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Design of Bulkheads for Controlling Water in Underground Mines

By Gregory J. Chekan



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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	psi	pound per square inch
gal/h	gallon per hour	psig	pound per square inch, gauge
in	inch	V dc	volt, direct current
mA	milliamperere	wt pct	weight percent
min	minute	yr	year
mm	millimeter		

DESIGN OF BULKHEADS FOR CONTROLLING WATER IN UNDERGROUND MINES

By Gregory J. Chekan¹

ABSTRACT

This Bureau of Mines report presents three methods for designing bulkheads to impound water underground: (1) thin and thick plate design; (2) South African plug design; and (3) single and double bulkhead seal design. Related areas critical to the long-term effectiveness of underground water impoundments are also addressed. These include bulkhead anchorage, concrete specifications and placement, the grouting of permeable strata, and the sizing of barrier pillars. A case study involving hydrostatic tests conducted on a single bulkhead seal constructed in the Safety Research Coal Mine of the Bureau's Pittsburgh Research Center is presented in an appendix.

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INTRODUCTION

Bulkheads are commonly used to seal abandoned workings and protect adjacent active mines from explosion; however, bulkheads can also be used to control unwanted inflows of water. Ground water seepage from poorly sealed shafts, water-bearing strata, and abandoned mine areas used for impoundment are the major sources of water inflow. In some instances, water levels in these abandoned areas can rise rapidly or go completely undetected while the areas are accumulating excessive hydrostatic pressure. This poses a potential inundation hazard to the active mine, especially if the bulkhead is not suitably designed to retain water.

The Federal Coal Mine Safety and Health Act of 1977 requires that bulkheads which seal abandoned areas be "explosionproof" but makes no requirements on their ability to perform as water seals.² The Bureau has conducted extensive research into the design and construction of explosionproof bulkheads and the forces exerted upon them from coal dust and methane ignitions. Although these designs may have application for impounding water, there are differences between explosion pressures and hydrostatic pressures and the forces that they exert on a structure.

In the case of an explosionproof bulkhead, the structure may never experience a significant loading until an explosion occurs. A methane or coal dust explosion exerts a dynamic loading on the bulkhead that rarely exceeds 50 psig. As a general rule, pressure at 200 ft or more from the origin of an explosion will not exceed 20 psig unless coal dust accumulations are abnormal and the incombustible content of the dust is far less than required by law (1).³ In contrast, inundation bulkheads are usually subject to a constant hydrostatic pressure, a static

loading, which could be present for the entire life of the bulkhead. In extreme cases, this pressure may reach 500 psi (approximately 1,150 ft of waterhead) and last for several days, until pumping or draining operations can be initiated. Permeation of acid water is another major structural concern, for it deteriorates the bulkhead and its anchorage, as well as the ground around the bulkhead.

When designing and constructing a bulkhead for the purpose of impounding water, several general criteria should be met:

1. The bulkhead should be designed to withstand the static forces of hydrostatic pressure rather than the dynamic forces of an explosion.
2. The bulkhead should be constructed from a material, such as concrete, which will resist deterioration by water.
3. The bulkhead should be constructed sufficiently thick and properly anchored, and the surrounding strata should be pressure grouted to minimize water seepage.

The ability to safely impound water underground will become increasingly important in future years. Inundation bulkheads will be needed to protect active workings in areas where mining is in close proximity to surface water bodies or water-bearing strata. Mining companies are also beginning to examine the possibility of impounding water underground as a means of eliminating the costly treatment of acid mine water before discharge. Presently, there is no commonly accepted design method for constructing bulkheads for this purpose. Prior to constructing a bulkhead for impounding water, a mine operator must first notify the Mine Safety and Health Administration (MSHA) and then submit detailed design and construction plans for

²Regulations governing the sealing of abandoned areas are covered in the Code of Federal Regulations, Title 30, Chapter 1, Part 75, Subchapter D, Subparts 329-1, 329-2, 330 and 330-1.

³Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

approval. This usually requires the assistance of a professional engineering consultant who has had prior experience in this subject.

It is strongly emphasized that this report is not intended to serve as a complete guide to the design of bulkheads for impounding water underground. Published literature on this subject is

marginal, and more research needs to be conducted to add to our present knowledge of plug and bulkhead design. This report seeks to increase the mine operators' understanding of inundation bulkhead design and other problems associated with underground water impoundments. Such information is essential to safe mining in areas where inundation is possible.

BULKHEAD DESIGN METHODS

TYPES OF BULKHEADS (2)

Bulkheads constructed for impounding water can be classified into five types.

Control.--Bulkheads that are planned in advance and constructed to seal abandoned mines and prevent the inflow of water into an adjacent active mine. They are installed between barrier or chain pillars with no means of access to the sealed-off area. Pipes with valves are usually cast into the bulkhead to measure and control water levels. They are designed to withstand the maximum water pressure that can develop. This is usually equal to the depth of the bulkhead below the surface.

Emergency.--Bulkheads constructed under emergency conditions to seal off unexpected intrushes of water. They are designed to withstand the maximum water pressure that can develop, with no means of access to the sealed-off area.

Precautionary.--Bulkheads planned in advance and constructed in main entries and haulage roads to control flooding should an inundation occur. Watertight doors are cast into the bulkheads to provide a travelway for workers and equipment. These bulkheads are designed to withstand the maximum water pressure that can develop.

Consolidation.--Bulkheads constructed to control water inflow during high-pressure grouting and ground consolidation operations. They are temporary structures which are removed after ground sealing is completed.

Open Dam Walls.--Open dam walls are used to impound water for treatment or conservation and reuse. They do not seal

the entire entry and simply limit the height of water to the height of the dam; but large volumes of water can be impounded in this way.

FACTORS TO CONSIDER IN BULKHEAD DESIGN

Several factors should be considered before designing and constructing a bulkhead to impound water:

1. The bulkhead should be located in competent ground that is not excessively fractured or broken, preferably in areas of stable ground (1). However, in most coal mines ground movements such as roof convergence and floor heave are inevitable, and supplemental roof supports (timbers and cribs) should be installed at the site.

2. The bulkhead, in most cases, should be designed to withstand the maximum hydrostatic pressure that can develop. Practical limits of potential inundation can be determined by plotting on a coal contour map the expected mine pool elevations and corresponding ground surface elevations. Areas where excessive waterheads may accumulate can then be projected. To convert waterhead, which is expressed in feet, to hydrostatic pressure, which is expressed in pounds per square inch, multiply the waterhead by 0.434.

3. The concrete for constructing the bulkhead must be properly mixed and placed to achieve acceptable strengths upon curing. (See section on "Concrete Specifications and Placement Methods.")

4. Anchorage of the bulkhead to mine roof, ribs, and floor is important, and depends on design as well as on strata type and condition. Some design methods rely on the strength of the concrete bearing against the irregularities in the rock surface to provide anchorage. Others require the excavation of trenches. Anchorage requirements for each design method are discussed in their respective sections.

5. Adequate pressure grouting of the immediate strata surrounding the bulkhead is probably the most significant factor in the bulkhead's long-term performance. Deterioration of the anchoring strata by acid water permeation is a major structural concern, especially if large pressures are anticipated over the life of the bulkhead. A brief review of grouting materials and methods frequently used to seal coal mine strata is given in the section on "Pressure Grouting."

THIN AND THICK PLATE DESIGNS (3)

Thin and thick plate formulas for designing bulkheads are derived through static analysis techniques, but the effectiveness of these designs for impounding water has not been thoroughly evaluated through full-scale prototype tests. These designs apply only to bulkheads constructed from homogeneous and isotropic materials.

Thin Plate Design

This design assumes that the bulkhead is to act as a simply supported thin plate, spanning the width of the entry; its structural behavior under static load is characterized by bending at midspan. Under these conditions, bending failure is governed by the tensile strength of the construction material. Using this analysis, the required bulkhead thickness is predicted to be

$$T = 0.865 a \sqrt{p/f_t} \quad (1)$$

where T = bulkhead thickness, ft;

a = maximum entry dimension, ft;

p = hydrostatic pressure, psi;

and f_t = allowable tensile strength of construction material, psi.

If $a = 18$ ft, $p = 100$ psi (230 ft of waterhead), and f_t (for concrete) = 150 psi (1), a bulkhead approximately 12.7 ft thick and unanchored⁴ would be needed to impound 230 ft of water.

In practice, this design formula may be conservative. Research indicates that bulkheads designed accordingly have resisted much higher dynamic loads (explosion pressure) with a considerable margin of safety (1). This observation suggests not only that bulkheads designed by this method can resist a much higher dynamic load, but also that the design method could be modified to more realistically represent the response of the structure under static load. Such is the case in thick plate design.

Thick Plate Design

The Bureau conducted a series of model test in the early 1930's (4-5) and found that restraining the edges of a bulkhead caused a dramatic increase in strength, well beyond what was expected from plate theory. Full-scale explosion tests also showed that bulkheads that were recessed into the roof, ribs, and floor, and that had thickness-to-width ratios of at least 1 to 10, resisted much higher pressures than the design pressure. It was concluded that recessing the ends of the bulkhead into the surrounding strata allows the structure to act as a flat arch. Under load, this arching behavior transmits a lateral thrust to the strata, which then act as a buttress.

Attempts have been made to explain this arching behavior through static design models. Whitney (6) developed an arch model that assumed the bulkhead to fail as two rigid walls, fractured at both

⁴Anchorage is supplied by bearing resistance between rock and concrete.

sides and along the midspan. Using this assumption, the design formula is predicted to be

$$T = \beta a \sqrt{p/f_c} \quad (2)$$

where T = bulkhead thickness, ft;

a = maximum entry dimension, ft;

p = hydrostatic pressure, psi;

f_c = allowable compressive strength of construction material, psi;

$$\beta = \frac{1}{\sqrt{2}} \left[1 - \left[\frac{S_c}{E} \frac{\sqrt{1 + 4\gamma^2}}{\sqrt{1 + 4\gamma^2} - 1} \right] \right],$$

where E = Modulus of elasticity of construction material, psi;

S_c = ultimate compressive strength of construction material, psi;

and $\gamma = T/a$, thickness-to-width ratio.

For average concrete mixtures; $S_c \approx 3,000$ psi, $E \approx 3$ million psi and with thickness-to-width ratios (γ) of at least 1 to 10, β is ~ 0.670 . Therefore, the thickness formula becomes

$$T = 0.670 a \sqrt{p/f_c} \quad (3)$$

If $a = 18$ ft, $p = 100$ psi (230 ft of waterhead), and f_c (for concrete) = 1,000 psi, a bulkhead approximately 3.8 ft thick and firmly anchored (recessed into the roof, ribs, and floor) would be needed to impound 230 ft of water.

Design equation 3 is very similar to design equation 1, the major difference being that the allowable tensile strength (f_t) is replaced by the allowable compressive strength (f_c). For most materials, f_c is 5 to 10 times f_t . This allows a reduction in required design thickness of 50 to 70 pct, provided that there is adequate anchorage. Excavating trenches

to recess the bulkhead into the roof, ribs, and floor contributes to this increased strength. The trenches assure that the applied load develops through the bulkhead and is then transferred to the load-bearing capacity of the coal roof, ribs, and floor.

The thick plate design approach has two principal drawbacks. First, the arching behavior described earlier does not occur until there is considerable cracking or fracturing of the bulkhead. The failure of a bulkhead under these circumstances can be catastrophic, especially if the hydrostatic pressure exceeds the design pressure. Second, the strength of the bulkhead depends directly on the bearing strength of the coal, roof, ribs, and floor strata. The Bureau has conducted research along these lines to determine the compressibility and bearing strength of in-place coal (5, 7). Future design criteria should include the bearing strengths of the coal, the roof, and the floor to assure adequate design.

Trench Depth (1, 4)

The required trench depth to properly anchor bulkheads has not yet been determined through either model or full-scale tests. However, acceptable requirements for minimum trench depths for bulkheads less than 3 ft thick can be presumed from research conducted on explosionproof bulkheads.

For concrete bulkheads, Rice (4-5), recommended trench depths, in the coal ribs, of at least one-tenth the width of the entry (0.1 W) after all loose coal on either rib had been scaled away. However, if the coal is distinctively soft or broken, a trench depth of one-fifth the width of the entry (0.2 W) was advised. In accordance, Mitchell (1) recommended that rib trench depths be at least 2 ft or the thickness of the bulkhead, whichever is greater.

Floor trenches should be a minimum of 12 in deep, provided the immediate floor strata have not been softened by water. If this is the case, trenching should

proceed until a competent stratum is reached. After excavation, holes should be drilled along the centerline of the trench to accommodate steel reinforcing rods of at least 7/8-in diam and 38 in long. The steel rods should be firmly grouted no less than 18 in deep, and spaced at no more than 18-in intervals.

If feasible, trenching of the roof is recommended. Owing to roof sag, the roof is usually where most water seepage will occur. Trenching the roof may be a difficult task because of the unpredictable nature of most roof rock. The immediate area should be stabilized with supplemental supports, and care should be exercised during the trenching operation. Trenches should be cut at least 8 in deep. Once the trenches are complete, additional anchorage should be provided with steel reinforcing rods of at least 7/8-in diam and 30 in long. The steel rods should be firmly grouted into the roof along the centerline of the bulkhead at a depth of no less than 18 in, with no more than 18-in spacing between rods.

When excavating the trenches the following should be observed:

1. Select a site where the ribs, roof, and floor are competent and not affected by long-term weathering or excessive ground movement and stress. As a routine measure, supplemental supports should be installed at the selected site.

2. Trim all loose coal from the ribs, making them as straight as possible. The same applies for loose rock on the floor and roof.

3. Cut the trenches with hydraulic or pneumatic tools, taking care to avoid unnecessarily fracturing the strata. Explosives should not be used to excavate the trenches unless very hard, competent strata are encountered.

4. Keep the width of the trenches the same as that of the bulkhead. All trenches should be cut as square as possible, especially at the inner and outer corners where the floor and rib trench meet.

SOUTH AFRICAN PLUG DESIGN (2, 8-9)

South African plug research was conducted during the late 1950's and early 1960's to resolve inundation problems encountered in the mines of the Witwatersrand and Orange Free State gold fields. W. S. Garrett and L. T. Campbell Pitt (8-9) designed, constructed, and tested an experimental concrete plug that withstood a hydrostatic pressure in excess of 6,000 psi. Their research led to a better understanding of the criteria that influence plug design. Although their tests were conducted under conditions unique to deep gold mines of South Africa, the assumptions and theory which formed the basis for their design formula can also be applied to water impoundments in underground coal mines.

Plug Design Formulas

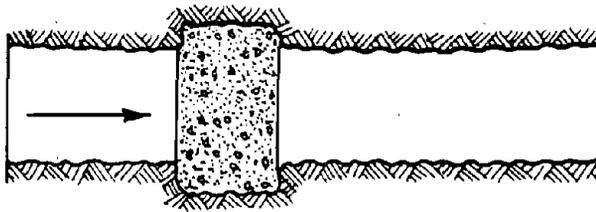
Garrett and Campbell Pitt considered three possible methods for designing plugs to retain high water pressures (fig. 1):

1. The plug would be constructed as a slab with all four sides recessed into the rock, with or without steel rod reinforcement (plate design).

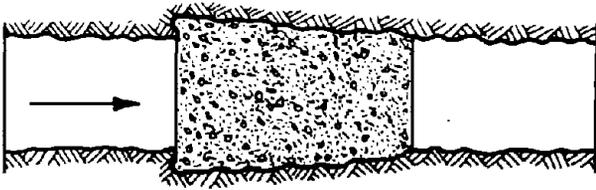
2. The walls of the drive would be tapered so the load could be transmitted from the plug to the rock wall by compression.

3. The plug would be parallel to the walls of the drive, and there would be no need for recessing or tapering. Anchorage would be provided by the concrete bearing, against the irregularities in the rock surface, after all loose material had been scaled away.

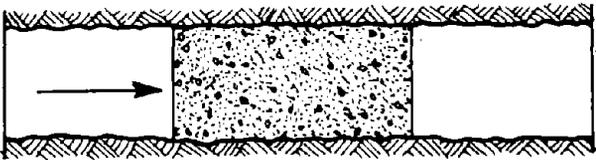
In many instances, these plugs had to be constructed under emergency conditions. Time was the most important factor, and site preparation had to be minimal. For this reason, they choose the third method (parallel plug design), rather than the first two methods, both



Slab keyed into walls



Taper plug



Parallel plug

KEY

→ Direction of hydrostatic pressure

Not to scale

FIGURE 1. - Methods of designing plugs to retain high water pressures. Adapted from W. S. Garrett and L. T. Campbell Pitt (8).

of which required ground excavation before the plug could be installed.

At that time, the accepted theory for parallel plug design assumed that the load, induced by hydrostatic pressure, was transmitted from the concrete plug to the rock as punching shear around the perimeter of the plug and along its full length. This was accepted by the

Government Mining Engineer as adequate criteria for parallel plug design. The length of the plug was derived from

$$pab = 2(a+b)lf_s \quad (5)$$

$$\text{Therefore: } l = \frac{pab}{2(a+b)f_s}$$

where l = length of the plug, ft,

a = width of the entry, ft,

b = height of the entry, ft,

p = hydrostatic pressure, psi,

and f_s = allowable shear stress for rock or concrete, whichever is the lesser,⁵ psi.

To learn more about this design, Garrett and Campbell Pitt constructed a smaller experimental plug, with doors, and tested it hydrostatically (8). The dimensions of this experimental plug are shown in figure 2. With each test, the hydrostatic pressure was increased and the strata surrounding the plug were pressure-grouted more extensively to seal leaks. A summary of the test results is shown in table 1. Upon completion of the test Garrett and Campbell Pitt made several observations, on which basis they revised the parallel plug design under the assumption that when a plug is installed in an entry, half of the rock surfaces will be at an angle (45°) that would resist movement of the plug by compression. The other half of the rock surfaces would resist movement by tension, provided the contact between rock and plug was ensured through adequate pressure grouting. The length of the parallel plug was represented as

⁵The Government Mining Engineer of South Africa recommends 85 psi as the allowable shear stress (f_s) for concrete placed in the normal manner and 120 psi for plugs where positive contact between rock and plug is ensured by subsequent pressure grouting (2).

$$pab = 2(a+b)l/2 l \tan 45^\circ f_c \quad (5)$$

Therefore: $l = \frac{pab}{(a+b)f_c}$

where l = length of the plug, ft,

a = width of the entry, ft,

b = height of the entry, ft,

p = hydrostatic pressure, psi,

and f_c = allowable compressive strength of the rock or concrete, whichever is the lesser,⁶ psi.

Garrett and Campbell Pitt realized that the two formulas were oversimplifications

⁶Garrett and Campbell Pitt used 600 psi as the allowable compressive strength of concrete.

of a very complicated stress condition. They felt that movement of the rock, from stress induced by the hydrostatic load, might likely be the governing factor in assessing the stress condition in the concrete of the plug itself. Therefore, the values that could be set on either allowable shear stress or allowable compressive strength depend on the effectiveness with which the concrete of the plug is confined by the surrounding rock. Using this analysis, it is impossible to recommend a particular formula for assessing the stress condition in the concrete until some satisfactory quantitative results can be produced on what actually takes place in the rock surrounding a plug under a hydrostatic load (9).

Table 2 gives a list of parallel plugs, constructed in the Witwatersrand and Orange Free State gold fields. Garrett and Campbell Pitt calculated the respective values of f_s and f_c from the two

TABLE 1. - Summary of test results on experimental plug

Test	Date	Cementation	Pressure, psi	Remarks
1....	7/31/57	No cementation.	75; 200; 310.	Heavy leakage on rock and concrete contacts particularly at hanging; tappings on hanging contact closed off to build up pressure >75 psi.
2....	8/15/57 to 9/ 5/57	Rock and concrete contacts cementated at 3,000 psi.	650- 1,750	Leakage on the rock and concrete contacts reduced; leakage past plug 50 gal/h at 1,750 psi.
3....	9/12/57	Rock surrounding the plug cementated at 6,000 psi.	1,800; 2,500.	Total leakage past plug 156 gal/h at 1,800 psi; 300 gal/h at 2,500 psi.
4....	10/ 3/57	Leaks sealed by cementation.	4,300	An old diamond drill hole began to leak at 3,000 psi; leakage 128 gal/h at 4,300 psi; leakage stopped when pressure was reduced to 2,000 psi.
5....	10/ 8/57	Further cementation to seal leaks.	5,700	Leakage not measured; pipe sleeve corrugated with crests of corrugations 15 in, 27 in, and 37 in from the door face.
	10/15/57	-----	6,200	Leakage in footwall of the drive ~400 gal/h; no further distortion of the pipe sleeve was apparent.
	10/17/57	Footwall leak cementated.	6,800	Leakages in footwall and hanging of main drive; pressure could not be raised further.

Source: W. S. Garrett and L. T. Campbell Pitt (8).

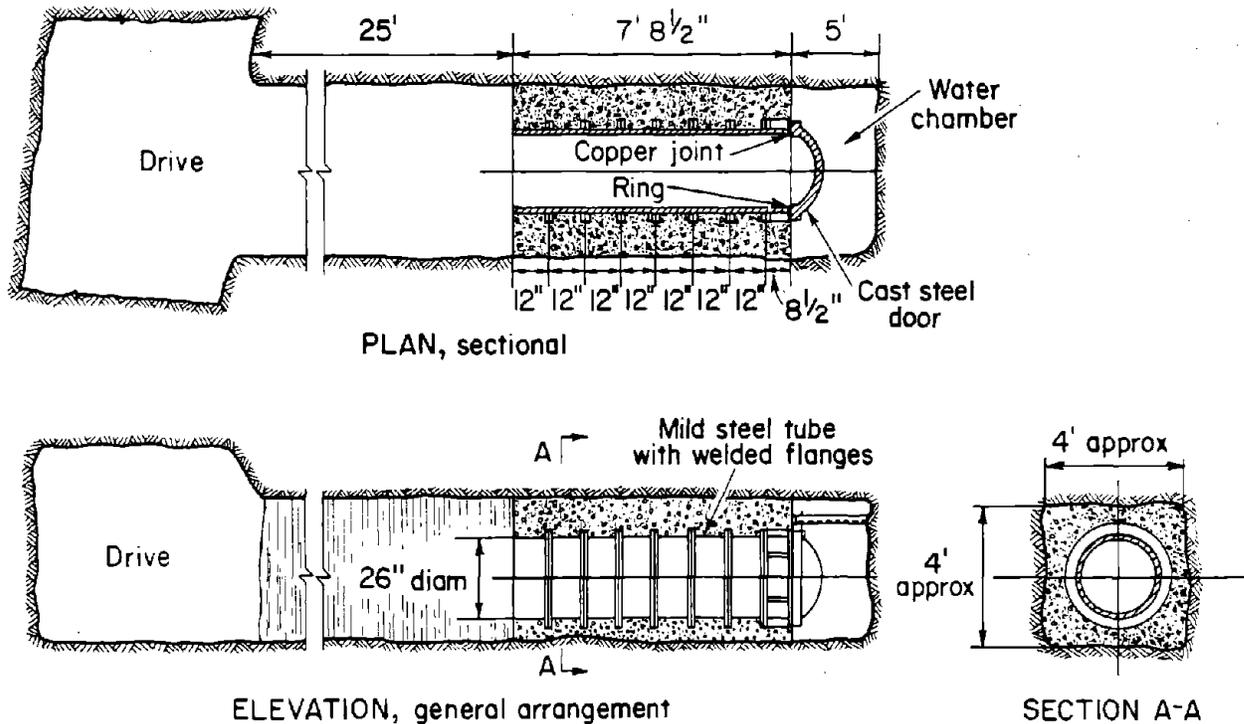


FIGURE 2. - Dimensions of experimental plug. Adapted from W. S. Garrett and L. T. Campbell Pitt (8).

TABLE 2. - Parallel plugs of the Witwatersrand and Orange Free State gold fields for which there are records of loads applied of over 1,000 psi

Mine and location	Dimensions, ¹ ft			Pressure, psi	f_s , psi	f_c , psi	Pressure gradient, psi/ft
	H	W	L				
Free State Geduld: No. 2 Shaft..	47	11	100	2,250	100	200	22.5
West Driefontein:							
Experimental.....	4	4	7.6	6,800	885	1,790	887.0
8 and 12 levels.....	13	10	41.6	1,827	124	248	43.5
Virginia: 31 Haulage South.....	13.5	10	63	1,650	75	150	26.2
Virginia-Merrie:							
Boundary plug.....	12.25	11	36	1,340	108	216	39.2
Temporary plug.....	12.25	11	12	1,340	324	648	111.7

¹H = height; W = width; L = length.

Source: W. S. Garrett and L. T. Campbell Pitt (9).

design formulas. Note the high values of f_s and f_c for the West Driefontein experimental plug, the plug that formed the basis for their design assumptions.

A plug similar to those constructed in South Africa is shown in figure 3. This particular plug is situated on the 1,200-ft level of the Friendsville Zinc Mine (owned by Gulf and Western Industries),

located near Allentown, PA. This precautionary plug separates the main shaft from the stopes. In the event of an inundation, the watertight doors are closed to prevent the main shaft from flooding.⁷

⁷For more information on the Friendsville Mine, see Cox (10).

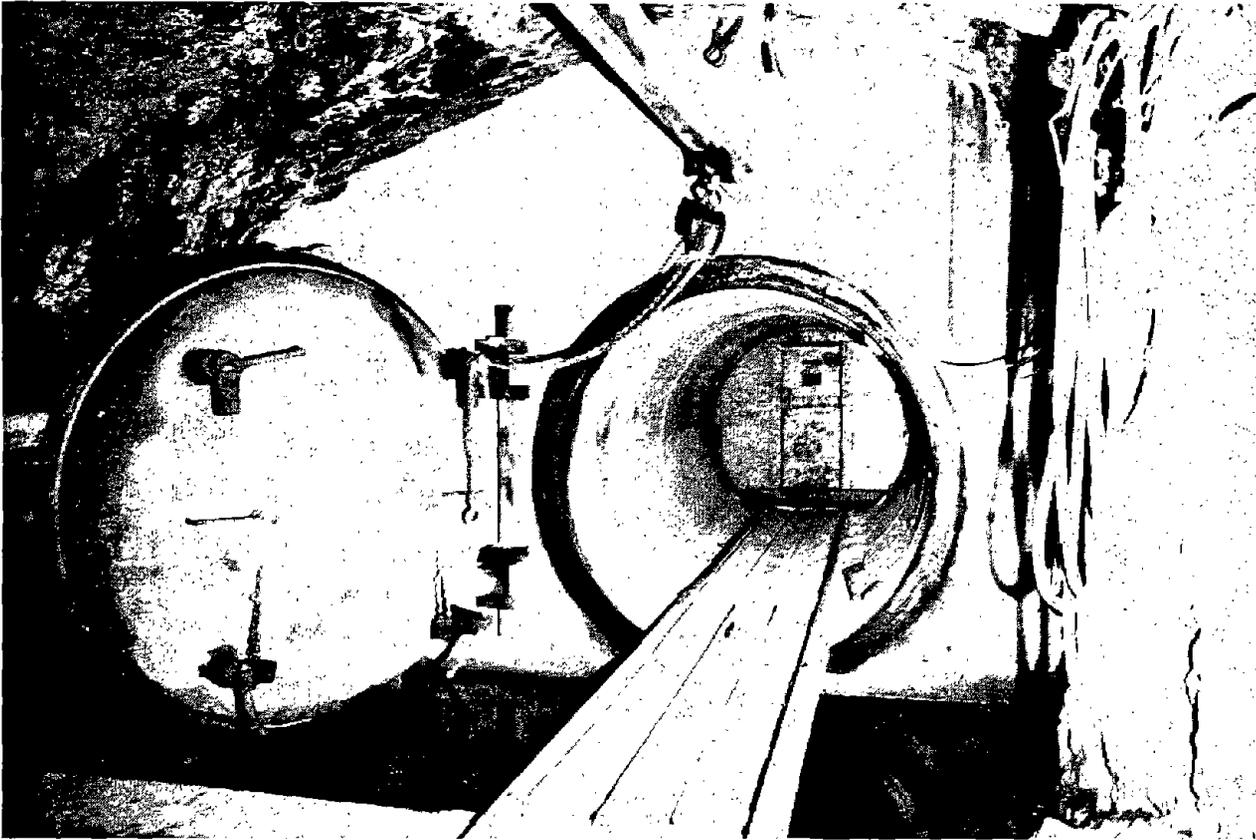


FIGURE 3. - Plug constructed on the 1,200-ft level of the Friendensville Zinc Mine.

The Relation of Water Leakage
to Plug Length

The effectiveness of a plug to impound water depends on the ability to minimize water leakage. Water can leak past a plug in several ways: along the plug-rock interface; through the cracks, fractures, and fissures in the rock surrounding the plug; or through the concrete of the plug itself. These three modes of water leakage are dependent upon the length of the plug and the resistance of the rock to the permeation of water. Garrett and Campbell Pitt felt that the leakage aspects of the rock could be used as criteria for plug design. They expressed this leakage as a pressure gradient in the rock:

$$p.g. = p/l \quad (6)$$

where $p.g.$ = pressure gradient, psi/ft,

p = hydrostatic pressure, psi,

l = length of plug, ft.

According to the tests on the experimental plug in table 1, the limiting value of the pressure gradient was achieved on four occasions when leakage became extensive and obvious:

1. Before grouting of the plug-rock interface when hydrostatic pressure reached 75 psi, the pressure gradient was $75 \text{ psi}/7.67 \text{ ft} = 9.8 \text{ psi/ft}$.

2. After grouting the plug-rock interface but before grouting the rock, when the hydrostatic pressure reached 1,750 psi the pressure gradient was $1,750 \text{ psi}/7.67 = 228 \text{ psi/ft}$.

3. After grouting the rock to 6,000 psi with cement, an approximate

hydrostatic pressure of 3,000 psi was exerted. The pressure gradient was $\pm 3,000$ psi/7.67 ft = ± 400 psi/ft.

4. After extensive chemical grout injections in the rock, the hydrostatic pressure rose to 6,800 psi and the pressure gradient was $6,800$ psi/7.67 ft = 887 psi/ft.¹

The pressure gradients calculated above are unique to the particular rock (quartzite) in which the experimental plug was constructed, but the theory of using a safe pressure gradient as design criterion offers a valuable means of taking into account the important factor of the ground surrounding the plug. Garrett and Campbell Pitt believed that values for minimum and maximum pressure gradients could be established experimentally for various rocks. Also, they recommended that plugs designed accordingly should have a leakage factor of safety of at least 4 and as much as 10 in some cases, depending on conditions such as fractures in the rock after mining and the subsequent redistribution of stress, porosity of the rock, and its acceptance of grout.

Figure 4 shows the minimum length of plugs based on ultimate pressure gradient values obtained from the tests on the experimental plug. Also given are curves for plugs with safety factors of 4, 6, 8, and 10 with the provision that the surrounding rock is grouted to at least the same pressure which the plug is designed to resist.

SINGLE AND DOUBLE BULKHEAD SEALS (11-13)

Single and double bulkheads seals, also known as hydraulic seals, are commonly used to permanently seal abandoned drift and slope mines and protect the environment from the undesirable effects of acid mine drainage. Historically, thickness and anchorage requirements for these seals have been derived from experience and are based on the immediate ground conditions and the amount of water to be impounded. Various types of hydraulic seals have been demonstrated in the United States. Most of this sealing work

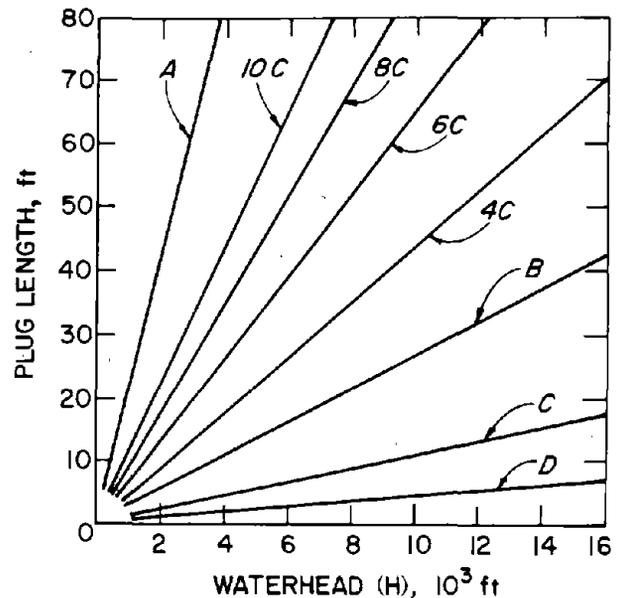


FIGURE 4. - Length of plugs based on ultimate pressure gradient values. *A*, Minimum length of plug that would be required if the contact between plug and rock is ungrouted. No factor of safety; *B*, minimum length when the contact is grouted but before the rock is grouted. No factor of safety; *C*, minimum length when normal grouting of rock was at 6,000 psi. No factor of safety. (*4C*, e.g., means $4 \times C$); *D*, similar to *C*, but with the addition of chemicals to seal rock fissures. *C* is then applicable to a normally grouted plug but with no factor of safety. Adapted from W. S. Garrett and L. T. Campbell Pitt (8).

was performed in the East, as part of Federal and State acid mine drainage research and abatement programs (11, 13).

Single Bulkhead Seals

Single bulkhead seals are usually constructed from concrete, grouted aggregate, or concrete block. They are commonly used to seal off abandoned mines from active workings, and such seals have been documented to withstand water pressure as high as 70 psi (161.5 ft of waterhead) (11). In many instances, plate theory is used in their design,⁸ or minimum thicknesses and anchorage

⁸Thick plate design, discussed earlier in this report, is applicable for determining thickness and anchorage requirements for single bulkhead seals.

requirements are derived from research on explosionproof bulkheads. The Bureau recommends that a bulkhead must withstand a dynamic pressure of at least 50 psi for it to be explosionproof (1).

To learn more about the application of explosionproof designs for impounding water, the Bureau hydrostatically tested a concrete block bulkhead commonly used in coal mines to resist explosion. The bulkhead is 16 in thick with the block laid in a transverse pattern and a plaster at center span for additional support. It withstood 50 psi of water pressure before tests were stopped owing to water leakage through the bulkhead structure. Details of this research are presented in appendix A.

There are numerous problems associated with the impoundment of water by single bulkhead seals. The long-term effectiveness of these seals is questionable even under low pressure, because of their relatively short thicknesses. When large hydrostatic pressures are anticipated, double bulkhead seals are considered more effective.

Double Bulkhead Seals

The double bulkhead seal is constructed by placing two retaining bulkheads in a mine entry and then placing an impermeable seal in the space between them (fig. 5). The front and rear bulkheads provide a form for the center seal which is formed by placing concrete or injecting grout into a preplaced aggregate. The retaining bulkheads are constructed from concrete, concrete block, or brick and should be sufficiently thick and well anchored to hold the center seal in place while it is poured and as it cures.

The required thickness for double bulkhead seals range from 10 to 45 ft depending on the ground conditions, the strength of the concrete, and the amount of water to be impounded. There are no recommended designs for calculating this

CONCRETE SPECIFICATIONS AND PLACEMENT METHODS

SPECIFICATIONS

Concrete for constructing bulkheads can achieve different strengths depending

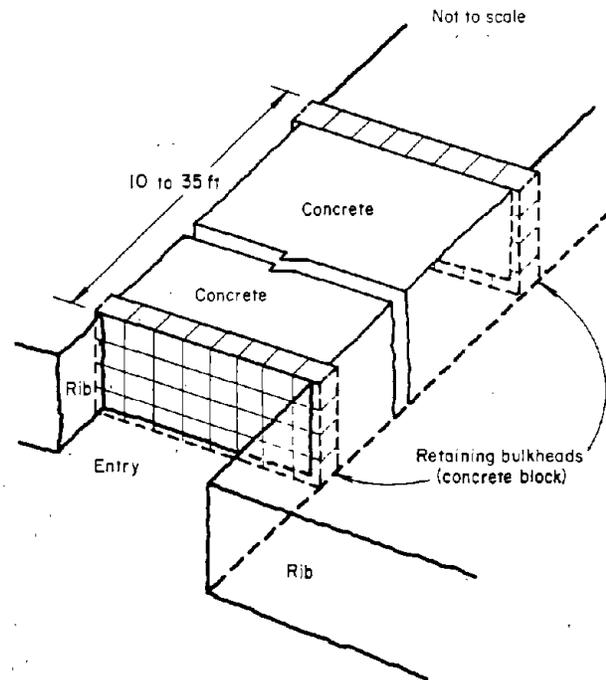


FIGURE 5. - Double bulkhead seal showing retaining bulkheads and concrete center.

thickness, but the South African plug design may be applicable in this situation. Since no trenching is required for the center seal, the anchorage depends on the strength of the concrete bearing against the irregularities in the rock surface. However, steel rods can be grouted into the roof, ribs, and floor surrounding the center seal to provide additional shear strength.

The double bulkhead method of sealing mine entries has been successfully demonstrated at Moraine State Park, Butler County, PA, under the State's "Operation Scarlift" reclamation program. These seals were placed in inaccessible mine entries through vertical boreholes drilled from the surface. A total of 69 seals were installed ranging in thickness from 17 to 40 ft. The seals were constructed from a fly ash, sand, gravel, and cement mixture (12).

upon the method of construction, the thickness of the bulkhead, the contents and proportions of the mix and curing time.

For explosionproof bulkheads the Bureau recommends (1, 4-5) a mix, by volume, of 1 part type I Portland⁹ cement, 2 parts clean sand, and 4 parts clean gravel. Only enough water should be added to make the mix homogeneous and give a stiffness consistency that will enable it to be properly placed in the form. Overwatering must be avoided, for it reduces the strength of the concrete. The Bureau contracted a professional engineering laboratory to conduct strength tests on the above mix. Test cylinders were prepared, and after curing for 28 days the samples were tested for ultimate compressive and tensile strengths. Shear strength was calculated by using an equation developed from Mohr's Circle which relates compressive, tensile, and shear strength of the sample. The strength values are given in table 3.

TABLE 3. - Ultimate compressive, tensile, and shear strengths for 1:2:4 concrete mix

	Test 1	Test 2	Average
Strength, psi:			
Compressive...	2,933	3,074	3,004
Tensile.....	233	255	244
Shear.....	NAP	NAP	766
Slump, in.....	NAP	NAP	1.5

NAP Not applicable.

Equations 1-5 require using the allowable flexural, shear, and compressive strength values of the construction material so as to provide adequate margins of safety. As a rule of thumb, allowable strength values range from 20 to 30 pct of the ultimate strength. According to Garrett and Campbell Pitt (9), concrete of great strength is not important. If 2,500 psi ultimate compressive strength is obtained after 28 days, the safety factor is >4. They used 600 psi as the allowable compressive strength (f_c) for concrete plugs designed according to equation 5. In addition, plug design equations 4 and 5 require that the

allowable shear or compressive strengths of the concrete or rock be used. In most cases, the allowable shear and compressive strengths of coal and other stratified rock will be less than those for concrete and should be used in these design equations to assure adequate margins of safety.

During the curing of a large mass of confined concrete, such as a plug, cracking and shrinkage can occur. For this reason, prolonged, thorough curing is a significant factor in attaining impermeable watertight concrete. Cracking is usually caused by high heat of hydration generated during curing. This weakens the concrete and may affect its ability to resist design pressure. Shrinkage can affect anchorage and is a result of excessive water content or inadequate aggregate composition. Some shrinkage is inevitable in concrete, and pressure grouting is necessary to improve contact between the bulkhead and surrounding rock. The addition of pozzolans, such as fly ash, to concrete can improve workability, reduce heat of hydration and shrinkage, and increase resistance to sulfates contained in water. However, caution must be exercised in the selection of pozzolans, because their properties vary widely and excessive amounts may have adverse effects on the concrete, such as increased shrinkage and reduced strength and durability (14). Before selecting a mix, trial mixes should be made, especially when using admixtures and pozzolans.

To attain concrete with specific properties, other types of Portland cement can be used. Type II is for general use, more specifically when moderate sulfate resistance and heat of hydration are desired. Type IV gives low heat of hydration, and Type V is used when high sulfate resistance is desired. Standard specifications for Portland cement are given in ASTM Designation C150, Part 14. Standard specifications for fly ash and raw or calcined natural pozzolans for use as mineral admixtures to cement concrete are given in ASTM Designation C618, Part 14.

⁹Reference to specific equipment (or trade names or manufacturers) does not imply endorsement by the Bureau of Mines.

PLACEMENT

There are several commonly used methods for placing concrete for bulkheads in accessible mine entries. When constructing only one or two bulkheads, concrete can be mixed underground by hand or machine and placed in the forms either manually or with concrete pumps (fig. 6). If several larger bulkheads are to be constructed, concrete is usually placed from the surface through a vertical borehole to a central underground site where a slurry-distributor is located. The slurry-distributor remixes the wet concrete and pumps it to the individual bulkhead sites (fig. 7). Another variation of this method requires the drilling of one or several vertical boreholes directly to the entry where the bulkhead(s) are to be placed. This method is used when several large plugs or double bulkhead seals are needed. Retaining bulkheads or rigid wood forms are then built between the boreholes, and concrete is then introduced directly from the surface through the boreholes to the space between the forms (fig. 8).

When placing large volumes of concrete, such as a plug, the coarse aggregate may separate from the mix and settle, causing the concrete to lose its strength characteristics upon curing. To avoid this and also to improve concrete workability, the coarse aggregate can be preplaced between the retaining bulkheads or forms and concrete grout injected into the aggregate. The aggregate can be preplaced by hand or stowed pneumatically.¹⁰

For bulkheads less than 3 ft thick (1), concrete can be mixed underground by hand or machine and forms constructed from lumber. Plywood forms should be at least 3/4 in thick and support boards 2 in by 4 in. Boards must be properly spaced so the forms can resist the hydraulic head of the concrete as it is placed and cures. The ends of the forms should be flush with the edges of the trenches in the roof, ribs, and floor and should not extend into them. On the outby side (the

side from which the concrete is placed), the form boards should be about half height with the remainder of the boards cut and readily available for insertion as needed.

Before placing the concrete, any water in the floor trench must be removed. The concrete is placed in successive horizontal layers, with care taken to fill the rib recesses completely. There must be no delay greater than 30 min between mixing and placing the concrete for the entire bulkhead, because greater delays cause cold joints that could weaken the structure. However, if unavoidable delays are foreseen, steel reinforcing rods, of at least 7/8-in diam and 16 in long, should be installed vertically in the last layer about 18 in apart and projecting upward 8 in or more. The surface of the cold joint should be cleaned before placing fresh concrete. As the roof is approached, placing the concrete becomes more difficult but cannot be neglected. Concrete should be worked well into the roof cavity and also around the reinforcing rods extending from the roof and into recesses in both coal ribs.

Forms should not be removed for at least 4 to 7 days after the concrete is placed. Noticeable voids on the outby side of the bulkhead can be filled with stiff concrete or a cement gun, if available.

For bulkheads over 3 ft thick, building retaining bulkheads for forms is the best approach. Retaining bulkheads can be constructed from concrete, concrete block, or brick, but the latter two are preferred to forego the need of constructing wood forms for the concrete. Mortar for block and brick must be properly mixed to ensure good bonding.

Concrete for the center plug can be mixed and placed underground by machine or from the surface through vertical borehole(s). Hand mixing and placing should not be attempted, owing to the large volumes involved. As mentioned earlier, the coarse aggregate can be preplaced between the retaining bulkheads and concrete grout injected through the outby side of the bulkhead or from the surface through vertical boreholes.

¹⁰Details for building seals and placing aggregate by pneumatic stowing are provided by Maksimovic (15-16).

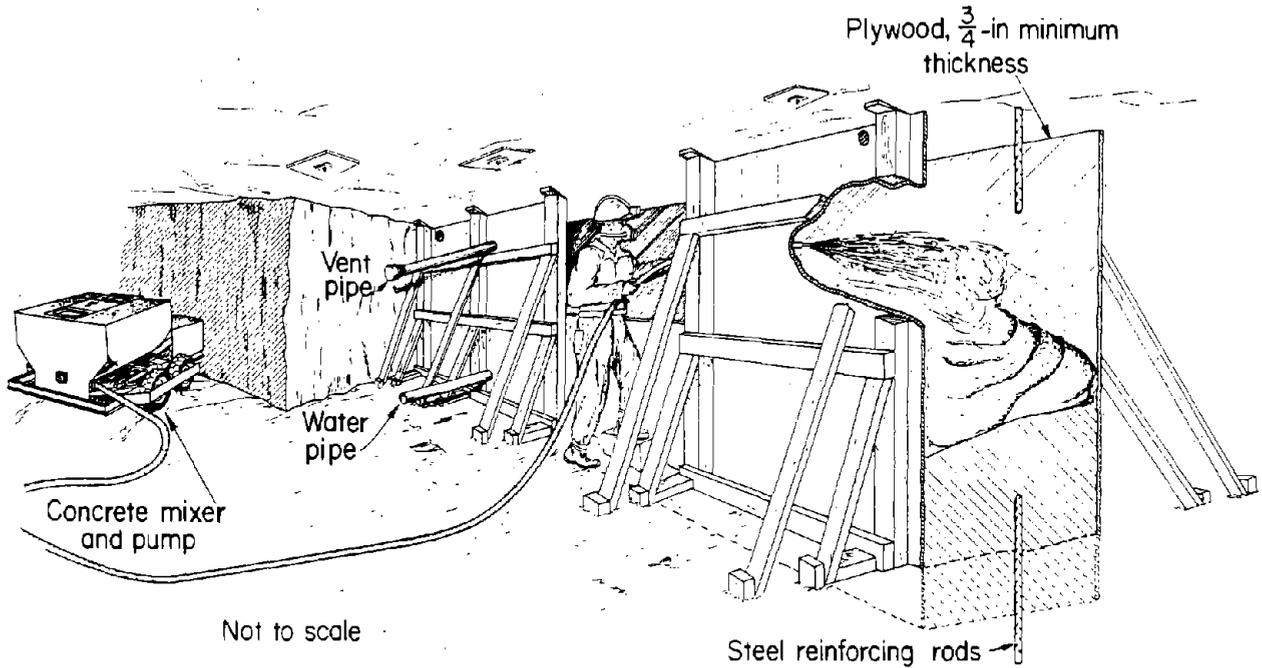


FIGURE 6. - Concrete being mixed underground and placed in forms by concrete pump.

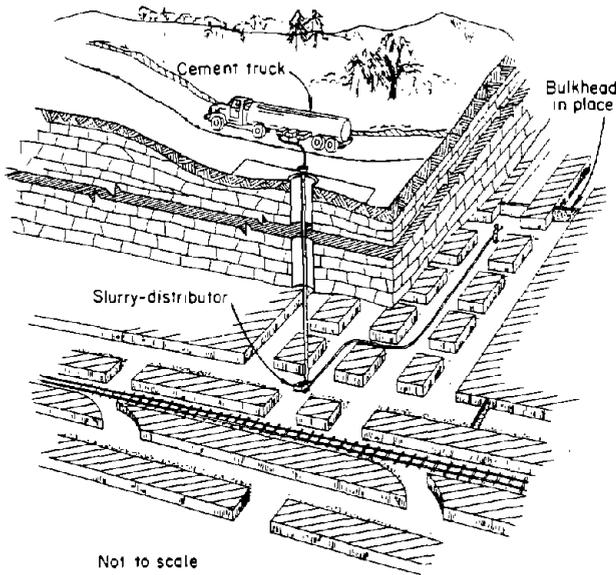


FIGURE 7. - Pumping concrete from the surface through a single vertical borehole to a central underground site.

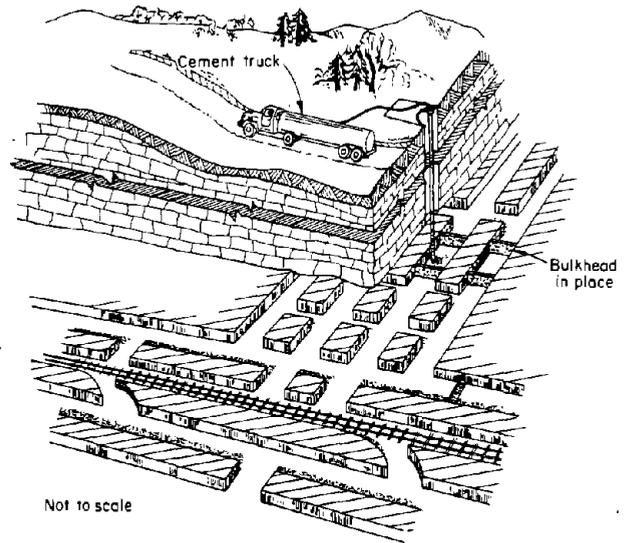


FIGURE 8. - Pumping concrete from the surface through a vertical borehole directly to bulkhead site.

PRESSURE GROUTING (17)

Pressure grouting involves the injection of fluid materials, under pressure, into rock or soil to fill pore spaces, consolidate material, and prevent water migration. Grouting the strata

surrounding inundation bulkheads is a most significant factor in their long-term performance, because it reduces strata permeability and increases strength and durability with respect to

aqueous solutions. There are many factors to consider in planning a grouting program, such as the drilling, spacing, and depth of holes; the proper selection of grouting materials and equipment; the control of grout volumes and injection pressures; and a knowledge of the strata to be grouted. Pressure grouting is a highly specialized technique requiring experience and sound engineering judgment, so that procuring the services of qualified personnel is essential.

In some respect, pressure grouting is an art, for which the establishment of rigid rules and procedures is not feasible. However, a knowledge of basic grouting materials and methods is recommended.

GROUTING MATERIALS

An important factor in the successful grouting of permeable coals and other stratified rock is the selection of a suitable grouting material. There are four basic types of grout: Portland cement, asphalt, clay, and chemical grouts. Technical literature and field experience show that Portland cement and chemical grouts are the most applicable and effective for grouting coal mine strata.

Portland Cement Grout

Portland cement is the most widely used grouting material because of cost, availability, and everyday knowledge of the material. Neat cement grout consists of Portland cement and water, but mineral admixtures are often used with this base to attain grouts with specific characteristics. There are five types of Portland cement (excluding air-entrained cements) that conform to ASTM Designation C150 and can be used for cement grouts. Each type possesses specific properties that may be needed to meet job requirements.

Type I is a general-purpose cement suitable for most grouting jobs. It is used when the special properties of the other four types are not needed. Type II has moderate resistance to the sulfates in groundwater. With type II the heat of hydration is less and develops at a slower rate than that of type I. Type

III is used when early strength gains are required within 10 days or less. It also has a finer grind, which improves its injectability. Type IV generates less heat than type II and develops strength at a very slow rate. It is rarely used in grouting. Type V has a high resistance to sulfates and is used when groundwater with extremely high sulfate content is encountered.

Mineral admixtures are finely divided materials that are added to neat cement grout to improve or achieve a specific characteristic. Calcium chloride, sodium silicate, and gypsum, when used in small amounts (2 to 4 wt pct), act as accelerators and decrease the setting time of the grout. Accelerators are used when there is little heat to aid in setting. They may also be used to reduce grout migration, reduce erosion of new grout by groundwater, and increase the rate of early strength gains. When high temperatures are encountered, retarders such as sodium chloride and calcium lignosulfonate are used to increase setting time. These admixtures allow the grout to migrate properly into fine pore spaces before setting.

Fly ash and natural pozzolans such as diatomite and pumicite are admixtures that when used in small amounts improve the pumpability of the mix. They may also be used as a filler and can compose up to 30 wt pct of the mix. In this case, they react chemically with the cement to produce cementitious properties and improved bonding. Other admixtures include bentonite, which is used to increase water requirements and reduce the unit weight of the mix; latex additives, which improve bonding and increase grout resistance to acids and other corrosive solutions; and aluminum powder, which increases viscosity and causes the grout to expand slightly.

Water-to-cement ratios for Portland cement grouts are indicated by either weight or volume. The volume method is more convenient and most frequently used in the field. A sack of cement is considered to equal 1 ft³. The mixing ratios of water to cement used most frequently range from 1:1 to 4:1. The choice of a starting mix depends on such

factors as the size and amount of pore spaces in the strata, the amount of water the strata bears and experience with grouting similar strata. In general, grouting is started with a thin mix. Thicker mixes are used based on the ability of the strata to accept the grout. If the strata accepts the starting mix readily without pressure buildup, thicker mixes are considered in accordance with the objectives of the grouting program.

Chemical Grouts

In recent years, the use of chemical grouts to consolidate permeable rock and soil has gained increased popularity. The primary advantages of chemical grouts over Portland cement grouts are their improved bonding characteristics, low viscosity, better flowability, and good control of setting time. Some chemical grouts are water reactive and expand slightly by contact with water, a feature that is advantageous in sealing fine pore spaces in the rock. Some disadvantages include possible toxicity, so that they may not meet MSHA permissibility standards for use underground. Also, they are relatively higher in cost than Portland cement grouts.

Research and development is continuing at a rapid pace, and currently a number of commercial manufacturers produce chemical grouts and injection equipment. Most grouts consist of two or more components that must be mixed before injection. Because of the critical nature of proportioning, this mixing should only be done under the supervision of company personnel. It is beyond the scope of this report to review all commercial grouts currently available. If one is considering the use of a chemical grout, the best approach is to consult directly with a company that has a proven grouting technique.

GROUTING METHODS

Procedures for grouting permeable strata vary, as dictated by the characteristics of the strata and the program objectives. Regardless of how much exploratory drilling and other pregrouting

investigation is done, the size and continuity of pore space in the strata will remain relatively unknown. The art of successful grouting requires the ability to treat these unknowns through experience obtained from similar grouting work. Three basic grouting methods are used in mine to seal and consolidate permeable strata surrounding a bulkhead: curtain grouting, blanket grouting, and contact grouting.

Curtain grouting involves the construction of a curtain or barrier of grout by drilling and grouting a linear sequence of holes. Its primary purpose is to reduce strata permeability. A grout curtain can consist of a single row of holes or two or more parallel rows. "Primary" holes are initially drilled into the roof, ribs, or floor on rather widely spaced centers ranging from 20 to 40 ft. After the two primary holes have been grouted, a first intermediate hole is drilled midway between them. After this hole is grouted, two secondary intermediate holes are drilled midway between the primary and first intermediate hole. This pattern of drilling and grouting continues until grout consumption indicates the strata to be sufficiently tight. Grout consumption should decrease as the spacing of intermediate holes become smaller.

The hole depth for curtain grouting depends on the flowability of the grout, the ability of the strata to accept grout, and the distance the grout must migrate to create a satisfactory seal. Generally, the primary holes are the deepest, with intermediate holes being drilled less deep with each successive grouting.

Blanket grouting involves the injection of grout, under low pressures, into shallow holes drilled on a grid pattern. Its primary purpose is to increase the bearing strength of the strata. Blanket grouting may be used to form a grout cap prior to curtain grouting and serve as a barrier to improve the migration of higher pressure grout into deeper horizons, but it is more commonly used to consolidate fractured or severely weathered strata in a mine entry prior to bulkhead construction. This grouting method

strengthens the strata and provides bearing support when constructing a large plug or excavating trenches to recess a bulkhead. Holes are drilled on 5- to 7-ft centers and are shallow, 3 to 5 ft deep. Severely fractured strata may require the holes to be drilled on tighter spacings of 1 to 3 ft.

Contact grouting involves the grouting of the voids between the roof, ribs, and floor of the entry and the bulkhead or plug. These voids result primarily from improper concrete placement and concrete shrinkage while curing. This is considered a most important grouting procedure, because it improves bonding and prevents

water seepage along this concrete-strata interface. Over the long term, it minimizes the premature failure of bulkhead anchorage.

Holes for contact grouting are usually provided for by placing steel pipe or packers at predetermined locations along the concrete-strata interface before the concrete is poured. The pipes, which protrude from the forms, act as a travel-way for the grout after the concrete cures. At times, during the pouring of the plug, the pipe may fill with concrete which must then be drilled out so that grout can migrate properly along the interface.

BARRIER PILLARS

PILLAR CONSIDERATIONS

Bulkheads can be designed to withstand a considerable amount of hydrostatic pressure, but the seal is only a small part of the water impoundment. The perimeter of the abandoned area, consisting of chain or barrier pillars, forms a large part of the impoundment and at times may not be capable of withstanding the design pressure. Practical limits of inundation can be determined by plotting on a coal contour map the expected mine pool elevations and corresponding ground surface elevations. Areas of excessive pressure are projected, and determinations are made as to the capability of the coal pillars to withstand the anticipated water pressure.

There are no specific Federal regulations concerning the size of barrier pillars that separate active mines from inundated abandoned areas. In general, there are two ways MSHA handles potential inundations involving barrier pillars. Their first concern is whether the situation presents an imminent danger to the mine and the workers. Second, if no imminent danger exists, is whether proper procedures (such as drilling, etc.) are being followed when mining toward or adjacent to impounded water.¹¹ A number of questions are considered to determine if an imminent danger exists. First, does the coal barrier have an adequate width? Second, what is the hydrostatic

head and the amount of water impounded? Third, what is the physical condition of the barrier? Fourth, if the barrier were to fail, is there sufficient time to warn and evacuate workers (18)?

In most cases, before an underground impoundment is created by constructing bulkheads, the width of the coal pillars is known. Determinations must then be made as to the limits of hydrostatic pressure that the pillars can withstand.

PILLAR WIDTH FORMULAS (18-21)

Determining whether an existing coal pillar is sufficiently wide to resist a specific waterhead is a complex problem that cannot be solved with a high degree of certainty. However, several formulas, based on experience and empirical observation, have been developed for this purpose.

The first is the Ashley, or Mine Inspector, Formula, established by a seven-member commission for the Commonwealth of Pennsylvania for incorporation into State law. The primary objective of the commission was to develop a method of

¹¹Section 107(a) of the 1977 Act covers the imminent danger situation and Sections 75.1200, 1200-1, 1200-2, 1201, 1202, 1202-1, 1203, 1204, and 1701 of Title 30, Code of Federal Regulations, outline the criteria governing MSHA's enforcement activities.

designing coal barriers to impound water and protect active mines from unexpected inundations. From the findings of the commission, the minimum width of the barrier is expressed as

$$W = 20 + 4T + 0.1D \quad (7)$$

where W = Width of the coal pillar, ft,

T = average thickness of the coal seam, ft,

and D = depth of overburden or the height of waterhead, ft.

Knowing W and T , the maximum waterhead that a barrier can withstand (D) can be determined.

A second formula, developed in England through observation and measurement, is based on the pressure arch concept of stress distribution. Here the width of the barrier is presumed to be

$$W = 0.15D + 60 \quad (8)$$

where W = Width of the coal pillar, ft,

and D = depth of overburden, ft.

This formula does not take into account the thickness of the seam and consequently may be unsatisfactory for water impoundments. Data and field experience presented during the development of the Ashley Formula indicate that seam thickness is an important factor in the design of coal barriers. With all other factors being equal, a thick seam requires a thicker barrier than a thin seam.

The third formula, developed by C. T. Holland (20), is the least used of the three. It has been stated that this formula is not suitable for computing water dams, although it has been compared with the two previous formulas (21). The width of the barrier is given as the greater of

$$W = 15T \text{ or } 5 \left(\frac{\log 2 W_2}{0.09 \log \lambda} \right) \quad (9)$$

where W = Width of the coal pillar, ft,

T = average thickness of the coal seam, ft,

W_2 = the estimated convergence on the high stress side of the pillar, mm,

λ = the base of the natural system of logarithm (2.72),

5 = a constant which includes a factor to convert metric to English units and a safety factor;

and 0.09 = a coefficient if caving following mining is permitted.

Holland suggests that the convergence factor, W_2 , be estimated as a function of overburden depth according to

$$W_2 = 10 \lambda^{0.0012D} \quad (10)$$

where W_2 = Convergence, mm,

λ = 2.72,

and D = depth of overburden, ft.

This relationship gives the convergence at various depths for a coal bed 7 ft thick and having a strength of 3,000 psi in a 3-in cube.¹² It should be noted that under the assumed conditions, the Holland Formula will give wider barriers than the Ashley Formula at all depths.

The actual safety factor associated with these formulas cannot be readily determined because of the many elements that have an unknown effect on the barrier. These include stress redistribution after mining, subsidence, geologic features such as slips and faults, the long-term effects of water seepage, pore water pressure, ground saturation, and deterioration and the favorable aspects of pressure grouting. Since no one formula is universally applicable, mine personnel must exercise sound engineering judgment

¹²To estimate convergence for coals having different seam thickness and strengths, see Holland (20).

in determining the practical limits of potential inundation. The design of bulkheads for underground water

impoundments should be based on the maximum hydrostatic pressure that a coal barrier can withstand.

MONITORING WATER PRESSURE

The hydrostatic pressure in the inundated area should be monitored. There are two basic methods to accomplish this: (1) from vertical boreholes drilled from the surface to the inundated area, and (2) in-mine, through piping cast into the bulkheads themselves. The first method involves the drilling of a vertical borehole from the surface to the inundated area and measuring the height or pressure of a column of water with a water-level indicator or pressure transmitter. These instruments are commercially available from manufacturers of geophysical and hydrological instrumentation.

One type consists of a detection meter and a water-sensitive electrode attached to 300 to 500 ft of electrical cable numbered in 1- to 5-ft intervals. The level of the water below the surface is measured by lowering the electrode down the borehole until a sharp needle deflection on the meter indicates that water is contacted. The approximate waterhead is determined by subtracting this distance from the total depth to the coalbed where the bulkhead(s) is(are) located. To convert waterhead expressed in feet to hydrostatic pressure in pounds per square inch, multiply by 0.434.

Another system uses a float to measure the water column in the monitor wells. The float is connected to a steel wire upon which are crimped brass beads at 6-in intervals, to prevent line slippage. The line wraps around a measuring wheel and an idler pulley, and the wheel movement drives a depth recorder. On the older mechanical recorders, the wheel drove a pen directly, and a spring or electric motor ran a time drive. The spring drives can operate for up to 6 months without winding, and the chart paper comes in rolls good for up to 2 yr, both depending upon drive speed. Newer recorders have been especially designed for telephone transfer of the data, and an add-on device is available to convert the older mechanical recorders to

transmitting recorders. The floats come in various sizes, with a 3-in-diam float presently being the smallest. Because the float must be counterweighted and the excess line must hang in the hole, the smallest practical hole size is 4 in ID, although larger sizes are recommended to allow the float and counterweight to pass each other without interference. The float-beaded line systems have been used in holes as deep as 650 ft, with float depths up to 350 ft, with no difficulty.

Still another method of monitoring pressure from vertical holes is to install strain-gauge type pressure transmitters. Pressure transmitters capable of operation in water at depths as great as 5,000 ft are readily available. Although the difficulties of finding drift-free transducers for long-term installation and connecting them to a cable are not trivial, a few manufacturers have partial systems available. Pressure transmitter systems are also available from companies serving oilfield needs. Most of these are strain-gauge type systems, although one company makes a system which uses a small-diameter tube and a gas-filled chamber at the bottom of the hole with the pressure transducer at the surface. Both the strain-gauge systems and the gas chamber system are capable of operating under high pressures. However, these systems are very expensive and many are available for rental only, and on a short-term basis.

A second and more direct method of monitoring hydrostatic pressure involves casting a pipe into the bulkhead and installing a pressure gauge or pressure transducer. Pipes can be either plastic or metal, though metal pipes must be corrosion resistant. Care must also be taken if plastic pipe is used to insure that the pipe will be able to withstand the maximum anticipated hydrostatic pressures (this of course applies to all valves and fittings). Pipes should be installed 6 to 12 in from the floor and 12 to 18 in

from the rib having the lowest elevation. The pipe should have a 1- to 2-in ID and extend 2 to 3 ft from either side of the bulkhead. Both ends of the pipe must be threaded to permit the installation of a piezometer installed on the inby side of the bulkhead (water side) and a pressure gauge or pressure transducer and valve on the outby side. The piezometer allows water to pass into the pipe, but traps sediments that can clog the pressure gauge and affect readings. Piezometers can be handmade from a porous, fine-grained material such as sandstone, but a more preferable type is constructed from porous polyethylene. This type is available commercially; it is lightweight and relatively inexpensive.¹³

It may often be desired to allow remote reading of pressures from behind the bulkheads. Strain-gauge pressure transducers for this use are readily available. Unlike the case of the vertical boreholes where the transducer (or transmitter) case and cable connector must withstand hydrostatic pressure and be leakproof, the in-mine transducers need only be intrinsically safe and be airtight to prevent dust entry. Many pressure transducers are especially made for use in hazardous environments.

Two types of transducers are available. Both may be obtained in the same sizes, and both require input voltages in the range of 6 to 60 V dc. The first type has a constant current output, usually in the range of 16 to 20 mA, and a fluctuating voltage in the range of 0.5 to 5.0 V dc. The second type maintains a constant voltage, and the output signal is a changing current, usually varying between 4 and 20 mA. The first type allows data transmission over a greater distance but requires higher power, and the second type is more likely to be available in intrinsically safe models.

The cases of the pressure transducers come in a variety of materials, the most common being stainless steel (several

types) and titanium. They can be made with a number of thread types so that the gauges can be screwed directly into a pipe cast into the bulkhead.

The pressure gauges and pressure transducers must be chosen such that their range is greater than the maximum hydrostatic pressure that can develop behind the bulkhead; they should be calibrated before installation. A valve should also be included in the line between the bulkhead and any pressure transducer or gauge to allow their removal for replacement or calibration. Usually the valve is kept shut for direct reading gauges, except when the gauges are being read. When readings are made the valve should be opened slowly to prevent shock damage to the gauge.

Finally, it may be necessary in some cases to have a warning system, should an inundation occur by bulkhead or barrier pillar failure. One method of accomplishing this is to install remote reading water-level warning devices in the areas of interest. A number of on-off type sensors are available for this use. Most of these are float-level switches and indicators. These devices come in a wide variety of configurations and power ranges. Many of them are also designed to actuate equipment, such as alarms, pumps, or motors. The problem with these devices is that most have moving parts that may be frozen by dust or corrosion.

Another device, which has no moving parts, is the capacitive proximity sensor. These sensors are only suitable for sensing, in a yes-no fashion, the presence or absence of water, but they require little power and have no moving parts. Typical capacitive proximity sensors operate on 10 to 12 V dc at currents of 5 to 20 mA. They are not actuated by a moisture film on the sensor head and are not affected by moderate quantities of dust.

To insure the safety of the mine and the workers, hydrostatic pressure must not exceed the capacity of the bulkhead(s) or coal barrier(s). If dangerous pressures are suspected, ways of reducing excessive pressure should be implemented.

¹³For more information regarding polyethylene piezometers, see "Installation of Piping" in appendix A.

This can be accomplished by pumping the water out from the surface or draining

the area behind the bulkhead into sumps in the active working areas.

OBTAINING MSHA APPROVAL

Creating an underground water impoundment by constructing bulkheads requires the approval of the MSHA District Manager. Federal regulations governing mining activities near water bodies, the construction and inspection of bulkheads, the width of coal barriers needed, and MSHA's enforcement role are covered in Title 30, CFR, Part 75. State regulations may be more specific and stringent,

and mine operators should familiarize themselves with the State law. Initially, the mine operator is required to prepare detailed plans on bulkhead design, construction, location, etc., and submit them to the appropriate MSHA district office for approval. If disapproved, areas of insufficiency are defined and the operator must make changes as recommended.

DISCUSSION

The practice of constructing bulkheads in underground coal mines for the purpose of impounding water will become increasingly important in future years. While most of the practical experience of designing and constructing bulkheads has been in hard-rock mining, it can be concluded that no stringent guidelines or theoretical design criteria have been widely accepted. Bulkhead design can differ depending on the condition of the surrounding rock and the anticipated hydrostatic pressure. Over-design is a common practice. Bulkheads are usually constructed sufficiently thick to resist the force of hydrostatic pressure and the surrounding strata pressure grouted to minimize water seepage.

Little reference has been made in this report to the safety factors associated with the designs discussed. Such safety factors are difficult to assess because of the many variables that can affect bulkhead design. These include the maximum waterhead the bulkhead is designed to withstand; the type of anchorage; the strength and condition of the anchoring strata; the existence of geologic anomalies in the immediate area; the favorable aspects of pressure grouting; and the maximum pressure that the barrier pillars can safely withstand. However, acceptable margins of safety can be made inherent to these designs if one selects

conservative strength values for rock and concrete in the design equations. It is not an uncommon practice to increase required bulkhead thickness by a factor of 1.5 to 2, because a large safety factor far outweighs most criteria in the theory of design.

The success of any underground impoundment depends on the ability of the entire dam structure, consisting of the bulkheads and barrier pillars, to withstand the anticipated hydrostatic pressure. In some instances, the barrier pillars may form the weakest link in the impoundment and therefore, dictate the feasibility and practical limits of potential inundation. This is an important consideration because with time the barrier pillar can be just as prone to failure as the bulkhead. The deterioration of coal barriers and surrounding roof and floor strata by water seepage can be minimized through pressure grouting.

Creating an underground water impoundment also creates the potential for an inundation hazard. Mine personnel must exercise sound engineering judgment in design. To insure the safety of the workers and the mine, water levels should be monitored and controlled, ground movements near the impoundment area stabilized with supplemental supports, and the bulkheads and barrier pillars inspected regularly.

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APPENDIX A.--HYDROSTATIC TESTING OF A SINGLE BULKHEAD SEAL

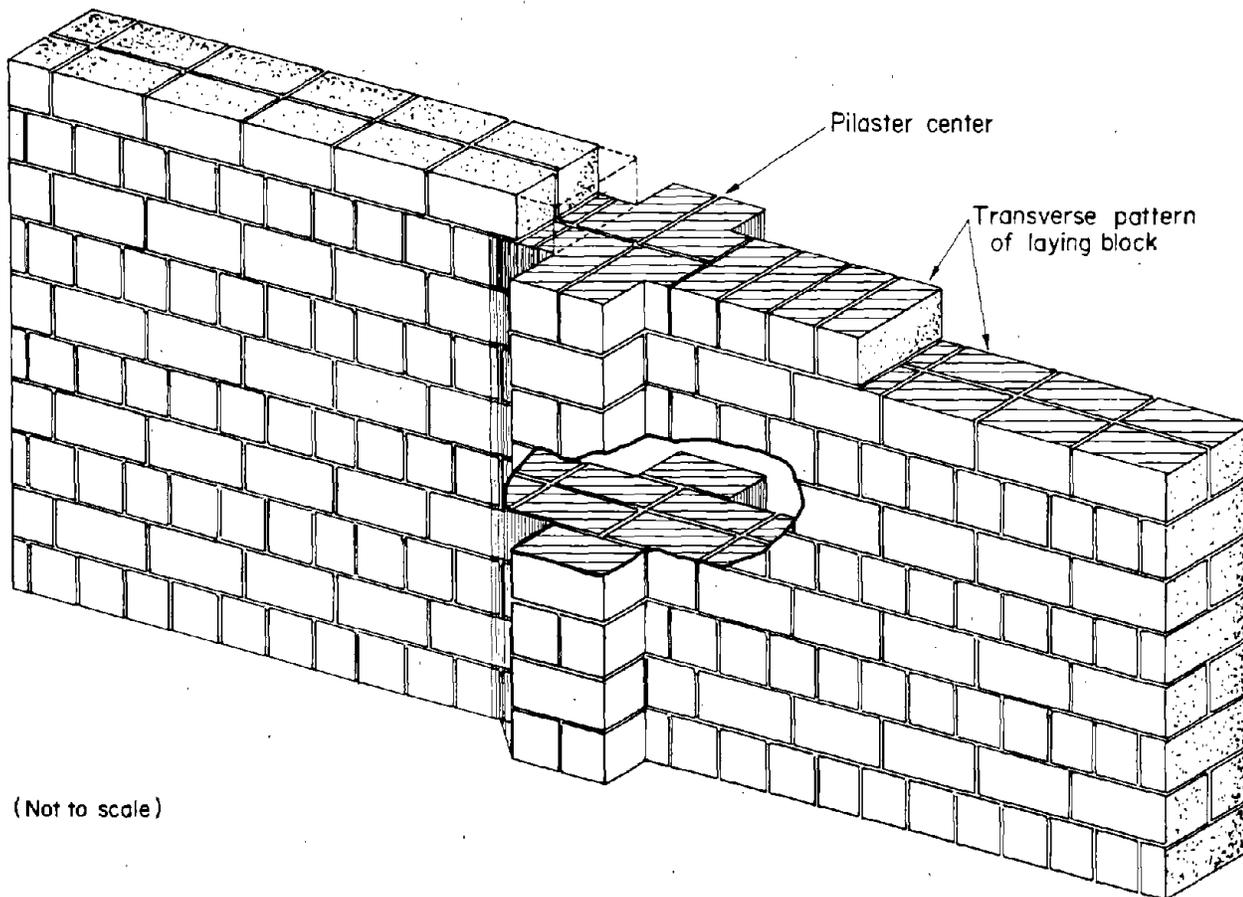
BULKHEAD CONSTRUCTION

The general diagram of the bulkhead is shown in figure A-1. It was constructed from 6- by 8- by 16-in solid concrete block and was located in a 6- by 18- by 20-ft dead-end room of the Bureau's Safety Research Coal Mine, as shown in figure A-2. The first task was to trench the ribs and floor to provide anchorage for the bulkhead. The roof was not trenched because this was considered too hazardous. Using an air-driven jack hammer and chisel, trenches were dug 16 in into each rib and 22 in into the floor. Care was taken during this operation so that the strata were not unnecessarily cracked or fractured. When the trenching was completed, debris was removed from the floor

trench and a level concrete footer approximately 4 in thick was poured. After allowing the footer to set, construction of the bulkhead began, as shown in figure A-3.

To facilitate the installation of an air release, water inlet, and pressure gauge, piping had to be built into the bulkhead. Special blocks were made by drilling 1-1/4-in holes lengthwise through the block and grouting a 1-in steel pipe into place, as shown in figure A-4. The blocks were then laid in their respective courses as the bulkhead was constructed, as shown in figure A-3.

As the bulkhead approached roof level, gunite was sprayed in the cavity behind



(Not to scale)

FIGURE A-1. - Diagram of single bulkhead seal.

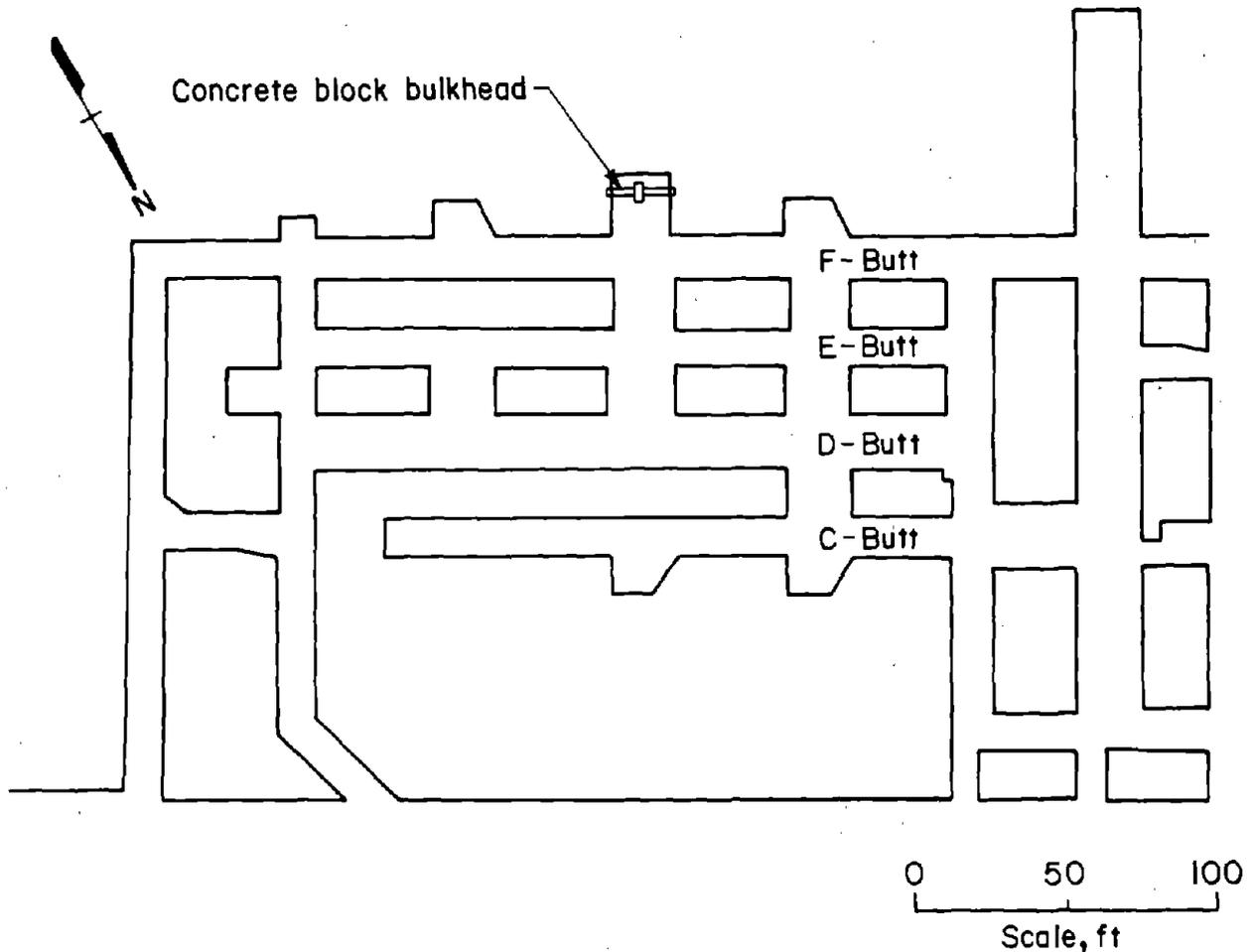


FIGURE A-2. - Location of bulkhead in Safety Research Coal Mine.

the bulkhead, approximately 1/2 in to 1 in thick, to seal cracks in the roof, ribs, and floor and provide a watertight chamber. The bulkhead was then completed to roof level and sealed tight against the roof using 2- by 8- by 16-in solid block and mortar. Roof anchorage was provided by securing 4- by 4-in angle irons on either side of the bulkhead's

pilaster on both the inby and outby sides. Eighteen-inch mechanical roof bolts were used in securing the angle irons to the roof. The bulkhead cured for a week before gunite was sprayed, 1/2 in to 1 in thick, on the outby side. After spraying, the bulkhead was allowed to cure for another week before testing began.

TEST APPARATUS

Figure A-5 shows a diagram of the test area with the following apparatus:

1. Water pipe - inlet for water.
2. Air release - allows air to escape as the chamber is filled with water.
3. Standpipe - a clear plexiglass tube that indicates water level behind the bulkhead.
4. Pressure gauge - measures hydrostatic pressure behind bulkhead.

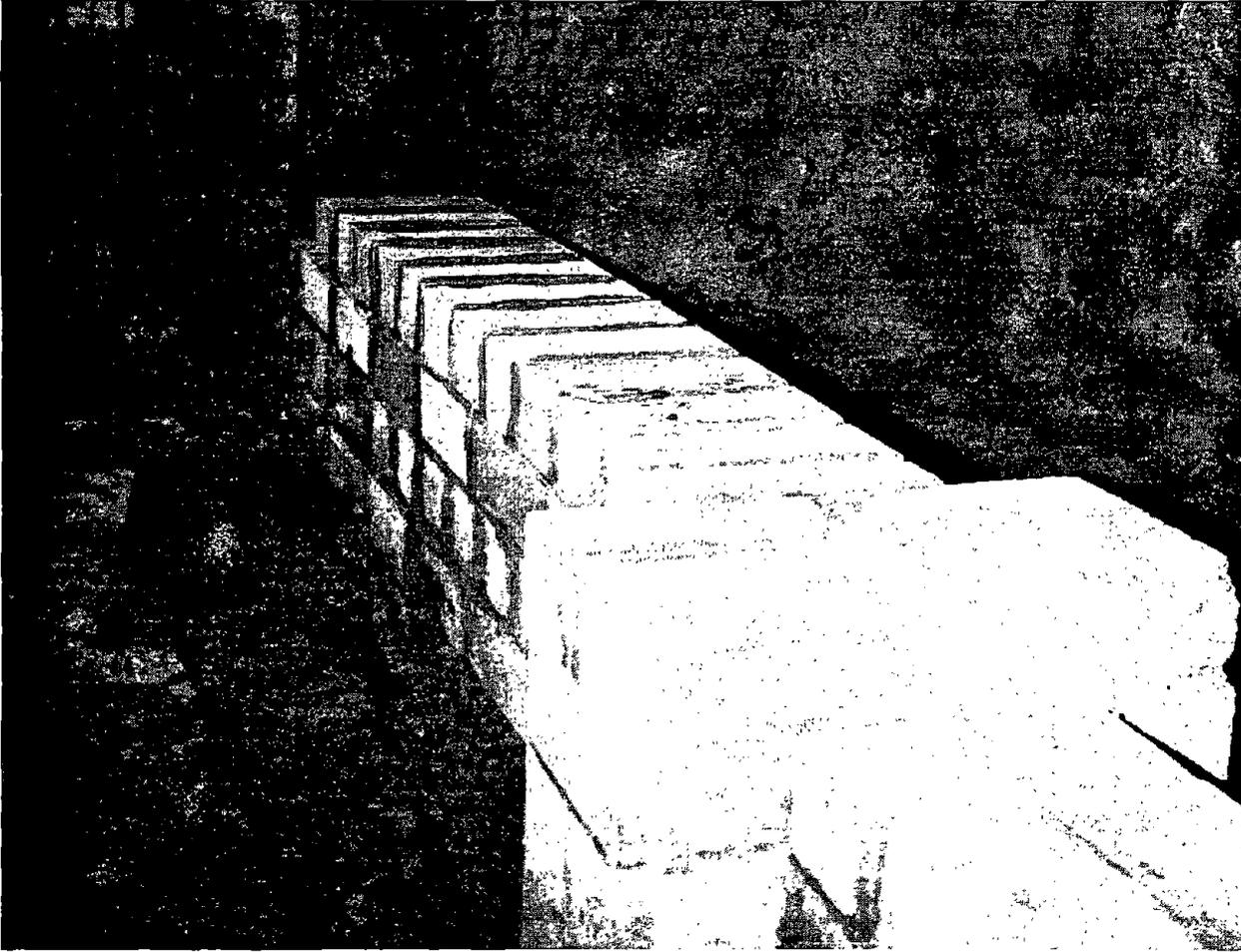


FIGURE A-3. - Bulkhead under construction in Safety Research Coal Mine.

5. Water meter - measures amount of water used during testing.

7. Water tank - water storage for test.

6. Pump - air-driven pump with controls to regulate pressure behind bulkhead.

TEST PROCEDURE

The test procedure consisted of incrementally building and then relieving hydrostatic pressure behind the bulkhead. This procedure simulated the actual in-mine practice of allowing hydrostatic pressure to build to a maximum level, and then relieving it by pumping or draining excess water behind the bulkhead. Initial pressure was started at zero and increased at 5-psi intervals. Each

increment was maintained for approximately 10 min. Pressure was then dropped back to zero and a new series of tests started, as shown in table A-1.

The bulkhead was inspected after each series of tests. The decision to proceed to the next test depended on several factors: (1) success of the previous test; (2) excessive water leakage or damage to roof, ribs, or floor strata; (3) visible

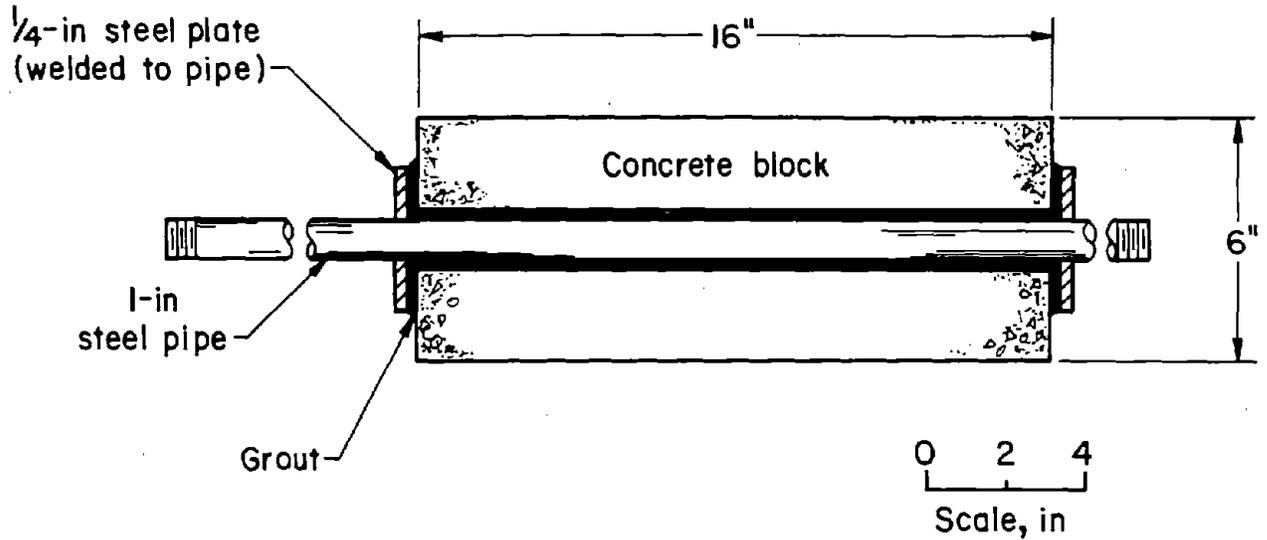


FIGURE A-4. - Cross section of 1-in pipe grouted into concrete block.

TABLE A-1. - Test procedure for incrementally pressurizing bulkhead

Test	Date	Pressure interval, ¹ psi	Time, min
1.....	4/28/82	0- 5	10
2.....	4/28/82	0-10	20
3.....	4/28/82	0-15	30
4.....	4/29/82	0-20	40
5.....	5/ 3/82	0-25	50
6.....	5/ 3/82	0-30	60
7.....	5/ 3/82	0-35	70
8.....	5/ 4/82	0-40	80
9.....	5/ 4/82	0-45	90
10.....	5/ 5/82	0-50	100

¹5-psi intervals.

water leakage or damage to the bulkhead structure.

When testing commenced, water immediately began to leak from the roof, ribs, and floor strata surrounding the bulkhead. During the fourth series of tests at 20 psi pressure, water leakage became excessive, but there was still no leaking through the bulkhead itself. Apparently, the gunite did not make a good sealant and the pressure was forcing the water through the gunite and into the strata. Testing was temporarily discontinued for

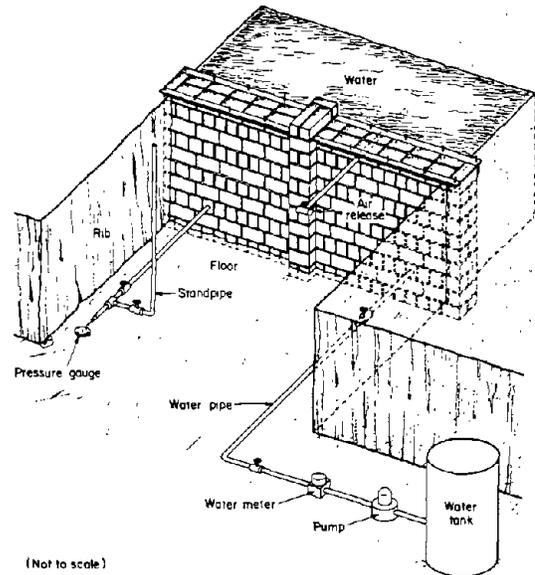


FIGURE A-5. - Diagram of test apparatus.

fear that infusing the strata with water would create larger cracks and generally weaken ground conditions in the test area. To seal and strengthen the surrounding strata, the application of a pressure grouting technique was considered the most practical approach.

PRESSURE GROUTING

Pressure grouting was considered the most practical method of sealing the strata in the test area. The strategy was to stop water permeation by forming a grout curtain around the water chamber behind the bulkhead. In addition to minimizing seepage, the grout would strengthen the ground by consolidating the fractured strata. The Bureau sought a company with expertise in a proven pressure grouting technique to do the work. Representatives of Mobay Chemical Corp. were contacted; after consultation, the decision to inject their Roklok B-4 waterstop system into the fractured strata was made.

The B-4 system is a two-component polyurethane grout consisting of a polymetric isocyanate (component A) and a polyol resin (component B), which are mixed and injected into the strata. The mixture has a low viscosity, which enables it to flow freely into fine cracks and fissures. As it migrates into the strata, it encounters water and expands driving any remaining water out. The component mixture solidifies in approximately 5 min.

The major concern was grout migration to the blind face located behind the bulkhead, because it was suspected that most of the water was seeping through this area. A drilling plan for injecting the chemicals was developed. To reach the blind face behind the bulkhead, two holes over 50 ft long had to be drilled from entries to the right and left of the bulkhead. Other holes would be drilled around the bulkhead to seal the ribs, roof, and floor, as shown in figure A-6. A total of 14 holes, varying in length from 4 ft to 50 ft, were drilled and injected.

Injecting the grout was relatively simple. A hole was first drilled into the strata and the packer-mixer assembly, with an expansion shell, was inserted into the borehole and anchored tightly, as shown in figure A-7. This assembly was then connected to the pumping unit by high-pressure hoses. The two components were pumped separately, then mixed and injected into the strata via

the mixer-packer assembly. The grout was pumped continuously, under pressure, as it migrated into the strata. Injection pressures ranged from 500 to 700 psi. When the grout emerged from the strata, as shown in figure A-8, the injection was stopped, the hole abandoned, and a new hole was drilled and injected. The injection started with hole H₁ and proceeded in numerical order to hole H₁₄.

Some roof sag was experienced when the grout was injected into the roof. To provide additional support, four timbers on 4-ft centers were installed across the entry, approximately 5 ft from the bulkhead. Extensometers, which detect roof sag, were installed and monitored

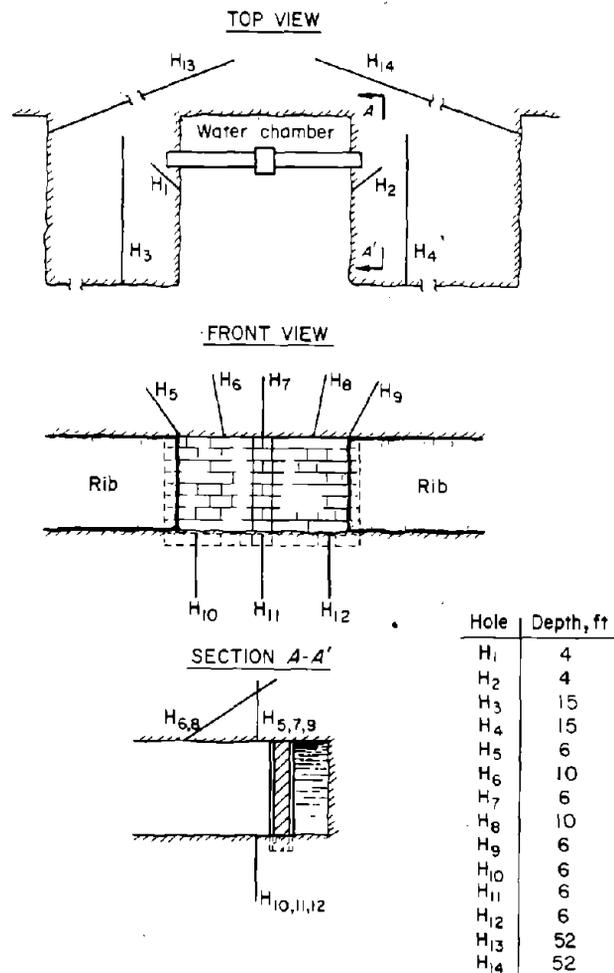


FIGURE A-6. - Drill plan for injecting polyurethane grout in strata surrounding the bulkhead.



FIGURE A-7. - Packer-mixer assembly installed in borehole.



FIGURE A-8. - Polyurethane grout emerging from strata.

continuously. Approximately 0.3 in of roof sag was measured during the roof injection, but no roof problems were encountered.

Periodically during the injection, the bulkhead was pressurized at less than 20 psi to determine if the grout was

migrating properly. These spot checks showed that the technique was working well. The pressure rose rapidly as water was pumped into the chamber behind the bulkhead and visible water seepage from the roof, ribs, and floor was significantly less.

FINAL TESTS AND RESULTS

With the pressure grouting completed, testing resumed and followed the original plan of incrementally pressurizing the bulkhead (see table A-1). Tests 1 through 7 proceeded well; 35 psi (80 ft of waterhead) was reached with no signs of failure in the bulkhead or its anchorage. Water seepage from the surrounding strata was minimal, showing that the grout adequately sealed the water chamber behind the bulkhead. When 40 psi (92 ft of waterhead) was reached during test 8, the bulkhead began to show signs of failure. Water was leaking, although not excessively, at roof level and also through mortar joints located near the base of the bulkhead. Testing proceeded to tests 9 and 10. With each pressure increase, water leakage through the roof and mortar joints became more severe. At 50 psi (115 ft of waterhead) the bulkhead and roof strata were leaking excessively. It was at this point the bulkhead was considered to have failed and testing was stopped. Though testing continued to 50 psi, the point at which the bulkhead

initially showed signs of failure (40 psi) was considered the maximum pressure the bulkhead could withstand.

It should be noted that the hydrostatic pressures were applied over a much shorter time than under actual mine conditions. Infusing the strata with water was considered dangerous to ground stability, limiting the time duration of tests. The maximum pressure the bulkhead withstood, 40 psi (92 ft of waterhead), includes no factor of safety, and actual pressures should be kept well below this limit because of this time factor. A flexural strength analysis of this bulkhead, given in appendix B; includes the maximum allowable stress a bulkhead of this type could safely withstand.

Tests show that certain construction and maintenance procedures should be followed when building this particular bulkhead, especially if it is to act as both an explosionproof and water seal. These procedures are detailed in the next section.

CONSTRUCTION AND MAINTENANCE PROCEDURES

The following procedures for bulkhead construction and maintenance are based on test experiences and pertinent literature. If implemented properly, they will decrease the possibility of an unexpected inundation and provide a greater degree of safety to the mine.

CONSTRUCTION

1. Construct the bulkhead in competent ground that is not excessively broken or fractured, preferably where ground movement has settled (1).¹

2. Proper anchorage of the bulkhead to the mine roof, ribs, and floor is important and depends on strata type and condition. In general, most coals have good anchorage characteristics, and trench depths in the ribs of 16 to 24 in should be adequate (4). Fireclays, limestones, and shales, which compose most floor strata, usually make good support

¹Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

material unless softened by water (3). Floor trenches should be at least 16 in deep if the strata are in good condition. If the floor is in poor condition, trench until competent strata are reached.

3. If feasible, trenching of the roof is highly recommended. Due to roof sag, the roof is typically the place where most seepage occurs. Also, during tests, most water seepage occurred at roof level because the bulkhead was not keyed into the roof. To trench the roof, first remove any headcoal or other deteriorating roof rock so as to expose competent strata. Trenches should be made at least 8 in deep, and care should be taken when trenching because of the unpredictable nature of most roof rock.

4. Trenches can be cut with any hydraulic or air-driven tools, continuous miners, or cutting machines. If extremely hard strata are encountered, trenching may be carried out by drilling and shooting, but care should be taken to avoid unnecessarily fracturing the strata (3).

5. Use only solid concrete block to construct the bulkhead. Remove all debris from the floor trench, and pour a level concrete footer on which to build. Mix cement properly to assure good bonding between blocks and make sure all courses are laid level.

6. As the bulkhead is being built, fill in all gaps and cracks in the anchorage with concrete or cement. When completed, use the same material to seal the bulkhead tightly against the roof, ribs, and floor (3).

7. The bulkhead will need a water sealant to protect it from prematurely deteriorating but allow the bulkhead to cure for several days before application. In constructing the bulkhead for tests, gunite was used to seal the bulkhead. But, because gunite is sprayed on, air becomes trapped in the material; this may make it porous. To avoid this, use sealants that can be applied with a trowel

such as a waterproofing cement. Apply several coats, and if possible seal both sides of the bulkhead.

8. Pressure grouting is recommended depending on the permeability and strength of the surrounding strata. Often, the deterioration of the roof, rib, and floor anchorage by water permeation creates a most significant structural concern. Tests showed that pressure grouting will minimize water permeation, especially if large pressures are anticipated over the life of the bulkhead. If pressure grouting is necessary, the mine operator should carefully plan his strategies and select a company with a proven pressure grouting technique.

MAINTENANCE

1. The bulkhead should be inspected according to the Code of Federal Regulations, Title 30, Parts 75.303 and 75.305. Records of these inspections should be kept and include significant factors such as present waterhead, visible water seepage through bulkhead or immediate strata, or any visible deterioration in the bulkhead or ground conditions.

2. Ground movements, such as floor heave, roof convergence, and pillar spalling, can damage the bulkhead and its anchorage, especially if it is constructed from rigid materials such as concrete or concrete block (1). Ground movements are difficult to predict, and in most mines they are inevitable. Because of this, supplemental roof supports such as cribs and timbers should be installed around the bulkhead as a routine measure.

3. With time, water may weaken the bulkhead and anchorage, but this can be minimized by repatching and resealing. In extreme cases, where strata or bulkhead deterioration may endanger worker safety or the mine, more extensive measures such as pressure grouting or reconstruction may be necessary.

4. Water pressure should not exceed the design capacity of the bulkhead. This capacity can vary, depending on such factors as construction practices, strength and permeability of anchoring strata, and ground stability. In addition, large volumes of water stored behind a bulkhead (such as an open dam

wall) can be just as dangerous as excessive water pressures. If dangerous water volumes are suspected, methods for reducing excess water should be implemented. This can include pumping the water out from the surface or draining the water from behind the bulkhead to underground sumps.

INSTALLATION OF PIPING

Pipes for monitoring water levels behind the bulkhead are recommended. The pipes can be either plastic or metal. If metal, they should be corrosion resistant. Installation of pipes, by grouting them into the concrete block, is discussed earlier in this report.

Pipes should be installed 6 to 12 in from the floor and 12 to 18 in from the rib that has the lower elevation. The pipe should be at least 7 to 10 ft in length with a 1- to 2-in ID. Both ends of the pipe must be threaded to

facilitate the installation of the following: (1) A pressure gauge and stand pipe, installed on the outby side of the bulkhead; (2) a porous tube which traps sediment, but allows water to pass through, installed on the inby side. Figure A-9 shows this arrangement in detail.

The pressure gauge measures hydrostatic pressure on the bulkhead and should be able to register at least 50 psi. The standing pipe indicates the exact waterhead behind the bulkhead in a direct height-to-height relationship. It can be constructed from any clear plastic tube, such as plexiglass. It should be installed vertically to roof level with a valve, capable of withstanding a static pressure greater than 50 psi, separating the pressure gauge from the standing pipe.

The porous tube used in tests was made of polyethylene and acquired from Piezometer Research and Development Corp. Figure A-10 shows this tube installed on the inby side of the bulkhead. The tube allows water to pass without affecting pressure readings, and traps sediments that may clog the standing pipe and pressure gauge.

The valve that separates the standing pipe from the pressure gauge should remain closed until use. To determine the waterhead behind the bulkhead, open the valve and measure the height of the water in the standing pipe. If the water overflows from the standing pipe, the water behind the bulkhead has reached at least roof level. If this is the case, close the valve so that the waterhead can be determined from the pressure gauge. Read the gauge, then divide the reading by 0.434 to determine the waterhead behind the bulkhead.

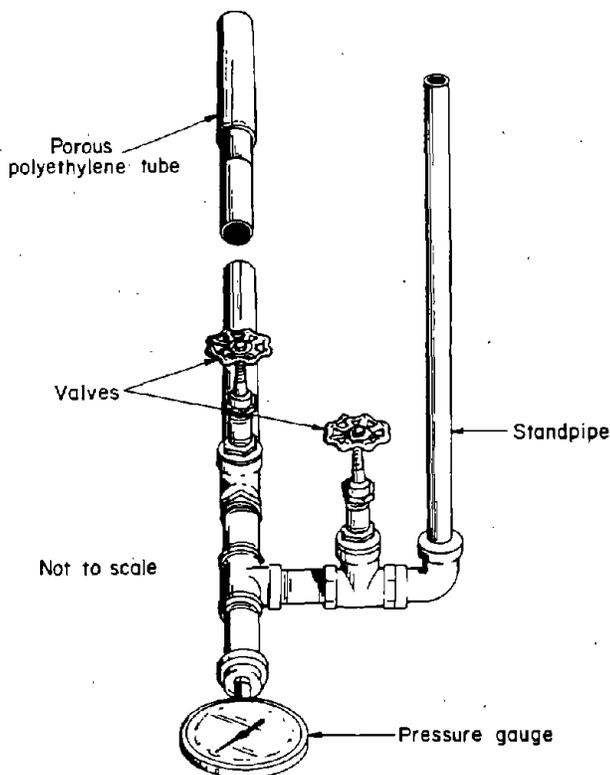


FIGURE A-9. - Diagram of standpipe, pressure gauge, and porous tube arrangement.

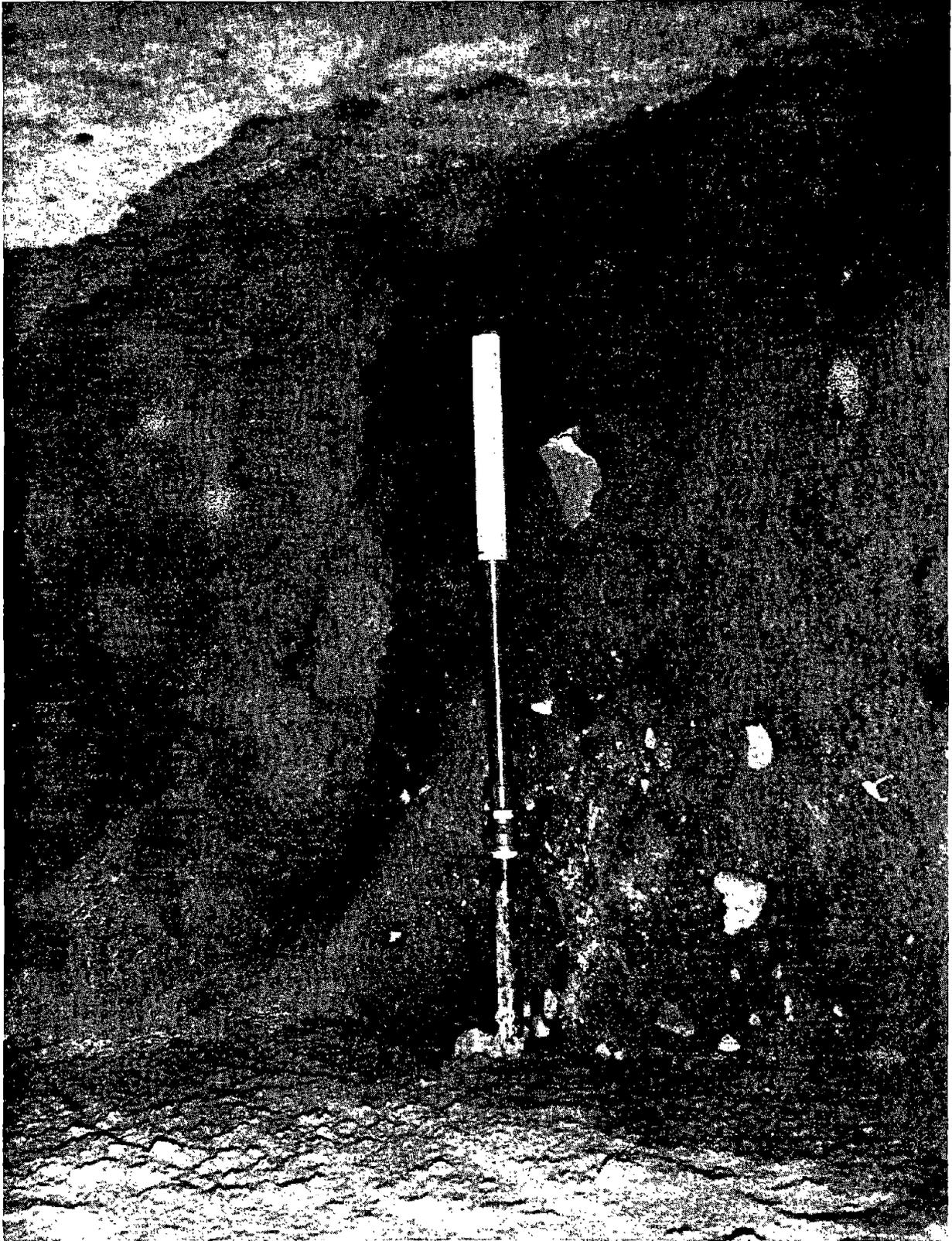


FIGURE A-10. - Polyethylene porous tube installed on the inby side of bulkhead.

APPENDIX B.--FLEXURAL STRENGTH ANALYSIS FOR CONCRETE BLOCK BULKHEAD

Properly constructed bulkheads that are fixed on at least three sides (both ribs and floor) when subject to a hydrostatic pressure are most likely to fail in flexure (22).¹ The flexural stress on the bulkhead is given by the following equation (23):

$$F_{\dagger} = \frac{\beta p b^2}{T^2} \quad (\text{A-1})$$

where F_{\dagger} = the flexural stress on the bulkhead, psi;

β = correction factor, no units;

p = hydrostatic pressure, psi;

b = bulkhead height, in;

and T = bulkhead thickness, in.

β is a correction factor dependent upon the width-to-height ratio of the bulkhead and the particular loading condition. Figure B-1 (22) gives the correction factor for various waterheads, H . Using the maximum condition given $H = b$, and a width-to-height ratio of $a/b = 3$, β is approximately 0.80. Substituting into equation A-1 and solving for F_{\dagger} :

$$F_{\dagger} = \frac{\beta p b^2}{T^2}$$

where $\beta = 0.80$;

$p = 2.6$ psi (6 ft of waterhead);

¹Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

$b = 72$ in;

and $T = 16$ in.

therefore $F_{\dagger} = 42.1$ psi.

The maximum allowable flexural stress for nonreinforced masonry unit constructed of solid block is 40 psi as recommended by the ACI Code (24). Therefore, the maximum allowable pressure that the bulkhead described in appendix A can safely withstand, keeping within the limits of the ACI Code, is approximately 2.6 psi (6 ft of waterhead). This maximum allowable pressure may seem unreasonably low when compared with the ultimate pressure of 40 psi that the bulkhead resisted. But, it must be realized that the time duration of tests was very short when compared with actual mine conditions. This analysis neglects the pilaster center, the gunite coating, and the transverse pattern of laying the block. These design features are difficult to access but would provide additional resistance to flexural failure.

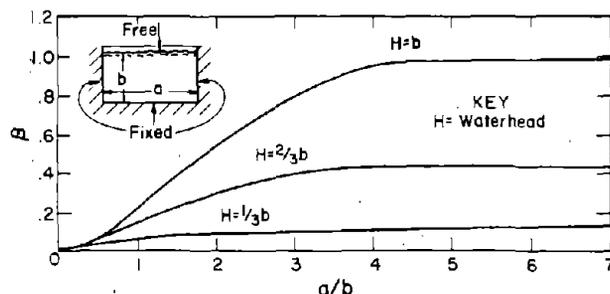


FIGURE B-1. Correction factor for bulkhead width-to-height ratios. Adopted from F. S. Kendorski, I. Khosla, and M. M. Singh (22).