ENGINEERED STRUCTURES FOR SEALING UNDERGROUND MINES

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INTRODUCTION

Throughout most of the Appalachian coal fields, abandoned deep mines are considered to be the principal source of acid mine drainage pollution. The reasons for this perception are based on the sheer number of abandoned deep mines, the number of very large acreage abandoned mines and the fact that nearly all older mines were developed to the rise to promote gravity drainage.

The scope of AMD problems associated with older deep mines include inadequate barrier pillars between mines, inadequate outcrop barriers and the fact that common practice included the hydraulic interconnection of adjacent mine complexes and/or connection of superimposed mines.

While AMD problems associated with some of these older mine complexes can be addressed by remining of the abandoned mine complex, economic considerations typically make this option not viable for a significant majority of abandoned mine complexes in the Appalachian coal fields.

Mine sealing can, in many instances, be an effective and economically viable means of eliminating or minimizing the AMD pollution associated with abandoned deep mines.

REGULATORY CONSIDERATIONS

Regulators were faced with an increased awareness that the practice of developing gravity drainage deep mines by positioning mine entries through stratigraphically low areas that should be left as barriers contributed to an ever increasing AMD pollution problem. They responded by requiring that deep mines be scaled at closure to ensure public health and safety. Following are changes that various governmental bodies instituted in mine development and abandonment.

In 1961, the Commonwealth of Pennsylvania passed the "Bituminous Coal Mine Act" which mandated that all permanently abandoned mines be plugged, sealed or filled (1).

In 1977, Office of Surface Mining (OSM) regulations relative to deep mine surface facilities and entry closure became law as part. of the Surface Mining, Conservation and Reclamation

Act (2).

in 1978, the Mine Safety and Health Administration (MSHA) adopted regulations which further defined the procedures and conditions for sealing an- abandoned underground -mine (3).

Currently, nearly every US agency and state agency that regulates deep mining has adopted some regulations mandating mining to the dip and mine sealing at closure to minimize AMD effects and to ensure the health and safety of the public. Conversely, throughout much of the rest of the world, the practice of mining to the rise to facilitate gravity drainage continues unabated.

DEEP MINE SEALING: DEFINITION & DESIGN GOALS

Deep mine sealing is defined as closure of mine entries, drifts, slopes, shafts, boreholes, barriers, outcrops, subsidence holes, fractures and other openings into underground mine complexes.

Deep mine seals are constructed to achieve one or more functional design goals including:

1. eliminate potential access to the abandoned mine works following closure
2. minimize AMD production by limiting infiltration of air and water into the deep mine
3. minimize AMD production by maximizing inundation of the mine works
4. minimize AMD exfiltration through periphery barriers to surface water systems
5. develop staged internal mine pools to regulate maximum hydraulic head and pressure

DEEP MINE SEAL TYPES

The primary factor affecting the selection design and construction of underground mine seals is the anticipated hydraulic pressure that the seal will have to withstand when sealing is completed.

Surface Access (Dry) Seals

Surface access seals are installed in entries (drifts, slopes, shafts and subsidence areas) where little or no hydrostatic pressure will be exerted on the seals. The primary functions of the seals are:

1. eliminate potential access to the abandoned mine works following closure
2. minimize AMD production by limiting infiltration of air and water into the deep mine

Typically, these seals are installed in entries positioned in the structurally upgradient areas of the mine where the majority of the mine works lie "below" the mine seal site.

These seal areas are often backfilled from the front side of the seal to the ground surface and then the seal backfill areas are stabilized, amended, resoiled and revegetated. These seals have good long term effectiveness due to the lack of hydraulic head (pressure) on the seals.

Figures 1 and 2 show construction typical drawings of surface access seals.

Surface access seals have been used extensively throughout the world and use continues today. The lack of hydraulic head allows these seals to be both simple in construction and low cost. Surface access seals are typically constructed using concrete block or masonry although more recent surface seals have been constructed using compacted clay and concrete-flyash mixtures.

Air Trap Seals

Air trap seals were installed in mine entries where mine discharges flowed from the mine. Conventional deep mine sealing using air-trap seal methods began in the 1920's and was used extensively in the 1930's in the US, primarily in conjunction with the Works Project Administration (WPA) mine sealing efforts. The primary functions of these seal types are:

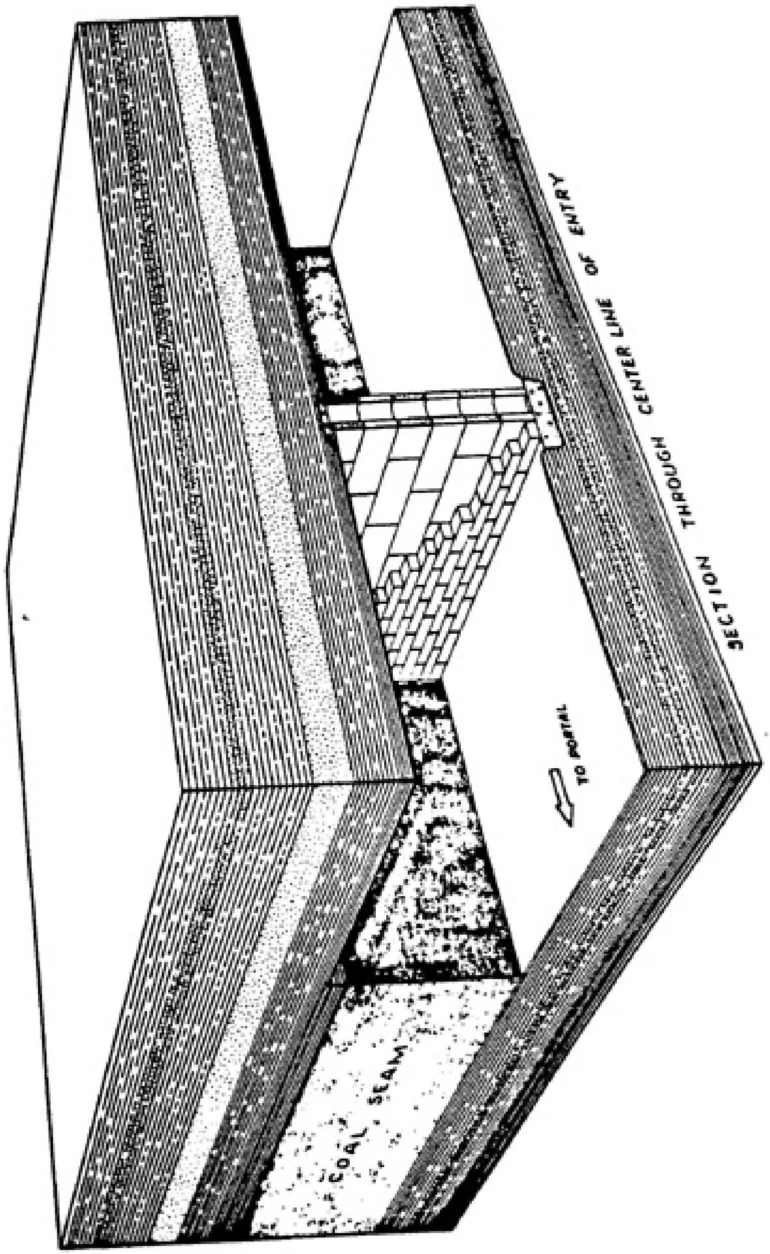
1. eliminate potential access to the abandoned mine works following closure
2. minimize AMD production by limiting infiltration of air and water into the deep mine

The initial appeal of the air-trap sealing system was that this was a simple, low-cost sealing approach that provided a means to construct a mine seal that would eliminate access to the abandoned works, minimize air infiltration into the mine and still allow water to discharge without affecting the mine seal integrity. Construction was almost always using concrete blocks.

Figures 3 and 4 show the construction typical drawings of air-trap seals.

In a typical air-trap sealing program, surface access seals were first constructed in the upgradient mine entries (which were sometimes backfilled) and then the air-trap seals were constructed in the downgradient mine entries where water historically discharged from the mine.

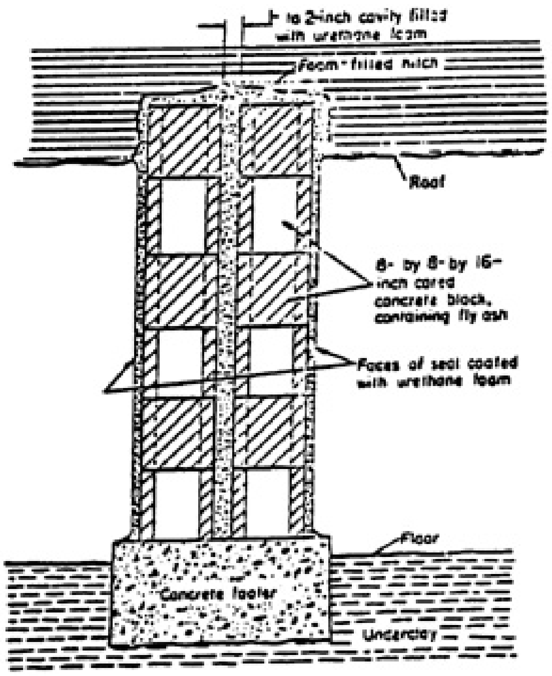
Unfortunately, the long-term effectiveness of this sealing method was generally poor. Failures of these seals usually occurred when rock, wood, debris and sediment clogged the air-trap. This restricted outflow from the mine causing increases in volume and head of the impounded water in the mine. The subsequent increase in pressure caused many of these seals to collapse.



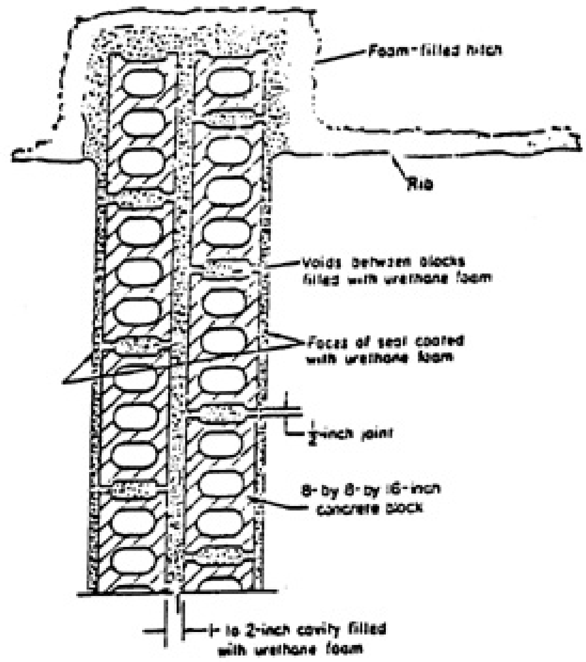
TYPICAL MASONRY SEAL

AIR SEAL - VENTILATION STOPPING

FIGURE 1

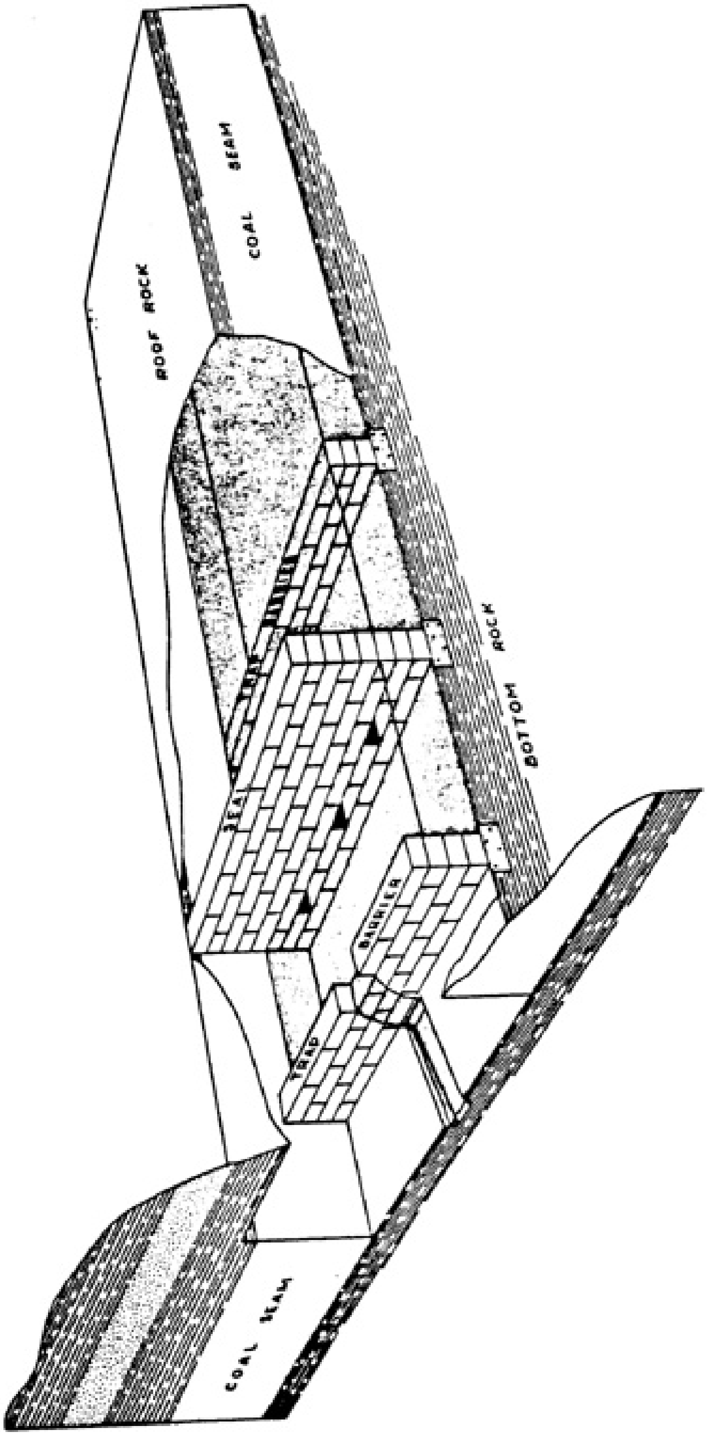


Cross-Sectional View of Masonry Seal Showing Method of Construction, Hitching Into Roof, and Concrete Footer.



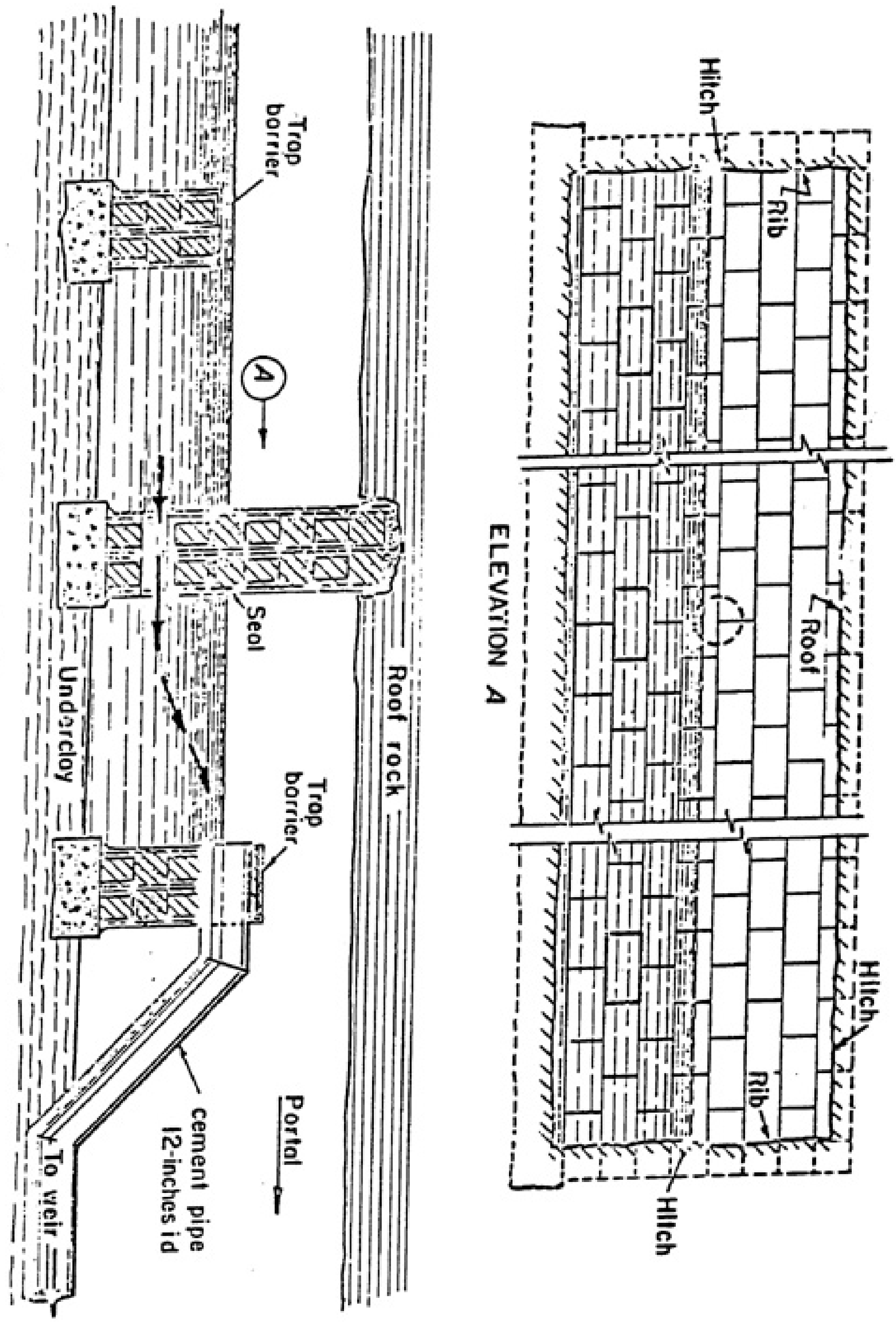
Top View of Masonry Seal Showing Method of Construction and Hitching Into Rib.

FIGURE 2



CONVENTIONAL TYPE AIR SEAL WITH DISCHARGE

FIGURE 3



General Arrangement of a Wet Seal With Air Trap.

FIGURE 4

DEEP MINE SEAL TYPES

<u>Hydraulic Mine Seals</u>

Currently, the predominance of deep mine seals being constructed are hydraulic mine seals although surface access seals are still used in "no water, no head" situations for economic reasons. The numerous, long term failures of the air-trap seal systems coupled with the inability of this design to withstand significant hydraulic pressures has caused these seals to become obsolete.

Hydraulic mine seals are installed in entries (drifts, slopes, shafts and adjacent strata) where significant hydrostatic pressure will be exerted on the seals. The primary functions of the seals are:

1. eliminate potential access to the abandoned mine works following closure
2. minimize AMD production by limiting infiltration of air and water into the deep mine
3. minimize AMD production by limiting exfiltration of water and maximize inundation

Further, hydraulic mine seals have been constructed to repair/replace breached areas of coal barrier pillars and to provide "constructed internal barriers" in sections of the mine complex to:

4. minimize AMD exfiltration through coal barrier pillars to adjacent flow systems
5. develop staged internal mine pools to regulate maximum hydraulic head and pressure

The primary goal in the design and installation of hydraulic mine seals is to construct a mine seal system that serves as a structural bulkhead and acts as a water tight dam capable of withstanding the maximum hydrostatic head that may develop as a result of the flooding of the mine complex.

A secondary consideration in the design and siting of hydraulic mine seals is the hydrologic performance of the seal. The adjacent stratum has natural joints, bedding planes and subsidence cracks (from mining) that may serve to transmit significant water around the mine seal area.

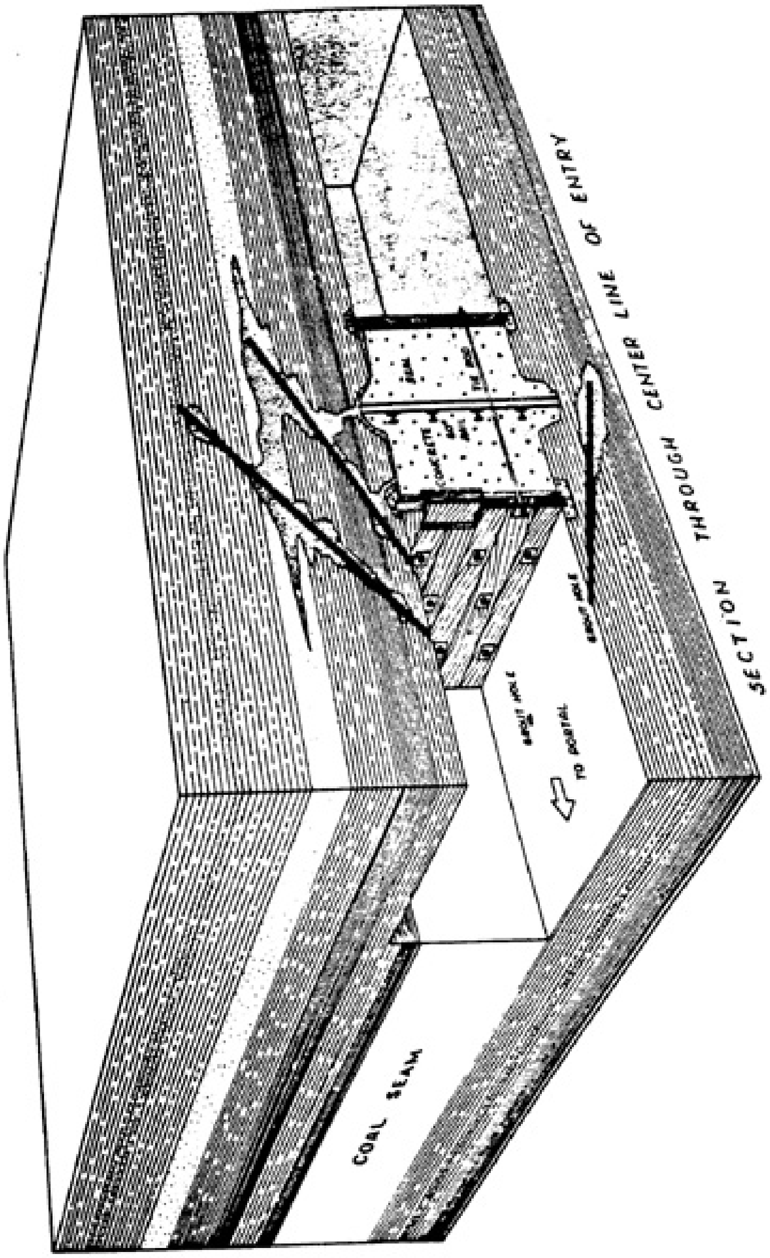
Thus, while the structural design will specify a minimum required thickness necessary to safely impound the water at design heads and pressures, the potential for water to migrate around the mine seal area through adjacent strata must be compensated for in the design.

Typically, there are three common and successful approaches used separately or in combination to minimize the potential migration of impounded water around the mine seal area. These are:

1. Pressure grouting of the adjacent strata - this process injects grout into the natural and mining related cracks in adjacent strata thus minimizing migration of water past the seals.
2. Increase mine seal thickness - this increases "flowpath distance" that migrating water must travel to bypass the seals and greatly increases the safety factor for the structural design.
3. Install secondary mine seals - provides redundant mine seals to limit potential migration around seals. This approach is mostly limited to very high head sites due to the high costs.

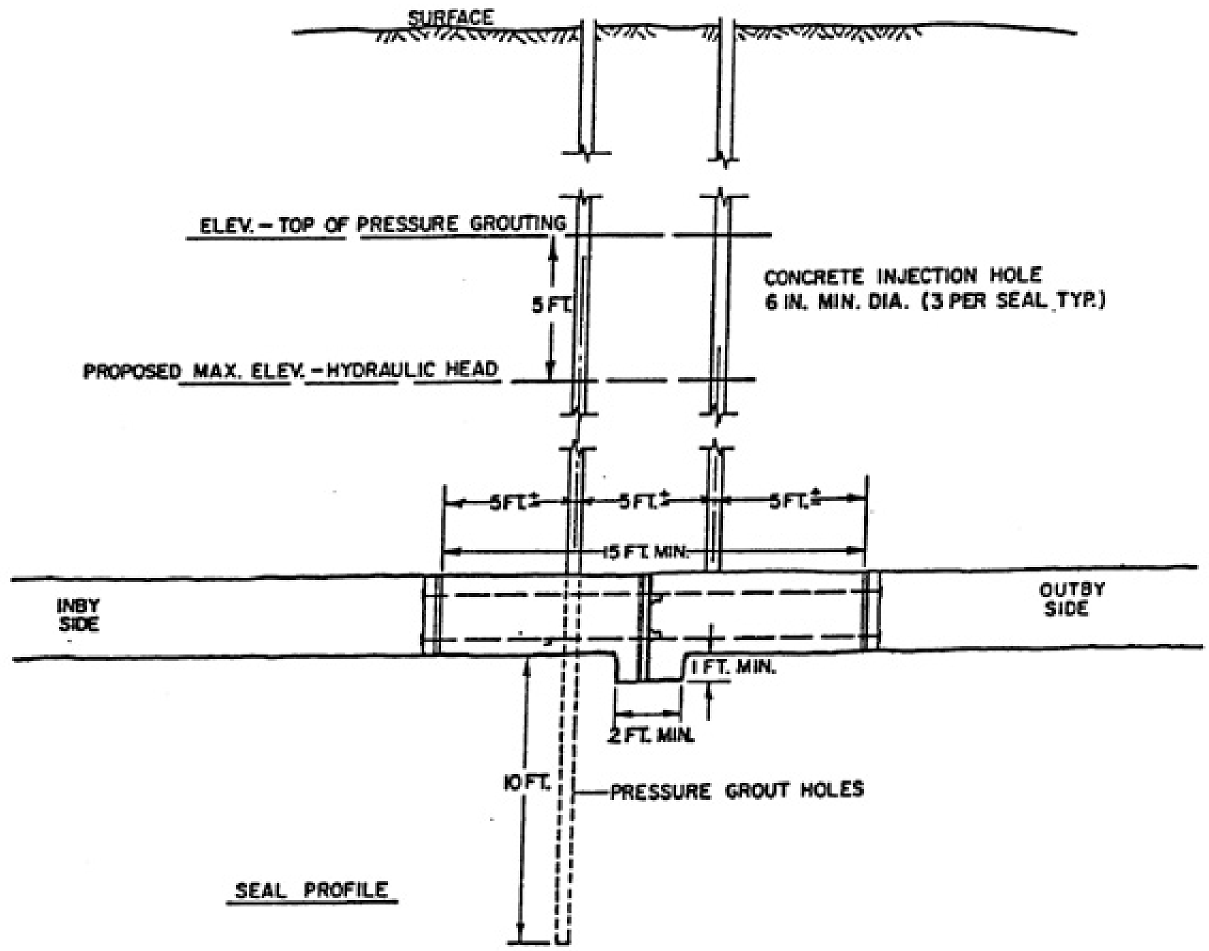
Another fundamental design consideration in the siting of mine seals is the accessibility the mine entries where the seals are to be constructed. In most abandoned mines and in areas of active mines where conditions are unreasonable or unsafe, mine seals can be remotely placed.

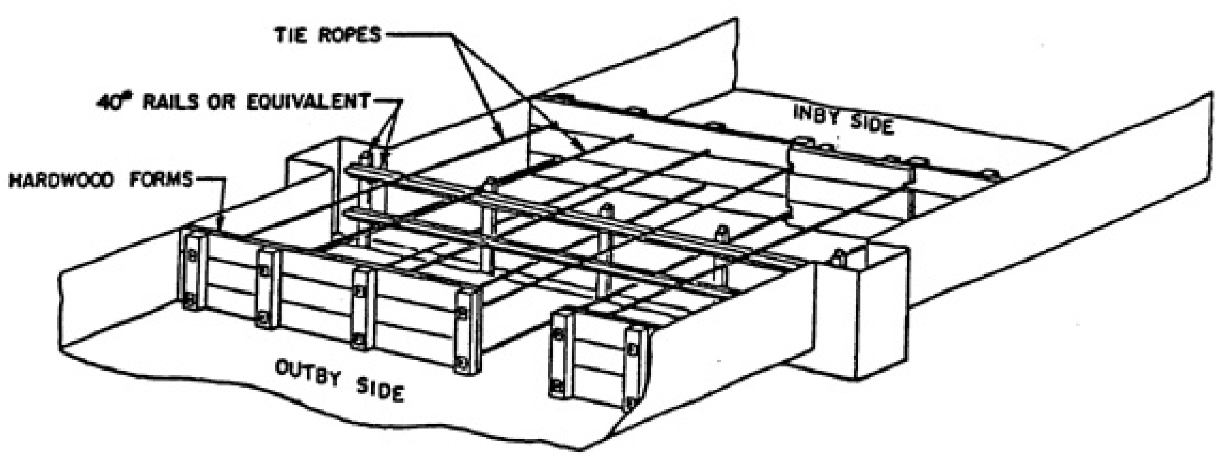
Figures 5 and 6 are typical drawings showing various accessible hydraulic mine seal designs. Figures 7 through 10 are typical drawings showing remotely placed hydraulic mine seal designs.



DEEP MINE HYDRAULIC SEAL - UNDERGROUND BARRIER DAM

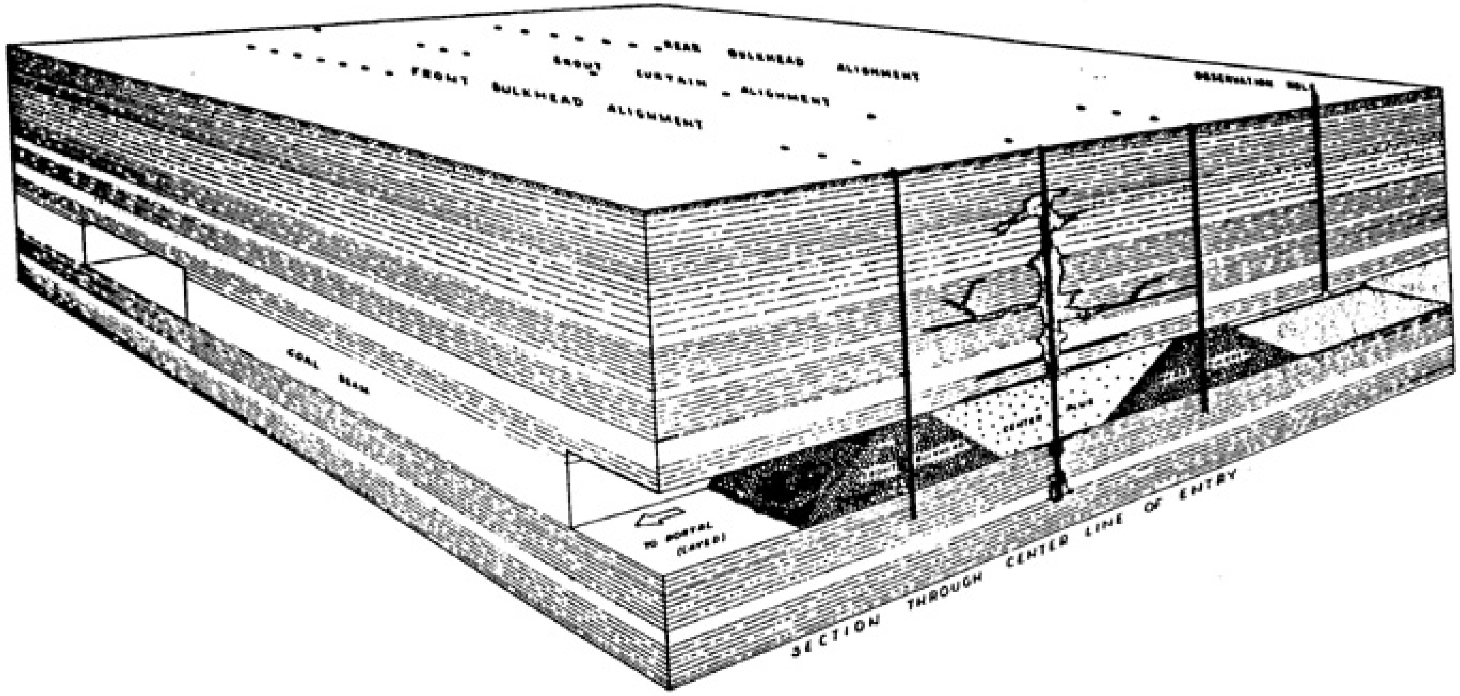
FIGURE 5





MINE SEAL FORM DETAILS PRIOR TO INSERTION OF CONCRETE

FIGURE 6



DEEP MINE HYDRAULIC SEAL BY REMOTE INSTALLATION

FIGURE 7

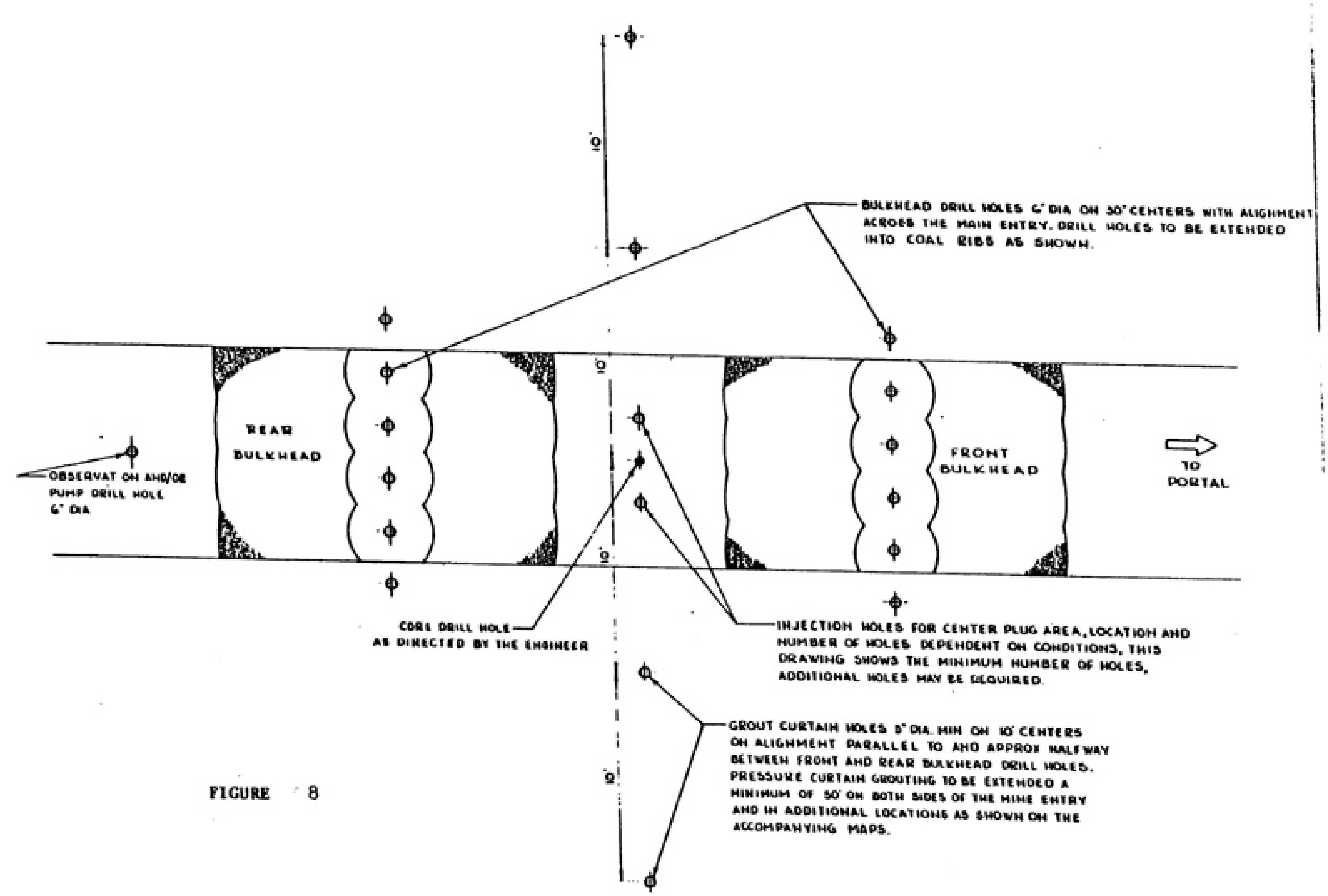
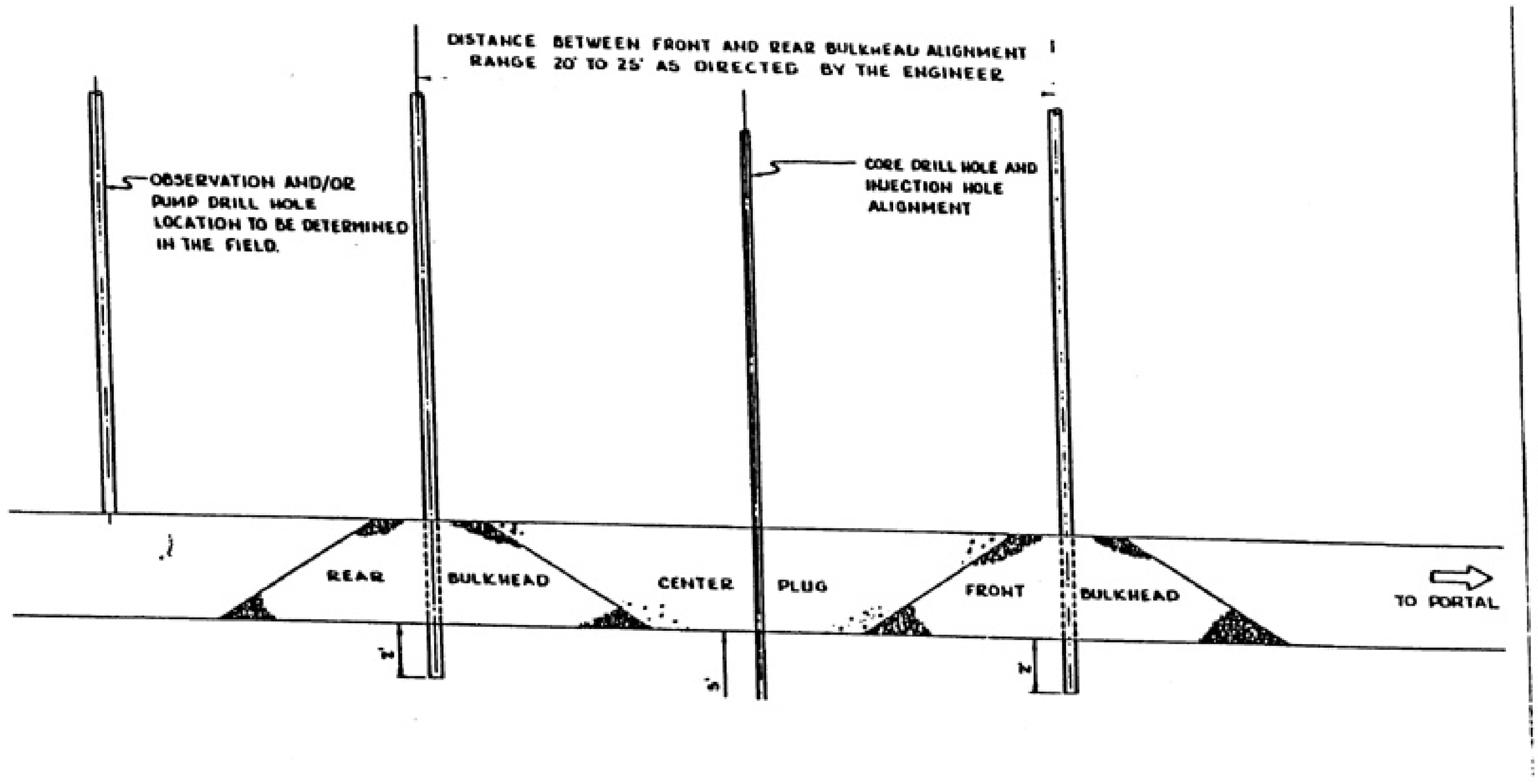

BULKHEAD DRILL HOLES 6" DIA ON 30' CENTERS WITH ALIGNMENT ACROSS THE MAIN ENTRY. DRILL HOLES TO BE EXTENDED INTO COAL RIBS AS SHOWN.
10'
REAR BULKHEAD
FRONT BULKHEAD
TO PORTAL
OBSERVATION AND/OR PUMP DRILL HOLE 6" DIA
CORE DRILL HOLE AS DIRECTED BY THE ENGINEER
INJECTION HOLES FOR CENTER PLUG AREA, LOCATION AND NUMBER OF HOLES DEPENDENT ON CONDITIONS, THIS DRAWING SHOWS THE MINIMUM NUMBER OF HOLES, ADDITIONAL HOLES MAY BE REQUIRED.
GROUT CURTAIN HOLES 3" DIA. MIN ON 10' CENTERS ON ALIGNMENT PARALLEL TO AND APPROX HALFWAY BETWEEN FRONT AND REAR BULKHEAD DRILL HOLES. PRESSURE CURTAIN GROUTING TO BE EXTENDED A MINIMUM OF 50' ON BOTH SIDES OF THE MINE ENTRY AND IN ADDITIONAL LOCATIONS AS SHOWN ON THE ACCOMPANYING MAPS.

FIGURE 8



CONSTRUCTION DRAWING OF DEEP MINE SEAL

FIGURE 9

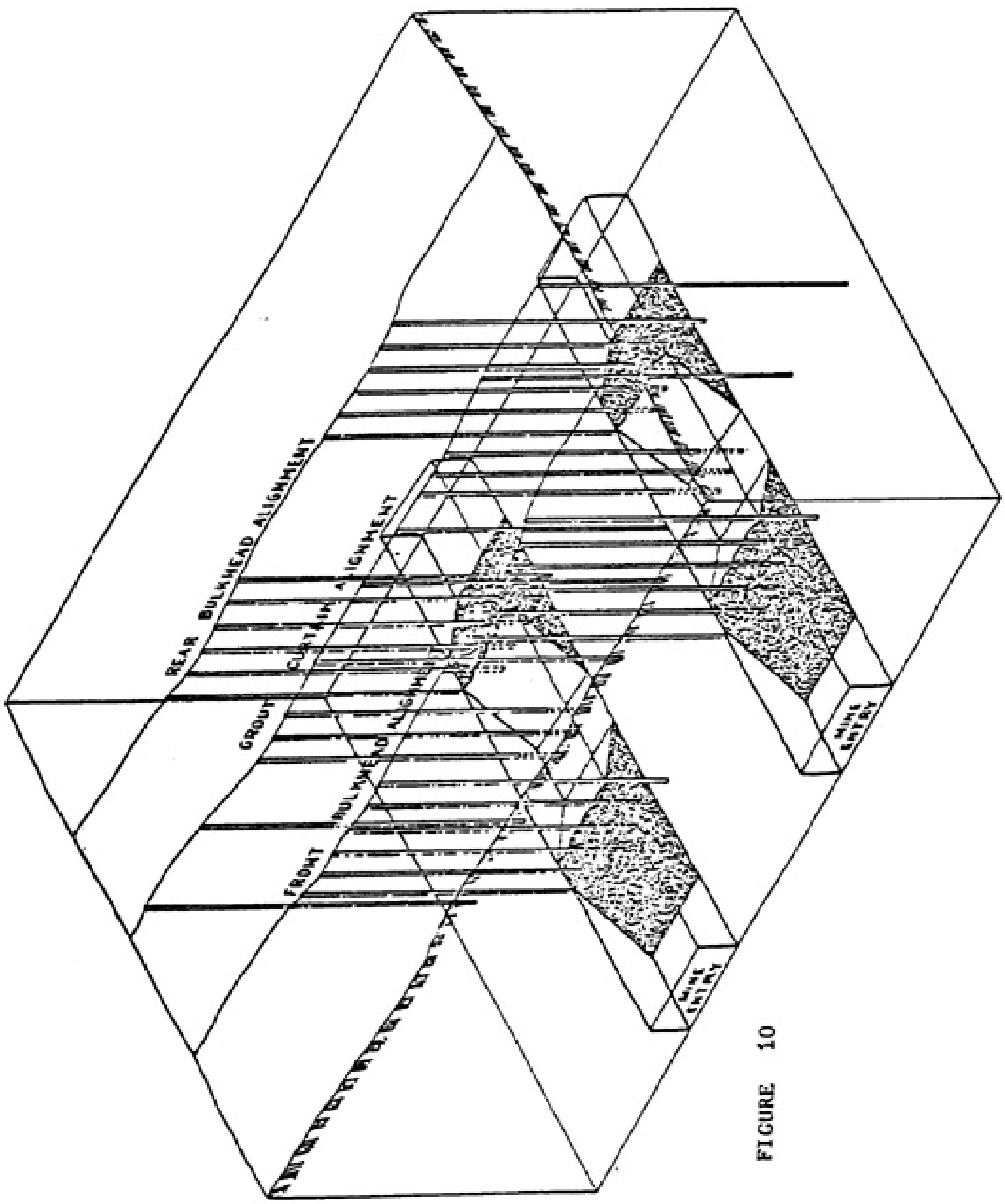


FIGURE 10

ISOMETRIC DRAWING OF DEEP MINE SEALS

NO SCALE

Hydraulic Mine Seals - Drift areas

Mine drifts are horizontal entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure and the choice of construction materials used for the seals is an economic decision.

Generally, drift seals at active mine sites are constructed in surface accessible areas and thus these mine seals are rarely constructed using remote placement construction methods unless severe subsidence is occurring or believed to be possible. Conversely, drift seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Foreman (1964) designed and constructed the first known remotely placed, double bulkhead mine seal at an abandoned deep mine with a pollutional discharge situated on the Altoona City Authority watershed (Blair Co.,, PA). The seal eliminated the pollutional discharge and proved that mine seals could be effectively placed using remote methods.

Foreman, Bullers and Hong (1969) constructed sixty nine (69) remotely placed deep mine seals at Moraine State Park (Butler Co., PA). These seals were constructed to abate AMD Discharges emanating from twenty-two (22) abandoned mine complexes which drained to Lake Arthur. Maksimovic, et. al. (1982) performed an followup hydrogeologic and geochemical assessment of the mine scaling for the US Bureau of Mines. They concluded that total mean discharge, alkalinity, and iron increased while total mean acid loads were decreased and that "Overall, mine scaling has improved the water quality of Lake Arthur".

Foreman, Ward and Bullers (1970) constructed thirty two (32) remotely placed deep mine seals at the Argentine/Whiskerville project area (Butler Co., PA). These seals were constructed to abate AMD discharges emanating from several abandoned mine complexes which drained to Slippery Rock Creek. Followup hydrogeologic and geochemical assessment of the mine sealing by PA DER staff concluded that the mine seals were functioning and the mine achieved about twenty feet of inundation before reaching equilibrium without any AMD discharge to Slippery Rock Creek..

Foreman, Hong and Foreman (1979) designed and constructed a large clay dike and thirty five hydraulic drift seals at Lake Hope State Park in Zaleski National Forest (Vinton Co, OH). These seals were constructed to abate severe AMD discharges emanating from six (6) abandoned deep mine complexes which drained to Lake Hope. Nichols, et. al. (1983) performed a followup hydrogeologic and geochemical assessment of the mine scaling for the USGS, US EPA (Ohio) and the Ohio DNR. After only six (6) months following construction they reported an increase in "mean" pH of nearly 2 points and corresponding decreases in conductance (25%), sulfates (40%) and total iron (84%). Subsequently, Lake Hope has improved to the point where a viable bass fishery has been reestablished.

Beck and Foreman (1982, 1985) constructed and evaluated 6 concrete seals installed at the Oneida Mining Co. - Dilltown facility (Indiana Co., PA) which were designed to prevent a post-mining AMD discharge from the mine after closure and inundation. The hydrologic and geochemical assessment of the mine seals concluded that the seals proved to be effective with no discharge found and no impact to underlying groundwater systems.

Hydraulic Mine Seals - Drift areas

Foreman, Beck and Foreman (1984) designed and constructed 35 concrete drift seals installed at the PA Mines Corp. - Lady Jane Collieries deep mine (Clearfield Co., PA) which were designed to prevent a post-mining AMD discharge from the mine after closure and inundation.

This mine scaling program included construction of several internal mine seals whose function was to develop staged internal mine pools to regulate maximum hydraulic head and pressure. The development of the several small, isolated mine pools limited the maximum hydrostatic head on coal barriers above regional drainage along the periphery of the mined area. The hydrologic and geochemical assessment of the mine seals concluded that the seals proved to be effective with no discharge found and no impact to underlying groundwater systems.

Foreman and Davis (198S) designed and constructed 12 concrete drift seals installed at the G.M.&W. Coal Co. - Grove #3 and Grove #5 deep mines (Somerset Co., PA) which were designed to prevent a post-mining AMD discharge from the mine following closure and inundation. Following construction and closure, no discharges were found.

Foreman and Foreman (1985) designed and constructed 19 concrete drift seals installed at the Island Creek Coal Co. - Bird #2 and Bird #3 deep mines (Cambria Co. & Somerset Co., PA) which were designed to prevent or minimize post-mining AMD discharges from the mines following closure and inundation.

Foreman, Moss and Foreman (198S) designed a concrete drift seal and a high pressure internal mine seal for construction at the abandoned Walker deep mine (California) which mined copper ore and had become a significant source of AMD. This was reported to be a success and abated the outflow of AMD from the mine.

Foreman and Foreman (1982) designed a a large clay dike to abate a severe AMD discharge emanating from an abandoned deep mine complex underlying the active Peabody Coal Co. - Simco #4 surface mine (Coshocton Co., OH) and which was the subject of compliance actions with the Ohio DNR.

Foreman, Moore and Foreman (1982) designed and constructed a remotely placed deep mine seal in an entry which breached the periphery barrier of the Guarnieri deep mine complex for the Adobe Coal Mining Co. (Lawrence Co., PA) to restore the function of the barrier and eliminate drainage of the deep mine reservoir into the active surface mine pit adjacent to the mine. Following construction, the drainage was abated and Adobe was able to surface mine without further inflows from the adjacent deep mine reservoir.

Foreman, Hong and Ward (1977) designed and constructed a clay dike to abate the discharge from an abandoned deep mine (Mercer Co., PA). The clay dike was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The clay was then backfilled and compacted to an elevation exceeding the maximum structural elevation of the deep mine. This provided a hydraulic barrier to prevent lateral discharge from the abandoned deep mine and assured that the mine would be fully flooded. The clay dike seal was effective since there was no discharge following construction and the deep mine became fully inundated.

Hydraulic Mine Seals - Slopes

Mine slopes are angular entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure and the choice of construction materials used for the seals is an economic decision.

Generally, slope seals at active mine sites are constructed in surface accessible areas and thus these mine seals are rarely constructed using remote placement construction methods unless severe subsidence is occurring or believed to be possible. Conversely, slope seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Foreman and Foreman (1985) designed and constructed 2 concrete slope seals which were installed at the Island Creek Coal Co. - Bird #2 and Bird #3 deep mines (Cambria Co. & Somerset Co., PA) which were designed to prevent or minimize post-mining AMD discharges from the slope following closure and inundation. No post-construction discharge has been identified from the slope.

Foreman and Foreman (1992) designed and constructed a concrete slope seal which was installed at the PA Mines Corp. - Rushton deep mine (Centre Co. & Clearfield Co., PA) which were designed to prevent or minimize post-mining AMD discharge from the slope following closure and inundation. No post-construction discharge has been identified from the slope.

Hydraulic Mine Seals - Shafts

Mine shafts are vertical entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure and the choice of construction materials used for the seals is an economic decision.

Generally, shaft seals at active mine sites are constructed in surface accessible areas and thus these mine seals are rarely constructed using remote placement construction methods unless severe deterioration is occurring or believed to be possible. Conversely, shaft seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Beck and Foreman (1982, 1985) constructed and evaluated I concrete shaft seal installed at the Oneida Mining Co. - Dilltown facility (Indiana Co., PA) which were designed to prevent a post-mining AMD discharge from the mine after closure and inundation. The hydrologic and geochemical assessment of the shaft seals concluded that the seal proved to be effective with no discharge found and no impact to underlying groundwater systems.

Foreman, Beck and Foreman (1984) constructed and evaluated 1 concrete shaft seal installed al. the PA Mines Corp. - Lady Jane Collieries deep mine which was designed to prevent a post-mining AMD discharge from the shaft after closure and inundation. The hydrologic and geochemical assessment of the shaft seal concluded that the seals proved to be effective with no discharge found and no impact to underlying groundwater systems.

Foreman and Foreman (1985) designed and constructed 7 concrete shaft seal which was installed at the Island Creek Coal Co. - Bird #2 and Bird #3 deep mines (Cambria Co. & Somerset Co., PA) which were designed to prevent or minimize post-mining AMD discharges from the shaft following closure and inundation. No post-construction discharge has been identified from the shaft.

Foreman and Foreman (1992) designed and constructed a concrete shaft seal which was installed at the PA Mines Corp. - Rushton deep mine (Centre Co. & Clearfield Co., PA) which were designed to prevent or minimize post-mining AMD discharge from the shaft following closure and inundation. No post-construction discharge has been identified from the shaft.

Hydraulic Mine Seals - Coal Barrier Pillars

Coal barrier pillars are intact blocks of coal left unmined to provide hydraulic barriers for water management as well as to assist in ventilation and roof support. Occasionally, coal barrier pillars are breached during active operations and need to be repaired to return them to original condition. Coal barrier pillars can be classified into 2 functional groups:

1. Periphery barriers - intact coal at the edge of the deep mine works
2. Internal barriers - intact coal located in the interior of the mine works

Generally, both periphery and internal coal barrier pillars at active mine sites are accessible areas and thus hydraulic barrier seals installed at these mine seals are rarely constructed using remote placement methods unless the area is flooded or is abandoned.

Typically, periphery barriers at abandoned mine sites are accessible if the barriers are situated above regional drainage levels. Conversely, both periphery barriers below regional drainage and internal barriers at abandoned mine sites are typically unventilated and often flooded making them unsafe. These are often constructed using remote methods.

Periphery coal barrier pillars are often limiting factors in the design of mine seals for abandoned mines, particularly along downgradient outcrop areas of mines situated above regional drainage levels. Further, internal coal barrier pillars are often limiting factors to achieving maximum inundation in upgradient mines where significant recharge potential exists for water movement through the barrier to adjacent, downgradient mine works.

Finally, there remain significant legal issues associated with migration of water from flooded mines through internal barriers to adjacent deep mines. This is true for both adjacent, abandoned mine complexes as well as adjacent, active mine complexes.

Case Studies:

Foreman, Moore and Foreman (1982) designed and constructed a remotely placed deep mine seal in an entry which breached the periphery barrier of the Guarnieri deep mine complex for the Adobe Coal Mining Co. (Lawrence Co., PA) to restore the function of the barrier and eliminate drainage of the deep mine reservoir into the active surface mine pit adjacent to the mine. Following construction, the drainage was abated and Adobe was able to surface mine without further inflows from the adjacent deep mine reservoir.

Foreman, Hong and Foreman (1978) constructed a large clay dike and thirty five (35) hydraulic drift seals at Lake Hope State Park in Zaleski National Forest (Vinton Co., OH.). This mine sealing project was undertaken to abate severe AMD discharges emanating from six (6) abandoned deep mine complexes which drained to Lake Hope. The clay dike was constructed to continuously replace the inadequate downgradient outcrop barrier along the edge of the mine. The functional repair of the barrier allowed the mine complex to achieve full inundation when coupled with the construction of the mine seals. Nichols, et. al. (1983) performed a followup hydrogeologic and geochemical assessment of the mine sealing for the USGS, US EPA (Ohio) and the Ohio DNR. After only six (6) months following construction they reported an increase in "mean" pH of nearly 2 points and corresponding decreases in conductance (2S%), sulfates (40%) and total iron (84%). Subsequently, Lake Hope has improved and a viable bass fishery has been reestablished.

Foreman and Foreman (1985) constructed a concrete mine seal in the breached barrier of the active Island Creek Coal Co. - Providence #1 deep mine (Webster Co., KY) to reestablish the functional aspect of the barrier and return the mine to active production. The miners at the Providence deep mine had inadvertently mined through the barrier into the adjacent, abandoned Hall-Luton #9 deep mine which was fully flooded at that time. The resultant inflow flooded over 60% of the Providence mine causing full evacuation of the workforce and complete destruction of most of the ventilation stoppings in the mine. Because of the presence of an overlying, flooded mine complex, the cost of placing remote seals was deemed excessive and it was decided to renovate the immediate section and construct the mine seal at the face. The MSHA approved mine sealing was totally successful and allowed the mine to be reopened and returned to full productivity.

Foreman, Hong and Ward (1977) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Mercer Co., PA). The slurry trench was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The trench was then backfilled with a soil-bentonite stabilized slurry which provided a hydraulic barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

Foreman and Glenn (1980) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Clarion Co., PA). The slurry trench was developed along the peripheral. outcrop barrier of the mine and was excavated from 'the surface using large backhoes. The trench was then backfilled with a stabilized soil-cement slurry which, when set-up, provided a relatively impervious barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

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