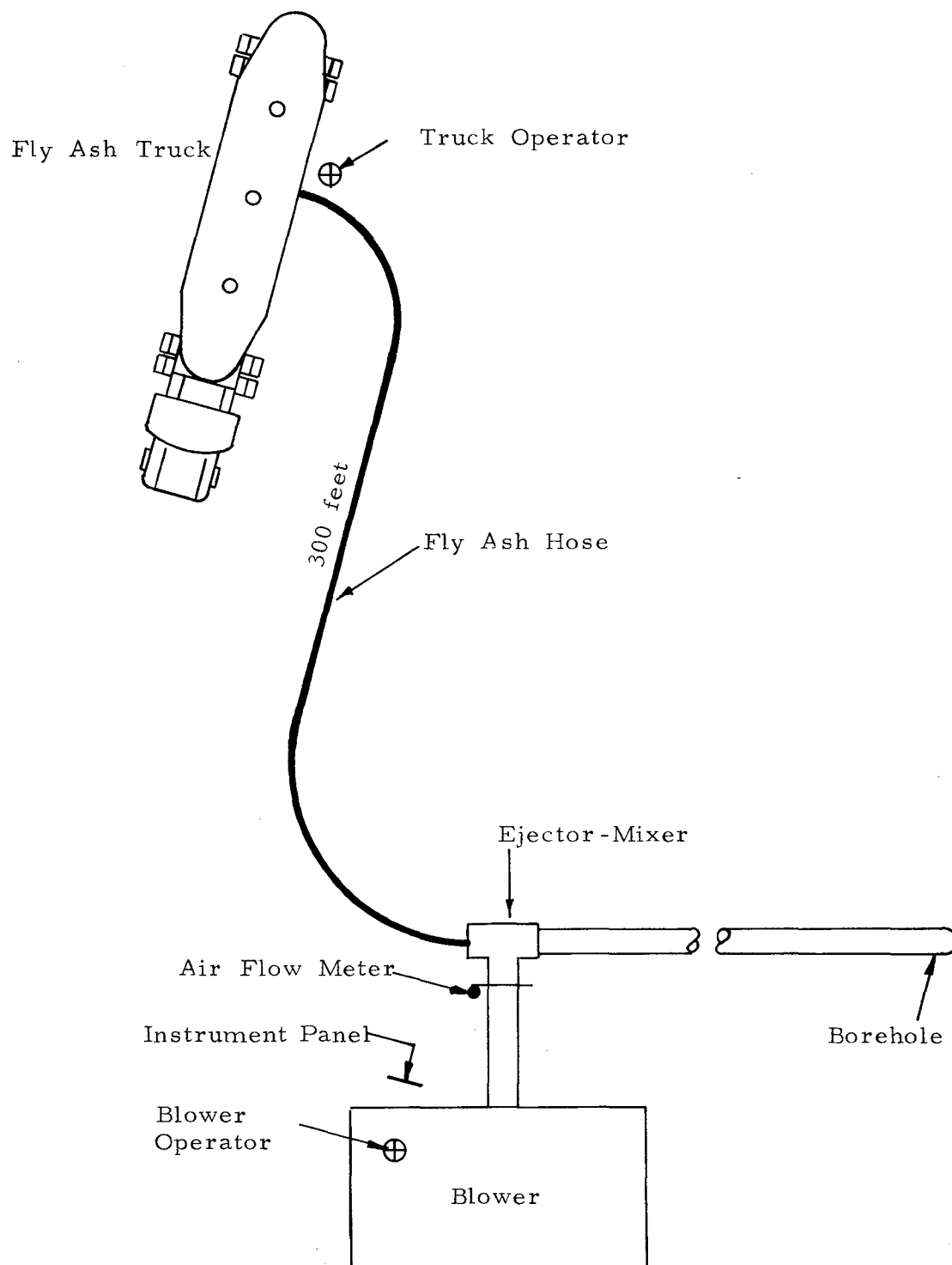
8.4.2.1 Field Layout of the System

Figure 100 shows the complete layout of all the major system components of the fly ash delivery system. It consists of a fly ash truck parked at the entrance to the field on a wooden ramp. The fly ash truck is connected to the ejector-mixer by approximately 300 feet of 4-inch diameter flexible fly ash hose. The blower supplies auxiliary air to the ejector through 10 inch diameter steel pipe. The dilute air-fly ash mixture is transported from the mixer discharge to the borehole inlet through 8 inch diameter plastic pipe.

The system is provided with instrumentation to measure air flow rate from the blower, blower pressure, solids flow rate and borehole pressure.

The photographs of Figures 101 through 104 show the general layout of the field. Figure 101 shows the wooden parking pad for fly ash trucks and the road leading from the main road onto the field. Figure 102 shows a fly ash truck parked on the pad pumping fly ash; the blower can be seen in the distance. Figure 103 is a picture of the blower with the ejector-mixer in the foreground, the fly ash hose entering the ejector and the 8-inch diameter discharge pipe system leaving the ejector. Figure 104 shows the resulting fly ash-air mixture when pumped out into the air on the ground surface.

A list of the equipment required for the fly ash system may be found in Appendix E. A more detailed description of the system components follows.

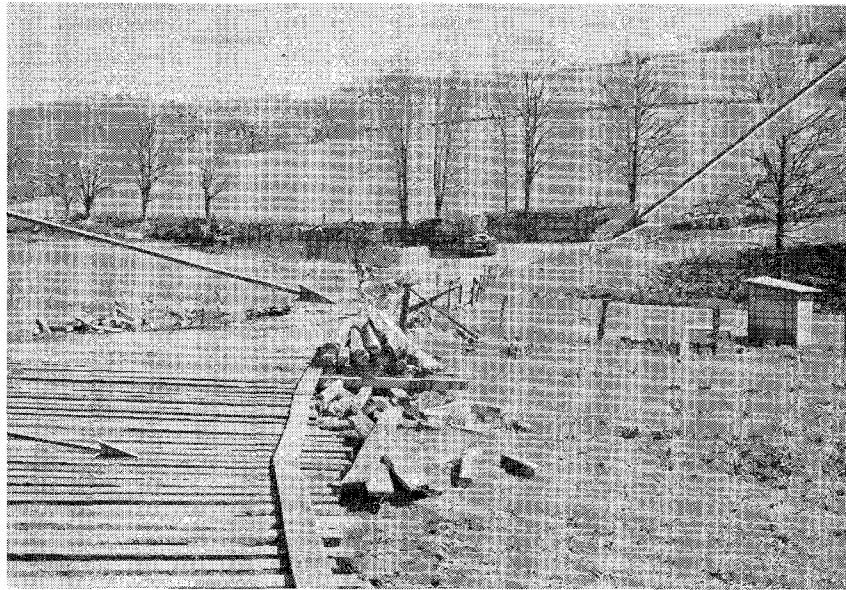


Field Layout of Fly Ash Mine Sealing System

Figure 100

Road
Leading
to Field

Fly Ash
Truck
Parking
Pad



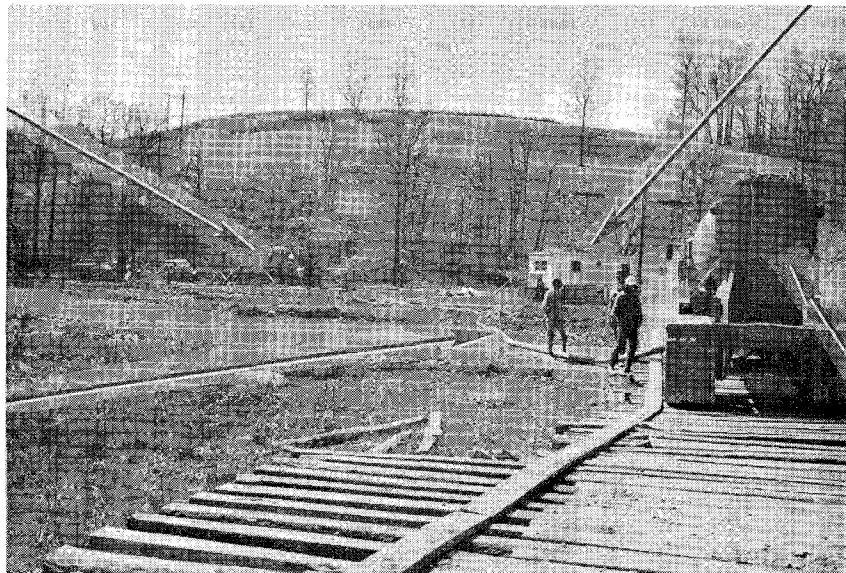
Photograph of Entrance to Field and
Fly Ash Truck Parking Ramp

Figure 101

House Trailer

Blower

Fly Ash
Hose



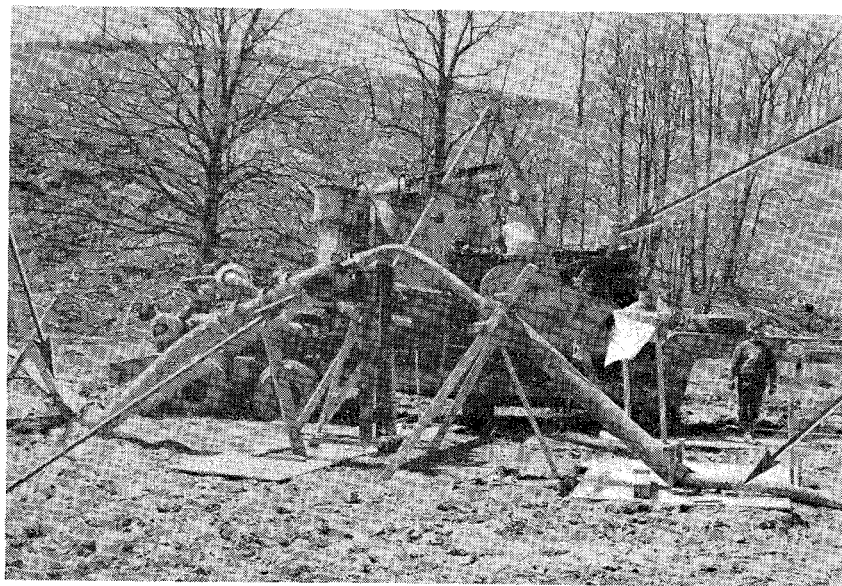
Fly Ash
Truck

Photograph of Field Layout of
Fly Ash Mine Sealing System

Figure 102

Discharge
Pipe
Leading
to
Borehole

Ejector
Mixer

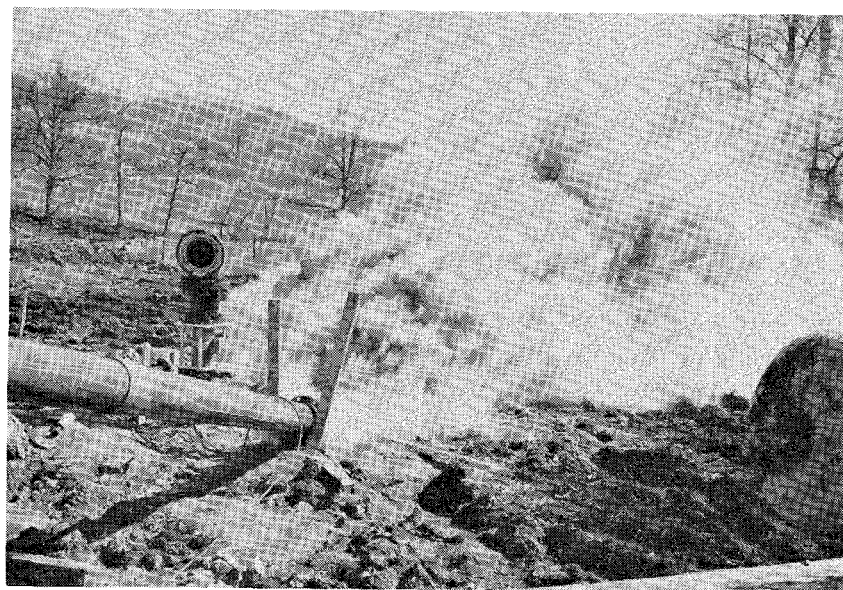


Blower

Fly Ash
Hose

Photograph of Blower and Mixing Section

Figure 103



Photograph of Fly Ash Air Mixture

Discharged on the Surface

Figure 104

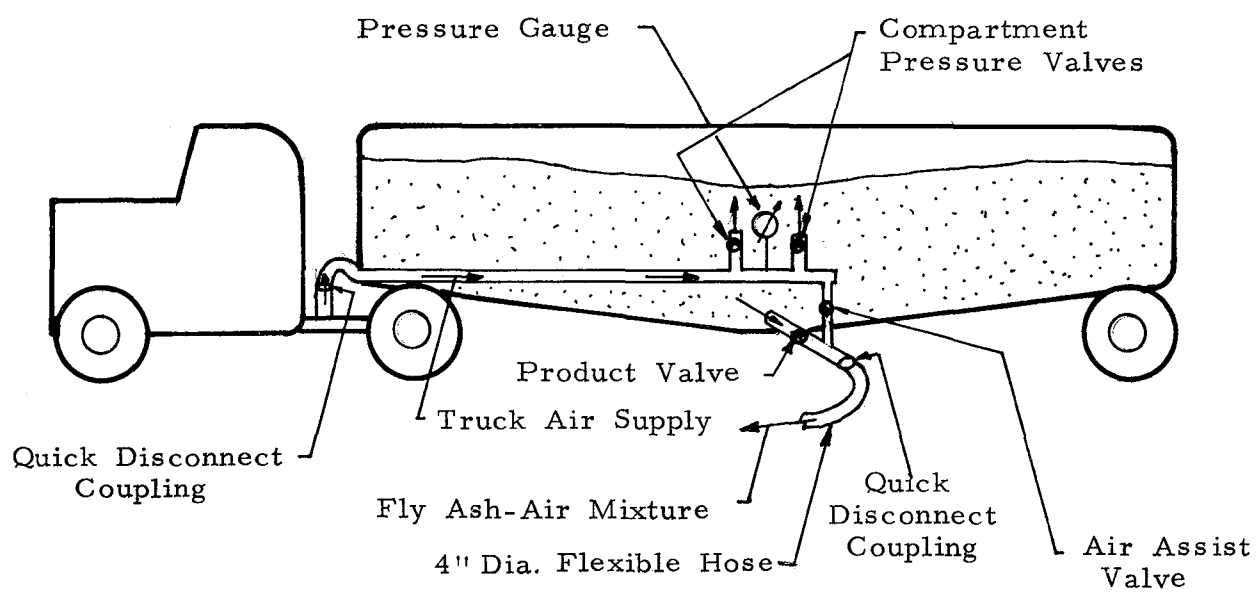
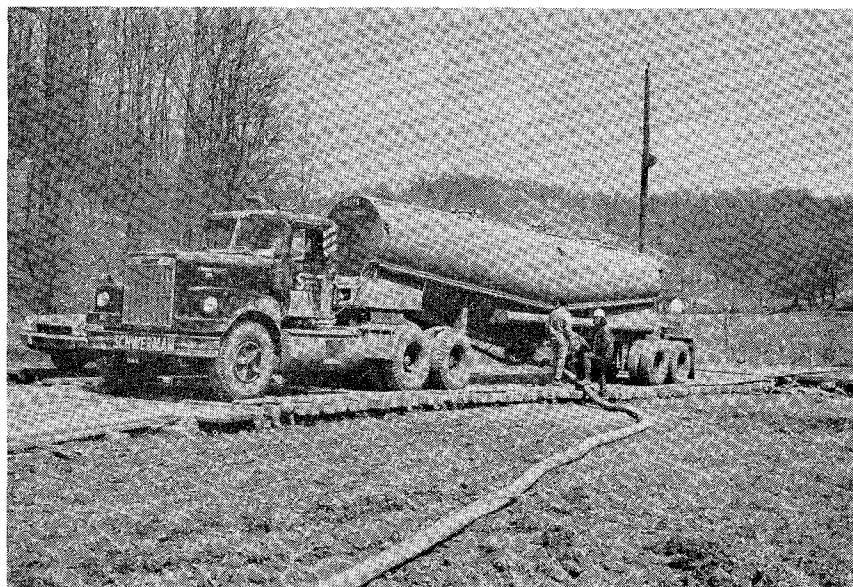
8.4.2.2 Fly Ash Delivery Truck

Figure 105 shows the type of fly ash delivery truck used for the field tests. This type of truck is designated as an "air slide" truck and it was selected for the field demonstration because of its low overall height and high ground clearance; the former characteristic permitted its passage over bridges having low clearance heights, and the latter was necessary to drive down the road to the field and onto the parking ramp.

The fly ash container in the truck is pressurized by injecting air at a pressure of approximately 15 psi; the air injection also helps in agitating and fluidizing the fly ash. This fluidized mixture is discharged under pressure through the 4-inch diameter fly ash hose. A product control valve is provided to control the flow rate of fly ash. In addition, an "air assist" valve diverts air from the blower into the fly ash discharge to adjust the fly ash concentration in the hose for optimal pumping, i.e., maximum fly ash discharge rate with minimum pressure loss.

The truck mounted blower was either a turboconveyor consisting of an exhaust driven turboblower or a CEC (Compressor-Engine-Converter) in which two cylinders of the truck diesel engine drove the other four as a compressor, depending on the particular truck used. The turboconveyor could not supply more than 20 psi, while the CEC required the use of a relief valve to keep operating pressures below 20 psi. Both units supply about 300 to 400 scfm of air.

Normal fly ash delivery operations are conducted at an operating pressure of about 12 psi. However, for these field tests, higher operating pressures of 15 to 18 psi were required to overcome the friction pressure drop in the long, 300-foot horizontal, fly ash line and the back pressure at the ejector-mixer inlet.



Fly Ash Truck and Schematic of Plumbing System

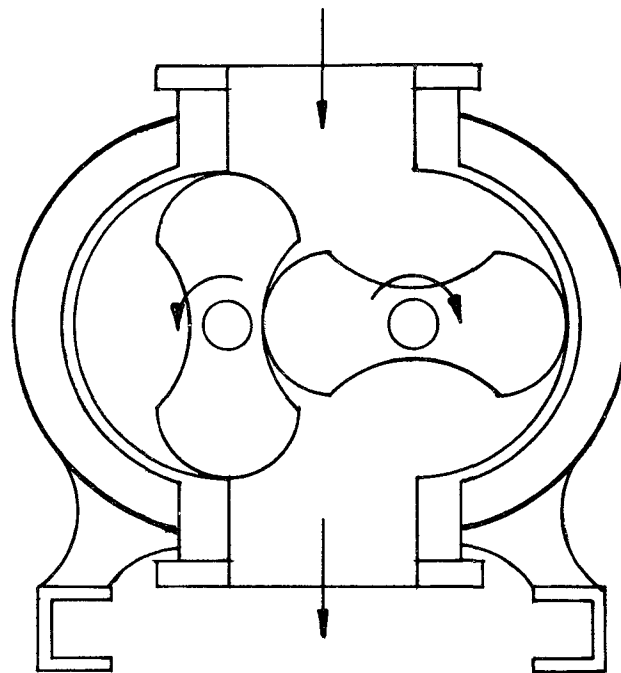
Figure 105

8.4.2.3 Blower

A diesel-driven rotary positive-displacement blower was selected to provide the specified air supply of 5000 scfm at 10 psi maximum. Reciprocating types of air compressors commonly used in the construction industry are basically high pressure, low air-flow rate machines. They are not suited for most pneumatic transport operations which require high flow rates at low pressure. Centrifugal blowers would require multistaging to generate the 10 psi pressure required. They have a drooping pressure-flow characteristic where the flow rate drops off rapidly with increasing pressure. This can lead to flow instability and plugging.

Two types of rotary positive-displacement machines are acceptable: the Lysholm type of helical or screw compressor made by Gardner Denver Corporation or Fairbanks-Morse Corporation, or the lobe type blower made by Sutorbilt Corporation or Roots Connersville (Dresser Industries).

A Sutorbilt Series 3200 blower shown in Figure 106 was selected, as it was available on loan from the U. S. Bureau of Mines, Minneapolis, Minnesota. It is capable of providing a maximum of 5700 scfm at 10 psi. The blower is driven by a variable speed diesel engine drive so that the flow rate can be varied from 1000 scfm to 5700 scfm. Figure 107 shows a photograph of the blower unit received from the Bureau. It was originally set up for vacuum operation and consequently included considerable auxiliary equipment, such as separators and filters not required for pressurized operation. The blower was modified for pressure operation by Fenix & Scisson, Inc., Tulsa, Oklahoma under contract to Foster-Miller. In the photograph of Figure 107 the equipment required for the field operation is in the foreground



Sutorbilt Blower

Figure 106

Auxiliary
Equipment
Required
for
Vacuum
Operation

Outlet
Pipe

Blower



Diesel Drive

Blower Mounted on Flatbed Trailer with Other Equipment

Figure 107

and has been identified in the figure. The auxiliary equipment required for vacuum operation was disconnected but left on the flat bed. It is visible in the background.

8.4.2.4 Instrumentation

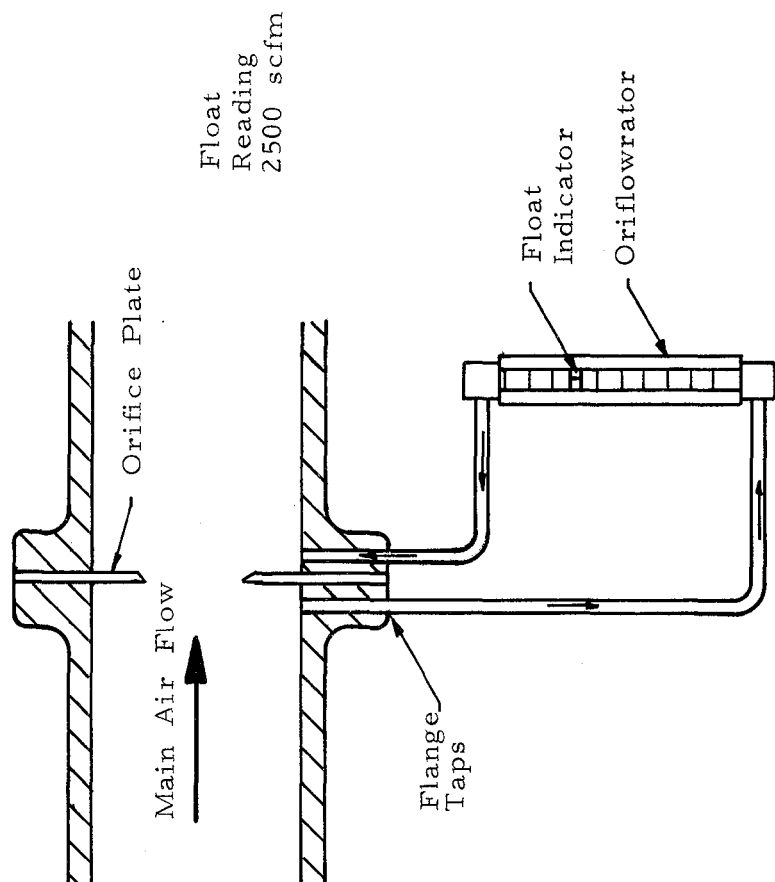
(1) Air Flow Meter

The blower discharge air flow rate was measured with a Fischer-Porter oriflowrator in conjunction with an orifice plate. With this system, the volume flow of air is measured by the differential pressure produced by an orifice restriction in the system. Figure 108(a) shows the flow arrangement, and Figure 108(b) is a photograph of the flow meter readout. The orifice plate constricts the main air flow and the oriflowrator, which is a kinetic manometer, translates the resulting pressure differential into a measure of the main air flow. Accurate measurement of flows up to 6000 scfm requires the use of a 6-1/2-inch diameter orifice placed in a 10-inch diameter line, with about 10-feet of straight 10-inch pipe upstream of the flowmeter to ensure flow stabilization.

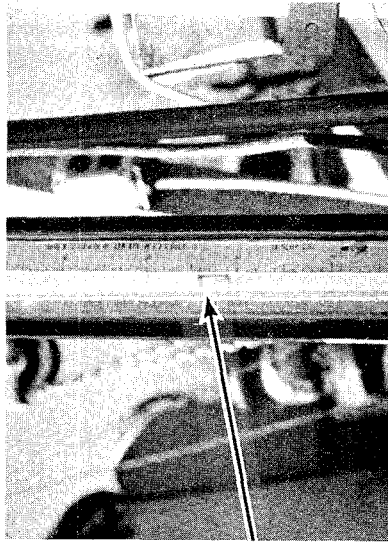
(2) Fly Ash Solids Flow Meter

The rate of fly ash delivery into the borehole was measured using a Kent-Fielden Flow Telstor,* which measures the mass flow of air-borne particulate solids. Figure 109 provides a description of the flow meter. Physically, this meter consists of a one foot section of pipe through which the fly ash-air mixture passes. An electrode, flush-mounted on the inside diameter of the pipe measures turbulent noise, and the signal is sent back to an integrator which converts it into a measurement of fly ash flow. The system requires calibration, after which the meter can be read directly in tons/hour of fly ash.

* Trade Name



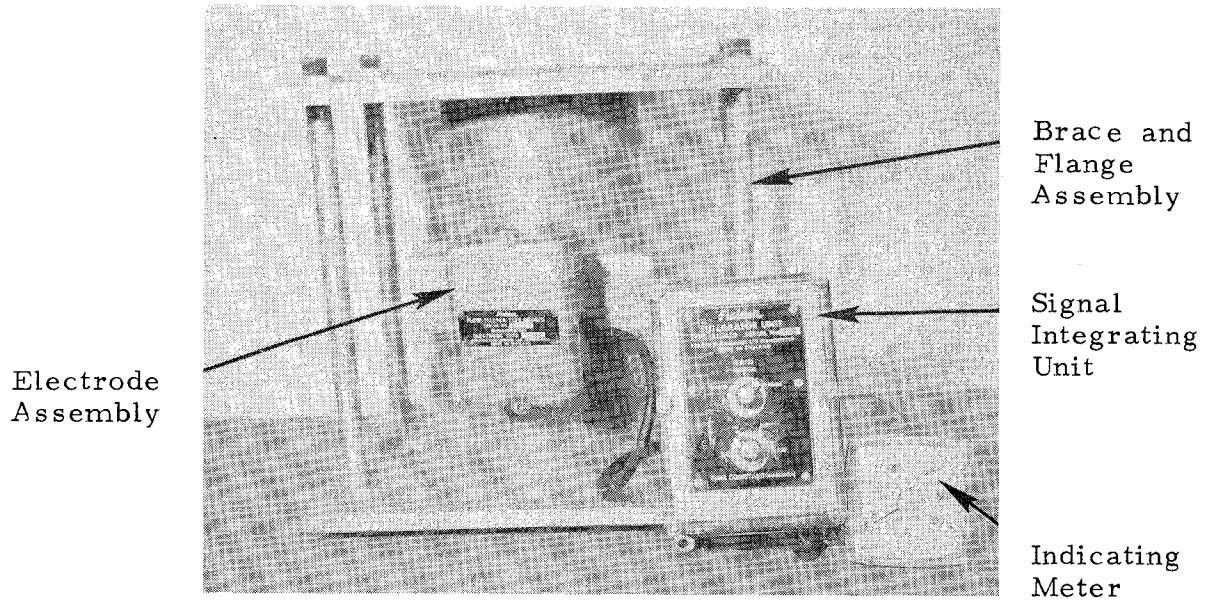
(a) Flow Schematic



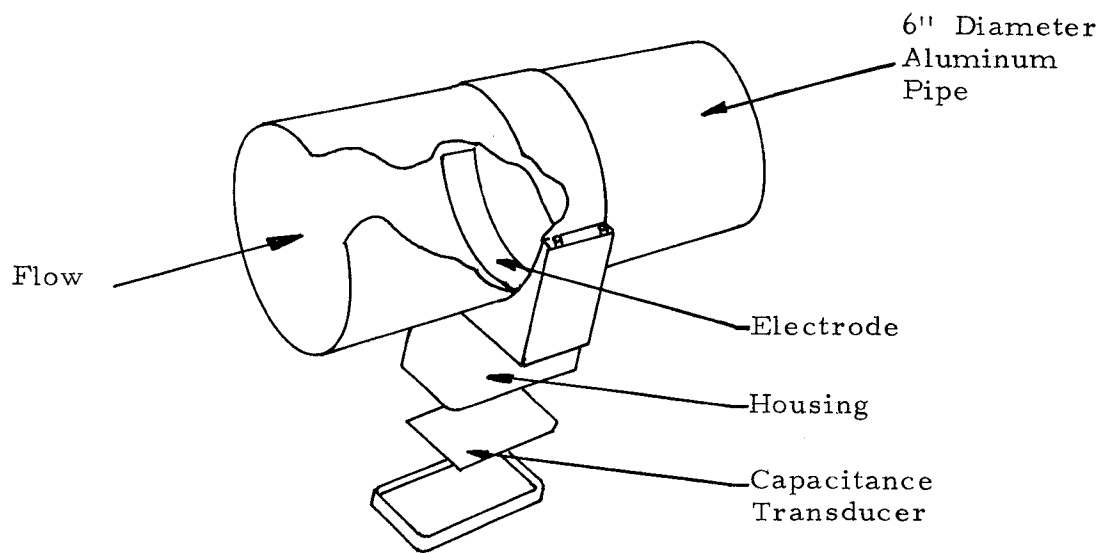
(b) Photograph of Oriflowmeter Readout

Combined Orifice Plate and Oriflowmeter Air
Flow Rate Measuring System

Figure 108



(a) Complete Unit



(b) Detail of Pipe Section

Solids Flow Meter

Figure 109

(3) Borehole Pressure at the Surface

Pressure measurements at the top of the borehole were taken with a pressure transducer. It was felt that conventional pressure lines would quickly clog with fly ash. The transducer had a 15 psi range and was adjusted to read from -5 to +10 psig.

(4) Blower Back Pressure

A conventional 0-10 psi pressure gauge was connected upstream of the air flow meter to measure the back pressure on the blower. This pressure gauge was constantly monitored to prevent blower overloading. The pressure readings were also used to adjust the air flow rate measurement of the oriflowrator for system pressure.

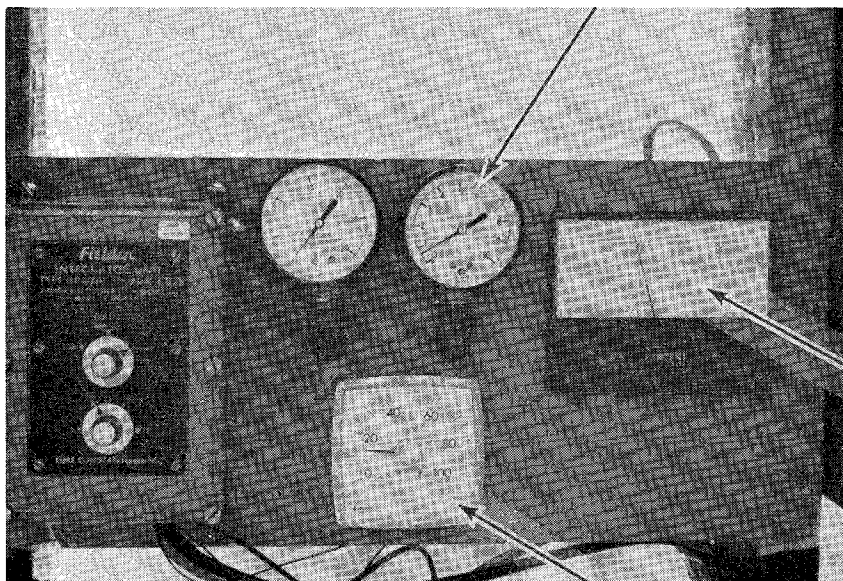
(5) Instrument Panel

With the exception of the oriflowrator, the measurement gauges were mounted on an instrument panel near the blower. Figure 110 shows a photograph of the instrument panel

8.4.2.5 General Piping Layout

Figure 111 shows a schematic of the complete piping system. A 6-inch diameter bleed valve was provided at the blower outlet so that low air flow rates could be obtained without running the blower too slowly. Figure 112 shows a drawing of the ejector-mixer used for blending the fly ash from the truck with the air supply from the blower. The venturi resulted in a reduction in the static pressure of the auxiliary air supply and back pressure at the fly ash discharge. Thus the truck pressure required to pump fly ash was kept at a minimum.

Blower Back
Pressure

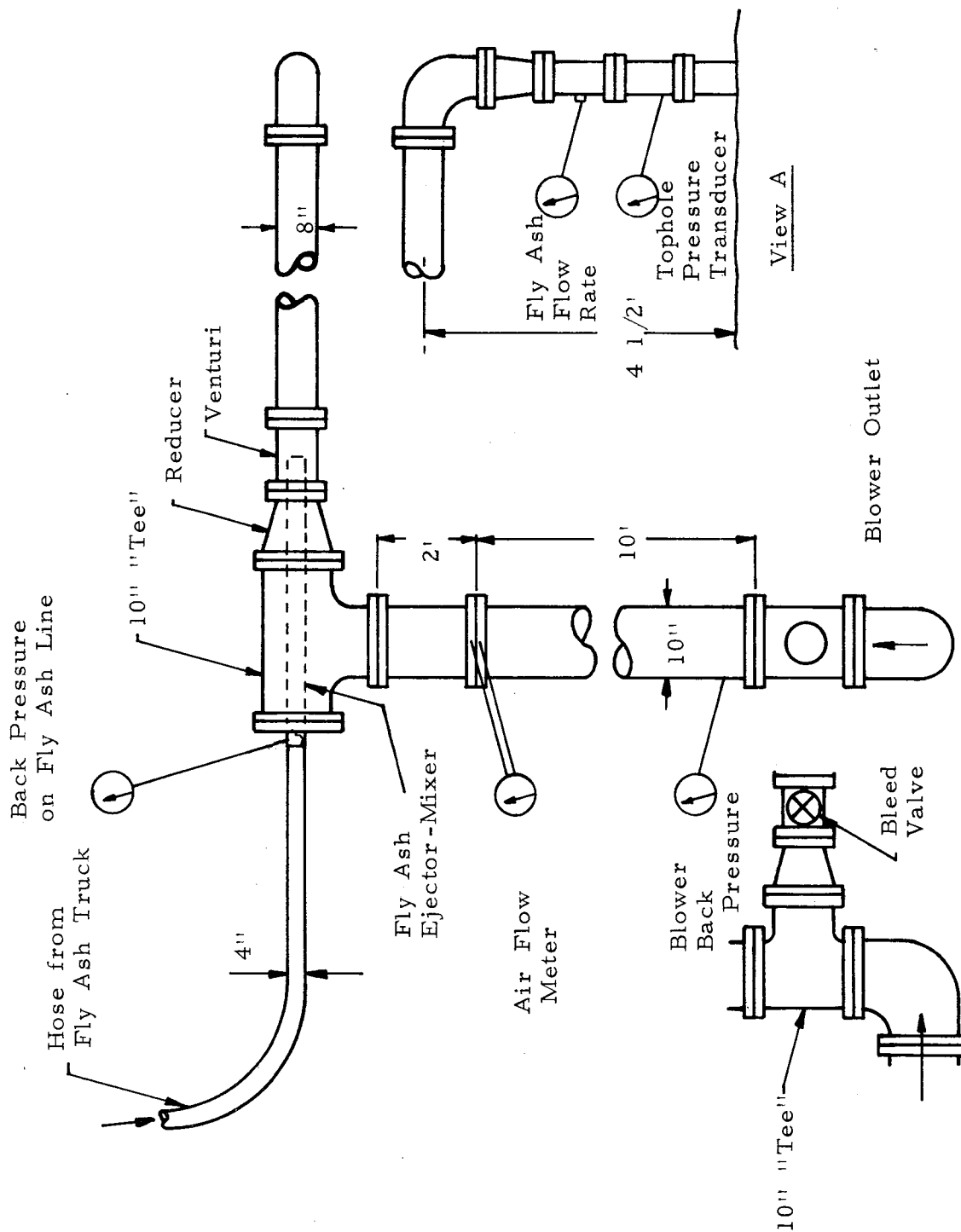


Pressure
at top of
Borehole

Fly Ash Flow
Meter Reading

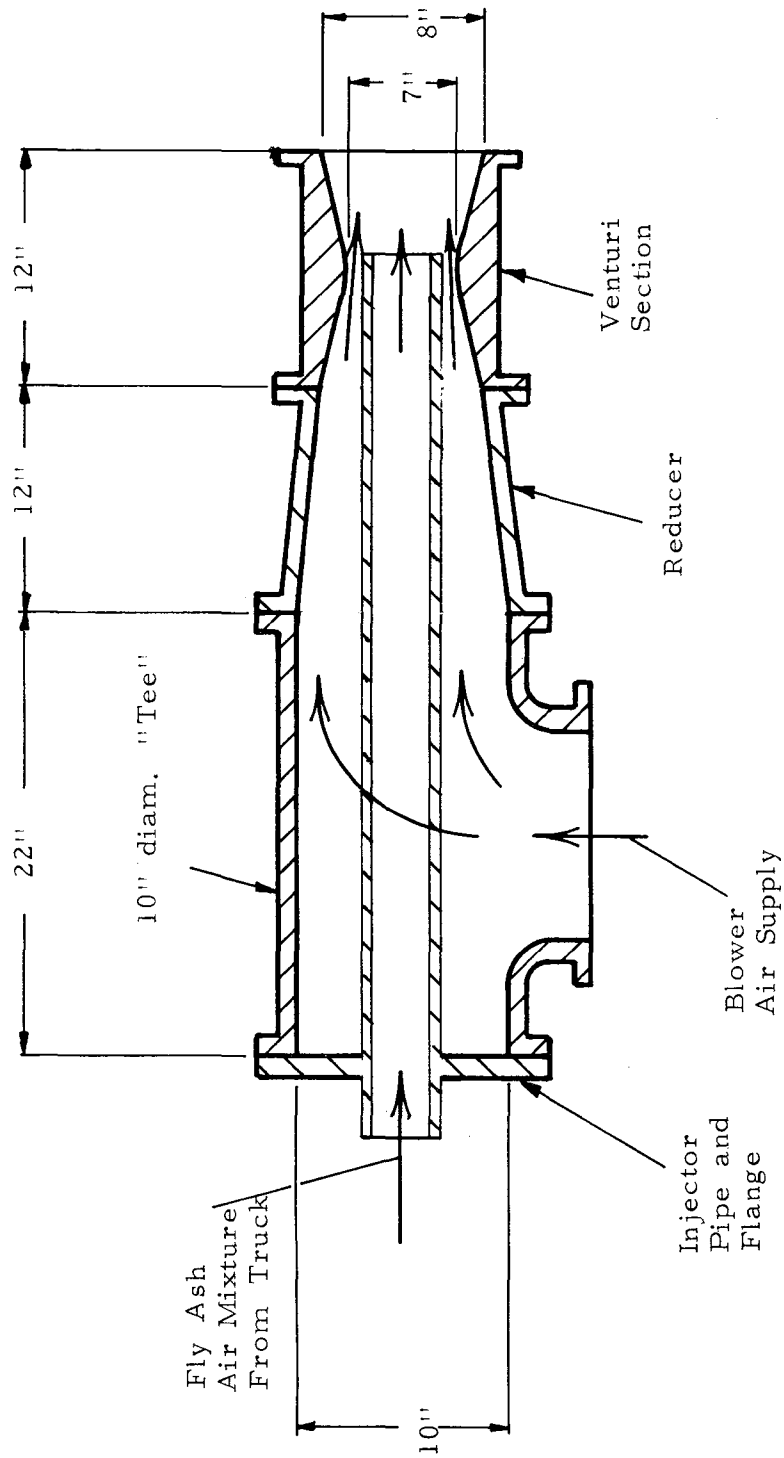
Instrument Panel

Figure 110



Fly Ash - Air Flow System

Figure 111



Fly Ash Ejector-Mixer

Figure 112

The blower was connected to the ejector by 12 feet of 10" diameter steel pipe. This pipe diameter was determined by the specifications of the oriflowrator which required a 6 1/2" diameter orifice in a 10 inch diameter pipe in order to measure air flows up to 6000 scfm. Surface piping from the ejector to the borehole was sized at 8 inches to keep the pressure drop low at the maximum design air flow rate of 5000 scfm. PVC pipe was selected because it is light, easy to handle and can be fabricated at site into different lengths very easily. Pipe fittings are also readily available. A 10 foot section of 8 inch diameter flexible hose used between the ejector and the PVC pipe provided the necessary flexibility for alignment to different boreholes.

Figures 113 through 115 show photographs of the typical piping arrangements used for the different borehole locations.

8.4.3 Field Test Procedures for Making Fly Ash Seals

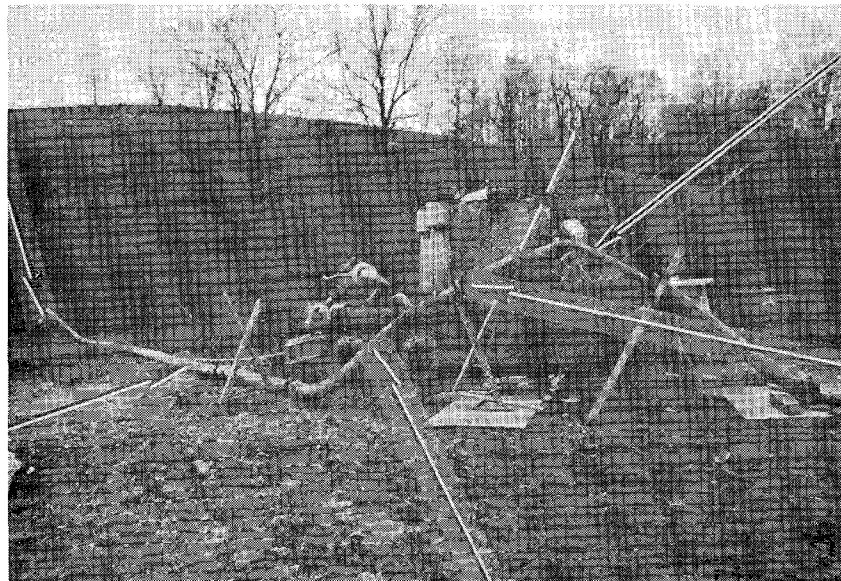
The test procedures outlined in this section were generally used for making all the fly ash seals in this program. They consist essentially of procedures for equipment set-up and system operation. This description assumes that the site preparations described in Section 8.2 have been completed.

(1) Piping Connection from Ejector-Mixer to Borehole

Sections of PVC pipe were laid out

Borehole

8" Dia.
PVC Pipe



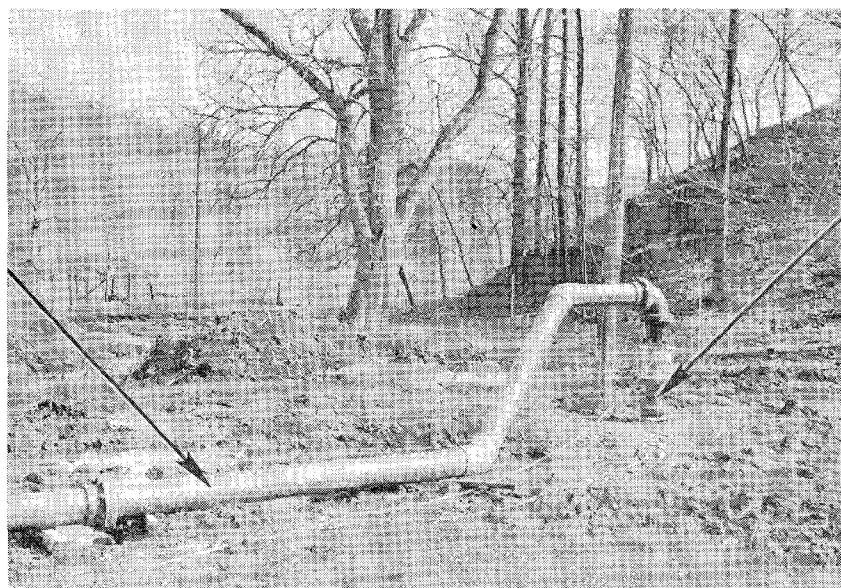
4" Line From
Fly Ash Truck

"Tee" and
Ejector
Assembly

10" Section of 8" Diameter
Flexible Hose

(a) Complete Piping Layout

8" Dia.
PVC Pipe

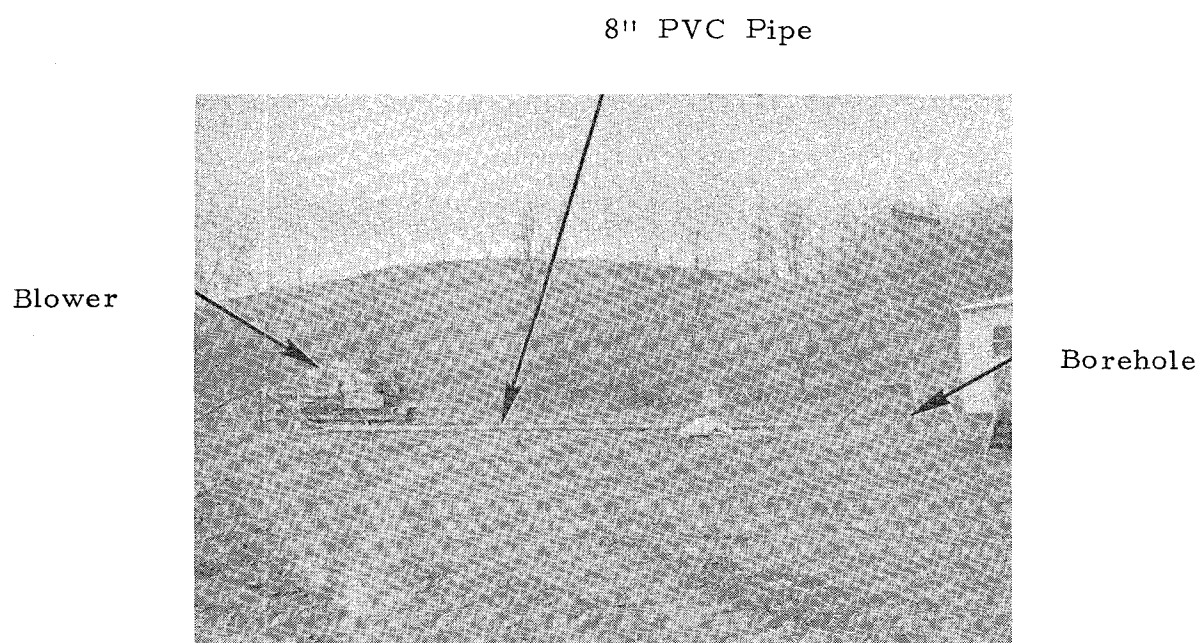


Borehole

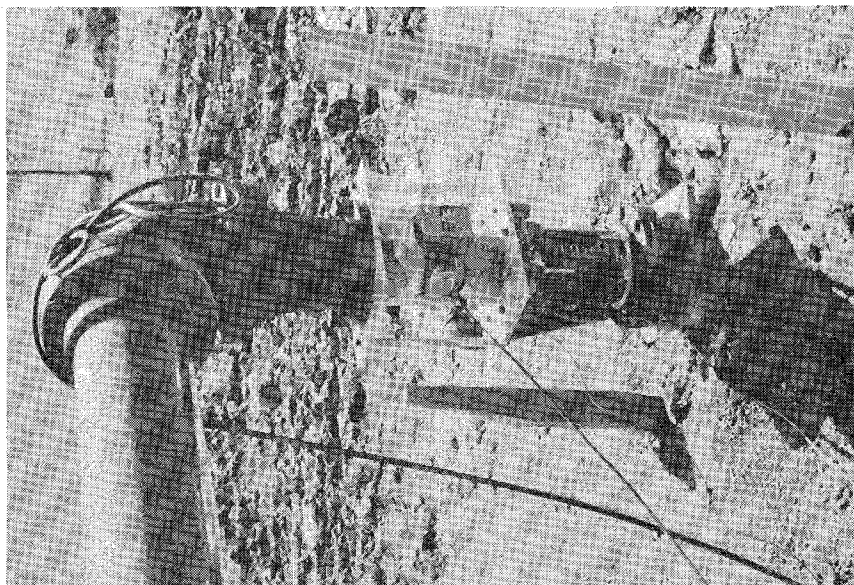
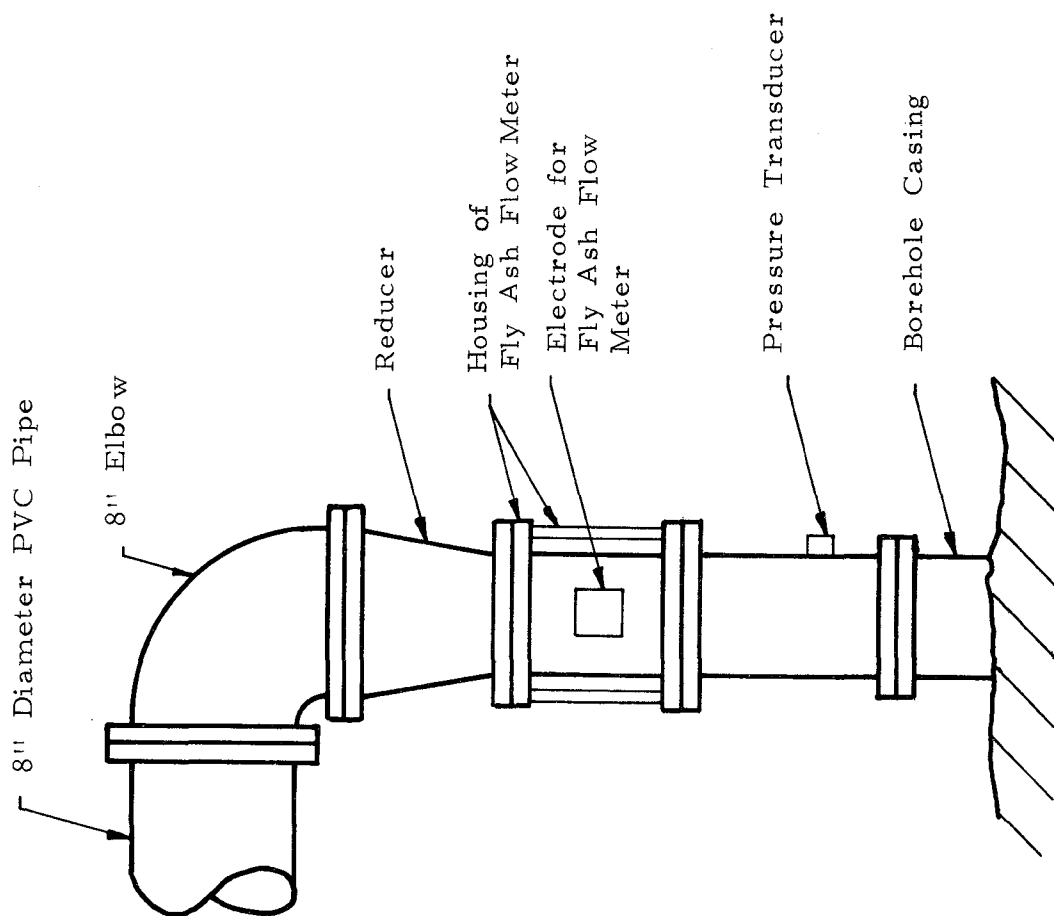
(b) Final Sections of Pipe

Typical Piping Layout (4-Way Intersection)

Figure 113



Piping Layout to Straight Passage Borehole
Figure 114



Pipe Stack on Top of Borehole

Figure 115

to the new borehole location and cut to length. The pipe assembly on top of the borehole was moved as a unit to the borehole and bolted to the borehole and to the PVC pipe. The wiring to the pressure transducer and fly ash flow meter was then reconnected.

(2) Arrangement for Fly Ash Truck Deliveries

The required volume of fly ash was calculated from the following formula:

$$\text{Number of Fly Ash Trucks} = .00175 \text{ hw} \left(\frac{h}{\tan \Theta} + w \right)$$

where

- h = height of fly ash pile
- w = width of passage
- Θ = slope angle of pile
- Θ = 15° for partial fly ash seal
8° for complete fly ash seal

This formula assumes a seal of trapezoidal section.

Based on this approximate number of fly ash trucks required, arrangements were made with the fly ash trucker so that deliveries were at approximately one hour intervals.

(3) Selection of Air Flow Rate

Results from laboratory tests indicated that the air flow rate should be increased with passage width using the following formula.

$$\text{Air flow (cfm)} = 2 \times (\text{passage width in feet})^{5/2}$$

The fact that an effective seal can be made with a large range of crater diameters suggests that the above formula is approximate, and required flows can be adjusted according to available equipment. This is discussed in more detail in Section 6.2.6.

The air flow includes the 300 to 400 cfm supplied by the truck. Corrections were also made for the straight passage and the 4-way intersection, both of which required extra air flow because of the high roofs.

(4) Development and Calibration of
Seal Checker

Before fly ash is poured, the seal checker was deployed either through the seal checker borehole at Borehole #1 or by manually carrying it into place underground at Borehole #2. A reference reading was then taken to identify the initial unsealed area of the passage.

The system was now ready for operation.

(5) Arrival of Truck

The truck to be pumped drove down the road to the field and onto the truck parking ramp, where it was connected to the 4-inch delivery line.

(6) Blower Startup and Pressurization
of Fly Ash Truck

The blower was started before any pumping of fly ash began to prevent fly ash from getting into the blower. Once the blower was on and the appropriate flow rate reached, the blower operator signaled the truck operator to pressurize the fly ash compartments on the truck.

(7) Delivery of Fly Ash

When the truck pressure reached about 15 psi, the air assist line was opened to blow any remaining fly ash out of the 300-foot fly ash line. Then the truck product valve was opened to begin delivery of fly ash.

(8) Monitoring of Flow Conditions

During the fly ash delivery, the blower operator would check pressures and flow rates. After the fly ash pumping began, for example, the additional load on the blower would produce a lower air flow rate, as indicated on the air flow meter. The blower operator would constantly monitor and correct the air flow rate. Blower pressure was monitored to avoid excessive loading of the blower. 10 psi was considered to be the maximum allowable operating pressure. The solids flow meter continuously monitored the fly ash delivery. If delivery were slow or sporadic, the blower operator would signal the fly ash operator to check for any pressure reduction or clogging in the truck delivery system.

(9) Termination of Truck Delivery

The blower operator would signal the truck operator to shut the product valve and bleed off the pressurized tank when the fly ash flow meter indicated that the truck was empty. After the truck valves were shut, the blower was turned off. The fly ash truck then backed off the ramp and out to the main road, a process which usually took about 5 to 10 minutes. The entire process, from arrival to departure, took about one hour.

Most of the problems which occurred during fly ash pumping occurred at the truck. Improperly set relief valves, leaking hatches, and bad hose connections frequently prevented the pressure from going above 12 or 13 psi, and the result was frequent shutdowns because the truck was not delivering fly ash. The frequency of occurrence of these problems reduced with time and experience. It soon became clear that truck pressure alone dictated how well the truck would pump fly ash; efficient pumping requires the operating truck pressure to be 15-18 psi, as compared to 12 psi for conventional fly ash pumping.

8.4.4 Description of Field Tests of Mine Sealing with Fly Ash

8.4.4.1 Program Plan

The fly ash sealing field test program was designed to demonstrate the capability of making fly ash seals in 3 mine passage configurations. In increasing order of estimated complexity, these were:

- a. Simulated straight mine passage with a low roof under number 3 borehole.
- b. Straight mine passage under number 1 borehole.
- c. Four-way intersection under number 2 borehole.

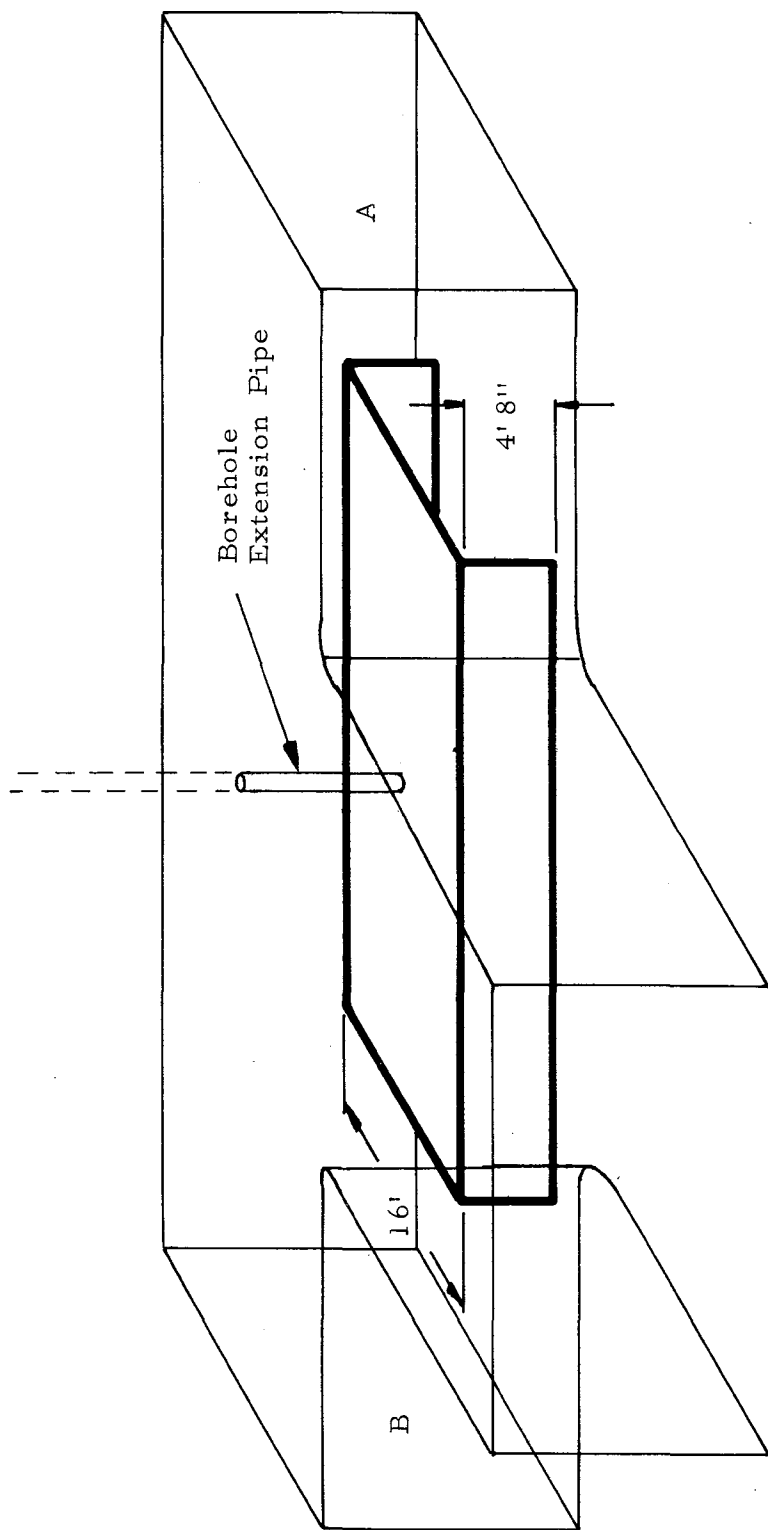
In addition, studies were conducted to determine the following:

- a. Flow characteristics with longer boreholes.
- b. Capability of achieving higher fly ash flow rates by pumping two fly ash trucks simultaneously.
- c. Effect of borehole water flow on fly ash seal development.

In the two straight passages, fly ash was used as a bulk filler only with the final seal made by froth urethane foam as described in Section 8.5. The 4-way intersection was sealed completely with fly ash only. The results of these tests are described in the following sections.

8.4.4.2 Test Results of Sealing the Simulated Low Roof Straight Passage with Fly Ash

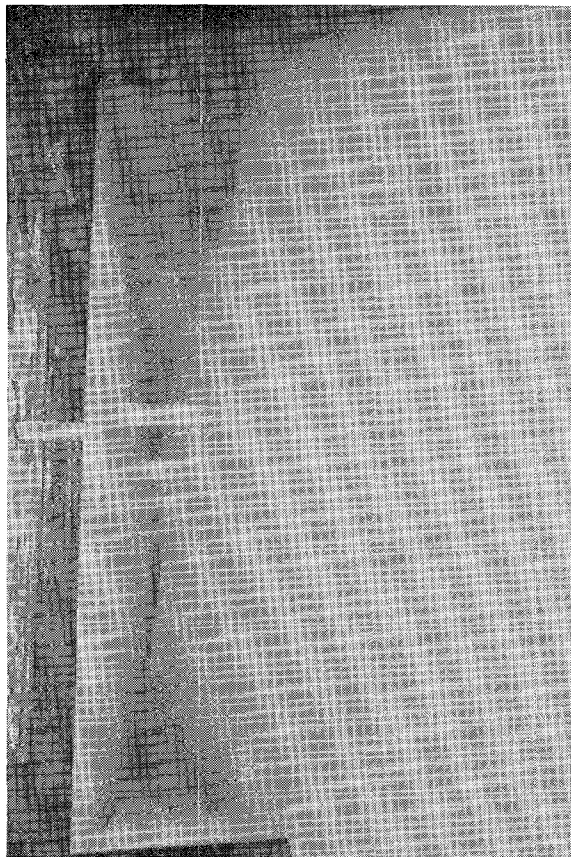
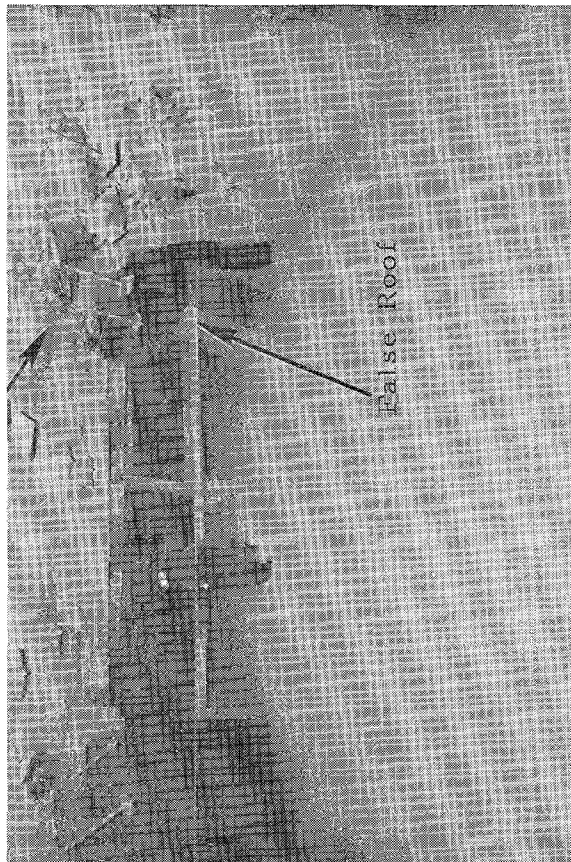
Figure 116 shows the geometry of the false roof passage. The false roof was placed at the "Tee" intersection for easy access, so that the roof panels could be removed for examination of the seal. Because the entire passage was not being sealed, the acoustic seal checker could not be used for this test.



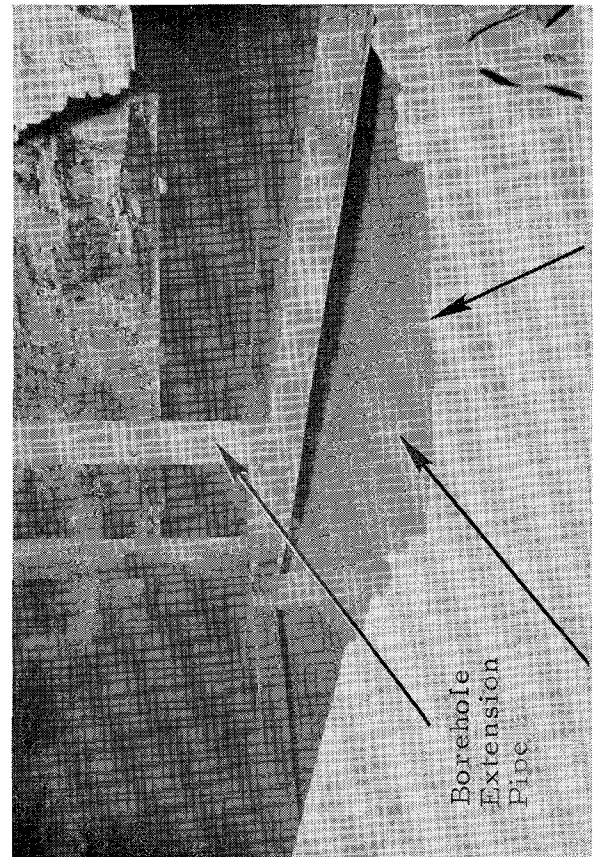
False Roof Passage at 3-Way Intersection

Figure 116

Mine Roof



- (a) View from A
- (b) View from B
- (c) View into Crater with
Roof Panel Removed



False Roof Seal Test

Figure 117

The fly ash was delivered at an air flow rate of 2500 scfm and an average fly ash flow rate of approximately 3/4 ton per minute, which corresponds to unloading a fly ash truck in 25 to 35 minutes. Five truck loads of fly ash produced the seal shown in Figure 117. A sharp rimmed, 12-foot-diameter crater was formed with the lowest portion of the rim about 4 inches below the passage roof. The crater roofed at one rib of the passage and about 4 feet from the other rib. The seal was stopped at this point to allow for the froth foam topping.

Based on visual observations of the fly ash pile geometry, this fill represents 90 to 95 percent seal and was achieved with 100 tons of fly ash.

The volume of material required and the general geometry of the in-place fly ash compared well with predictions based on the 1/4-scale mine passage.

During the test at this air flow rate of 2500 scfm, the blower pressure fluctuated between 2 and 3 psi and the borehole pressure at the surface between 0 and 0.6 psi. The fly ash delivered by the trucks would come through as high density slugs every 4 or 5 seconds. This behavior was indicated by fluctuations of the solids flow meter and by the pulsing and whipping of the 4-inch flexible fly ash hose. Although the fly ash flow rate varied greatly over a time constant of about 5 seconds, the total fly ash delivered per minute was constant. As the operators gained experience with the system, it was possible to virtually eliminate the surges of fly ash through careful monitoring of the fly ash truck controls, each of which had somewhat different operating characteristics.

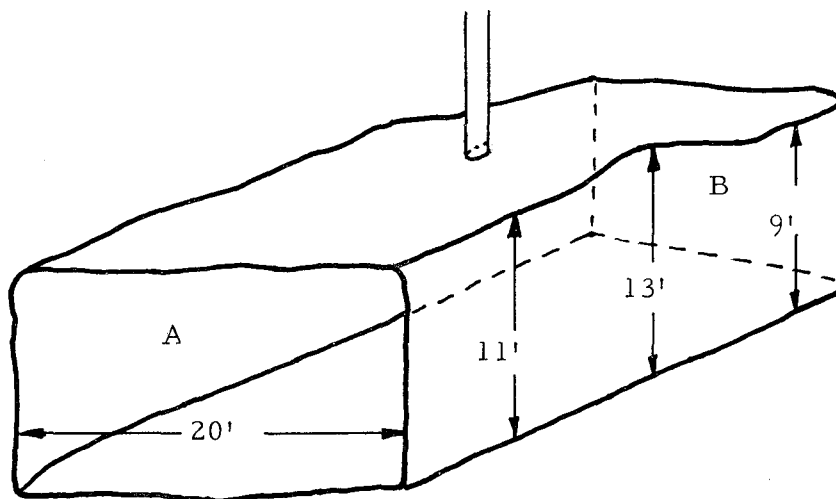
Throughout the fly ash pour, the flow instrumentation gave no indication of the build-up of the fly ash pile; the instrument readings remained essentially unchanged. After the completion of every truck pour, the build-up of the fly ash pile was visually observed underground. Because of the large gap between the false roof and the actual mine roof, the acoustic seal checker could not be used for this test.

8.4.4.3 Test Results of Sealing the Straight Mine Passage with Fly Ash

The second sealing demonstration was carried out in the straight mine passage under number 1 borehole. Figure 118 shows the general layout of the passage and Figure 119 a photograph of the roof and ribs. The presence of the protruding roof bolts, trolley wire and gob material on the floor are obvious from the photograph. The photograph does not show the wide variation in roof height in the area to be sealed. As shown in the drawing, the roof height varied from 9 feet to 11 feet with a dome about 13 feet high near the borehole. This difference of 2 feet in roof height from 9 to 11 feet explained the type of fly ash seal obtained in the tests, where one side of the roof was almost sealed with fly ash while on the other side there was almost a 2 foot clearance.

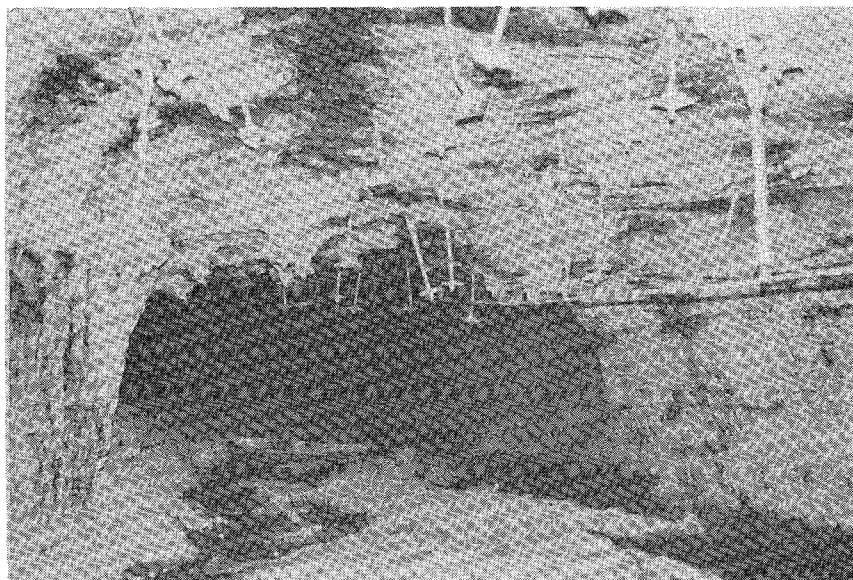
The acoustic seal checker was deployed during this test with the speakers on side B and the microphone receiver on side A. The seal checker monitored the build up of the fly ash pile throughout the test. Its results were compared with visual estimates of the percentage of the area sealed. A detailed description of the seal checker monitoring of the seal is to be found in Section 8.6.

The test was conducted at a blower air flow rate of 3000 scfm. Figure 120 shows the first burst of fly ash entering the passage through the borehole. The high velocity jet of fly ash laden air penetrating all the way to the floor without much dispersion can be seen, as can the spreading of the fly ash along the floor to the ribs of the passage.



Schematic of Straight Passage

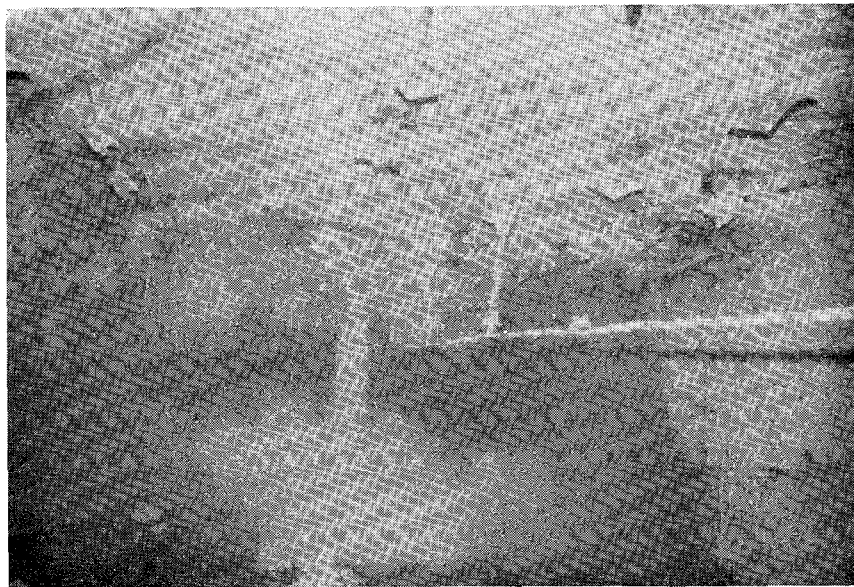
Figure 118



Straight Passage Before Seal

Photo Taken From Under the Borehole

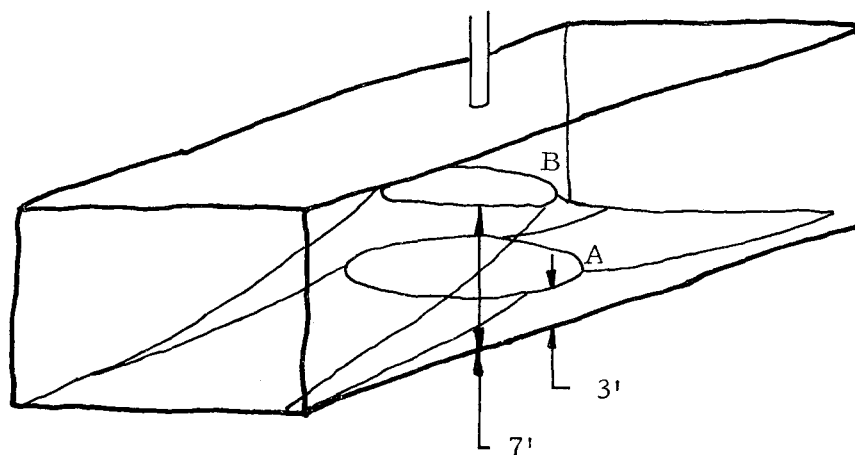
Figure 119



Straight Passage - Initial Fly Ash Pour

(Taken From A)

Figure 120



A - after 5 trucks
B - after 14 trucks

Straight Passage - Stages of Seal Development

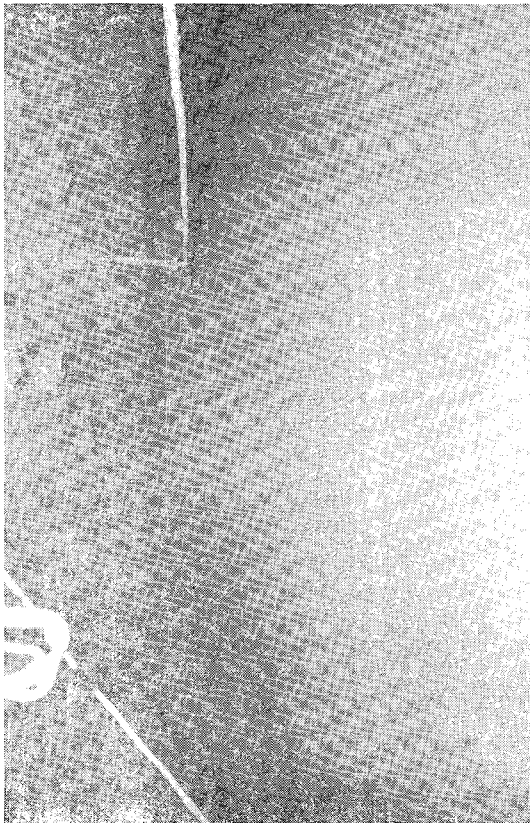
Figure 121

Figure 121 shows two stages in the development of the fly ash seal. As shown, an elliptical crater, whose long axis spanned the width of the passages, was formed in the early stages of sealing. This crater continued to exist throughout the sealing process and resulted in filling the passage from the outward corners in towards the center. This kept the borehole clear of fly ash and ensured filling of the corners.

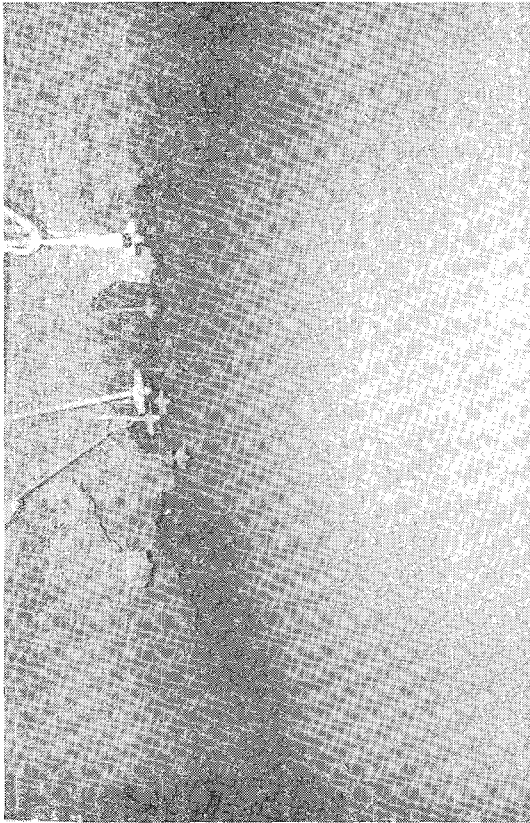
Figures 122(a) and (b) show the two sides of the seal after 14 truck loads or almost 280 tons of fly ash. The fact that side B is better sealed than side A due to the 2 foot difference in roof height is apparent but a little difficult to see from these photographs. This stage represents an estimated 96 percent fly ash seal based on the smallest unsealed area, which is on side B.

Figure 122(c) was taken from side B after 22 trucks, or 50 percent more fly ash than in the previous photographs (a) and (b). The improvement in the seal or reduction in open area is not that dramatic. The acoustic seal checker showed an improvement in seal quality from 96 percent to 99 percent, which represents only a 3 percent increase for a 50 percent increase in fly ash. In fact, it was found that as the seal approached the roof greater quantities of fly ash were required to make small reductions in the minimum unsealed area.

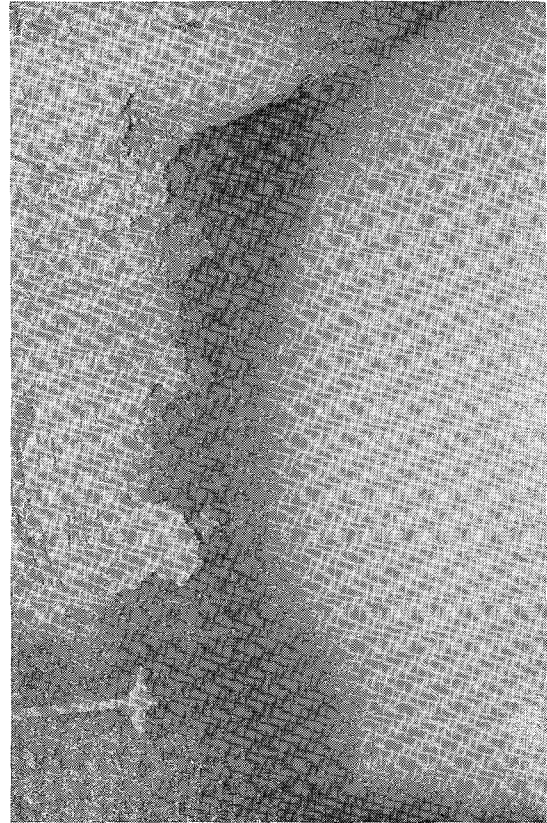
As discussed in the laboratory test results of Section 6.2, the seal spread by depositing fly ash along the sloping sides rather than building up to the roof by depositing in the crater zone. This type of behavior can be attributed to the reduced flow area in the crater zone leading to higher air velocities which prevent fly ash from depositing in this zone. The air flow rate must be reduced to induce fly ash deposition in the crater zone.



(a)



(b)



(c)

- (a) After 14 trucks (from A)
- (b) After 14 trucks (from B)
- (c) After 22 trucks (from B)

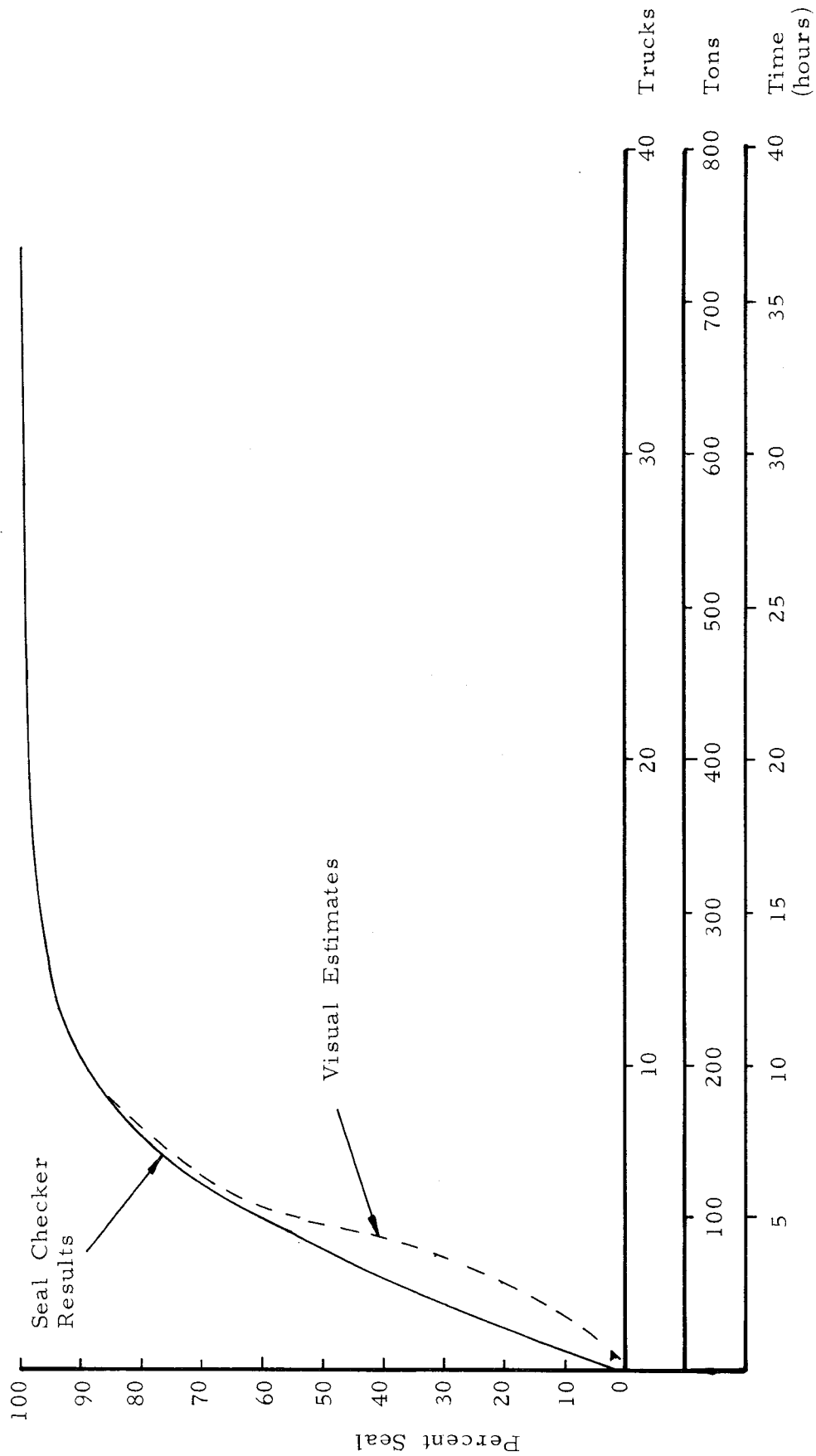
Straight Passage Fly Ash Seal Development

Figure 122

Therefore, the final four trucks were pumped at a reduced flow rate. Trucks 18 to 21 were pumped at 2000 scfm and truck 22 at 1500 scfm. At this point there was an estimated 2-square-foot opening on the 'B' side of the seal and an estimated 6-square-foot opening on the 'A' side of the seal. Based on the minimum opening, this represents a 99 percent seal. Figure 123 shows a curve of the percentage seal versus tons of fly ash material required and estimated time for filling the fly ash. The estimated percent seal is shown for both visual observation and acoustic seal-checker data.

The seal checker is not sensitive to the initial buildup of the pile and thus the curve is not very accurate at the low seal values of less than 70 percent. Estimates of fly ash tonnage in this zone could be in error. However, the zone of major interest is in seals of greater than 90 percent quality. In this range, it is obvious from this curve that considerable savings in fly ash material and time for pouring fly ash can be achieved by stopping the seal at about 95 percent seal and then completing the final seal with foam. The actual fly ash pour time to make a 95 percent seal was 7 hours, or a total elapsed time of less than 14 hours with a total material requirement of 280 tons. To increase the seal to 98 percent required 80 more tons of fly ash or 4 hours total delivery time. To further increase the seal to 99 percent required an additional 80 tons and another 4 hours of delivery time. The results of froth foam topping of this seal are described in Section 8.5.

At this operating flow rate of 3000 scfm of air, the blower pressure was in the range of 5 to 6 psi and the borehole pressure fluctuated in the range of 0 to 1 psi. The fluctuations were primarily due to the fluctuating fly ash flow rate delivered by the trucks. Once again the flow instrumentation did not provide any indication of the build up of the fly ash pile. As described above and later in Section 8.6, the acoustic seal checker monitored the pile development accurately. Its use provides the fly ash



Straight Passage Seal - Seal Checker Results - Percent Seal vs. Amount of Fly Ash (or Time)

Figure 123

sealing system with an excellent on-line monitor of the continuous development of the seal. Its results can be used to control the fly ash flow rate so that sealing can be achieved with the minimum amount of material.

8.4.4.4 Field Test of Sealing Four-Way Intersection with Fly Ash

The third seal test took place at the four-way intersection shown in the sketch of Figure 124. The passages coming into the intersection were about 21 feet wide, making the diagonal width at the intersection about 35 feet. The passage roof heights were once again quite different, varying from a low of 7 feet in passage B to a high of 10 feet in passages A and D. During the borehole drilling operation a major roof fall occurred when the borehole broke through the roof. Consequently, four cribs A, B, C and D were built to support the roof. The roof fall also formed a dome in the 4-way intersection, so that the roof height in the center portion of the 4-way averaged 12 feet. The presence of the cribs and the peculiar geometry of the passages created an important test of the fly ash sealing system.

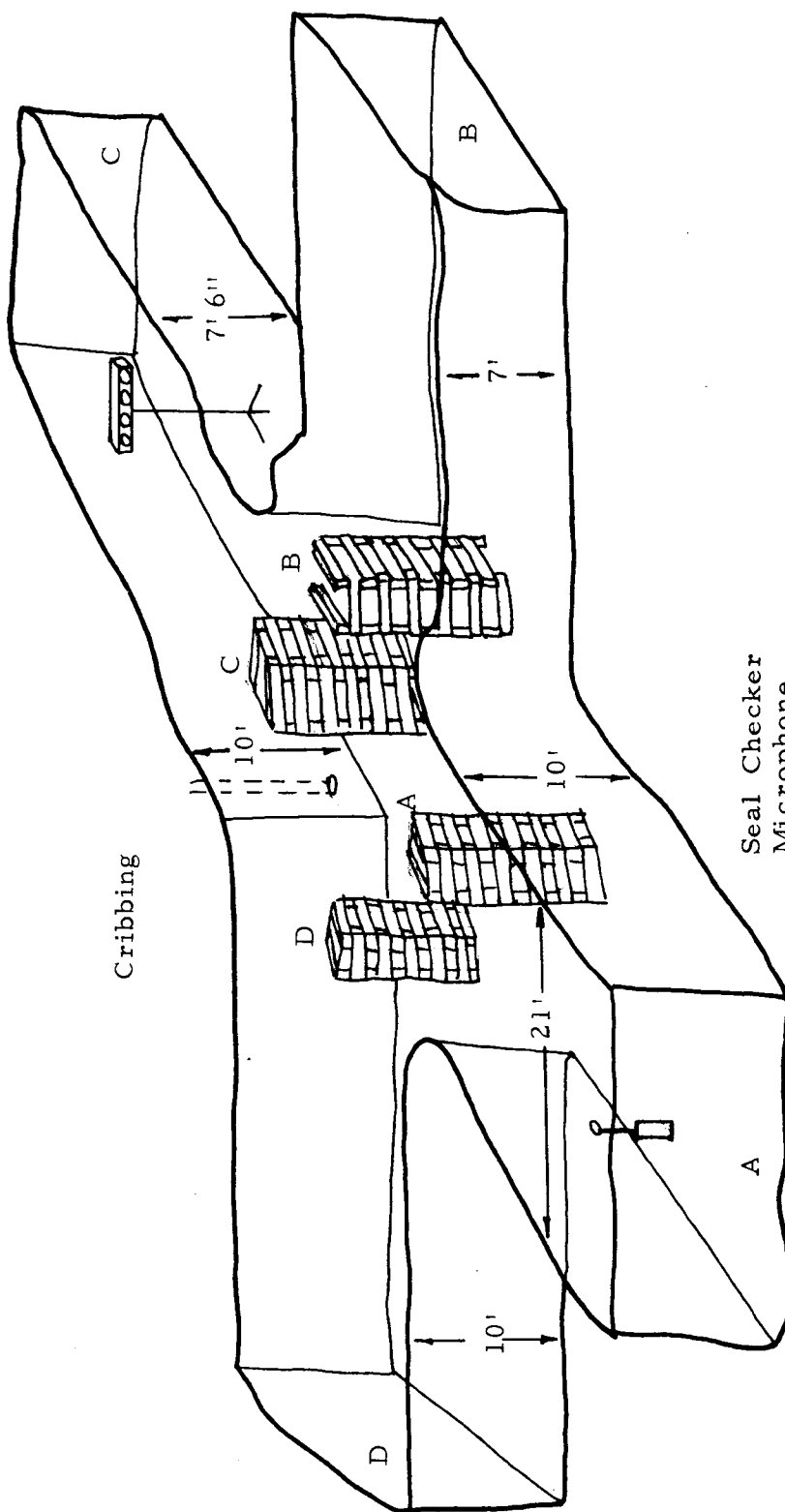
It was decided to make this a complete fly ash seal -- no foam would be used for topping. The fly ash seal checker was manually deployed in passages A and C as shown in Figure 125 with the microphone in passage A and the speaker system in passage C.

Figure 125 shows photographs of the seal checker deployed in the 4-way. The system was deployed underground by manually carrying the components from their location at the No. 1 borehole straight passage test site to the

Seal Checker Speakers

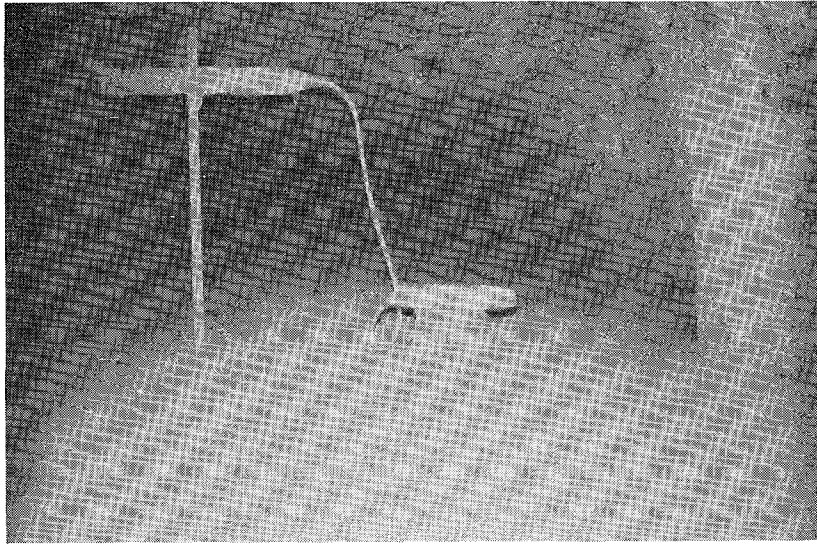
Cribbing

Seal Checker
Microphone

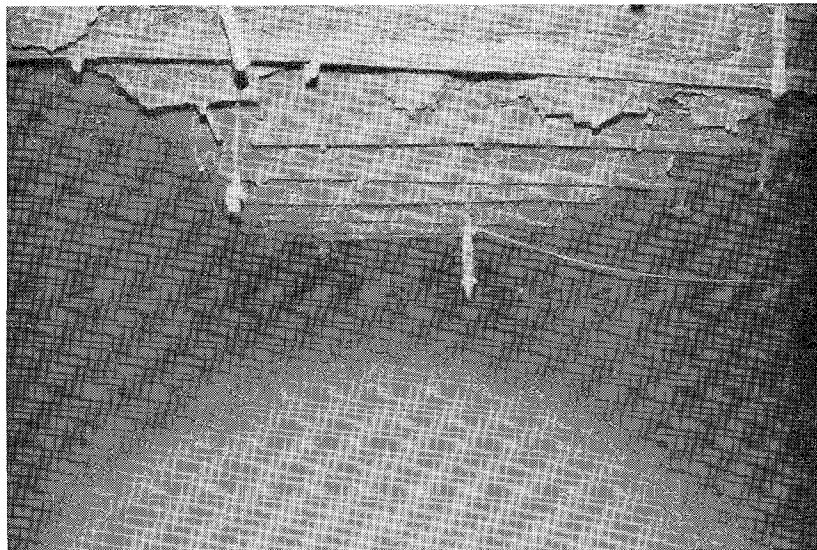


4-Way Intersection

Figure 124



(a) Speaker Assembly



(b) Microphone Assembly

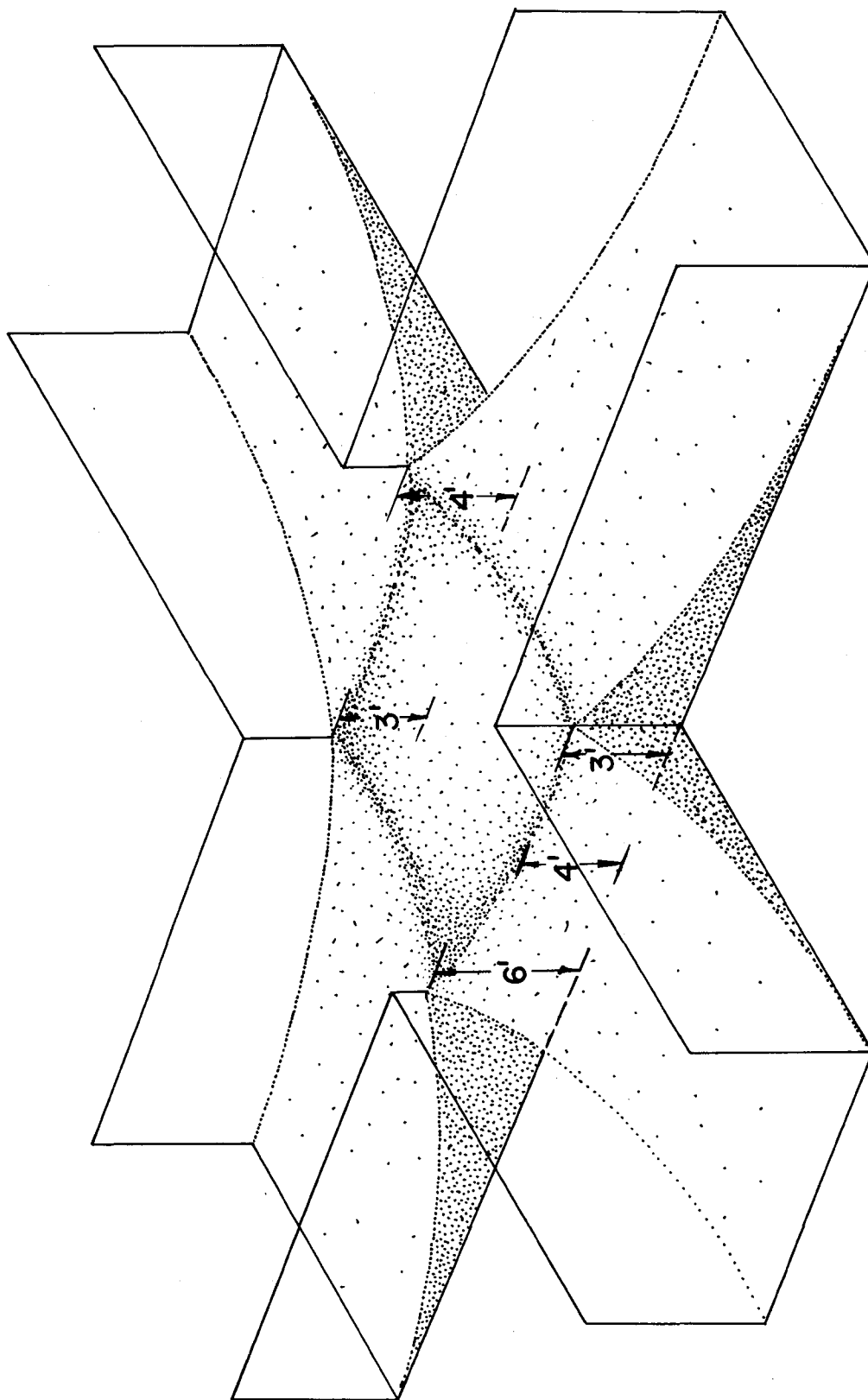
Seal Checker in 4-Way Sealing Test

Figure 125

positions shown in Figure 125. The seal checker boreholes at the No. 1 borehole test site were used for signal transfer to the surface. An extra length of 500 feet of microphone and speaker cable were added underground to extend connections to the 4-way speaker and microphone locations. Unfortunately, due to certain electrical grounding problems described in detail in Section 8.6, it was not possible to monitor the initial development of the seal. However, these problems were isolated by the time the seal was nearing completion so that final verification of a total seal was possible.

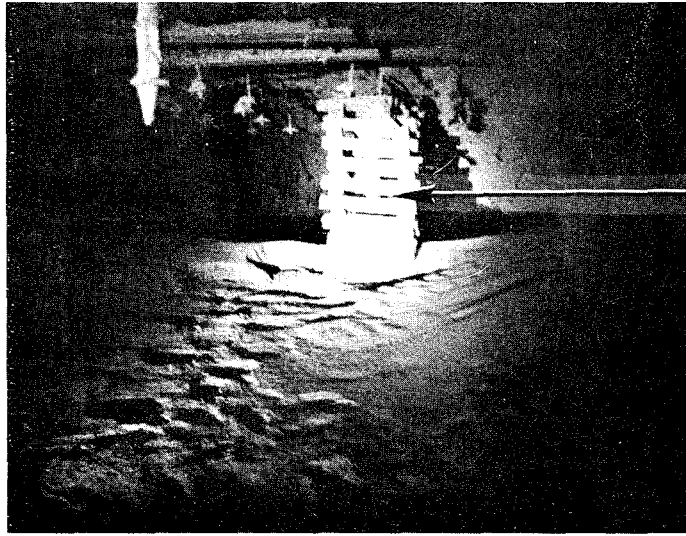
Due to the size of the area, the blower air flow rate was increased to 3500 scfm. Figure 126 shows a sketch of the initial development of the seal after 11 truck loads, or about 220 tons, of fly ash. Figure 127 shows two photographs of the same seal development from passages A and D. Figure 128 shows photographs of closer views of the crater development at this stage. As is obvious from Figure 128, the initial crater was square in plan with a rim that connected the four corners of the intersection. The height of the rim varied from 3 to 6 feet. The presence of the cribs had practically no effect on the development of the fly ash pile.

Further development of the seal transformed the crater to a circular rim about 20 feet in diameter. After a total of 23 trucks, or approximately 460 tons, of fly ash the crater rim was about 3 feet from the roof of passage A. Figure 129 shows a sketch of this pile development. Photographs of the fly ash seal taken from the four passages are shown in Figure 130. Passage B is almost completely sealed because of its low roof - 7 feet in height. Figure 131 shows closeup photographs of the crater after 23 trucks.



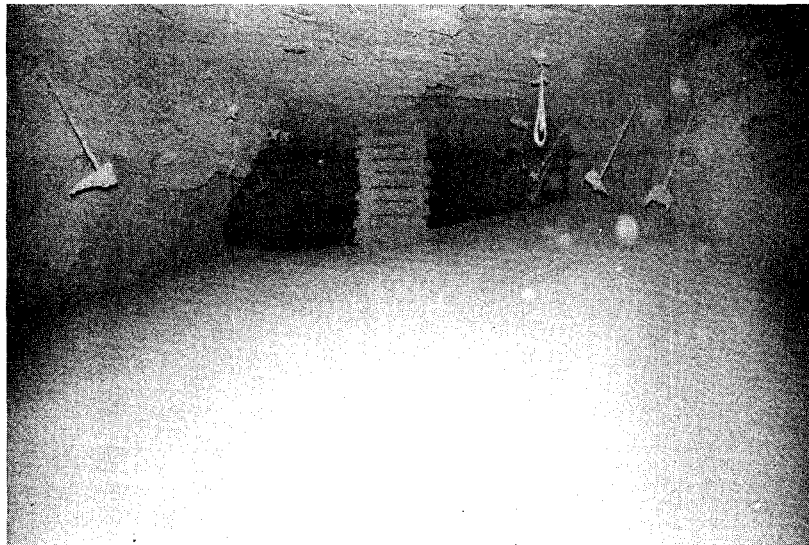
Seal at 4-Way Intersection After 11 Trucks of Fly Ash

Figure 126



Crib

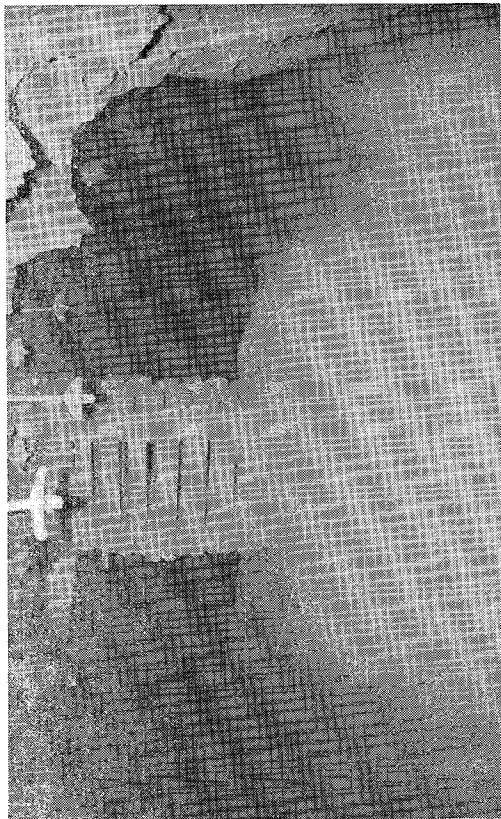
(a) View from Passage "A"



(b) View from Passage "D"

Initial Stage of 4-Way Seal (11 Trucks)

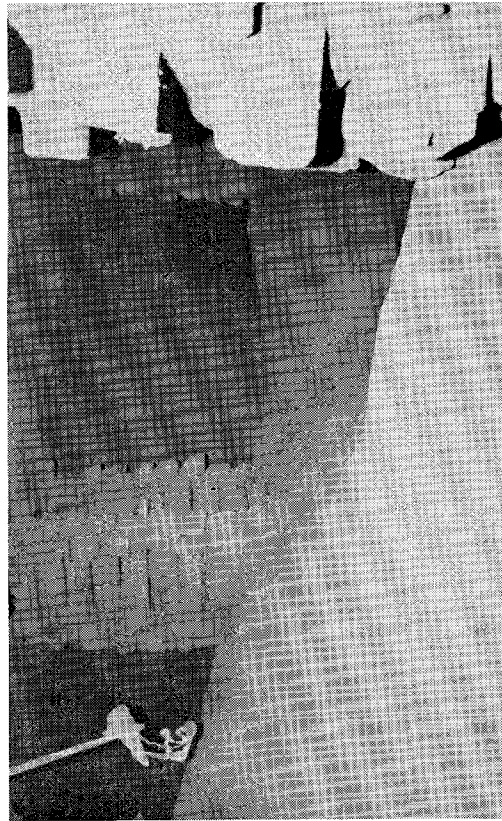
Figure 127



(a)



(b)

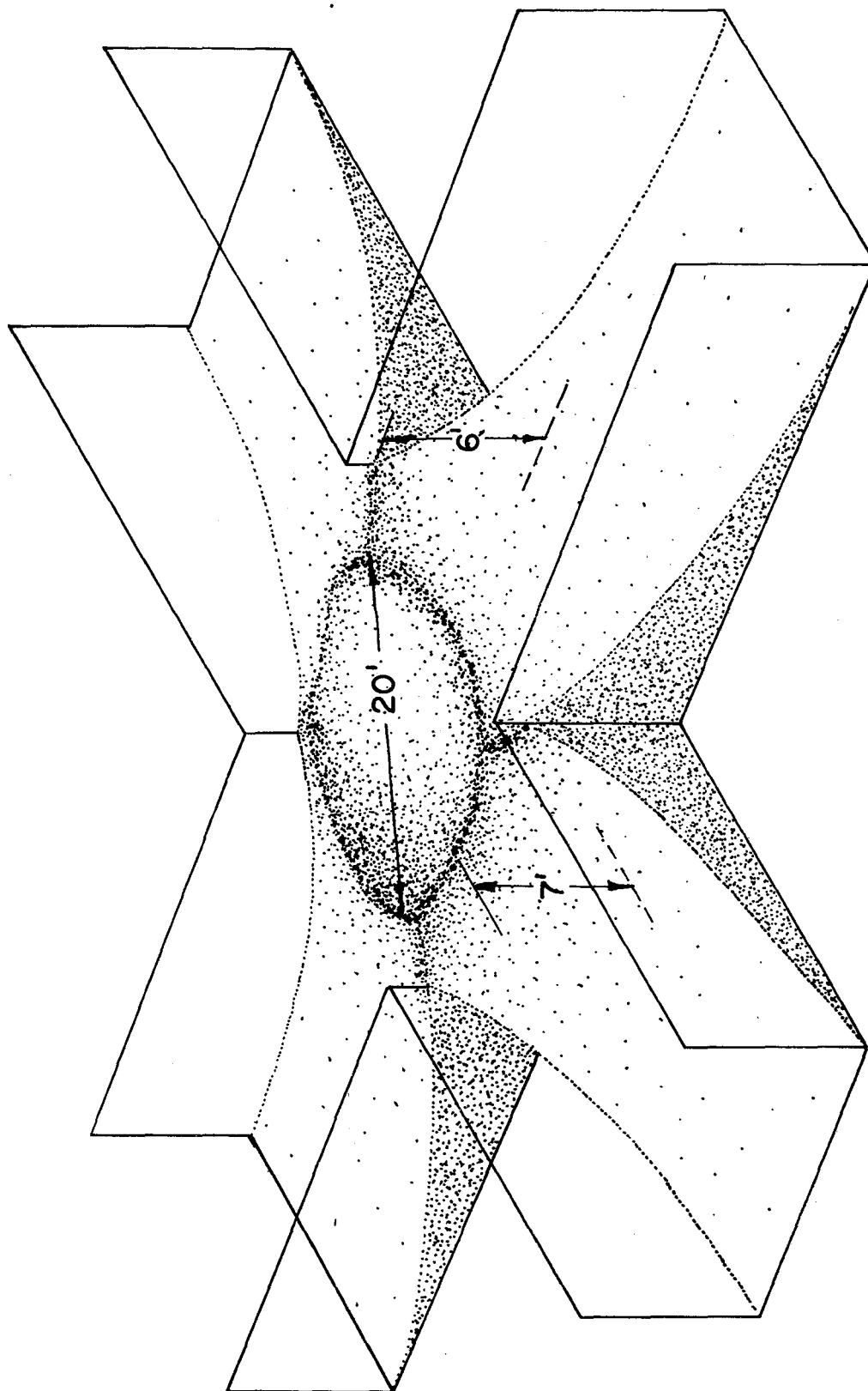


(c)

- (a) View from A passage
- (b) View from crib A to crib C
- (c) View from crib A to crib D

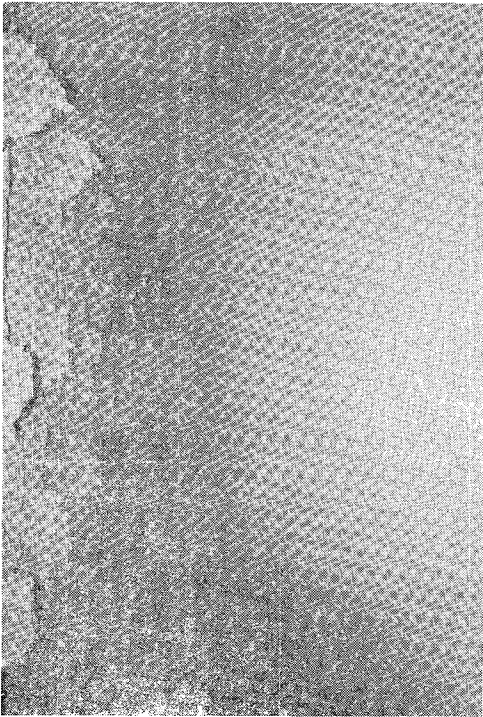
Initial Square Crater at 4-Way Seal

Figure 128



Seal at 4-Way Intersection after 23 Trucks of Fly Ash

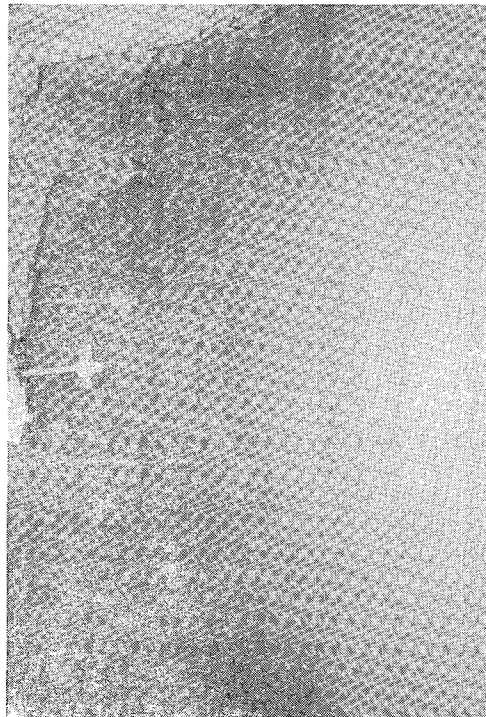
Figure 129



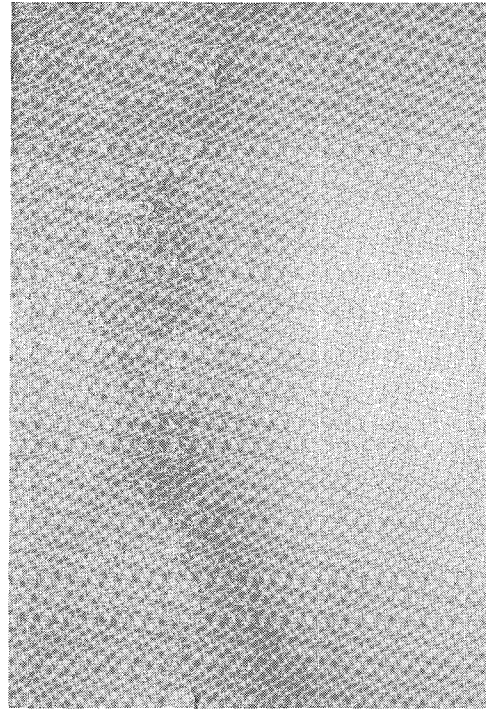
(a) From "A"



(b) From "B"



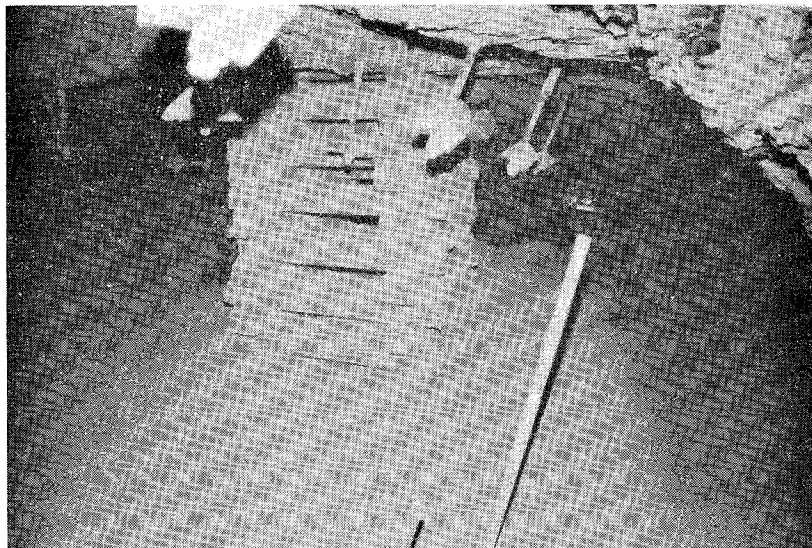
(c) From "C"



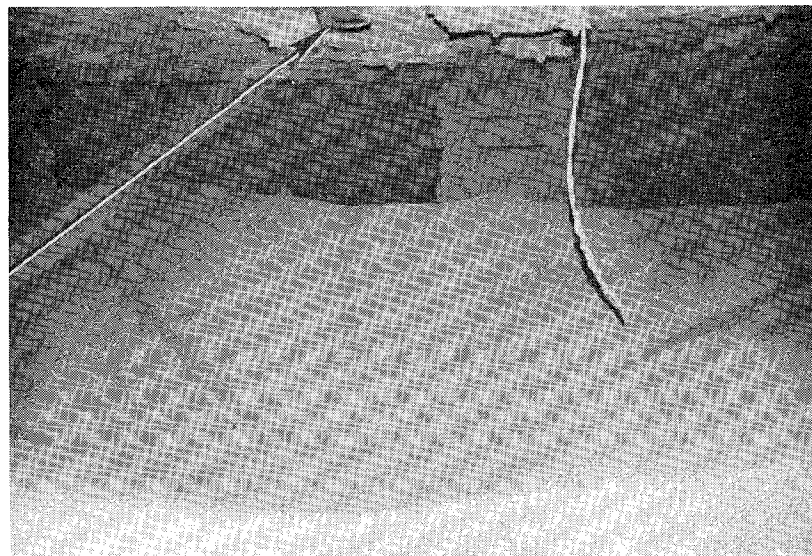
(d) From "D"

4 Views of the 4-Way Seal after 23 Truck Loads
of Fly Ash

Figure 130



(a) View from Behind Crib "A" Looking Towards Crater



Borehole

(b) View into Crater - Diagonally Across from the Right of Crib "A"

Closeup Photos of the Crater at the 4-Way

Seal after 23 Fly Ash Trucks

Figure 131

The fly ash pours were continued and the crater rim slowly approached the roof. Since a complete fly ash seal was desired, the flow rate was maintained at 3500 scfm in order to spread the roofed crater. During this stage of sealing, visual inspection of the seal was difficult because of poor access to the top of the pile. Figure 132 shows a view of the seal after 40 trucks, or approximately 800 tons, of fly ash. The tracks in the pile are those of the adventurous engineer who inspected the completeness of the seal.

The seal was terminated after 55 trucks, or approximately 1100 tons, of fly ash. At this point, the seal checker indicated a complete seal from passages "A" to "C". Passage "B" was assumed to be sealed, both from visual inspection and the fact that it had a low roof. Passage "D" did not appear to be sealed, but a complete seal of a 4-way intersection requires sealing only 3 of the 4 passages. The borehole flow measurements did not reflect any downstream resistance due to sealing, and it was assumed that all of the fly ash pumped in during the final stages was channeling directly into passage "D". Photographs of the final seal are shown in photographs 133 and 134.

8.4.5 Simultaneous Pumping of Two Fly Ash Trucks

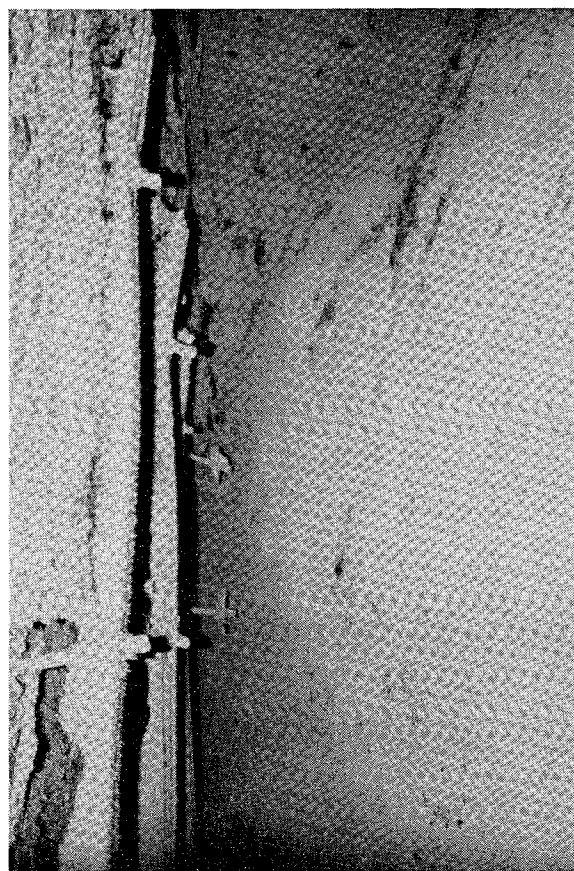
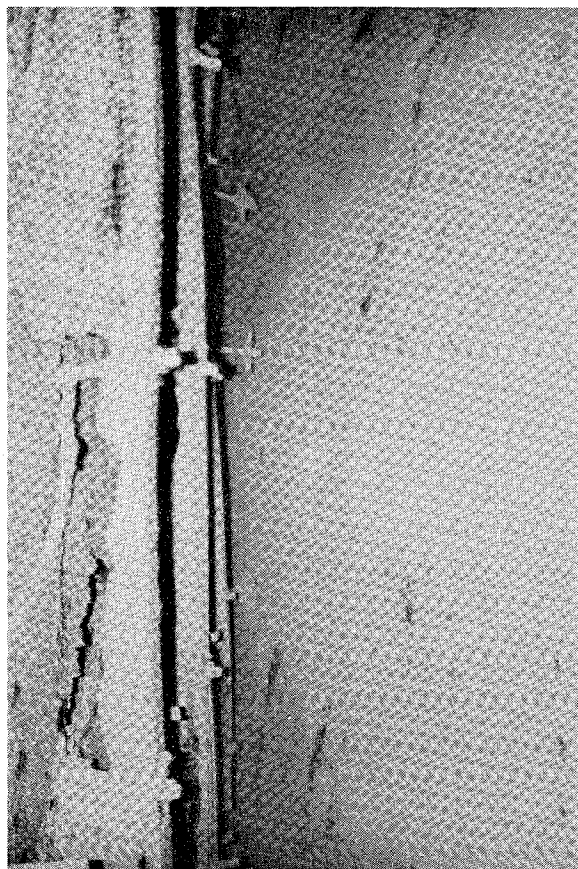
The potential capability of the fly ash delivery system to pump two trucks of fly ash simultaneously was demonstrated in this series of tests. This inherent system capability could be used in a variety of ways to decrease the total time required for sealing the mine with fly ash.

In general, the field operation showed that considerable time was lost between the time one truck finished pumping and the next truck started. One way to reduce or eliminate this lost time is to have two or more trucks pumping simultaneously. If



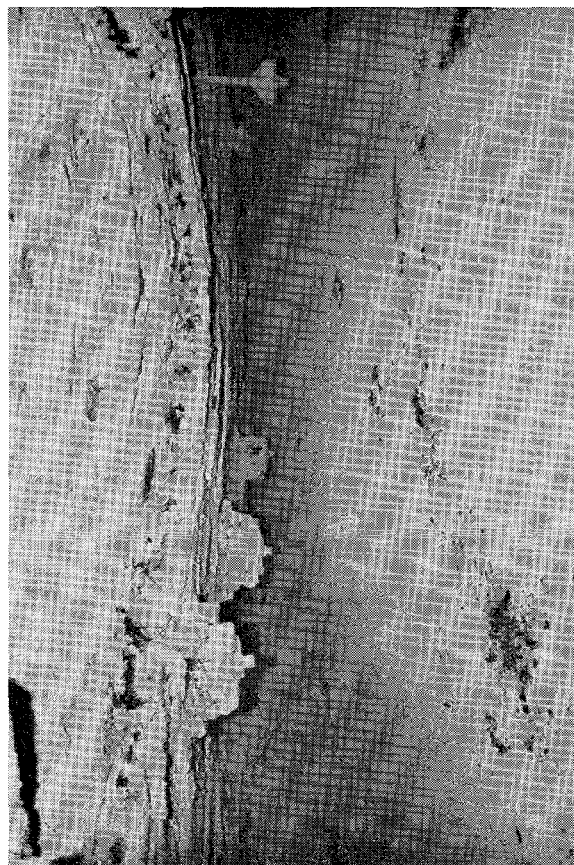
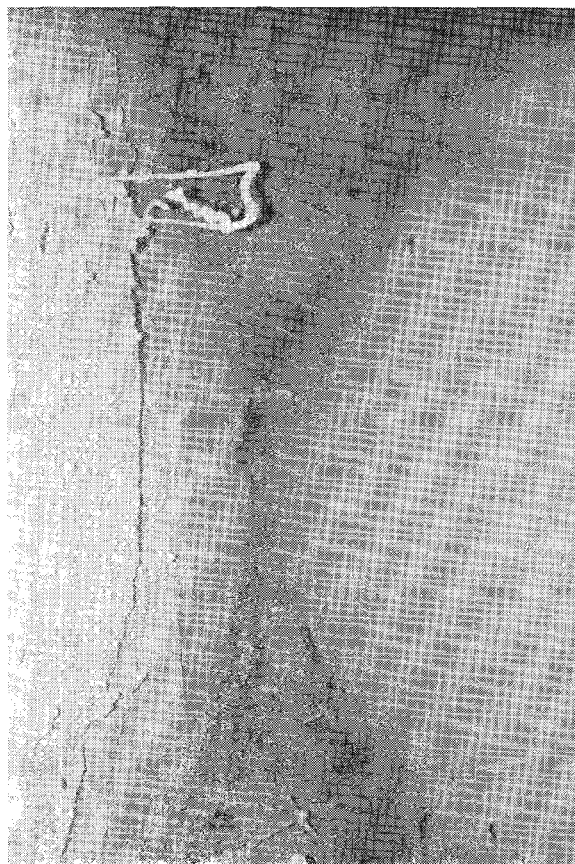
4-Way Seal Nearing Completion - View from Passage "A"

Figure 132



Photographs of Fly Ash Seal of Side A of the Four-Way Intersection

Figure 133



Photographs of Fly Ash Seal of Side B of the Four-Way Intersection

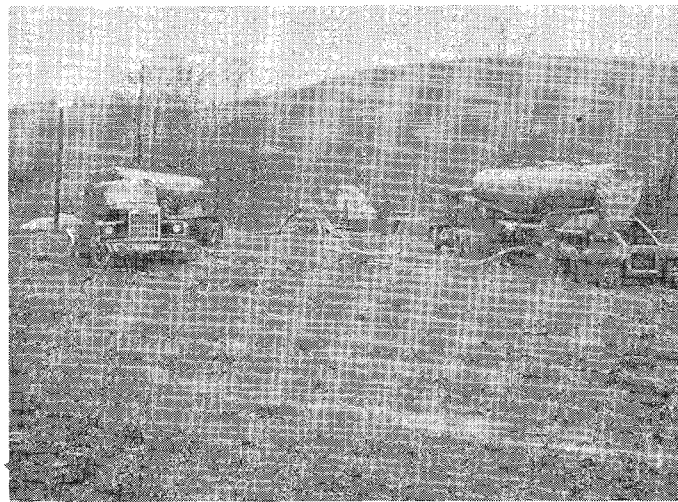
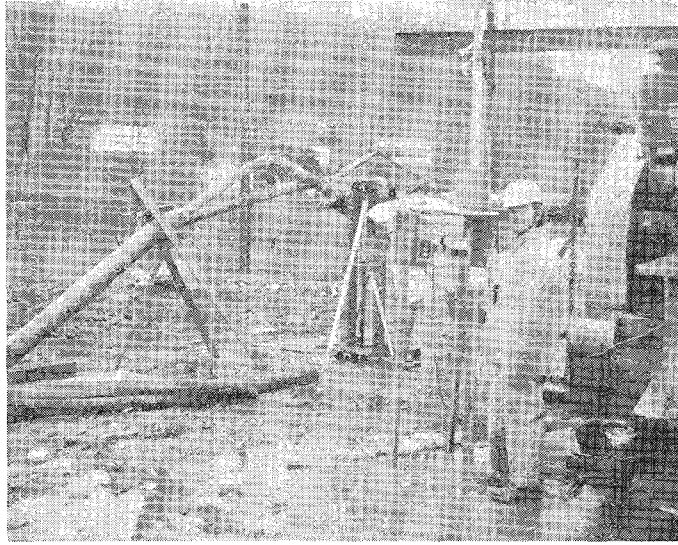
Figure 134

one finishes before the other, it drives away, and another one connects up while the other truck continues to pump. With this method almost continuous pumping of fly ash may be possible, thus almost doubling the average rate of fly ash delivery into the mine passage. In addition, the blower could run continuously without being required to start and stop for the unloading of each fly ash truck.

In order to test the feasibility of this technique, a 4-inch diameter "Y" was added to the fly ash inlet of the ejector-mixer. Two trucks were connected simultaneously to the ejector, each by its own fly ash hose. Since the total length of fly ash hose available at the site was limited, the fly ash trucks had to be moved onto the field closer to the blower. Figure 135(a) shows the two fly ash hoses connected to the Y inlet to the ejector. Figure 135(b) shows the field arrangement with the two trucks parked on the field, facing in opposite directions, so that the unloading valves can face each other.

Standard pumping procedure was followed with a blower air flow rate of 3000 scfm. Both trucks pumped only air first, then one truck was brought on line, pumping fly ash, while the other continued to pump air only. After the first truck was unloading satisfactorily, the second one was brought on line, pumping fly ash. This procedure was followed to prevent backup of fly ash in the truck which had not yet begun to pump fly ash.

The first series of tests with two trucks were unsuccessful due to a lack of proper communication between the two fly ash truck operators. One of the trucks had mechanical problems with a stuck fly ash valve. This prevented it from pumping fly ash while the other truck continued to pump.



(b) Field Layout

Simultaneous Pumping of Two Trucks

Figure 135

The second series of tests were conducted with two of the same type of fly ash trucks. Satisfactory operation was achieved by careful monitoring of the controls on the two trucks. The tests showed that 2 fly ash trucks could pump simultaneously with this arrangement and deliver two loads of fly ash in 50 percent more time than that required for one truck. Total unloading time for the two trucks was 31 minutes. The fly ash flowmeter indicated flows which averaged 75 tons per hour and reached short term peaks of 150 tons per hour.

8.4.6 Fly Ash Sealing in the Presence of Borehole Water Flow

A series of tests were run to evaluate the high air flow rate fly ash sealing technique in the presence of 50 gpm of borehole water flow. The test was set up in borehole No. 3; in the passageway there was a clear opening of about 2 to 3 ft. between the mine roof and the false roof.

Visual observations of the flow discharging out of the borehole into the mine passage showed that the fly ash had little difficulty in flowing down the borehole in the presence of 50 gpm of water. However, the fly ash discharge was sufficiently wet so that it did not spread but formed a conical pile right under the borehole. The pile built up very rapidly until it bridged the borehole and plugged it. This was registered immediately on the air flow meter at the ground surface which dropped suddenly to zero. The plug formed was extremely tight as it was supporting a couple of hundred feet of water head in the borehole without leakage. The total test time was only 5 minutes and the plugging occurred very rapidly with no warning at the surface of the impending situation.

Thus, the system will not operate with a 50 gpm borehole water flow. Its performance at lower water flow

rates could not be determined. However, the question is probably academic, since there is no practical way of ascertaining, with any assurance, the exact value of the borehole water flow rate. Thus, an essential requirement of the system is that the borehole be cased and grouted.

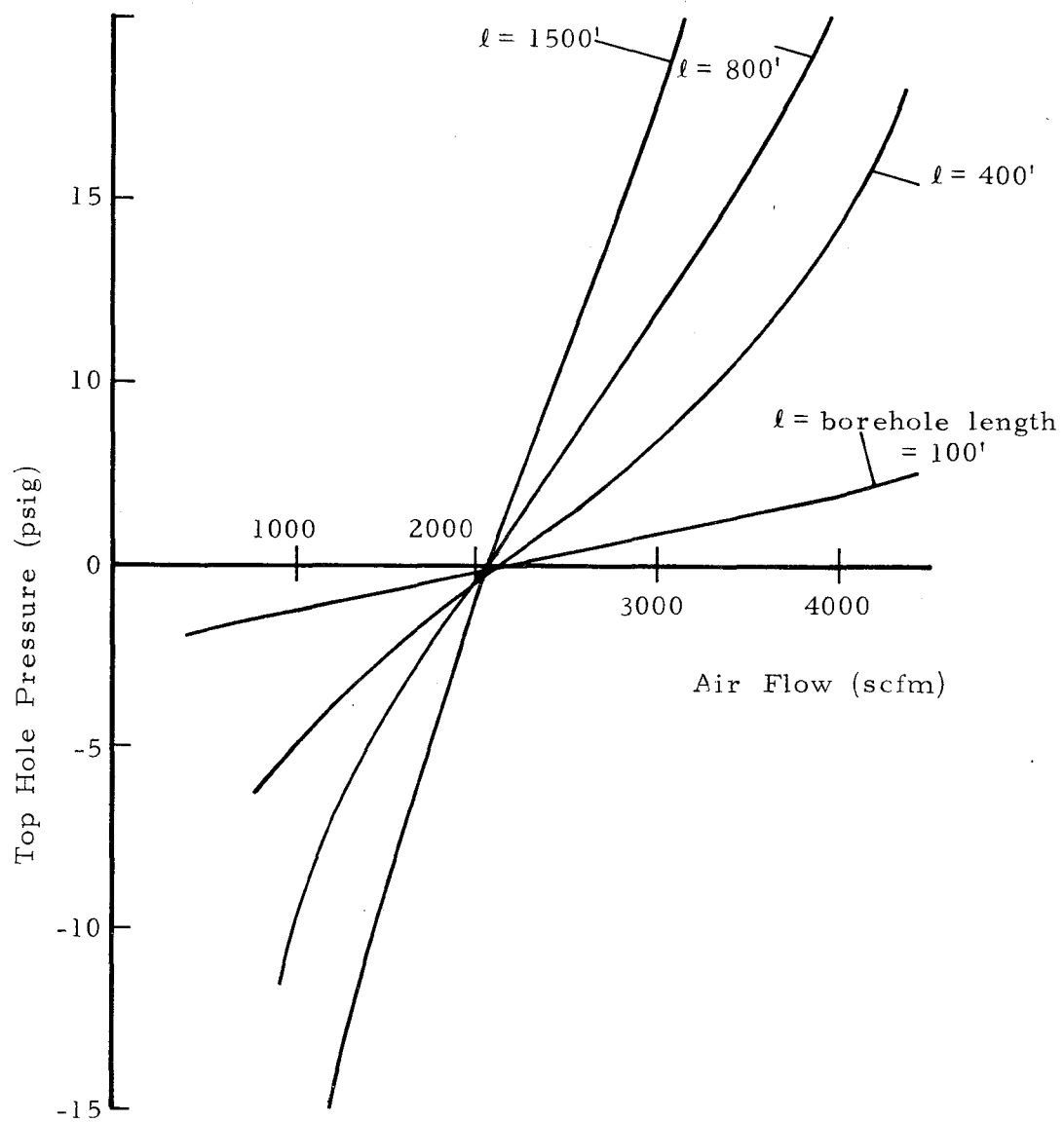
8.4.7 Borehole Flow Characteristics of Fly Ash-Air Mixtures

During the fly ash sealing tests, measurements of air flow rate, fly ash flow rate and borehole pressure were continuously measured. These measurements have been used in the borehole flow analysis of Appendix A to develop a realistic model for the flow process. The model can be used to predict the pressure flow characteristics for longer boreholes and to identify the operating limits of the system.

An additional series of borehole flow tests were conducted with a variable restriction placed at the outlet of one of the boreholes in order to vary the back pressure. This was done to simulate flow conditions in longer boreholes where higher pressures would be encountered. The 400-foot borehole would then represent the top 400-feet of a longer borehole. The actual length of the simulated borehole could be calculated from the top hole pressure using the fluidized flow calculations.

A 4-inch-diameter flexible rubber pinch valve was used for this purpose. Five different constriction areas were tested ranging from 12.5 square inches to 3 square inches. For each constriction, pressure and solids flow measurements were made at a number of different air flow rates, ranging from 1000 to 4000 scfm. All of the data were obtained using one truck load of fly ash. The results of these tests are presented in Appendix A.

The results of the theoretical analysis of borehole flow are summarized in Figure 136 which shows the variation of borehole pressure with borehole depth and air flow rate for two fly ash solids flow rates and borehole diameter of 6 inches.



Theoretical Incompressible Pressure-Flow Curves for Fly Ash-Air
Mixture Flowing in a 6.625" I.D. Cased Borehole

Figure 136

8.4.8 Conclusions

The major conclusions obtained from the field testing program are summarized as follows:

a. The seal testing programs conducted both in the laboratory and in the field demonstrated that the fly ash sealing process could be accurately represented in smaller scale models with the appropriate adjustment of air flow rate. The formation of a crater under the borehole was characteristic of all fly ash seals, and this characteristic was exploited to generate a more effective fly ash sealing technique.

b. The fly ash sealing technique was used satisfactorily as a bulk filler in a straight passage and to make a complete seal in a large four-way intersection. This latter test showed that an all-fly ash seal can be made, though for a greater cost and time than for a fly ash foam seal.

c. The slope angle of the deposited fly ash, both in the laboratory and in the actual mine, varied from about 20° at the crater rim to 10° at the far end of the slope. This contradicted previous experience that the fly ash would settle at a "natural" angle of repose of 8° . Previously used techniques, producing the 8° angle of repose, would require significantly more fly ash -- 20% more in the case of the 4-way passage.

d. As the fly ash seal approaches the roof, greater quantities of material are required to produce small reductions in the unsealed area. The total material required to make a 99 percent seal is 50 percent greater than a 95 percent seal. This behavior is due to the fact that the air velocity through the unsealed area increases as the pile builds up and prevents deposition of fly ash in this area. The fly ash spreads laterally, building up the sloping sides of the pile and reducing the pile angle from a high of 20° to values closer to 10° . Spreading of the seal and reduction in side slope take precedence over height development.

e. At high percentage seal values, greater than 90 percent, undesirable spreading of the fly ash can be reduced by lowering the air flow rate in final stages of fly ash sealing.

f. Both fly ash material and sealing time can be saved by using the fly ash only as a bulk filler to make a 90 to 95 percent seal and then making the final seal with foam. The actual savings in time and material would depend on the size and depth of the mine passage. These savings would be largest for large passages at shallow depths and least for small passages at large depths. For example, it is estimated that about 15 hours of fly ash pour time could have been saved by stopping the pour at 95 percent seal instead of 98 percent.

g. The choice of air flow rate proportional to passage width to the $5/2$ power proved to be generally satisfactory for the field tests. The calculated air flow rate should be increased by 10 to 20 percent for a passage having a small height to width ratio, for example less than $1/3$, and for a four-way intersection.

h. The average pumped flow rate of the fly ash is about 1 ton per minute. The actual average rate of fly ash filling of the mine, taking into account the truck turnaround time, is in the range of 0.3 to 0.4 ton per minute or about 1 truck per hour.

i. It is possible to pump two fly ash trucks simultaneously, thus nearly doubling the total material delivery rate to 0.6 to 0.8 ton per minute or almost 2 trucks per hour.

j. Air flow rates in the range of 2500 to 3500 scfm were sufficient to seal the large passages in the

Federal No. 1 mine. Under these conditions the maximum borehole pressure was 3 psi and the maximum pressure at the blower 7 psi. The blower selected has more than adequate capacity for these types of mine sealing conditions.

k. The boreholes must be cased and grouted to prevent borehole water flows. The fly ash sealing system will not operate with a 50 gpm borehole water flow rate.

l. Pressure, density, and flow rate measurements of borehole flow of the fly ash-air mixture made in the field were combined with an analytical theory to predict the pressure flow characteristics of boreholes of different lengths. At an air flow rate of 3500 scfm and a fly ash flow rate of 1 ton per minute, the borehole pressure increased from 7 psi for a 100-foot borehole to 12.5 psi for a 1500-foot borehole.

8.5 Field Evaluation of Froth Foam Seal Topping System

8.5.1 Design Considerations in System Development

The test program described in Section 6.4.3, demonstrated the effectiveness of using froth foam as a seal topping material to make a 100 percent seal. These tests were conducted in a full-size simulated mine passage. The design of a froth foam system to seal a mine passage by topping a fly ash pile is basically the same as the one used for sealing the simulated mine passage on the surface, except for the requirement of lowering the mixing head 400 feet down a 6-inch-diameter borehole and retrieving it after completion of the foaming operation. The static head of the liquid column and the pressure exerted on the downhole isocyanate and polyol relief valves have to be taken into consideration in system design.

The foam used in the Franklin, Tennessee, tests was a TDI based foam. The TDI vapors liberated by the foam were tolerable in the open atmosphere of the surface tests at Tennessee but were considered to be totally unacceptable in the enclosed mine environment. An MDI or PAPI type of polyurethane foam was preferred.

It was essential for system operation in the mine that good and proportional mixing of the two components be maintained at all times so as to minimize the risk of a fire due to autoignition of poorly mixed components. This was an important consideration in the selection of froth foam and the flow metering system to be described in the following sections.

8.5.2 Selection of Foam

A commercial froth foam from Olin Corporation designated Autofroth A 202C4 was selected. The foam consists of a

polymeric isocyanate with a TDI prepolymer blended into it. The prepolymer is prepared from a fire retardant polyol to produce flame retardancy. It has about 6 percent of fluorocarbon 12 blended into it. The polyol portion of the foam consists of a sucrose-based autocatalytic polyol containing about 6 percent of fluorocarbon 12. The catalyst levels are adjusted to give a tack-free time of 90 seconds, about the same as that used for the tests of Section 6.4.3.

The foam was supplied in two tanks of nominal 5,000 lb capacity, one for each component.

The viscosity of the isocyanate and polyol components is extremely sensitive to temperature. It increases by a factor of 3 between a temperature range of 77° and 53°F. It is, therefore, important to maintain the components at about 77°F or higher. Accordingly, the foam tanks were covered by a canopy and hot air from two oil-burning space heaters was continuously blown into the covered area to maintain the tank temperature at approximately 80°F. Figure 137 shows a photograph of the covered tanks and heaters. The tanks were pressurized by bottled nitrogen gas up to a pressure of 250 psi.

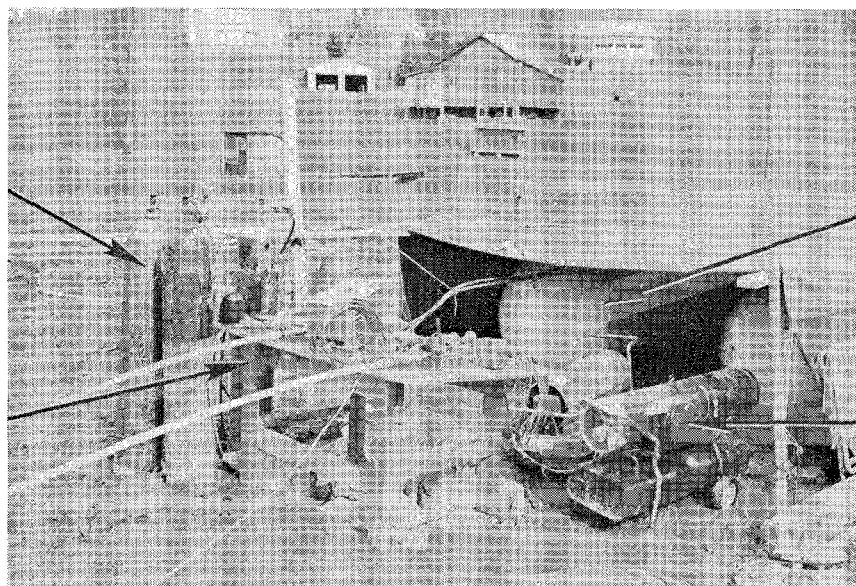
8.5.3 Description of Froth Foam System for Mine Sealing

A list of the required equipment for the complete froth foam system is given in Appendix E. The down-hole, froth foam mine sealing system is shown schematically deployed in the hole in Figure 138. A flow diagram of the system is shown in Figure 139. The system consists of the following major subsystems:

- a. Component Feed and Flow Metering System

Nitrogen
Bottles

Control
Stand

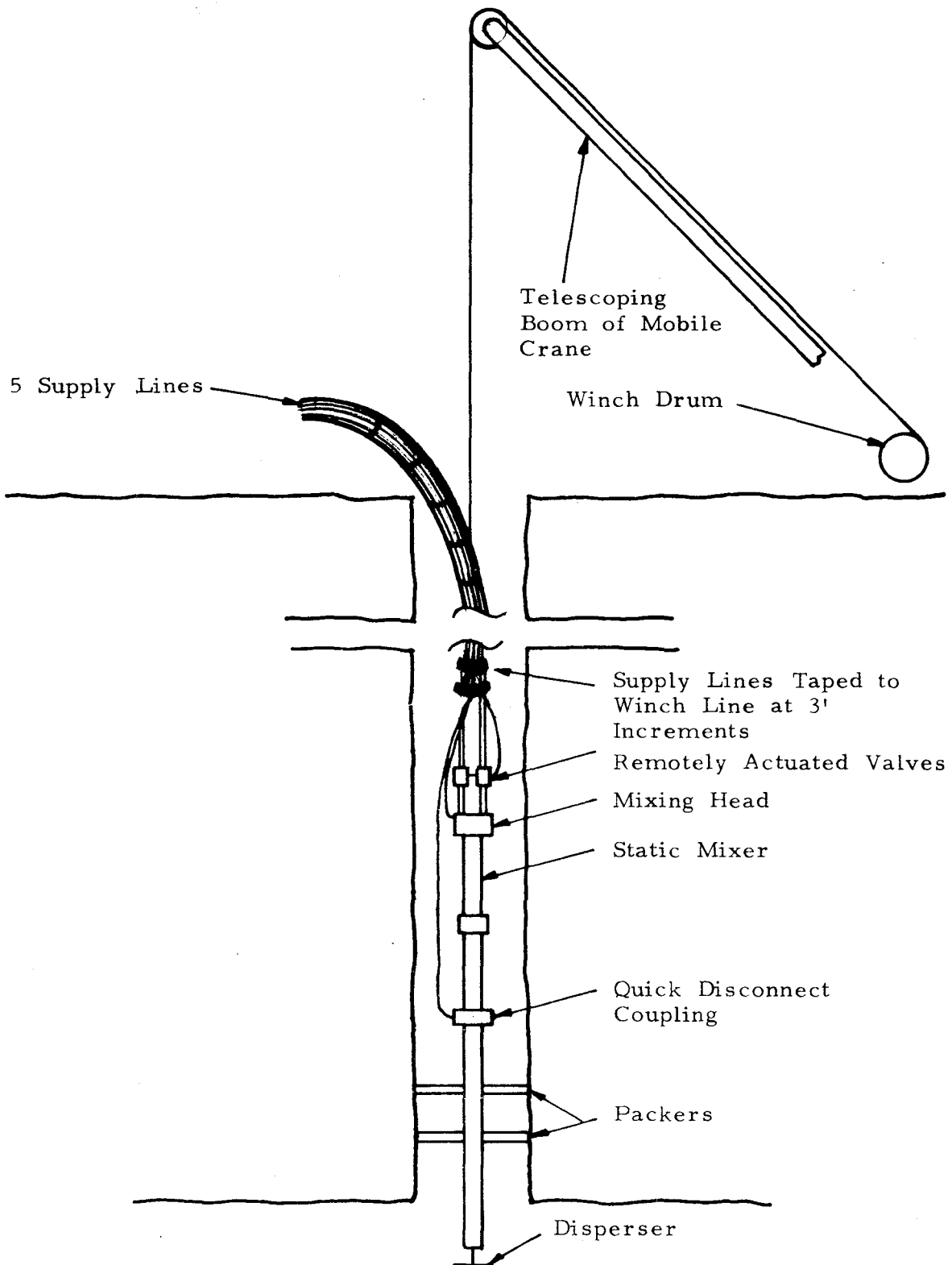


Tanks

Heaters

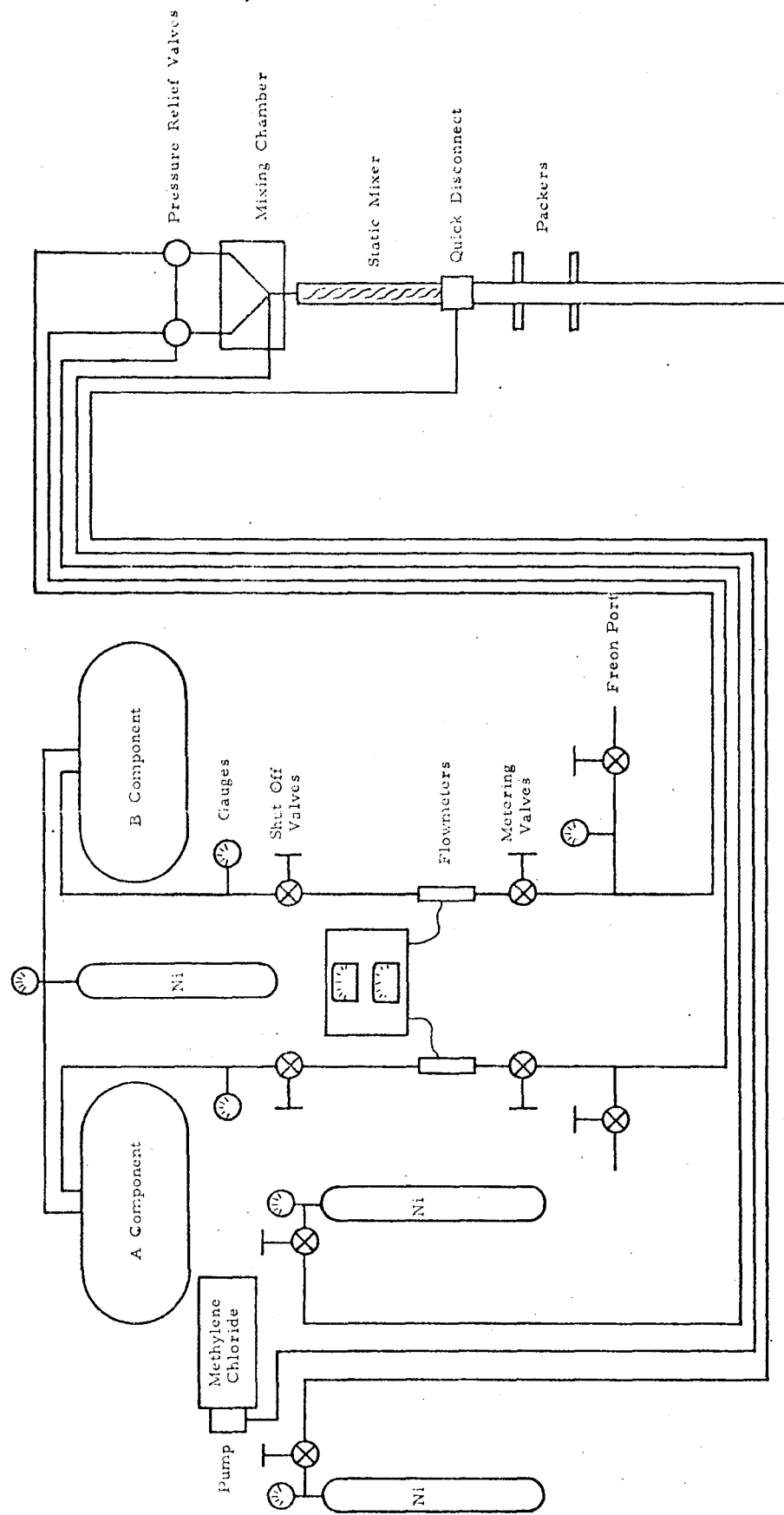
Foam Tanks in Canopy with Heaters

Figure 137



Schematic of the Froth Foam System Deployed in the Mine Passage

Figure 138



Flow Diagram of Froth-Foam System
Figure 139

- b. Component Mixing System
- c. Methylene Chloride Cleaning System
- d. Downhole Deployment and Retrieval System

8.5.3.1 Component Feed and Flow Metering System

The isocyanate and polyol components of the foam are stored in tanks shown in Figure 137 and pressurized to 250 psi by bottled nitrogen. The flow control and component metering system consists of a control panel on the surface and two pressure relief valves deployed downhole at the mixing head.

The two foam components are fed to the mixing head deployed downhole in the mine through two 3/4-inch-diameter, nylon core, Synflex* hoses.

The use of the dissolved fluoro-carbon as a frothing agent requires that the components be maintained at an adequate pressure all the way to the point of mixing. If the materials froth in the system prior to mixing, it is almost impossible to measure the flow and control the mixing ratio.

The system is provided with two variable pressure relief valves, one for each component line, located at the mixing head deployed down in the borehole. The relief valves are connected by an air line through a regulator to a nitrogen bottle at the surface. The relief valve pressure is adjusted to a suitable value so as to maintain a high enough pressure in the lines and prevent frothing in the lines. For normal operation this pressure was set at

* Trade Name.

approximately 100 psi. Figure 140(a) shows a photograph of the downhole mixing head with the two pressure relief valves assembled on it. Figure 140(b) is a photograph of the complete mixer assembly with the relief valves being retrieved after completion of a foaming operation.

The on-surface flow metering and control panel is shown in the photograph of Figure 141. It consists of two Fluidyne* positive-displacement-type flow meters to measure the individual component flows, two strainers to filter out any crystallization which could cause clogging of the system, pressure gauges to monitor tank and relief valve pressure, temperature gauges, and special stainless steel, teflon seat, ball valves designed for isocyanate service. In operation, the component flow rate was regulated by adjusting the relief valve back pressure.

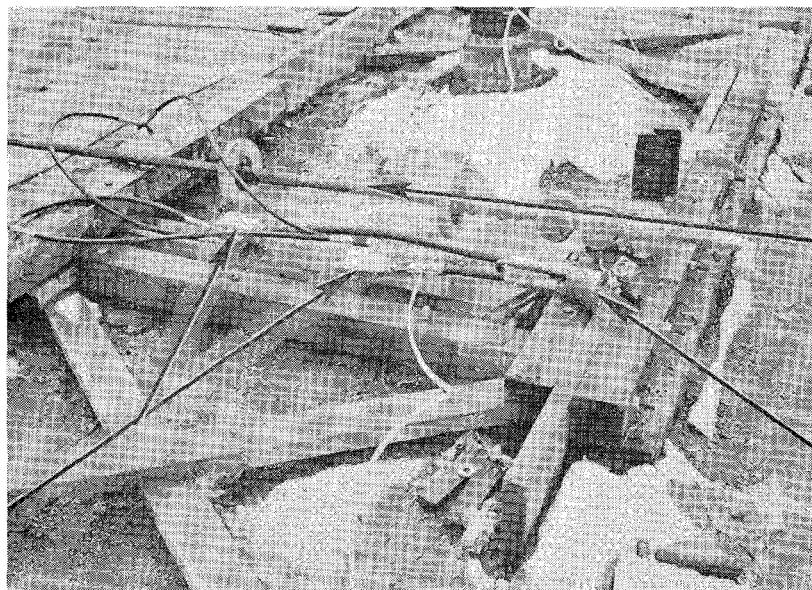
Two freon injection ports are provided in the system, one for each component line, to charge up the empty 500 foot length of Synflex* hose with freon. This freon-charging operation is to ensure good component mixing at the start of foaming. It serves two purposes: first, it displaces the air which acts as a cushion in the line and can lead to an error in metering of the components at the start; and second, it dissolves in the components, providing for extra bubbling, frothing and mixing of the components first entering the mixer. These components are likely to be lower in temperature, having cooled down in the hoses, and may therefore be more viscous and difficult to mix. The excess freon helps to mix these components.

8.5.3.2 Component Mixing System

The component mixing system consists of a mixing head for blending the two components together followed by a 3-foot-long, 1-inch-diameter Kenics* static mixer. The static mixer is followed by a 6-foot length of 1-inch diameter pipe.

* Trade Name.

Component
Pressure
Relief
Valves



Packer
Assembly

Mixing
Head

(a)

Pressure
Relief
Valves

Mixing Head

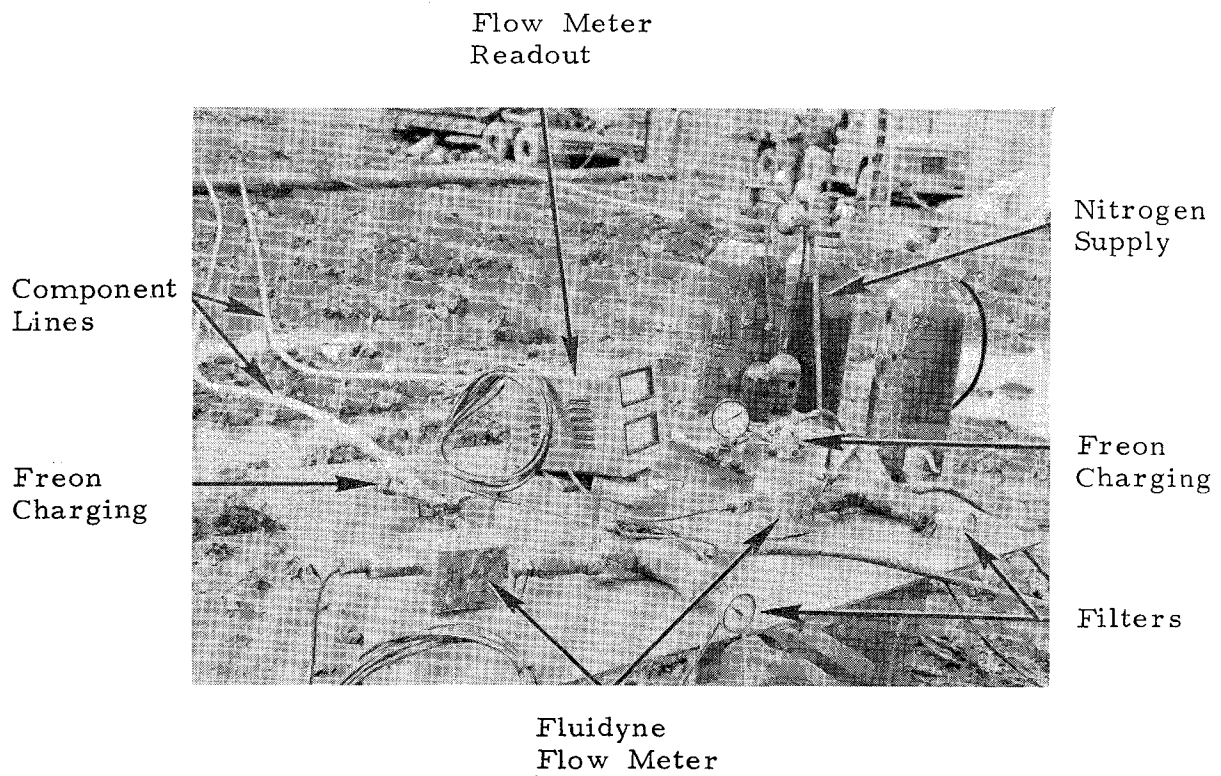
Kenics
Static
Mixer



(b)

Photographs of Mixing Head with Pressure Relief Valves

Figure 140



Flow Control Panel of Froth Foam System

Figure 141

This pipe is connected to a second piece of pipe, 10 feet in length, by a quick disconnect coupling air-actuated from the control station. The second pipe has two packers on it to prevent the foam from flowing back up the borehole. The end of the second pipe is provided with a 1-1/4-inch diameter flat plate disperser and homogenizer which provides the final mixing. The mixing head and static mixer can be seen in Figure 140 (b).

8.5.3.3 Methylene Chloride System

The inclusion of the methylene chloride cleaning system provides the system with a stop-restart capability. The foaming can be stopped, the mixing section cleaned with methylene chloride and foaming restarted whenever required. A nitrogen actuated reciprocating pump is used to pump the methylene chloride into the downhole mixing head through a 1/4-inch-diameter plastic air line.

8.5.3.4 Deployment and Retrieval System

The design of the deployment and retrieval system is closely tied to the type of downhole sealing or packing system used to prevent foam from flowing up the borehole. Two different types of packing and two different types of deployment systems were tested.

The first design was based on a cheap throwaway system using two rubber disc type packers having an interference fit in the borehole so that foam could not leak up through the tight seals. Due to irregularities in the borehole casing, the friction between the packers and the casing was high enough to require a positive force to push and lower the system. To achieve this, rigid PVC pipe 3/4-inch in diameter was used, instead of flexible Synflex hose, for the component lines. These pipes could be used to lower the system into place by pushing. After completion of a normal foaming operation, the system would be left in the borehole.

In our field tests, however, the system concept was designed to be lowered and retrieved after foaming. A 1 H.P. electric wire rope winch was connected to a shackle at the mixing head. The winch was designed to provide a maximum pull of 1000 lbs which was considered adequate to retrieve the system. However, the system did not perform as expected. Snaking of the PVC pipe in the borehole, caused by buckling under its own weight, gave rise to enough friction in the borehole that the system could not be retrieved by the 1 H.P. winch. The system was retrieved after both component lines were drained of liquid to reduce their weight. The winch was able to retrieve the empty system. In addition to these retrieval problems, handling the rigid PVC pipe was extremely difficult. The method was abandoned in favor of one using a cable-lowered system with flexible Synflex hoses for the component lines.

The second, more successful, system used the winch on a truck-mounted hydraulic crane to deploy and retrieve the system. The rubber disc packers were reduced in size to have a loose clearance fit with the borehole casing. A set of lead weights were added just downstream of the Kenics static mixer to aid in lowering as shown in Figure 142. A pneumatically actuated quick disconnect coupling was provided immediately below the static mixer and above the rubber packers. The quick disconnect could be actuated from the surface in the event the packing section was grouted in by the foam and could not be retrieved. This would allow for retrieval of the rest of the system containing the major cost items and including the mixer, mixing head, relief valves and hoses. The system would be ready for reuse by the simple addition of the packers and the final length of pipe for foam injection.

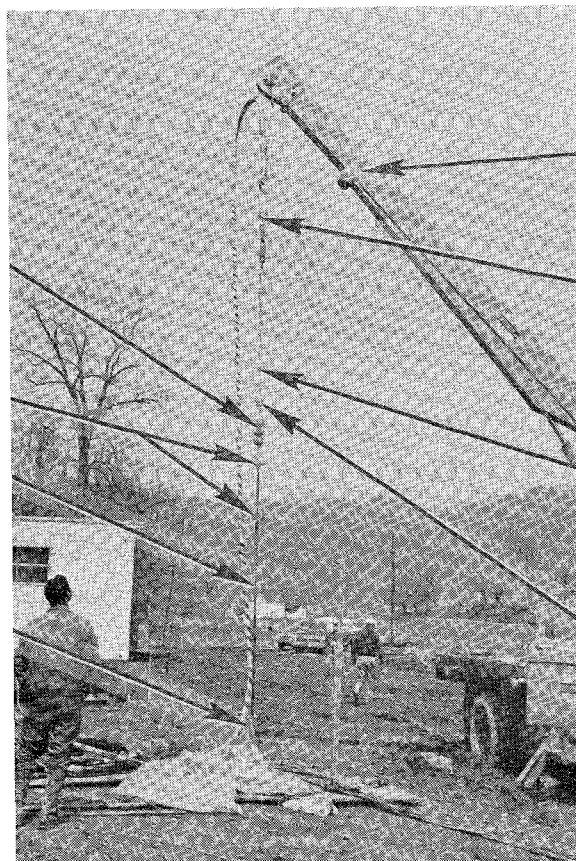
A photograph of the complete assembly is shown in Figure 142 as it is about to be lowered down a borehole.

Lead Weights

Packers

Foam Injection
Pipe

Flat Plate
Disperser



Boom of
Hydraulic Crane

Mixing Head and
Relief Valve

Kenics Static
Mixer

Quick Disconnect
Coupling

Photograph of Complete Assembly of
Downhole Froth Foam System

Figure 142

There are a total of five hoses deployed in the borehole: two 3/4-inch-diameter Synflex* hoses for the polyol and isocyanate components, one 1/4-inch-diameter airline for the pressure regulating relief valves, one 1/4-inch-diameter airline for the quick disconnect coupling and one 1/4-inch line for the methylene chloride. In order to avoid snagging, the hose connections at the mixing head, the relief valves, mixing head and hoses were tightly wrapped with 'duct' tape as shown in Figure 143. All five hoses were taped together into a bundle also using the duct tape. Figure 144 shows the bundle of hoses lying on the ground after retrieval from the number 1 borehole. In order to avoid snaking of the hoses against the walls of the borehole the hose bundle was taped tightly to the lowering cable at 3 foot intervals. Figure 145 shows a photograph of the hoses being lowered into the number 3 borehole for foaming of the simulated passage with the low roof. For transport, the hose was stacked on the bed of the truck, from which it was fed directly into the borehole. The hoses were taped to the cable as it was lowered.

The first time this procedure was implemented, it was convenient to feed the hoses in separately from their individual reels and tape them together to the winch cable during the process of lowering. On retrieval of this system, the hoses were cut loose from the cable and immediately taped together to form the hose bundle shown in Figure 144. Figure 146 shows a picture of the hoses being retrieved and cut free of the winch cable.

* Trade Name.



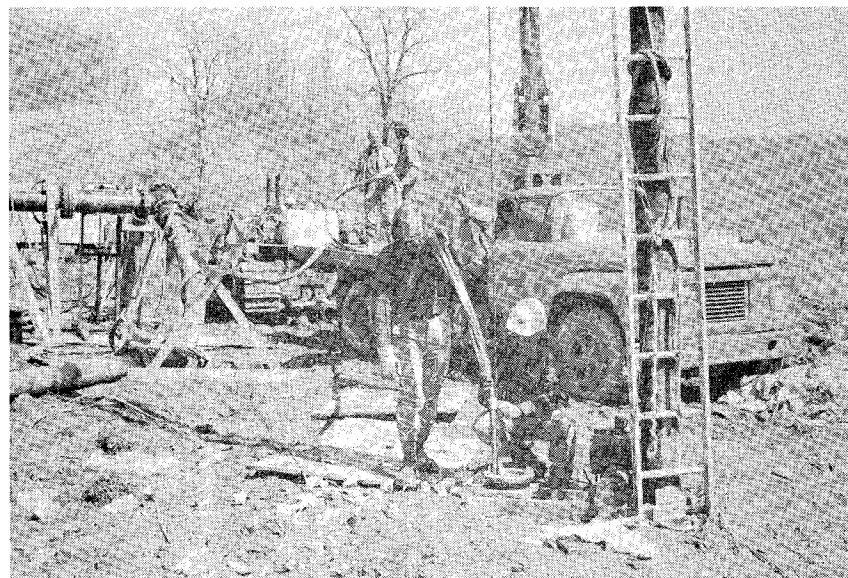
Taping of Downhole Mixing Head Pressure Relief Valves

Figure 143



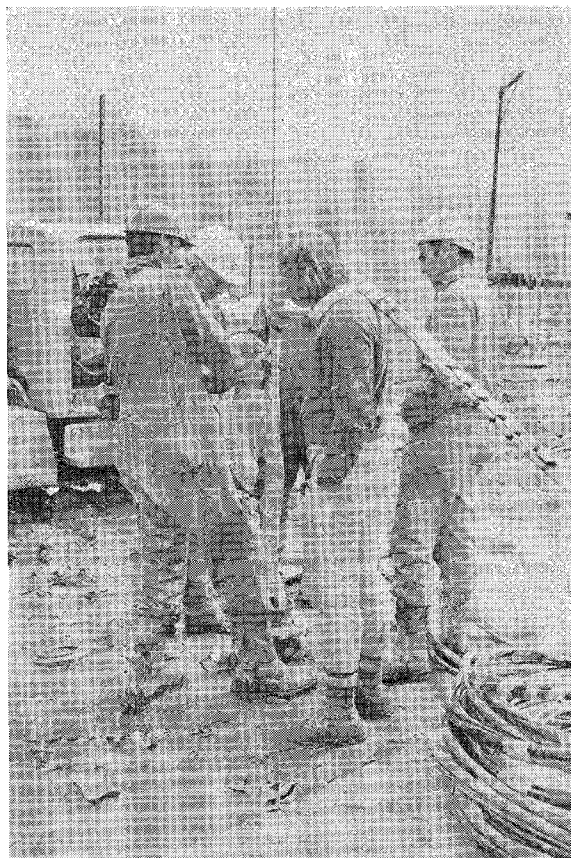
Taped Hose Bundle

Figure 144



Hose Deployment in Number 3 Borehole

Figure 145



Hose Retrieval from Number 1 Borehole

Figure 146

8.5.4 Field Test Operating Procedure

1. Installation of Foam Tanks

The first step in the field procedure was receiving and unloading the foam tanks from the Olin carrier and placing them in a convenient location central to all the test site boreholes. The foam tanks were covered with a canopy, and hot air was continuously blown in to maintain the foam components at a uniform temperature of about 80°F.

2. Assembly of Equipment

This included the assembly of the flow control panel and the downhole assembly.

3. Assembly of Total System

The hose bundle was prepared by taping all the five hoses together and placing it on the bed of the hydraulic crane. The hose bundle was connected to the flow control panel and to the respective outlets in the downhole assembly. The shackle on the mixing head was connected to the winch cable of the hydraulic crane. The mixing head, pressure relief valves and hoses were taped together and then taped to the winch cable (using duct tape) into a compact assembly with no protrusions.

4. Deployment of System into the Mine Passage

The hydraulic crane boom was positioned so that the froth foam downhole assembly was centered over the borehole. The assembly was lowered in 3-foot increments and the hoses fed from the truck platform were taped to the winch cable at 3-foot intervals.

The exact length to be deployed was calculated from available information on the depth of the borehole. This can be obtained from either mine maps, the driller and his estimate of drilling and casing length, or from the initial probing operation. For these tests it was always possible to have underground observation of the lowering operation. Deployment was stopped with the flat plate disperser about a foot below the mine roof.

5. Initial Loading of Component Lines with Freon

The air in the lines was initially purged with freon. The downhole pressure relief valves were opened for this purging. About 5 lbs of freon were used in each line. After completion of the purging operation, the downhole pressure relief valves were set to open at 350 psi by pressurizing them with 350 psi nitrogen. The lines were now full of freon and were maintained in this state until the start of foaming.

6. Start of Foaming

The component lines were charged with the isocyanate and polyol from the pressurized tanks by opening the stop valves on the control panel. The initial charging flow rate was high and dropped off as the lines filled. When the charging flow

dropped off to zero, the lines were known to be completely filled. The freon in the lines compressed, liquified and mixed with the components.

Foaming was started by opening the downhole pressure relief valves. The relief valve pressure was set to about 60 to 80 psi by bleeding the nitrogen control line. Immediately after opening the relief valve pressure was increased to 140 psi. The final flow rate and mixture ratio were adjusted by the metering valves on the control panel.

During the first 10 minutes of the foaming operation the temperature of the isocyanate and polyol components in the lines gradually increased until a steady state was reached. This increase in temperature resulted in a decrease in the viscosity of the fluids and a corresponding decrease in the flow pressure loss. To counteract this variation and maintain the desired flow rate, the relief valve pressure had to be gradually increased from about 140 to 180 psi. Once the temperature and environmental conditions had stabilized, only minor adjustments were required.

7. Foaming

During the foaming operation, close control on the flow rate and mixture composition was maintained. The flow meter settings were maintained at about 44 for the isocyanate and 42 for the polyol, corresponding to a total foaming rate of approximately 42 lbs per minute. The foam was about 10 percent isocyanate rich to ensure complete foaming. Close watch on the temperature was kept to ensure component temperatures of about $80^{\circ}\text{F} \pm 5^{\circ}\text{F}$.

8. Foam Shut Off

The foam was shut off downhole by pressurizing the relief valves to 350 psi. After the flow had stopped, as indicated by the flow meter, the system was shut off at the control panel on the surface. This procedure prevented gravity drainage of the components and minimized the risk of improperly mixed components being discharged into the mine.

9. Cleaning Downhole Mixer with Methylene Chloride

Immediately after foaming was stopped, methylene chloride was pumped into the downhole mixer to prevent foam from setting in the mixing head. The methylene chloride was pumped for at least 3 minutes to ensure good cleaning.

10. Retrieval of System

After initiation of the methylene chloride purge, the winch pulled up on the system to break it out of the foam. Should the downhole mixing head be grouted so firmly by the foam that winch torque is not sufficient, the system can be freed by actuating the quick disconnect coupling. A clear pop is heard when the disconnect functions.

The system was raised by the winch. The hose bundle was freed from the cable by cutting the duct tape holding the two together and the hoses laid on the truck bed for rapid transfer to the next seal site.

11. Resetting for Foaming of Next Seal

If a number of foam sealing operations are to be conducted in quick succession, the hose lines are kept filled with the isocyanate and polyol components and the system redeployed immediately down the next borehole. If the quick disconnect was used another assembly of the packers and foam injection pipe was added and the system redeployed.

The next foaming operation could start immediately.

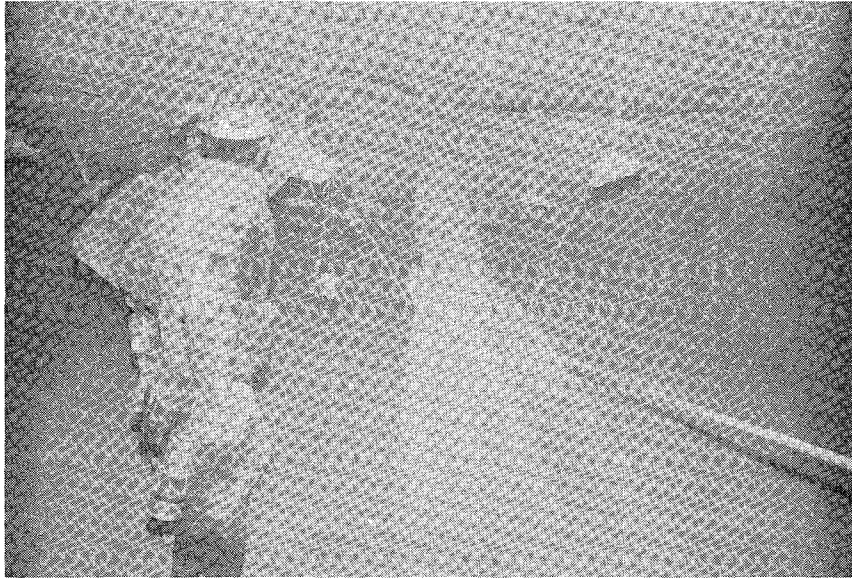
12. End of Foaming Operation

At the end of the foaming operation, the isocyanate and polyol were drained out of the component hoses by opening the relief valves. The internal pressure was sufficient to drain most of the liquid. Finally, the lines were flushed with methylene chloride. The hoses could then be reused.

8.5.5 Initial Field Tests to Prove Out System

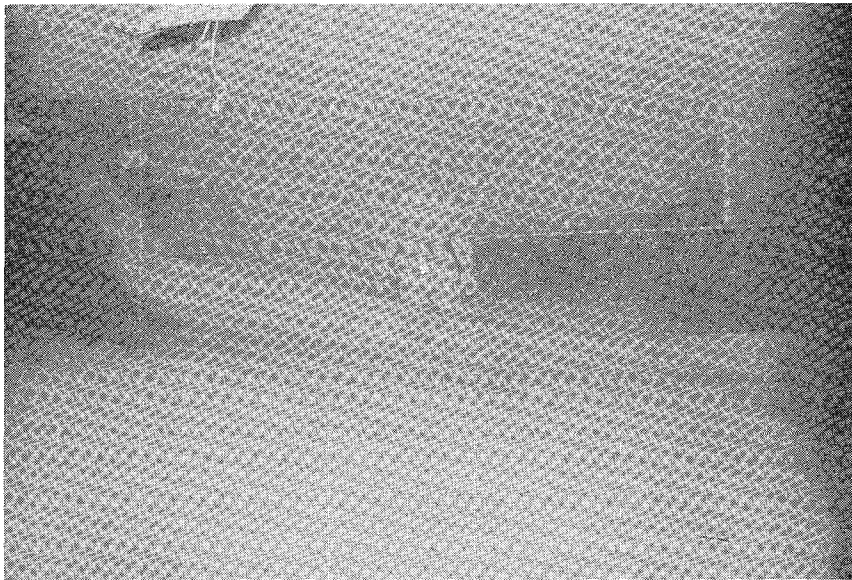
An initial field test was conducted to prove out the operation of the downhole mixer system. The system was lowered down the seal checker borehole used to lower the microphone at the number 1 straight passage test site. A 28-inch diameter polyethylene tubing was attached to the foam injection pipe, as shown in Figure 147. The foam was poured into the tubing where it flowed to form a foam sausage of the type shown in Figure 148.

The foam flowed about 15 feet downstream of the injection point before it plugged and the expansion pressure split the tubing as shown in Figure 149. This foam test was conducted at a flow rate of about 42 lbs per minute. The foam produced was of good quality indicating good mixing.



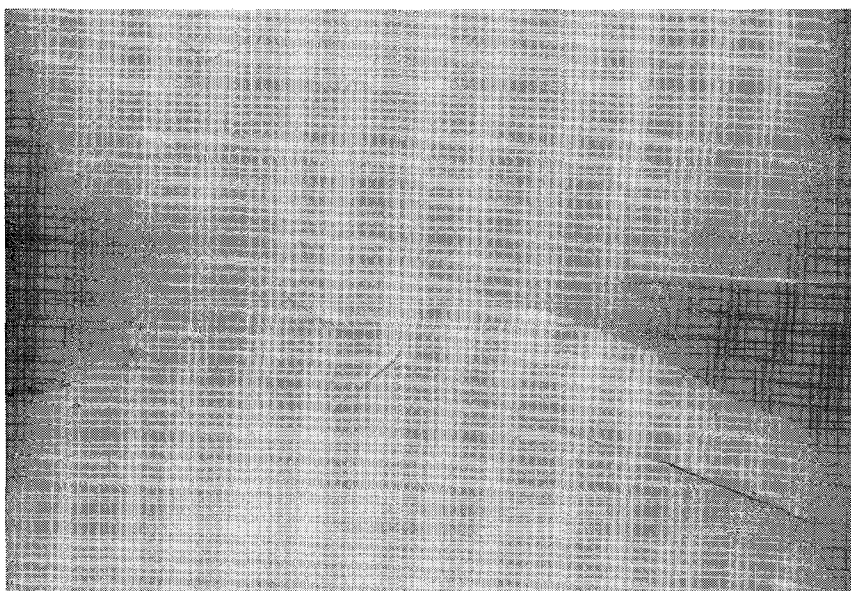
Initial Foam Test into Plastic Tubing

Figure 147



Foam Flowing Down Plastic Tubing in Initial Foam Tests

Figure 148



Plastic Tubing Split Due to Expanding Foam Pressure

Figure 149

After the completion of this test, the foaming was stopped, the mixing head and mixer cleaned with methylene chloride and the test repeated. There were no problems with restarting the system.

Based on these tests it was concluded that the foam system was operating satisfactorily, generating an acceptable flow rate of 42 lbs per minute of good quality foam, and the foaming operation can be stopped and restarted.

The foam sausages were dumped into a coal car and transported out of the mine to reduce any risk of fire.

8.5.6 Field Test of Foam Topping of the Simulated Low Roof Straight Passage

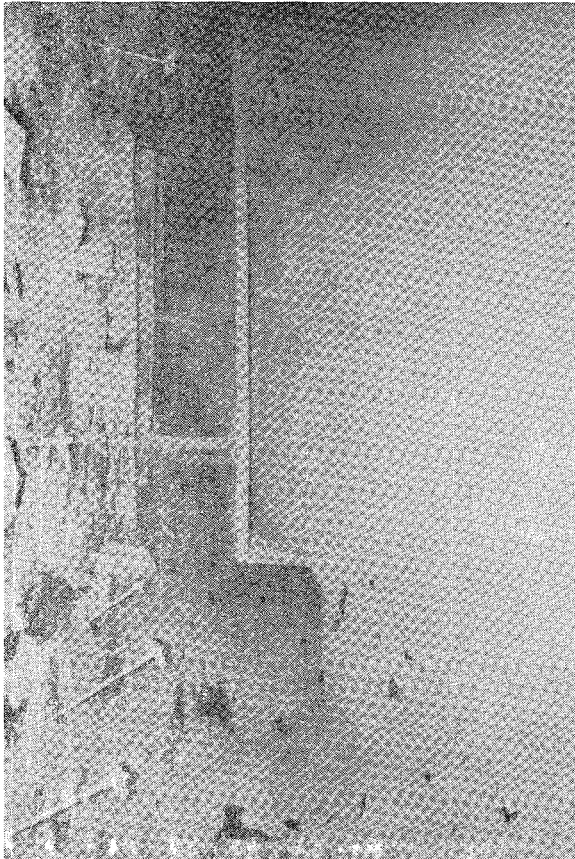
The first test of the froth foam topping system was conducted in the simulated low roof straight passage located in the three-way under borehole No. 3. The configuration of the fly ash pile was described in Section 8.4.5.2. The pile contained a shallow crater about 2-feet deep and 12-feet in diameter.

The downhole foam system was deployed down borehole No. 3 and set up with the disperser about one foot below the wooden roof. The actual lowering time was about 45 minutes. The component Synflex hoses were filled with a charge of freon as described in Section 8.5.5 to ensure good mixing at the start of foaming. The foaming operation was started by opening the downhole pressure relief valves, as described earlier. The system was set at an average foaming rate of 42 lbs per minute by adjusting the metering valves on the surface control panel and the pressure on the downhole relief valves. The mixture ratio was adjusted so that it was running about 10 percent rich in isocyanate.

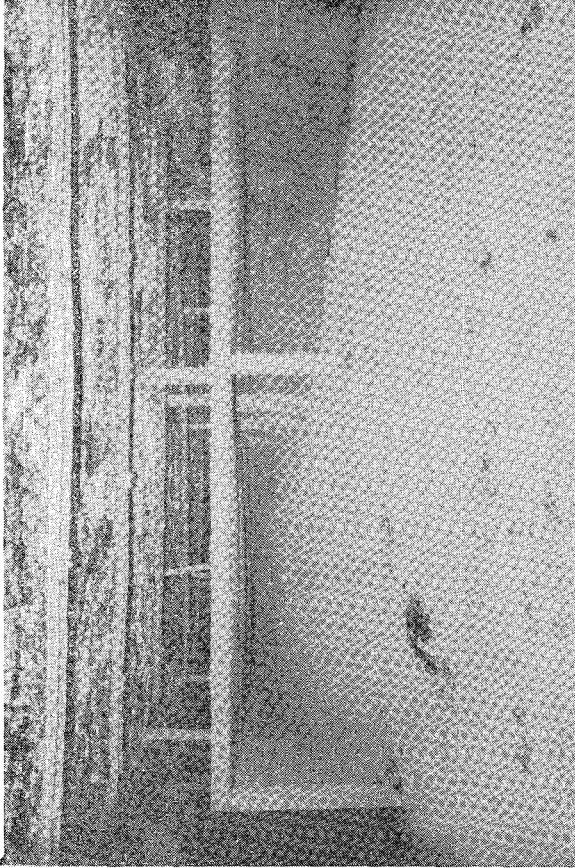
The foam buildup was similar to that in the tests at Franklin, Tennessee described in Section 6.4.3. The foam channeled and set up into sections, gradually sealing off the open area between the fly ash pile and the roof. Photographs of the in-progress foaming operation were destroyed inadvertently and cannot be presented here. Figure 150 shows photographs of the completed seal obtained after 20 minutes of foaming and 840 lbs of foam material. The seal was a complete 100 percent seal. The foam had a density of about 2.25 lbs. per cu. ft.

A number of precautionary measures were enforced during the foam pour to minimize the risk of fire. Both sides of the wooden box were circled with fire hoses fed by high pressure water lines specially laid for this purpose. Carbon monoxide was monitored every 30 minutes during foaming and for 6 hours after foam completion. Carbon monoxide is the most sensitive detector of combustion. Measurements indicated no CO at any time.

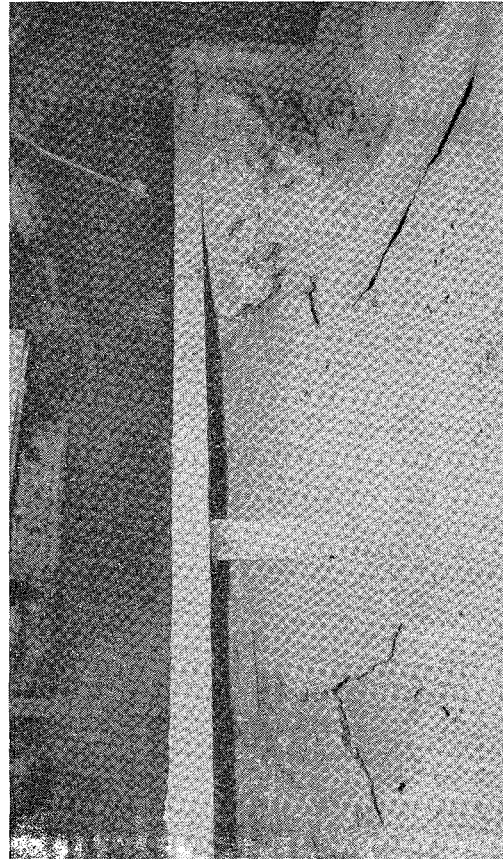
The foam topping operation was considered a success by all the observers in the mine. The foam system was retrieved immediately after the foaming was stopped. The hydraulic crane winch had no difficulty in breaking loose the foam head from the foam. The mixing head and mixer were cleaned with methylene chloride. Total retrieval time was less than 15 minutes. The hoses were laid on the truck bed and the system moved over to the No. 1 borehole for the start of the second foam sealing field test.



(a) Side A



(b) Side B



(c) Close Up of Side A

Final Foam Seal in Simulated Low Roof
Straight Passage
Figure 150

8.5.7 Field Test of Foam Topping of the Straight Passage

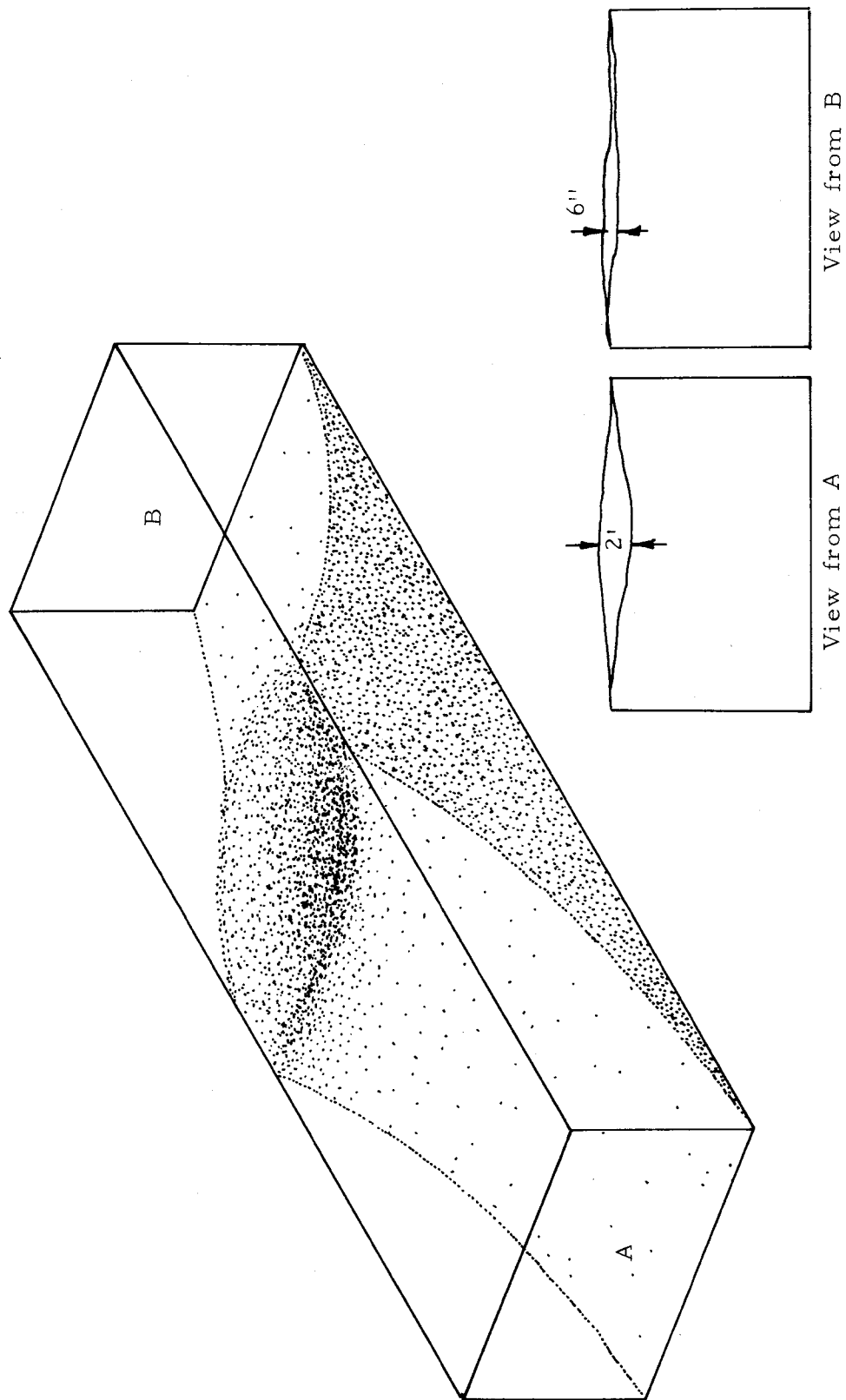
The second mine sealing test with foam was conducted in the straight passage under No. 1 borehole. The system was lowered down the borehole and located with the disperser about 1-1/2-feet below the mine roof. The exact location was guided by underground observation. However, by pure surface control of deployment it was possible to achieve a position within 6 inches of the desired location. This surface control was based on the depth of the borehole obtained from mine elevation data and careful measurement of the length of hoses deployed down the borehole.

The configuration of the fly ash pile at the end of the fly ash pour was described in Section 8.4.5.3 and is shown schematically in Figure 151. The fly ash had a large crater extending almost to the walls. In fact both roof-rib corners were almost sealed with fly ash. There was a very small clearance of about 4 inches between the fly ash and the roof on side B but a much larger clearance of about 18 to 24 inches on side A. Thus, it was to be expected that the foam would first flow down side A after it had filled the crater.

The seal checker was used to monitor the foam sealing operation. Details are to be found in Section 8.6.

The foaming operation was started using the normal procedure with the lines full of the two components from the previous tests. The lines were warm enough so that good mixing could be expected from the start. A foaming rate of about 42 lbs per minute was maintained with a 10 percent isocyanate-rich foam mixture.

The foam first filled the large crater. It



Final Configuration of Fly Ash Seal in Straight Passage

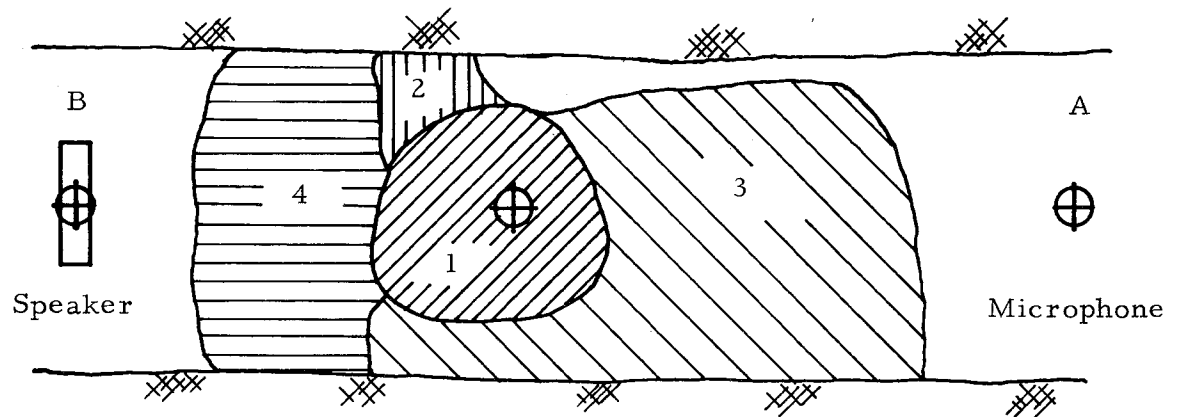
Figure 151

took about 15 minutes and about 650 lbs. of foam to fill this crater, at the end of which time the seal checker indicated a complete 100 percent seal. Underground visual observations confirmed this conclusion. However, foaming was continued for a total time of 80 minutes to observe further foam development. After filling the crater the foam started to channel down side A as shown in Figure 152. Once again photographs of the foam seal development were inadvertently destroyed. After most of passage A was filled, the foam finally broke out on the other side to form section 4. Though there was an open channel on side A, the seal was undoubtedly a 100 percent seal. The development of the foam seal is shown schematically in Figure 152.

Figures 153 and 154 show photographs of the completed seal from both sides of the passage. Once again the foaming operation was deemed a success by observers underground during the operation.

The seal checker was shown to be a very effective method of monitoring the foam seal and minimizing the amount of foam material required per seal. The fly ash crater is an ideal receptacle for foam.

The fire prevention measures described in the previous test were also enforced during this foam pour. Fire hoses were deployed on both sides of the seal. Carbon monoxide tests were made every 30 minutes during the foam pour and for four hours after completion of the pour. No CO was detected, indicating the absence of any combustion.



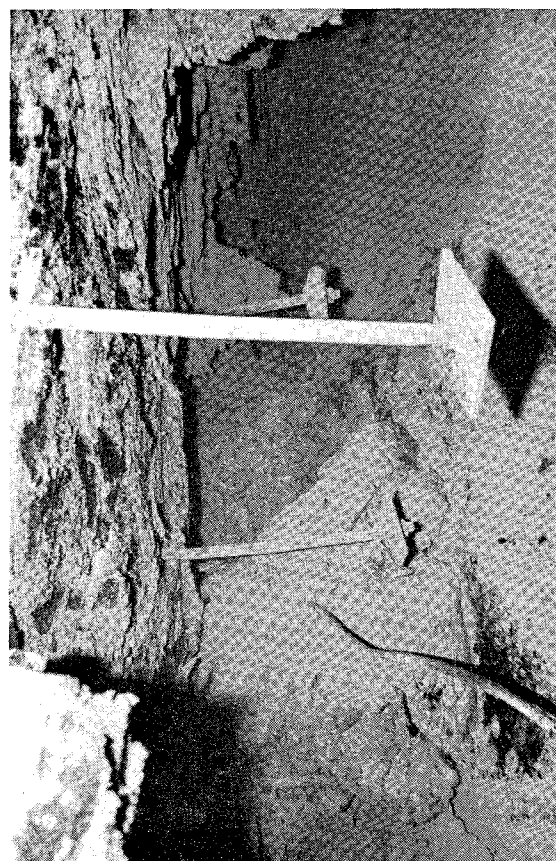
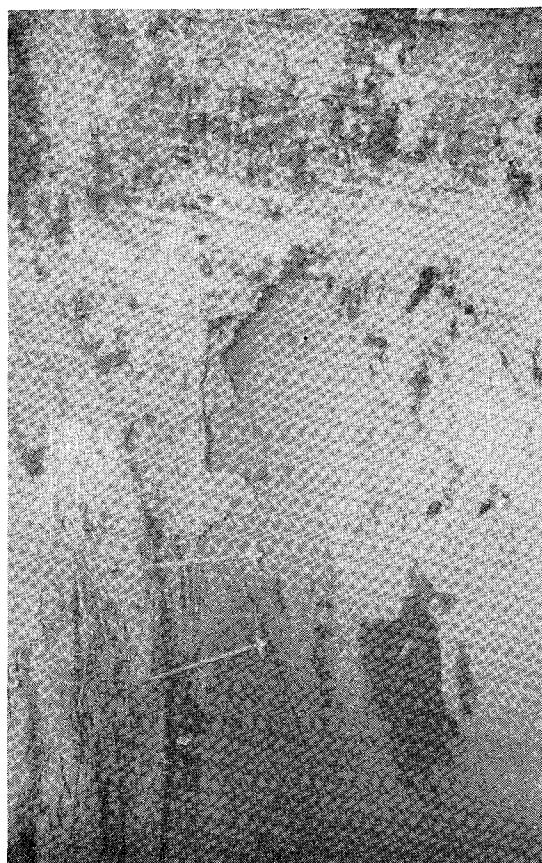
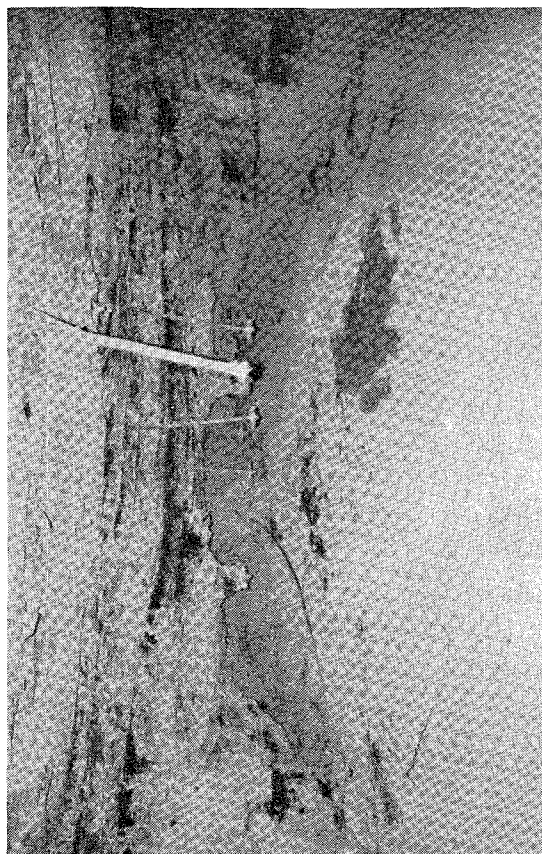
Plan View, Development of Foam Seal in Mine Straight Passage

Figure 152



Photographs of Foam Seal on Side A of the Straight Passage

Figure 153



Photographs of Foam Seal on Side B of the Straight Passage

Figure 154

8.6 Evaluation of Acoustic Seal Checker

The evaluation of the acoustic seal checker included four distinct tasks which spanned the two month test program at Federal No. 1 mine. The four tasks included:

- (a) Deployment
- (b) Preliminary Experimental Evaluation
- (c) Monitoring The Fly Ash Seal Emplacement
- (d) Monitoring The Foam Topping Operation

These tasks will be discussed in detail in the following sections, followed by a summary of the results, and conclusions based on the field test.

8.6.1 Deployment

Deployment of the seal checker modules was performed using the equipment listed in Appendix E. Deployment of the microphone-preamplifier module includes:

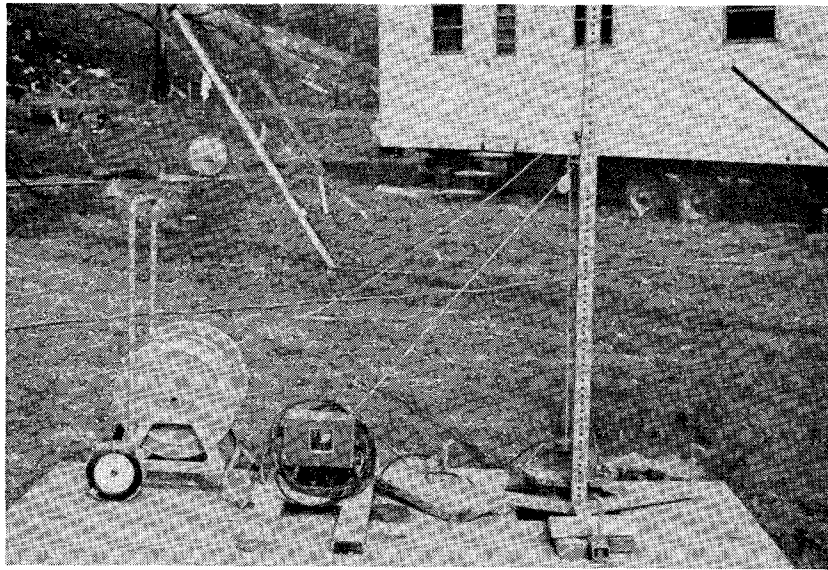
- (a) attachment of module to 1/8-inch steel cable
- (b) lowering the cable using the winch
- (c) attaching the electrical cable to the mechanical cable to avoid overstressing the electrical cable.

Figure 155(a) shows the winch and cable reel used to deploy the microphone module. The stand shown in the photograph supports the pulley which guides the cable. For most applications the stand is not necessary. Figure 155(b) shows the microphone module lowered through the borehole into the passage.

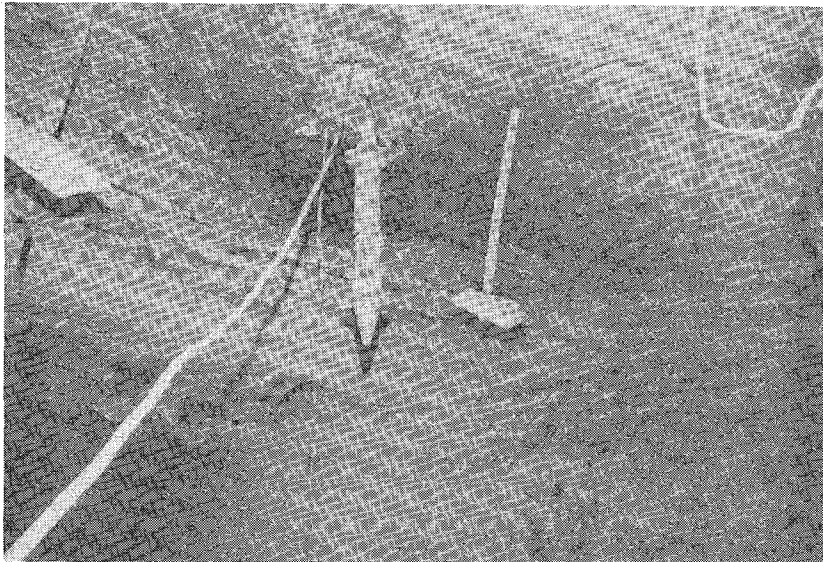
Deployment of the linear acoustic array includes:

- (a) determination of optimum deployment direction
- (b) "cocking" the array for automatic deployment
- (c) lowering using 20-foot aluminum tubes
- (d) supporting electrical cable
- (e) automatic deployment at floor of passage
- (f) orientation
- (g) retrieval

The location of the borehole with respect to the ribs must be known to permit horizontal deployment of the linear array to the most satisfactory side. By deploying away from the closest rib, physical interference with the rib is eliminated and acoustic interference minimized. This information may be determined directly by using the sonar probe in the acoustic sensor borehole or indirectly from the probing of the pouring borehole and a survey map of the passage.



(a) Surface Deployment Equipment



(b) Module Deployed Through Borehole

Microphone Module Deployment at Federal No. 1

Figure 155

Having determined whether left-hand or right-hand deployment is preferred, the linear array was cocked in the desired position and locked in place with the foot release rod.

Attachment to the aluminum poles, as per Section 8.3.3, and connection of the 20 conductor electrical cable were straightforward. Lowering proceeded as described in Section 8.3.3. For this application the Victaulic couplings provided support for the electrical cable every 20 feet using Kellem*clamps on the cable. The winch and support scaffolding are shown in Figure 156 (a).

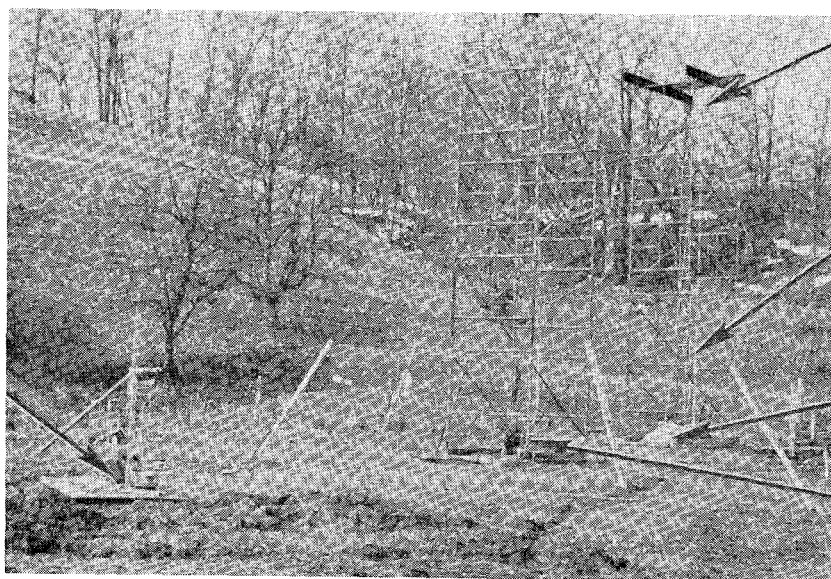
Lowering proceeded rapidly until the module reached the passage. As the passage floor was approached the lowering rate was decreased. Contact with the floor of the passage and successful automatic deployment of the linear array were signalled by a clear "pop" transmitted through the pipe stack to the surface. At this time the winch was reversed and the linear array was raised to a satisfactory operating level near the roof of the passage. A photograph of the linear array positioned through the borehole is presented in Figure 156 (b).

The proper orientation was determined prior to pinning the aluminum poles into position by activating the acoustic source as well as the microphone and signal processing equipment. Rotating the pipe stack to produce the strongest signal assured the optimum orientation. The pipe stack was then drilled and pinned to prevent subsequent motion.

Retrieval was accomplished by drawing up on the winch with sufficient force to shear a brass pin, permitting the linear array to hang vertically below the pipe stack and be drawn back up through the borehole by reversing the lowering procedure.

* Trade Name

Microphone
Deployment
Borehole



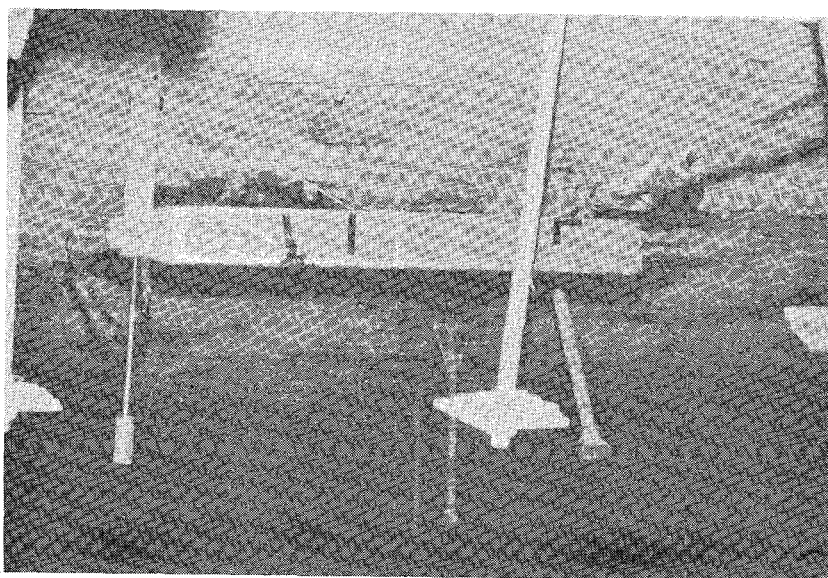
Support
Pulley

Speaker
Deployment
Borehole

Winch

Sonar
Deployment
Borehole

(a) Scaffolding Towers and Support Equipment for
Deployment of Down-Hole Instrumentation



(b) Linear Array Deployed Through Borehole

Acoustic Module Deployment at Federal No. 1 Mine

Figure 156

8.6.2 Preliminary Experimental Evaluation of Acoustic Array

An experimental program was performed in the mine prior to the emplacement of any seal material. This program was intended to evaluate the relative merits of several features included in the design of the linear acoustic array. Future designs will be simplified based on the results of this program. The design features of particular interest and the objectives of the test program were:

- (a) horizontal deployment of linear
 acoustic array - evaluate the
 improved directionality realized
 with the horizontal array
- (b) number of speakers - evaluate
 the advantages of a line source
 over a point source of equal
 power
- (c) exact height positioning - determine
 the sensitivity of signal level to
 relative height of speakers and
 microphone
- (d) rotary positioning - determine the
 sensitivity of received signal to
 rotary orientation of speaker
 module

The value of the several design features was determined through a series of "acoustic profiles" in the mine near the acoustic source. Acoustic profiles are composed of a series of

sound intensity readings at several locations in the vicinity of the source. Plotting the sound intensity against the location on rectangular coordinates yields a profile of the sound level at the various locations. Profiles of this sort provide a means for comparing the acoustic fields produced by various geometries. During the test program "profiles" were taken using the General Radio* Type 1561 Sound Level Meter. The following variations in the acoustic source were included in the test program:

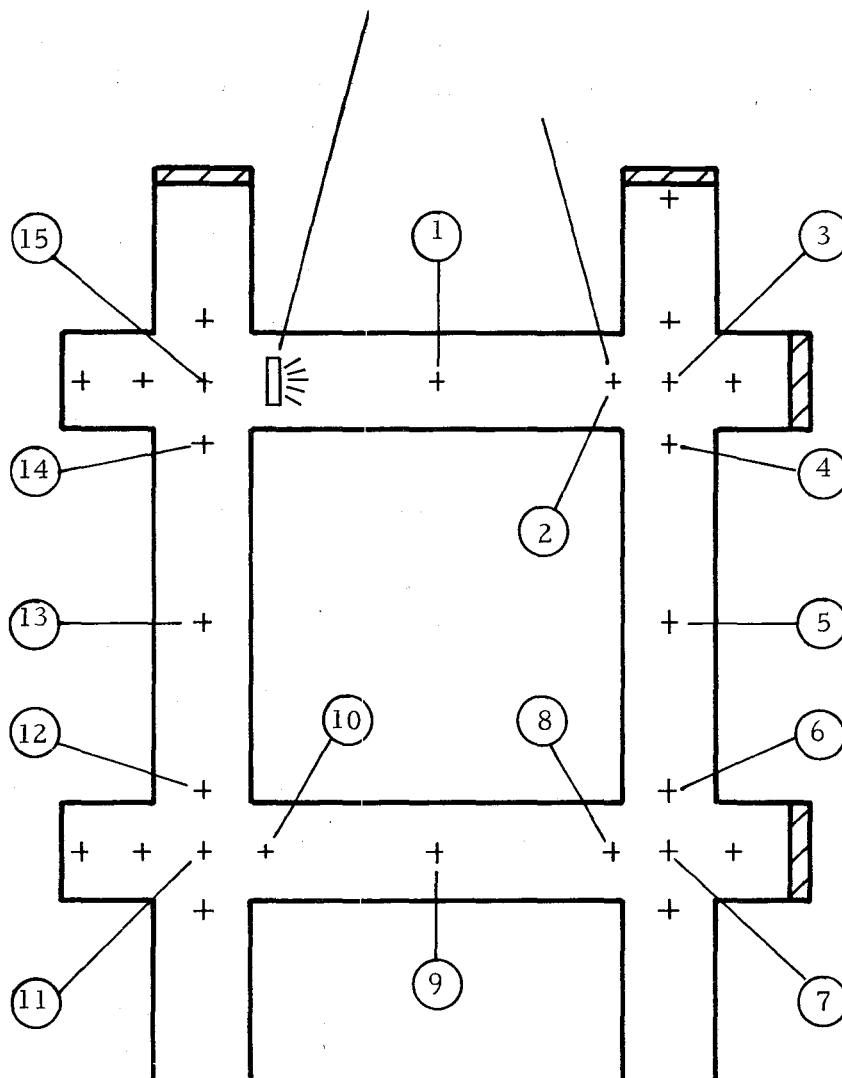
- (a) linear array deployed horizontally and vertically
- (b) power to 3 speakers and 8 speakers
- (c) array positioned at several heights in the passage
- (d) array skewed with respect to passage direction

Through comparison of the acoustic profiles for various combinations of the above parameters, it was possible to determine the relative importance of the several design features.

The layout of the mine passages in the vicinity of the acoustic source is shown in Figure 157 with the locations marked at which sound intensity was recorded. For the "acoustic profiles" only the locations which lie in a continuous path were included. These are designated as circles on the mine layout.

Four typical profiles are presented for discussion in Figure 158. All four profiles were established with equivalent total power into the speaker module and with the center of the module at the same height from the passage floor. The four

* Trade Name

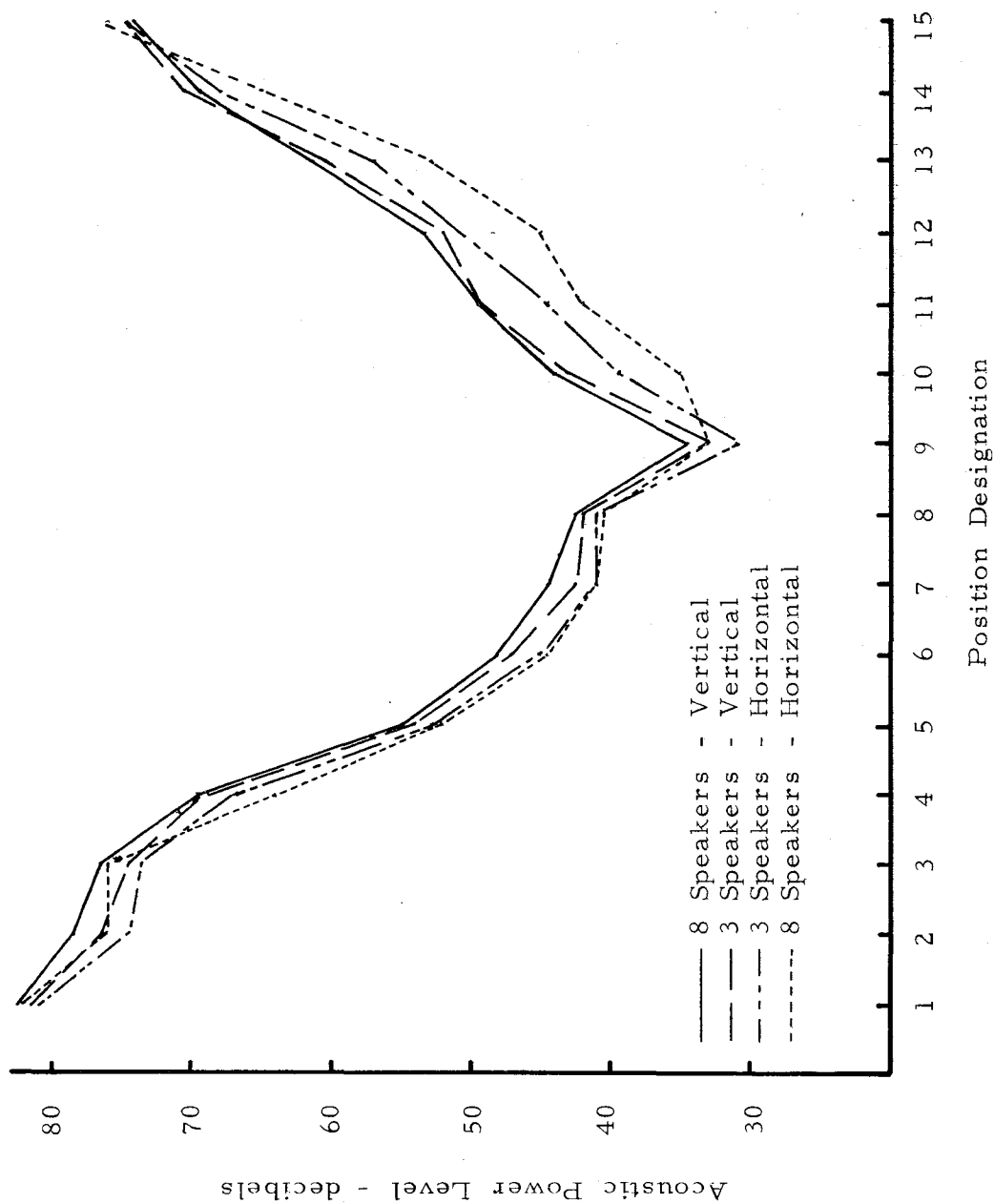


+ Microphone locations.

○ Locations used to measure acoustic profile shown in Figure 158.

Mine Layout Near Acoustic Source

Figure 157



Acoustic Profile In Main Passage and Flanking Path

Figure 158

profiles represent all combinations of vertical or horizontal deployment and 3 speaker or 8 speaker operation. The 8 speaker, horizontal deployment case provides the most directional source as indicated by the low sound level at positions in the passage behind the speaker module. Reducing the number of speakers to 3 while maintaining the same total power reduces the tendency of the module to behave like an ideal directional line array. This can be observed in the higher sound intensity levels at locations 13, 14 and 15 on Figure 158, indicating increases in the side lobes of the acoustic field.

Turning the module to the vertical position eliminates all directionality, due to the line geometry, regardless of the number of speakers. The curves for 3 speaker and 8 speaker operation in the vertical orientation are virtually identical.

Comparison of these profiles indicates that horizontal deployment of a linear acoustic array is of some value in reducing the acoustic energy transmitted along flanking paths. It does not, however, significantly increase the intensity of the acoustic signal in the passage toward which it is directed.

A series of profiles with the linear acoustic array positioned at various heights indicated that, in general, height of the array from the floor was not critical. Positioning the microphone within one foot of the floor or ceiling did produce some irregularities in the data.

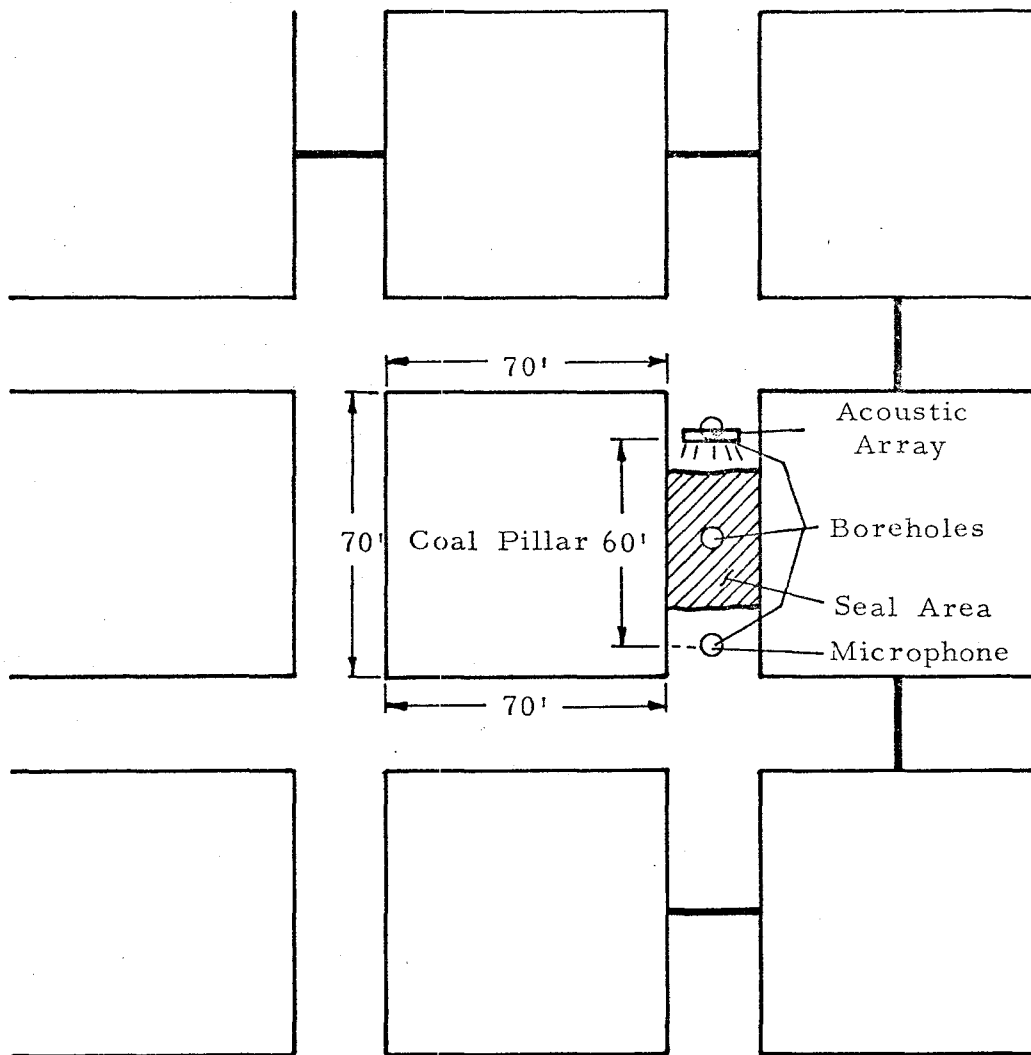
A series of tests in which the acoustic array was rotated about the borehole axis, while data was gathered in the main passage, indicated that accurate direction of the speakers may be obtained from the signal received at the microphone.

The following conclusions may be drawn from the preliminary test program at Federal No. 1 mine:

- (a) Reducing the number of speakers at the same total power reduces the line source effect and increases slightly the energy level in the flanking passages.
- (b) Horizontal deployment of the acoustic array reduces slightly the acoustic energy transmitted down the flanking paths. It does not however increase the intensity of the signal in the direct path.
- (c) The height of the acoustic array or the microphone module is not critical although positions within one foot of floor or ceiling should be avoided.
- (d) Microphone signal is adequate to permit accurate rotary positioning of the array about the borehole axis.

8.6.3 Monitoring Fly Ash Seal Construction - Straight Passage

The acoustic seal checker was employed to monitor the emplacement of the fly ash seal in the two-way passage. The original cross-sectional area of the passage is 200 square feet. The length of the direct path and flanking path may be determined from Figure 159. The direct path distance between the speaker array and the microphone module was just over 60 feet. A setting of 70 feet was selected on the microphone-speaker distance adjustment on the console to insure that gating of the received signal began after the acoustic signal had reached the microphone.



Direct and Flanking Path Geometries for Straight
Passage Seal Test

Figure 159

The length of the shortest flanking path is approximately 230 feet. The "window" size for the gating circuit must be selected to close prior to the arrival of the signal via the flanking path. The maximum window size may be determined from:

$$\text{maximum window size} = \frac{(\text{Flanking path length}) - (\text{Direct path length})}{\text{Speed of Sound}}$$

For the dimensions of Figure 159 this yields a maximum window size of 140 milliseconds. A conservative window size of 130 milliseconds was selected for our tests. A two-second signal repetition rate was selected arbitrarily.

To compare the performance of a linear array and a more standard geometry, two sets of data were gathered during the emplacement of the fly ash sealant material. One set of readings was taken with power to all eight speakers, approximating a linear acoustic array, the other set with only three speakers operating - typical of a more conventional acoustic source. For this test sequence the power to each speaker, not the total power, was held constant.

Base level readings were established for the open passage and then readings were taken after the emplacement of each load of fly ash. The data gathered during the pour is presented in Table VI. The initial data points have been corrected slightly for zero drifts and spurious signals which plagued the initial measurements. These corrections in no way affect the bulk of the data however.

Also included on Table VI are estimates of the percentage of passage area blocked by the fly ash barrier based on the reduced signal received by the microphone. These estimates

TABLE VI

ACOUSTIC SEAL CHECKER DATA FOR 2-WAY SEAL

Fly Ash In (Truck Loads)	Signal Level (Decibels)		Passage Area Blocked (Percent)
	8 Speakers	3 Speakers	
0-baseline	76	71	0
1	75 1/2	70 1/2	
2	75	70	
3	73 1/2	69 1/2	
4	73	68 1/2	50
5	72 1/2	67 1/2	
6	70 1/2	65 1/2	
7	70	65 1/2	75
8	70	66	
9	68 1/2	65	
10	66 1/2	63	87
11	--	--	
12	64	60	94
13	63	58 1/2	
14	62	58	
15	--	--	
16	61	57	97
17	60	56 1/2	
18	59	55	
19	58 1/2	55	
20	57	53	98.5
21	56 1/2	52 1/2	
22	55	51	99

are based on the curve of Figure 67 in Section 7.1. Visual inspections of the seal indicated agreement between the actual area blocked and the predicted values.

The final readings after 22 loads of fly ash indicate a reduction of 21 decibels in signal strength. At 3 db reduction per area halving, this indicates that 0.9 percent of the passage area (approximately 1.8 square feet) remains unsealed. Careful visual inspection of the seal indicates the existence of a rectangular opening four feet by four inches on a side. The actual open area was therefore 0.7 percent of the original area while the acoustic checker indicated 0.9 percent - accuracy to fractions of one percent. Recall that the fly ash sealing was stopped at this point to allow room for the foam topping process. Monitoring the topping operation is described in the following section.

8.6.4 Monitoring Foam Topping

The acoustic seal checker may be used in a different manner to monitor the completeness of the foam topping operation. The nature of the foam material demands a continuous pour rather than the batch pouring operation used with the fly ash emplacement. The acoustic seal checker must therefore be used during the actual pouring operation. This is complicated by the random noise emitted by the frothing action of the foam as it is ejected from the mixing head under pressure. This random noise is monitored by the microphone, integrated and indicated on the signal level meter in such a way as to mask the signal from the pulsed source.

A visual observation of the dynamic behavior of the sound level meter and comparison with the dynamics of the power input meter does provide a meaningful indication of foam

topping progress. During seal checker operation the input power meter needle bounces with each power pulse into the speakers. The needle on the sound level meter also pulses at the same rate providing the seal is incomplete. The amplitude of the needle motion decreases with hole size, but the frequency is fixed.

As the foam topping operation begins, the regular bounce of the needle dominates the random motion due to the foam noise. As the seal becomes complete, the regular needle motion disappears completely and the needle indicates the ambient noise level, except during bursts of foam noise.

For the foam topping in the two-way passage the background noise level was 31 decibels. As stated in the previous section, the signal penetrating the hole in the seal indicated 51 decibels. The sound level meter showed strong steady pulses on the 50 decibel scale. As foaming began, random meter motion was scarcely noticeable on the 50 decibel scale but the regular pulses continued with decreasing amplitude as the foam material continued to form the seal.

On the 40 decibel scale the amplitude continued to decrease in the presence of noticeable noise. When the amplitude of the regular pulses dropped to a level observable only on the 30 decibel scale, the random motion made readings difficult. After a very short time the regular motion of the sound level meter ceased completely and the meter read the 31 decibel ambient level between bursts of noise from the frothing foam.

This entire process required approximately twelve minutes.

8.6.5 Monitoring Fly Ash Seal Construction-Four-Way Intersection

During the monitoring of the fly ash emplacement in the 4-way intersection, considerable difficulty was caused by the leakage of electrical noise from the amplifier speaker circuit to the microphone-preamp-sound level meter circuit. Unlike the 2-way passage situation, the level of the electrical noise was the same as the acoustic signal. The differences in the tests for the two passages included:

- (a) Acoustic source leads extended to 1000 feet
- (b) Microphone leads extended to 1000 feet
- (c) Entire test site covered with puddles of water.

Considerable attention was given to complete isolation within the electronics cabinet of the circuits which send and receive the acoustic signal and careful grounding of the two systems to the borehole casings. This reduced the magnitude of the electrical noise considerably but did not completely eliminate the problem.

The remaining electrical noise was traced to leakage through the shielding on the microphone cable. This effect was magnified for the 4-way seal because of the longer cable length and the wet conditions at the site. A series of tests involving isolating the cable from the wet ground indicated, despite all precautions, that significant electrical noise was being transmitted through the wet ground to the microphone cable.

Isolation of the cable from the wet ground reduced the noise to acceptable levels and the test program was concluded. For future efforts the microphone cable should be double shielded for better electrical isolation and have a covering with considerable mechanical strength and abrasion resistance.

8.6.6 Conclusions and Recommendations

Based on the results of the field test program, the following conclusions may be drawn regarding operation of the existing acoustic seal checker system:

- (a) The acoustic technique provides an excellent indication of the percentage of area blocked at any time during the seal emplacement process.
- (b) The technique appears insensitive to passage irregularities and sealant material selections.
- (c) The pulse gating approach is extremely valuable in broadening the applicability of the system.
- (d) The horizontally deployable linear acoustic array provided marginal benefit in terms of directionality.
- (e) The microphone-preamplifier provided the desired sensitivity in a small package at reasonable cost.

- (f) The microphone leads were not sufficiently rugged for the downhole application.

Recommended modifications for future seal checker system designs include:

- (a) Elimination of the horizontal deployment features of the linear acoustic array.
- (b) Replacement of the 8 speaker array with a more compact unit with fewer speakers.
- (c) Replacement of the rigid pole lowering system with a more rapid cable system.
- (d) Selection of more rugged shielded cables for the microphone-pre-amplifier lead.
- (e) Reduction in size for 4-inch-diameter borehole deployment.

9. Remote Sealing System Sensitivity

9.1 Introduction

In the previous sections a description of the overall system has been presented along with detailed descriptions of the equipment and techniques employed with the preliminary probing system, the seal emplacement system and the seal checking system. In addition, the use of these subsystems in a specific mine application has been described in considerable detail.

A broad range of parameters of interest was specified in the contract, as summarized in Section 1.3. Most of these are a function of the general location; i. e., the location of the mine, and the specific location; i. e., the location of the boreholes. These parameters of interest include passage size, shape, depth, slope and water conditions. The length, diameter and location of the boreholes within the mine passage and on the surface are critical parameters as well. A few additional parameters may affect one or more of the remote sealing subsystems. These include temperature, topography, rock and soil conditions, and underground water. While variation in these parameters will not render the system inoperative, consideration of them in the planning stages will simplify and expedite the field operation.

In the following sections the effect of the various parameters on the remote sealing operation will be discussed. For clarity, the several tasks, borehole drilling and casing, preliminary probing, fly ash delivery, foam topping and seal checking, will each be considered separately.

The effect of variation of the parameters on the following system characteristics has been considered:

- (1) confidence in successful operation
- (2) material and equipment required
- (3) setup, deployment and retrieval time
- (4) task completion time.

Although the systems will function over a wide range of inputs, the confidence in system performance may vary for extreme values of a particular parameter or a particular combination of parameters. Situations beyond the range of those tested where this might occur are discussed.

Material and equipment requirements may vary drastically for certain combinations of parameters. Fly ash requirements increase rapidly with increases in roof height, for instance, and blowers with higher pressure capabilities may be required to accommodate the long borehole situations.

The preparation time for the operation -- including setup, deployment and retrieval of all equipment -- is critical in planning an efficient remote sealing operation. The effect of variations in on-site parameters on preparation time is critical.

The time to complete the actual task is also critical but is frequently sensitive to different parameters. For this reason the effect on the preparation and completion portions of the program are presented separately.

9.2 Drilling and Casing of Boreholes

The primary factors affecting the borehole drilling operation are the depth and diameter of the boreholes, as well as the presence of borehole water flow. Changes in any of these parameters will significantly change the type and quantity of material, equipment, and the time required to complete the boreholes.

To a lesser extent, local soil and rock conditions, as well as the surface topography, will also affect the drilling and casing procedures. The effects of these variables on total system performance are summarized in Table VII and discussed in the following sections.

9.2.1 Confidence in Successful Operation

The success of the borehole drilling operation is affected by four factors:

- (1) the accuracy of the mine map
- (2) the accuracy of the surface survey
- (3) the time and care of the drill operator
- (4) the depth of the borehole.

If the surveys for the mine map and the surface were properly done and closed out to the coal company standards (typically 1 part in 10,000), and if a conscientious drilling contractor proceeds at a cautious pace, the effect of the first three factors will be positive. The confidence in successfully intercepting the mine passage does depend upon borehole depth. The deeper the borehole the greater the cumulative drilling error with consequent reduction in confidence.

TABLE VII
EFFECTS OF ON-SITE VARIABLES ON BOREHOLE DRILLING AND CASING

Parameter	Effect on Dilling Operation
Borehole Depth	Increases in depth require proportionally longer drilling times as well as additional materials and equipment. Deeper holes also require greater care to insure borehole intersects passage.
Borehole Diameter	Drilling time and costs per foot increase significantly with the size of the hole required.
Underground Water	The presence of underground water flowing into the borehole requires casing of the hole with considerable increase in time and cost. This casing is required on the main borehole but may be eliminated in some situations for the seal checker holes.
Soil and Rock Conditions	Unusual soil and rock conditions affect the drilling operation. Voids and underground pools may also affect the grouting operation.
Surface Topography	Surface topography affects the drilling setup time and the access of support equipment.

From the field experience of Federal No. 1, it appears that with proper care boreholes 400 feet deep will intercept the passage roof within 2 feet of the target.

If the drill encounters solid coal at the passageway depth, the operation should be terminated until the cause of the error has been determined. Many companies offer borehole surveying services which can accurately plot the course of the hole. From this information it can be determined whether the drill strayed from a true course or the survey was inaccurate. In either case, the corrective remedial action will increase the confidence level in the accurate drilling of subsequent holes.

The underground rock conditions may affect the grouting operation required with cased boreholes. Voids in the rock strata can drain off grout, or underground water may dilute it. Where this behavior is anticipated, the grouting technique described in Section 8.2.5 will insure successful grouting.

9.2.2 Material and Equipment Required

The material and equipment required for drilling, casing and grouting are listed in Appendix E. Deeper holes will require additional lengths of drill pipe and casing, and each different diameter requires a different size drill, stabilizer, drill pipe, and casing. In the rare instances where no underground cavities or pools of water are encountered, casing may be eliminated with the exception of that needed to hold the topsoil.

9.2.3 Time Required for Operation

As mentioned previously, soil and rock conditions and surface topography can affect the drilling operation and the time required for its successful completion. Surface topography will not

directly affect the drilling time once the operation has started. However, difficult terrain will obviously require more preparation and increase the time required to set-up the drill rig. In addition, the drilling time will be affected by the type of bedrock encountered. For the purposes of this report, typical, or average, conditions have been assumed in determining the representative drilling times shown in Figure 160.

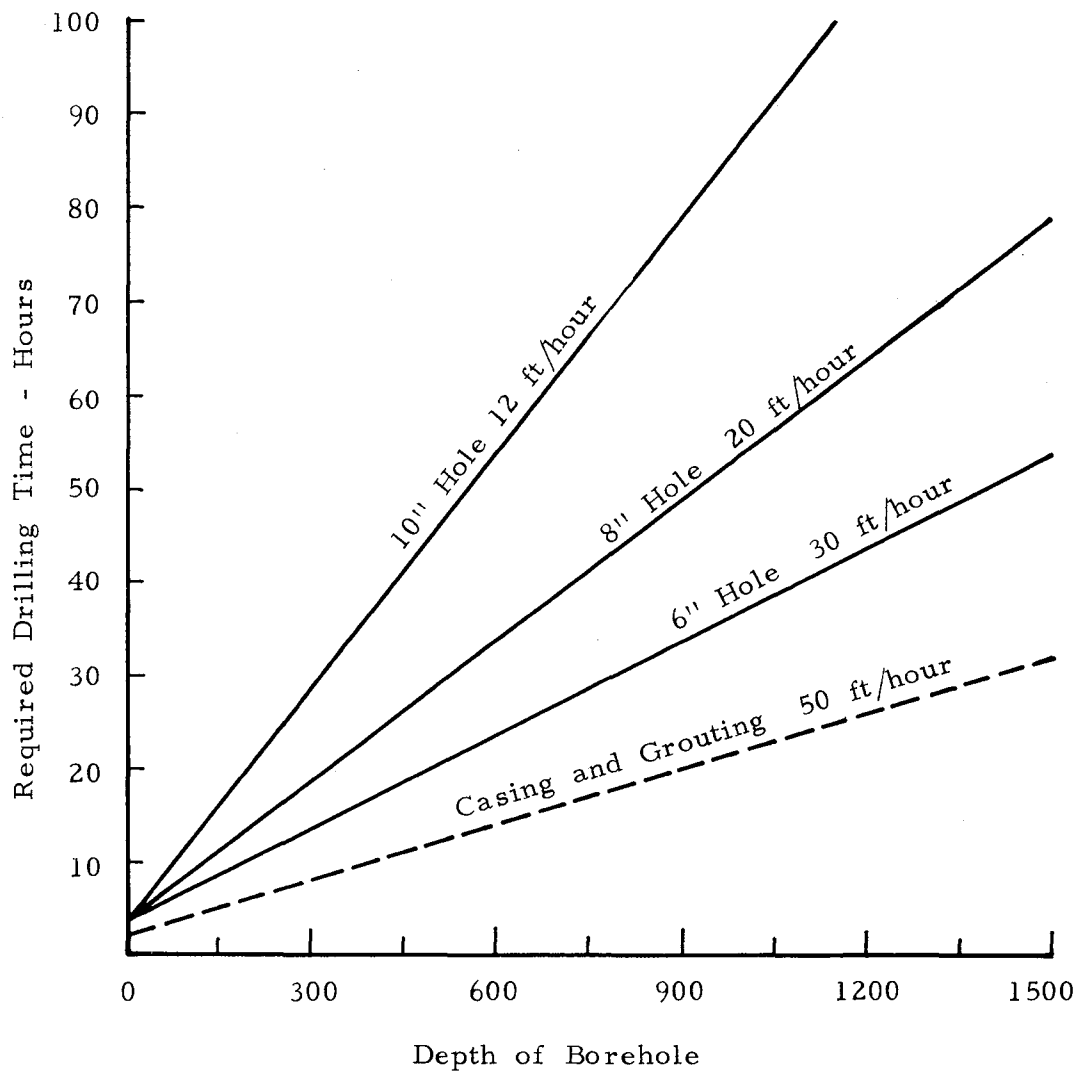
This figure indicates that drilling time, after setup has been completed, is a linear function of borehole depth and strongly affected by borehole diameter.

Rock structure and underground water conditions may affect the borehole casing requirements. For all situations, casing of the main borehole is strongly advised.

The time required for the casing and grouting operation has been shown separately in Figure 160 to permit its inclusion when required. It has been assumed that the positive pressure grouting technique of Section 8.2.5 would be employed. Note that an 8-inch cased borehole yields the same diameter hole as an uncased 6-inch hole.

9.3 Sonar Probing System

Table VIII summarizes the effects of on-site variables on the sonar probing system. From this table it can be seen that the only factor affecting the time and equipment required for operation is the depth of the borehole. Variables affecting confidence in the satisfactory operation of the system include the passage height, condition of the roof, and roof falls or other passageway obstructions. The actual effects of these variables on system operation are discussed in the following sections.



Required Drilling and Casing Times for Boreholes

Figure 160

TABLE VIII
EFFECTS OF ON-SITE VARIABLES ON PRELIMINARY PROBING

Parameter	Effects on Sonar Performance
Passage Height	Low roofs can make data interpretation more difficult.
Passage Slope	Minimal effect.
Roof Condition	Rough roof can make data interpretation more difficult.
Passage Blockage	Partial passageway blockage will show on the display; however, proper interpretation can be more difficult.
Borehole Depth	Deeper holes will necessitate longer time for raising and lowering probe; requires more hardware.
Borehole Diameter	Minimal Effect.

9.3.1 Confidence in Satisfactory Operation

As mentioned in Section 5.3.2, the major limitation of the sonar probe is the absence of a highly directional transducer. The readout unit will display large targets which are not directly on the transducer axis. For this reason, interpretation of data obtained from the sonar probing system will be more difficult when the passageway is low in height, when the roof is rough, or when there are major obstructions in the passage.

When the sonar probe is "looking" down a passageway of low height, both the roof and the floor surfaces are quite close to the probe. This proximity increases the probability that some of the signal from the probe will be reflected by irregularities along the roof and floor. These reflections, if sufficiently intense, will be displayed as targets in the direct line of the transducer. This behavior will be accentuated by the degree of roughness of the roof and floor. A more detailed description of this phenomenon can be found in Section 5.4.1.

Partial obstructions of the passageway may cause similarly ambiguous readings. If, for example, there is an obstruction, such as a piece of mining equipment, in front of a rib, the readout unit will indicate targets at the appropriate distances for both the rib and the equipment. Roof falls which cover only a portion of the passageway can be expected to produce similar results. Cribs, on the other hand, produce a unique image on the display which is unmistakable.

Passageway slope and borehole angle have the same effect on the sonar system, causing the axis of the probe to be non-parallel with the plane of the passageway floor. However, for reasonable values of passageway slope and skew-angle of the borehole, this non-parallelism should have virtually no effect on the operation of the system.

Conditions like low roof, rough roof and rubble piles, while making the sonar display more difficult to interpret, should not severely restrict the utility of the system.

With the deployment system producing accurate information as to the compass heading of the remote probe, and an up-to-date mine map providing a frame of reference, the sonar operator can make an accurate assessment as to the location of the borehole and a reasonable estimate of the location and size of major obstructions in the passageway.

9.3.2 Material and Equipment Required

A complete listing of all required equipment is provided in Appendix G. The depth of the borehole is the only variable which will affect this list. With a hole deeper than the 370 feet encountered during the field testing, additional lengths of 1-1/2-inch aluminum pipe and the associated couplings will be required. An "extension cord" of the 20-5 electrical cable will also be needed.

Changes in borehole diameter might also have a minor effect on the sonar housing. The current housing has a 4-inch outside diameter. As there are no critical components inside the housing which have a dimension greater than 2 inches, the housing could be made smaller. However, the size of the borehole required will probably continue to be dictated by the needs of the sealing system and not limited by the size of the sonar housing.

9.3.3 Deployment and Task Completion Times

The major variable affecting the time required for successful operation of the system is the depth of the borehole. The time required for set-up and the time for scanning the passageway will be virtually constant for any borehole, but the time for lowering

and retrieving the probe will be a linear function of the depth of the hole. The total time for operation of the system, as a function of borehole depth, is shown in Figure 161.

Passageway irregularities which produce ambiguous readings on the display may require the operator to spend a few extra minutes to resolve some of the more questionable areas in the passageway.

9.4 Fly Ash Delivery System

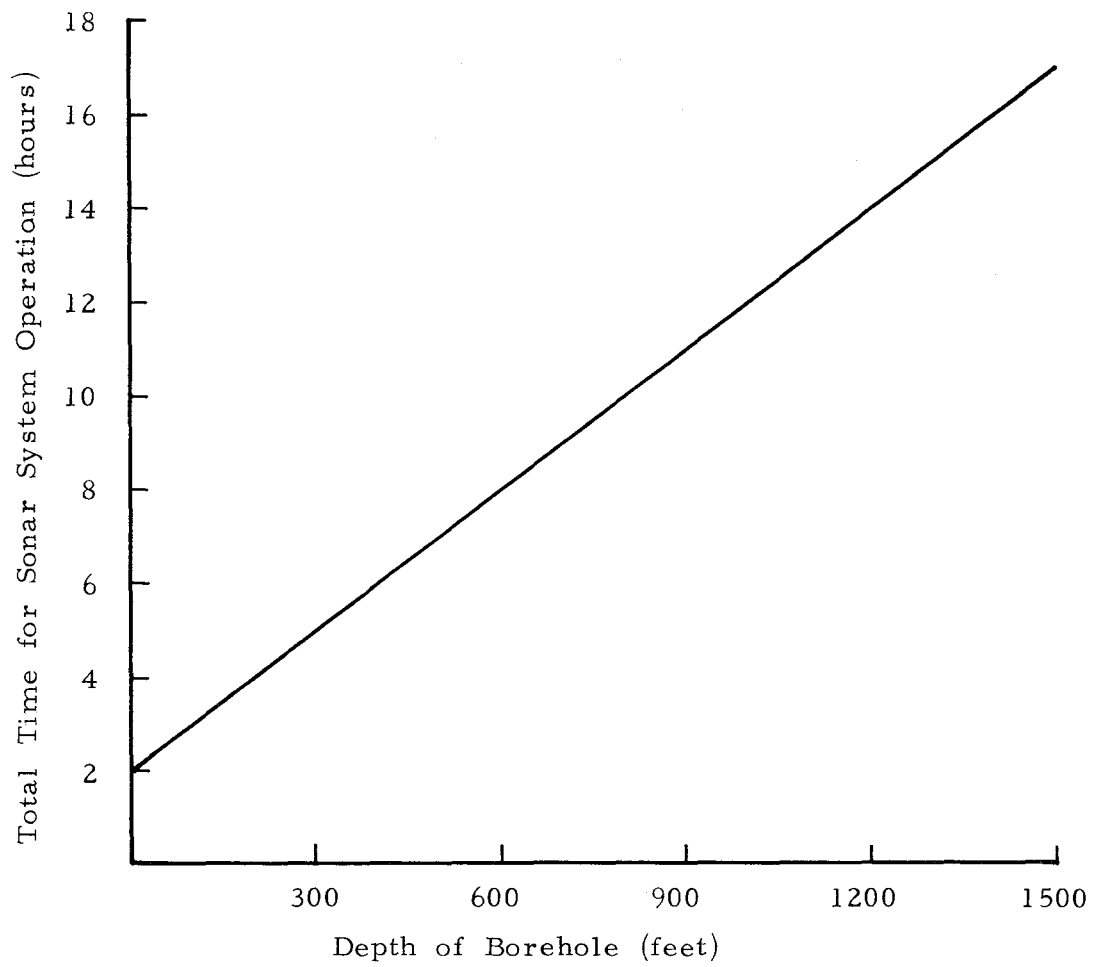
The fly ash delivery system was developed to perform effectively under a wide variety of passage and borehole conditions. The system is effective for a variety of passage geometries and slopes. Rubble piles and roof irregularities may be accommodated as may be a wide range of borehole depths and borehole positions in the passage.

Variations in the on-site parameters do alter the requirements and performance of the system. Table IX summarizes the effect of these field parameters.

9.4.1 Confidence in Successful Operation

Successful emplacement of the fly ash barrier demands a dry borehole. The properties and behavior of fly ash found desirable for this application are degraded by the addition of water. It is strongly recommended that the main borehole be carefully cased and grouted to eliminate the borehole flow.

Water flow along the passage at rates greater than 10 gpm may undermine the fly ash seal. For situations of this type, the gravel-grout system is recommended.



Total Time for Sonar System Operation
as a Function of Borehole Depth
Figure 161

TABLE IX

EFFECT OF ON-SITE VARIABLES ON FLY ASH DELIVERY SYSTEM

Parameter	Effect on Fly Ash Delivery
Passage Width	Increases in passage width increase the required blower capacity. The amount of material and time required for filling increases linearly with passage width.
Passage Height	The amount of material and time required for filling increases with the square of the passage height.
Passage Blockage	Rubble piles or other obstructions reduce the total amount of material required.
Borehole Water Flow	Reliable performance demands casing and grouting to stop water flow.
Passage Water Flow	Performance satisfactory for flows up to 10 gpm. Greater flows require gravel grout technique and cement-fly ash mix, involving increases in setup and sealing time.
Borehole Depth	Increased borehole depth increases blower pressure required. The increased backpressure reduces the truck discharge rate, slowing the filling process.
Borehole Diameter	Smaller borehole diameters increase backpressure and slow discharge rate.
Borehole Surface Location	Truck to blower distance should be minimized to reduce hose length and losses. Blower to borehole position must optimize blower position and plumbing requirements.
Borehole Location in Mine	Mid-passage is most desirable. Seal configuration less desirable when emplaced from the side.

Reduction in borehole diameter increases the flow velocity and increases the backpressure. In addition to requiring increased blower pressure, this increases the backpressure on the fly ash truck with a consequent reduction in the fly ash delivery rate and increased probability of line plugging. Decreased borehole diameters are not recommended.

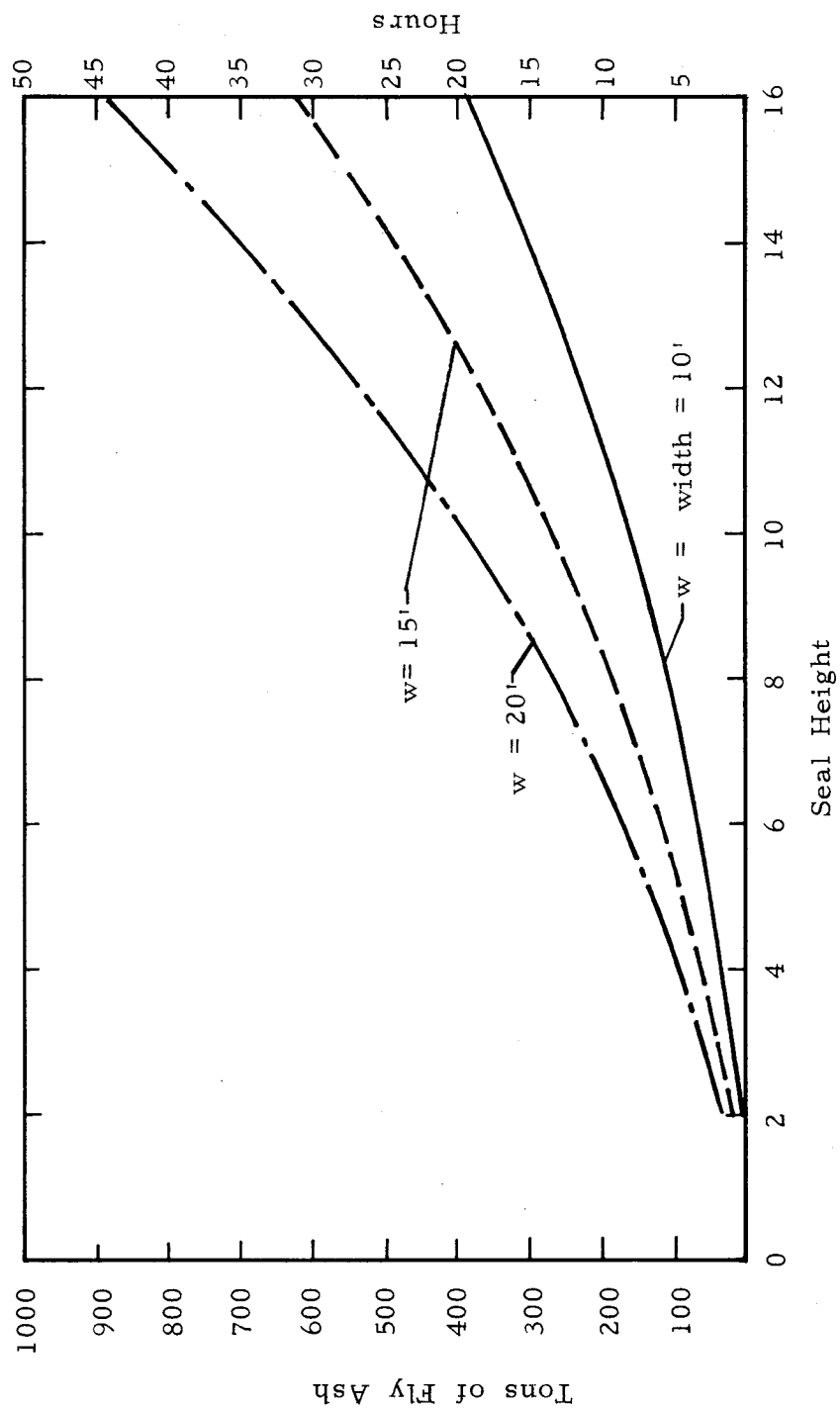
Borehole location in the mine passage affects the shape of the barrier but not its effectiveness. System confidence may be reduced if the distance from the borehole to the blower or fly ash truck is too great. Both distances should be minimized to whatever extent possible.

9.4.2 Material and Equipment Required

The amount of fly ash required depends on the passage geometry -- both width and height. The amount of material required for a 95% seal for a variety of passage geometries is shown in Figure 162. Seals of this type require foam topping using the equipment and materials of Section 8.5.4. 100% fly ash seals require additional fly ash as shown in Figure 163 but the foaming equipment is not required.

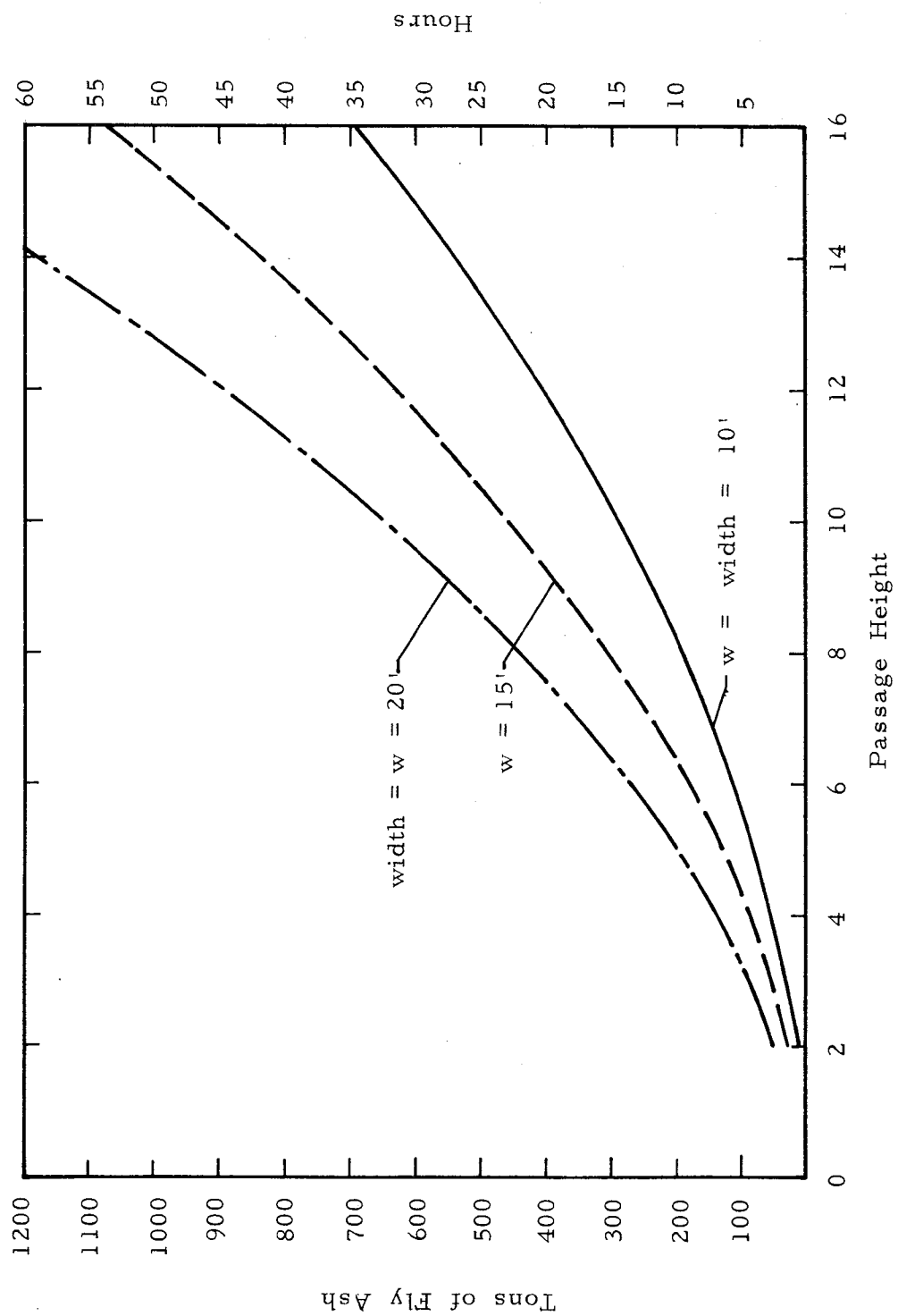
The width of the mine passage determines the blower air flow capacity, while the borehole length and the air flow rate determine the required output pressure. These requirements are presented graphically in Figures 164 and 165. Figure 164 indicates that there is considerable latitude for required crater diameter to produce a seal. Consequently the demands of the $5/2$ power scaling law can be somewhat relaxed for wide passages.

Surface conditions at the borehole dictate the hose and piping requirements. Should these become excessive, more mobile equipment will be required.



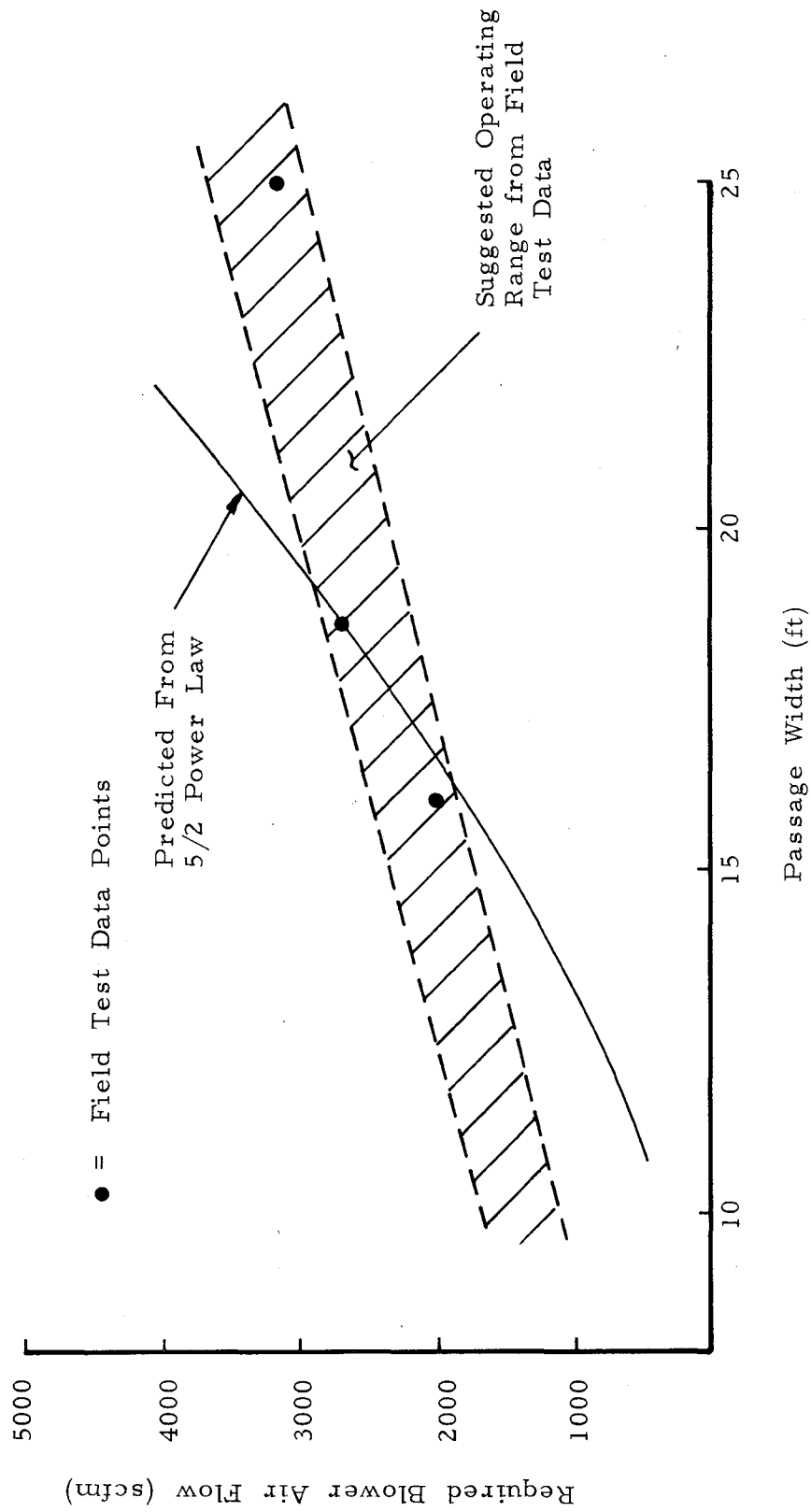
Amount of Fly Ash for 95 Percent Fly Ash Seal

Figure 162



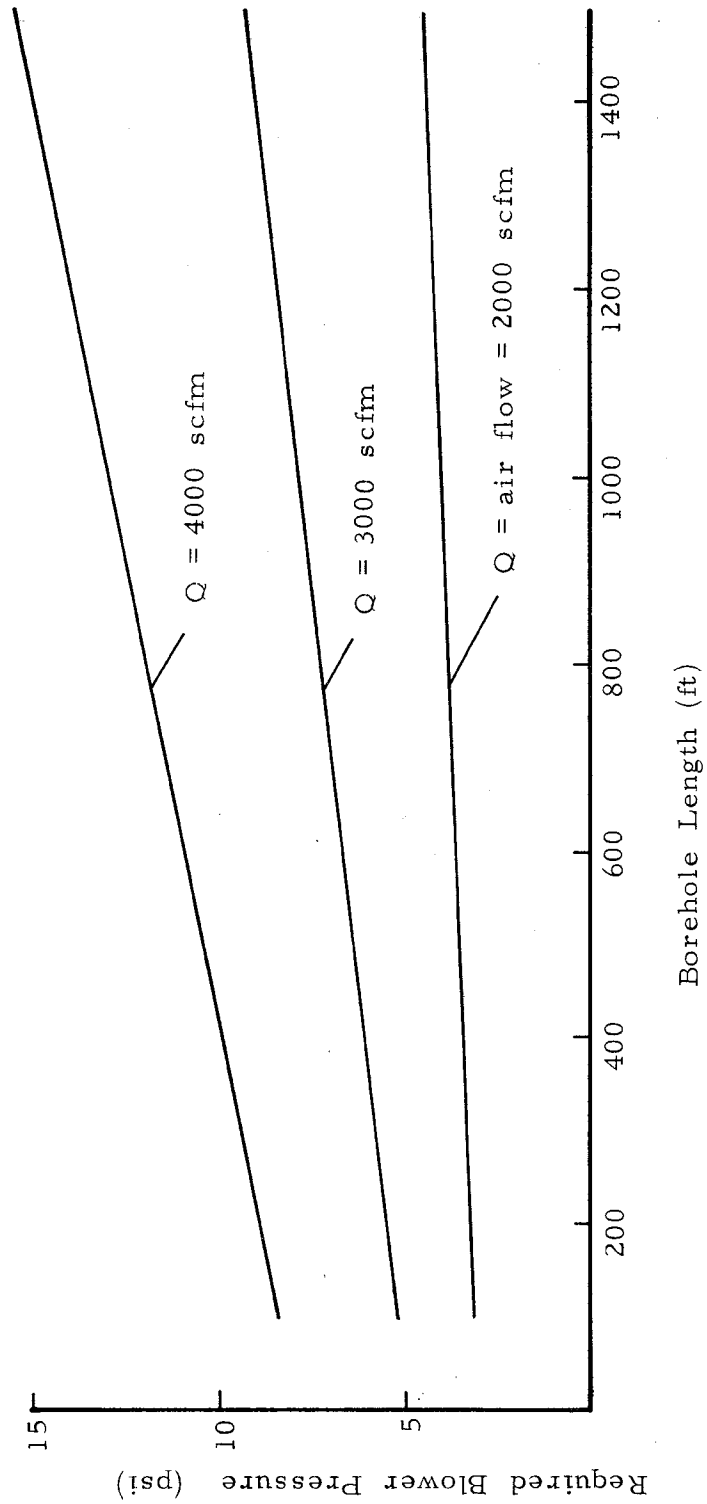
Amount of Fly Ash for 100 Percent Fly Ash Seal

Figure 163



Required Blower Air Flow for Different Passage Widths

Figure 164



Required Blower Pressure vs. Borehole Length for Different Air Flows

Figure 165

9.4.3 Setup Time

Setup time depends strongly on borehole location and surface conditions. The time required to connect from the blower to the borehole will depend on the distances and terrain involved. Short lengths of flexible hose are recommended to reduce this time.

Blower pressure, influenced by borehole length and passage dimensions, will determine the pressure differential available from the truck. This differential and the length and slope of the hose from truck to blower will determine the flyash pumping rate and the unloading time. If the anticipated unloading is very slow, the time may be better spent in setup, improving the access and moving the truck closer to the blower.

9.4.4 Completion Time

The time to complete a given seal, once setup has been completed, will depend on the total material requirement and the truck turnaround time. Turnaround time depends on pumping rate and the quality of the access.

Pumping rates vary significantly from truck to truck but are also operator influenced. Truck arrival and departure times vary with access conditions. The tradeoff between time in access preparation and time in truck maneuvering should be based on the total number of trucks anticipated to use that access. An average fly ash pumping rate of 0.3 to 0.4 tons/min with one truck and 0.6 to 0.8 tons/min with two trucks can be achieved.

9.5 Foam Topping System

In general, there are only three parameters which significantly affect the operation of the foam topping system: borehole depth, borehole diameter, and ambient temperature. Borehole depth affects the deployment and retrieval times and the type of equipment required, the borehole diameter is limited by the size of the equipment which must be deployed downhole, and ambient temperature affects the method of operation and some of the required equipment.

Passageway geometry, including size of passage, local obstructions, and position of the borehole, will have virtually no effect on the system. The froth foam flows around and over most obstructions. Based on the results of simulated full-scale testing, the quality of the seal does not appear to be affected even when the borehole is close to one rib.

Surprisingly, the amount of foam required, and the corresponding time required to generate it, is relatively insensitive to passage size for the range of sizes of interest. There are two primary reasons for this. First, fly ash fills approximately 95% of the passage, so that the final open volume requiring foam topping is quite small. The second factor which makes the required quantity of foam virtually independent of passageway geometry is the random flow pattern of the material, discussed in detail in Section 8.5.8. The froth foam channels to form discrete sections of material. Regardless of borehole location, the general geometry of the fly ash pile, or the initial flow direction, the first 3 or 4 sections created produce a 100% seal. The time required for total sealing depends only on the location of the sections; in none of the tests did this time exceed one-half hour for a seal at least ten feet thick. Longer pours merely increase the thickness of the seal.

In the ensuing section, the major characteristics of the foam topping system are discussed in terms of the on-site variables which will affect the system operation.

9.5.1 Confidence in Satisfactory Operation

As mentioned in the previous paragraphs, the froth foam topping will spread out in random directions to seal any passageway geometry in less than one-half hour. Furthermore, the acoustic seal-checker can be made available to monitor the progress of the final seal and to insure that all leakage paths have been closed off.

9.5.2 Material and Equipment Required

The foam topping system and all required equipment were discussed in Section 8.5. Three factors may affect the equipment required.

The depth of the borehole directly affects the length of hose and winch line required. Holes greater than 500 feet in depth may require redesign of the down hole components such as the hoses and pressure relief valves, because of the high pressure in the foam lines created by the large static heads.

The size of the borehole could also limit the capability of the system. The current system was designed for use in a 6-inch cased borehole. A smaller borehole would require a significant redesign of the down-hole components, possibly involving the sacrifice of some of the system capability. This is not likely as the fly ash system requires a borehole of at least 6-inch diameter.

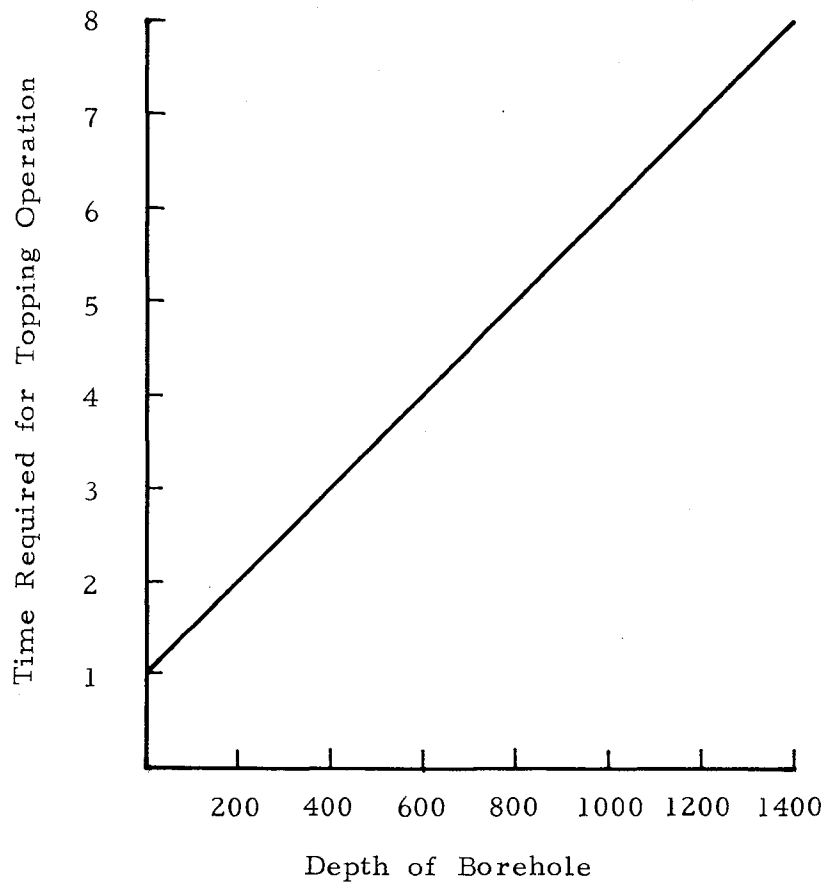
Ambient temperature has a pronounced effect on the viscosity of the two components of the foam. As mentioned in Section 8.5, temperatures below 75°F require the foam tanks be supplied with a heating system to keep the polyol and isocyanate warm. At temperatures below 30°F, additional precautions might be required to keep the deployed hoses warm also. These might include sealing the borehole at the surface to prevent the in-rush of cold air or the use of electrically-heated hose.

9.5.3 Deployment and Task Completion Times

The only parameter affecting the total time required for successful operation of the system is the depth of the borehole. This affects the time needed to raise and lower the system. Figure 166 shows the relationship between the time required and the depth of the borehole. The "constant" time of one hour includes removing the fly ash plumbing from the borehole and setting up the lowering system, as well as the actual foam-topping operation. Additional time is required for locating the foam tanks, nitrogen bottles and other equipment, but this work can be done while fly ash is being poured.

9.6 Seal Checking

The primary factors affecting the seal checking operation are borehole depth and the presence of water flow down the borehole or along the passage. Borehole depth increases the equipment and time required for deployment; longer cables, with a corresponding increase in electrical resistance, are required. Borehole water flow will markedly reduce system sensitivity if it occurs in the microphone hole since it will mask the reduced speaker signal as the seal nears completion.



Foam Topping Time

Figure 166

To a lesser extent passage blockage, passage water flows and passage dimensions affect the seal checker performance. The effect of these and other variables is summarized in Table X and discussed in the following sections.

9.6.1 Confidence in Successful Operation

The effectiveness of the acoustic seal checker would be reduced by water flow through the microphone borehole. The noise due to microphone contact and splashing on the mine floor would increase the ambient noise level and seriously reduce the sensitivity of the system by masking the reduced signal from the speakers as the seal is completed. Casing and grouting of the microphone borehole is recommended.

Water flow through the speaker borehole is not critical since the signal contribution at the microphone from the water flow gets reduced with the speaker signal as the seal is completed. An uncased speaker borehole is acceptable.

Passage water flow is not likely to create problems because the seal will dam up the water, stopping the flow and, thereby, reducing the ambient noise level.

Passage dimensions have no effect on system sensitivity, but blockage of significant portions of the passage area by rubble or machinery could result in readings which reflect larger openings than those which actually exist. This effect becomes unimportant, however, as the seal reaches completion. In general, the seal checker performance is insensitive to passage shape, size, or irregularity within the limits likely to be found in coal mines.

TABLE X

EFFECT OF ON-SITE VARIABLES ON SEAL CHECKING

Parameter	Effect on Remote-Seal Checking Operation
Passage Width Passage Height	No effect on individual seal checker reading. More readings may be taken due to additional material required to fill larger passages.
Passage Blockage	May affect sensitivity during initial pouring slightly. No significant effect on final results.
Water Flow in Borehole	Water flow down microphone borehole will reduce sensitivity by increasing the background noise level. Water flow down speaker borehole has only minor effect on system.
Water Flow Down Passage	System is sensitive to passage water flow only to the extent that the water flow increases the ambient noise level.
Borehole Depth	Borehole depth increases electrical resistance of cables and the time and equipment required for deployment.
Borehole Diameter	Microphone module could easily be adapted to smaller boreholes. Speaker system would require major redesign.

Borehole depth affects the seal checker performance by increasing the losses in the speaker cable and the microphone cable. The system has been designed to operate satisfactorily with the full 1500 feet of speaker and microphone cables. Testing with 1000 feet of cable yielded the predicted results, indicating that the operation at 1500 foot depths should be satisfactory.

9.6.2 Material and Equipment Required

Increasing borehole depths demand additional deployment poles, couplings and speaker cable for the speaker module. For the microphone module the mechanical and electrical cables need only be lengthened. Increased winch capacity may be required for the microphone module.

The increased borehole depth results in reduced power from the speakers due to input line losses and reduced signal-to-noise ratio from the microphone due to losses in the signal cable. To compensate for line losses, the speaker power may be adjusted to higher levels. To improve the microphone signal-to-noise level, the 10X setting on the preamplifier should be used.

Reduced borehole size would require only minor redesign of the microphone module. Extensive redesign of the speaker module would be required to adapt it to a smaller borehole.

9.6.3 Setup, Deployment and Retrieval Time

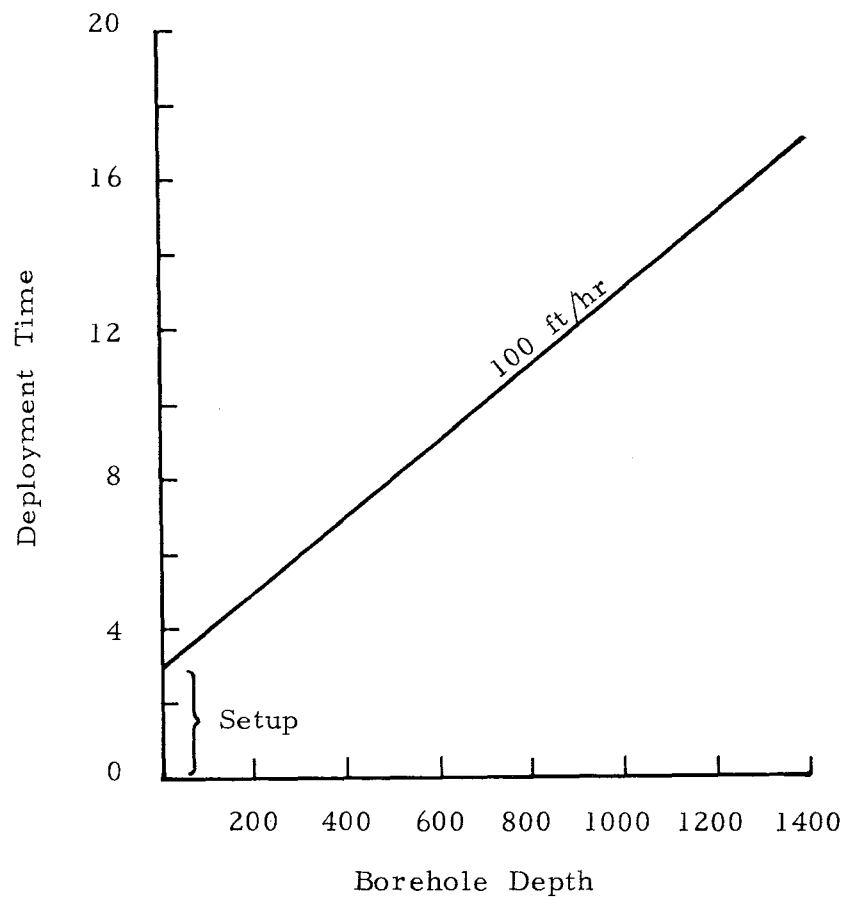
Setup, deployment and retrieval time are strongly affected by borehole depth. If borehole drilling time for the two seal checker holes is considered as setup, then the time required is also a function of borehole diameter since smaller holes may be drilled faster. Since borehole drilling and casing were discussed in Section 9.2. They will be excluded from this discussion.

Setup and deployment time for the acoustic equipment are presented in Figure 167. Setup refers to the erection of scaffolding, poles, or crane for the speaker module deployment and is independent of borehole depth. Deployment refers to lowering of the speaker module and is a function of borehole depth. No time is shown for the microphone module since its deployment is simpler and may be done during the speaker deployment.

Retrieval of the system requires approximately the same time as deployment and is similarly affected by borehole depth.

9.6.4 Task Completion Time

Because seal checker readings are taken each time fly ash trucks are changed, the total seal checking time is proportional to the volume of material pumped and, therefore, to the size of the passage. The time for each reading is independent of all parameters being evaluated. The time required to check the completeness of the seal is a very small percentage of the total sealing time and, in most cases, may be performed during the truck change so that no increase in the sealing time is required.



Time for Deployment of Speaker Module

Figure 167

9.7 Remote Seal Emplacement Time

The time required to emplace a single seal depends on the depth of the mine passage from the surface and the dimensions of the mine passage.

Passages at greater depths require deeper boreholes with considerable increases in the time required for drilling and casing. In addition, the deeper boreholes require additional deployment time for the sonar probe, for the seal checker speaker and microphone modules, and for the foam equipment, if required. The additional time and cost required for the drilling and casing operations overshadow the other effects.

Tables XI, XII, and XIII compare the required seal completion times for a variety of conditions. Considered in these tables are:

- (1) borehole depths of 100, 400 and 1500 feet;
- (2) passage dimensions of 4 x 13 feet and 7 x 20 feet;
- (3) 100% fly ash seals and 95% fly ash seals topped with foam;
- (4) the effect of multiple drill rigs.

Each table presents the information for a single borehole depth and two passage sizes. The effect of borehole depth on the drilling and casing times and the several downhole deployment operations may be determined by comparison of similar operations on the three tables. Note that the drilling and casing time for a single borehole increases from about 13 hours to 110 hours as the depth increases from 100 to 1500 feet.

The effect of multiple rigs may be determined by comparing the completion times for the 1, 2 and 3 drill rig situations presented on each table. Adding one or two drill rigs does not proportionally reduce the time before fly ash may be poured because holes drilled sequentially may be used for probing and deployment of the seal checker modules while additional holes are being completed. In general, the second drill rig provides greater incremental benefit than does the third. For boreholes of 100-foot depth the addition of a second drill rig reduces the elapsed time until fly ash is poured from 40 hours to 27 while the third drill rig further reduces it to 16-1/2 hrs. For extremely deep passages like that of Table XIII the drilling and casing times are so long that single rig drilling has not been considered.

The effect of passage size and seal type are presented for each borehole depth. The dimensions assumed for the small passage are 4-feet x 13-feet and for the large passage are 7-feet x 20-feet. From Figures 162 and 163, the small passage requires 46 tons of fly ash for a 95% seal and a total of 76 tons for a 100% fly ash seal. The large passage requires 213 tons and 343 tons, respectively. The filling times, determined using a 20 ton/hour fly ash delivery rate, are presented on the tables. The 95% fly ash seal time applies to the 100% fly ash seal and the foam topped seal. The time shown for the 100% fly ash seal is the incremental time for the last 5% seal and may be replaced by the time for the foam topped 95% seal.

The time required to pump fly ash is independent of borehole depth but a strong function of passage size. Foam topping time, on the other hand, is affected strongly by deployment time through the long borehole and only to a minor extent by the size of the passage. Consequently, foam topping is generally more attractive for large passages and shallow boreholes while 100% fly ash seals are more suitable for smaller passages of greater depths.

Tables similar to those discussed may be prepared for any combination of borehole depth and passage dimensions by using Figures 160 thru 167 to determine the appropriate times.

In general, the following conclusions may be drawn:

- (1) Multiple drill rigs are desirable in all situations. Their desirability increases in direct proportion to the borehole depth.
- (2) Foam topping is generally more attractive for large passages at shallow depths, while 100% fly ash seals are more suitable for smaller passages at greater depths.

TABLE XI
MINE PASSAGE SEALING SCHEDULE

BOREHOLE DEPTH ~100 FEET; PASSAGES: 4' x 13' and 7' x 20'

Task		Time After Start - Hours					
		10	20	30	40	50	60
1 Drill Rig	Drill Borehole No. 1	10:00					
	Drill Borehole No. 2	10:00					
Small Passage	Drill Borehole No. 3	10:00					
	Preliminary Probing	10:00					
Large Passage	Speaker Module Deployment	10:00					
	Microphone Deployment	10:00					
Small Passage	95 Percent Fly Ash Seal	10:00					
	100 Percent Fly Ash Seal	10:00					
Large Passage	Foam Topped 95 Percent Seal	10:00					
	95 Percent Fly Ash Seal	10:00					
Small Passage	100 Percent Fly Ash Seal	10:00					
	Foam Topped 95 Percent Seal	10:00					
Large Passage	95 Percent Fly Ash Seal	10:00					
	100 Percent Fly Ash Seal	10:00					
Small Passage	Foam Topped 95 Percent Seal	10:00					
	95 Percent Fly Ash Seal	10:00					
Large Passage	100 Percent Fly Ash Seal	10:00					
	Foam Topped 95 Percent Seal	10:00					
Small Passage	95 Percent Fly Ash Seal	10:00					
	100 Percent Fly Ash Seal	10:00					
Large Passage	Foam Topped 95 Percent Seal	10:00					
	95 Percent Fly Ash Seal	10:00					
Small Passage	100 Percent Fly Ash Seal	10:00					
	Foam Topped 95 Percent Seal	10:00					
Large Passage	95 Percent Fly Ash Seal	10:00					
	100 Percent Fly Ash Seal	10:00					
Small Passage	Foam Topped 95 Percent Seal	10:00					
	95 Percent Fly Ash Seal	10:00					
Large Passage	100 Percent Fly Ash Seal	10:00					
	Foam Topped 95 Percent Seal	10:00					

TABLE XII
MINE PASSAGE SEALING SCHEDULE

BOREHOLE DEPTH ~ 400 FEET; PASSAGES: 4' x 13' and 7' x 20'

Task		0	30	60	90	120
1 Drill Rig	Drill Borehole No. 1		_____			
	Drill Borehole No. 2			_____		
	Drill Borehole No. 3				_____	
Small Passage	Preliminary Probing		_____			
	Speaker Module Deployment				_____	
	Microphone Deployment					_____
Large Passage	95 Percent Fly Ash Seal				_____	
	100 Percent Fly Ash Seal				_____	
	Foam Topped 95 Percent Seal				_____	
2 Drill Rigs	95 Percent Fly Ash Seal				_____	
	100 Percent Fly Ash Seal				_____	
	Foam Topped 95 Percent Seal				_____	
Small Passage	Drill Borehole No. 1		_____			
	Drill Borehole No. 2		_____			
	Drill Borehole No. 3			_____		
Large Passage	Preliminary Probing			_____		
	Speaker Module Deployment				_____	
	Microphone Deployment					_____
3 Drill Rigs	95 Percent Fly Ash Seal				_____	
	100 Percent Fly Ash Seal				_____	
	Foam Topped 95 Percent Seal				_____	
Small Passage	Drill Borehole No. 1		_____			
	Drill Borehole No. 2		_____			
	Drill Borehole No. 3			_____		
Large Passage	Preliminary Probing			_____		
	Speaker Module Deployment				_____	
	Microphone Deployment					_____
Small Passage	95 Percent Fly Ash Seal				_____	
	100 Percent Fly Ash Seal				_____	
	Foam Topped 95 Percent Seal				_____	
Large Passage	95 Percent Fly Ash Seal				_____	
	100 Percent Fly Ash Seal				_____	
	Foam Topped 95 Percent Seal				_____	

TABLE XIII
MINE PASSAGE SEALING SCHEDULE

BOREHOLE DEPTH ~ 1500 FEET; PASSAGES: 4' x 13' and 7' x 20'

Task		Time After Start - Hours				
		60	80	100	120	140
3 Drill Rigs	Drill Borehole No. 1					
	Drill Borehole No. 2					
	Drill Borehole No. 3					
	Preliminary Probing					
	Speaker Module Deployment					
Small Passage	Microphone Deployment					
	95 Percent Fly Ash Seal					
	100 Percent Fly Ash Seal					
Large Passage	Foam Topped 95 Percent Seal					
	95 Percent Fly Ash Seal					
	100 Percent Fly Ash Seal					
	Foam Topped 95 Percent Seal					

Note: For holes of this depth, multiple drill rigs are essential

BIBLIOGRAPHY

1. Dougherty, John J., "Control of Mine Fires", Publication of the Mining Extension Service, School of Mines, Appalachian Center, West Virginia University (1969).
2. Coal Age, "Fire, Explosions and Recovery, Federal No. 1 Mine", November, 1963.
3. Nagy, et al., "Sealing a Coal Mine Passage through a Borehole: A Progress Report", U.S. B. M. Publication No. 6453, (1964).
4. Murphy, et al., "Use of Fly Ash for Remote Filling of Underground Cavities and Passageways", U.S. B. M. Publication No. 7214, (1968).
5. Pennsylvania Drilling Company, Pittsburgh, Pennsylvania. Personal Review of Equipment.
6. Industrial Hazards and Communication, Division of U.S. B. M. Personal Communication with John Murphy and Merle Bowser.
7. Instrument Technology, Inc., Borescopes and CCTV Systems for Inspections of Nuclear Reactors; Personal Communication.
8. "Public Works", July, 1972.
9. The Industrial Hazards and Communications Division of the U.S. B. M., Personal Communication regarding Cohu Model No. 2006.
10. "Bibliography on Underwater Photography and Photogrammetry", Eastman Kodak Pamphlet No. P-124.
11. Optical Properties and Visual Effects of Smoke-Stack Plumes, U.S. Department of HEW, 1967.
12. Middleton, W. E. K., "Vision Thru the Atmosphere", Univ. of Toronto Press, 1952.
13. Kodak "High Speed Infra Red" film and Singer Corporation Model T1 Silicon Vidicon TV Camera.
14. Night Vision Laboratory, Fort Belvoir, Maryland; Barnes Engineering Company, Stamford, Connecticut, Model, T-101; AGA Inc., Secaucus, New Jersey, Model, "Thermovision" 680.

15. Skiing Magazine, November 1972.
16. University of Kentucky Research project.
17. Dowell (Division of Dow Chemical) and Seismagraphic Services Corp. (Division of Raytheon), Tulsa, Oklahoma.
18. The Sensory Aids Department, Massachusetts Institute of Technology, Cambridge, Massachusetts, Personal Communication.
19. Dougherty, John J., op. cit.
20. "Sealing off Fires Underground", The Mining Engineer (Great Britain), No. 23, August 1962.
21. Nagy, et al., op. cit.
22. "Use of Gypsum Powders in the Construction of Stoppings", National Coal Board (Great Britain), 1969.
23. Murphy, et al., op. cit.
24. Nagy, et al., op. cit.
25. Laird, William, Director of Research, Eastern Gas and Fuel Associates, Coal Division, Personal Communication.
26. Halliburton Co., "New Mine Sealing Techniques for Water Pollution Abatement", Report for the Federal Water Quality Administration, (1970).
27. Layne-New York Co., Inc., "Mine Water Barrier", United States Patent No. 3,469,405 (1969).
28. Bruce, Richard, Layne-New York Co., Personal Communication.
29. Watama, Paul J., "To Save A Sinking City", Public Works February 1972.
30. Sturges, Frank C. and John H. Clark, "Fly Ash - The Answer to Mine Subsidence Protection", Coal Mining and Processing, April 1970.
31. Ackenheil, Alfred C., and Murray T. Dougherty, "Recent Developments in Grouting for Deep Mines", Journal of the Soil Mechanics and Foundations Division, ASCE, January 1970.
32. Bendenelli, Ralph, U.S. Army Corps of Engineers, Vicksburg, Miss. Personal Communication.

33. National Ash Association, Bulletin.
34. Smith, Millard, Slickbar Inc., Saugatuck, Conn. Personal Communication.
35. Heavilon, Jerry L., Dennis A. Jones, and Barton Thomas "Method for Mine Fire Control", United States Patent No. 3,421,587, (1969).
36. Magnuson, Malcolm O., and Wilbert T. Malenka "Utilization of Fly Ash for Remote Filling of Mine Voids", Proceedings of the Second Ash Utilization Symposium, U.S. Bureau of Mines Information Circular No. 8488, (1970).
37. Consolidation Coal Co., "Fly Ash Sealing Successful in Pursglove Mine Fire Area", Consol News V. 8, No. 3 (1969).
38. Nevel, A.M., Properties of Concrete, John Wiley and Sons, New York (1963).
39. Loadwick, F., "Some Factors Affecting the Flow of Concrete through Pipelines", presented at Hydrotransport 1, First International Conference on the Hydraulic Transport of Solids in Pipes, University of Warwick, England (1970).
40. Short, A. and W. Kinniburgh, Lightweight Concrete, John Wiley and Sons, New York (1963).
41. The Mearl Corporation, Roselle Park, New Jersey, Technical Bulletin FC-703A.
42. Huron Cement, Division of National Gypsum Co., Alpena, Mich. Technical Information Brochure.
43. Mr. Boland, Diebold Inc., Hamilton, Ohio, Personal Communication.
44. Universal Atlas Cement, Division of United States Steel, New York, N. Y. Technical Information Brochure.
45. Marshall, Mervin D., MSA Research Corp., Division of Mine Safety Appliances Co., Evan City, Pa. Personal Communication.
46. Lorman, William R., "Engineering Properties of Shotcrete", U.S. Naval Civil Engineering Laboratory, Port Hueneme, Calif. Technical Report R429 (1968), Also American Concrete Institute (ACI) Publication SP-14A.

47. "Placing Concrete by Pumping Methods", Report of American Concrete Institute (ACI), Committee 304, ACI Journal, May 1971.
48. Moavenzadeh, Fred, Associate Professor, Massachusetts Institute of Technology, Dept. of Civil Engineering, Materials Division, Personal Communication.
49. Watkinson, John, Union Carbide, Silicates Division, Tarrytown, New York, Personal Communication.
50. Barth, Edwin J., Asphalt-Science and Technology, Gordon and Breach, New York 1962.
51. American Cyanamid Co., "AM-9 Chemical Grout", Technical Brochure.
52. Ultrasonic Detection Handbook, Hewlett-Packard Co., Delcon Division, Mountain View, California, 1968.
53. Forbes, J. J., and Grove, G. W., "Procedure in Sealing and Unsealing Mine Fires and in Removal Operations following Mine Explosions," U.S. Dept. of the Interior Miners' Circular 36, 1948.

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APPENDIX APNEUMATIC TRANSPORT OF FLY ASH1. Introduction

Two types of pneumatic transport of fly ash are critical to the success of

- (1) Transport of fly ash from the fly ash truck to the entrance to the borehole. Depending on the surface topography, this may be horizontal, decential and ascential.
- (2) Vertical downflow of fly ash through the borehole.

All fly ash trucks have limited pressure with which they can pump the fly ash. Thus, the pressure drop in the fly ash hose will define the maximum length for pumping and consequently the maximum distance that the fly ash truck can be parked from the auxiliary blower. The same relationships describe the flow of the dilute fly ash-air mixture produced by mixing with the auxiliary air from the blower and thus define the selection of the pipe diameter. These are important considerations in the proper selection of the location of the passages to be sealed and the type of surface preparation required.

The flow characteristics of fly ash down the borehole determine the selection of the minimum borehole diameter and the blower pressure.

This appendix presents theoretical analyses of these flow regimes and summarizes the limited experimental data obtained during the field tests at Grant Town, described in Section 8.4.

The analysis for the borehole flow is presented first as it is of greater interest to the program. This is followed by a discussion of the horizontal flow.

2. Borehole Down Flow of Fluidized Fly Ash

2.1 Discussion of the Problem

The remote sealing of a coal mine with dry fly ash involves pumping a mixture of air and fly ash down a long vertical borehole. Previous experiences with fly ash sealing using the fly ash truck as the only fluidizing medium often led to premature stoppages of the operation due to borehole rejection. This rejection could occur due to one of two reasons -- either the mine passage was full or the borehole was plugged. The former condition is desirable while the latter results in improperly constructed seals. In a number of cases, it was impossible to determine which condition caused the rejection.

To better understand the borehole plugging phenomenon, a theoretical analysis of the compressible flow of the fly ash-air mixture down the borehole was conducted. Existing literature on the downflow of two-phase materials was reviewed.

There is some evidence in the literature, Zenz⁽¹⁾ and Kojabashian,⁽²⁾ to indicate that under certain conditions the dense phase gravity flow of fluidized solids down a pipe can lead to densification and plugging. Fine diameter particles are particularly susceptible to sticking especially in the presence of moisture. The actual conditions that lead to plugging are difficult to define. However, it is well established that plugging can result from densification and bridging of the material. Thus, it is the purpose of this analysis to identify those flow conditions which can lead to densification.

The flow characteristics of the mixture are a function of the air flow rate and the fly ash flow rate. Our experience with pumping fly ash during the field tests showed that the fly ash delivery from fly ash trucks is non-uniform and pulsating. Fly ash is delivered in the form of high density slugs. Though the average solids density of the mixture delivered by the truck is of the

order of 6 lbs/ft^3 , it is quite likely that the actual solids density of the slugs could be considerably higher. The bulk density of fly ash is of the order of 90 lbs/ft^3 . Any flow condition where the solids density approaches 30 to 50 percent of this value is likely to be unstable with the possible danger of bridging and plugging.

It is possible that with the past method of pumping fly ash, certain flow conditions generated slugs of fly ash having a density of the order of $30 \text{ to } 40 \text{ lbs/ft}^3$ and that such high density slugs flowing down the borehole led to borehole plugging. To avoid this possibility, the high air flow rate technique was developed during this program where the average solids density is $0.5 \text{ to } 0.7 \text{ lbs lbs/ft}^3$. With this type of flow rate, the potential for slugs of fly ash is significantly reduced and the risk of plugging practically eliminated.

2.2 Theoretical Analysis

The usual analysis for one-dimensional steady-state flow of an incompressible fluid in a duct involves three forces - pressure, gravity and friction. Because of the incompressibility of the fluid, the average velocity does not change in a constant-area duct and consequently, there are no inertia forces acting on the fluid. The usual analysis for one-dimensional steady-state flow of a gas in a duct involves pressure, friction and inertia forces. The latter are included because density changes result from pressure changes and in turn require changes in fluid velocity.

The effect of friction on the compressible adiabatic flow of a gas in a duct causes changes in the pressure and velocity and the results are

$$\frac{dp}{p} = - \frac{km^2 \left[1 + \frac{(k-1)m^2}{2} \right]}{2(1-m^2)} \quad 4f \frac{dx}{D} \quad (A-1)$$

$$\frac{dV}{V} = \frac{km^2}{2(1-m^2)} \quad 4f \frac{dx}{D} \quad (A-2)$$

$$\frac{dm}{m} = \frac{km^2}{2(1-m^2)} \left(1 + \frac{k-1}{2} m^2 \right) \quad 4f \frac{dx}{D} \quad (A-3)$$

where

- p - static pressure
- k - ratio of specific heats
- f - friction factor $= 2 \tau / \rho V^2$
- V - velocity
- D - duct diameter
- m - mach number $= V/c$
- c - sound speed, $c^2 = kRT$ (perfect gas)

Equations (A-1), (A-2), and (A-3) demonstrate that for subsonic flow ($M < 1$) the pressure decreases, and the velocity and Mach number increase in the direction of flow. For supersonic flow ($M > 1$) the opposite occurs. The Mach number always tends toward unity and when reaching that value further flow along the duct is impossible - the upstream conditions must change for flow through a longer duct.

Gas and Particle Flow

When the flowing gas also carries solid particles, then both compressibility and gravitational effects must be included in the analysis, especially if the solid flow rate is not negligible compared with the gas flow.

The basic governing equations are conservation of mass, the momentum equation, energy considerations and property relationships.

Density Relationship

If the gas and particles move at equal velocities at each and every point (i.e., the settling velocity is much lower than the flow velocity), then the solids loading in the gas, α , are the same as the mass flow ratio of solids and gas, m . The density of the mixture can then be expressed as

$$\rho = \frac{1 + \alpha}{1 + \frac{\rho_g}{\rho_s} \alpha} \quad \rho_g \equiv m \rho_s \quad (A-4)$$

For a typical case of fly ash particles in air, $\alpha \leq 60$ and $\rho_s / \rho_g \approx 2000$ so that m does not change significantly along the flow and is given approximately by

$$m \approx 1 + \alpha \quad (A-5)$$

Conservation of Mass

For flow of a particle-gas mixture in a constant area duct, the continuity equation gives

$$\rho V = \rho_1 V_1 \quad (A-6)$$

where the subscript refers to some reference conditions such as at the duct inlet. Differentiating Equation (A-6) yields

$$\frac{d\rho}{\rho} + \frac{dV}{V} = 0 \quad (A-7)$$

which yields the usual result for compressible flow in a constant area duct -- a decrease in density corresponds to an increase in velocity.

Momentum Equation

Writing Newton's Law in the direction of flow along the duct yields for steady-state one-dimensional flow

$$- dp + \left(g \rho \frac{dz}{dx} - \frac{4}{D} \tau \right) dx = \rho V dV \quad (\text{A-8})$$

where dz is the change in verticle elevation across the element dx with positive Az measured vertically downwards. For horizontal flow $dz/dx = 0$, for vertically upward flow $dz/dx = -1$ and for vertically downward flow $dz/dx = +1$.

Property relationships

For flow of a perfect gas

$$p = \rho_g RT \quad (\text{A-9})$$

Energy Equation

If the external heat transfer is zero, then the energy equation yields a relationship between the initial gas temperature, current gas temperature, initial and current particle temperatures and the gas and particle kinetic energy. In the current example of interest however, the mass flow of particles is significantly greater than the gas flow ($\alpha \approx 60$) so that heat transfer between the particles and gas will tend to maintain the gas and particle temperatures constant at the value of the initial temperature of the particles. Thus, for isothermal flow, the change in pressure and gas density may be written

$$\frac{dp}{p} = \frac{d\rho_g}{\rho_g} \quad (\text{A-10})$$

Since m in Equation (A-4) is a weak function of gas density and therefore ignored, Equation (A-10) may be written

$$\frac{dp}{p} = \frac{d\rho}{\rho} \quad (A-11)$$

For compressible fluid flow through a duct, the shear stress τ has been found experimentally to be given in terms of the friction factor f as

$$\tau \equiv f \rho_g V^2 / 2 \quad (A-12)$$

where f is a slowly varying function of the Reynolds number.

For pneumatic transport of materials, Zenz⁽¹⁾ presents a relationship to account for the increased friction due to the presence of solids. Empirically, this has been included by modifying f as

$$f_m = f \left(1 + \frac{f_p}{f} m \right) \quad (A-13)$$

where f_p is the particle friction factor and f_m is the equivalent friction factor for the mixture, and where f_p is given by another empirical correlation as

$$f_p = \frac{3 \rho_g C_D}{2 \rho_p} \frac{D}{D_p} \left(\frac{V_g - V_p}{V_p} \right)^2 \quad (A-14)$$

where $V_g - V_p$ represents the slip velocity of the particle.

For the case under consideration, this slip velocity for the fly ash particles is very small, of the order of 1 to 2 ft/sec in an average air velocity of 200 ft/sec. Thus, the value of f_p is very small and can be neglected.

Thus $f_m = f$ and Equation (A-12) can be used for the air-solids mixture. The significance of this assumption is that the presence of the particles does not increase the wall shear and the slip velocity of the particles is so small that the loss caused by interparticle friction is negligible.

Combining Equations (A-12), A-11), (A-9), (A-8), and (A-7), yields the relation

$$-\frac{dp}{p} = \frac{dV}{V} = \left(\frac{V^2 - \beta^2}{\frac{c^2}{m} - V^2} \right) \frac{2f}{mD} dx \quad (A-15)$$

$$\text{where } \beta^2 = \frac{gDm}{2f} \quad (A-16)$$

The physical significance of β^2 is the ratio of gravitational to frictional forces in the flow. When $V = \beta$, these forces are completely balanced and there is no change in pressure or air velocity down the borehole. Equation (A-16) shows that β is purely a function of the pipe and independent of the solids mass flow while the assumptions leading to Equation (A-18) show that β is indeed a function of the solids flow rate. For convenience in describing the various flow regimes, Equation (A-15) is rewritten as

$$-\frac{dp}{p} = \frac{dV}{V} = \frac{2f}{mD} \left(\frac{V + \beta}{\frac{c}{\sqrt{m}} + V} \right) \left(\frac{V - \beta}{\frac{c}{\sqrt{m}} - V} \right) dx \quad (A-17)$$

and the term $\left(\frac{V - \beta}{\frac{c}{\sqrt{m}} - V} \right)$ is defined as ζ .

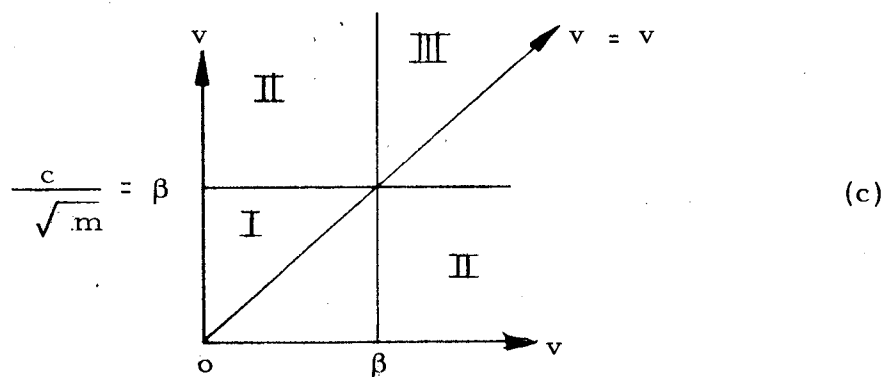
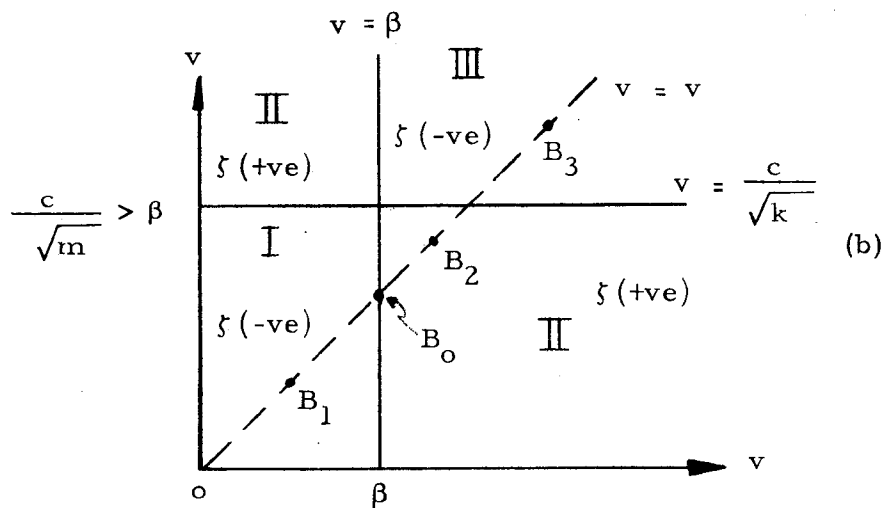
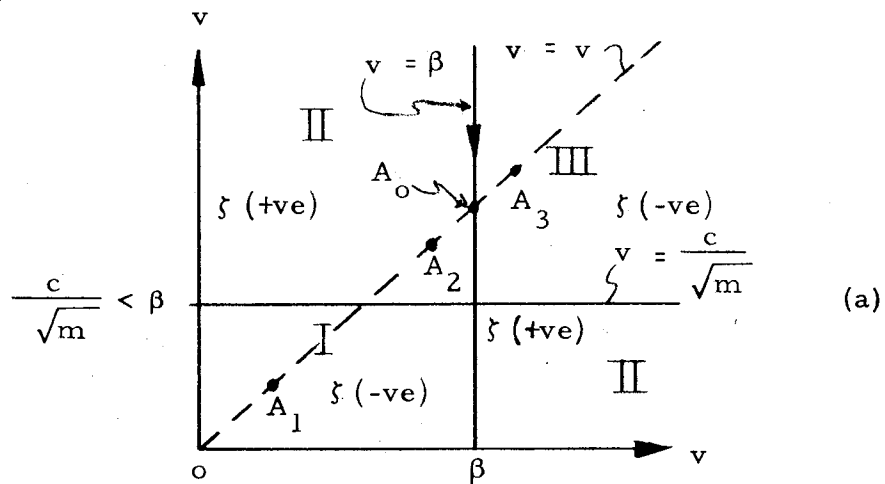
2.3 Discussion of the Various Flow Regimes

The different flow regimes are described with reference to Figure A-1. Let the velocity at a point in the duct be V . The velocity V is plotted on both the abscissa and the ordinate. Thus the velocities in the hole correspond to points on the line $V = V$, inclined at 45° to the abscissa. By drawing the lines $V = \beta$ and $V = \frac{c}{\sqrt{m}}$ the $(V - V)$ plane can be divided into four parts which correspond to three flow regimes.

Figure (a) shows the case when $\frac{c}{\sqrt{m}} < \beta$ which corresponds to very dense flow. For this case, for $V < \frac{c}{\sqrt{m}}$, such as, for example, for point A_1 , which corresponds to regime I, ζ is negative, so that the velocity will decrease down the hole. In regime II, such as for point A_2 , which for this case corresponds to $\frac{c}{\sqrt{m}} < V < \beta$, ζ is positive, so that the velocity increases down the hole. Finally, in regime III, which in this case corresponds to $V < \beta$, ζ is again negative, so that the velocity decreases down the hole.

Figure (b) shows the same diagram for the case when $\frac{c}{\sqrt{m}} > \beta$ which is typical for mine sealing. Here again, for regime I, which corresponds to $V > \beta$, and for regime III, which corresponds to $V > \frac{c}{\sqrt{m}}$, ζ is negative so that the velocity decreases down the hole (points such as B_1 and B_2). On the other hand, for regime II, for which $\beta > V > \frac{c}{\sqrt{m}}$, the velocity increases down the hole.

An interesting limiting case, corresponding to $\beta = \frac{c}{\sqrt{m}}$, is shown in Figure (c). For this special case, ζ is always negative for all values of V , so that the velocity always decreases.



Regimes in Borehole Flow

Figure A-1

Finally, from Equation (A-14) it follows that for $V = \beta$, corresponding to point A_0 in Figure (a) and point B_0 in Figure (b) dv/dx is zero, so that V is a constant down the hole.

A decrease in velocity down the borehole corresponds to an increase in density and an increase in pressure. A corresponding increase in velocity down the borehole corresponds to a decrease in density and pressure down the borehole.

Specifically, it can be stated that:

- (a) If the initial velocity V_o is less than β , the velocity decreases down the borehole accompanied by an increase in density and pressure. In this case the gravitational force exceeds the frictional force. Because of the increasing density, the possibility of plugging must be considered. The pressure at the borehole exit is atmospheric and therefore the inlet pressure is below atmospheric.
- (b) If $\beta < V_o < \frac{c}{\sqrt{m}}$, the velocity increases down the borehole accompanied by decreasing density and pressure. Plugging due to increasing density should not occur. The pressure at inlet is above atmospheric in order to match the outlet atmospheric boundary condition.
- (c) As V_o approaches $\frac{c}{\sqrt{m}}$, the rates of change with x increase rapidly corresponding to the usual choking in compressible flow.
- (d) If V_o is greater than $\frac{c}{\sqrt{m}}$, the velocity again approaches $\frac{c}{\sqrt{m}}$ and chokes. As this is supersonic-type flow, shocks may also exist. To obtain an initial value of V_o greater than $\frac{c}{\sqrt{m}}$, suitable converging-diverging nozzles must be used. This is not a useful regime in which to operate.

2.4 Borehole Pressure Drop - Vertical Downflow

The borehole pressure drop is obtained by integration of Equation (A-15) as

$$x - x_o = \frac{c^2}{2gm} \left[\ln \left(\frac{V_o^2}{V^2} \right) + \left(\frac{-m\beta^2}{c^2} - 1 \right) \ln \left(\frac{V_o^2 - \beta^2}{V^2 - \beta^2} \right) \right]$$

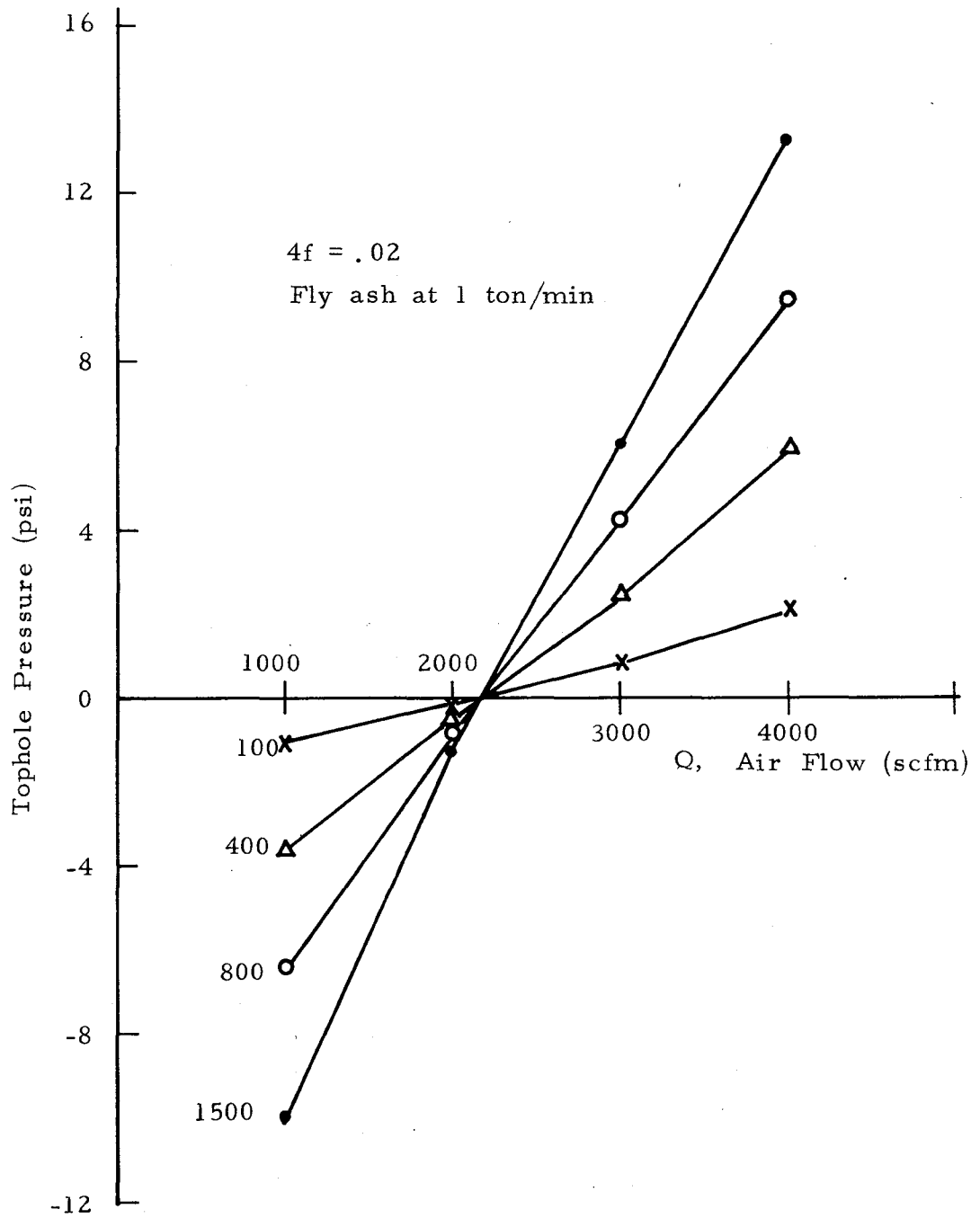
$$\beta^2 = \frac{gDm}{2f} \quad (A-18)$$

and $\frac{V}{V_o} = \frac{P_o}{P}$ for isothermal flow

where V_o and P_o are the flow velocity and pressure at the borehole inlet.

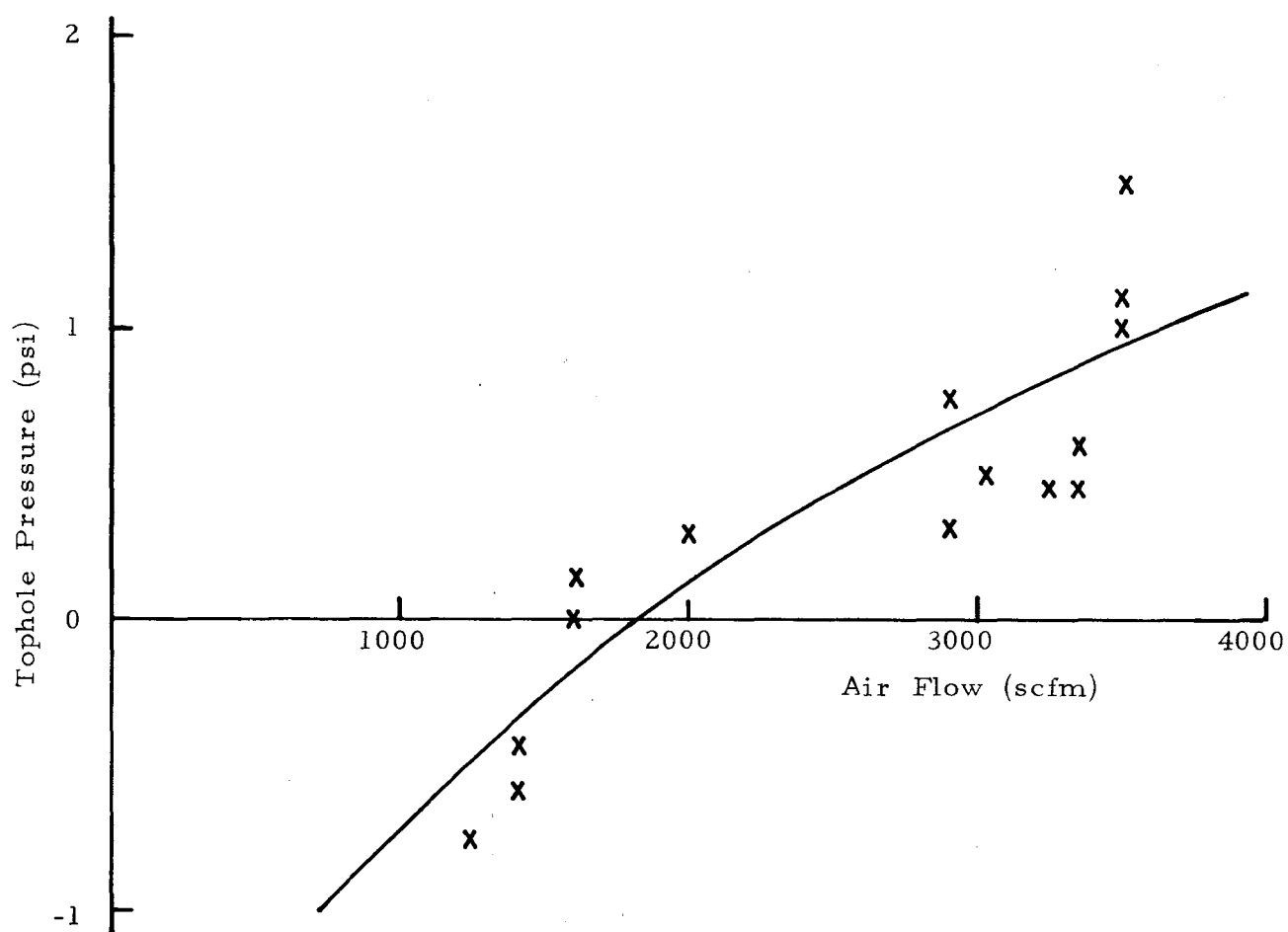
Figure A-2 shows the pressure drop as a function of air flow rate for different borehole depths ranging from 100 feet to 1500 feet. These values were calculated at a fly ash flow rate of one ton/min which roughly corresponds to the pumping rate of one fly ash truck. A value of $f = 0.005$ was assumed in the calculation. The experimentally measured values of the pressure drop are shown in Figure A-3. These values are for a 400 foot borehole and one fly ash truck unloading rate. Comparing the theoretical predictions with measured values shows that

- (1) The flow rate for zero pressure drop, of approximately 1700 scfm, shows good agreement between theory and practice.
- (2) The theoretically predicted pressure drop is higher than the measured value at flow rates greater than 1700 scfm. This indicates that the actual measured friction pressure drop is less than that predicted theoretically. The value of f used has to be reduced.



Tophole Pressure vs. Flow Rate

Figure A-2

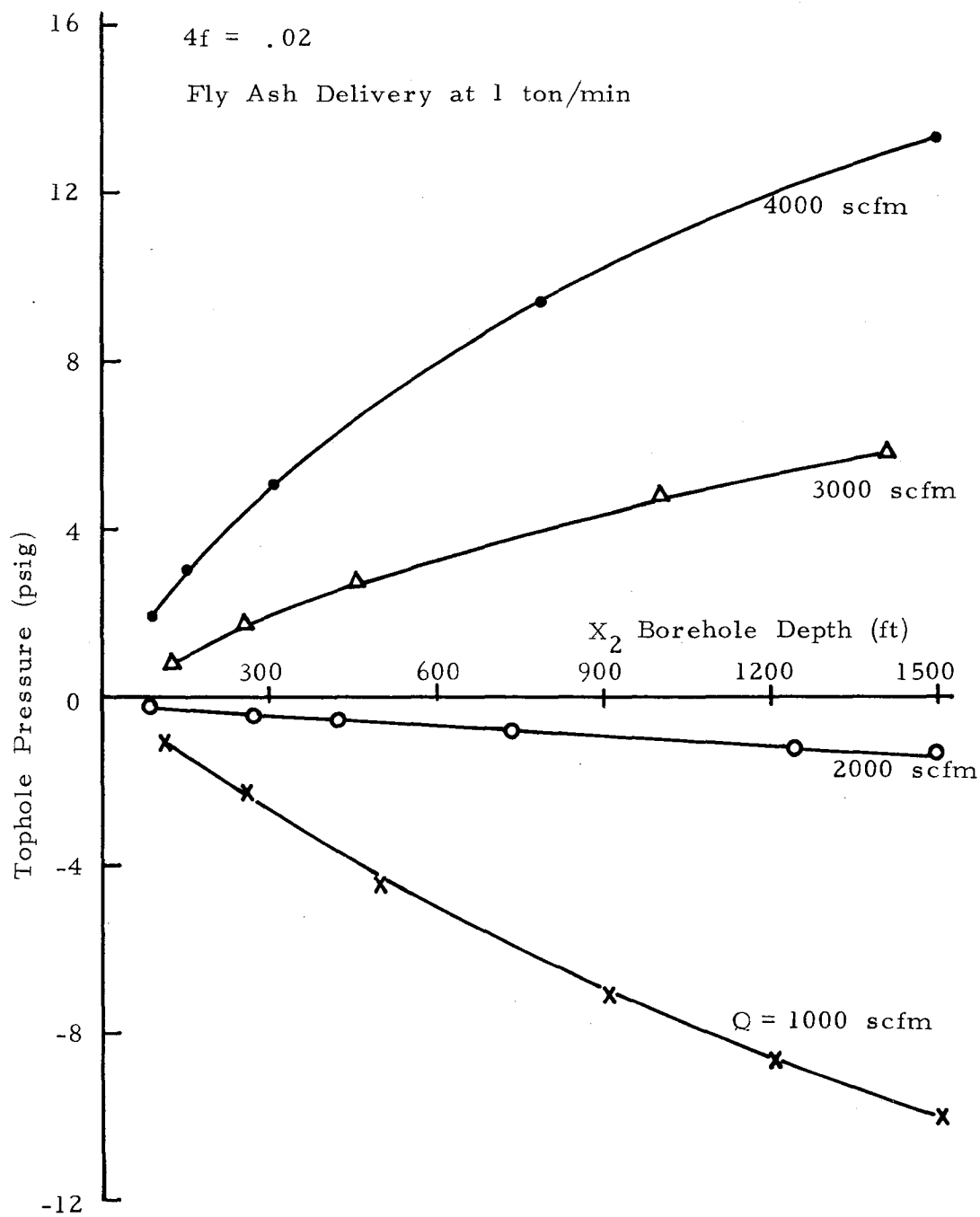


Pressure Flow Field Data for Borehole Flow of Fly Ash-Air Mixture
Figure A-3

- (3) At flow rates lower than 1700 scfm, the measured vacuum at the surface is less than that predicted theoretically indicating that the actual friction loss is greater than that predicted theoretically. Thus, the friction coefficient f has to be increased.

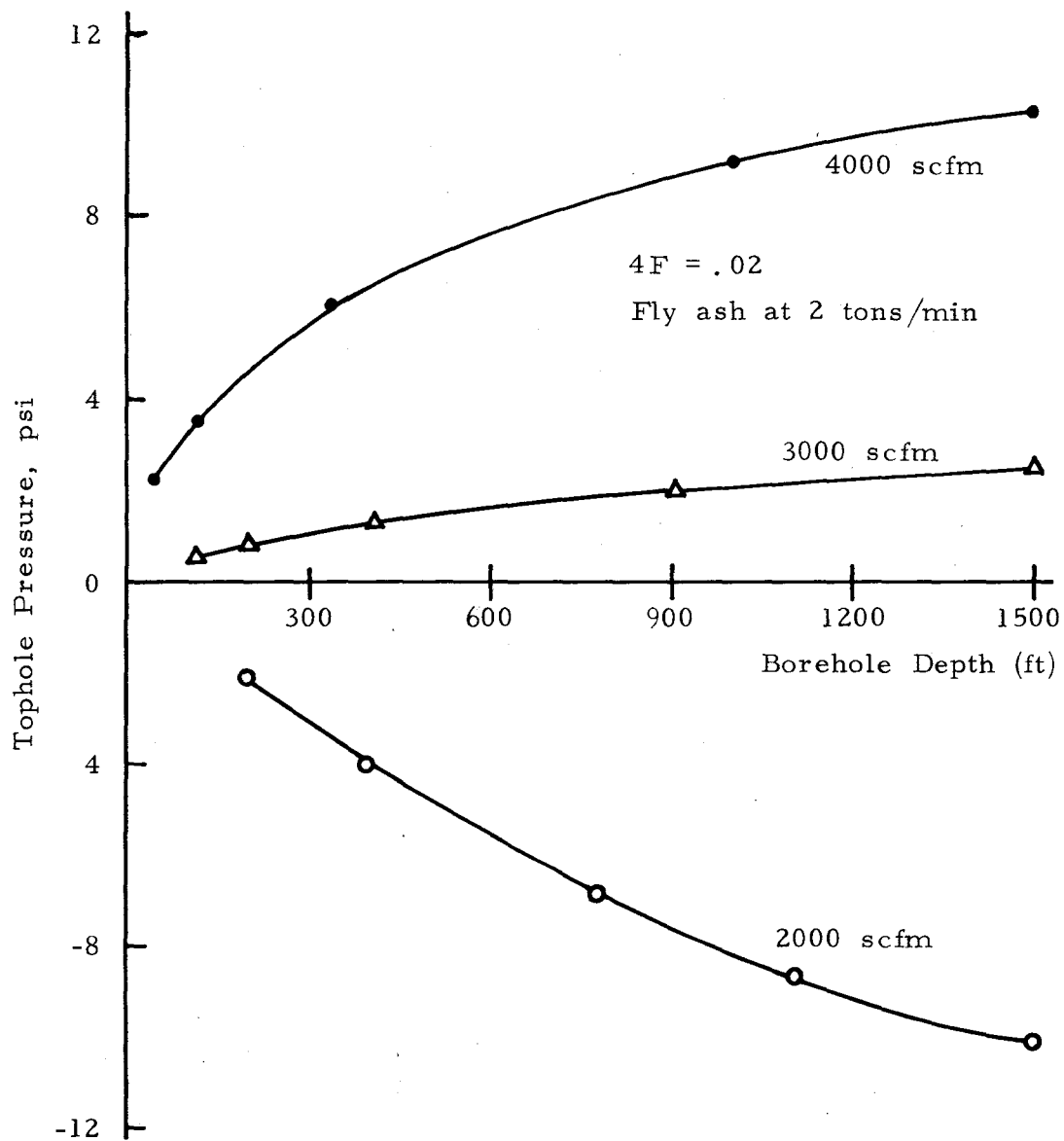
This leads to the conclusion that the theoretical predictions of pressure drop in the operating range of interest; i.e., greater than 1700 scfm are quite conservative and can be safely used for design.

Figures A-4 and A-5 show the variation of estimated borehole pressure drop with borehole depth for certain design flow rates. Figure A-4 is for one fly ash truck unloading and Figure A-5 is for two trucks unloading simultaneously.



Tophole Pressure vs. Borehole Length

Figure A-4



Tophole Pressure vs. Borehole Length

Figure A-5

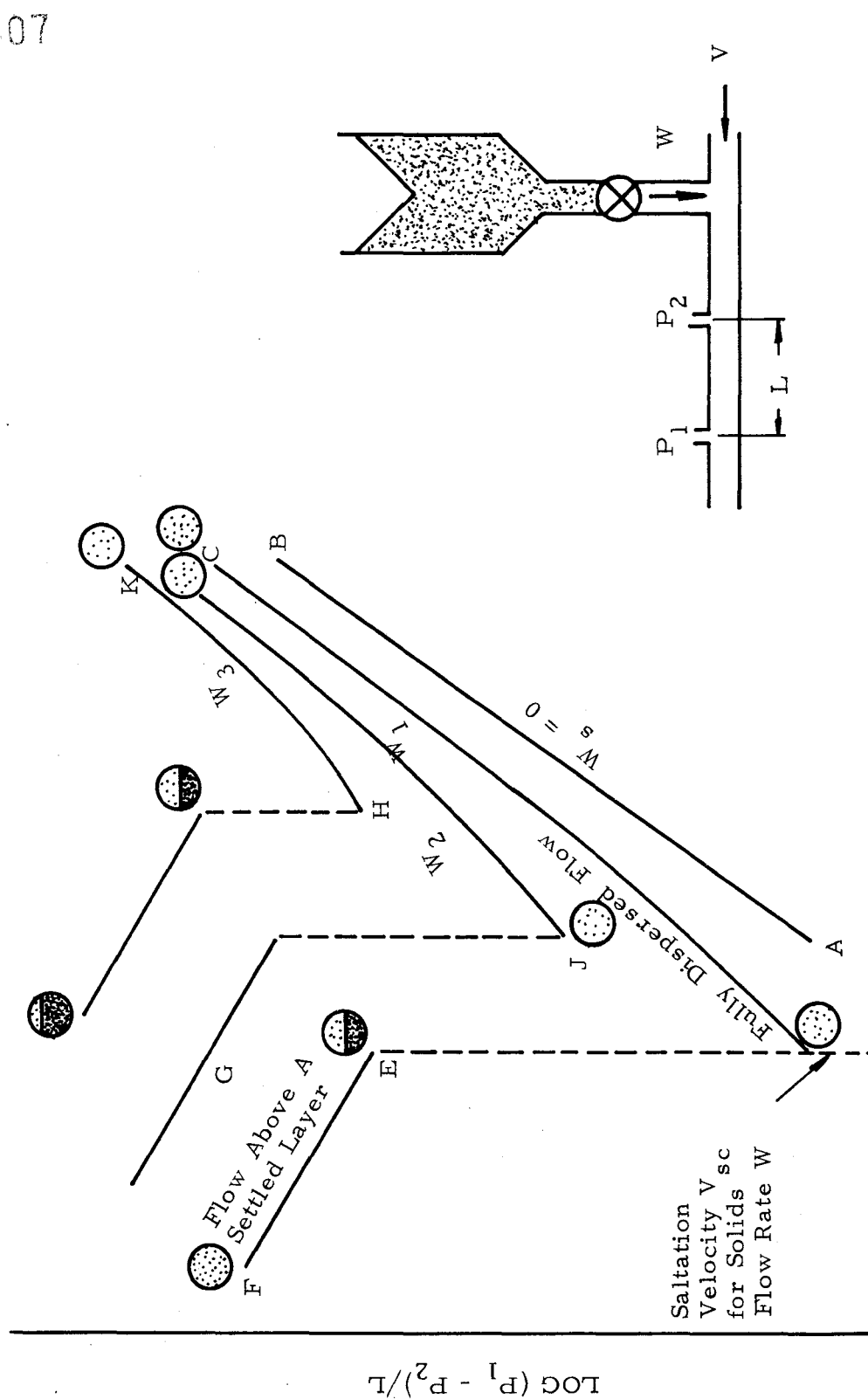
3. Horizontal Pneumatic Transport of Fly Ash in Pipes

3.1 Introduction

Except for extremely fine powders in the submicron range, particles are transported pneumatically in the form of heterogeneous mixtures by saltation where the particles move along in a series of jumps on the bottom of the pipe. These particles can either be transported in the dilute phase at a high transport velocity with particle concentrations up to five pounds per cubic foot of air, or in the dense phase at much higher concentrations and correspondingly higher pressure drops.

Due to the large pressure drops involved, dense-phase techniques have been applied only for transporting fine particles over short distances. This method has found greatest application in the process industries, being used for the transport of catalysts, separation of minerals, and heat treating of granular materials. Dense-phase flow of coarse particles is difficult to maintain; it changes rapidly into the slug type of flow with consequently much higher operating pressures and power levels.

For horizontal conveying, Figure A-6 (taken from Zenz⁽¹⁾), shows the variation of pressure drop with fluid velocity at various constant rates of transport of solids. The line AB (labelled $W_s = 0$) represents the pressure drop with air alone through the pipe. The other curves labelled CD, JI, HK represent the pressure loss variation with increasing solids transport rate. It is seen that the pressure drop increases with increasing solids. The points D, J, and H indicate the minimum velocities at which the particles can be transported in suspension and represent saturation conditions for the particular concentrations of solids. When a saturation condition is reached, settling of the particles begins. However, the transition is not uniform, and the layer builds up until a steady-state condition is again reached as shown by point E. The time interval for the transition region DE depends on the solids transport rate and the length of the pipeline.



LOG Superficial Fluid Velocity Schematic Representation of Fluid-Solids Flow Characteristics in Horizontal Transport - Zenz (1)

Figure A-6

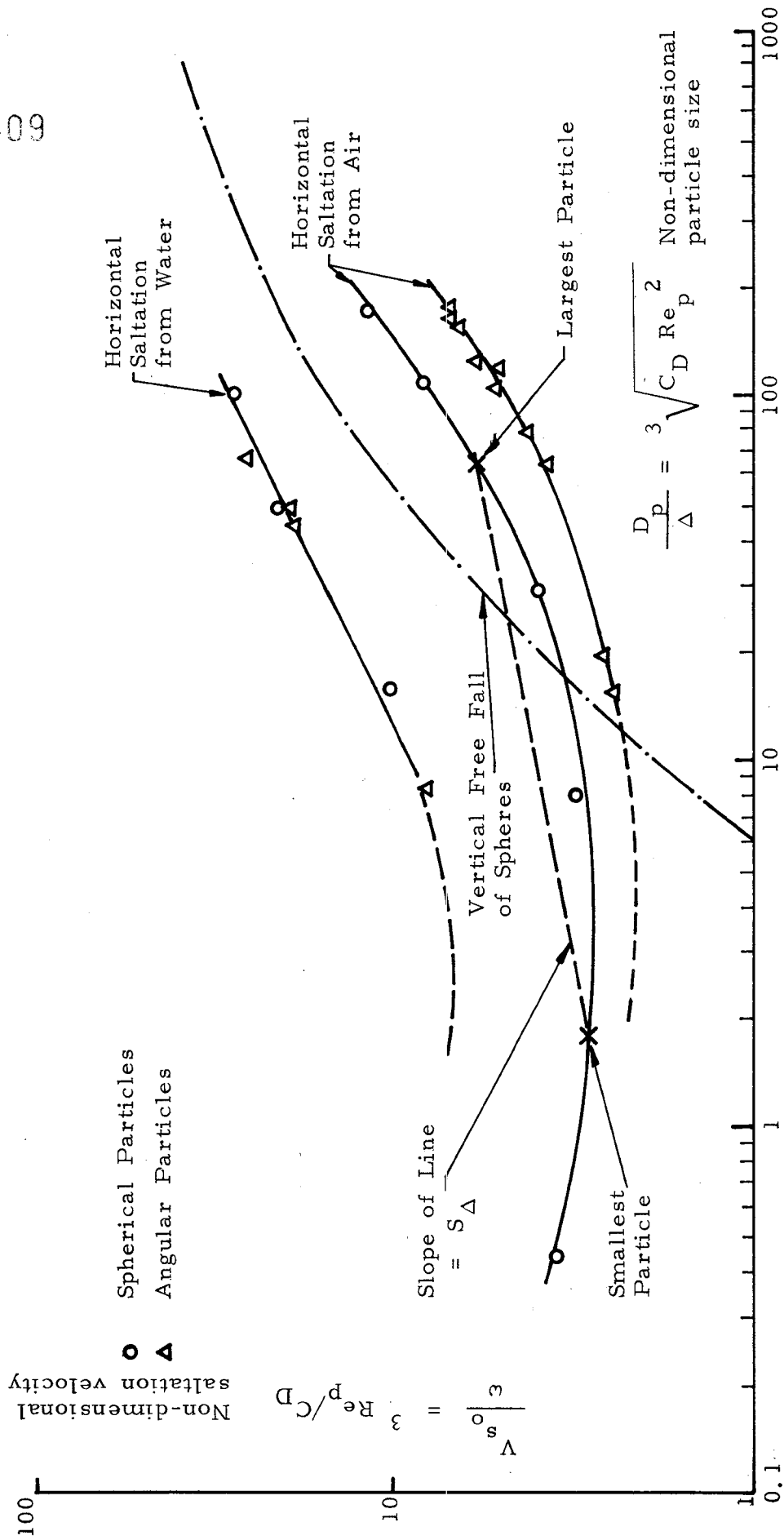
Longer pipe lengths have longer transition times. After an equilibrium layer of settled particles has been established, the flow of solids continues by suspension above the solid layer and also by way of slug flow in the solid layer itself.

In the deposit regime, an equilibrium condition exists between the fluid flow and the solids. The fluid velocity is low enough so that solids settle out at the bottom of the pipe, thereby decreasing the cross-sectional area and resulting in an increase in the fluid velocity in the obstruction region. The deposit layer builds up until a certain minimum fluid velocity is achieved which is sufficient to prevent any further settling of the particles. However, the pressure drop in this dense flow regime is substantially higher than in the dilute phase transport. Thus the phenomenon is inherently stable if the compressor or blower is capable of supplying the resulting increase in pressure drop in the transport line. Improper selection of the blower could lead to instability and total blockage. Hence, it is very important to determine the minimum velocity, since it corresponds to the most economical operating flow condition.

3.2 Minimum Velocity

The determination of this minimum velocity has been the subject of much theoretical speculation. Various empirical relationships have been put forward, but there is no one method which encompasses a large variety of particle sizes, pipe diameters, and material specific gravities. The correlation of Zenz represents the best available data for predicting the minimum velocity for pneumatic transport of small particles up to approximately 1/4-inches.

In his recent paper⁽³⁾, Zenz has put forward a correlation between the minimum velocities required for transport of solids at various degrees of loading and the single particle saltation velocity for that size of particle in the mixture most difficult to transport. Figure A-7 taken from Zenz⁽³⁾ shows the saltation velocity required for



Single-Particle Saltation Velocities in a 1 1/4-inch Inside Diameter Lucite Tube - Zenz⁽³⁾

Figure A-7

the transport of a single particle. Here, V_{s_o} is the saltation velocity in ft/sec for a single particle of diameter D_p and represents the minimum superficial velocity required to convey a single particle horizontally without it settling out and lying stagnant at the bottom of the tube. The saltation velocity and particle size are non-dimensionalized with respect to the parameters defined as:

$$\Delta = \left[\frac{3\mu_f^2}{4 g \rho_f (\rho_s - \rho_f)} \right]^{1/3} \text{ ft} \quad (\text{A-19})$$

$$\omega = \left[\frac{4 g \mu_f (\rho_s - \rho_f)}{3 \rho_f^2} \right]^{1/3} \text{ ft/sec} \quad (\text{A-20})$$

and

- D_p = particle diameter
- μ_f = fluid viscosity
- ρ_s = density of the solid
- ρ_f = density of the fluid
- R_{ep} = particle Reynolds number
- C_D = drag coefficient

The data presented in the figure indicate a minimum in the curve accounting for an anomalous effect observed in many practical conveying installations; i.e., the smallest particle is not the most easily transportable.

Zenz has found for pneumatic transport, as Durand had for hydraulic transport, that the size distribution of particles has a tremendous effect on the minimum velocity required for transport. This effect is shown by Figure A-7 where S_Δ represents a size distribution parameter. In effect, S_Δ is the slope of a curve of a single particle saltation velocity versus particle diameter as shown in Figure A-7. It can be expressed as

$$\frac{V_{s_o}}{\omega} = (\text{constant}) \left(\frac{D_p}{\Delta} \right)^{S_\Delta} \quad (\text{A-21})$$

Figure A-7 shows the experimental conveying velocities for various solids loadings as a function of the single particle saltation velocity. To a first approximation, it may be represented analytically as

$$\frac{W}{\rho_s} = 0.7 (S_\Delta)^{1.5} \frac{(V_{sc} - V_{s_o})}{V_{s_o}} \quad (\text{A-22})$$

where

W = solids mass-velocity, lb/sec x sq ft of pipe cross section

V_{sc} = minimum superficial velocity required to convey horizontally at finite rate W , without layer of solids forming at bottom of pipe, ft/sec

For application of these critical velocity data to other pipe sizes, Zenz recommends, based on findings for hydraulic transport and from other pneumatic transport data, that V_{s_o} be proportional to the square root of pipe diameter.

Typical estimates of minimum solution velocity for fly ash at the solids flow rate under consideration are in the range of 50 to 60 feet per sec. The fly ash truck delivers fly ash at an air flow rate of about 300 scfm through a 4-inch-diameter hose which corresponds to a flow velocity of about 50 ft/sec. Thus, the flow is operating just at the saltation condition which explains the slugging phenomenon observed in the tests. Dense phase pressure drop

relationships would apply. To improve the uniformity of flow, it would be preferable to increase the flow rate to an air velocity of almost 70 ft/sec. In actual practice, this is difficult to achieve because of pressure limitations on the fly-ash truck.

In the field test program, the fly ash air mixture delivered by the truck is mixed with an additional 2500 to 3500 scfm of auxiliary air. This dilute mixture is transported through an 8-inch-diameter pipe to the borehole. At this flow rate the air velocity is of the order of 120 to 150 ft/sec which is considerably higher than the saltation velocity. Thus the vertical down flow is definitely in the dilute phase.

3.3 Pipeline Pressure Drop - Horizontal Flow

Generally, dilute phase pneumatic transport operates at solid-to-air ratios of 0.5 to 5.0 lbs/lb. of air. High ratio solids-gas horizontal transport using fluidized feeders may operate at solids-gas ratios of 25 to 100 lbs/lb. or more. Empirical relationships to predict the pipe line pressure drop in these two regimes are provided.

3.3.1 Dilute Phase Transport

A number of different empirical relationships to predict pipeline pressure drop are available in the literature. One simple relation provided by Stepanoff⁽⁴⁾ and bearing some similarity to the correlation for hydraulic transport by Durand⁽⁵⁾ and Babcock⁽⁶⁾ is

$$\frac{\Delta p_m}{\Delta p_a} = (1 + m \phi) \quad (A-23)$$

where

Δp_a = friction pressure drop for air alone

Δp_m = friction pressure drop for the fly-ash air mixture

m = the ratio of the $\frac{\text{mass flow rate of solids}}{\text{mass flow rate of air}} = \frac{W_s}{W_a}$

$$\text{and } \phi = \frac{81gD}{V^2} \cdot \frac{S_s}{\sqrt{C_D}} \quad (\text{A-24})$$

D = pipe diameter

V = air velocity

C_D = drag coefficient

S_s = specific gravity of the material

The constant in Equation (A-24) is applicable to most low pressure pneumatic transport systems operating at an average air density of 0.075 lb. per ft³. It may be modified to apply to other air densities by modifying the constant of Equation (A-24)

$$81 \left(\frac{0.075}{\rho_a} \right) \text{ where } \rho_a \text{ is the air density.} \quad (\text{A-25})$$

The air pressure drop in Equation (A-23) is calculated by the normal Fanning Equation

$$\Delta p_a = \frac{4fLV^2\rho_a}{2gD} \quad (\text{A-26})$$

where

f = is the friction coefficient

L = length of pipe

D = pipe diameter

V = air velocity

ρ_a = air density

For smooth pipes f can be approximated to be about 0.005 for Reynolds number greater than 10⁵. (Typical Reynolds number in field tests of fly ash system was 10⁶.)

A plot of Equation (A-23) is given in Figure A-8 which shows the pressure drop per 100 ft of 8-inch-diameter pipe for different air flow rates and a solids flow rate of 1 ton per minute.

3.3.2 High Solids-Gas Ratio Transport

A different relationship must be used to compute the pressure drop in the 4-inch hose leading from the fly ash truck to the blower as this is dense flow.

The following empirical relation for high ratio solids-gas transport has been reported by Leva⁽⁷⁾ using the work of Wen⁽⁸⁾. In simplified form it can be written as

$$\frac{\Delta p}{L} = 2f_s \frac{G_s V_s}{gD} \quad (\text{A-27})$$

where

G_s = the solids velocity

V_s = the solids velocity

f_s = an experimental friction factor to be obtained from Figure A-9

The value of $V_s \cong 0.5 V_a$ for most of these flow conditions^().

Typical case of pumping one fly ash truck:

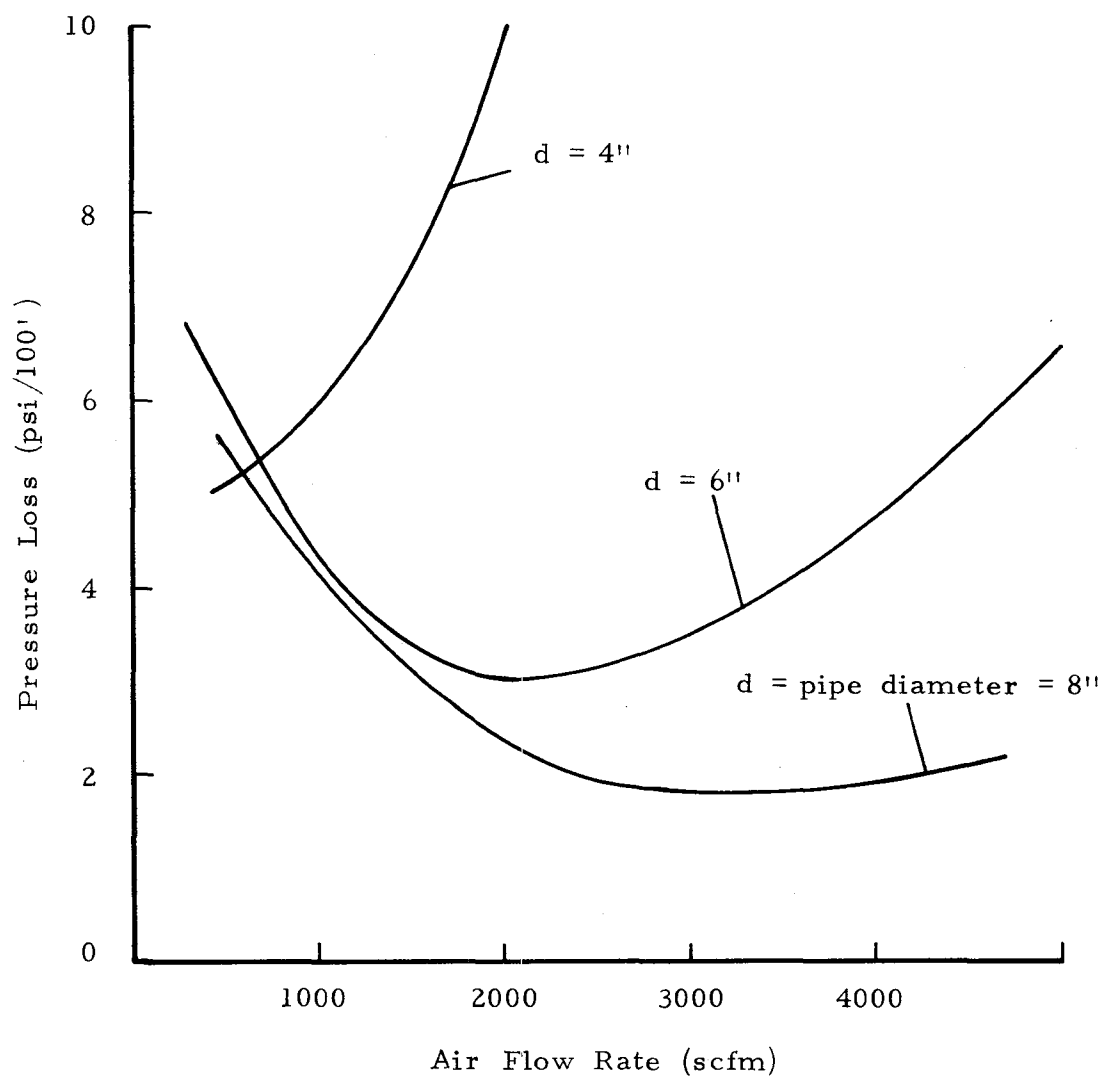
$D = 4$ inches, $Q = 300$ scfm,

$W_s = 1$ Ton/min, $V_a = 25$ ft/sec and from

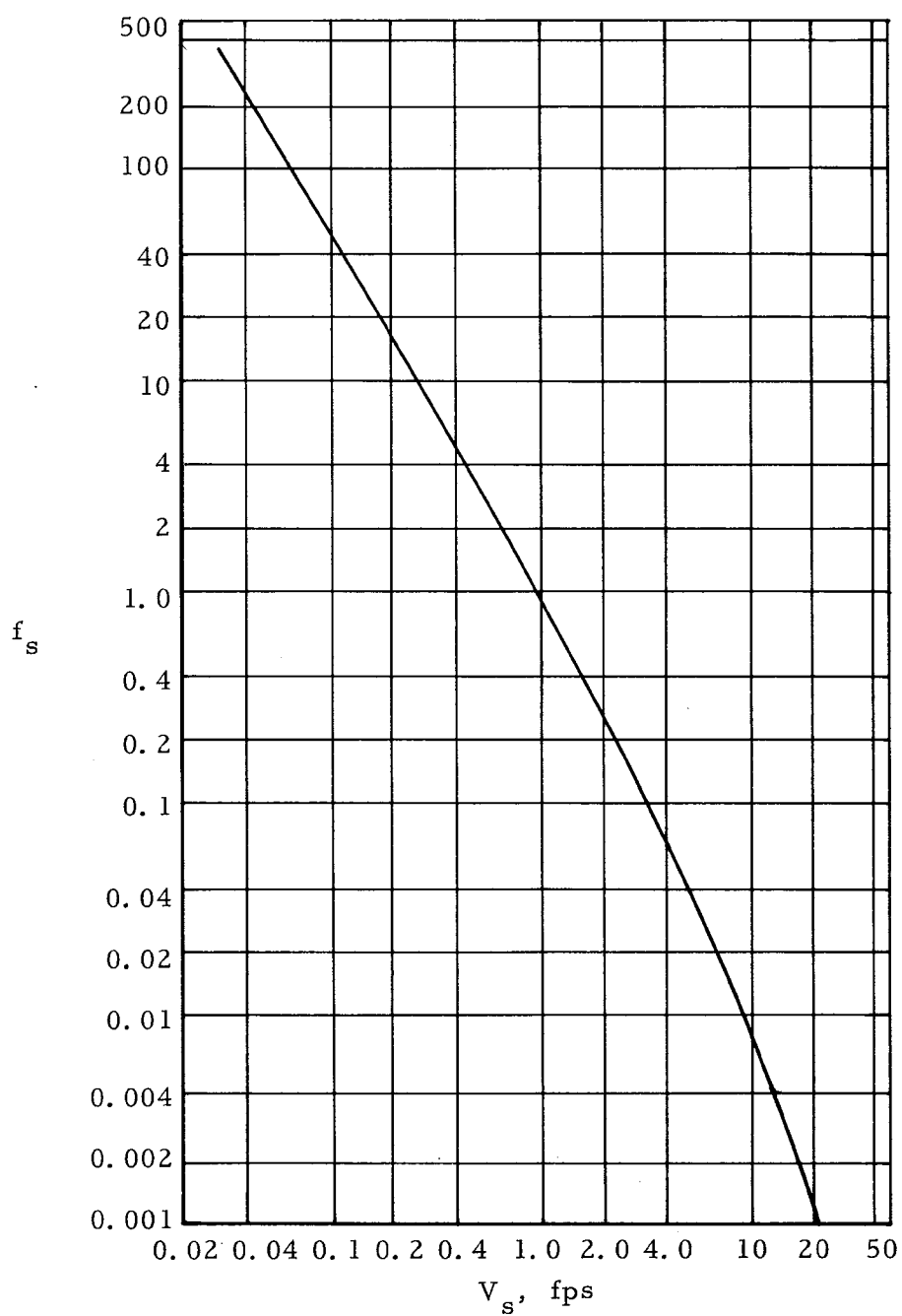
Figure A-10, $f_s = 0.001$.

$G_T = 330$ lbs/sec ft²

Using these values in Equation A-27, pressure drop of one psi per 100 ft of 4" hose is calculated.



Horizontal Flow of Fly Ash-Air Mixture
Pressure Loss per 100' vs. Air Flow Rate
Figure A-8



Correlation of Friction Factors With Particle
Velocity for High-Solids-Ratio Flow in Horizontal Pipes

Figure A-9

REFERENCES

1. Zenz, F. A. and Othmer, D. F., "Fluidization and Fluid-Particle Systems," Reinhold Publishing Corporation, New York, 1960.
2. Kojabashian, C., "Properties of Dense-Phase Fluidized Solids in Vertical Downflow," Ph.D. Thesis, MIT, 1958.
3. Zenz, F. A., "Conveyability of Materials of Mixed Particle Size," Industrial and Engineering Chemistry Fundamentals, Vol. 3, 1964, pp 65-75.
4. Stepanoff, A. J., "Pumps and Blowers -- Two Phase Flow," John Wiley Publishing Company, New York, 1965.
5. Condolios, E. and Chapus, E., "Transporting Solid Materials in Pipelines," Chemical Engineering, June 24, July 8, and 22, 1963.
6. Babcock, H. A., "The State of the Art of Transporting Solids in Pipelines," Report No. 62-1, American Institute of Chemical Engineers, National Meeting, Denver, Colorado, 1962.
7. Leva, M., "Fluidization, McGraw Hill Book Company, Inc., New York, 1959.
8. Wen, C. Y., Ph.D. Thesis, West Virginia University, 1956.

APPENDIX BDEVELOPMENT OF FOAM-CONCRETE SLURRY MINE SEALANT1. Introduction

This appendix describes the results of an experimental development and laboratory evaluation of foam-concrete as a rapid setting, lightweight, self-supporting mine sealant material.

Foam concrete, otherwise known as Aerated Concrete, is a form of lightweight concrete whose structure consists of air bubbles held together by a hardened cement mortar.

Its principal applications are found in roofing, insulation, shock absorbing, and backfill. The air bubbles in foam concrete are formed either by chemical reaction in the wet, placed mortar, or by introducing a stable foam into the mortar during mixing. The mortar is usually a cement slurry with fine sand or fly ash as filler.

Our attention focused on preformed foam concrete, since this is most adaptable to field applications. Equipment is available,* which simultaneously mixes and pumps a slurry of foam concrete. Such a slurry can be produced at a rate of up to 50 yards/hr and has been pumped in a 2-inch-diameter hose 1000-feet horizontally and 250 feet vertically up without significant bubble deterioration.

One very attractive feature associated with the use of foam concrete concerns site logistics. Foam concrete can be generated with densities as low as 20 lbs/ft³, and hence the total number of

* "Mobile Mearlcreter", The Mearl Corp., Roselle Park, N. J.
"Mason Continuous Flow System", Hoge-Warren-Zimmerman Co., Cincinnati, Ohio.

bulkhauler trucks delivering to the site would be about 1/4 of the number of trucks required for a fly ash seal of similar volume. In addition, the combined pumpability of the bulk cement truck and the continuous concrete generator would enable the truck to park as far as 1400 feet from a borehole. The fact that boreholes are frequently difficult to reach with heavy trucks gives this system a distinct logistical advantage.

The advantages of such a system are:

- (1) Water-based system which does not introduce air into the fire zone.
- (2) Potentially high angle of repose requiring less material to form seal.
- (3) Capable of developing good air- and water-tight seals - no collapse problems when supporting a high water head.
- (4) Rapid emplacement possible.

The experimental program consisted of two phases. The first phase involved testing small samples of a number of different cement and additive mixtures to determine the formulation best suited for this application. The second phase involved testing the selected formulations in simulated mine sealing situations.

The slurry system was designed to be premixed at the surface before being pumped down the borehole into the mine passage to be sealed. Consequently, the slurry set time had to be significantly longer than the time required to flow down the borehole.

By controlling the set time of the slurry, foam-concrete could be continuously placed in a mine passage and would build itself up to a complete seal. Figure B-1 illustrates the anticipated behavior. The initially-placed material would flow radially from the borehole along the mine floor until setting would stop the flow. This set material would then serve to support the ensuing material, until a pile was formed sealing the passage. The final seal would be achieved by pumping the slurry under pressure into the space between the pile and the roof.

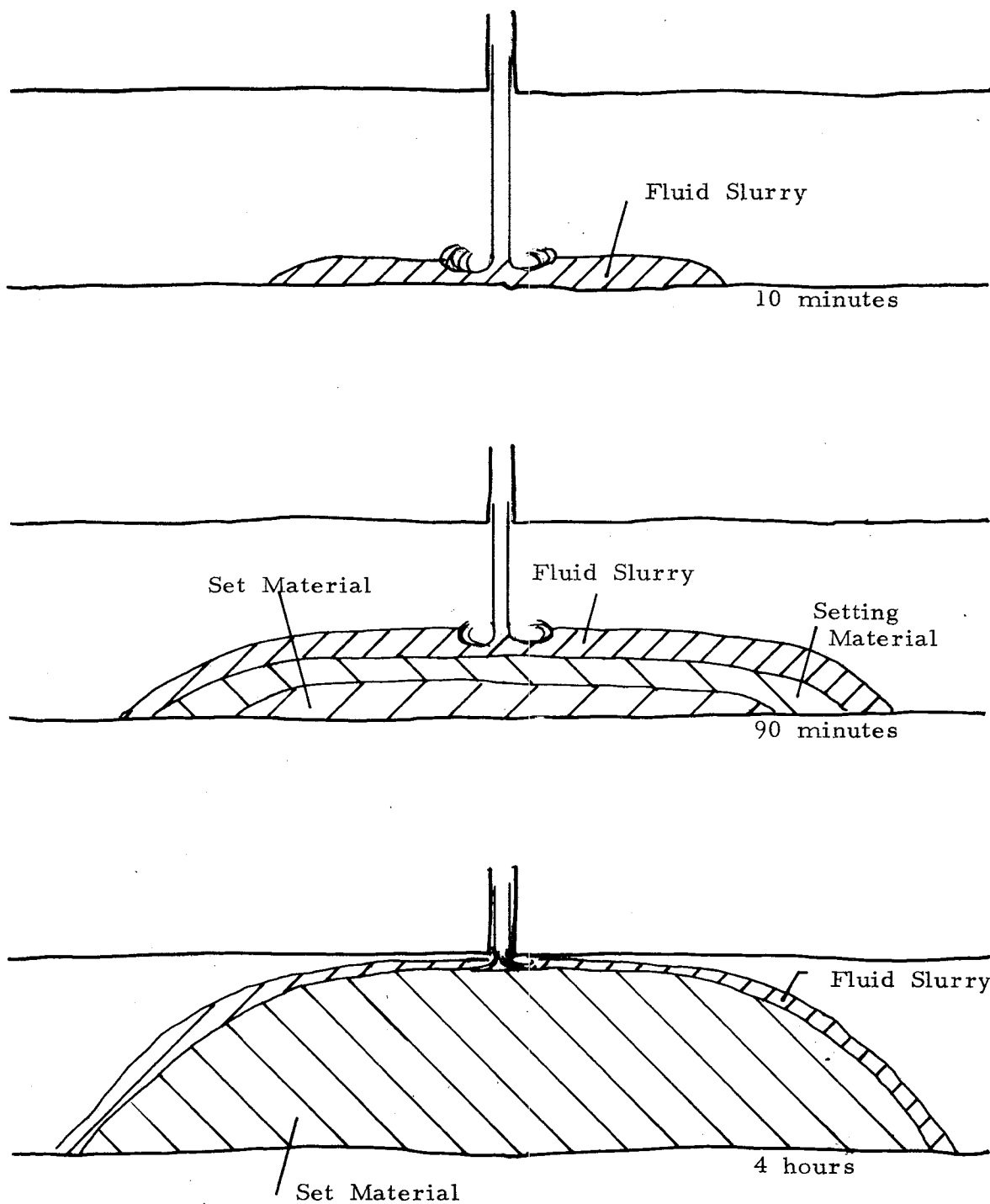
The behavior of a slurry as described above is a function of the rate of development of material shear strength. By considering the typical flow rate of about 40 yds/hr., an approximate criterion required the slurry to show significant setting (e.g., to support one foot of its own weight) in 30 minutes time. The following describes the test program.

2. Development of Slurry Formulation

Two procedures were used to measure slurry set characteristics. The ball drop test is an adaption of the Vicat needle and was considered to be more appropriate for foam concrete. It was used to measure the relative setting of different foam concrete slurries. It consisted of measuring the penetration of a hollow 20 mm diameter ball, dropped 12-inches into the slurry. (see Figure B-2). The results of this test were fairly reproducible. Once the more desirable slurry compositions had been identified through the ball drop test, direct measurement of shear strength was made using the TORVANE shown in Figure B-3. This is a pocket sized device used for making in situ shear strength measurements of cohesive soils.

Slurry set times were accelerated using CaCl_2 , NaHCO_3 , Na_2SiO_3 , Lumnite, and Gypsum Plaster as additives. Huron Regulated Set Cement and mixes containing fly ash as filler were

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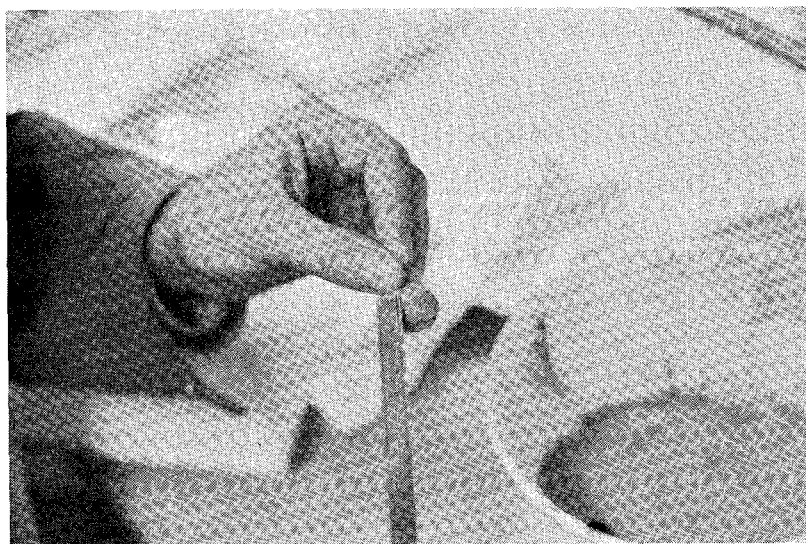


Development of a Seal with a Rapid Setting Slurry

Figure B-1



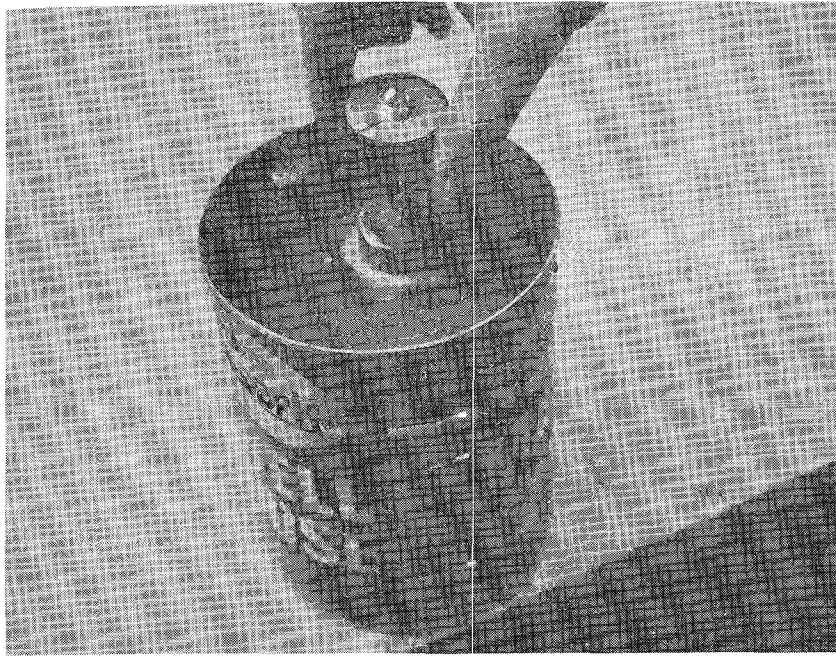
(a) Ball Being Dropped into Sample



(b) Measurement of Penetration

Ball Drop Test

Figure B-2



Measurement of Sample Shear Strength with a TORVANE

Figure B-3

also tested. Figures B-4 through B-6 show typical ball penetration and shear strength results.

Based on the test results the following slurry formulations were selected for further testing:

<u>Slurry A</u>	2 sacks cement	<u>Slurry B</u>	1 sack cement
	12 gallons water		1 50 lb bag fly ash
	4.8 cu. ft. foam		10 gallons water
	4 lbs CaCl_2		4.8 cu. ft. foam
			2 lbs NaHCO_3

The above slurries exhibited a controllable rapid set, as required. Slurries with Lumnite Cement additive and with Huron Regulated Set Cement also behaved in a desirable manner, but considerations of cost and field application led to the choice of slurries A and B above.

3. Test Simulation of Full Scale Behavior

3.1 Gravity Flow Test

3.1.1 Description of Test Facility

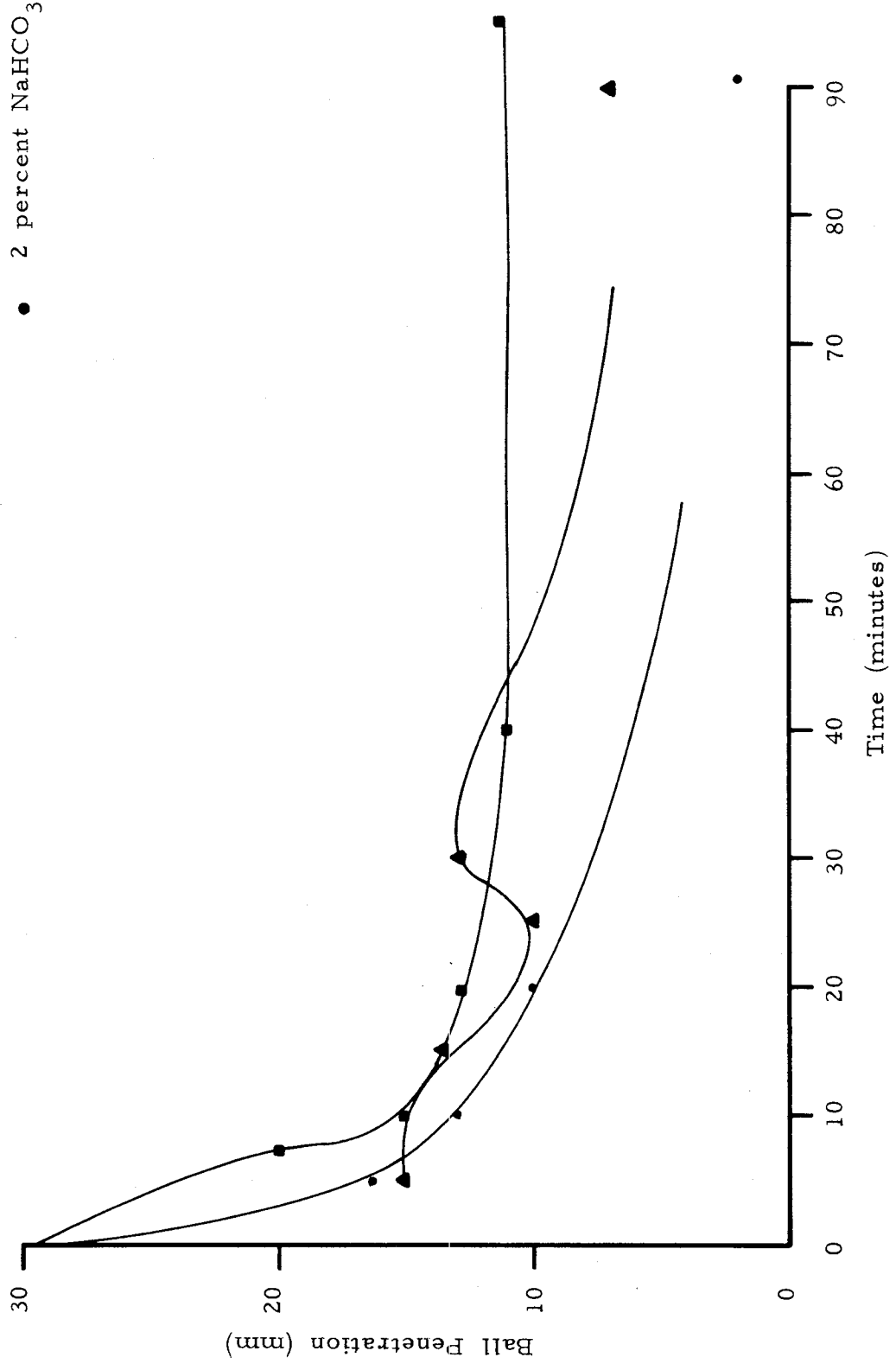
The first item of importance in testing the foam concrete slurry was to see if it would build itself up into a self-supporting pile as it was poured into a passage. To demonstrate this behavior, it was possible to separate the gravity behavior from the horizontal distribution behavior by dealing only with a thin vertical section of the total seal shown in Figure B-7. The symmetry of the sealing process allowed for the treatment of half of such a section. The actual test facility was a thin rectangular box, 20' x 6' x 9". The slurry was introduced at one end, and the vertical buildup during continuous pouring was observed.

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Additives: Percent by weight of cement

Basic Mix: 250 g Cement (Type 1)
 125 g Water
 390 ml Foam

- ▲ 2 percent CaCl_2
- 2 percent Na_2SiO_3
- 2 percent NaHCO_3

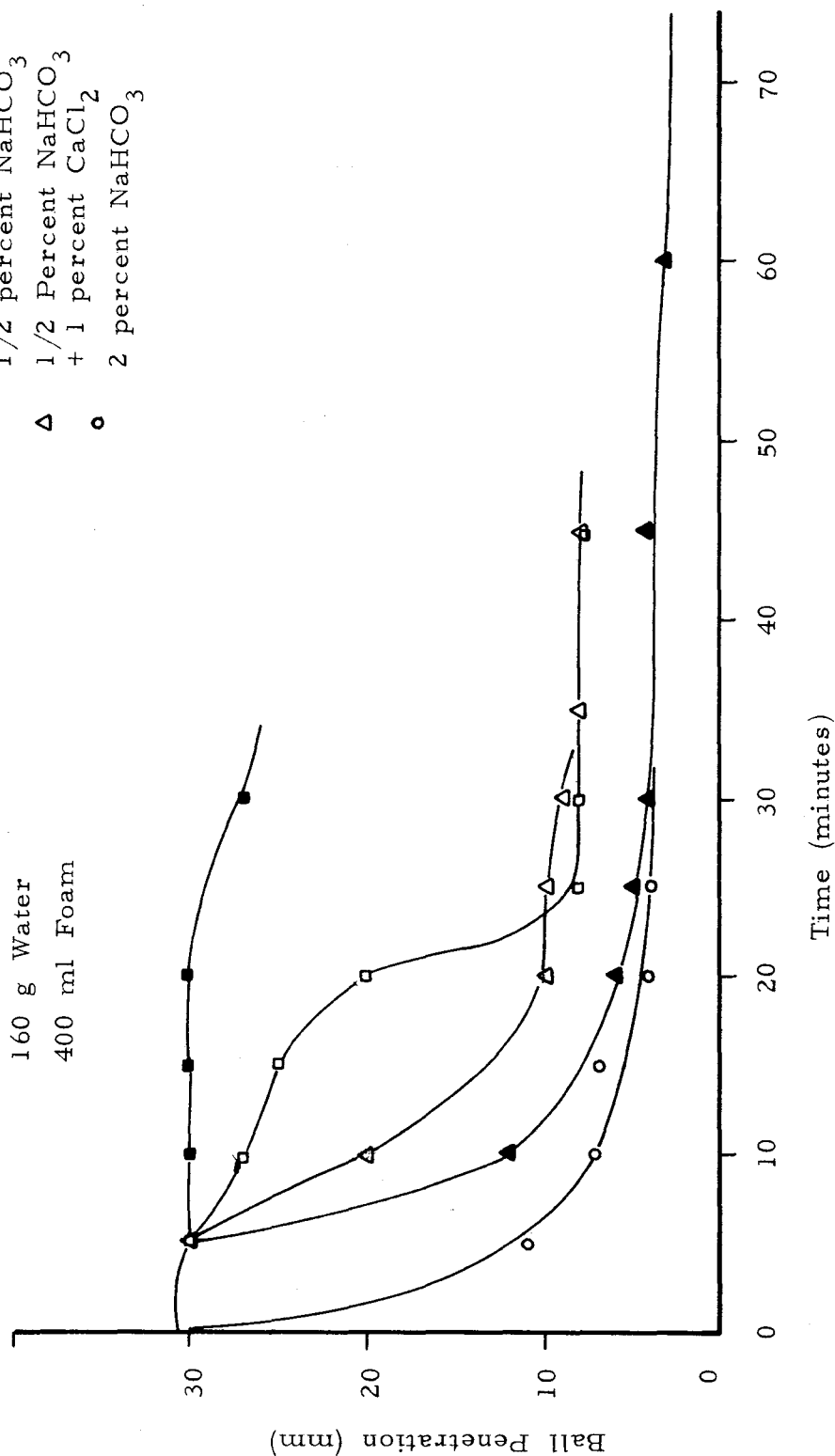


Ball Penetration vs. Time for Some Typical Test Mixes

Figure B-4

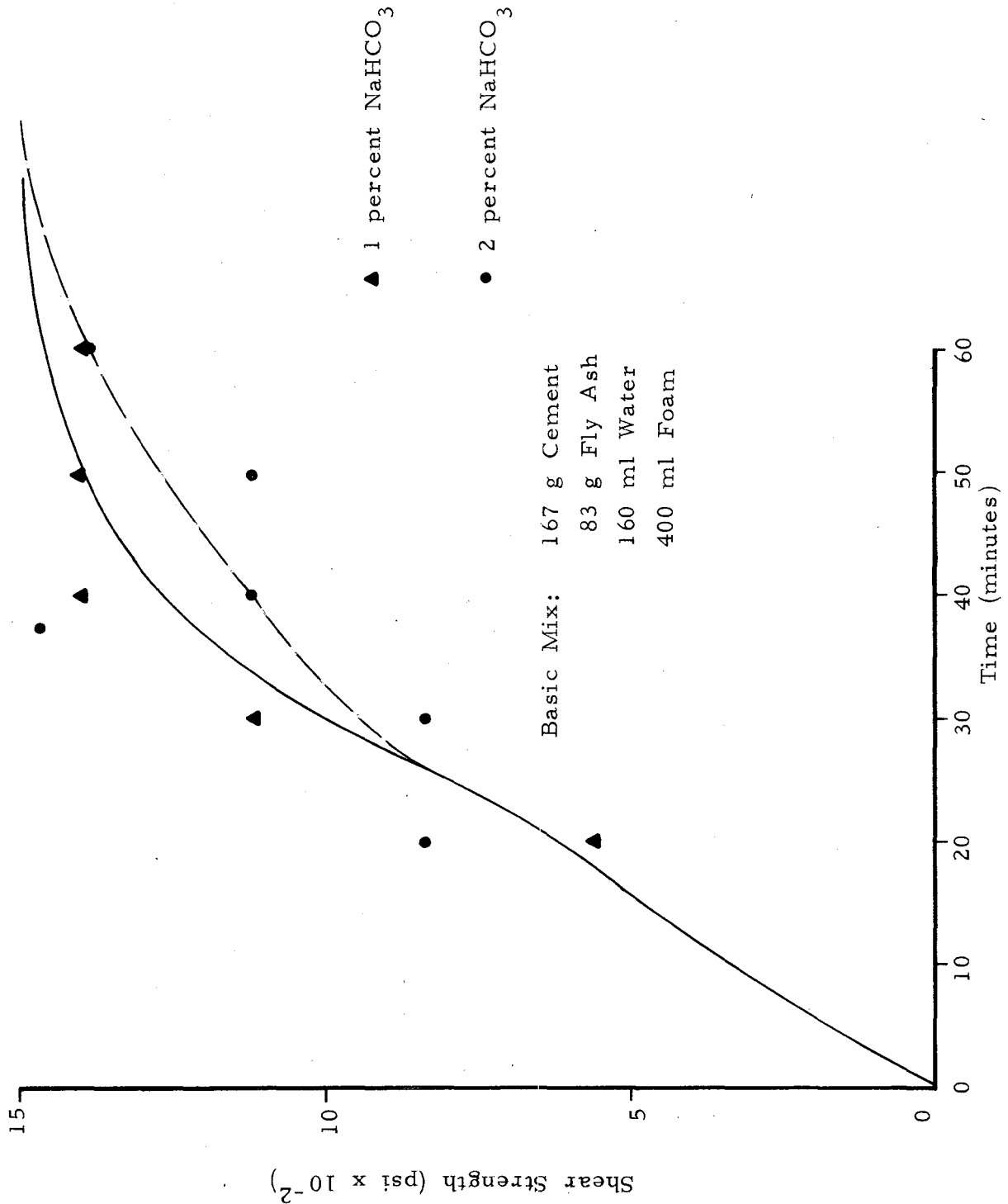
Additives: Percent by weight of cement
 ▲ 1 percent NaHCO_3
 ■ 2 percent CaCl_2
 □ 1/2 percent NaHCO_3
 △ 1/2 Percent NaHCO_3
 ○ + 1 percent CaCl_2
 ○ 2 percent NaHCO_3

Basic Mix: 167 g Cement (type 1)
 83 g Fly Ash
 160 g Water
 400 ml Foam



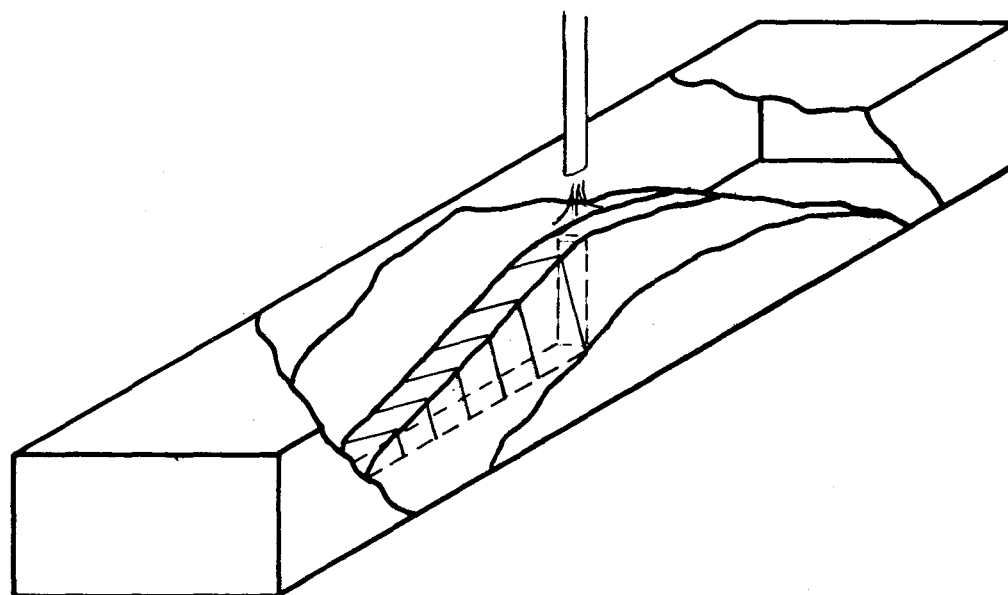
Ball Penetration vs. Time for Some Typical Test Mixes

Figure B-5

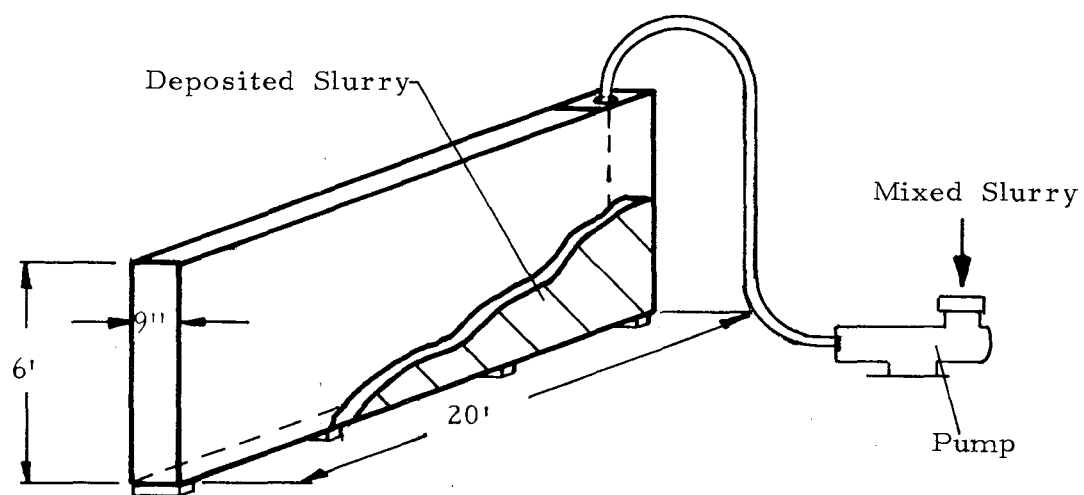


Shear Strength vs. Time for an Accelerated Set Foam Concrete Mix

Figure B-6



(a) Thin Vertical Section of a Foam Concrete Seal



(b) Gravity Flow Test Facility

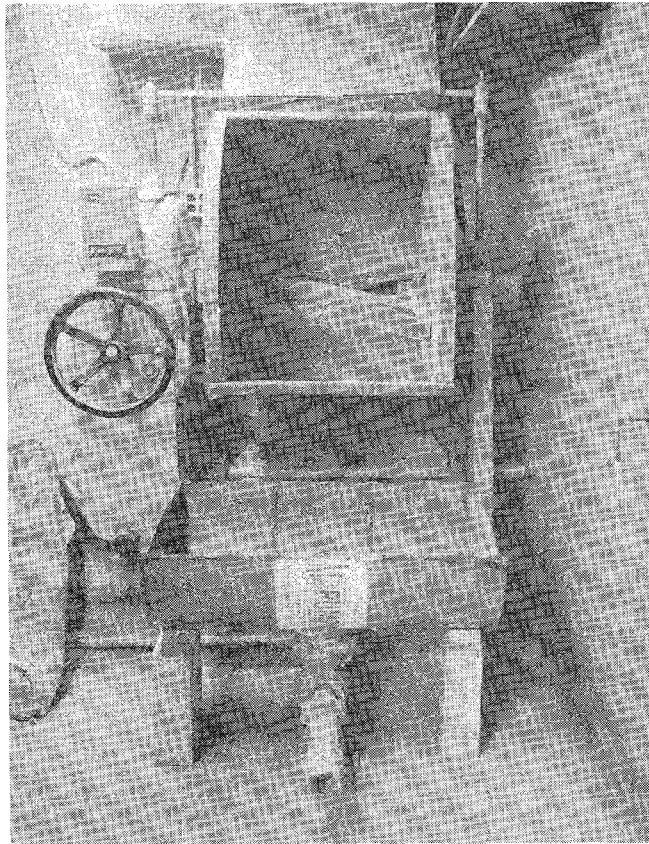
Gravity Flow Test

Figure B-7

Figure B-8 shows the mixing and pumping arrangement used. The slurry was mixed in a 12 cu. ft. blade mixer shown. The mixed slurry was poured into the hopper and pumped from there through 50 ft. of 1 1/4" I. D. hose by a Moyno 4L2 pump. During the pumping, a new batch was mixed, so that the pumping was continuous.

The 9-inch wide test facility was assumed to represent a 1/20 section of a 15 foot wide mine passage. This, coupled with the use of symmetry, indicated that the material flow rate should be 1/40 of 40 yds./hr. used in the field, or approximately 3 gallons/min.

The most significant problem encountered in the testing was in this scaled down continuous mixing and pumping operation. In a field operation the residence time of the slurry in the mixer is no more than 2 minutes. This is small enough so that its influence on the setting of the slurry is insignificant. In the lab we dealt with sack quantities of cement (and fly ash). Batches were about 7 cu. ft., and consequently, the residence time of the slurry in the hopper was about 15 minutes. Considerable amount of setting took place during this time. The set slurry was then broken down during pumping, resulting in clogged hoses, foam breakdown due to friction, and a resulting slurry which had lost its favorable setting characteristics. This problem was somewhat alleviated by introducing a solution of rapid setting additive, at a controlled rate, at the pump inlet. This procedure produced better results. However, problems were encountered in making sodium bicarbonate solutions and in creating a uniform mixture of slurry and additive solutions.



Mixing and Pumping Arrangement for
Foam Concrete Slurry
Figure B-8

3.1.2 Test Results

3.1.2.1 Slurry A

The results of the first test with the CaCl_2 slurry are sketched in Figure B-9. Due to a defective camera, most of the photos of this test were out of focus. The basic result of interest was the formation of a terraced pile.

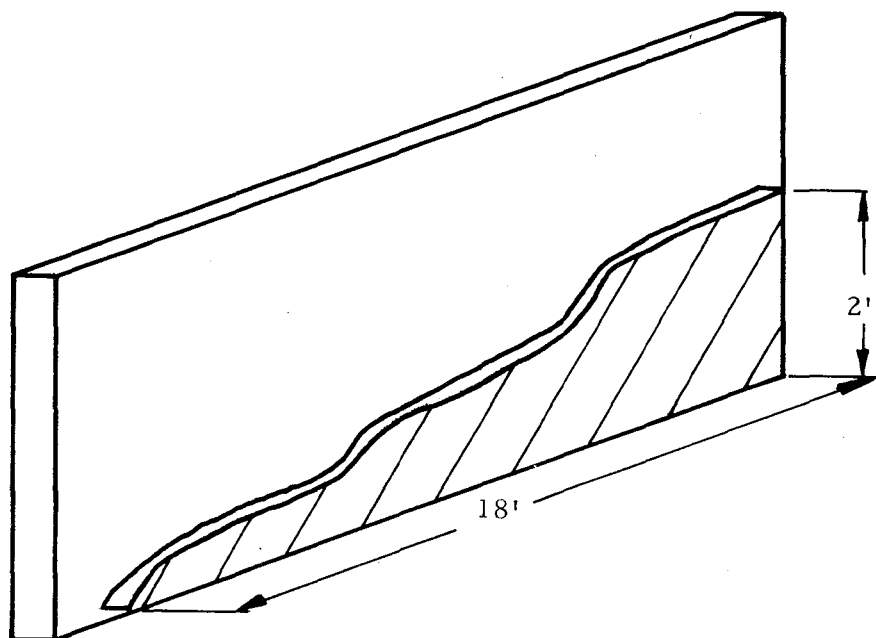
The slope of the pile, i.e., the ratio of height to length, was about 7° , which was considered to be insufficient. It should be noted that in this test the rapid set solution was added during mixing, and, hence the setting properties of the slurry deteriorated during pumping.

3.1.2.2 Slurry B

Figure B-10 shows the results of the test for slurry B. The slope of the first 3 feet of the layered profile was very small due to insufficient NaHCO_3 and excessive total mixing water. These quantities were changed to the proportions described as mix B, and the results identifiable as the top layer were obtained. The maximum slope here was about 45° , and the results were considered desirable for a self-supporting slurry.

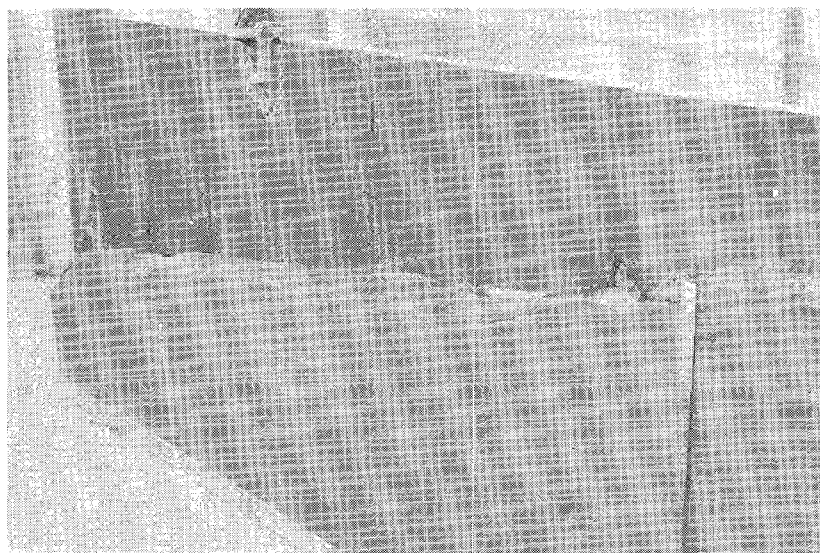
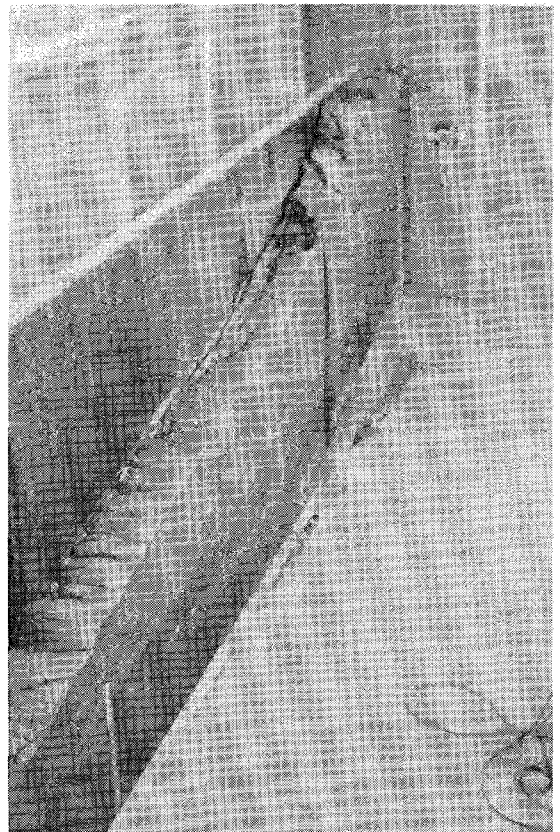
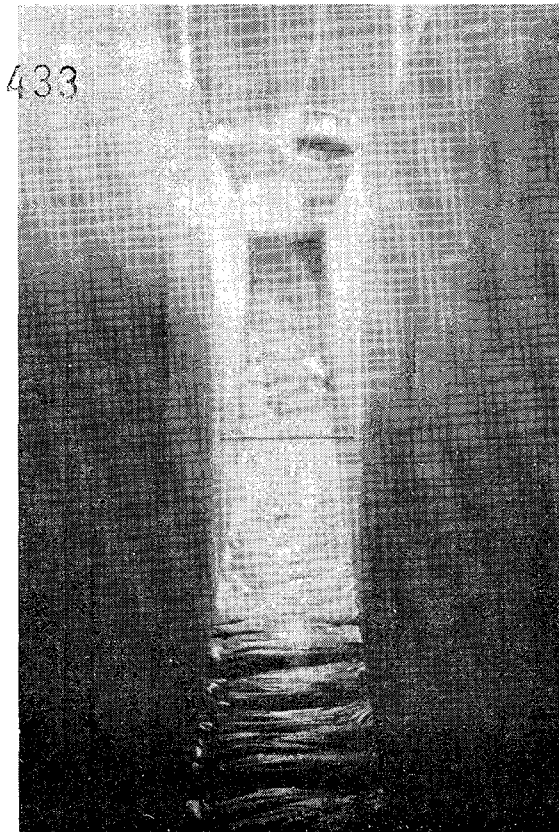
3.2 Grouting with Foamed Concrete

The test facility just described was used to test the ability of the foam concrete to grout the narrow space between the bulk of the seal and the mine roof. The box was turned on its side and treated as a symmetric half of the roof of the seal. The test results are shown in Figure B-11. With the roof off, it can be seen that the material bridged across the passage at the far end, and the capability of the foam concrete for this purpose was considered adequate.

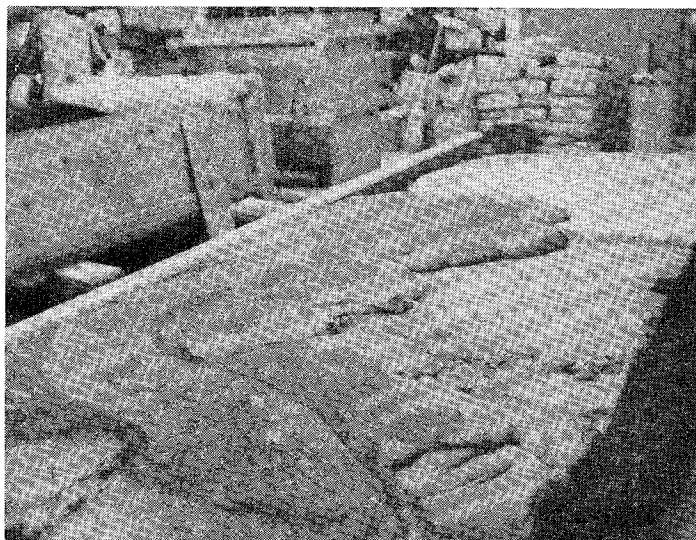
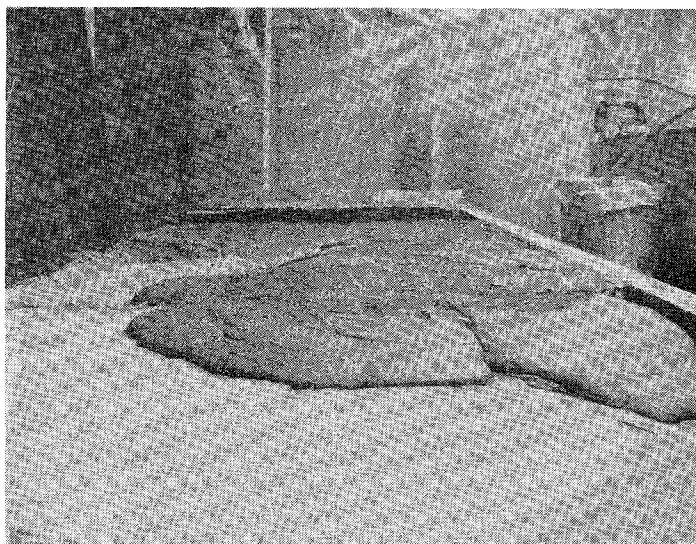


Gravity Flow Test Result for Slurry A

Figure B-9



Gravity Flow Test with Slurry B
Figure B-10



Grouting Final Seal With Foam Concrete

Figure B-11

3.3 Simulation of Mine Sealing in Quarter Scale Mine Facility

The 1/4-scale mine passage facility was used to conduct a scaled test of a complete foam concrete seal. For proper scaling, the slurry flow rate had to be reduced for geometric similarity. This was accomplished as follows. Small sample shear tests indicated that the development of shear strength, τ , with time, t , could be expressed as.

$$\tau = K \sqrt{t} \quad (B-1)$$

The shear strength indicates how high a pile can be formed at a given angle. From soil stability analysis, this critical height, h , can be expressed as

$$h = N \frac{\tau}{\gamma} = K_1 \sqrt{t} \quad (B-2)$$

where N depends on the slope angle, θ , and γ is the slurry density. Consideration of the volumetric development of the seal with time leads to the following non-dimensional parameter for geometric similitude.

$$\frac{Q \alpha}{w} \left(\frac{\gamma}{NK} \right)^2 \quad (B-3)$$

where

Q = flow rate

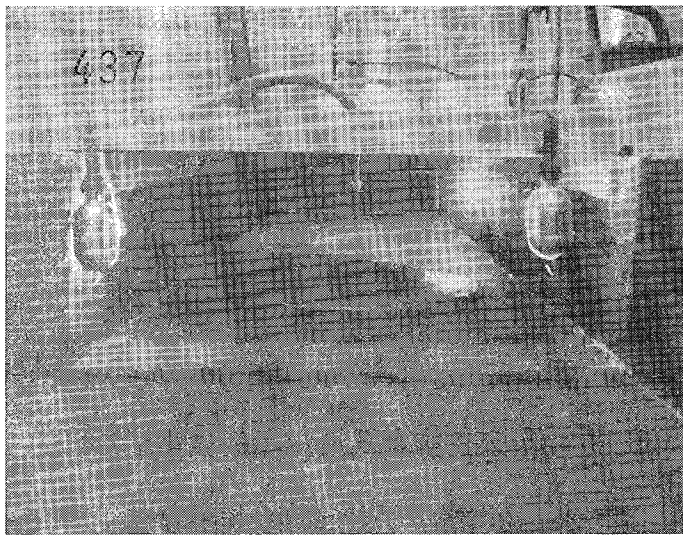
w = passage width

α = height to width ratio of passage

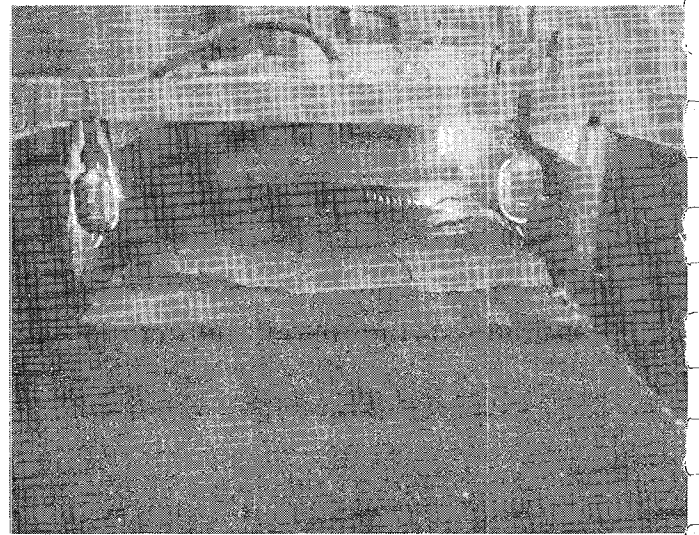
For the quarter-scale facility with height to width ratio of 3/8, the laboratory flow rate must be multiplied by 10 to obtain the equivalent field flow rate. The flow rate of 7 gpm used in the test is equivalent to 20 yds/hr in the field. Further calculations indicated that, for a

30° slope angle, the resulting seal in the quarter scale passage should be 4 feet long at the top.

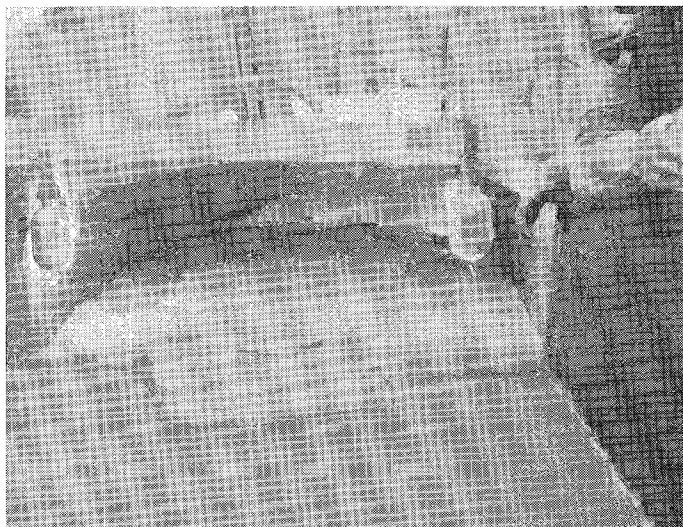
Figure B-12 shows sequential photographs of the seal. As can be seen, the cement did not fail due to excessive height development; i. e., gravity stresses were never a problem. Rather, the material failed along vertical planes, due apparently to radial pressures from the material being poured into the passage. These vertical planes formed radial "fingers", through which material flowed without resistance. These fingers caused excessive horizontal spread of the sealing material, resulting in a volume which was considered to be unsatisfactory for mine sealing applications.



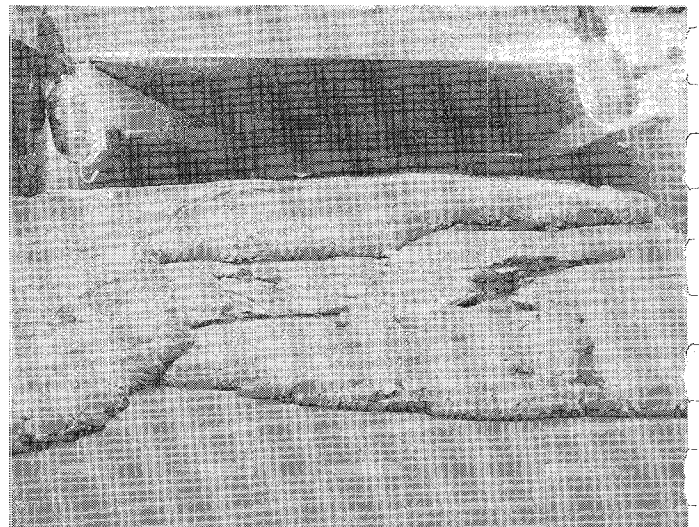
(a)



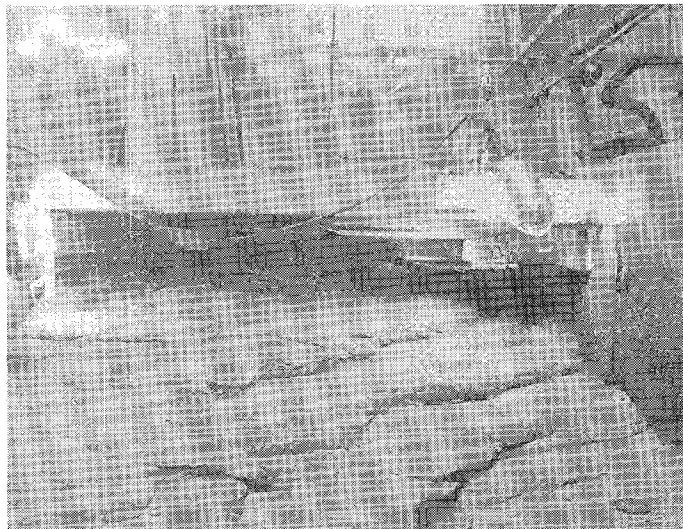
(b)



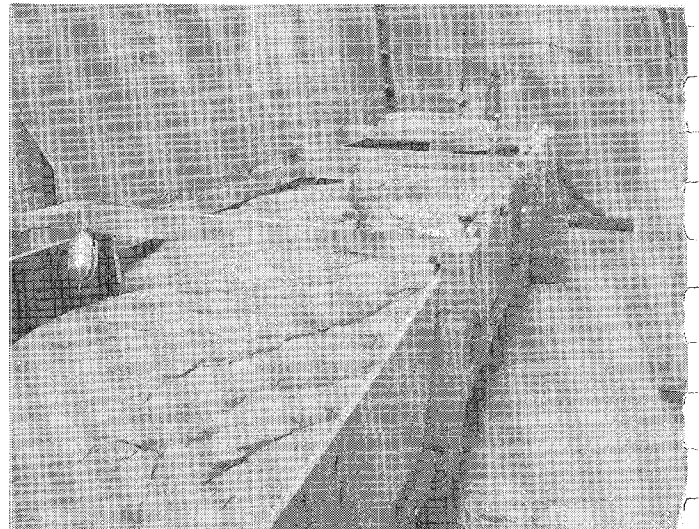
(c)



(d)



(e)



(f)

Sequential Photographs of the 1/4 Scale Foam Concrete Seal

Figure B-12

SCALING RELATIONSHIPS1. Scaling Law for Fly Ash Crater Formation

The scaling law derived for predicting crater diameters at different scales is developed below by considering the equation of motion of individual fly ash particles. It is assumed that the air drag on each particle is characterized by Stokes flow, and at the borehole - passage intersection the air velocity and the fly ash particle velocity are the same.

The equations of motion for a fly ash particle are the following, (see Figure C-1).

$$M \frac{d^2 x}{dt^2} = C_D (v_{a_x} - \frac{dx}{dt}) \quad (C-1)$$

$$M \frac{d^2 y}{dt^2} = Mg + C_D (v_{a_y} - \frac{dy}{dt}) \quad (C-2)$$

where

M = particle mass

C_D = drag coefficient

v_{a_x}, v_{a_y} = air velocity components

x, y = particle position

g = acceleration of gravity

t = time

Non-dimensionalizing these equations by the passage width w and the borehole velocity v_o .

$$X = x/w \quad Y = y/w \quad T = t v_o/w \quad (C-3)$$

the following non-dimensional equations of motion are obtained:

$$\frac{d^2 X}{dT^2} = K_1 v_{a_x} - K_2 \frac{dX}{dT} \quad (C-4)$$

$$\frac{d^2 Y}{dT^2} = K_3 + K_1 v_{a_y} - K_2 \frac{dY}{dT}$$

where

$$K_2 = \frac{C_D w}{M v_o} \quad \text{and} \quad K_3 = \frac{wg}{v_o^2} \quad \text{are}$$

non-dimensional coefficients, and $K_1 = \frac{C_D w}{M v_o^2}$

The components of the air flow field, v_{a_x} and v_{a_y} are complex functions of position due to the jet spreading and turbulence, and they also vary with time as the fly ash pile builds up. It is assumed, for simplicity, that during the crater formation period, the velocity decays radially from the borehole as it would from a point source; i. e.

$$v_a = \frac{A_o v_o}{4 \pi (x^2 + y^2)} \quad (C-5)$$

or, expressing the components in non-dimensional form

$$v_{a_x} = \frac{v_o A_o}{w^2} F_x(X, Y)$$

$$v_{a_y} = \frac{v_o A_o}{w^2} F_y(X, Y) \quad (C-6)$$

where F_x and F_y are non-dimensional functions of position.

Substituting these expressions into Equation C-4 the following non-dimensional equations of motion are obtained.

$$\frac{d^2 X}{dT^2} = K_1 F_x - K_2 \frac{dX}{dT}$$

(C-7)

$$\frac{d^2 Y}{dT^2} = K_3 + K_1 F_y - K_2 \frac{dY}{dT}$$

with the three non-dimensional coefficients,

$$K_1 = \frac{C_D A_o}{M v_o w} \quad K_2 = \frac{C_D w}{M v_o} \quad K_3 = \frac{wg}{v_o^2}$$

K_1 , K_2 and K_3 define parameters which must be the same for model and prototype in order for the model tests results to be similar to those of the prototype.

The particle mass M and drag coefficient C_D can be expressed in terms of the fly ash particle diameter, d . Factoring out those constants which can not change with scale (g , for example), the three parameters reduce to

$$K_1 = \frac{A_o}{w^2} \quad K_2 = \frac{w}{d^4} \quad K_3 = \frac{w}{v_o^2}$$

In reality, the particle diameter d can not be varied, because the fly ash used in both model and prototype is basically the same. The factor K_2 , however, indicates that scaling requires very small changes in particle diameter. For example, the particle diameter is 70 percent of actual fly ash for 1/4 scale and 40 percent for

1/40-scale. Considering the spectrum of sizes found in fly ash, this requirement is not very significant.

The parameter K_1 states that the borehole diameter must be proportional to the passage width. For any experiment, this can be adjusted accordingly. Finally, the parameter K_3 can be expressed in terms of the flow rate Q , as.

$$K_3 = \frac{w}{v_o^2} = \frac{w A_o^2}{Q^2} = \frac{K_1 w^5}{Q^2}$$

This statement implies that Q must be proportional to $w^{5/2}$; i.e., air flow rate is proportional to (mine passage width) $^{5/2}$.

2. Laboratory Modelling of Aggregate Deflection

The particle trajectories for deflected aggregate can be described in much the same way as for fly ash. For gravity fall there is no air flow field, and the air drag on the particles will be proportional to particle velocity. Figure C-2 shows a definition of the variables. The equations of motion are the following:

$$M \frac{d^2 x}{dt^2} = - C v \frac{dx}{dt}$$

$$M \frac{d^2 y}{dt^2} = Mg - C v \frac{dy}{dt}$$

where

M = particle mass

C = drag parameter

x, y = particle position

v = particle velocity

g = acceleration of gravity

t = time.

By defining the following non-dimensional variables

$$X = x/h \quad Y = y/h \quad V = \frac{v}{v_o} \quad T = \frac{tv_o}{h}$$

The equations of motion can be written in the following non-dimensional form:

$$\frac{d^2 Y}{dT^2} = - \left(\frac{Ch}{M} \right) V \frac{dx}{dt}$$

$$\frac{d^2 Y}{dT^2} = \left(\frac{gh}{v_o^2} \right) - \left(\frac{Ch}{M} \right) V \frac{dy}{dt}$$

The expressions in brackets are the non-dimensional parameters. We note that when v_o = terminal velocity for free fall, $v_o^2 = Mg/C$, and hence the two parameters are identical. It is assumed here for simplicity that there are no energy losses at the deflector, and hence the deflected velocity is also v_o . Expressing the particle mass in terms of its diameter, and expressing C in terms of the drag coefficient, particle dimensions and air properties, one obtains

$$\frac{Ch}{m} = \frac{6}{8} \frac{\rho_a}{\rho_s} \frac{C_D h}{d}$$

where

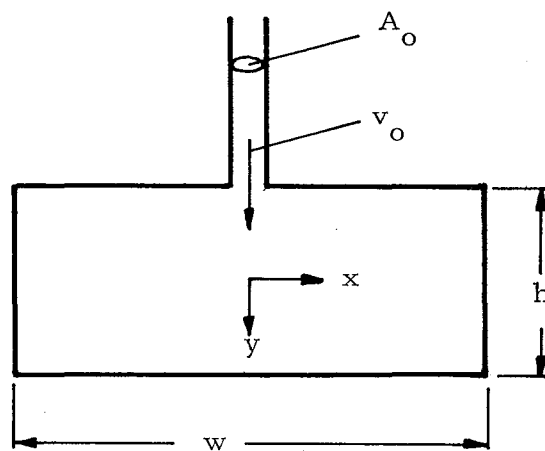
ρ_a = air density

ρ_s = particle density

C_D = drag coefficient

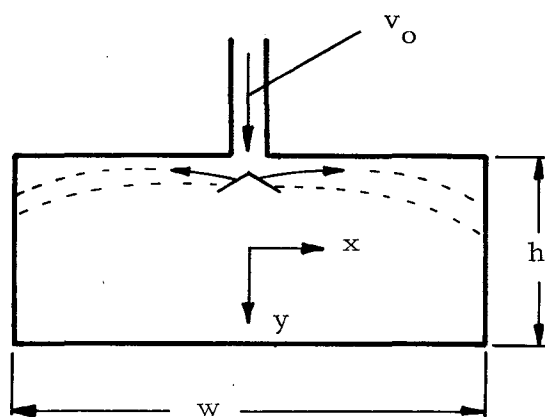
d = particle diameter

If we approximate the aggregate particles as spheres, whose density does not change with scale, the parameter Ch/M will be constant when the ratio h/d is constant; i.e., in a 1/30-scale passage, particles whose diameter is 1/30 of full-sized aggregate will deflect into a geometrically similar shape. This relationship indicated that .03 inch diameter uniform Ottawa silica sand would adequately represent 1 inch stone at this scale.



Definition of Variables for Fly Ash Scaling

Figure C-1



Definition of Variables for Scaling of Aggregate Deflection

Figure C-2

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100

DEVELOPMENT AND EXPERIMENTAL VERIFICATION
OF ACOUSTIC SEAL CHECKER THEORY

1. Introduction

In Section 7 of the report the acoustic seal checker concept was described in a general manner and the parameters which affect the signal level at the microphone were discussed briefly. In this appendix the theoretical basis will be presented and the experimental program described which permitted the extension of the theory into practice.

The basic goal of the acoustic seal checker is to relate the reduction in sound pressure level to the size of the residual hole in the fly ash barrier. The smallest hole size that may be measured is determined by the signal to noise ratio, where the noise in this case includes the ambient noise in the mine, the internal microphone noise and the sound transmitted from the acoustic source via the flanking paths through corridors adjacent to the one being sealed.

The latter source of noise can be discriminated against, at the expense of increased complexity of the acoustic system, by employing a pulsed source and pulse gating of the microphone signal set to accept sound via the barrier path and to reject the delayed flanking path signals.

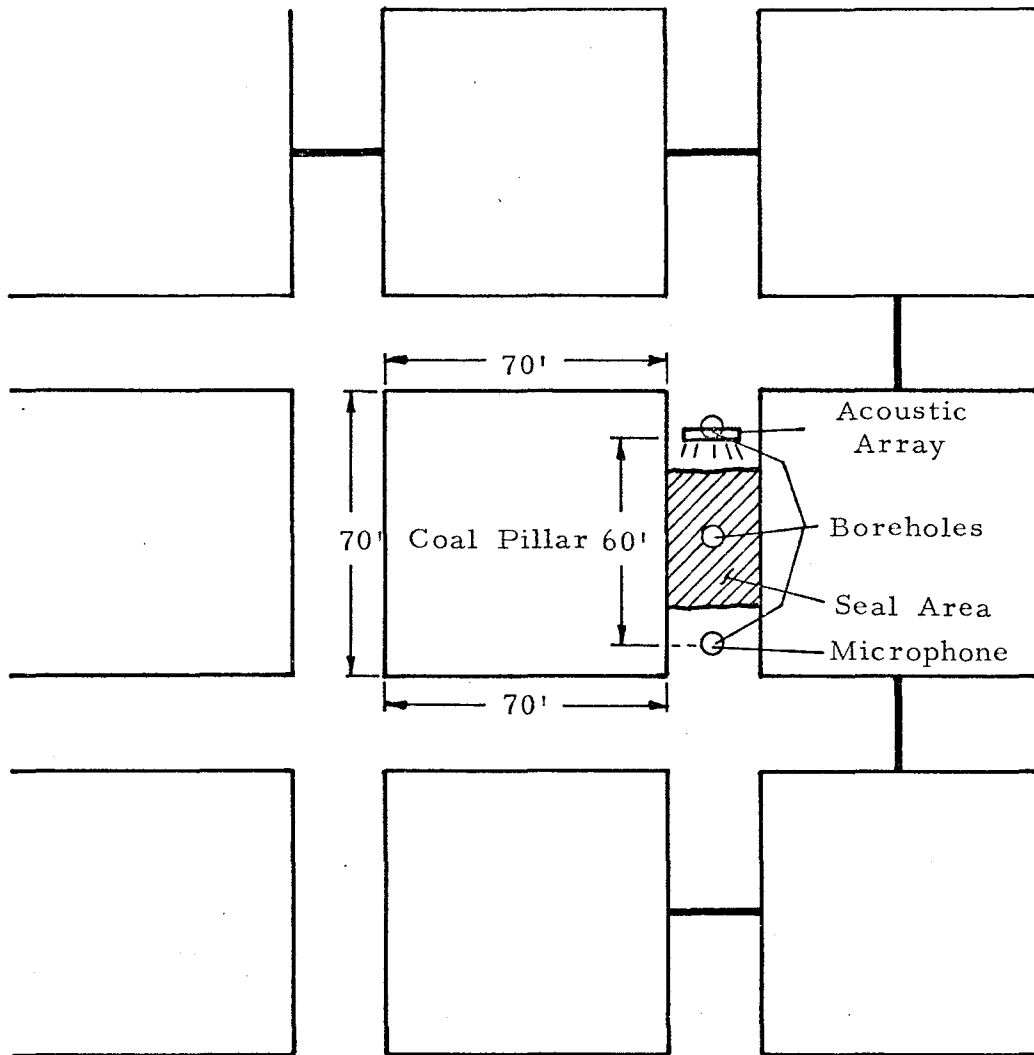
In order that the acoustic system be insensitive to precise source and microphone location and to permit assessment of system performance on an acoustic power flow basis, a broad frequency band of pseudo-random noise is emitted by the loudspeaker source. The preferred frequency range must be determined, the advantage of a directive source must be assessed, and the necessity

for pulse gating must be determined. If pulse gating is employed, then the required signal to noise ratio can be achieved simply by increasing the source level. On the other hand, the simpler continuous signal system requires careful assessment of the influence of flanking path levels and fly ash absorption upon the signal to noise ratio as these effects cannot be alleviated by increasing source level.

2. Theory of Corridor Propagation

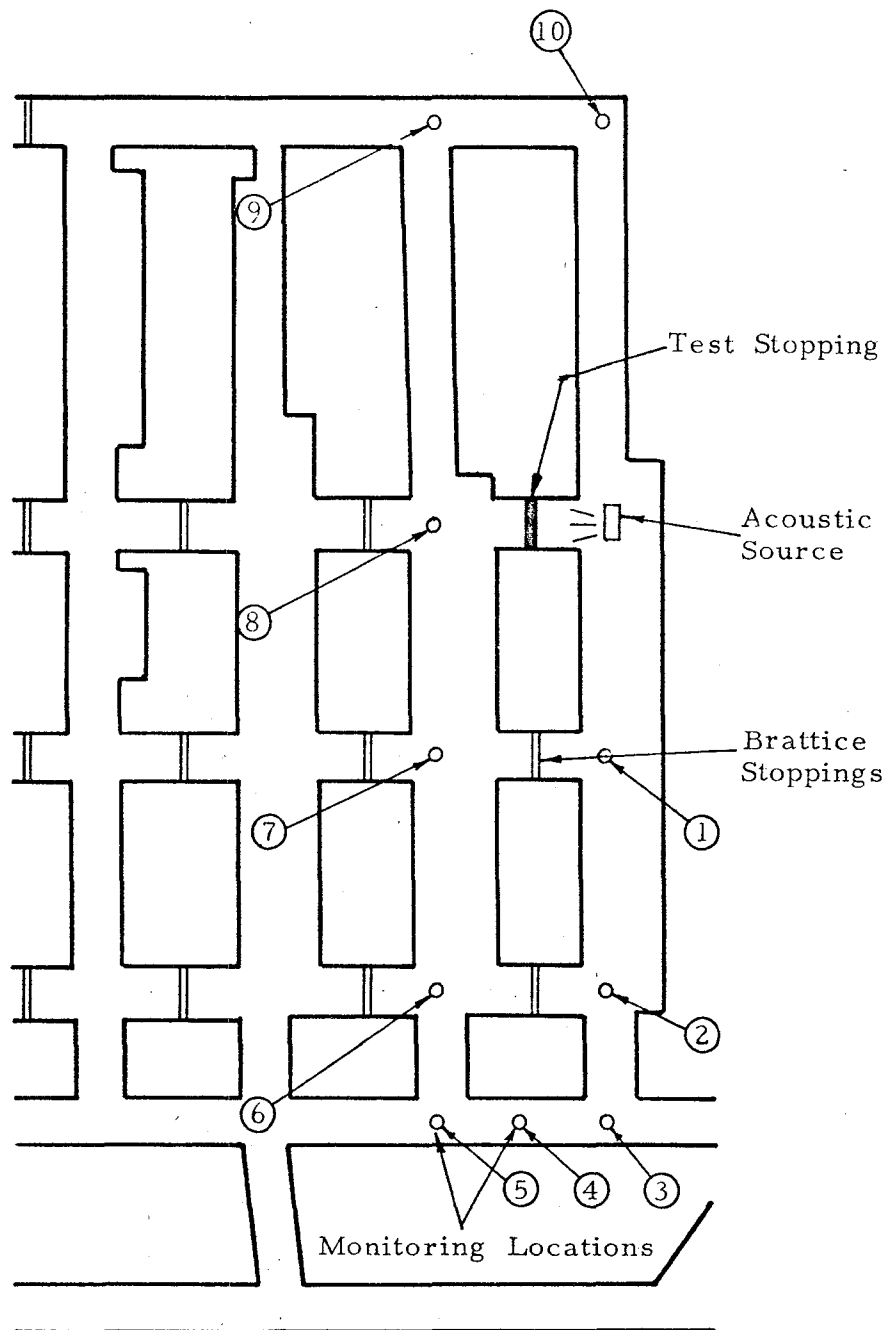
A typical mine is cut through the bed in a system of corridors, usually with right angle intersections, leaving rectangular pillars of coal up to 80 feet on a side as shown in Figure D-1 for Federal No. 1 Mine. The nominal corridor height for this mine is 6 to 7 feet. Occasionally, domes up to 12 feet high occur as a result of falling roof. In a large mine, which may extend over many square miles in area, the corridors are usually 20 feet wide. In a small mine, however, corridors are 11 feet wide with some branch corridors as narrow as 8-1/2 feet as found in the Bureau of Mines Experimental Mine at Bruceton, Pennsylvania. A layout of a portion of the Bruceton mine is shown in Figure D-2.

Shale has a characteristic impedance of 6.15×10^6 MKS rayls and a normal incidence absorption coefficient $\alpha = 2.7 \times 10^{-4}$. Here $1 - \alpha$ is the ratio of acoustic power reflected to incident acoustic power. Coal has a characteristic impedance of 1.55×10^6 MKS rayls and a normal incidence absorption coefficient $\alpha = 1.07 \times 10^{-3}$. Thus the shale corridor ceilings and floors and the part coal, part shale side walls are all highly reflective. These corridor boundaries, however, are quite rough. Side wall roughness is often increased by the presence of power terminal boxes and various other necessary mine fittings and equipment. Considerable scattering of sound occurs on corridor boundaries. This scattering tends to increase the effective absorption coefficient and to make the sound field more nearly uniform over a corridor cross-section.



Direct and Flanking Path Geometries for Straight
Passage Seal Test

Figure D-1



Layout of Mine for Theory Verification Tests

Figure D-2

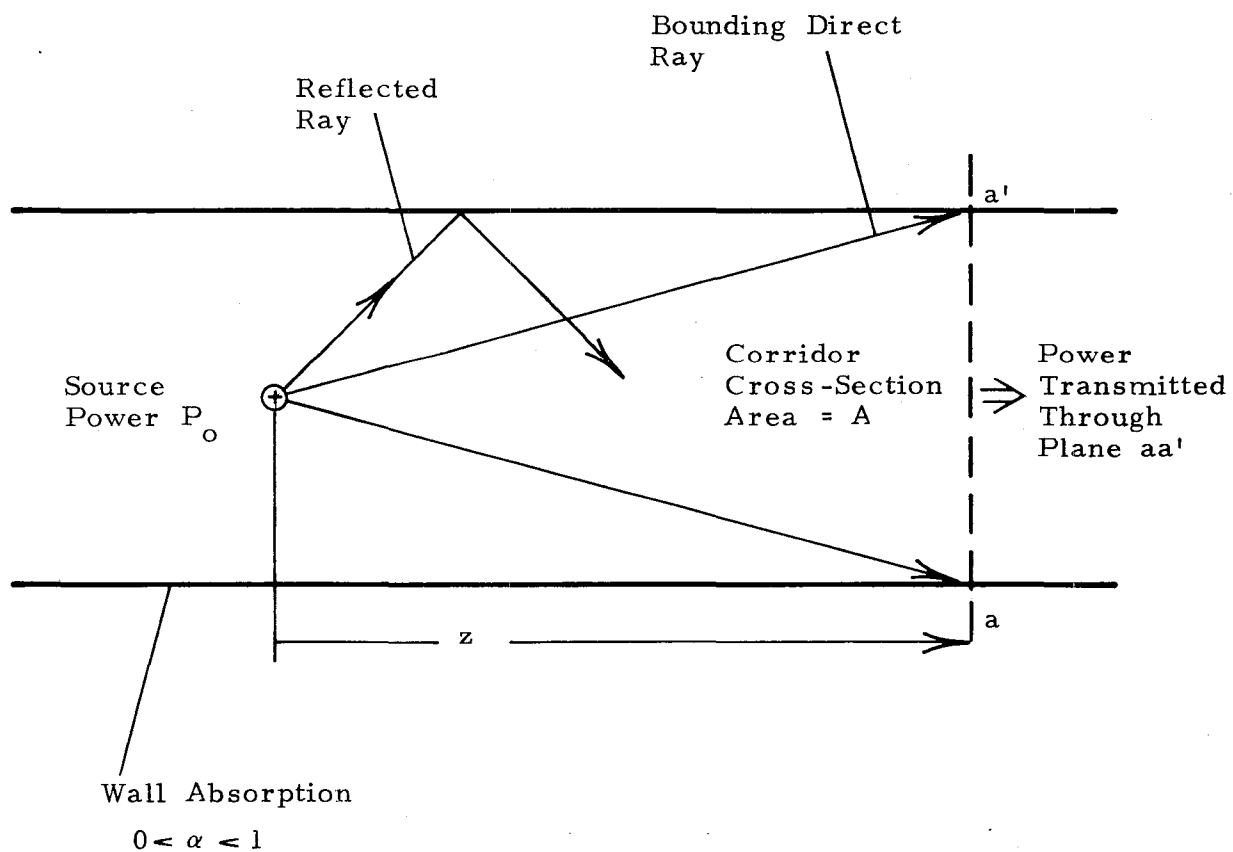
In Figure D-3, we have sketched an idealized infinite rectangular corridor of cross-sectional area A in which an omnidirectional sound source with acoustic power output P_o is located. If the corridor walls are perfectly rigid ($\alpha = 0$), it is obvious that the acoustic power transmitted through plane aa' is $P_o/2$. On the other hand, if the corridor walls are perfectly absorbing ($\alpha = 1$), then the situation is equivalent to spherical wave propagation and the acoustic power transmitted through plane aa' approaches

$$P_{aa'} = P_o A / 8 \pi Z^2 \quad (D-1)$$

as the distance Z along the corridor becomes very much greater than $\sqrt{A}$. For any condition between these two limits, the combined effects of wall absorption and scattering from roughnesses will tend to make the power transmitted be greater than the latter asymptotic limit.

In addition to the above considerations, measurements are taken in corridors of sound pressure level rather than of transmitted power. The analytical solution of the radiation from a point source in an infinite corridor, Morse and Ingard⁽¹⁾, shows the presence of pressure fields that decay exponentially with increasing distance along the corridor. Such fields contribute to the sound pressure level near the source but do not contribute to the transmitted power.

Since neither the effect of scattering from roughnesses nor the influence of the exponentially decaying components of the pressure field can be assessed quantitatively by analysis, we found it necessary to determine the propagation law for a mine corridor by experiment. No single corridor without branching side corridors was long enough to approach the free field limit of 6 decibels reduction per distance doubling implied by Equation (D-1), hence the effects of corridor intersections and corridor cross-sectional area changes had to be accounted for.



Infinite Corridor Model

Figure D-3

3. Effects of Corridor Area Changes and Corridor Intersections

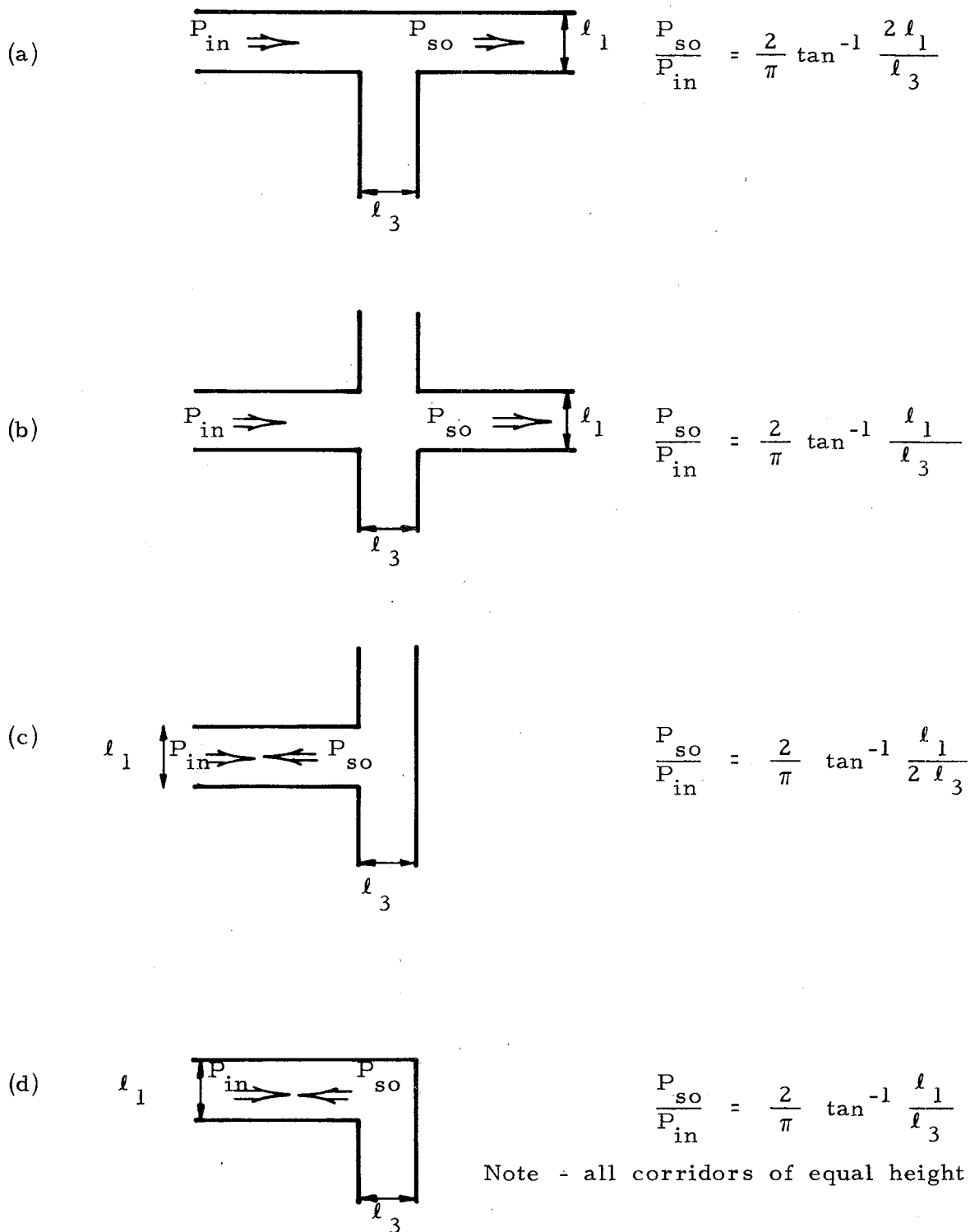
When a corridor cross-sectional area change occurs, a reasonable approximation is that the same acoustic power is transmitted along the corridor; hence, the sound pressure level must increase 3 decibels for a halving of corridor area. Mine corridor intersections are of three types: cross, tee or ell. Davies⁽²⁾ has analyzed the acoustic power flow into and through such branches for two cases of input acoustic power: one from an omnidirectional source in the corridor, the other from a large reverberant room at the input end of the corridor. Somewhat more power flows into a side branch in the former case than in the latter case, but the difference is generally less than one decibel. The latter case is somewhat easier to calculate and is used in this study with the justification that wall roughness tends to equalize energy among the propagating modes.

Davies' results are given in Figure D-4 in terms of input power P_{in} and power sent on past a branch, P_{so} . The power diverted into a branch is just $P_{in} - P_{so}$ in cases (a) and (d) and $1/2 (P_{in} - P_{so})$ in cases (b) and (c) in the figure. Note that P_{so} in cases (c) and (d) is actually power reflected back into the corridor and increases the sound pressure level there. Case (a) is the basic result, the others follow by symmetry arguments.

Since changes in sound pressure level are equal to changes in power level, we may convert the results of Figure D-4 to decibel reductions in sound pressure level by simply taking $10 \log_{10} (P_{so}/P_{in})$, etc. Examples typifying decibel reductions in mine corridors are given in Figure D-5.

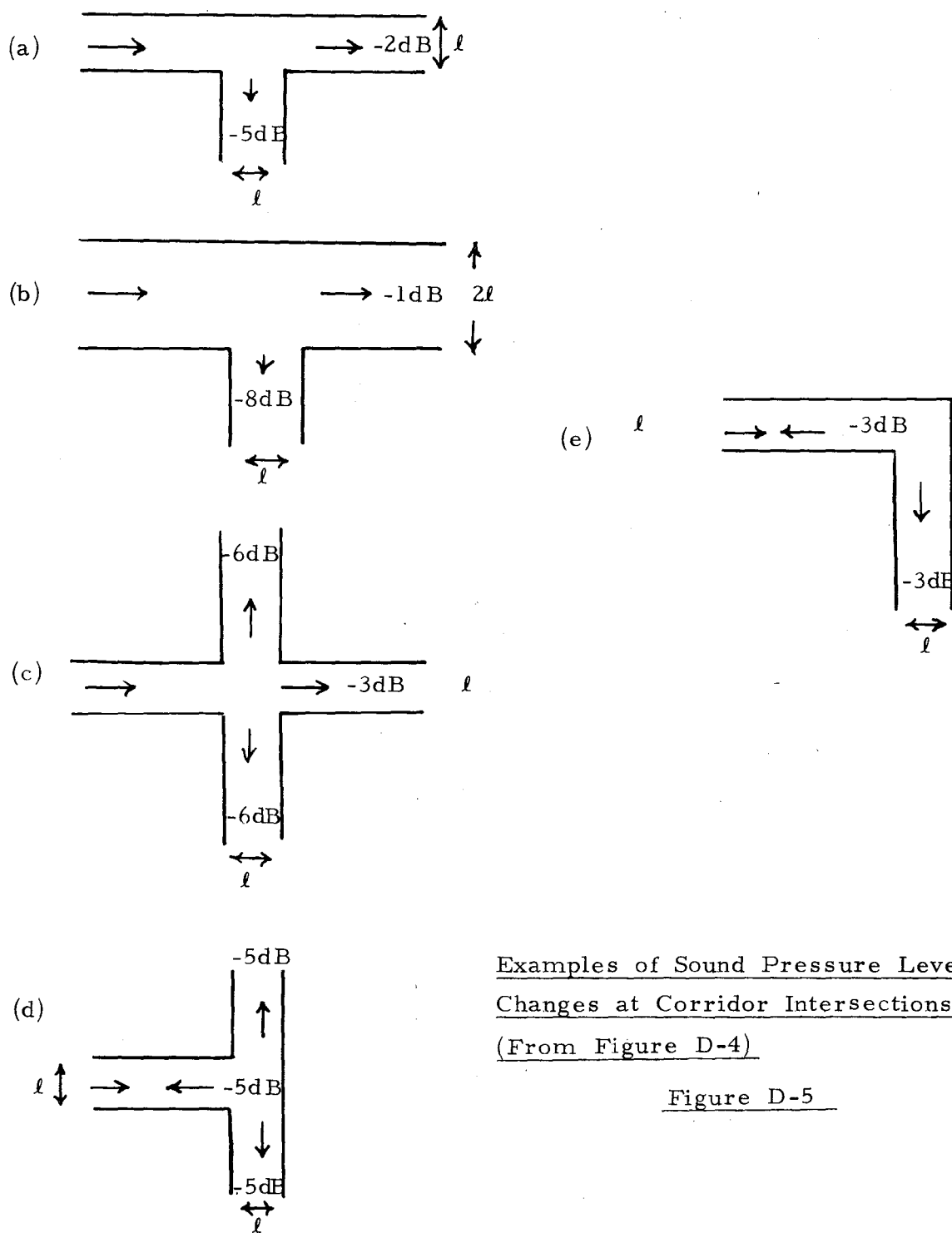
4. Experimental Study of Mine Corridor Propagation

Experiments were carried out in the U. S. Bureau of Mines



Power Flow Through Corridor Intersections

Figure D-4



Examples of Sound Pressure Level
Changes at Corridor Intersections
 (From Figure D-4)

Figure D-5

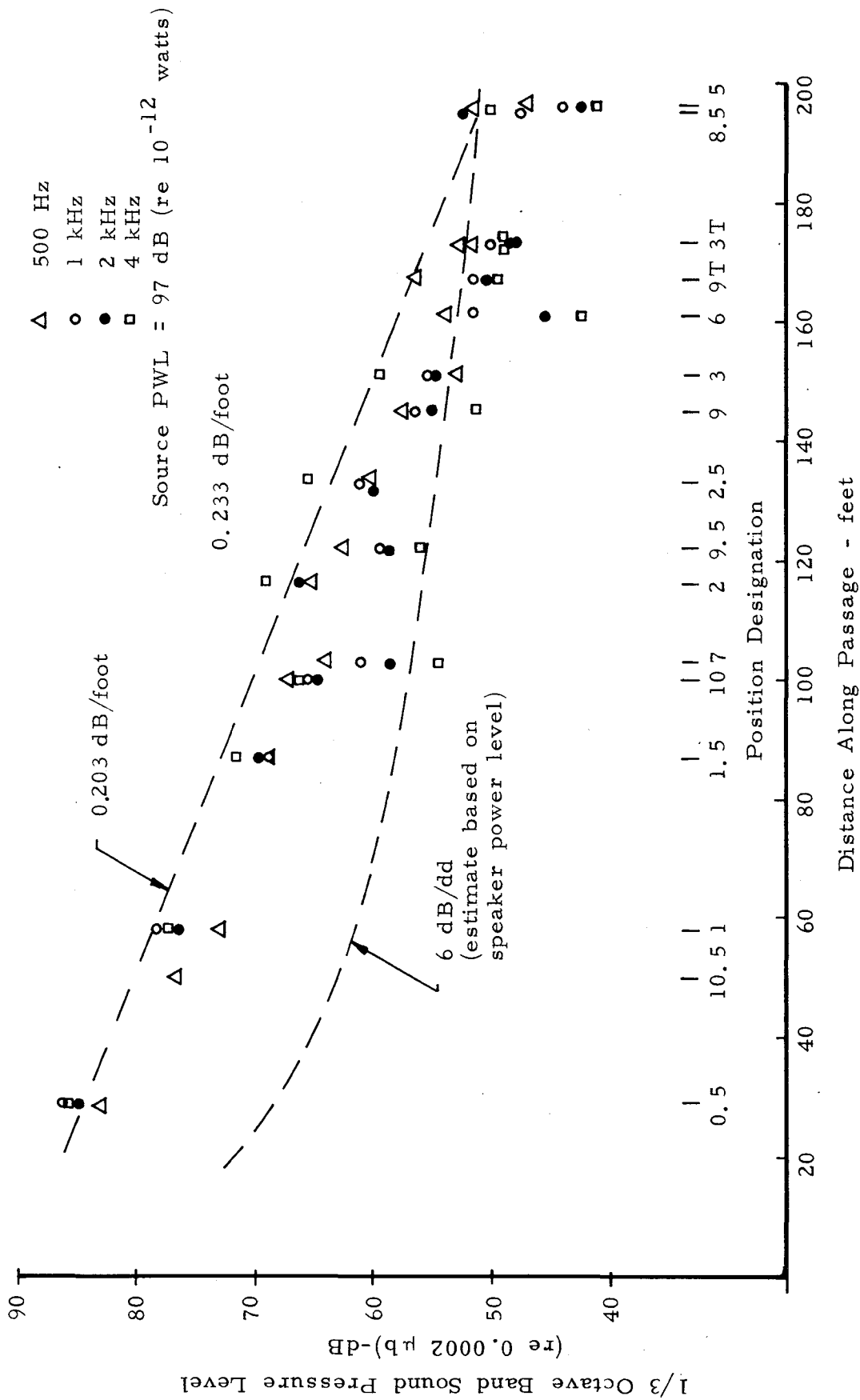
Safety Research Mine, Bruceton, Pennsylvania in, October, 1972, in order to determine flanking path transmission losses and the effect of barrier hole size upon direct path attenuation. A plan view of this mine is shown in Figure D-2. Numbers on this figure indicate measurement points for the flanking path transmission loss experiment.

A loudspeaker was placed at position 0 opposite a test stopping constructed of layers of plywood and sodium silicate foam. The loudspeaker was driven by 1/3 octave bands of random noise centered at 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz. Speaker acoustic power output levels in these bands had previously been determined in a reverberation chamber.

By comparing measurements with the speaker at position 0 and a sound level meter (SLM) at position 8 (opposite the test stopping) with measurements with the speaker at position 1 and the SLM at position 7 (on either end of a similar open corridor), the insertion loss (IL) of the test stopping was determined as:

Center Frequency	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Insertion Loss	25.5 dB	33 dB	36 dB	33 dB	36 dB

For each 1/3 octave band with the speaker at position 0, sound pressure levels were recorded at the various measurement positions shown on Figure D-2. Since the speaker changed directivity with frequency, measured levels were first adjusted to attain a common level at position 10.5 for each frequency band, preserving the level differences between positions. Then corrections were made for corridor area changes relative to a 7 foot by 11 foot cross-section and for intersection effects in accordance with Figures D-4 and D-5. The resulting sound pressure levels as a function of distance from the source are shown on Figure D-6.



Mine Corridor Acoustic Attenuation with Distance from Source

Figure D-6

Although there is considerable scatter among the band levels at certain positions, probably caused by local reflection effects, the data indicates clearly an average attenuation of 0.233 dB per foot.

We have also plotted on Figure D-6, the limiting free field attenuation based on the known speaker power output. This attenuation must be used beyond a distance of 165 feet from the source, as the power level in a corridor can never drop below the free field level (see Section D-2.)

It may also be seen from Figure D-6 that the theoretical predictions of corridor intersection effects tend to be somewhat conservative. Where several branches or intersections are passed on the shortest path from source to measurement position; e.g., position 5 or 6, the measured levels were somewhat lower than would be predicted by using 0.233 dB per foot attenuation in conjunction with Figures D-2 and D-3.

5. Effect of Barrier Hole Size Upon Direct Path Transmission

Consider an omnidirectional speaker with acoustic power output P_o placed a distance r_o on one side of a barrier in a mine corridor. A microphone is placed a distance r_l on the other side of the barrier and sound is transmitted through a hole of cross-sectional area A in the barrier. The sound level received by the microphone along this direct path is influenced by the mine corridor walls, the area A of the hole and, in the case of a long fly ash barrier, by the absorption along the length of the hole.

If the speaker is sufficiently close to the hole so that the influence of the mine corridor walls can be neglected the sound intensity incident on the hole is

$$I_h = P_o / 4 \pi r_o^2$$

and the acoustic power transmitted through the hole is

$$P_h = I_h A \quad (D-2)$$

If no hole dimension is significantly greater than an acoustic wavelength, the hole may be considered as a non-directive source of power P_h . Then the intensity I_m at the microphone is

$$I_m = P_h / 4 \pi r_l^2$$

This is the direct field approximation.

If the speaker and microphone are separated more than a corridor width or height from the hole, we must consider both the incident and transmitted fields as semi-reverberant. Then the intensity incident upon the hole⁽²⁾ is

$$I_h = \overline{p_h^2} / 3 \rho c \quad (D-3)$$

where $\rho c = 415$ MKS rayls is the characteristic impedance of air and $\overline{p_h^2}$ is the incident mean square pressure at the hole as determined from Figure D-6. For Figure D-4, the source power level, PWL (re 10^{-12} watts), is 97 dB; hence, the incident sound pressure level (SPL) at the hole must be adjusted for any changes in source power level. By Equation D-3, the intensity level IL at the hole is

$$IL = SPL - 10 \log_{10} 3 = SPL - 5 \text{ dB} \quad (D-4)$$

Then by Equation D-2, the power level of the hole as a source is

$$PWL = IL + 20 \log h - 10 \quad (D-5)$$

where h is the side of a square hole or, approximately, the diameter of a round hole expressed in feet. Figure D-6 is also used similarly to determine the reduction in sound pressure level from the hole to the microphone.

In both the direct and reverberant field cases, Equation D-2 applies, hence we always find that the sound pressure level and the intensity level are reduced by 3 decibels for each halving of the hole area.

In the case of a fly ash barrier, any residual hole is likely to have a length of about 15 feet with the sides of the hole formed partially by fly ash. For a hole diameter h no greater than an acoustic wave length only the fundamental mode will propagate along the hole. Morse⁽³⁾ gives the attenuation of this mode as

$$4.34 \frac{\alpha}{h} \text{ dB per foot} \quad (\text{D-6})$$

where h is given in feet and α is the absorption coefficient of the side walls of the hole.

6. Experiments on the Effect of Barrier Hole Size Reduction

Rectangular holes 5 inches by 6 inches, 5 inches by 11-3/4 inches and 9-3/4 inches by 11-3/4 inches were cut successively from the same location in the test stopping. For each hole, sound pressure levels were measured at position 8 with the speaker in position 0 transmitting 1/3 octave bands of random noise from 500 Hz to 8 kHz.

By comparison with the flanking path transmission tests, it was determined that transmission via direct path from the speaker to the microphone dominated. This was true even when there was no hole in the test stopping as the insertion loss of this stopping was too low for the flanking path to dominate at position 8 (see insertion loss levels, Section D-4).

The following results were obtained from those tests:

- (a) A 3 decibel reduction with halving of hole area was verified for all frequency bands.
- (b) Direct path transmission was semi-reverberant. Measured levels corresponded very well with calculations based on corridor propagation, whereas direct field calculations gave levels that were too low.
- (c) The transmitted signal through the largest hole in the 1/3 octave band centered at 8 kHz was very directional since hole dimensions were much larger than the acoustic wave lengths. Although this sensitivity to microphone location could be reduced by moving the microphone back into the next continuing corridor, it was considered that the highest practical signal frequency was 4 kHz.

7. System Considerations

The foregoing analyses and experiments in the Safety Research Mine demonstrate that practical engineering estimates can be made for acoustic propagation in mine corridors and that it is feasible to determine residual hole sizes in corridor barriers by measurement of the changes in broad band sound pressure level transmitted through such barriers. Tests in the Safety Research Mine demonstrated that it was possible to determine residual holes in a simple barrier as small as 30 square inches in cross-sectional area without interference from flanking path noise. The preferred signal frequency range is from 500 Hz to 4 kHz, the lower limit set by speaker efficiency, the upper limit by the need to limit directivity of the signal transmitted through a large hole.

Two aspects are important in scaling these results to a large mine with corridors sealed by fly ash barriers:

- (a) flanking path transmission losses must be scaled to the dimensions of the large mine;
- (b) the absorption by fly ash along the length of a residual hole in a barrier must be accounted for.

Figure D-1 is a plan view of a large mine, Federal No. 1, Grant Town, West Virginia, in which tests of a fly ash barrier and the acoustic detection system were carried out in April 1973. Corridor widths were 20 feet, corridor heights varied from 7 feet to 12 feet and the coal pillars bounding the corridors were approximately 75 feet on a side. One fly ash barrier was poured at a corridor midway along a corridor. The base of the barrier spread about 50 feet well into the intersections with a repose angle of about 15° . A typical residual cavity between the dome of the intersection and the fly ash formed at the sides of the dome with a small hole at either end. The length of this passage was approximately 15 feet.

The attenuations in dB per foot should be reduced somewhat from the value 0.233 dB per foot of Figure D-6, because of the increased corridor width. It is reasonable to assume a value of 0.20 dB per foot to 195 feet from the source, and then apply spherical spreading loss. This line has also been plotted on Figure D-6. Intersection losses in accordance with Figures D-4 and D-5 are not changed. The flanking path transmission losses relative to the direct path transmission losses are increased somewhat because the pillars are square rather than rectangular. This is partially offset by the presence of more cross intersections. Also the source and receiver were deployed within the test corridor rather than at intersections. By Figure D-5(c) this affords about a 3 dB directivity gain to each.

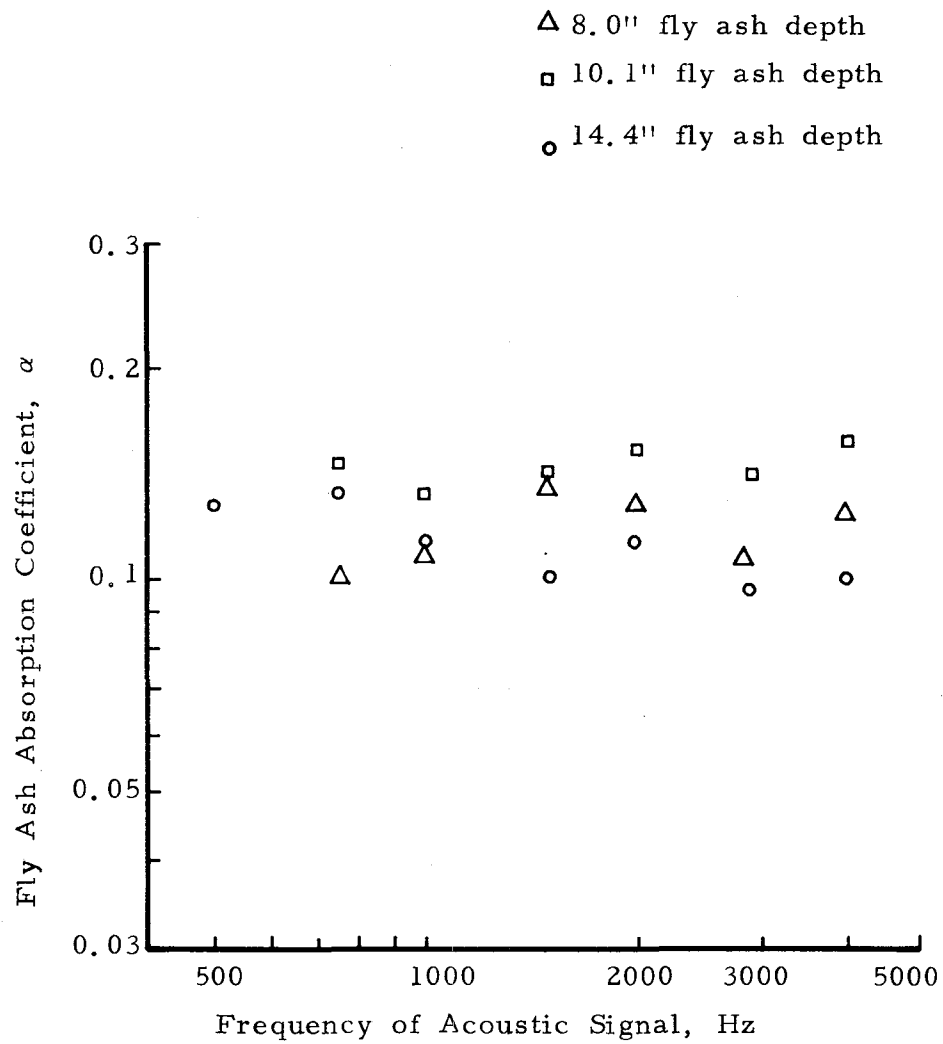
Discrimination against flanking path noise can be achieved by forming the source and/or the receiver as a line array. Klapper and Steele⁽⁴⁾ show that as much as 12 dB gain can be achieved at 2 kHz with a 66-inch long array of 13 speakers. The array, however must be deployed with its axis horizontal and across the corridor.

In order to assess the excess direct path attenuation along a hole length in a fly ash barrier, the normal incidence absorption coefficient, α , of fly ash was measured in a standing wave tube apparatus. The results of this test are shown in Figure D-7. An average value $\alpha = 0.12$ over the frequency range from 500 Hz to 4 kHz was determined. Assuming the fly ash bounds one-half the cross-section of the hole the average absorption is $\bar{\alpha} = 0.06$; hence from Equation D-6 the excess attenuation along a 15 foot hole length in terms of hole diameter h in feet is:

h in feet	2	1	1/2
dB attenuation	2	4	8

Referring to Figure D-8, we can make a sample calculation of flanking path and direct path attenuations. We assume a source PWL = 97 dB. The shortest flanking path from source S to receiver R is $95 \times 3 = 285$ feet. At 195 feet from S, the SPL is 52 dB from Figure D-4. The additional attenuation in $285 - 195 = 90$ feet is $20 \log (285/195) = 3$ dB. 6 dB is lost at each of the two crosses A and B, and 1 dB is lost at S and at R (half way through a tee, see Figure D-3). The resulting SPL at R is 35 dB (re. $0.0002 \mu b$).

The direct path from S to the near side of the barrier hole is 40 feet. From Figure D-6, the SPL at the hole entrance is 82 dB. From Equation D-4 the IL there is 77 dB. For three hole diameters h , we construct the following table:



Fly Ash Absorption Data from Standing Wave Tube Tests

Figure D-7

h in feet	2	1	1/2
dB attenuation	-2	-4	-8
20 log h	6	0	-6
PWL at exit	71	63	53

absorption along 15 feet length
from Equation D-5

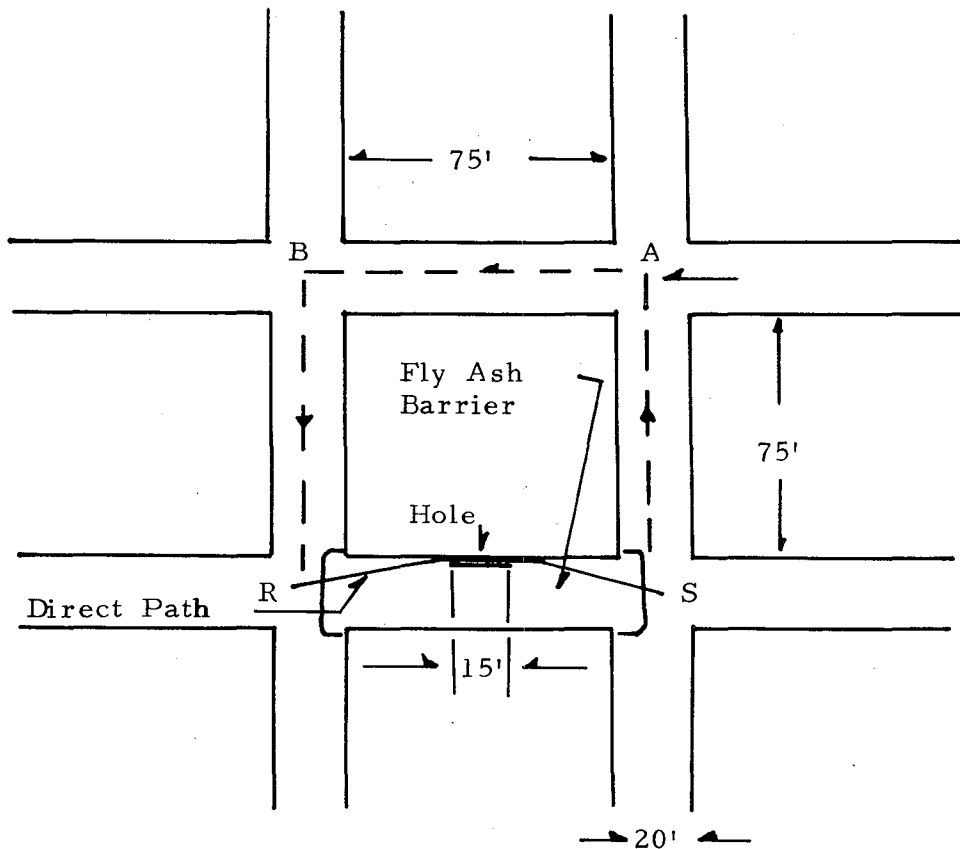
From Figure D-6, $PWL - SPL = 97 - 82 = 15$ dB in 40-feet from hole exit to R. Reducing the resulting SPL by an additional 2 dB for the tees at S and R, we get the final direct path results:

h in feet	2	1	1/2
SPL at R	54	46	36

We note that the effect of fly ash absorption is to increase the dB attenuation with hole size beyond the 3 dB per area halving. The smallest hole size, however, has its signal nearly at the flanking path level.

Flanking path signals can be discriminated against by emitting pulses of broad band random noise from the source and pulse gating the received signal. With sound speed $c = 1100$ ft/sec for the situation in Figure D-8, the same wave front initiated at source S arrives at receiver R via the flanking path 0.173 seconds later than it arrives at R via the direct path through the barrier. Thus, if the random noise pulse duration is less than this time, one may gate the received signal so as to eliminate the flanking path contribution.

Mine ambient noise levels cannot be discriminated against in this way. Ambient noise levels were measured in the Safety Research Mine while all mine operations were secured. The octave band levels were so low, from 10 to 18 dB, that they were practically at the noise floor of the sound level meter. An operating mine is much noisier; 1/3 octave band levels from 30 to 40 dB



Example of Acoustic Flanking and Direct Paths

In a Large Mine - S = Source, R = Receiver

Figure D-8

must be expected. If the acoustic system is to operate in this environment, the source level must be increased correspondingly. Microphone system noise should not be important, a conventional General Radio ceramic microphone and preamplifier have lower internal noise levels than the ambient levels in any but a completely dead mine.

It appears that pulse gating yields a limited, but definite, advantage. It would be needed if the flanking path were shorter than in our example, if the crosses at A and B were replaced by ells, if the hole length were significantly greater than 15 feet, or if detection of holes smaller than those in our example were required. Pulse gating is recommended to maximize the flexibility of the system.

REFERENCES

1. Morse, P.M. and Ingard, K. U., "Theoretical Acoustics", McGraw-Hill, New York, N. Y.
2. Davies, H. G. (1971), "Noise Propagation in Corridors", M. I. T. Acoustics and Vibration Lab. Report to be published in J. Acous. Soc. Amer.
3. Morse, P.M. (1948), "Vibration and Sound", McGraw-Hill, New York, N. Y.
4. Klapper, D. L. and Steele, D. W. (1963), "Constant Directional Characteristics from a Line Source Array", J. Audio. Engin. Soc., 11, 2, 198-202.

APPENDIX EEQUIPMENT USED FOR FIELD TESTING OF MINE SEALING SYSTEMI. Drilling Operation - Equipment supplied by local drilling contractor

1. Mobile drill rig.
2. Flat bed truck, containing 20 lengths of drill pipe.
3. Auxiliary compressor.
4. Pickup truck for small parts and supply of diesel fuel.
5. Bulldozer.
6. Water supply, in this case the nearby stream.
7. Supply of casing, positioned next to the drill rig.
8. Ready mixed cement grout.
9. Drill bits, stabilizer units, cutting and welding equipment, other miscellaneous tools and supplies.

II. Sonar Probing Operation

1. 25 foot tower with pulley mounted atop. - FMA*
2. Electric winch with 100 feet of 1/4-inch cable, Model No. 100A, City Engineering Co., Indianapolis, Indiana.
3. 400 feet of 1-1/2-inch-diameter aluminum pipe with alignment holes and coupling grooves. - FMA*

* Foster-Miller Associates - Special fabrication.

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4. Quick connect couplings, Model No. 75, Victaulic Corp. S. Plainfield, N. J. - modified to accommodate item II. 9. - FMA
 5. Split flange, alignment tool, holding pin, pipe coupling joint for mine rope - FMA
 6. Remote sonar probe housing - FMA
 7. 500 feet of cable, 20-5.
 8. Sonar readout unit - FMA
 9. Kellems* cable clamp No. 073-04-001 - Harvey Hubbell Inc., Stonington, Conn.

III. Fly Ash Sealing Operation

1. 300 feet of 4-inch diameter flexible fly ash hose with couplings.
2. 12 feet of 10-inch I. D. Steep Pipe.
3. Fly Ash Ejector-Mixer (special Fabrication).
4. 10 feet of 10-inch I. D. Flexible Hose.
5. 200 feet of 8-inch I. D. PVC Pipe.
6. 5000 scfm 10 psi capacity Diesel Driven Positive Displacement Type Rotary Blower, Series 3200 Sutorbilt*, Div. of Fuller Company, Compton, Calif.

* Trade Name.

7. 1, 15 psi range diaphragm type pressure transducer, Model AB with AD-1 Adaptor, Tyco, Watertown, Mass.
8. 1, Kent Cambridge Solids Flowmeter with 6-inch diameter Electrode Assembly System P390 Kent Cambridge RD60D, RD61D, A10195 and 10-ma F.S.D. meter Ossining, N. Y.
9. 1, Fischer-Porter Oriflorator,* 0-6000 scfm capacity, Model No. 10B1000 and No. 10B3565S, Fischer-Porter, Warminster, Pa.
10. 1, 8-inch Pipe Elbow
11. 1, 4-inch Diameter Gate Valve
12. 1, 8-inch to 6-inch Reducer
13. 1, 10-inch to 6-inch Reducer
14. 1, 10-inch "Tee"
15. 1, of 6-inch I. D. pipe with flanges
16. 1 standard 10 psi range pressure gauge, with 1/4 NPT pipe thd.

IV. Foam Topping Operation

1. 1 set of 2 tanks 5000 lbs each of Olin Autofroth* A202C4 Olin, Cleveland, Ohio.

* Trade Name.

2. 1, Canopy to cover tanks
3. 1, Diesel Fuel fired space heater
4. 1, Foam Flow Control Panel** comprising metering valves, two Fluidyne flow meters, strainers, etc.
5. 2, Variable Pressure Relief Valves**
6. 1, Mixer Assembly** including mixing head, Kenics mixer, and quick disconnect coupling
7. 1, Packer assembly** including two rubber disc packers, foam injection pipe, and flat plate disperser
8. 2 sets - 500 feet each of 3/4-inch diameter Synflex nylon core hose 3000 series - Samuel More and Co., Mantau, Ohio
9. 1, Freon Bottle
10. 12 Nitrogen Bottles
11. 1, Methylene chloride barrel with air actuated reciprocating pump**
12. 1500 feet 1/4-inch diameter Synflex nylon core hose, 3000 series - Samuel More and Co., Mantua, Ohio.
13. Miscellaneous pipe fittings

** Developed jointly by Foster-Miller and Geologic Associates, Franklin, Tenn.

14. 1 Truck mounted hydraulic crane with at least 600 feet of 3/8 inch diameter wire rope on winch - local construction equipment company.

V. Acoustic Seal Checker Operation

1. Eight Speaker Linear Acoustic Array - FMA.
2. Acoustic Array Deployment Module - FMA.
3. Speaker Cable - 14 gage 18 conductor - 500 feet reel.
4. Signal Generating and Processing Console, containing Bose Model No. 1801 Amplifier, Framingham, Mass. Testronic Dev. Labs. No. 108M5, Las Cruces, N.M. General Radio No. 1551C, Concord, Mass. Signal Processing Unit - FMA.
5. Microphone-Preamplifier Module, - FMA, containing General Radio No. 1560-9570 and No. 1560-P40 Concord, Mass. with housing (special fabrication).
6. Microphone Cable - 500 foot reel, General Radio No. 1560-P72, Concord, Mass.
7. Winch and 400 feet of 1/8 diameter cable, No. 100A City Engineering Co., Indianapolis, Indiana.
8. Winch and 100 feet of 1/4 cable - same as item II. 2.
9. Pulley support - scaffolding, pole or hoist truck same as item II. 1.

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10. 400 feet of 1-1/2 inch diameter aluminum pipe,
same as item II. 3.
11. Victaulic couplings - same as item II. 4.
12. Cable Clamps, Kellems No. 022-03-015, Harvey Hubbel
Inc., Stonington, Conn.
13. Split Flange, alignment tool, holding pin, pipe
coupling joint for wire rope, same as item II. 5.