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INACTIVE & ABANDONED UNDERGROUND MINES

Water Pollution Prevention & Control

U.S. ENVIRONMENTAL PROTECTION AGENCY
Washington, D.C. 20460

This report is issued under Section 304(e)(2)(B) of Public Law 92-500. This Section provides:

"The Administrator, after consultation with appropriate Federal and State agencies and other interested persons, shall issue to appropriate Federal agencies, the States, water pollution control agencies, and agencies designated under Section 208 of this Act, within one year after the effective date of this subsection (and from time to time thereafter) information including. . . (2) processes, procedures, and methods to control pollution resulting from –

(B) mining activities, including runoff and siltation from new, currently operating, and abandoned surface and underground mines; . . ."

This publication is the second in a series issued under Section 304(e)(2)(B) of Public Law 92-500 concerning the control of water pollution from mining activities. The first report, "Processes, Procedures and Methods to Control Pollution from Mining Activities", was issued in October 1973 (Publication No. EPA-430/9-73-011).

This report provides technical and cost information on alternative control measures. Sufficient descriptive information is provided to guide the reader in the tentative selection of alternative measures to be applied in specific cases. The details of application and methods of construction of each measure must be ascertained on a case-by-case basis by qualified professionals in the mining and water pollution control fields.

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Water Pollution Prevention and Control

Prepared for

Office of Water and Hazardous Materials
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Washington, D.C. 20460

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ABSTRACT

Underground mining operations across the United States produce a number of environmental problems. The foremost of these environmental concerns is acid discharges from inactive and abandoned underground mines that deteriorate streams, lakes and impoundments. Waters affected by mine drainage are altered both chemically and physically.

This report discusses in Part I the chemistry and geographic extent of mine drainage pollution in the United States from inactive and abandoned underground mines; underground mining methods; and the classification of mine drainage control techniques. Control technology was developed mainly in the coal fields of the Eastern United States and may not be always applicable to other regions and other mineral mining.

Available at-source mine drainage pollution prevention and control techniques are described and evaluated in Part II of the report and consist of five major categories: (1) Water Infiltration Control; (2) Mine Sealing; (3) Mining Techniques; (4) Water Handling; and (5) Discharge Quality Control. This existing technology is related to appropriate cost data and practical implementation by means of examples.

A summary of the mineral commodities mined in the United States follows Part II and relates to type, locale and environmental effects.

A list of minerals, mineral formulas, glossary and extensive bibliography are included to add to the usefulness of this report.

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ABBREVIATIONS AND SYMBOLS

AASHO – American Association of State Highway Officials
ac – acre(s)
cfm – cubic foot (feet) per minute
cu m – cubic meter(s)
cu m/hr – cubic meter(s) per hour
cu yd – cubic yard(s)
EPA – Environmental Protection Agency
gal/acre/day – gallon(s) per acre per day
gal/hour – gallon(s) per hour
gpm – gallon(s) per minute
ha – hectare(s)
hr – hour(s)
I.D. – inside diameter
kg – kilogram(s)
kg/day – kilogram(s) per day
lb/acre – pound(s) per acre
lb/day – pound(s) per day
LF – linear foot (feet)
LM – linear meter(s)
MGD – million gallons per day
mg/l – milligram(s) per liter
O.D. – outside diameter
psi – pound(s) per square inch
SCFH – standard cubic feet per hour
sq ft – square foot (feet)
sq m – square meter(s)
sq yd – square yard(s)
tons/day – tons per day

I

UNDERGROUND MINES AND WATER POLLUTION

1.0

MINE DRAINAGE POLLUTION IN THE UNITED STATES

In the United States water pollution resulting from mining activities has long been recognized as a major environmental problem. Mine drainage pollution results from many types of mining activities and includes both physical (i.e., sedimentation) and chemical (i.e., acidification, metal contamination, etc.) pollutants. Active and abandoned surface and underground mines, mineral processing plants, mine and processing plant waste disposal areas, haulage roads, and tailing ponds are typical sources of mine related water pollution (130).

One of the most serious pollution problems arising from mining activities is acid mine drainage resulting from the chemical reaction of sulfide minerals (commonly iron sulfides) and air in the presence of water. Acid mine drainage is commonly associated with coal and hard rock mining areas in the United States. In general the more serious and extensive acid mine drainage problems exist in the more humid coal regions east of the Mississippi River (11). In 1964 the U.S. Department of the Interior, Fish and Wildlife Service, reported that acid mine drainage adversely affected fish and wildlife habitat in 9,477 kilometers (5,890 miles) of streams and 6,062 hectares (14,967 acres) of impoundments in 20 states in the United States (64). Of the total affected waters, coal mining operations accounted for 97 percent of the acid mine drainage pollution reported for streams and 93 percent of that reported for impoundments.

In 1970 more than 19,308 kilometers (12,000 miles) of streams in the United States were reportedly significantly degraded by mining related pollution (130). Of the total affected kilometers, 16,920 kilometers (10,516 miles) or approximately 88 percent were located in the Appalachian coal region (Pennsylvania, West Virginia, Ohio, eastern Kentucky, Tennessee, Maryland, and Alabama). In addition, more than 965 kilometers (600 miles) of streams reportedly were degraded by coal mining in states in the Illinois, Western Interior, and Rocky Mountain coal regions. The remaining portion of the stream pollution resulted from the mining of: (1) copper (california, Montana, Nevada, New Hampshire, Tennessee, Virginia, and Wyoming); (2) lead and zinc (Colorado, Idaho, Kansas, Missouri, Montana, Oklahoma, and Tennessee); (3) uranium (Rocky Mountain States); (4) iron (Lake Superior iron region); (5) sand and gravel (all states); (6) phosphate (Florida and other states); (7) gold (Alaska); (8) bauxite and barite (Arkansas); and (9) molybdenum, gold, and other metals (Colorado).

Abandoned mines and abandoned mine waste disposal areas contribute a large portion of the total pollution resulting from mining activities. Numerous abandoned underground mines are located throughout the United States and many are discharging mine drainage pollutants. In 1966 the U.S. Bureau of Mines estimated that more than 88,000 inactive and abandoned underground mines were in existance (126). A listing of these mines by state is presented in Table 1.0-1. More recent estimates indicate that this list is incomplete. In Colorado alone there is

Table 1.0-1

Abandoned and Inactive Underground Mines
In The United States as of 1966

State	Coal	Metal	Nonmetal
Alabama	310	64	27
Alaska	6	--	--
Arizona	--	773	6
Arkansas	269	186	--
California	32	3,045	82
Colorado	565	1,699	7
Connecticut	--	6	3
Delaware	--	--	--
Florida	--	--	--
Georgia	115	62	28
Hawaii	--	--	--
Idaho	11	1,749	208
Illinois	1,605	39	124
Indiana	960	--	2
Iowa	1,138	60	--
Kansas	528	681	13
Kentucky	12,045	4	120
Louisiana	--	--	1
Maine	--	7	--
Maryland	564	7	--
Massachusetts	--	7	1
Michigan	--	278	6
Minnesota	--	87	--
Mississippi	1	--	1
Missouri	466	1,520	36
Montana	334	1,691	146
Nebraska	--	--	--
Nevada	5	1,346	10
New Hampshire	--	24	3
New Jersey	--	26	--
New Mexico	48	277	23
New York	--	61	17
North Carolina	5	78	1,129
North Dakota	--	12	--
Ohio	2,187	35	53
Oklahoma	251	283	--
Oregon	61	1,140	3
Pennsylvania	7,824	160	55
Rhode Island	--	2	4
South Carolina	--	30	17

Table 1.0-1 (cont.)

State	Coal	Metal	Nonmetal
South Dakota	1	172	--
Tennessee	2,931	42	11
Texas	21	31	--
Utah	44	1,348	8
Vermont	--	17	3
Virginia	14,397	14	6
Washington	247	907	52
West Virginia	20,616	--	9
Wisconsin	--	389	1
Wyoming	26	295	--
Total	67,613	18,654	2,215

reportedly more than 10,000 abandoned prospector pits. Recent studies estimate that in excess of 200,000 inactive and abandoned underground mines exist in the United States.

All abandoned underground mines do not discharge mine drainage pollutants. The extent and distribution of pollution discharging from abandoned underground mines will depend upon such factors as: hydrology, geology, topography, and climatology of the mine site; extent and method of mining; availability of air and water; and the distribution of sulfide minerals.

For many years abandoned underground coal mines have been recognized as major sources of mine drainage pollution. Of the sources of mine drainage pollution located and described in Appalachia during 1964 to 1968 by the Federal Water Pollution Control Administration, abandoned underground mines were found to contribute 52 percent of the acid discharged to streams (130). In 1973 acid production from abandoned eastern underground mines totaled more than 2.3 million kilograms per day (5 million lb/day), which was the largest single source of acid mine drainage pollution in the United States.

Acid mine discharges from abandoned non-coal mines do occur in the United States, but reportedly are not as severe or extensive as coal mine drainage. Many non-coal underground mines are developed below drainage, and therefore naturally flood when they are abandoned. Mines located in arid or semi-arid areas of the West are less likely to discharge, since water is not readily available to transport pollutants. However, adverse environmental effects resulting from the discharge of pollutants from abandoned, underground non-coal mines have been documented in the Rocky Mountain States and other mining areas of the United States.

REFERENCES

1, 5, 11, 23, 34, 50, 63, 64, 80, 93, 94, 96, 120, 120, 126, 128, 129, 130, 131

2.0

CHEMISTRY OF MINE DRAINAGE POLLUTION

Mine drainage may be defined as ground or surface water draining or flowing from, or having drained or flowed from, a mine or area affected by mining activities. The type and characteristics of drainage produced by a particular mine or mined area will depend upon the mineral commodity mined and the nature of the surrounding geologic formations. Waters affected by mine drainage typically are altered chemically by the addition of iron, sulfate, acidity (or alkalinity), hardness, dissolved solids, and various metals and altered physically by the addition of suspended solids such as silt and sediment (1, 54).

The characteristics of mine drainage range from acid to neutral to alkaline. Acid mine drainage is generally defined as having a low pH, net acidity, high iron, high sulfates, and significant concentrations of aluminum, calcium, magnesium, and manganese. Alkaline mine drainage is generally defined as having a pH near or greater than neutrality, net alkalinity, high sulfates, low aluminum, and significant concentrations of calcium, magnesium and manganese (54). Based upon studies performed by the Federal Water Pollution Control Administration, a classification of mine drainage has been developed. These four classes are presented in Table 2.0-1.

Alkaline mine drainage usually does not have as severe adverse effects upon the environment as does acid mine drainage. Alkaline drainage may result where no acid producing minerals are associated with a mineral body or where neutralization of acid drainage has occurred. In underground mine situations, alkaline drainage may become acid as the result of the oxidation and hydrolysis of ferrous iron. The potential for alkaline drainage exists in many mining areas of the West where overburden material is highly alkaline and sometimes saline. However, documentation of alkaline and saline drainage problems is almost nonexistent (59).

Acid mine drainage results from the oxidation or decomposition of sulfides and sulfosalts which are commonly associated with mineral bodies. The general formula for sulfides is A_mX_n where A consists of the metallic elements or sometimes arsenic, antimony, and bismuth. Elements of sulfides are (49, 51):

A					X	
Ag	Fe	Pb	As	Ru*	S	As
Cu	Co	Hg	Sb*	Sn*	Se	Sb*
Tl*	Ni	Mn*	Bi*	Mo*	Te	Bi*
Au*	Zn	Ca*	Pt*	W*		
		Cd				

*Rare or uncommon

Table 2.0-1

Mine Drainage Classes

	Class 1 Acid Discharges	Class 2 Partially Oxidized and/or Neutralized	Class 3 Oxidized and Neutralized and/or Alkaline	Class 4 Neutralized and Not Oxidized
pH	2 - 4.5	3.5 - 6.6	6.5 - 8.5	6.5 - 8.5
Acidity, mg/l ($CaCO_3$)	1,000 - 15,000	0 - 1,000	0	0
Ferrous Iron, mg/l	500 - 10,000	0 - 500	0	50 - 1,000
Ferric Iron, mg/l	0	0 - 1,000	0	0
Aluminum, mg/l	0 - 2,000	0 - 20	0	0
Sulfate, mg/l	1,000 - 20,000	500 - 10,000	500 - 10,000	500 - 10,000

The general formula for sulfosalts is $A_mB_nX_p$. The major elements of the sulfosalts are:

A	B	X
Cu	As	S
Ag	Sb	
Pb	Bi	
Sn	Sn	

Due to the number of chemical elements and the complexity of composition, the diversity of chemical combinations is great. More than 125 sulfides and sulfosalts are known to occur naturally. Thus, the potential for trace metals in discharges from mines is also present. A list of naturally occurring sulfides and sulfosalts is presented in Table 2.0-2.

The most common sulfides are the sulfides of iron (pyrite, marcasite, and pyrrhotite). Pyrite (FeS_2) is the most common and abundant of sulfide minerals known. Marcasite is found in surface or near surface deposits and is more frequently associated with limestone, clays and lignite. Pyrrhotite is commonly associated with pentlandite ($(Fe,Ni)_9S_8$) and other sulfides. It is given the formula $Fe_{1-x}S$ where x varies from 0 to 0.2 (49).

The oxidation of these iron sulfides in the presence of air water is responsible for the formation of acid drainage from mines. In recent years much research regarding the oxidation of FeS_2 has been conducted in the Appalachian coal region of the United States. The following equations represent the basic chemical reactions which describe an acid drainage situation:

$$FeS_2(s) + 7/2\ O_2 + H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^+ \quad (1)$$

$$Fe^{+2} + 1/4\ O_2 + H^+ = Fe^{+3} + 1/2\ H_2O \quad (2)$$

$$Fe^{+3} + 3H_2O = FeOH_3(s) + 3H^+ \quad (3)$$

$$FeS_2(s) + 14Fe^{+3} + 8\ H_2O = 15Fe^{+2} + 2SO_4^{-2} + 16H^+ \quad (4)$$

Equation 1 represents a heterogenous reaction involving crystalline pyrite with gaseous or dissolved oxygen and liquid or vapor water. As can been seen from the equation, oxygen oxidizes the sulfide in pyrite to sulfate. The basic function of the water is to transport the oxidized material from the surface as accumulation of these products will affect the oxidation rate.

Table 2.0-2

Sulfides and Sulfosalts

Aquilarite – Ag_4SeS
Alkalinite – $PbCuBiS_3$
Alabandite – MnS
Alaskaite – $Pb(Ag,Cu)_2Bi_4S_8$ possibly
Andorite – $PbAgSb_3S_6$
Aramayoite – $Ag(Sb,Bi)S_2$
Argentite – Ag_2S
Argyrodite – Ag_8GeS_6
Arsenopyrite – FeAsS
Baumhauerite – $Pb_4As_6S_{13}$
Beegerite – $Pb_6Bi_2S_9$
Benjaminite – $Pb(Cu,Ag)Bi_2S_4$ possibly
Berthierite – $FeSb_2S_4$
Berthonite – $Pb_2Cu_7Sb_5S_{13}$
Bismuthinite – Bi_2S_3
Bornite – Cu_5FeS_4
Boulangerite – $Pb_5Sb_4S_{11}$
Bournonite – $PbCuSbS_3$
Braggite – (Pt,Pd,Ni)S
Bravoite – $(Ni,Fe)S_2$
Canfieldite – Ag_8SnS_6
Chalcocite – Cu_2S
Chalcopyrite – $CuFeS_2$
Chalcostibite – $CuSbS_2$
Chiviatite – $Pb_3Bi_8S_{15}$ possibly
Cobaltite – CoAsS
Colusite – $Cu_3(As,Sn,V,Fe,Te)S_4$
Cooperite – PtS
Cosalite – $Pb_2Bi_2S_5$
Covellite – CuS
Cubanite – $CuFe_2S_3$
Cylindrite – $Pb_3Sn_4Sb_2S_{14}$
Daubreelite – Cr_2FeS_4
Diaphorite – $Pb_2Ag_3Sb_4S_8$
Digenite – $Cu_{2-x}S$
Dimorphite – As_4S_3
Dufrenoysite – $Pb_2As_2S_5$
Emplectite – $CuBiS_2$
Enargite – Cu_3AsS_4

Famatinite – Cu_3SbS_4
Fizelyite – $Pb_5Ag_2Sb_8S_{18}$ possibly
Franckeite – $Pb_5Sn_3Sb_2S_{14}$
Freieslebenite – $Pb_3Ag_5Sb_5S_{12}$
Fuloppite – $Pb_3Sb_8S_{15}$
Galena – PbS
Galenobismutite – $PbBi_2S_4$
Geocronite – $Pb_5(Sb,As)_2S_8$
Germanite – (Cu,Ge)(S,As)
Gersdorffite – NiAsS
Gladite – $PbCuBi_5S_9$
Glaucodot – (Co,Fe)AsS
Gratonite – $Pb_9As_4S_{15}$
Greenockite – CdS
Gruenlingite – Bi_4TeS_3 or near $Bi_2(Te,Bi)S_2$
Gudmundite – FeSbS
Guitermanite – $Pb_{10}As_6S_{19}$
Hammarite – $Pb_2Cu_2Bi_4S_9$
Hauerite – MnS_2
Heteromorphite – $Pb_7Sb_8S_{19}$
Hutchinsonite – $(Pb,Tl)_2(Cu,Ag)As_5S_{10}$
Jamesonite – $Pb_4FeSb_6S_{14}$
Jordanite – $Pb_{14}As_7S_{24}$
Joseite – $Bi_3Te(Se,S)$
Kermesite – Sb_2S_2O
Klaprothite – $Cu_6Bi_4S_9$
Kobellite – $Pb_2(Bi,Sb)_2S_5$
Laurite – RuS_2
Lautite – CuAsS
Lengenbachite – $Pb_6(Ag,Cu)_2As_4S_{13}$
Lillianite – $Pb_3Bi_2S_6$
Linstromite – $PbCuBi_3S_6$
Linnaeite Series – $(Co,Ni)_2(Co,Ni,Fe,Cu)S_4$
Livingstonite – $HgSb_4S_7$
Loellingite – $FeAsS_2$
Lorandite – $TiAsS_2$
Marcasite – FeS_2
Matildite – $AgBiS_2$
Meneghinite – $Pb_{13}Sb_7S_{23}$
Metacinnabar – HgS
Miargyrite – $AgSbS_2$

Table 2.0-2 (cont.)

Millerite – NiS
Molybdenite – MoS_2
Nagyagite – $Pb_5Au(Te,Sb)S_{5-8}$
Oldhamite – GaS
Orpiment – As_2S_3
Owheeite – $Pb_5Ag_2Sb_6S_{15}$
Pearceite – $Ag_{16}As_2S_{11}$
Pentlandite – $(Fe,Ni)_9S_8$
Plagionite – $(Pb_5Sb_8S_{17})$
Platynite – $PbBi_2(Se,S)_3$
Polybasite – $(Ag,Cu)_{16}Sb_2S_{11}$
Proustite – Ag_3AsS_3
Pyrargyrite – Ag_3SbS_3
Pyrite – FeS_2
Pyrostilpnite – Ag_3SbS_3
Pyrrhotite – $Fe_{1-x}S$ (x lies between 0 and 0.2)
Ramdohrite – $Pb_3Ag_2Sb_6S_{13}$
Rathite – $Pb_{13}As_{18}S_{40}$
Realgar – AsS
Rezbanyite – $Pb_3Cu_2Bi_{10}S_{19}$
Samsonite – $Ag_4MnSb_2S_6$
Sartorite – $PbAs_2S_4$
Schirmerite – $PbAg_4Bi_4S_9$
Seligmannite – $PbCuAsS_3$
Semseyite – $Pb_9Sb_8S_{21}$
Smithite – $AgAsS_2$
Sphalerite – ZnS
Stannite – Cu_2FeSnS_4
Stephananite – Ag_5SbS_4
Sternbergite – $AgFe_2S_3$
Stibnite – Sb_2S_3
Stromeyerite – $AgCuS$
Sulvanite – Cu_3VS_4
Teallite – $PbSnS_2$
Tennantite – $(Cu,Fe)_{12}As_4S_{13}$
Tetradymite – Bi_2Te_2S
Tetrahedrite – $(Cu,Fe)_{12}Sb_4S_{13}$
Tungstenite – WS_2
Ullmannite – $NiSbS$
Voltzite – Zn_5S_4O
Wehrlite – Bi_8Te_5S possibly

Table 2.0-2 (cont.)

Weibullite – $PbBi_2(S,Se)_4$
Wittichenite – Cu_3BiS_3
Wittite – $Pb_5Bi_6(S,Se)_{14}$
Wurtzite – ZnS
Xanthoconite – Ag_3AsS_3
Zinkenite – $Pb_6Sb_{14}S_{27}$

The products of pyrite oxidation undergo additional reactions as shown in Equations 2 thru 4. Ferrous iron produced by pyrite oxidation is oxidized to ferric iron (Equation 2). The ferric iron hydrolyzes to form insoluble ferric hydroxide (Equation 3). The ferric iron may be reduced by pyrite to form ferrous iron (Equation 4) which is then available for oxidation via Equation 2. Four equivalents of acidity are produced during this cycle. Two equivalents are produced during the oxidation of sulfide and the remaining two with the resulting hydrolysis of ferric iron.

The acid produced by the oxidation of iron sulfides lowers the pH of water draining from the material. The iron sulfides are seldom pure and are commonly associated with other sulfides or sulfosalts. As the iron sulfides oxidize, associated sulfides and sulfosalts are oxidized or exposed to extreme chemical conditions which result in their breakdown. This breakdown results in the release of metallic, non-metallic, and sulfate ions to the environment (49, 51).

In addition to the chemical reactions involved in acid mine drainage formation, certain bacteria are capable of oxidizing sulfide minerals. These bacteria are:

(1) Thiobacillus ferrooxidans

(2) Ferrobacillus ferrooxidans

(3) Thiobacillus sulfooxidans

These bacteria rely solely upon the oxidation of inorganic materials such as iron and sulfur for their energy source. Presently, at least nineteen metallic sulfides and sulfosalts are known to be oxidized by this bacteria group (49).

The concentration and number of different metal ions in acid mine drainage will depend upon the sulfides and sulfosalts present, and the chemical characteristics of the metal ion and water. Iron is the most common metal found in acid mine drainage. The principal species are ferrous iron (Fe^{+2}), ferric iron (Fe^{+3}), ferrous hydroxide ($Fe(OH)_2$), and ferric hydroxide ($Fe(OH)_3$). Metallic and non-metallic ions may precipitate on may be carried away in solution. It is known that ions such as copper, cobalt, manganese, zinc, and nickel all form soluble salts under acid mine drainage conditions. However, lead forms relatively insoluble salts under similar conditions and is rarely found in high concentrations in mine drainage discharges (49). Analysis of mine drainage samples collected in the Appalachian coal region by the Federal Water Pollution Control Administration revealed that zinc, cadmium, beryllium, copper, silver, nickel, cobalt, lead, chromium, vanadium, barium, and strontium were commonly found in concentrations less than one milligram per liter (54).

REFERENCES

1, 21, 30, 34, 48, 49, 50, 51, 54, 59, 79, 102, 130

3.0

ENVIRONMENTAL EFFECTS OF POLLUTION

The discharge of pollutants from inactive and abandoned underground mines adversely affects the potential use of affected streams and impoundments in all forms: domestic, industrial, recreational, navigational, municipal, and agricultural. Acid production resulting from the oxidation and decomposition of sulfide minerals is one of the most, if not the most, serious environmental problem resulting from underground mining activities. Acid drainage results in the deterioration of receiving waters by lowering pH, reducing alkalinity, increasing hardness, and adding undesirable amounts of suspended material, and metallic and non-metallic ions.

Acid mine drainage can be extremely damaging to aquatic life. Acid waters support only limited water flora, such as acid-tolerant molds and algae, and usually will not support fish life. The coating of stream bottoms with precipitated metal salts smothers invertebrate life, decreases oxygen content, and reduces the breeding area for aquatic species. Metallic and non-metallic ions found in acid drainage are often in concentrations sufficient to be harmful or even toxic to aquatic life. As previously discussed (see Section 1.0), a 1964 report estimated that fish and wildlife habitat were adversely affected by acid mine drainage in 9,477 kilometers (5,890 miles) of streams and 6,062 hectares (14,967 acres) of impoundments in the United States.

Physical mine drainage pollution (i.e., sedimentation and siltation) adversely affects the environment by filling stream beds with sediment, destroying fish habitat, and increasing treatment costs for industrial, municipal and domestic supplies. Physical pollution problems commonly result from surface mining activities. Underground mining results in little surface disturbance and subsequently produces only minor physical pollution problems. However, mine waste piles usually associated with underground mines are common sources of siltation and acid mine drainage.

Some damages resulting from mine drainage pollution may be evaluated in monetary terms. Treatment costs for municipal, industrial and other water uses will increase as a result of additional treatment required and the replacement of equipment damaged by polluted waters. Additional expenditures will also be required for the inspection, maintenance, and early replacement of water structures and equipment such as bridges, culverts, locks, boat hulls, pumps, and possibly concrete structures. Water affected by mine drainage pollution may also be limited for such recreational uses as fishing, boating, swimming, camping, and picnicking.

REFERENCES

1, 5, 48, 49, 64, 80, 120, 126, 128, 129, 130, 131

4.0

METHODS OF UNDERGROUND MINING

Underground mining methods are those in which access to a mineral body is made via shaft, slope, or drift entries. A shaft is a vertical entry employed when the mineral is located a substantial distance under the ground surface. A slope entry is an inclined shaft commonly developed when the mineral body is located at a distance beyond the outcrop. A drift entry is a horizontal or near horizontal opening driven into the outcrop of a mineral body (21). These methods of entry as used in a typical underground coal mine are depicted in Figure 4.0-1.

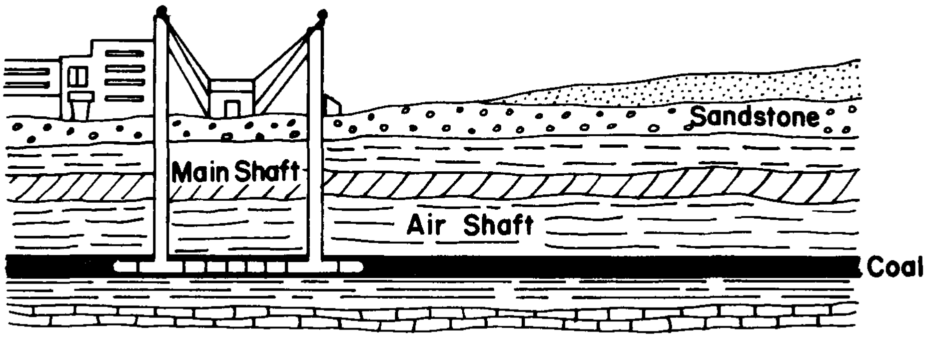
The particular underground method of mining employed will generally depend upon the size and shape of the mineral body. In coal mining the two principal underground methods are room and pillar, and longwall. In room and pillar mining, main entries, cross entries, panel entries, and rooms are driven into the coal seam (130). This method divides the underground mine into a series of mined out rooms with pillars left for roof support. Although room and pillar mining is primarily applied to coal mining, it may be utilized in the mining of any mineral that occurs as a bedded deposit. Figure 4.0-2 shows a plan view of a typical room and pillar system.

Longwall mining is a method of removing a mineral seam by means of a longwall or working face which may exceed 305 meters (1,000 feet) in length. The primary advantages of longwall mining are increased production and efficient mineral recovery. Longwall mining is discussed in this manual (in conjunction with downdip mining and daylighting) as a method of mining that may be implemented to prevent or control the formation of mine drainage pollutants (See Part II, Section 3.0 – Mining Methods).

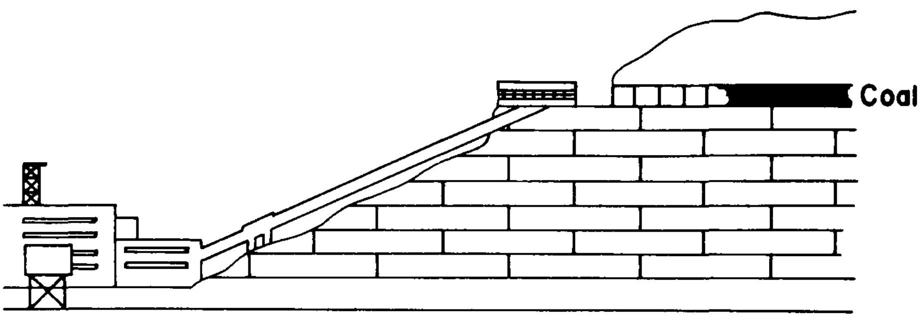
Due to the irregular shape of ore bodies, metal, and non-metallic minerals are generally mined by stoping methods. Stoping is a method of excavation in which a mineral body is drilled, blasted, and removed by gravity through chutes to a haulage level below (49). Three common stoping methods are: (1) shrinkage stope; (2) cut and fill stope; and (3) square set stope.

The shrinkage stope is most used in steeply dipping vein deposits where the walls and mineral body require little or no support. As the mineral is blasted down,sufficient mineral is removed through the chutes, to allow miners to drill and blast the next section (46, 49). An example of the shrinkage stope is shown in Figure 4.0-3.

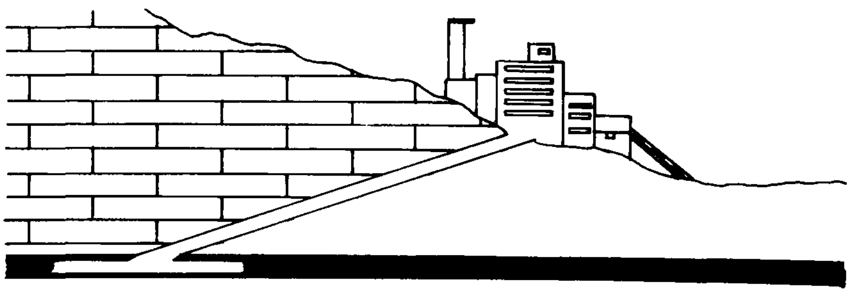
The cut and fill stope is used in wider irregular mineral bodies. The mineral is blasted down and removed from the stope. Prior to removal of the next section of mineral, waste material is placed in the stope for wall support. This method of mining is shown in Figure 4.0-4.



SHAFT ENTRY



DRIFT ENTRY



SLOPE ENTRY

FIGURE 4.0-1

METHODS OF ENTRY TO UNDERGROUND COAL MINES
(Adapted from Ref. 129)

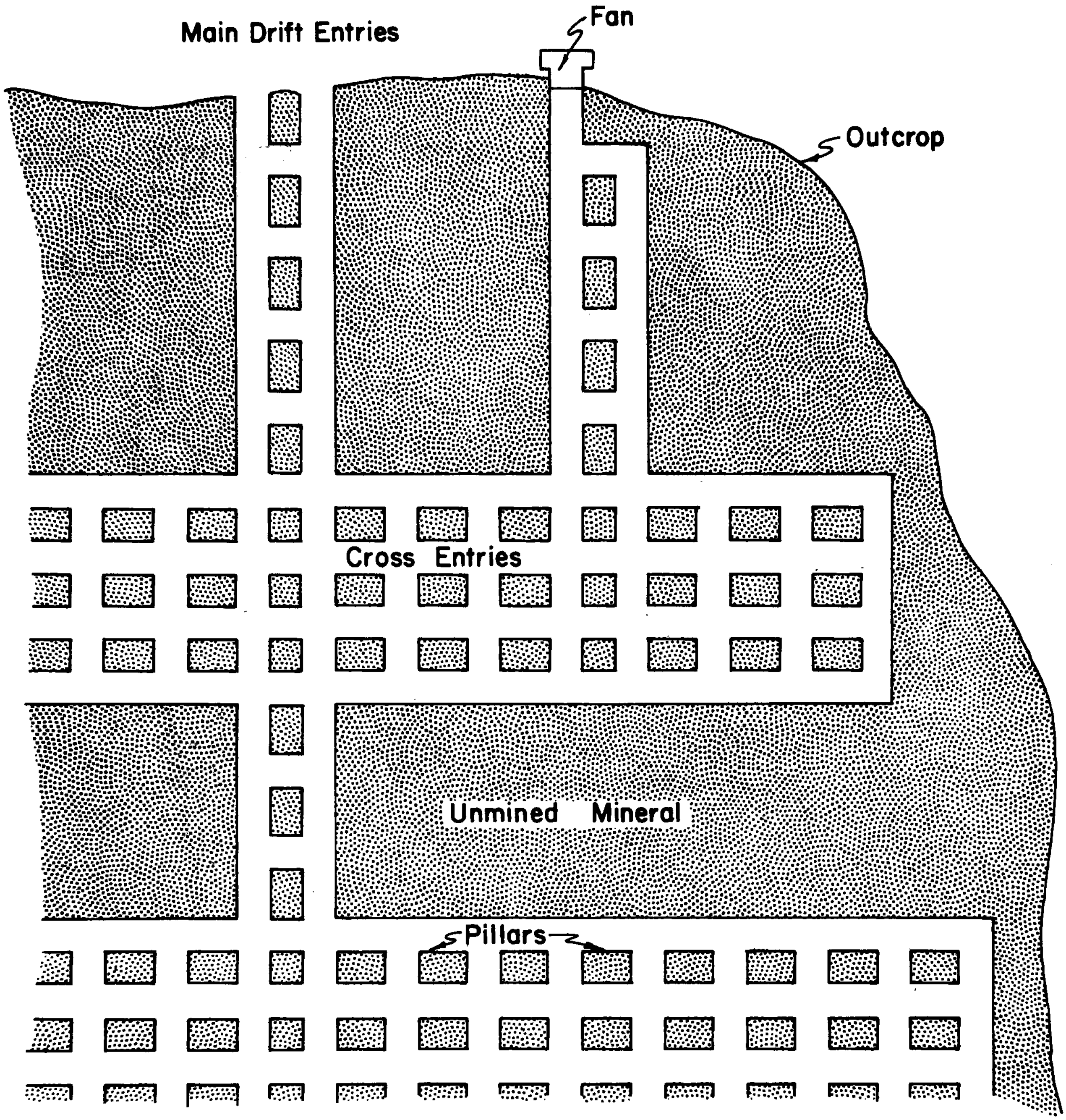


FIGURE 4.0-2

ROOM and PILLAR METHOD OF MINING

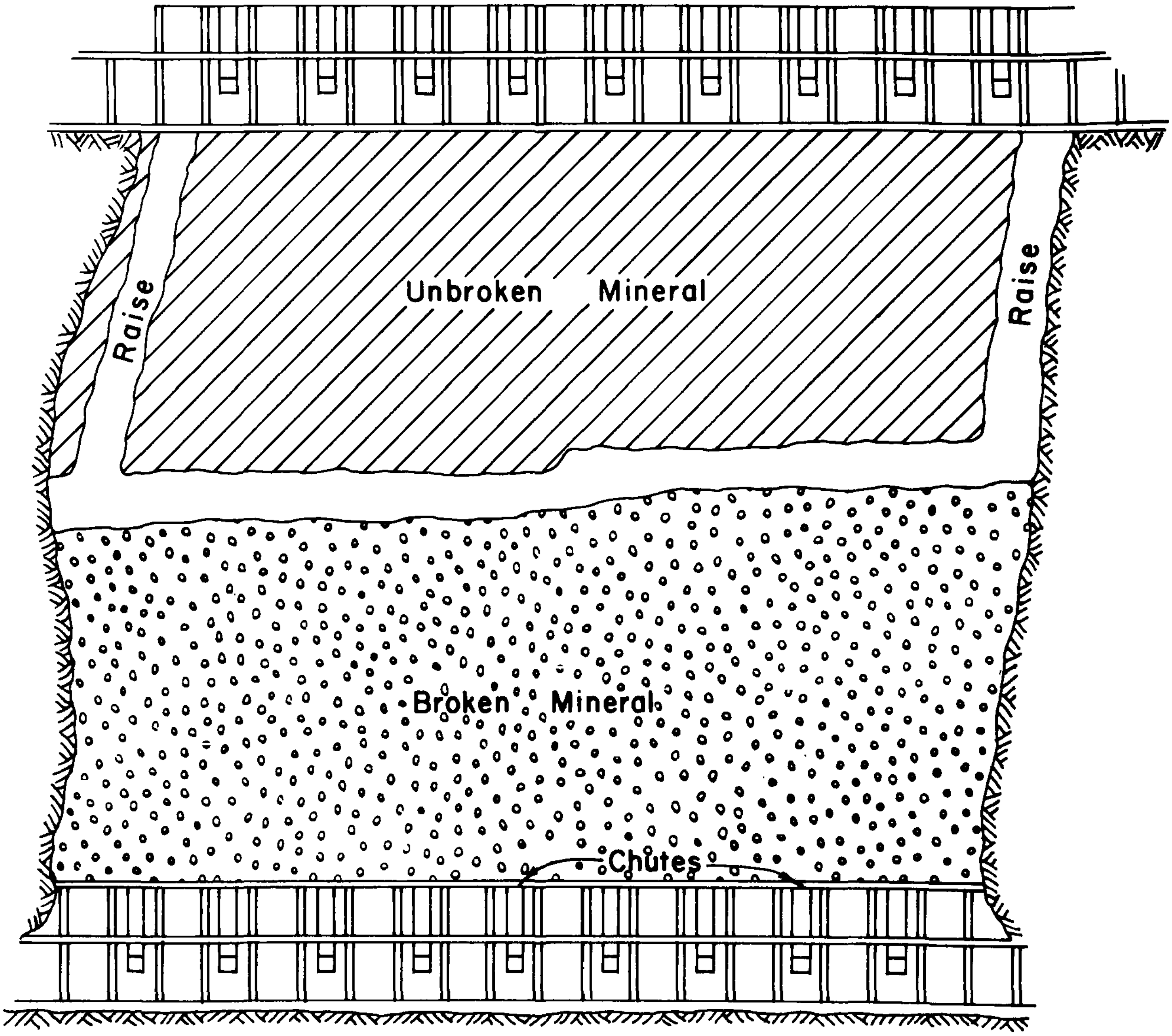


FIGURE 4.0-3

METHOD OF SHRINKAGE STOPING

(Adapted from Ref. 130)

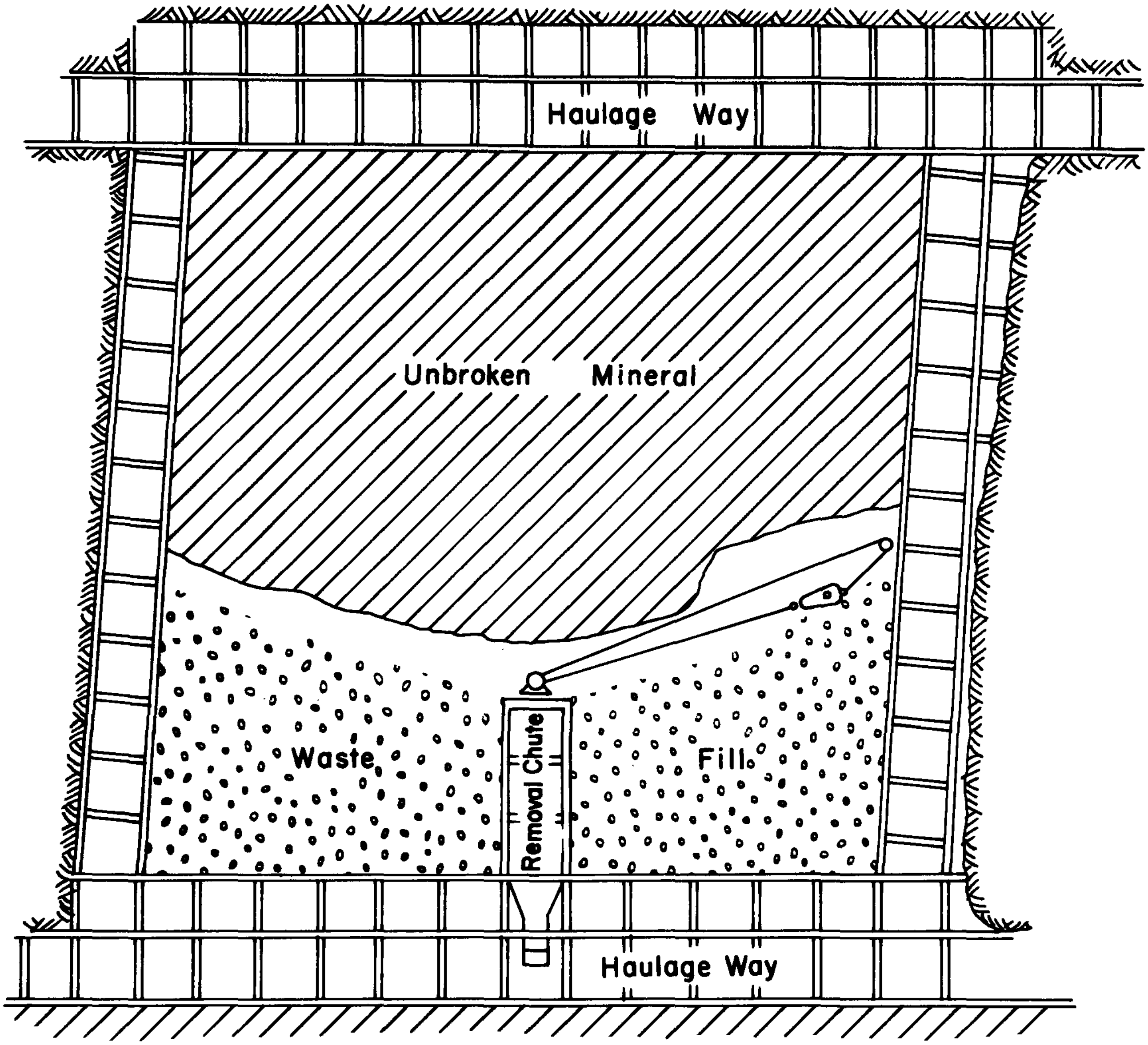


FIGURE 4.0-4

METHOD OF CUT AND FILL STOPING

(Adapted from Ref. 130)

In a square-set stope, square-set timbers are used to support the walls as the mineral is removed. After each blast, the square-set timbers are erected, chutes, and manway are raised, and waste material is backfilled (49). The square-set stoping method is shown in Figure 4.0-5.

REFERENCES

21, 46, 48, 49, 126, 128, 129, 130

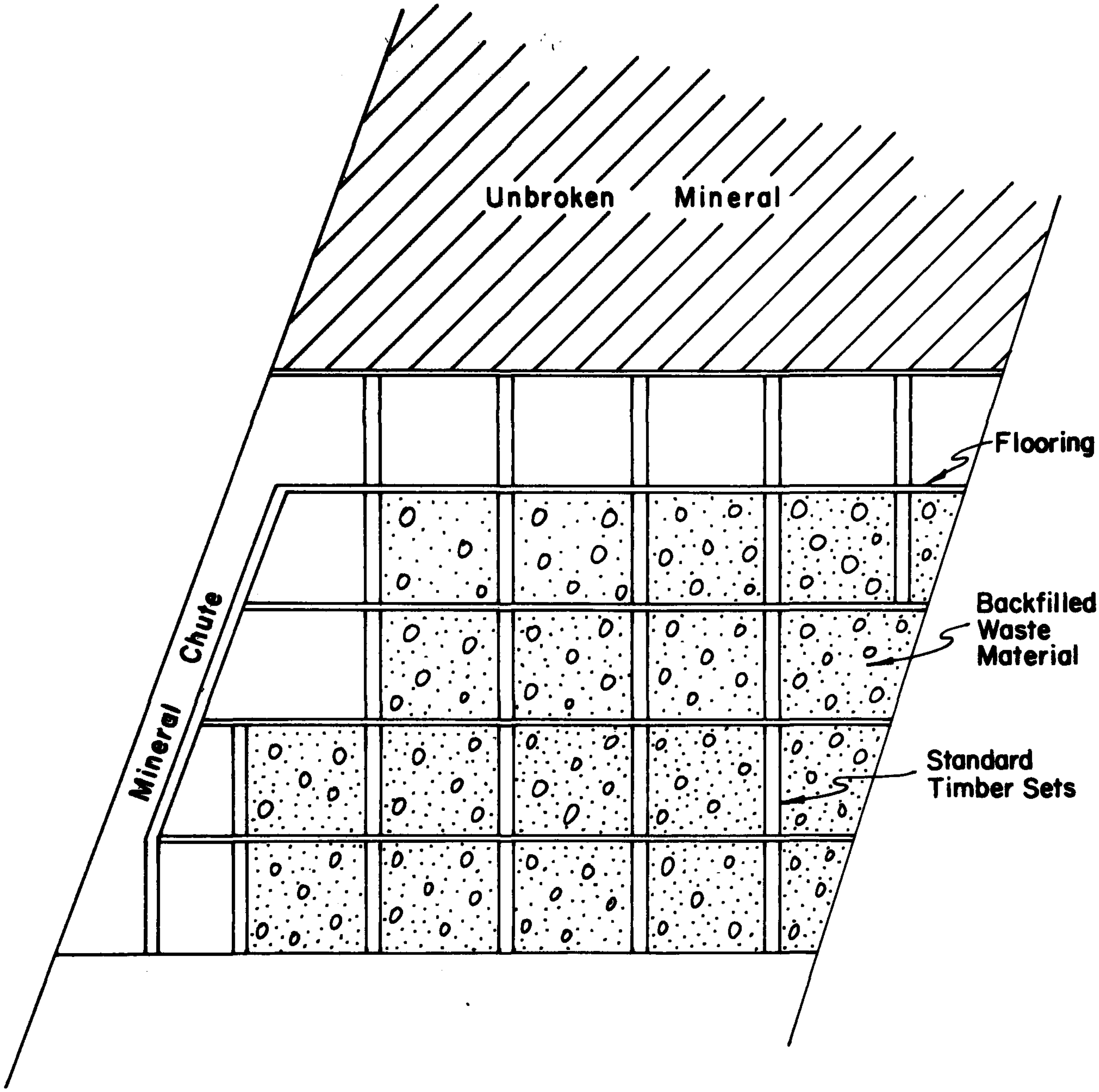


FIGURE 4.0-5

METHOD OF SQUARE-SET STOPING

5.0

CONTROL OF MINE DRAINAGE

Mine drainage control techniques may be divided into two major categories: (1) at-source and (2) treatment. At-source techniques are those which are designed to prevent or control the formation and/or discharge of mine drainage pollutants. Treatment involves the collection and processing of mine drainage to produce a water of quality suitable for discharge to the environment. In general, at-source techniques appear to be more feasible than treatment for controlling pollution discharges from abandoned underground mines. At-source techniques may be permanent and not require continuous expenditures for maintenance and operation as do treatment techniques. The various at-source techniques applicable to abandoned underground mine situations are described in this manual.

Although the effects of mine drainage pollution have been recognized since the 1800's, little research and demonstration of methods for controlling this pollution was performed prior to the 1930's. At this time various methods of mine sealing to control pollution were investigated by the U.S. Bureau of Mines and other Federal agencies. Beginning in the early 1960's an intense research and demonstration effort was begun in the United States. As a result of this effort many at-source control techniques applicable to active and abandoned surface and underground mines were demonstrated with varying degrees of success.

Many of the at-source control techniques that have been developed to date are applicable to abandoned underground mines. The demonstration of a majority of these techniques has been limited to underground coal mines in the Appalachian coal region. Therefore, the discussion of the various techniques in this manual in general will be related to coal mines. However, in most instances the techniques discussed are applicable to underground mines of all types.

REFERENCES

1, 5, 23, 51, 96, 97, 128, 129, 130

II

MANUAL OF

AT-SOURCE POLLUTION

CONTROL TECHNIQUES

This section will identify at-source pollution prevention and control techniques applicable to inactive or abandoned underground mines, whose practicability or feasibility have been successfully demonstrated or strongly indicated by research results. These control measures have been classified under five major headings: (1) Water Infiltration Control; (2) Mine Sealing; (3) Mining Techniques; (4) Water Handling; and (5) Discharge Quality Control. Information on these pollution control techniques includes a general description of each technique, a description and evaluation of various applications, detailed cost information, an evaluation of the effectiveness and practicability of each technique, and when applicable, recommended procedures for selection and implementation.

1.0

WATER INFILTRATION CONTROL

1.1 GENERAL DISCUSSION

Water infiltration control techniques are designed to reduce the total volume of water entering an underground mine, and thus, reduce the volume of mine water discharge. During the development of underground mines, water may be encountered in various quantities. This water must be pumped from the mine during active mining, and in many situations, the weight of water removed will be more than the total weight of mineral extracted. After abandonment of the mine, infiltrating water either floods the mine workings or discharges from the mine (27, 127).

Infiltrating water may enter underground mines from above, below, or laterally through adjacent rock strata. Earth fractures such as faults, joints, and roof fractures resulting from surface subsidence are commonly primary causes of water entrance into abandoned underground mines. Factors affecting the quantity of water entering a mine will be the depth of the mine, location of water bearing strata, and ground water flow patterns. Investigations of the quantity of water entering underground coal mines have found the average rate of infiltration to range from approximately 6,262 to 10,280 liters per hectare per day (670 to 1,100 gal/acre/day) (27).

Water flowing through underground mines flushes pollutants from the mine and may result in their discharge to the environment. A reduction in the amount of flow usually results in a reduction in total pollution load discharging from the mine. The techniques discussed in this section can be used to reduce the volume of surface and groundwater available to enter the mine system and transport pollutants. The selection of a control technique will depend upon the characteristics of the mine system and the expected cost effectiveness of the technique. In order for water infiltration control to be effective in controlling mine drainage pollution, the reduction in mine water flow must not be accompanied by an increase in concentration of pollutants (127).

REFERENCES

2, 27, 51, 58, 127, 132

1.2 SUBSIDENCE SEALING AND GRADING

DESCRIPTION

Before or after abandonment of underground mines, fracturing or general subsidence of overlying strata often occurs. This increases the vertical permeability of the strata, and can result in the flow of large volumes of water into the mine. The volume of water diverted into the underground mine will depend upon the structure of the overlying rock, and the surface topography and hydrology of the area (21, 27). A drawing depicting the vertical infiltration of water through a subsided area is shown in Figure 1.2-1.

Water infiltration can be effectively controlled by increasing surface water runoff. Grading subsidence areas will eliminate surface depressions and increase surface water velocity. During the 1930's U.S. Public Health Service sealing program, subsidence areas were either filled with earth or ditched on the downhill side to prevent the accumulation of water.

Vertical permeability may be decreased by placing impermeable materials in the subsided area. These materials may be compacted on the surface and graded, or placed in a suitable sealing strata below groun level. Materials which have been successfully utilized for subsidence sealing are rubber, clay, concrete, and cement grout.

IMPLEMENTATION

Roaring Creek – Grassy Run Watershed

In 1964, a mine sealing demonstration program was initiated in the Roaring Creek – Grassy Run Watershed near Elkins, West Virginia. The program was a cooperative effort between Federal agencies and the state of West Virginia. Sealing was to involve construction of dry and air seals, water diversion from mines, backfilling strip mines, and sealing subsidence areas and boreholes (57, 101).

During a six month survey, a total of 1,563 subsidence areas, holes, and surface cracks were located in the watershed. Of these 1,128 were located within 91 meters (300 feet) of strip mine highwalls. In an effort to seal these openings, the U.S. Bureau of Mines negotiated a cooperative agreement with the Dowell Division of the Dowell Chemical Company, to experiment with chemical grouting of the subsidence areas (37).

Five sites with cover ranging from 18.3 to 27.4 meters (60 to 90 feet) were selected for the experimental program. At each site holes were drilled and a cement-bentonite grout was pressure injected. The grout proved to be ineffective in

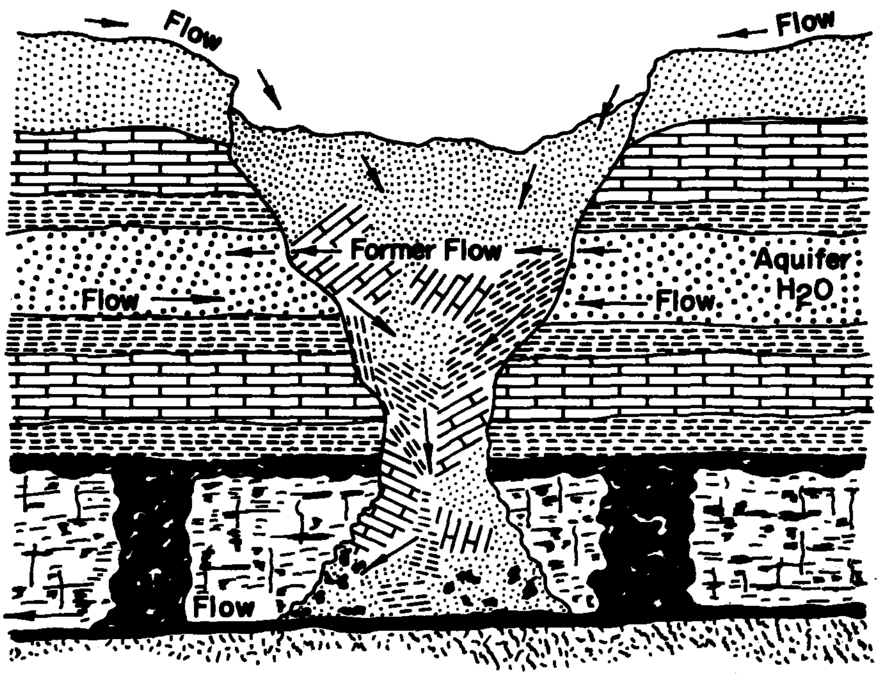


FIGURE 1.2-1

INFILTRATION OF WATER THROUGH SUBSIDED AREA

(Adapted from Ref. 21)

sealing the areas. Extensive fracturing of underlying rock permitted the grout to flow into abandoned workings in the Lower Kittanning coal seam. A total of 2,000 bags of cement and 200 bags of bentonite were used during grouting. Drilling and grouting costs were $4,342 and $8,411, respectively, for a total cost of $12,753.

Successful sealing of subsidence areas may be achieved in areas where rock fracturing is less severe. In such instances the grout will move laterally from the injection holes and form a horizontal grout curtain. Grout injection has been successful in sealing discharges from subsided areas and abandoned mine shafts.

Backfilling of subsidence areas was also demonstrated at the Elkins site. Within individual subsidence areas, vegetation was cleared and weathered material was removed by dozer down to bedrock. The weathered material, plus suitable material from other areas, was backfilled in 31 to 61 centimeter (12 to 24 inch) layers and compacted. The areas were graded to the approximate original contour to increase surface runoff. This backfilling technique successfully curbed the infiltrating water problem and most probably prevented the entrance of air into the mine (8, 27). The costs of backfilling and grading individual subsidence areas are not available.

A single sheet of 0.24 centimeter (3/32 inch) butyl compound was placed over a subsidence area located in a wooded area with rocky terrain. In preparation for applying the butyl sheet, all trees, stumps, and other vegetation, and approximately 0.3 meters (1 foot) of topsoil were removed from the area. A ditch 15.2 centimeters (6 inches) deep was dug around the subsided area and the sides of the 6.1 by 12.2 meter (20 by 40 foot) butyl sheet were tucked into it. The sheet was sealed by compacting clay in the ditch and covering the sheet with soil originally removed from the area (8, 27). The cost of the butyl compound was approximately $10.76 per square meter ($1.00/sq ft). Initial indications were that the butyl sheet successfully sealed the area.

Chemical surface sealants were experimentally applied to two subsidence areas in the watershed (117). On one area, Dowell applied a chemical powder that was to form a self-sealing gelatinous coating upon being wetted. The material proved not to be self-sealing, and after a heavy rain washed to the center of the area. Consequently this method was considered an unsatisfactory approach. Costs of applying the chemical were not available.

Diamond Alkali Company sprayed a mixture of Siroc Nos. 1 and 2 and cement over a small cleared subsidence area. The Siroc accelerated the drying time, but the material cracked. Bentonite was spread over the surface and wetted to fill the cracks. The technique was considered unsatisfactory, since bentonite could not be mixed and applied with the other ingredients. Costs for this technique were not available.

Pennsylvania Operation Scarlift Projects

Backfilling and grading of subsidence areas, to control water infiltration has been performed under several of Pennsylvania's Operation Scarlift projects. Specific projects which have involved sealing subsidence areas are: SL 102-1-1 Mohawk Valley, South Fayette Township, Allegheny County; SL 118-1 Shaw Mine Complex, Elk Lick Township, Somerset County; and SL 182-1 Blacklegs Creek Watershed, Young and Conemaugh Townships, Indiana County.

Project SL 102-1-1 involved filling and grading of subsidence holes, and excavating and lining of approximately 1,280 linear meters (4,200 LF) of drainage channel to prevent the loss of natural surface water to an underground mine. The project work was performed by Richard Construction Company, Inc. and completed in September, 1970 (84).

Drainage channels were excavated and the bottoms lined with a 15.2 centimeter (6 inch) loose layer of a bentonite and sand mixture (5 parts sand to 1 part bentonite). Subsidence holes, were filled to one-half depth with 0.6 meter (2 foot) maximum size rock. The top layer of rock was of smaller size. Soil was placed in 20.3 centimeter (8 inch) layers and compacted to 90 percent of maximum density. The backfilled area was graded to 0.3 meters (1 foot) above natural ground level.

If the subsidence hole extended into the underground mine, porous rock was placed from the bottom of the mine to one-half the depth of overburden above the mine roof. The remainder of the fill and grading were performed as described above.

The total cost of the project, which included lump sum bids and contingent items, was $65,136.50. Itemized costs were as follows (84):

Lump Sum Bid

Clearing and Grubbing	5.3 ha (13 ac)	$11,700
Drainage Channel	8,411 cu m (11,000 cu yd)	16,500
Grading Subsidence Holes	3,823 cu m (5,000 cu yd)	3,750
Soil Treatment and Planting	5.3 ha (13 ac)	5,850

Contingent Items

Clearing and Grubbing	0.6 ha @ $1,750/ha (1.5 ac)($700/ac)	$ 1,050
Drainage Channel	1,392 cu m @ $3.92/cu m (1,820.5 cu yd)($3.00/cu yd)	5,461.50
Grading Subsidence Holes	114.7 cu m @ $1.31/cu m (150 cu yd)($1.00/cu yd)	150
Bentonite Clay	90.7 metric tons @ $220.51/metric ton (100 tons)($200/ton)	20,000
Planting	0.6 ha @ $1,125/ha (1.5 ac)($450/ac)	675

Project SL 118-1 involved backfilling and grading of a subsidence area, and placing a flume to conduct surface water across the work area. Work on the project was performed by the Sanner Brothers Coal Company and was completed in September, 1971 (84).

The scope of work performed under the contract included: clearing and grubbing of the subsided area; dismantling and removal of structures from the work area; spreading and compacting mine spoil piles; filling subsidence areas and mine drifts; regrading the entire work area; fertilizing and seeding; and furnishing and installing 1.2 meter (48 inch) bituminized fibre flume.

The total cost of the project was $21,090. Itemized costs were as follows (84):

Clearing and Grubbing	3.24 ha @ $617/ha (8 ac)($250/ac)	$2,000
Dismantle Existing Structures	Lump Sum	100
Spread and Compact Mine Spoil	229 cu m Lump Sum (300 cu yd)	3,000
Furnish and Install Flume	274 m @ $19.68/m (900 ft)($6.00/ft)	5,400
Fertilizing and Seeding	3.24 ha @ $740/ha (8 ac)($300/ac)	2,400

Foreman	120 hr @ \$6.00/hr	\$ 720
Laborer	500 hr @ \$5.00/hr	2,500
D-8 Angledozer and Operator	120 hr @ \$28/hr	3,360
3 cu yd Hi-lift and Operator	40 hr @ \$22/hr	880
Dump truck and Operator	40 hr @ \$12/hr	480
Field Officer	Lump Sum	250

In the Blacklegs Creek watershed, two subsidence areas were backfilled and sealed with bentonite to prevent the flow of surface water into an abandoned underground mine in the Pittsburgh coal seam. This work was performed under Project SL 182-1 in conjunction with stream channel reconstruction and lining. Work was completed in March, 1974 by the project contractor, B.R. Loughry (84).

Both subsidence areas were located in areas where cover over the mine was less than 7.6 meters (25 feet). Caving of the mine roof and overlying strata had created subsidence holes on the surface. Prior to backfilling with rock, all loose, pervious material was removed from the holes and the sides of the excavation were cleaned.

At both locations a porous rock ranging in size from 7.6 centimeters to 0.3 meters (3 inches to 1 foot) was placed from the mine floor to 1.2 meters (4 feet) above the mine roof. A 0.9 meter (3 foot) layer of No. 4 stone and a 0.3 meter (1 foot) layer of No. 2B stone were successively placed and compacted on top of the rock fill. To provide a water tight seal, a 0.3 meter (1 foot) layer of a bentonite and sand mixture was placed and compacted on the No. 2B stone. The remainder of the subsidence hole was backfilled with compacted soil. A section view of the backfill and bentonite seal placed at Location 1 in Young Township is shown in Figure 1.2-2.

Sealing of the subsidence holes, and reconstructing and lining of stream channels successfully reduced the infiltration of surface water into the underground mine. As a result of the project, flow in tributaries to Blacklegs Creek was increased.

Costs of backfilling and sealing the subsidence holes were not available. Lump sum bids for subsidence sealing and channel construction for Locations 1 and 6 were \$8,000 and \$4,000, respectively. At Location 1, 46 linear meters (150 LF) of channel with bentonite seal were constructed. At Location 6, channel construction included 61 linear meters (200 LF) with bentonite seal and 145 linear meters (475 LF) without bentonite seal.

Material requirements for backfilling and sealing the two subsidence holes were:

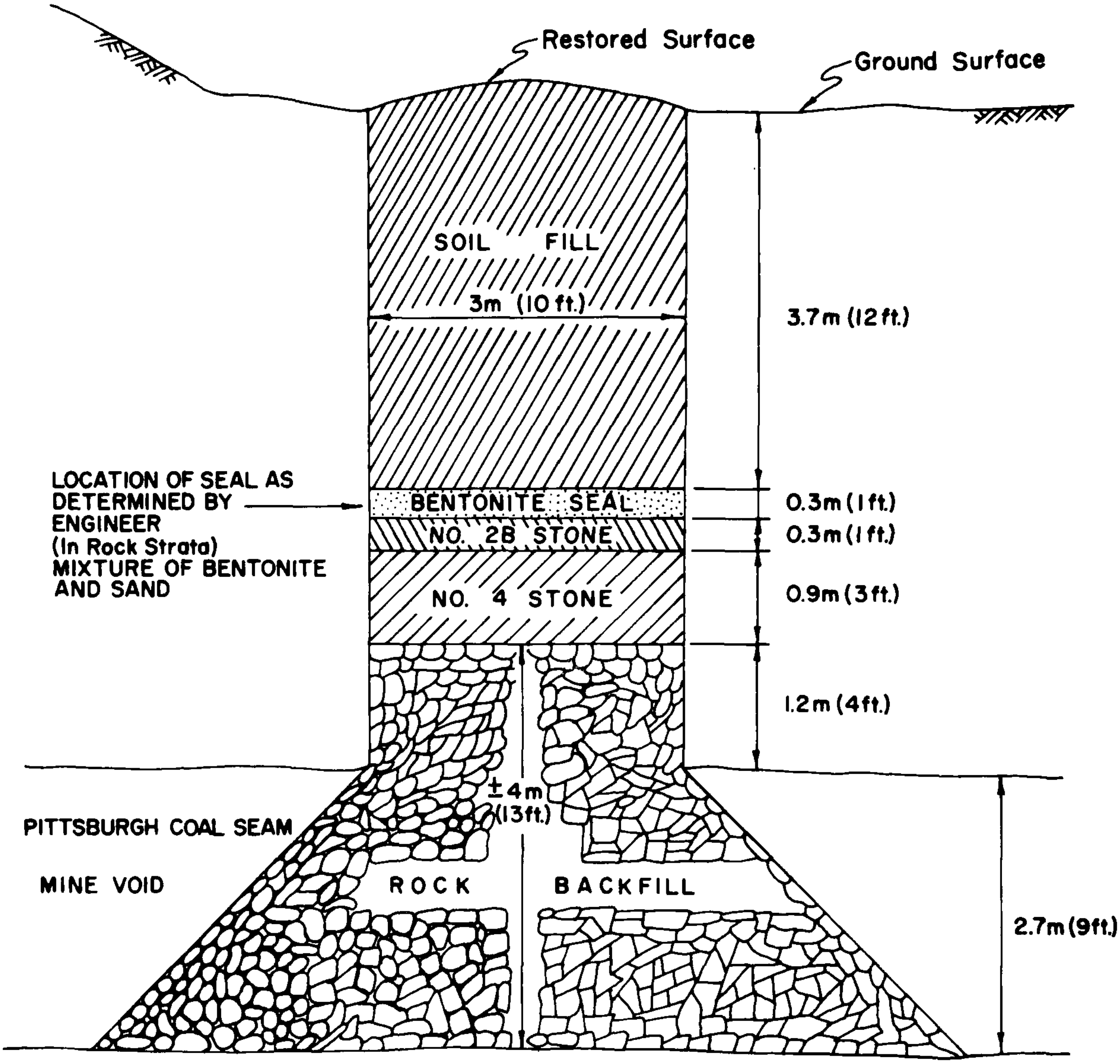


FIGURE 1.2-2

SUBSIDENCE HOLE BACKFILL, BLACKLEGS WATERSHED

(Adapted from Ref. 84)

	Location 1 cu m (cu yd)	Location 6 cu m (cu yd)
Rock Fill	101 (132)	75 (98)
No. 4 Stone	11 (15)	7 (7)
No. 2B Stone	4 (5)	2 (3)
Soil Backfill	53 (70)	6 (8)
Bentonite and Sand	4 (5)	2 (3)
Excavation	--	15 (20)

EVALUATION AND RECOMMENDATIONS

Sealing and grading of subsidence areas has been successful in reducing the volume of water entering abandoned underground mines. The effectiveness of this water infiltration control technique will depend upon the size of the area, extent of surface fracturing, materials utilized, and the method of construction. Concrete and clay type seals placed in subsidence holes should prove to be the most effective sealing method. These seals should also prove to be effective in controlling discharges from the underground mine water pool.

A compacted clay backfill may be placed in shallow surface depressions to prevent collection and diversion of surface waters into the mine. These areas should be either graded to increase the surface velocity of water or filled to above existing ground contours to divert water around the area. Diversion ditches may also be utilized to collect and convey water around the subsided area. The cost of backfilling will include clearing and grubbing, placing clay material, grading, and planting. The cost of clay will normally range from $2.62 to $5.23 per cubic meter ($2.00 to $4.00/cu yd) depending upon availability and transportation costs.

Grout materials may be applied to areas where vertical fracturing is not extensive. In severely fractured areas the grout will be unable to fill the voids and may flow directly to the mine void. Grouting costs will depend upon the size of the area being treated, drilling required, and the total amount of grout injected. Estimates for horizontal grout curtains range from $29,630 to $98,765 per hectare ($12,000 to $40,000/acre). The cost of grouting work performed at the mine sealing demonstration project near Elkins, West Virginia was approximately $2,600 per subsidence area.

The construction of concrete or clay seals will require excavation of the subsidence area, cleaning of the hole, backfilling with suitable rock fill, placement of the seal, grading, and revegetation of the affected area. Construction costs for these seals must be developed on an individual basis.

REFERENCES

8, 21, 27, 37, 52, 57, 75, 84, 100, 101, 117, 127, 129

1.3 BOREHOLE SEALING

DESCRIPTION

Underground mines are commonly intercepted by boreholes extending from the ground surface. These holes are often drilled during mineral exploration, but may be utilized for supplying power to underground equipment or discharging water pumped from active sections. Upon abandonment of an underground mine these boreholes may collect and transport surface and ground waters into the mine, or may discharge mine drainage from a flooded mine having a water level above borehole elevation.

These vertical, or near vertical, boreholes can be successfully sealed by placing packers and injecting a cement grout. Often abandoned holes will be blocked with debris and will require cleaning prior to sealing. The packers should be placed below aquifiers overlying the mine to prevent entry of sub-surface waters, but should be well above the roof to prevent damage to the seal from roof collapse. A typical method of borehole sealing with cement grout is shown in Figure 1.3-1.

A borehole may also be sealed by filling the hole with rock until the mine void directly below the hole is filled to the roof. Successive layers of increasingly smaller stone should be placed above the rock. A clay and/or concrete plug is then placed. The remainder of the borehole may be filled with rock or capped. This method of borehole sealing is shown in Figure 1.3-2.

IMPLEMENTATION

Tanoma Complex, Indiana County, Pennsylvania

A borehole was successfully sealed at the Tanoma Complex, Upper Crooked Creek, Indiana County, Pennsylvania under Pennsylvania project SL 107-6-1. Work was performed in September, 1973 by Pennsylvania Drilling Company. The seal was placed to eliminate the flow of highly acid water from the Lower Freeport coal seam to the Lower Kittanning coal seam (84).

The existing 26 centimeter (10.25 inch) diameter borehole was cleaned from top to bottom. A packer was connected to 17.8 centimeter (7 inch) O.D. steel casing and placed at 98.5 meters (323 feet). The packer was hydraulically set by pumping water through the 17.8 centimeter (7 inch) casing at pressures up to 703 thousand kilograms per square meter (1,000 psi). Cement grout was pumped through cementing ports to the outside of the casing until the cement rose to the Lower Freeport opening. The installation was completed by pumping a top cementing plug into place.

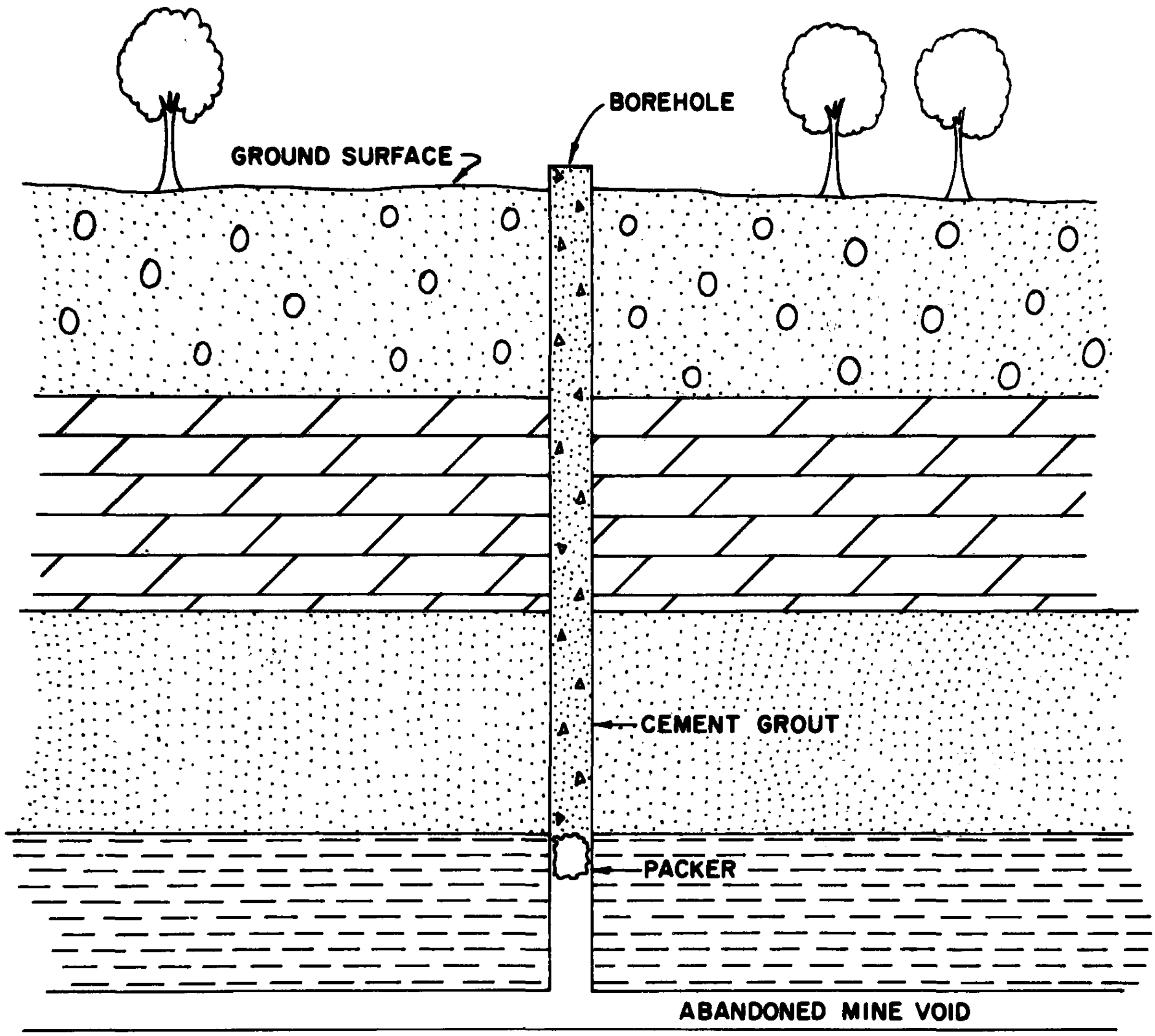


FIGURE 1.3-1

TYPICAL METHOD OF BOREHOLE SEALING
WITH CEMENT GROUT

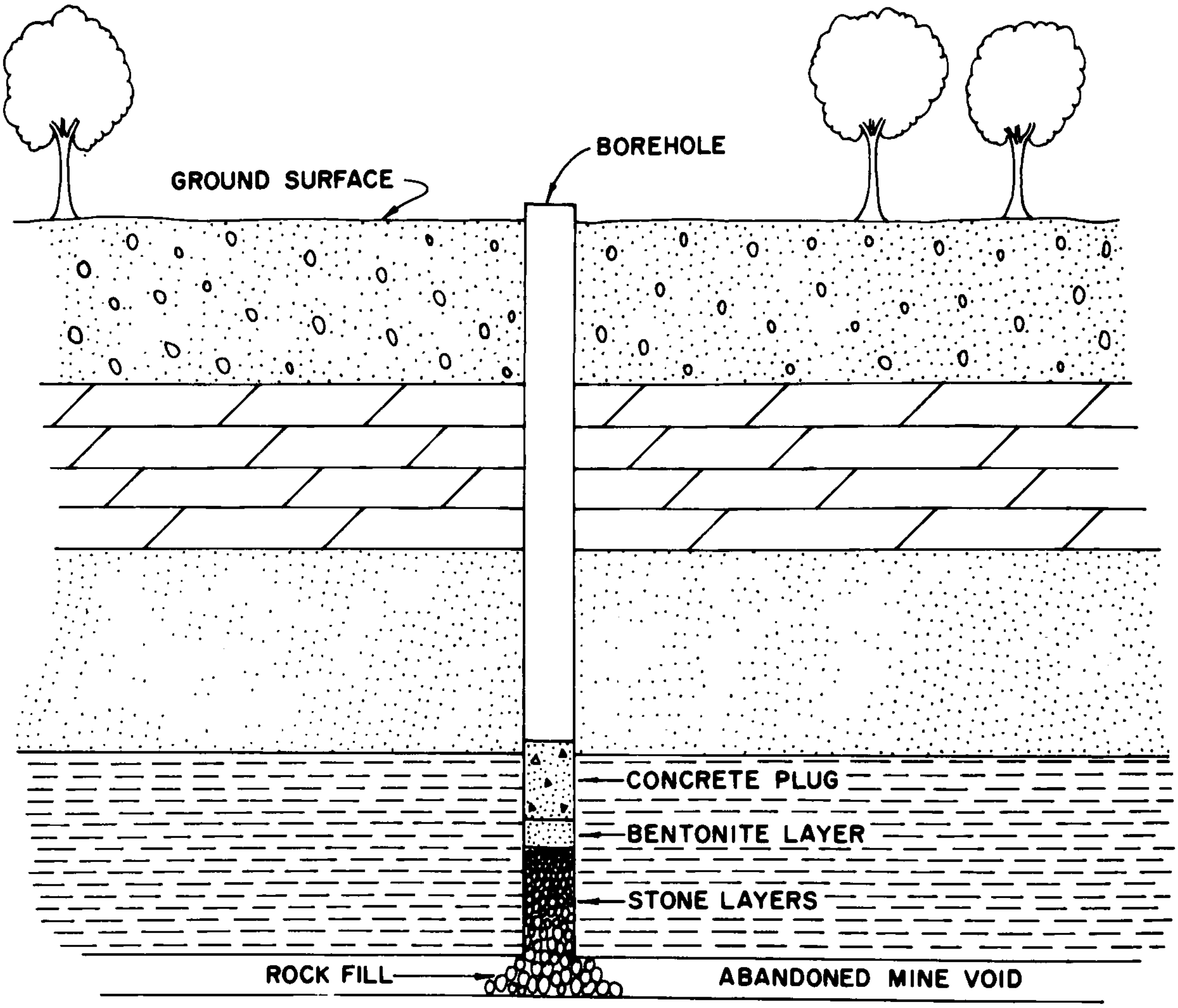


FIGURE 1.3-2

TYPICAL METHOD OF BOREHOLE SEALING WITH ROCK AND CONCRETE

A threaded cap was placed on top of the casing and a 0.6 centimeter (0.25 inch) thick plate was tack welded between the existing 26 centimeter (10.25 inch) casing and the 17.8 centimeter (7 inch) casing. The completed seal successfully stopped leakage between the two coal seams. Costs of constructing the seal were as follows:

Mobilization and Demobilization	Lump Sum	$1,000
Ream 26 Centimeter hole (10.25 inch)	99 LM @ $26.25/LM (325 LF)($8.00/LF)	2,600
Seal 26 centimeter hole (10.25 inch)	Lump Sum	5,011
	TOTAL	$8,611

Wildwood Mine, Allegheny County, Pennsylvania

In June, 1973 a discharge of approximately 5,678 cubic meters per day (1.5 MGD) with 300 mg/l iron occurred from an old diamond drill hole at the Wildwood Mine near Pine Creek, Hampton Township, Allegheny County, Pennsylvania. The mine is in the Upper Freeport coal seam and had been in operation until December, 1968. Subsequent sealing of shafts and boreholes resulted in a flooding of the mine to an elevation above the drill hole. The drill hole discharge was successfully sealed in October, 1973 by Pennsylvania Drilling Company, under Pennsylvania Project SL 198-1.

Sealing the hole involved exposing the 7.6 centimeter (3 inch) hole and cleaning it to a depth of approximately 54.9 meters (180 feet). A packer was placed and the hole was cemented to the top. Costs of construction were as follows (84):

Exploration, Cleaning and Plugging	$6,500.00
Cement in Place	262.50
TOTAL	$6,762.50

EVALUATION AND RECOMMENDATIONS

Boreholes act as conduits and are capable of transmitting large volumes of water to underground mines. They may also discharge mine water pollutants to the environment if the abandoned mine floods to a level above the borehole elevation. Boreholes may be successfully sealed by placing concrete plugs or other impermeable materials in the hole. The seals must be capable of withstanding the expected water pressure, but should be located well enough above the mine roof to prevent roof collapse. Borehole sealing should be performed in conjunction with mine closure and sealing programs.

The total cost of sealing a borehole will depend upon such factors as the depth and diameter of the hole, exploration and cleaning required, and the method of sealing. Prior to sealing the borehole should be cleaned for its entire length. Cleaning costs will normally range from $33 to $66 per linear meter ($10 to $20/LF). Sealing by injecting cement grout will normally range in cost from $49 to $66 per linear meter ($15 to $20/LF). The total cost of borehole sealing including exploration, mobilization and demobilization, labor, and materials should range from $66 to $132 per linear meter ($20 to $40/LF).

REFERENCES

70, 84, 127, 129

1.4 SURFACE MINE REGRADING

DESCRIPTION

Water discharging from underground mines often originates as surface water on non-regraded surface mines. This commonly occurs in the eastern United States where coal outcrops are contour stripped. These strip mines will often intercept underground workings or have underground mine entries and auger holes along the highwall. When these openings occur on the updip side of an underground mine, large volumes of surface water may be conveyed to underground workings. Surface mines may collect water and allow it to enter a permeable coal seam. This water can flow along the seam to adjacent underground mines (127).

Various methods of surface mine regrading have been practiced in the eastern coal fields. The selection of a regrading method will depend upon such factors as: the amount of backfill material available, the degree of pollution control desired, future land use, funds available, and topography of the area (29). Section views of contour and terrace regrading methods are shown in Figures 1.4-1 and 1.4-2. In both of these regrading methods, surface runoff is diverted away from the highwall. Prior to backfilling, impervious materials may be compacted against the highwall to prevent the flow of water to adjacent underground mines.

IMPLEMENTATION

Roaring Creek – Grassy Run Watershed

Surface mine regrading, to control water infiltration, was performed as part of an acid mine drainage demonstration project conducted in the Roaring Creek – Grassy Run watersheds near Elkins, West Virginia. The project was a cooperative effort between Federal agencies and the state of West Virginia. Strip mines along coal outcrops were collecting and diverting water into abandoned underground mines. Since the coal dipped from the Roaring Creek watershed to the Grassy Run watershed, water was diverted from one watershed to another through the underground workings, resulting in a flushout of acid mine drainage (57, 101).

Three methods of regrading were used on the surface mines – contour, pasture, and swallow-tail. Contour regrading was performed when the highwall was fractured and unstable. The top of the highwall was usually pushed down to complete the backfill. Pasture and swallow-tail regrading are variations of terrace regrading. They were performed when the highwall was stable. Cross sections of these two regrading methods are shown in Figure 1.4-3.

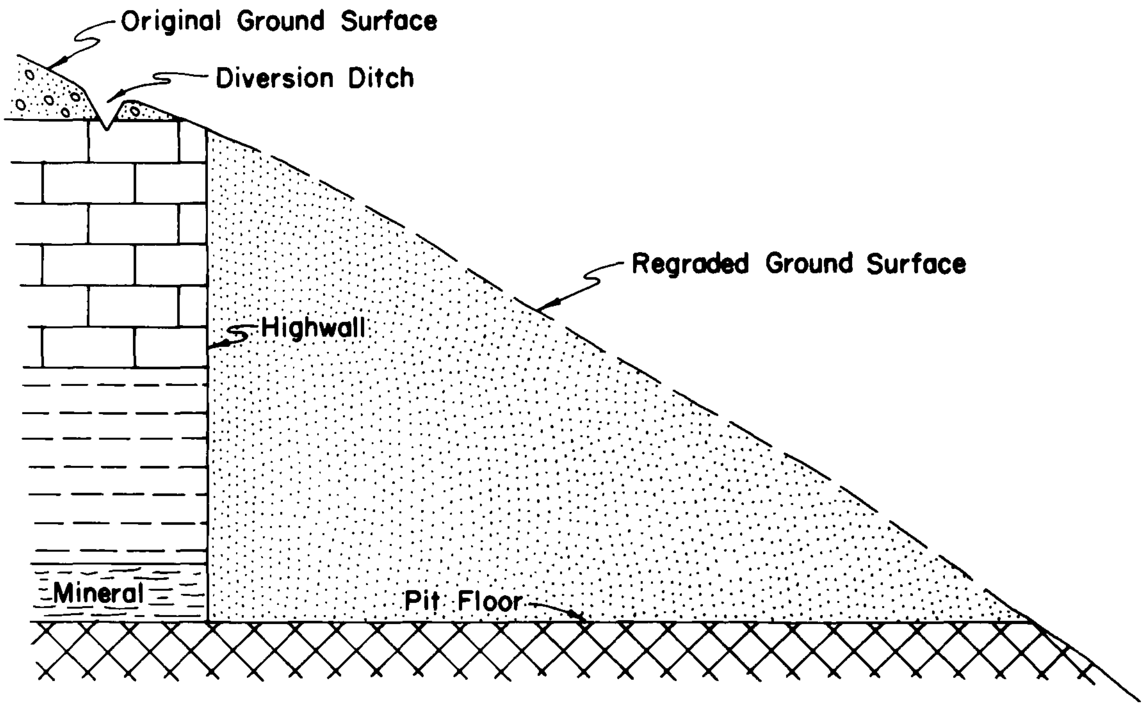


FIGURE 1.4-1

CROSS SECTION OF TYPICAL CONTOUR REGRADING
(Adapted from Ref. 127)

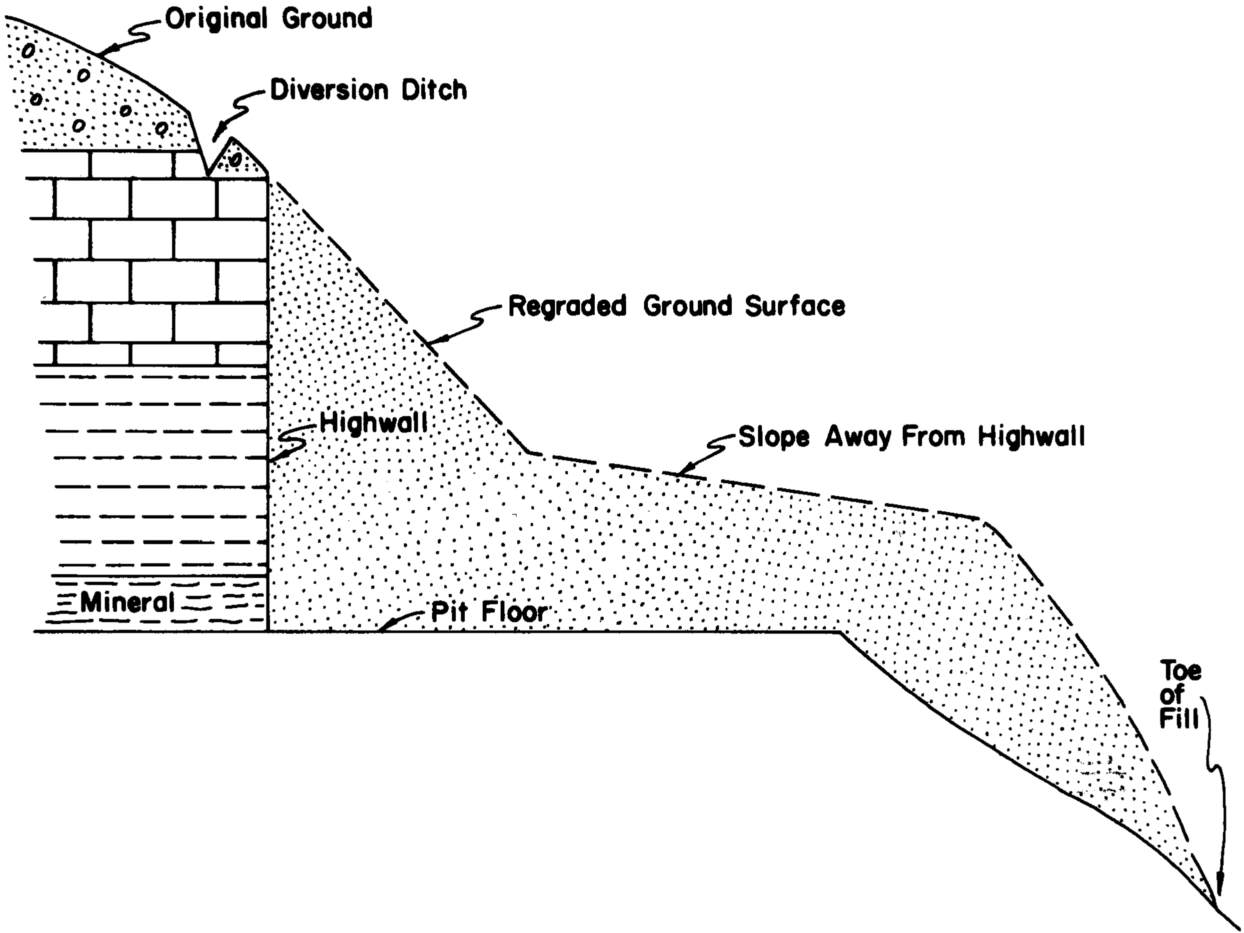
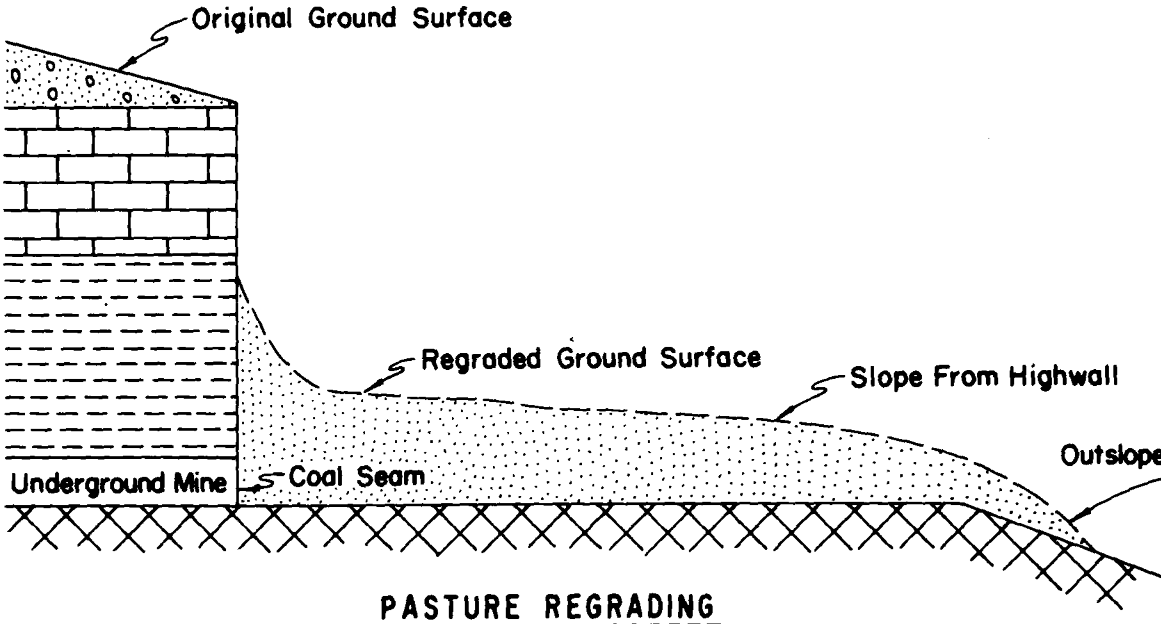
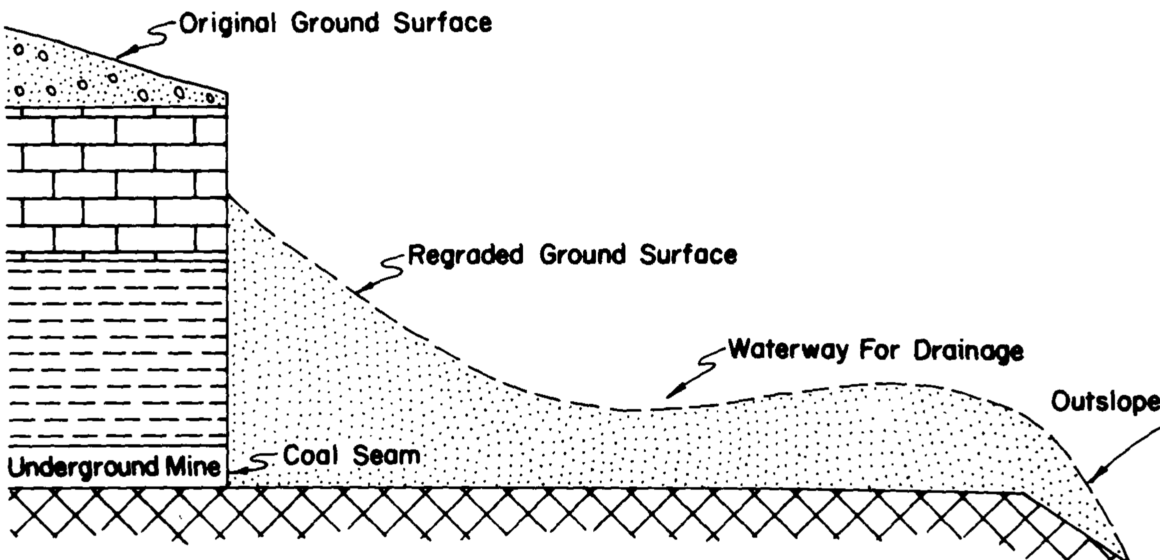


FIGURE 1.4-2

CROSS SECTION OF TYPICAL TERRACE REGRADING
(Adapted from Ref. 127)



PASTURE REGRADING



SWALLOW TAIL REGRADING

FIGURE 1.4-3
TYPICAL REGRADING METHODS
ELKINS, W.VA.
(Adapted from Ref. 32)

The effectiveness of the surface mine regrading was difficult to evaluate. Due to cost overruns, reclamation and sealing of a large 1,215 hectare (3,000 acre) underground mine was not completed. Therefore, the effectiveness of water infiltration control in reducing the mine discharge could not be evaluated. A preliminary evaulation of runoff from regraded areas indicated that flow in adjacent streams was increasing, and thus, less water was entering the underground mine.

The discharge from a smaller un erground me was reduced by eliminating the infiltration of water through an opening in a strip mine highwall. The pit floor was approximately 6.1 meters (20 feet) below an adjacent stream bed. The initial stripping operation had diverted stream flow toward the highwall. Instead of the water flooding the pit, flow was diverted through the highwall opening to an adjacent underground mine.

The infiltration was elminated by compacting clay against the highwall to above the base level of the stream, and regrading with available spoil to expedite surface runoff away from the highwall. The pre-stripping stream bed was also re-established by backfilling (8).

Surface mine regrading and revegetating were begun in the summer of 1966 and completed in the spring of 1968 (101). In total, 264 hectares (651 acres) were regraded at an average cost of $4,094 per hectare ($1,658/acre). During regrading a total of 2,339,676 cubic meters (3,060,000 cu yd) of material was moved at an average cost of $0.46 per cubic meter ($0.35/cu yd). The average costs of clearing and grubbing, and revegetating the 264 hectares (651 acres) were respectively $815 per hectare ($330/acre) and $612 per hectare ($248/acre) (101). Considering the average costs per hectare for clearing and grubbing, regrading, and revegetating, the overall surface mine regrading cost at Elkins was $5,221 per hectare ($2,236/acre).

The average direct cost (materials, equipment, and labor) for selected work areas ranged from a low of $1,165 per hectare ($472/acre) for contour regrading to a high of $2,793 per hectare ($1,131/acre) for combination pasture-contour regrading. Direct costs of surface mine regrading by various methods on selected work areas are presented in Table 1.4-1.

Dents Run Watershed

A demonstration project to control mine water pollution by water infiltration control is being conducted in the Dents Run watershed in Monongalia County, West Virginia. The project is a cooperative effort between the U.S. Environmental Protection Agency and the state of West Virginia. The program was established to fulfill the requirements of Section 14 of the Federal Water Pollution Control Act, as amended.

TABLE 1.4-1

Direct Cost of Surface Reclamation
by Various Methods on Selected Work Areas
Elkins, West Virginia

Area No.	Hectares	(Acres)	Type Of Backfill	Cost/Hectare (Cost/Acre) Reclamation		Type Seeding	Cost/Hectare (Cost/Acre) Reclamation + Seeding		Cost/Hectare (Cost Acre) Reclamation + Seeding + Clearing & Grubbing	
3	4.8	(11.9)	Pasture	$ 946	(383)	C & H	$1,316	(533)	$1,422	(576)
4	1.9	(4.7)	Pasture	138	(56)	C	346	(140)	430	(174)
5	1.7	(4.3)	Pasture	2,457	(995)	C	2,780	(1,126)	2,807	(1,137)
8	3.2	(7.9)	Pasture	1,827	(740)	C	2,074	(840)	2,556	(1,035)
9	4.7	(11.7)	Pasture	1,067	(432)	C	1,291	(543)	1,380	(559)
37	5.3	(13.0)	Pasture	1,970	(798)	C & H	2,252	(912)	2,538	(1,028)
MEAN	21.6	(53.5)		$1,402	(568)		$1,684	(682)	$1,877	(760)
23 & 24	31.5	(77.9)	Contour	$1,059	(429)	C, H, T	$1,652	(669)	$1,738	(704)
28	4.5	(11.0)	Contour	654	(265)	C, H, T	1,511	(612)	2,178	(882)
27	27.5	(68.0)	Contour	1,333	(540)	C & H	2,240	(907)	3,148	(1,275)
29 & 30	15.3	(37.7)	Contour	1,338	(542)	C, H, T	1,837	(744)	1,985	(804)
44	10.8	(26.7)	Contour	1,012	(410)	C, H, T	1,689	(684)	2,005	(812)
MEAN	89.6	(221.3)		$1,165	(472)		$1,862	(754)	$2,267	(918)
1	7.6	(18.7)	Swallow-Tail	$ 778	(315)	C, H, T	$1,348	(546)	$1,398	(566)
2	16.3	(40.3)	Swallow-Tail	1,743	(706)	C, H, T	2,012	(815)	2,081	(843)
MEAN	23.9	(59.0)		$1,437	(582)		$1,802	(730)	$1,864	(755)
10	56.8	(140.3)	Pasture/	$2,617	(1,060)	C, H, T	$3,052	(1,236)	$3,519	(1,425)
11	19.0	(47.0)	Contour	3,311	(1,341)	C	3,699	(1,498)	3,822	(1,548)
MEAN	75.8	(187.3)		$2,793	(1,131)		$3,215	(1,302)	$3,595	(1,456)

Type Seeding: C = Conventional, H = Hydroseeding, and T = Trees

Within the watershed the Pittsburgh, Redstone, Sewickley, and Waynesburg coal seams have been surface and drift mined. Water infiltration into underground mines is occurring through intersected underground workings, drift entries, and auger holes along strip mine highwalls. A feasibility study (132) identified four strip mines which diverted significant amounts of surface water to underground mine workings. Sealing of highwall openings and regrading of surface mines were proposed to control water infiltration. The effectiveness of the project was to be evaluated by monitoring stream flows and mine discharges within the watershed.

During 1972, three strip mines in the watershed were regraded – Section G, Strip Area R; Section G, Strip Area A; and Section C, Strip Area C. Work on the areas included: placing a diversion ditch above the highwall, compacting clay soil in auger holes and drift entries, contour or pasture regrading, soil treatment and seeding. Typical methods of regrading are shown in Figures 1.4-4 and 1.4-5. The costs of regrading and seeding the three areas ranged from \$9,351 to \$10,800 per hectare (\$3,787 to \$4,374/acre) (100). Itemized costs of regrading the three areas are presented in Table 1.4-2.

A final report evaluating the effectiveness of the water infiltration control project is to be completed in June, 1975. Based on data that has been collected, it appears that there may not be sufficient information to properly evaluate this technique in Dents Run. Since implementation of the project, borehole discharges have been affected by active underground mining. The failure to install continuous stream flow monitoring systems in the watershed may make it very difficult to analyze the effect of infiltration control.

EVALUATION AND RECOMMENDATIONS

Water infiltration resulting from surface mining operations can be effectively controlled by regrading. A hydrogeologic study should be performed to determine the nature and extent of infiltration and to assist in the development of a regrading plan. The regrading method must be designed to divert surface water away from the surface mine highwall and increase surface runoff. Impervious materials should be compacted into hydraulic openings between surface and underground mines. The regraded area should be revegetated to prevent erosion of the graded fill material and increase surface runoff.

The selection of a regrading method will depend upon such factors as the height and condition of highwall, original slope of ground, volume and condition of available spoil material, and available regrading equipment. Sufficient grading must be performed to conduct flow around the surface mine. The regrading method may include ditching and fluming of the mine area to facilitate surface runoff.

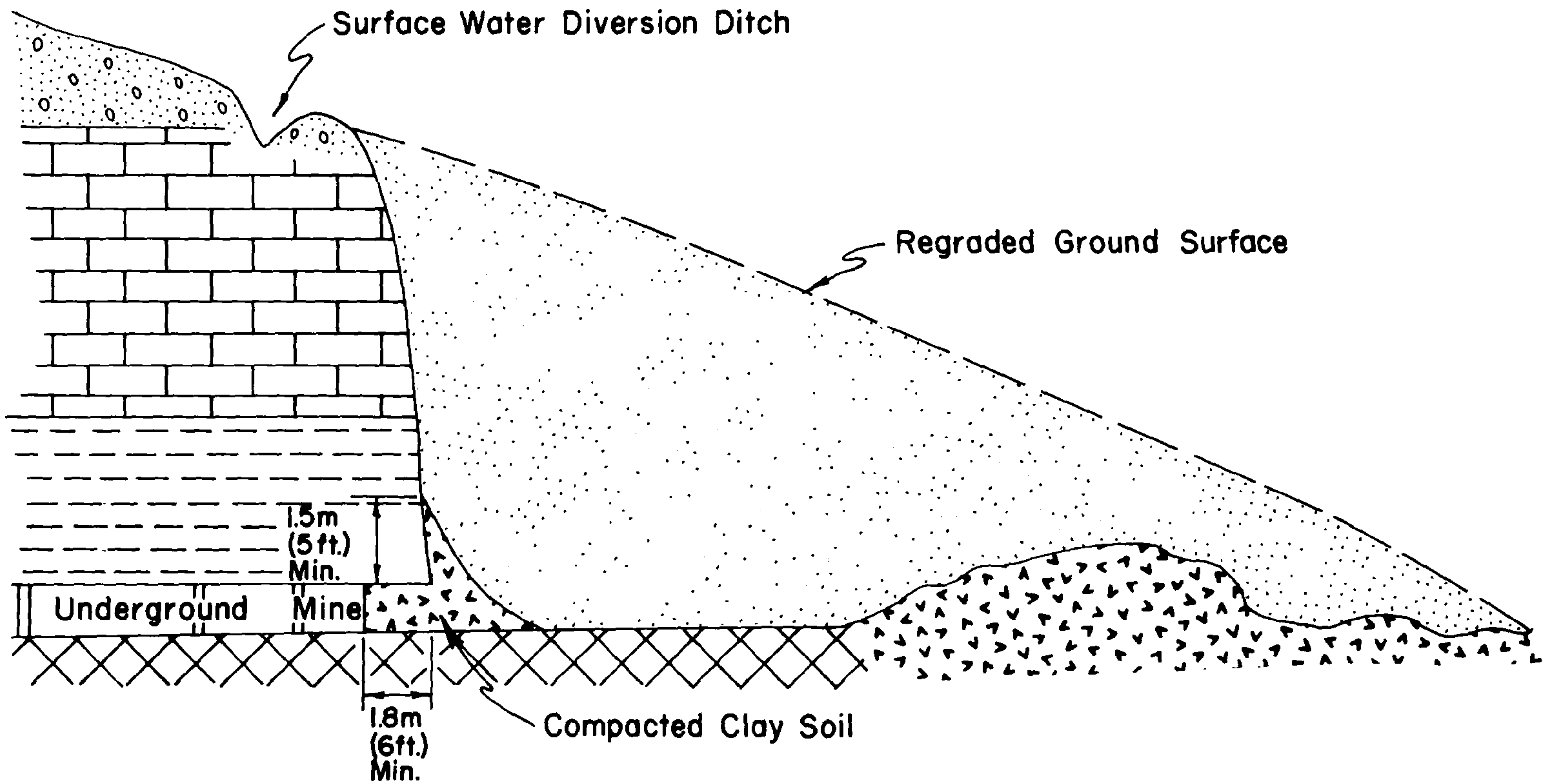


FIGURE 1.4-4

TYPICAL REGRADING UNDERGROUND MINE

DENTS RUN, W. VA.

(Adapted from Ref. 132)

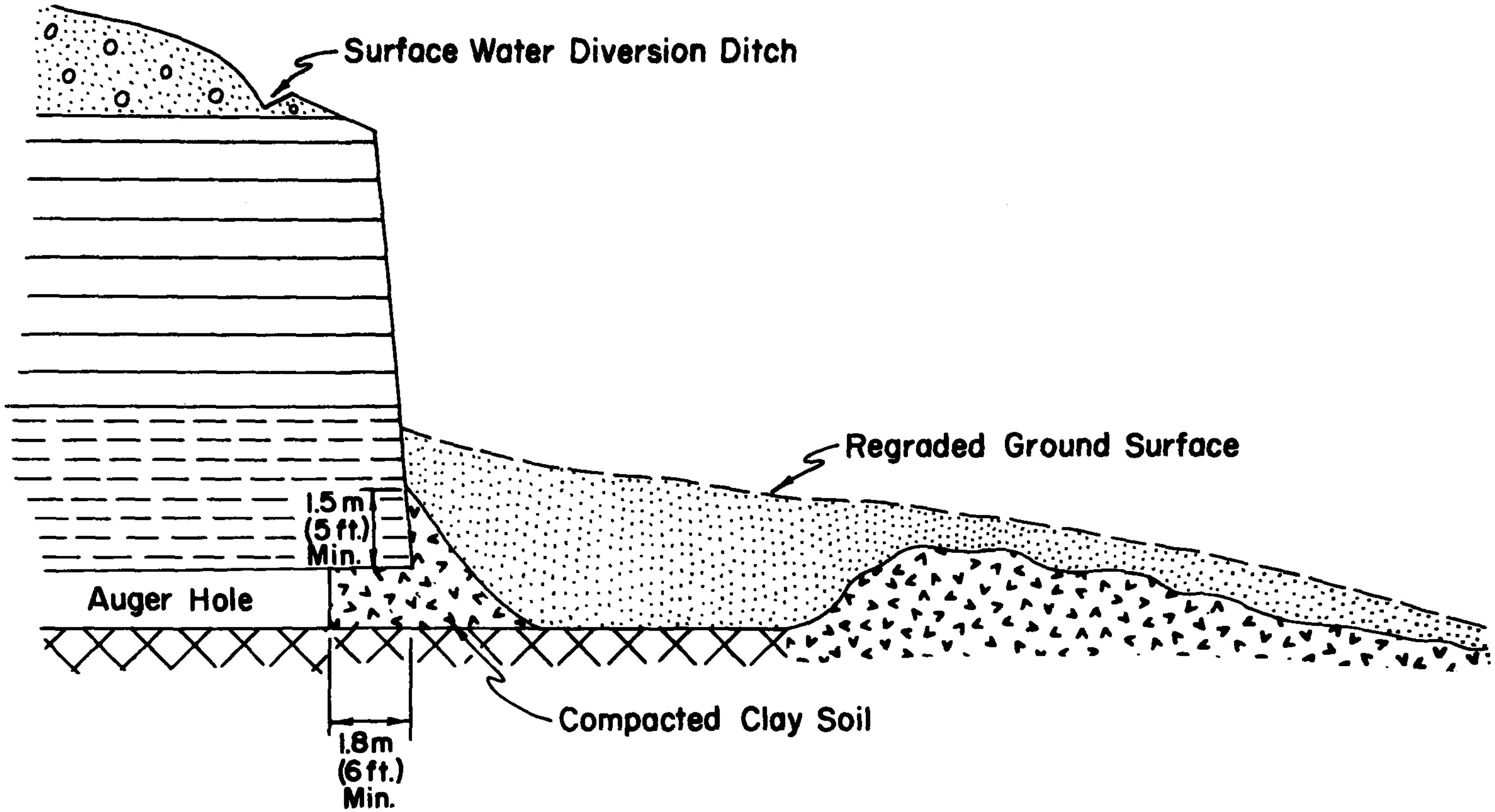


FIGURE 1.4-5

TYPICAL REGRADING AUGER HOLE

DENTS RUN, W.VA.

(Adapted from Ref. 132)

Table 1.4-2

Regrading Costs Dents Run Watershed

	Job 1 Section G Strip R		Job 2 Section G Strip A		Job 3 Section C Strip C	
Hectares (Acres)	6.5	(16)	4.1	(10)	9.2	(22.8)
Description of Work	Cost/Hectare (Cost/Acre)		Cost/Hectare (Cost/Acre)		Cost/Hectare (Cost/Acre)	
1. Grading	$ 8,148	(3,300)	$ 6,963	(2,820)	$ 9,444	(3,825)
2. Lime	62	(25)*	210	(85)	227	(92)*
3. Fertilizer	119	(48)	126	(51)	121	(49)
4. Seeding & Planting	595	(241)	541	(219)	533	(261)
5. Mulch	427	(173)	474	(192)	474	(192)
Total Hectare & Acre	$ 9,351	(3,787)	$ 8,314	(3,367)	$10,800	(4,374)
TOTAL COST	$60,592		$33,670		$99,727	

*Cost includes treatment of impounded water

All jobs consisted of diversion ditches, rip rap outslope, and compacted backfill in auger holes. Modified contour regrading was performed on Job 1. Jobs 2 and 3 were pasture regraded.

The cost of regrading will include backfilling and grading of the open cuts, and revegetation of the affected area. When old abandoned surface mines are regraded, additional expenditures for clearing and grubbing, and establishing mine access may be required. Regrading of these mines will normally be more difficult than regrading of active operations, since spoil material was placed without considering future regrading requirements. The construction of diversion ditches and sealing of highwall openings will further increase regrading costs.

Based on previous surface mine regrading costs, backfilling and grading using contour and terrace techniques should average respectively $4,938 per hectare ($2,000/acre) and $4,445 per hectare ($1,800/acre). Clearing and grubbing costs will be approximately $1,235 per hectare ($500/acre). Revegetation costs, including lime, fertilizer, seeding, and mulch will range from $1,235 to $1,358 per hectare ($500 to $550/acre). The range in total cost of regrading, including clearing and grubbing, backfilling, grading, and revegetation will generally be as follows: Contour Regrading – $4,445 to $9,383 per hectare ($1,800 to $3,800/acre) and Terrace Regrading – $3,704 to $8,395 per hectare ($1,500 to $3,400/acre).

REFERENCES

8, 29, 32, 47, 69, 75, 100, 101, 106, 127, 127, 132

1.5 SURFACE SEALING

DESCRIPTION

Water infiltration into underground mines can be controlled by reducing surface permeability. This may be accomplished by placement of impervious materials, such as concrete, soil cement, asphalt, rubber, plastic, latex, clay, etc., on the ground surface. Surface permeability may also be decreased by compaction; however, the degree of success will depend upon soil properties and compaction equipment utilized (127).

A seal below the surface would have several advantages over surface seals: it would be less affected by mechanical and chemical actions; land use would not be restricted; and the seal would be located in an area of lower natural permeability (115). The seal would be formed by injecting an impermeable material into the substrata. Asphalt, cement and gel materials have been used to control water movement below the surface. The effectiveness of various latexes, water soluble polymers, and water soluble inorganics has been demonstrated in laboratory and field tests. However, large scale applications of sub-surface sealants to control acid mine drainage have not been demonstrated.

IMPLEMENTATION

Impermeable Surface Seals

Several sealants have been used to reduce water infiltration into underground mines through subsided areas. Backfilling and compacting with clay to reduce vertical permeability in these areas is commonly practiced in the eastern coal fields. Other materials which have been demonstrated are sheets of butyl (rubber) compound, various chemical compounds, and cement grout.

Clay is one of the least expensive sealing materials. Costs for clay including installation may range from \$2.62 to \$7.85 per cubic meter (\$2.00 to \$6.00/cu yd). Costs for rubber range from \$5.38 to \$10.75 per square meter (\$0.50 to \$1.00/sq ft) installed. Costs of cement grout will depend upon the volume and mixture of materials placed and the amount of drilling required. The following unit prices have been used in preparing job bids: drilling – \$6.56 to \$9.84 per linear meter (\$2.00 to \$3.00/LF); cement – \$3.00 to \$4.50 per bag; cement admixture – \$4.41 to \$8.82 per kilogram (\$2.00 to \$4.00/lb); and fly ash – \$8.82 to \$22.00 per metric ton (\$8.00 to \$20.00/ton).

Asphalt and concrete prove to be excellent surface sealants but they are expensive. The only present economically feasible method of utilizing these materials as surface sealants is multi-purpose use. The surface could be sealed by constructing roads, parking lots, runways, etc. Concrete costs will normally range from \$39 to \$78 per cubic meter (\$30 to \$60/cu yd). Asphalt installation may range from \$2.00 to \$6.00 per square meter (\$0.19 to \$0.56/sq ft) (127).

Latex Soil Sealant

Uniroyal, Inc. conducted laboratory and field tests to determine the feasibility of using latex as a sub-surface sealant. Field experiments were conducted in 1972 at two sites in Clearfield County, Pennsylvania (115). Various latexes, water soluble polymers, clays, and water soluble inorganics were investigated in the laboratory. Field investigations were limited to ammonium hydroxide, sodium carbonate, and Naugatex J-3471 latex.

In laboratory tests good sealing efficiency was obtained when latex was applied at a rate equivalent to 4,484 to 5,605 kilograms per hectare (4,000 to 5,000 lb/acre). Application of a 5 percent rubber latex to a saturated core of soil reduced the seepage rate from 15 to 2 milliliters per minute (0.24 to 0.03 gal/hour).

During field tests, dilute solutions of sealants were sprinkled on test plots and flushed into the soil with water. The effectiveness of sealing was determined by comparing soil moisture and permeability of treated and untreated test plots.

Field testing of latex indicated that the latex was deposited progressively as it passed through the soil. The ideal situation would be for the latex to coagulate in a narrow zone 0.6 to 0.9 meters (2 to 3 feet) below the surface. Application of latex to field test plots resulted in a decrease in permeability in the top 25.4 centimeters (10 inches) of soil. An effective sub-surface seal was not demonstrated in the field. Based on application rates used in the field, raw material costs of latex would be approximately \$2,469 per hectare (\$1,000/acre). Equipment and operating costs would vrange from \$494 to \$1,235 per hectare (\$200 to \$500/acre), depending upon the size of area treated and availability of suitable water (115).

Effective seals were formed in both laboratory and field tests by applying dilute solutions of ammonium hydroxide or sodium carbonate. This seal is only temporary, however, since the two chemicals are water soluble. Very dilute clay dispersions were applied to laboratory soil columns. Pore blockage occurred at the surface, but in no case was penetration greater than 5.1 centimeters (2 inches).

Field test plots were located over abandoned underground coal mine workings. Since the size of the plots was small compared to the size of the mine, no change in mine effluent quality or quantity was expected. Therefore, the evaluation of sealing effectiveness did not involve monitoring of mine effluent.

EVALUATION AND RECOMMENDATIONS

The effectiveness of surface sealing will depend upon the type of material applied, the method of application, and the degree of maintenance performed. Surface sealants will be subjected to mechanical forces (traffic, weather, ground movement, vegetation, etc.) and chemical action (oxidation, etc.). In areas where surface sealing is utilized, the use of land for agriculture, industry, and recreation may be limited. Such factors may limit surface sealing to relatively small and remote areas.

The injection of grouting materials below the surface can be an effective method of surface sealing. However, in severely fractured areas, the grout will be unable to completely fill the void space and sealing efficiency will be reduced. Grouting costs will depend upon the size of the area being treated, drilling required, and the total volume of grout material injected. Estimates for horizontal grout curtains range from $29,630 to $98,765 per hectare ($12,000 to $40,000/acre).

Clay materials appear to be a practical sealing material. The clay should be compacted in layers and covered with soil to protect against weathering. The clay sealant will severely limit the use of land for agriculture and industrial purposes, but would be applicable to relatively small surface areas. The feasibility of clay sealants will normally depend upon the availability of suitable materials.

Asphalt, concrete, rubber, and plastic do not appear to be acceptable sealing materials. Asphalt and concrete are not economically feasible. Rubber and plastic are easily damaged and would require an extensive maintenance program. Attempts to cover these materials with soil have been unsuccessful. A soil cover proved to be unstable and any vegetative cover established would result in root damage to the seal.

REFERENCES

29, 57, 115, 127, 129

1.6 SURFACE WATER DIVERSION

DESCRIPTION

Surface cracks, subsidence areas, non-regraded surface mines, and shaft, drift and slope openings are often the source of surface water infiltration. Water diversion involves the interception and conveyance of water around these underground mine openings. This procedure controls water infiltration and decreases the volume of mine water discharge.

Ditches, trench drains, flumes, pipes, and dikes are commonly used for surface water diversion. Ditches are often used to divert water around surface mines. Flumes and pipe can be used to carry water across surface cracks and subsidence areas. To ensure effective diversion, the conveyance system must be capable of handling maximum expected flows. Riprap may be required to reduce water velocities in ditch type conveyance systems.

IMPLEMENTATION

Surface Mines

Diversion ditches are often placed on the uphill side of a highwall or an open pit. These ditches significantly reduce the volume of water entering both active and abandoned surface mines. The diversion ditch is the most commonly used method of water diversion in surface mining and, in fact, is required by law in some states.

Surface water flowing into abandoned surface mines is often diverted to adjacent underground workings, either through highwall openings or along a permeable mineral bed. The diversion of water around such areas will significantly reduce water infiltration.

Diversion ditches are often constructed above the highwall of a regraded surface mine. Surface water flowing over the highwall can percolate to the base of the highwall and flow to adjacent underground workings. The diversion ditch reduces the volume of percolating water and also prevents erosion of the regraded area.

Plans and specifications for surface mine regrading performed under Pennsylvania's Operation Scarlift Program frequently require the diversion of surface water around the mine. Project SL 132-2-101.1, Rattlesnake Creek watershed, required a diversion ditch and drainage flume to collect surface water above the highwall. The diversion ditch was constructed at a cost of \$3.28 per linear meter (\$1.00/LF). Unit costs for water diversion were as follows (84):

Diversion Ditch	56.4 LM @ $3.28/LM (195 LF)($1.00/LF)	$ 185
Riprap	50.2 sq m @ $23.92/sq m (60 sq yd)($20.00 sq yd)	1,200
Drainage Flume	96 LM @ $65.62/LM (315 LF)($20.00/LF)	6,300
Concrete Endwall	Lump Sum	1,000
	TOTAL	$8,685

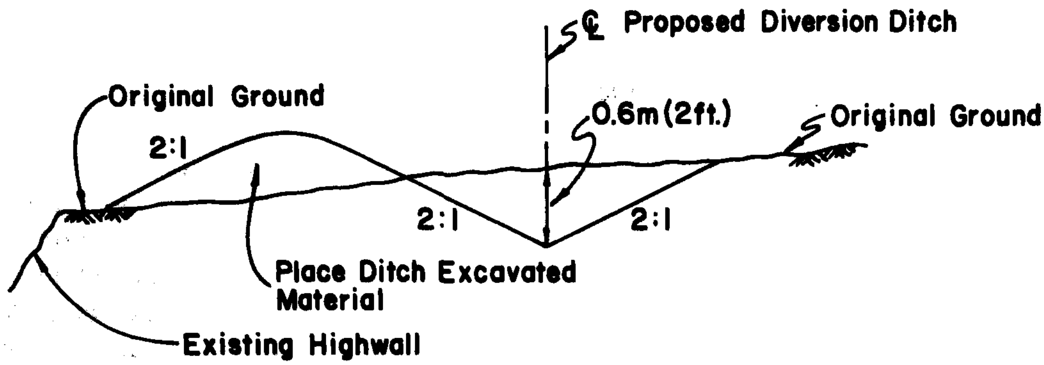
Plans and specifications for pollution abatement in the Cherry Creek watershed, Maryland, require the construction of a diversion ditch above surface mine highwalls (106). The ditch is to have side slopes of 2:1 and a minimum depth of 0.6 meters (2 feet). Excavated material is to be placed between the ditch and existing highwall. Dumped riprap is to be placed in specified areas to control water velocity and prevent ditch erosion. Cost estimates for constructing the diversion ditch and placing riprap were $1.31 per cubic meter ($1.00/cu yd) and $6.54 per cubic meter ($5.00/cu yd) respectively. Views of the diversion ditch and method of placing riprap are presented in Figure 1.6-1.

Underground Mines

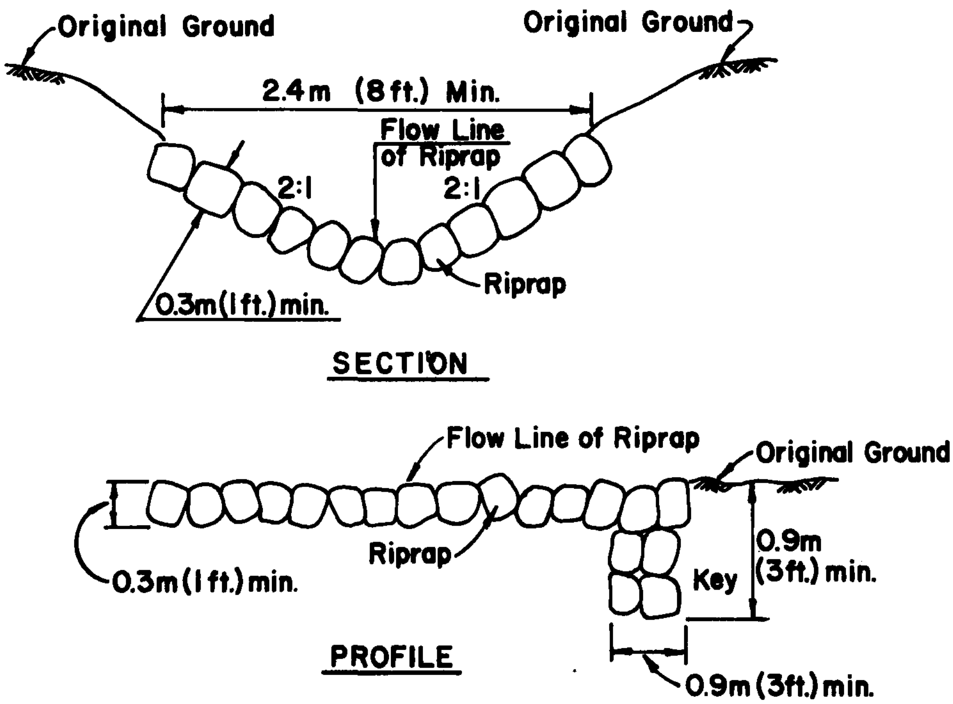
Surface water flowing directly to underground mines through surface cracks, subsidence areas, and slope, drift or shaft mine entries can be a major source of water infiltration. Water diversion around such areas will significantly reduce the volume of water entering underground mines.

A diversion ditch or dike will often effectively divert water around surface openings. Stream channels are often reconstructed and lined with an impervious material to carry water across fractured ground surface (See Section 1.7). If construction of a diversion ditch is infeasible, pipe, flumes or similar structures may be used to convey water around or over surface openings.

A 122 centimeter (48 inch) bituminized fibre flume was placed over a regraded subsidence area at the Shaw Mine Complex, Somerset County, Pennsylvania (84). This work was performed under Project SL 118-1. A total of 274 meters (900 feet) of flume was furnished and installed at a cost of $19.69 per linear meter ($6.00/LF). Regrading and fluming of the area reduced the flow of surface water to the underground mine.



DIVERSION DITCH DETAIL



DUMPED RIPRAP DETAIL

FIGURE 1.6-1

PROPOSED WATER DIVERSION DITCH
CHERRY CREEK, MARYLAND
(Adapted from Ref. 106)

EVALUATION AND RECOMMENDATIONS

Surface water diversion reduces the volume of water flowing into an underground mine, and thus, reduces the volume of water available to flush out mine drainage pollutants. The factors which will affect the selection and implementation of a diversion technique will be topography, availability of equipment, condition and type of soil, and the quantity of water expected. Any diversion technique when properly designed and utilized can greatly reduce the flow of surface water to underground mines. Although the costs of diversion may be high, this is an effective method of controlling mine drainage pollution from both active and abandoned mines. In most instances the cost of diversion will be significantly less than that required to treat an equal volume of mine water.

Diversion ditches are a relatively inexpensive, but effective method of collecting and conveying surface water. Lining of these ditches with concrete, asphalt or other material may be required to control water velocity and reduce erosion. Dumped riprap will prove to be an effective method of reducing water velocities in the ditch.

The range in costs for constructing diversion ditches will depend upon the width and depth of the ditch and the type of construction equipment utilized. Estimated costs range from $1.64 to $6.56 per linear meter ($0.50 to $2.00/LF) of ditch, with perhaps the average being approximately $3.29 per linear meter ($1.00/LF). Dumped riprap will normally cost between $6.54 and $26.16 per cubic meter ($5.00 and $20.00/cu yd).

The cost of flumes and pipe will depend upon their size, and labor and equipment required for installation. The estimated cost for placing a 92 centimeter (36 inch) half section of bituminized fibre pipe is $32.80 per linear meter ($10.00/LF). The cost of constructing dikes will usually be based upon the volume of material moved. The average cost of construction will normally range from $0.52 to $1.04 per cubic meter ($0.40 to $0.80/cu yd).

REFERENCES

8, 27, 29, 32, 57, 62, 69, 84, 106, 107, 127, 129

1.7 CHANNEL RECONSTRUCTION

DESCRIPTION

Vertical fracturing and subsidence of strata overlying underground mines often create openings on the ground surface. Streams flowing across these openings may have a complete or partial loss of flow to the underground workings. During active operations pumping of this infiltrating water places a physical and financial burden upon the mining company. Water infiltrating into abandoned underground mines is available to flush out mine drainage pollutants. In both active and abandoned underground mines the problems of infiltrating stream flow can be effectively controlled by reconstructing and/or lining the stream channel (127).

When practical, water infiltration will best be controlled by diverting the stream channel around underground mine openings. The reconstructed channel bottom may be lined with an impervious material to prevent seepage or flow to the underground mine. To ensure complete and effective diversion, the reconstructed channel must be capable of handling stream flow during peak flow periods.

In instances when stream flow cannot be diverted to a new channel, flow into underground mines can be controlled by plugging the mine openings with clay or other impervious material. The feasibility of sealing the channel bottom will depend upon the ability to locate fractures in the stream bed and successfully place the impervious material.

IMPLEMENTATION

Pennsylvania Operation Scarlift Projects

A 1974 report (32) prepared for the U.S. Environmental Protection Agency estimated the cost of channel reconstruction in the Monongahela River basin to be $65.62 per linear meter ($20.00/LF). The estimate included an allowance for increased construction costs, channel slope grading, soil treatment and seeding. This estimate was based on actual costs incurred in three Pennsylvania Operation Scarlift Projects: SL 102-1-1, Chartiers Creek, Allegheny County; SL 135-1, Catawissa Creek, Luzerne County; and SL 143-1, Alder Run, Clearfield County.

A total of 3,024 linear meters (9,920 LF) of stream channel was reconstructed under the three projects. The costs per linear meter of reconstructed channel were: Project SL 102-1-1 – $50.85 ($15.50/LF), Project SL 135-1 – $39.37 ($12.00/LF), and Project SL 143-1 – $88.58 ($27.00/LF). Unit costs for excavation ranged from $0.80 to $3.40 per cubic meter ($0.61 to $2.60/cu yd).

In total, 800 linear meters (2,625 LF) of stream channel were reconstructed at five different locations along tributaries of Big Run, Harpers Run, Sulphur Run, and Whiskey Run in Blacklegs Creek watershed, Young and Conemaugh Townships, Indiana County, Pennsylvania. Work was completed by B. R. Loughry in March, 1974 under Pennsylvania Project SL 182-1. Water in the tributaries was flowing into abandoned underground mine workings through subsidence holes, and cracks and crevices in the stream beds. At two locations channels were reconstructed around subsidence holes. Other sections of channel bottom were sealed with bentonite to ensure continuous flow of water across mine openings (84).

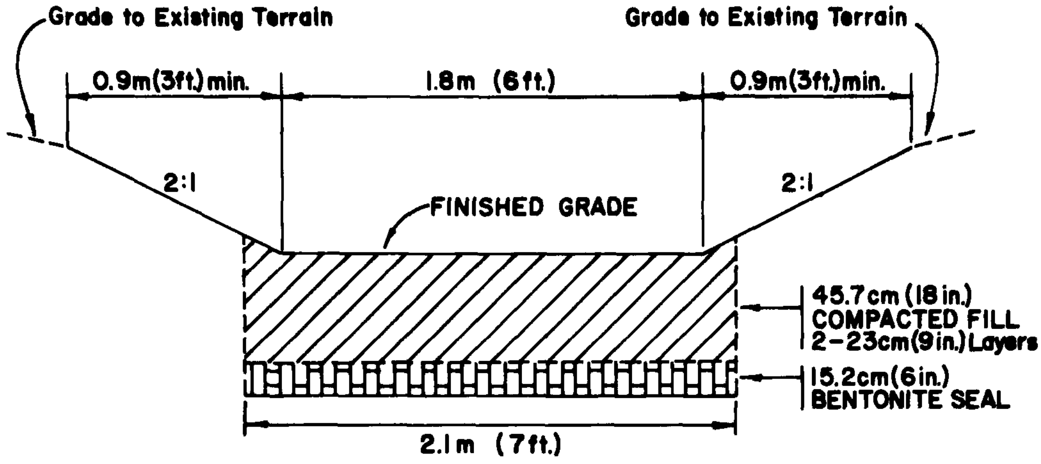
A bentonite seal was placed along the bottom of 412 linear meters (1,350 LF) of reconstructed channel. The channel was excavated to 0.6 meters (2 feet) below finished grade with a bottom width of 2.1 meters (7 feet). The bottom was graded and compacted in preparation for placing the bentonite seal. A 15.2 centimeter (6 inch) layer of 5 parts sand to 1 part granulated bentonite was placed and well compacted on the channel bottom. Two 23 centimeter (9 inch) layers of best available impervious material were placed and compacted over the bentonite. The width of the channel bottom at finished grade was 1.8 meters (6 feet).The channel sides were graded to a slope of 2:1 for a minimum of 0.9 meters (3 feet) from the channel bottom, then graded to existing terrain. Typical channel sections with and without the bentonite seal are shown in Figure 1.7-1.

Reconstruction and sealing of the channels resulted in increased flow in the Blacklegs Creek tributaries. At Locations 2, 3 and 4 a total of 549 linear meters (1,800 LF) of channel was reconstructed at an average cost of $20.04 per linear meter ($6.11/LF) Construction costs for the complete project, which included backfilling two subsidence holes, totaled $23,000 (84).

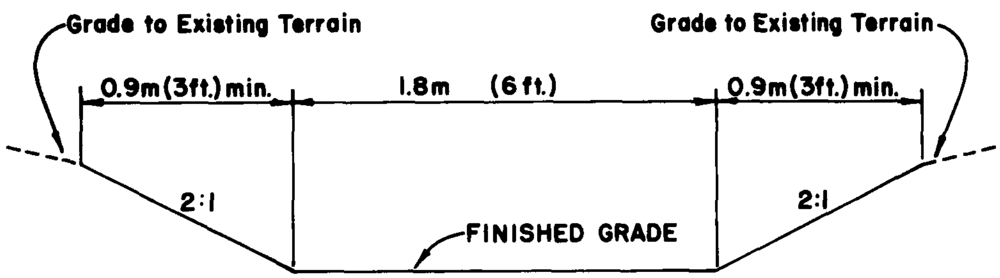
EVALUATION AND RECOMMENDATIONS

The reconstruction of stream channels is an effective method of reducing surface water infiltration to abandoned underground mines. The costs of stream diversion will normally be much less than treatment costs of an equal volume of mine water. There is not much documentation of the use of this diversion technique in mine related projects. However, there is considerable experience available in stream channel construction in conjunction with highway projects.

The feasibility of reconstructing a channel will depend upon channel size, topography, and extent of surface fracturing. If flow cannot be diverted to a new channel, the existing channel should be graded and lined to improve flow efficiency. Channel excavation costs will normally range from $1.31 to $3.92 per cubic meter ($1.00 to $3.00/cu yd). Lining of the channel bottom with clay will cost between $1.20 to $2.40 per square meter ($1.00 to $2.00/sq yd). The total cost of channel reconstruction may also include protection of channel slopes with riprap or



CHANNEL SECTION WITH BENTONITE SEAL



CHANNEL SECTION WITHOUT BENTONITE SEAL

FIGURE 1.7-1

RECONSTRUCTED CHANNEL, BLACKLEGS CREEK
(Adapted from Ref. 84)

vegetative cover. The total cost per linear meter of reconstructed channel will normally range from $32.81 to $82.02 ($10.00 to $25.00/LF).

REFERENCES

8, 27, 29, 32, 38, 57, 62, 69, 84, 107, 127, 129

2.0

MINE SEALING

2.1 GENERAL DISCUSSION

Mine sealing is defined as the closure of mine entries, drifts, slopes, shafts, subsidence holes, fractures, and other openings in underground mines with clay, earth, rock, timber, concrete blocks, brick, steel, concrete, fly ash, grout, and other suitable materials. The purpose of mine sealing is to control or abate the discharge of mine drainage from active and abandoned mines.

Mine seals have been classified into three types based on method of construction and function (32, 39). The three seal types are:

1. Dry Seal – The dry seal is constructed by placing suitable material in mine openings to prevent the entrance of air and water into the mine. This seal is suitable for openings where there is little or no flow and little danger of a hydrostatic head developing.

2. Air Seal – An air seal prevents the entrance of air into a mine while allowing the normal mine discharge to flow through the seal. This seal is constructed with a water trap similar to traps in sinks and drains.

3. Hydraulic Seal – Construction of a hydraulic seal involves placing a plug in a mine entrance discharging water. The plug prevents the discharge and the mine is flooded. Flooding excludes air from the mine and retards the oxidation of sulfide minerals.

Mine sealing performed in the early 1900's was for safety reasons and not mine drainage control. Seals were constructed to confine water in certain sections of the mine, to extinguish mine fires and to hold back gases.

The possibility of utilizing mine seals to control drainage from mines was discussed in several technical reports in the 1920's and early 1930's. Observation of mines where entries had been sealed by caving revealed a better quality discharge than mines where entries were open and water discharged freely. A mine sealing project sponsored by the Bureau of Mines in 1932 indicated that the air sealing of mines reduced the acidity of mine drainage.

The Federal Government started an extensive mine sealing program in 1933 as Works Progress Administration and Civil Works Administration projects (39, 69, 74). This program was continued for several years in Ohio, Pennsylvania, West Virginia, Indiana, Illinois, Kentucky, Tennessee, Maryland, and Alabama. Several investigations were made into the effectiveness of this sealing program, but no definite conclusions were drawn and the subject is still open to debate.

Mine sealing research was conducted in the 1940's, 1950's and 1960's by Bituminous Coal Research, Inc., Mellon Institute, U.S. Bureau of Mines, and various states and universities. Research and demonstration projects relative to mine sealing have been conducted in the past decade by the U.S. Environmental Protection Agency, and the U.S. Bureau of Mines assisted by both the U.S. Geological Survey and U.S. Corps of Engineers. As a result of this research, new sealing methods have been developed and many are presently being demonstrated.

The feasibility of sealing mines to control or abate pollution discharges will depend upon more than the ability to close existing mine openings. The characteristics and conditions of the underground mine system must be considered in the planning and implementation of any sealing program. Therefore, the first step in mine sealing is the collection and analysis of available site data which should include, but not be limited to the following (39, 112, 127):

Geology

The local structure will determine whether a mine will have a discharge and whether a mine can be effectively sealed. Since the geologic structure varies for different mineral seams it is important that geologic information be collected for each mine.

The geologic structure of the mine should be determined by drilling boreholes or examination of outcrops. From the borehole information a structure map is constructed which will show the strike and dip of the strata, folding, anticlines, synclines, fractures, and faults. The location and direction of joints should be plotted. The composition of the mineral seam and associated strata, mineral structure, contours, and outcrop lines are factors which also deserve consideration before mine sealing.

Hydrology

The elevation of the ground water table and the flow of ground water through rock strata are important factors in the design of mine seals. Ground water levels will determine the head expected against a seal. The flow of water in the mine will determine the location and type of seal placed in the mine. Some factors affecting ground water flow are rock type, dip of beds, joints, faults, and fracturing.

A water table map may be prepared by determining the elevation of all springs and swamps found above the outcrop line and water levels in boreholes and wells. These elevations should be plotted on a map and contoured. It should be assumed that any water located above the mineral seam will eventually flow into the mine and result in an increase of hydrostatic head on mine seals.

Mining Considerations

The method by which a mine is developed is important in determining sealing methods to be used. If a mine is developed updip then seals will be placed at the lowest elevation of the mine and there will be a maximum head created against these seals. In mines where mining is developed downdip the head against mine seals will be greatly reduced or completely eliminated. When the head against seals is kept to a minimum the seals will be safer and much more likely to abate pollution. Other mining factors affecting the success of sealing will be: the relationship of the sealed mine to other mines, both active and abandoned; the condition and width of mineral barriers along outcrops and between adjacent mines; and the location of seals with respect to solid strata and subsidence areas.

The construction of mine seals in abandoned or inactive underground mine may be generally classified as either accessible or inaccessible (32, 39). These two classifications may be defined as:

> Accessible – The mine is open from the portal or shaft to the construction area or may be opened with minor effort. Seals are constructed from within the mine and may be visually inspected during construction.
>
> Inaccessible – The mine is caved or flooded at the portal or shaft and would require major effort and expenditure to re-open. Mine seals would be placed from above ground through boreholes. There is no opportunity for visual inspection during construction other than borehole cameras.

The cost of constructing mine seals will depend upon various cost factors such as materials, labor, equipment, drilling, and grouting (29). The significance of each factor will depend upon the type of seal being constructed, the size and location of the seal, and the method of construction.

Materials which may be required during seal construction are aggregate, concrete, masonry block, mortar, clay or soil, mine timbers, pipe, and grouting materials. Labor costs will greatly depend upon the size of the job, the method of construction and the amount of site preparation required. The cost of equipment will depend upon such factors as equipment required for the particular method of construction, job size, and equipment availability.

Drilling costs will include drilling required to determine the location and alignment of mine entries and for placing materials in inaccessible mine seals. Drilling may also be required for inspection of the finished seal or preparing grout curtain drill holes in areas of permeable strata.

Often the seal and adjacent strata are grouted to reduce water percolation. The costs of grouting will include drilling, materials, labor, geologic testing, and equipment. If grouting is to be performed the cost will usually be listed separately from the price quoted per seal (29).

REFERENCES

8, 27, 29, 32, 34, 39, 40, 51, 69, 71, 74, 111, 112, 127

2.2 DRY SEAL

DESCRIPTION

Since the 1930's air sealing program of the U.S. Bureau of Mines (See Section 2.3), dry seals have been utilized in conjunction with various air sealing projects. Common practice has been to place dry seals in openings where there is little or no danger of a buildup of hydrostatic head. The main objective of this seal is to prevent the entrance of air and water into underground mines.

Dry sealing involves the placement of impermeable materials or structures in mine drifts, slopes, shafts, subsidence areas, fractures, and other openings. The seals may be constructed of masonry block, clay, soil, or other suitable materials. This type of sealing is generally confined to openings on the high side of a mine where the mine workings lie to the dip (32).

IMPLEMENTATION

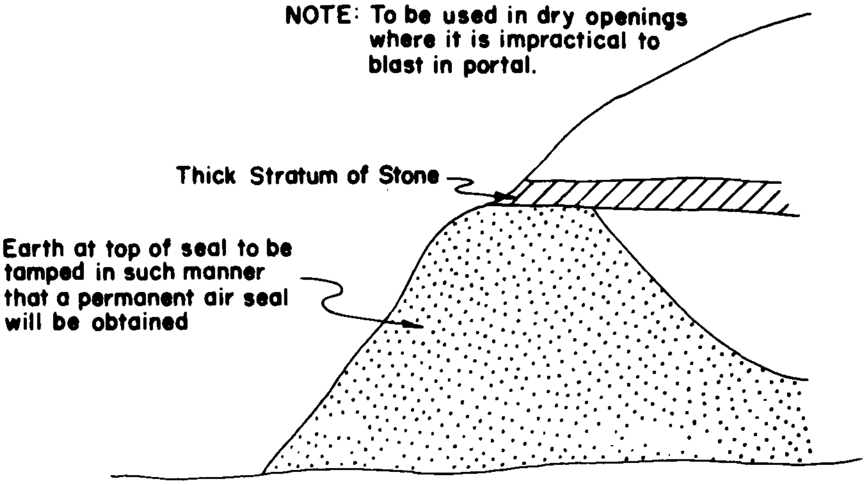
1930's Sealing Program

During the period from 1933 to 1939 and from 1947 to 1949 a $5.4 million mine sealing program was administered by the U.S. Public Health Service in several states east of the Mississippi River (69). As a result of this program an estimated 8,000 seals were placed in the openings of several hundred mines (73). The mines were sealed by placing dry seals in all entries except for one where an air seal was placed to allow water to discharge.

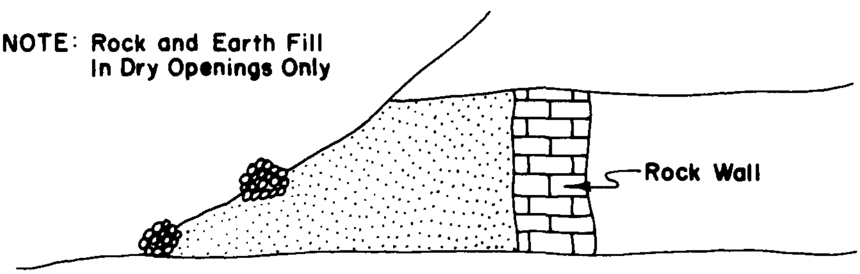
Often mine openings could be effectively dry sealed by blasting and caving mine portals. When this method was impractical stone and earth were used to fill the opening or a rock wall was constructed across the entry and backfilled with earth and rock. Sketches of such sealing methods are shown in Figure 2.2-1.

An actual evaluation of the effectiveness of the dry seals in preventing the entrance of air and water into mines was never made. Often the problem of air and water entry into sealed mines is due to cracks and fissures in overburden and along the outcrop, and not to leakage at sealed entries.

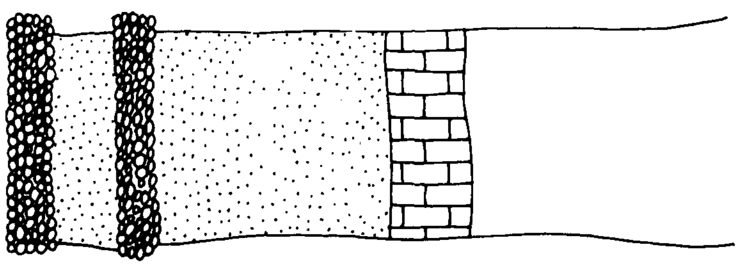
During the period from October 1, 1935 to September 1, 1937 a total of 84,844 openings were sealed in seven states under the Federal mine sealing program (9). The total cost of constructing these seals including technical supervision, labor, materials, equipment, and miscellaneous expenses was $3,327,799.01. No information was available on the cost of individual air and dry seals. However, the average cost per mine and opening sealed was $1,049.45 and $39.22, respectively.



EARTH SEAL FOR DRY OPENING



ELEVATION



PLAN

ROCK AND EARTH FILL SEAL

FIGURE 2.2-1

TYPICAL DRY SEALS, 1930's SEALING PROJECT
(Adapted from Ref. 36)

Bureau of Mines Sealing

Dry seals were constructed during a U.S. Bureau of Mines project to evaluate the effectiveness of air sealing on a 31 hectare (77 acre), abandoned, highly acid drift mine 64.4 kilometers (40 miles) northeast of Pittsburgh, Pennsylvania (73, 75). Sealing was started under contract in November, 1965 and completed in May, 1966. Seven dry seals were constructed on concrete footers, hitched into the roof and ribs, and coated with urethane foam. Timbering was also performed on either side of each seal for roof support. This type of dry seal is shown in Figure 2.2-2.

Additional work on the sealing project involved placing an air seal; constructing two concrete dams in the main drift and air course; backfilling, compacting, grading, and seeding of two strip mines on the outcrop; clay sealing and grouting of a badly caved drift. As a result of the sealing, oxygen content in the mine was reduced from 20.9 percent to about 17.0 percent. During a 32 month period after sealing, effluent volume was reduced a total of 26.5 million liters (7 million gallons) (75).

The average cost of each of the seven dry seals placed in the mine was $5,089 (75). Material costs and quantities per seal were as follows:

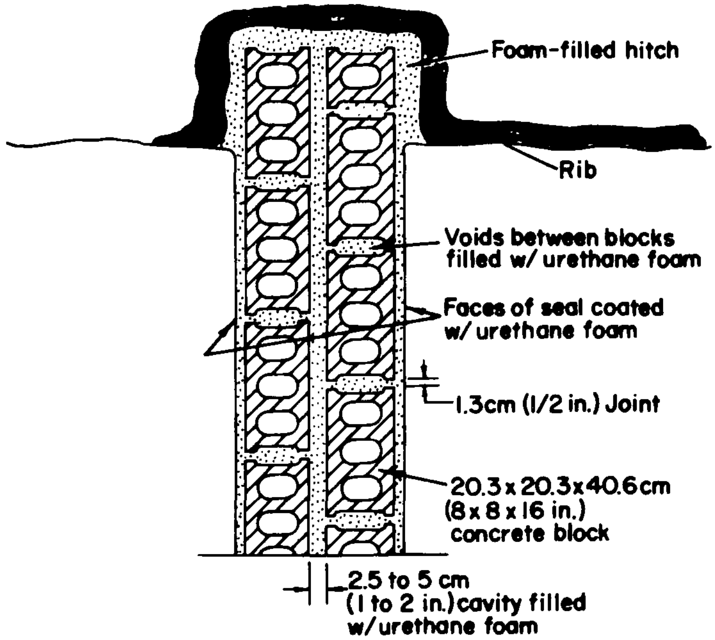
Materials	Quantity	Cost
Urethane Foam	100 kg (222 lb)	$390
Timbering	7.2 cu m (3,060 bd ft)	340
Masonry Blocks	222	58
Concrete Footers	2.1 cu m (2.8 cu yd)	50
TOTAL		$838

Labor requirements for constructing the seals (including the air seal) averaged 625 hours per seal at an average cost of $3,750 per seal. Average equipment costs, including operator, were $1,120 per seal. Equipment costs were chiefly related to clean-up of entries and grading for drainage and stability around the portals.

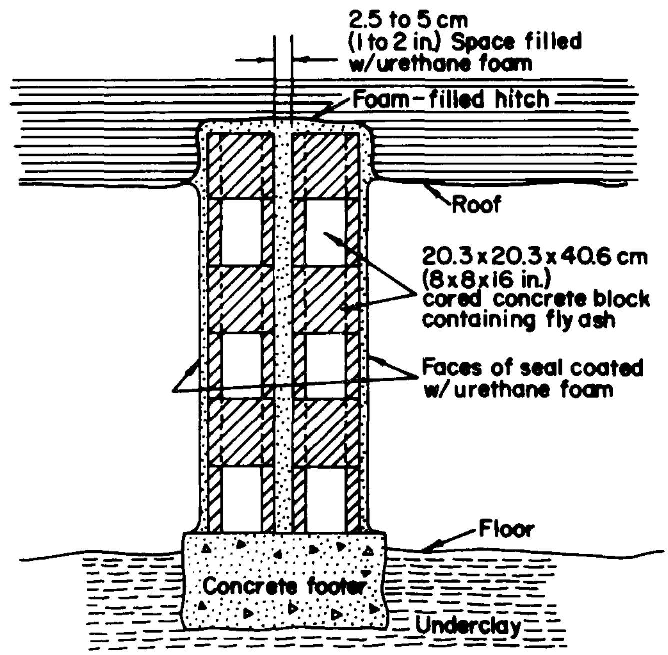
Roaring Creek – Grassy Run, West Virginia Seals

In 1964, a demonstration project site to evaluate mine sealing was selected in the Roaring Creek – Grassy Run watershed near Elkins, West Virginia (57, 101). The sealing was to involve sealing subsidence areas and boreholes, backfilling strip mines, water diversion from mines, and the construction of dry and air seals.

During the project 43 dry masonry seals were constructed in mine openings. The dry seals were constructed from two courses of fly ash blocks and coated with urethane foam on both sides to protect the blocks from acid attack. The mine was timbered on both sides of the seal to keep the weight of the roof off the seal.



TOP VIEW



CROSS-SECTION

FIGURE 2.2-2

U.S. BUREAU OF MINES DRY SEAL

(Adapted from Ref. 75)

The effectiveness of the dry seals could not be evaluated as air sealing of a large 1,215 hectare (3,000 acre) mine was not completed due to cost overruns. However, dry seals such as the ones constructed at Elkins should effectively prevent the entrance of air and water through mine entries.

An analysis of construction costs of 25 dry seals at the Elkins job showed a maximum cost of $6,376 per seal and a minimum cost of $1,358 per seal. The average cost per seal was $2,212 (101).

A breakdown of the seal construction was:

Work Area Number	Number of Seals	Direct Cost	Cost per Seal
2	2	$ 4,000	$2,000
7	3	5,298	2,766
8	1	6,376	6,376
14	1	1,358	1,358
27	12	23,706	1,975
30	6	14,574	2,429

The considerably higher cost of the dry seal on Work Area No. 8 was due to high labor cost involved in opening and timbering the portal prior to seal construction.

EVALUATION AND RECOMMENDATIONS

Dry seals are used only as a method of preventing the entrance of air and water into underground mines. These seals are not designed to withstand water pressure; therefore, their use must be limited to areas where little or no hydrostatic head is expected. Dry seals are commonly used to close shaft, slope and drift entries, subsidence areas, fractures, and other openings to underground mines.

The use of masonry block seals will be limited to horizontal or near horizontal accessible entries. These seals should be placed on a concrete footer and hitched into the roof and sides of the opening. Timbering of the mine roof may be required to keep the weight of overlying strata off of the seal. The cost of constructing this type seal will depend upon the size and condition of the mine opening and the amount of materials, equipment, and labor required. Masonry block seal costs will range from $2,500 to $5,000 per seal.

Often an effective dry seal can be constructed by compacting clay or other suitable materials into the mine opening. The cost of constructing these seals will include materials, labor, equipment, and any grading and revegetation required. The cost of this work can be measured on a cubic meter (cubic yard) basis or a lump sum fee. The unit price for placing clay seals will range from $2.62 to $5.23 per cubic meter ($2.00 to $4.00/cu yd). The costs of constructing clay bulkheads in mine openings will range from $2,500 to $4,500 per seal.

Masonry block walls and clay plug seals may also be used to hydraulically seal underground mines. These seals must be designed and constructed to withstand the maximum expected water pressure. The implementation of these seals is further discussed in Sections 2.4-2 and 2.4-5.

REFERENCES

5, 9, 21, 32, 36, 39, 42, 52, 56, 57, 60, 61, 62, 69, 71, 73, 75, 99, 101, 111, 127

2.3 AIR SEALS

DESCRIPTION

Air sealing of mines in the eastern coal fields has been practiced since the early 1920's. Several evaluations of various sealing projects have been made; however, the effectiveness of air seals remains a controversial issue.

Air sealing of underground mines involves the sealing with impermeable materials of all openings into the mine through which air may enter. One entry, usually the lowest entry to the mine, is provided with an air trap which allows water to discharge from the mine but prevents the entrance of air. In a successfully air sealed mine the oxidation of sulfide minerals will be retarded, and thus, the formation of mine drainage pollutants controlled.

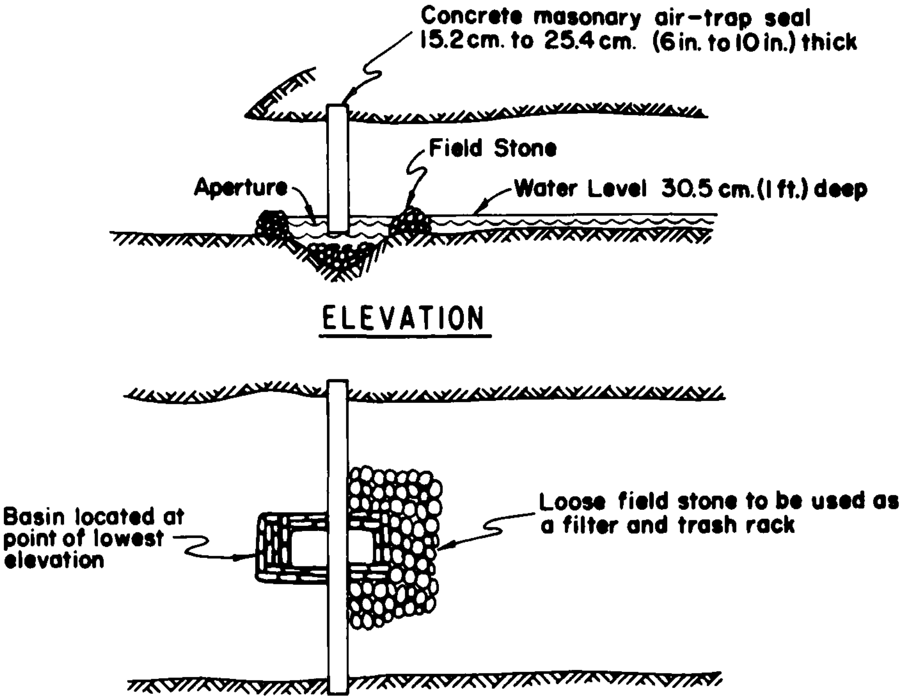
Results of previous air sealing projects indicate that the success of sealing will depend upon the ability to locate and seal all air passages to the mine. Underground mines have numerous air passages such as surface mines, boreholes, joints, fissures, and subsidence cracks. Even if all passages are located and sealed, porous overburden and fractured outcrops may allow breathing of the mine with each change in barometric pressure.

IMPLEMENTATION

1930's Sealing Project

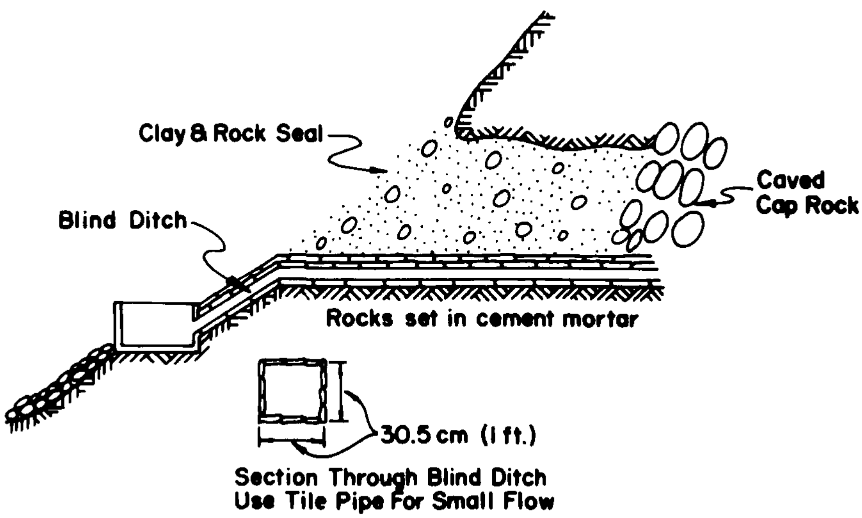
During the early 1920's, researchers for the U.S. Bureau of Mines observed that mines having caved or otherwise sealed entries were discharging water containing little or no acidity. It was concluded that caving and/or sealing of the entries excluded oxygen from the mine and prevented the formation of mine drainage. In order to evaluate air sealing, three mines were experimentally sealed by the Bureau in 1932 and discharges were analyzed. A reduction in acidity demonstrated that air sealing reduced or prevented the formation of mine drainage. As a result of this program, the Federal Government began an extensive mine sealing program in 1933 under Work Progress Administration and Civil Works Administration projects (69).

During the periods from 1933 to 1939 and from 1947 to 1949, the $5.4 million sealing program was administered by the U.S. Public Health Service in the states of Ohio, Pennsylvania, West Virginia, Indiana, Illinois, Kentucky, Tennessee, Maryland, and Alabama (69). As a result of this program, air and dry seals were placed in the openings of several hundred mines (73). The mines were sealed by placing dry seals in all entries except for one where an air seal was placed to allow water to discharge. Sketches of the types of seals used are shown in Figure 2.3-1.



PLAN

CONCRETE OR MASONRY AIR-TRAP SEAL



CLAY & ROCK WATER SEAL FOR CAVED PIT MOUTH

FIGURE 2.3-1

TYPICAL AIR SEALS, 1930's SEALING PROJECT

(Adapted from Ref. 36)

An overall evaluation was never made as to the effectiveness of the program in reducing mine drainage pollution. The U.S. Public Health Service estimated a 28 percent reduction in the acid load of the Ohio River. The Pennsylvania Sanitary Water Board partially attributed a decrease in acidity in the Monongahela River to the sealing program (73). It was also claimed that the program so reduced the mine drainage problem in Pennsylvania that in various streams fish life returned and water was used for industrial and domestic purposes (71). A West Virginia report (61) claimed that as of February 1, 1936, a reduction of 77.8 percent occurred in the acid load discharging from 345 sealed mines.

During the period from October 1, 1935 to September 1, 1937, a total of 3,171 mines and 84,844 openings were sealed in seven states under the Federal mine sealing program (9). Mines were sealed in the seven states as follows:

State	Mines Sealed	Openings Sealed and In Progress
Alabama	31	660
Indiana	60	910
Kentucky	488	2,625
Maryland	19	45
Ohio	1,769	18,111
Pennsylvania	468	58,212
West Virginia	336	4,281

A listing of the expenditures for these seals is shown in Table 2.3-1. An analysis of these costs reveals that the average cost per mine sealed and per opening sealed was \$1,049.45 and \$39.22, respectively. The average labor cost per hour was \$0.496 (9).

Pennsylvania Sealing Program

After the completion of the Federal sealing program, most areas failed to continue sealing abandoned mines. The Pennsylvania Department of Mines had been sealing mines since passage in 1935 of the Bituminous Mining Law, Act No. 55. In 1947, a Pennsylvania law created a Mine Sealing Bureau within the State Department of Mines and appropriated \$1,090,000 to continue work on mine sealing.

An evaluation of the Pennsylvania sealing work reported that (71): the Borough of Barnesboro began taking its water supply from the discharge of a sealed mine; between 1937 and 1950 the Youghiogheny River showed a decrease in acid load from 789 to 168 metric tons per day (870 to 185 tons/day); the Casselman River which had once been heavily polluted with mine drainage became alkaline and

Table 2.3-1

Expenditures October 1, 1937 to September 1, 1967
1930's Mine Sealing Project

State	USPHS Technical Supervision	Labor	Materials Equipment & Other	Total Expended
Alabama	$ 8,060.16	$ 35,124.24	$ 2,211.97	$ 45,396.37
Indiana	20,819.35	99,800.63	3,638.87	124,258.85
Kentucky	61,217.03	141,619.73	7,210.14	210.046.90
Maryland	11,304.39	24,606.06	2,440.98	38,351.43
Ohio	66,610.89	647,932.89	29,146.79	743,690.57
Pennsylvania	130,905.70	1,467,661.79	38,882.63	1,637,450.12
West Virginia	73,174.38	395,589.86	59,840.53	528,604.77
Region	$372,091.90	$2,812,335.20	$143,371.91	$3,327,799.01

fish appeared; and in several areas in the central part of the state, water discharging from sealed mines was being piped directly to homes and used for domestic purposes. As indicated, some remarkable results of sealing were claimed; however, no technical information was supplied to substantiate these results.

An investigation was begun in 1947 under the auspices of the Sanitary Water Board of the Department of Health of Pennsylvania to study the effectiveness of air sealing of coal mines to decrease the discharge of pollutants (18). Seven individual mines in Westmoreland and Fayette Counties in Pennsylvania were air sealed during 1949 and 1950. Water samples were periodically collected and analyzed between 1947 and 1960. The oxygen content of the mine atmosphere was also monitored after sealing.

From the data collected during this study it was concluded that air sealing did not result in a significant reduction in acid load or oxygen content. Therefore, it was determined that although correct in theory air sealing was ineffective in practice.

Bureau of Mines Sealing

To further evaluate the effectiveness of air sealing the U.S. Bureau of Mines sealed a 31 hectare (77 acre), abandoned, highly acid, drift mine 64.4 kilometers (40 miles) northeast of Pittsburgh, Pennsylvania (73, 75). Sealing was started under contract in November, 1965 and completed in May, 1966. Eight separate seals (one air and seven dry) were constructed. As shown in Figure 2.3-2 the seals were constructed on concrete footers, hitched into the roof and ribs, and coated with urethane foam.

Additional work in the sealing project involved constructing two concrete dams in the main drift and air course; backfilling, compacting, grading, and seeding of two strip mines on the outcrop; clay sealing of a 9.1 meter (30 foot) diameter subsidence hole; and clay sealing and grouting of a badly caved drift. Construction of the seals also involved timbering on either side of each seal for roof support.

Results of the chemical analysis of samples taken before and after sealing were as follows (75):

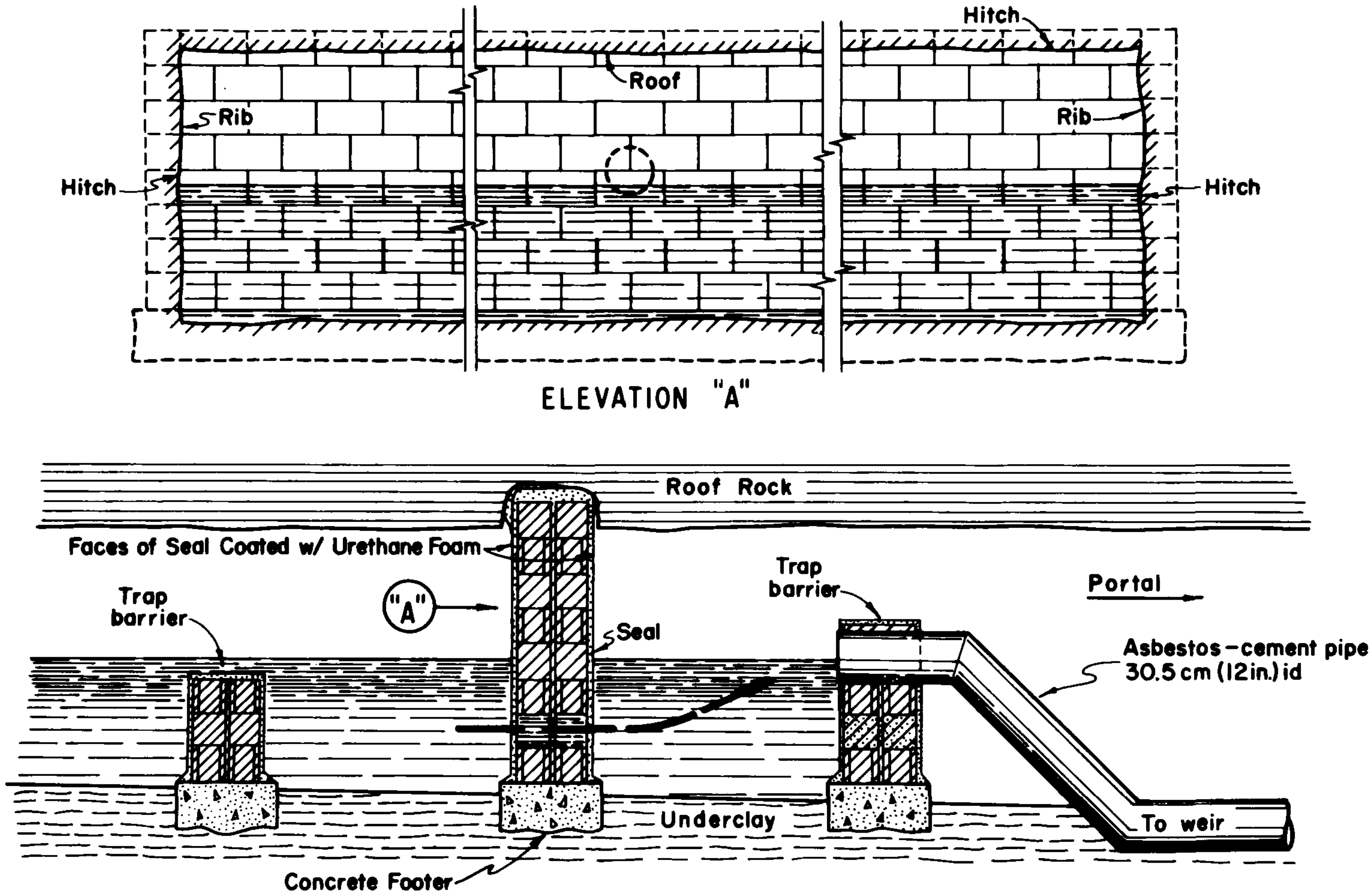


FIGURE 2.3-2

U.S. BUREAU OF MINES AIR SEAL
(Adapted from Ref. 75)

	Before Sealing		After Sealing	
Parameter	Range	Mean	Range	Mean
pH	2.9 – 3.2	3.1	3.0 – 5.5	3.4
Total Acidity (mg/l)	75 – 1,290	514	45 – 490	211
Sulfate (as SO_4)(mg/l)	655 – 2,260	1,403	356 – 1,180	874
Calcium (as $CaCO_3$)(mg/l)	203 – 1,242	505	36 – 625	405
Magnesium (as $MgCO_3$)(mg/l)	109 – 520	285	76 – 336	185
Total Iron (as Fe_2O_3)(mg/l)	13 – 508	160	5 – 160	62

Their results show an increase in the mean value of pH from 3.1 to 3.4 and a decrease in the mean concentrations of acidity, sulfate, calcium, mangnesium, and total iron. After sealing the oxygen content in the mine was lowered from 20.9 percent to about 17.0 percent.

After sealing a reduction of 26.5 million liters (7 million gallons) in effluent volume and a reduction of 150 mg/l in effluent acidity were attributed to the air sealing (75). The reduction in oxygen concentration seemed to stabilize the mine, and thus, decreased the variance in total acidity of the effluent.

The total cost for sealing, reclamation and related work at the mine was $57,420. A breakdown of the costs follows (75):

Timber treated – 56.9 cu m (24,390 bd ft)	$ 5,146
Urethane Foam – 908 kg (2,000 lb)	3,510
Masonry blocks – 2,002	524
Pipe – 51 m (167 ft)	528
Concrete – 21 cu m (28 cu yd)	504
Miscellaneous	288
TOTAL MATERIAL	$10,500

Equipment and operator	\$ 8,960
Labor (5,000 man-hours)	30,000
TOTAL EQUIPMENT AND LABOR	\$49,460
Sealing 2 strip pits 1.2 hectares (3 acres), 1 surface subsidence depression, and 1 caved entry	7,000
Grading access roads and portal areas	960
GRAND TOTAL	\$57,420

The cost of the air seal including mucking, timbering, hitches, footers, masonry blocks, and foam was \$14,800. This cost was high due to the size of the entry, 6.7 meters (22 feet) wide and 1.5 meters (5 feet) high. The average cost of each dry seal was \$5,089.

Shavers Fork, West Virginia Seals

In the spring of 1966 a fish kill was reported at the U.S. Bureau of Sport Fisheries and Wildlife Fish Hatchery at Bowden, West Virginia. This kill was reportedly due to the discharge of acid mine drainage into Shavers Fork. In an attempt to improve the water quality of Shavers Fork, the West Virginia Department of Mines air sealed several small mines which were discharging into Taylor Run, Red Run, and Fishing Hawk, all tributaries to Shavers Fork (99).

A total of twelve air seals and four dry seals were placed in five different abandoned coal mines. A breakdown of the seal placement follows:

		Seals Placed	Date Constructed	Coal Seam
Area 1	Big Knob Mine	6 Air Seals	October, 1967	Sewell
	Savage Mine	1 Air Seal 1 Dry Seal	November, 1967	Sewell
	Summerset-Cambria Mine	1 Air Seal 1 Dry Seal	September, 1967	Sewell
Area 2	Red Run Mine	2 Air Seals 2 Dry Seals	August, 1967	Sewell
Area 3	Fishing Hawk Mine	2 Air Seals	August, 1968	Sewell

All seals were constructed by prison labor under direction of the West Virginia Department of Mines. The mines were sealed by timbering the mine entries, placing solid concrete block seals, and backfilling against the block seal. A diagram of the air seal is shown in Figure 2.3-3.

Beginning in November, 1967, seasonal samples were collected at the seals and analyzed by the U.S. Environmental Protection Agency. A review of four years of data indicates that ion concentration and pollution loads discharging into Shavers Fork did not change to a great extent. Discharges at Big Knob and Savage Mines showed a reduction in mean acid loads of 60 to 80 percent, iron 25 percent, and sulfur 45 to 51 percent (99). This decrease in loads was due to a decrease in discharge and not an improvement in water quality. The results of the effectiveness of these seals was questionable as sufficient background data was not collected, and experienced technicians were not always available to collect samples and measure flows.

Roaring Creek – Grassy Run, West Virginia Seals

The Committee of Public Works of the U.S. House of Representatives issued a report, "Acid Mine Drainage," in 1962 which called for a demonstration program to evaluate mine sealing procedures. In 1964, the first demonstration project site was selected in the Roaring Creek – Grassy Run watershed near Elkins, West Virginia. The project was a cooperative effort between Federal agencies and the state of West Virginia (57, 101).

Work was begun on the air sealing of a large 1,215 hectare (3,000 acre) underground mine. Sealing was to involve sealing subsidence areas and boreholes, backfilling strip mines, water diversion from mines, and the construction of dry and air seals. Due to cost overruns sealing of this mine was never completed and only the south side of the mine was sealed. Eleven air seals were placed in the mine. Subsidence areas over much of the area were not corrected and several entries were not sealed. As a result of the incomplete sealing no reduction in oxygen concentration behind the seals was observed and there was little if any reduction in pollution load discharging from the mine (60).

A small (several acres) isolated mine, RT 9-11, was completely sealed during the Elkins project. Sealing work involved the placement of an air seal, the sealing of one portal with clay, and the regrading of 31.6 hectares (78 acres) of surface mined area.

Within two months after sealing the oxygen content in the mine dropped to 9.1 percent. The oxygen content varied between 7.0 and 10.8 percent until the fourth quarter of 1969 when the level raised to near 15 percent. It has remained near that level since (57, 60).

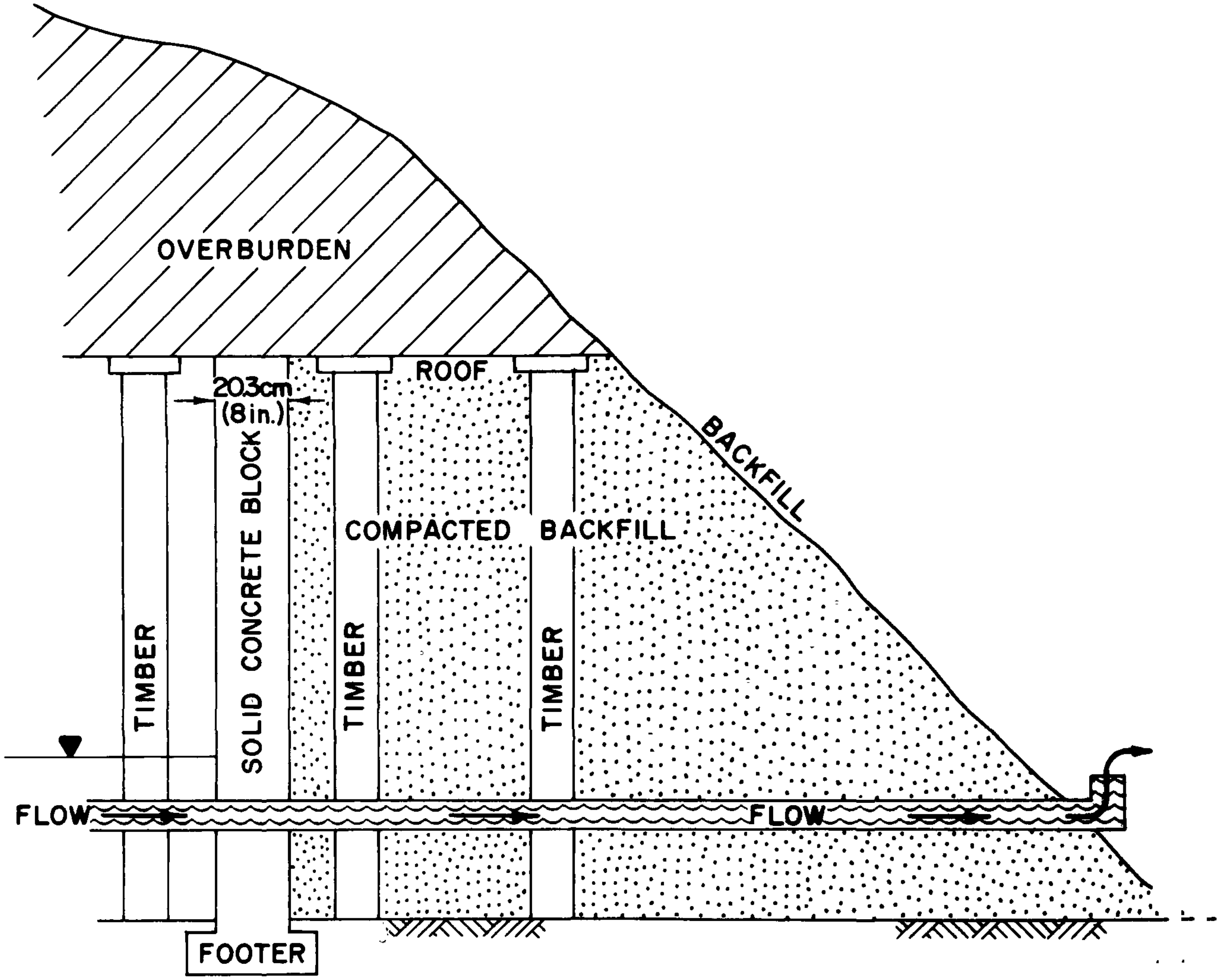


FIGURE 2.3-3

TYPICAL AIR SEAL

SHAVERS FORK, WEST VIRGINIA

(Adapted from Ref. 99)

Analysis of samples collected at mine RT 9-11 are shown in Table 2.3-2. A reduction in the concentration of acidity, iron, and sulfate has been observed. However, due to an increase in flow, there has been little reduction in pollution load discharging from the mine.

A total of 55 masonry seals (43 dry and 12 air) were constructed during the Roaring Creek – Grassy Run Project. A cost breakdown of the 55 seals follows (101):

Total Direct Labor	$ 65,949
Total Equipment	50,729
Total Indirect Cost	110,913
TOTAL	$227,591

Direct and indirect costs included clean-up of mine entrance, temporary and permanent timbering, concrete footers, concrete block walls, urethane foam coating, 75 percent overhead and 6 percent general and administrative.

The average cost per seal for the construction of the 55 seals was $4,138. Direct labor and equipment costs per seal averaged $1,199 and $922, respectively. An analysis of three air seals constructed shows that direct costs ranged between $3,128 and $5,032 and the average cost per air seal was $4,076.

EVALUATIONS AND RECOMMENDATIONS

Although air sealing has been performed since the early 1930's, there has not been much documentation of the effectiveness of this sealing technique. The evaluation of many air sealing projects has been based upon limited or insufficient data collected before and after sealing. The long term effectiveness of air sealing in controlling mine drainage pollution from abandoned underground mines has not been documented.

The most extensive air sealing project was the 1930's sealing program administered by the U.S. Public Health Service. However, no funds were provided for an evaluation of the project effectiveness or for routine inspection and maintenance of the seals. Many of these seals have been destroyed and many of the sealed openings are now discharging large quantities of pollution. A review of the more recent sealing projects reveals that there is a general disagreement among the various investigators as to the effectiveness of air sealing in controlling pollution discharged from abandoned underground mines.

Table 2.3-2

Analysis of Mine Water Samples
Mine RT 9-11

		Oxygen Within Mine Percent	Acidity $CaCO_3$ mg/l	pH[b]	Iron mg/l	Sulfate mg/l
<u>Before Sealing</u>[a]						
Mean		21	591	2.8	93	1,035
Minimum		--	438	3.1[c]	48	710
<u>After Sealing</u>						
Year	Quarter					
1967	4	9.1	359	3.2	85	797
1968	1	8.3	325	3.2	74	686
1968	2	10.8	334	3.2	68	702
1968	3	7.0	344	3.2	72	708
1968	4	7.4	265	3.2	72	627
1969	1	--	350	3.2	63	645
1969	2	--	339	3.2	91	656
1969	3	7.0	376	2.9	62	717
1969	4	14.8	327	3.1	71	678
1970	1	15.0	263	3.1	74	603
1970	2	12.0	310	2.9	49	628
1970	3	--	297	3.1	72	845
1970	4	13.3	294	3.3	83	606
1971	1	15.0	249	3.2	56	488
1971	2	15.3	248	3.2	47	508
1971	3	14.0	276	3.0	56	460
1971	4	--	326	2.9	73	535
1974[d]	-	--	370	3.1	10	410

[a]March 1964 - August 1967

[b]Median Value

[c]Maximum Value

[d]Samples collected August, 1974 by EPA Personnel

A majority of the air sealing projects have been performed in the eastern coal fields. The success of these projects has depended upon the ability to locate and effectively seal all air and water passages to the underground mine system. After completion of the sealing operation, new air passages may develop as a result of roof collapse and fracturing of overlying strata. Air sealing may also produce a pressure gradient between the mine and outside atmosphere which results in air flow into and out of the underground mine.

Although air sealing does not appear to be a suitable method of controlling mine drainage pollution in the eastern coal fields, this technique may be applicable to mines having thick, unfractured overburden and tight outcrops. Under such conditions a reduction in the oxygen concentration of the mine atmosphere and an improvement of water quality could be expected. However, the long term effectiveness of air sealing will depend upon the method of seal construction and the condition of the natural mine system.

The costs of constructing air seals will range from $4,000 to $6,000 per seal. The seals should be placed on concrete footers, hitched into the side and roof of the openings, and coated to protect against acid attack. Timbering of the opening should be performed to keep the weight of the roof off of the seal. Factors affecting the cost of construction will include the size and condition of the mine opening, method of construction, and the amount of equipment, materials, and labor required.

REFERENCES

2, 4, 5, 9, 18, 20, 21, 27, 32, 36, 39, 42, 52, 56, 57, 60, 61, 62, 69, 71, 73, 74, 75, 99, 101, 111, 118, 127

2.4 HYDRAULIC SEALS

Hydraulic sealing of abandoned underground mines creates an impoundment in which mine seals and the mine perimeter serve as an underground dam. The success of sealing will depend upon the ability of the entire dam structure to withstand water pressure and control mine water seepage. Properly designed and constructed hydraulic seals are capable of withstanding pressures in excess of 300 meters (1,000 feet) (39). However, mine seals form only a small portion of the underground dam. The mine perimeter which forms most of the impoundment determines the feasibility and practical limits of inundation.

Mineral barriers along the mine perimeters are often the weakest link in the underground impoundment. During active mining, barriers are left along mineral outcrops and between adjacent mines. These mineral barriers are of non-uniform thickness and frequently are unable to withstand water pressure. Physical failure of these barriers can occur; however, more often, seepage resulting from increased water pressure prevents significant increases in water level.

The first step in hydraulic sealing is to determine the ability of the natural mine system to impound water. This will require the collection and evaluation of available pertinent mine site data including (127):

1. Mine Maps
2. Hydrogeologic Data
3. Borehole Logs
4. Outcrop Lines
5. Mineral Structure Contours
6. Aerial Photogrammetric Mapping

This data will assist in identifying hydraulically unsound areas such as surface mined outcrops, subsidence holes, boreholes, fractured mineral barriers, and other highly permeable zones that may allow water to discharge.

The feasibility of inundating the mine is determined by plotting the expected limits of the mine pool on a mine map. All areas where water pressure will be exerted are identified and hydraulically evaluated to determine their ability to withstand the maximum expected pressure. The ability of hydraulically unsound areas to impound water may be improved by sealing or grouting. However, such remedial measures may be technologically or economically impractical. If the natural mine system severely limits the feasibility of mine inundation, the desired mine pool elevation will have to be lowered or the sealing project abandoned.

Mine seals can be constructed in a variety of ways, using many different types of materials. Seals can be placed to plug shaft, drift and slope entries, boreholes, subsidence areas, and similar discharging openings. The seals must have sufficient internal strength to withstand water pressure and should be anchored into the mine opening. Leakage often occurs around seals due to the fractured and unstable condition of the strata surrounding the seal. As previously mentioned, sufficient internal strength is easily obtained. Anchoring of the seal and controlling leakage will be much more difficult.

Mine sealing is a dangerous operation requiring the knowledge and judgment of persons having expertise in mining, engineering, and hydrogeology. Sudden discharges resulting from the failure of a seal or the natural mine system can have devastating downstream effects upon human life, property, and aquatic organisms. Mine sealing decisions related to seal design and construction, therefore, require technical evaluation by competent individuals.

The build up of excessive water pressure within a sealed mine can be controlled by drilling an emergency discharge borehole into the mine. The borehole would be drilled from a surface elevation equal to the maximum allowable mine pool elevation. As the mine pool approaches the maximum level, gravity discharge through the borehole prevents further water level increase. The borehole must be capable of discharging water at a rate equal to the maximum expected inflow to the mine pool. This emergency discharge system requires little maintenance and supervision. The borehole should be cased its entire length and protected at the surface to insure that it remains open and operational.

A mine pool drawdown system should also be included in the mine sealing plan. Theis system would allow the mine to be completely drained in emergency situations, or in the event that the mine is reopened. During mine sealing, a pipe should be constructed through a mine seal, preferably at the lowest mine entry. The pipe is equipped with a manual valve on the outby side of the seal. When the valve is opened water discharges from the mine and the mine pool can be lowered to its pre-sealing level.

Various types of hydraulic seals have been recently demonstrated in the United States. A majority of this sealing work has been performed on abandoned underground coal mines in the East, as part of Federal and state acid mine drainage research and demonstration programs. Few of these sealing techniques have been completely successful in controlling mine drainage discharges. In some instances, the lack of success has been due to failure of the seal, but in most cases is attributable to the condition of the natural mine system.

A major problem encountered during the various sealing efforts has been the inability to anchor the seal into the roof, ribs and floor of the mine. Leakage around the seal and through adjacent strata has often prevented significant increase of the mine pool. Curtain grouting adjacent to the mine seal has been partially successful in controlling seepage through highly permeable zones. The installation of grout curtains is presently required in many mine sealing projects.

The hydraulic sealing techniques described in this section include: double bulkhead, single bulkhead, permeable limestone, gunite, clay, grout bag, shaft, gel material, and regulated flow.

REFERENCES

2, 19, 27, 39, 42, 45, 46, 47, 58, 62, 72, 81, 111, 112, 127

2.4-1 DOUBLE BULKHEAD SEAL

DESCRIPTION

This seal is constructed by placing two retaining bulkheads in the mine entry and then placing an impermeable seal in the space between the bulkheads. These seals have been successfully demonstrated in both accessible and inaccessible mine entries (32, 127).

The front and rear bulkheads are placed to provide a form for the center seal. This seal is formed by injecting concrete or grout through the front bulkhead, if accessible, or through vertical pipes from above the mine. Bulkheads have been constructed with quick setting cement and grouted coarse aggregate.

Grouting of the bulkheads and center seal may be required to prevent leakage along the top, bottom, and sides of the seal. Curtain grouting of adjacent strata is often performed to increase strength and reduce permeability.

IMPLEMENTATION

Quick Setting Bulkheads

The Halliburton Company under contract to the Federal Water Quality Administration (now Environmental Protection Agency) developed a method for constructing double bulkhead seals in accessible mine openings. The front and rear bulkheads were constructed by preparing two separate slurries and mixing them together as they were pumped into the mine. The slurries react to give a viscous quick setting material which is able to support its own weight as it builds (47). The composition of the slurries was as follows:

Slurry No. 1	Slurry No. 2
Water – 3,293 liters (870 gal)	Water – 3,974 liters (1,050 gal)
Cement – 180 sacks	Bentonite – 318 kilograms (700 lb)
	Sodium Silicate – 1,949 liters (515 gal)

In February, 1969 a quick setting double bulkhead seal was constructed in Opening No. 5 of Mine 62-008 near Clarksburg, West Virginia. This is a small, 8.1 hectare (20 acre), abandoned drift mine in the Pittsburgh coal seam. Prior to sealing, water was discharging at a rate of 0.16 liters per second (2.5 gpm). Analysis of the water indicated that the discharge had a pH of 2.8, acidity of 2,260 mg/l, and total iron of 600 mg/l (98).

Front and rear bulkheads were constructed by hydraulically injecting the quick setting slurry. The void between the bulkheads was filled by pumping Halliburton Light Cement through grout pipes in the front bulkhead. A section view of the completed seal is shown in Figure 2.4-1-1.

Leakage from this seal did not occur until September, 1970. Samples of this discharge were collected and analyzed between September, 1970 and June, 1971. The mean flow rate during this period was 0.01 liters per second (0.22 gpm). With the exception of acidity which decreased, ion concentrations in the discharge were about the same as before sealing. The minimum flow through the seal did reduce the pollution load for all parameters by better than 90 percent. The maximum hydrostatic head established behind the seal was 170 centimeters (67 inches) (98).

The total cost of constructing this seal was $9,499. This included $894 for site preparation, $3,872 for materials, and $4,683 for equipment and operators.

A similar double bulkhead seal was constructed in the drift entry of an abandoned deep mine in the Kittanning coal seam (Mine RT 5-2) near Coalton, West Virginia. Prior to sealing in September, 1969, the mine was discharging at an average rate of 4.7 liters per second (74 gpm) (47, 98).

The rear bulkhead was constructed with quick setting cement material just in front of an existing air seal. Grout pipes and AASHO No. 67 limestone were placed in front of the rear bulkhead. The front bulkhead was then constructed of the same material as the rear bulkhead. The limestone aggregate was stablized and made impermeable by grouting with Halliburton Light Cement.

The completed seal successfully eliminated flow from the mine entry. Seven days after work completion the head behind the seal was 0.98 meters (3.22 feet). However, leakage was observed coming through an unknown opening to the right of the seal. Remedial work involved placing a permeable aggregate seal in this opening. As of October, 1969 the head behind the double bulkhead seal appeared to be stabilizing at approximately 1.2 meters (3.78 feet) (47).

A physical inspection was made of this seal in September, 1971. There was some flaking off of the front bulkhead, but no seepage was observed. The mine entry was in good condition as the portal had been timbered prior to sealing.

The total cost of constructing this seal was $9,463. This included materials, equipment, and $1,079 for site preparation.

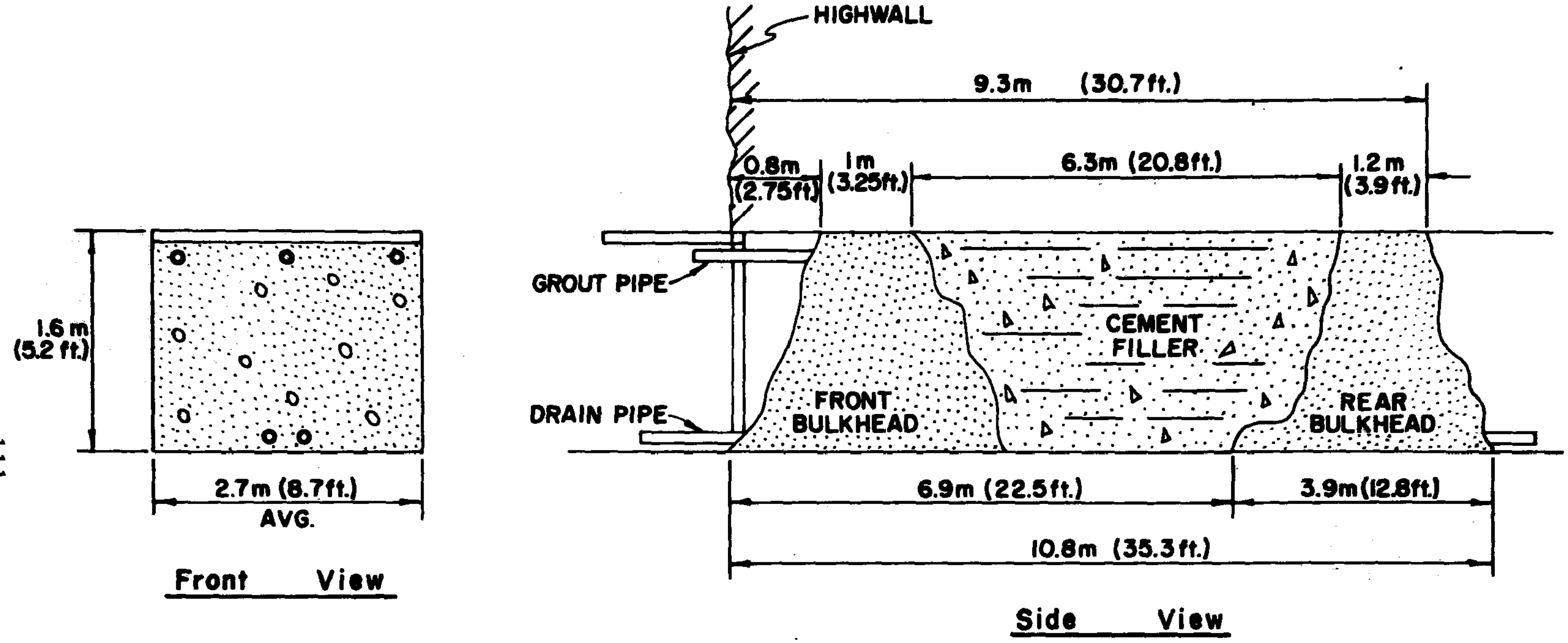


FIGURE 2.4-1-1

QUICK SETTING DOUBLE BULKHEAD SEAL

CLARKSBURG, W.VA.

(Adapted from Ref. 98)

Grouted Aggregate Seals

The grouted aggregate double bulkhead seal was developed for sealing inaccessible mine entries in Moraine State Park, Butler County, Pennsylvania. This area has been extensively surface and underground mined for the Middle Kittanning coal seam. In May, 1967, the Pennsylvania Department of Mines and Mineral Industries engaged Gwin Engineers, Inc. to perform extensive engineering and geologic investigations and recommend a mine drainage abatement program. The rehabilitation project was to restore the aesthetic appearance of the area and prevent mine drainage pollution of the proposed 1,306 hectare (3,225 acre) Lake Arthur (95).

The engineering report recommended the construction of 60 mine seals at an estimated cost of $15,000 per seal. A contract for sealing was awarded in 1969 and a total of 65 double bulkhead seals was constructed between February, 1969 and August, 1971. This work, Pennsylvania Project SL 105-3, was performed by B. H. Mott and Sons, Inc.

Front and rear bulkheads were constructed by placing coarse, dry aggregate through vertical drill holes. The bulkheads were then grouted to form solid front and rear seals. Water was pumped from the void between the bulkheads and concrete was poured to form a center plug. At each mine entry, curtain grouting of adjacent strata was performed for a minimum of 15 meters (50 feet) on both sides of the seal (32, 127). A construction drawing of this type of deep mine seal is shown in Figure 2.4-1-2.

The mine sealing program was successful in reducing pollution discharges from abandoned mines in the park. The hydraulic seals were constructed in the openings of 19 mines. After sealing, the discharges from these mines were as follows (43): eight mines had no flow; one mine had an average flow less than 0.06 liters per second (1 gpm); eight mines have reduced flow rates; one mine has the same flow rate; and one mine increased from 0.06 to 0.13 liters per second (1 to 2 gpm). As a result, flow rates have been reduced from 9.2 to 3.6 liters per second (146 to 57 gpm).

Water levels within the mines are fluctuating within a range of 0.3 to 1.5 meters (1 to 5 feet) which varies with precipitation and infiltration. The head behind the seals has ranged from less than 0.3 meters (1 foot) to a maximum of 11.6 meters (38 feet).

The total cost of constructing the seals and performing related grouting work was $1,266,213 (43). The costs per seal ranged from $8,308 to $58,437, with an average cost of $19,480 per seal. An average of 155 kilograms per day (341 lb/day) of acid was abated by the sealing program. This equals a cost effectiveness of $8,169 per kilogram per day ($3,713 per lb/day) of acid abated.

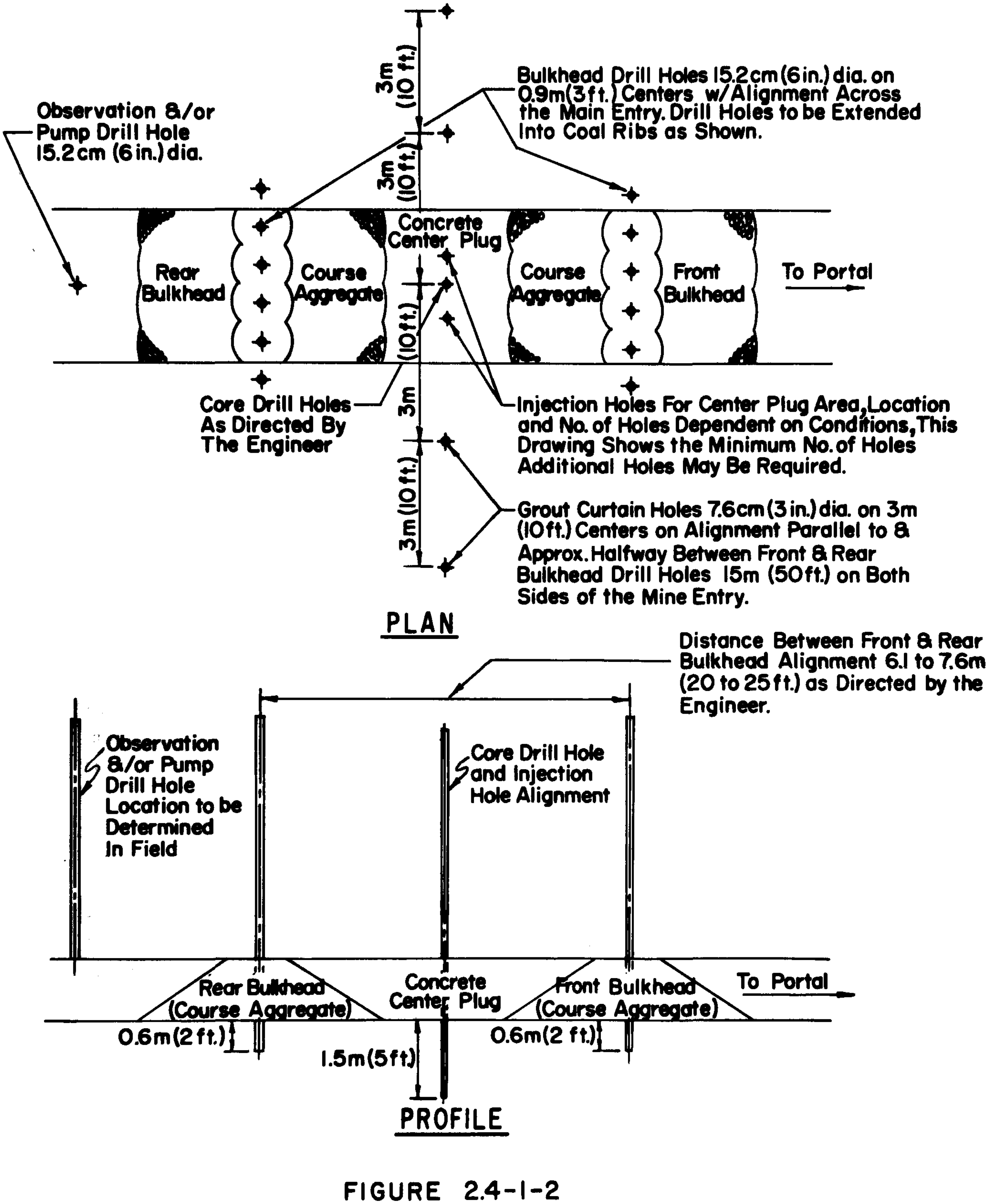


FIGURE 2.4-1-2

CONSTRUCTION DRAWING OF DEEP MINE SEAL

(Adapted from Ref. 43)

Curtain grouting of adjacent strata represented 60.6, percent of the total cost of the Moraine State Park project. Due to the inability to determine subsurface conditions, the quantities required for curtain grouting were difficult to estimate. Estimated contract costs and the actual costs for grouting were as follows (32):

	Estimated Contract Costs	Actual Costs
Total Curtain Grouting	$517,750.00	$819,745.60
% Total Project Cost	46.50	60.60
Cost/LM Drilled	24.05	26.80
(LF Drilled)	(7.33)	(8.17)
Cost/LM Curtain	169.82	262.47
(LF Curtain)	(51.76)	(80.00)

The double bulkhead grouted aggregate seal has been used in various main drainage abatement projects performed in Pennsylvania as a part of that State's Operation Scarlift Program. Nine of these seals were recently constructed under Project SL 110-1C, Stone House Area, Brady Township, Butler County (84). Work on this project was completed by the contractor, Allied Asphalt Company, Inc. in September, 1974. The estimated cost of construction including grouting the center concrete plug and curtain grouting adjacent strata was $11,740 per seal. The actual costs of construction were $17,881 per seal. A listing of the contract estimates is presented in Table 2.4-1-1.

EVALUATION AND RECOMMENDATIONS

The double bulkhead method of sealing mine entries has been successful in flooding abandoned underground mines and withstanding relatively large amounts of hydrostatic pressure. A majority of grouted aggregate seals constructed since 1969 have been placed in abandoned underground coal mines in Pennsylvania. These sealing projects are funded as a part of Operation Scarlift, Pennsylvania's $500 million bond issue for a Land and Water Conservation and Reclamation Fund. Demonstration of the quick setting bulkhead seals has been limited to projects performed by the Halliburton Company in West Virginia. Implementation of double bulkhead seals in abandoned underground mines outside the eastern coal fields has not been documented.

The maximum hydrostatic head established behind this seal type has been approximately 12.2 meters (40 feet). Properly designed and constructed seals should

Table 2.4-1-1

Contract Estimates
Mine Sealing - Stone House Area
Butler County, Pennsylvania

Description	Quantity	Estimated Cost
Mine Sealing Bulkhead Construction		
a. Drilling 15.2 cm (6 in) Holes	2,438 LM @ $9.84/LM (8,000 LF)($3.00/LF)	$ 24,000
b. Concrete Aggregate	544 metric tons @ $11.03/metric ton (600 tons)($10.00/ton)	6,000
c. Concrete	268 cu m @ $39.24/cu m (350 cu yd)($30.00/cu yd)	10,500
d. Borehole Camera Survey	15 days @ $300/day	4,500
Observation Drill Holes		
a. Drilling 15.2 cm (6 in) Holes	91 LM @ $9.84/LM (300 LF)($3.00/LF)	900
b. Casing Left in Hole	46 LM @ $6.56/LM (150 LF)($2.00/LF)	300
Pressure Grouting & Exploratory Drilling		
a. Drilling	2,134 LM @ $9.84/LM (7,000 LF)($3.00/LF)	21,000
b. Cement for Grouting	5,000 sacks @ $4.00/sacks	20,000
c. Fly Ash for Grouting	522 metric tons @ $22.05/metric ton (575 tons)($20.00/ton)	11,500

Table 2.4-1-1 (cont.)

Description	Quantity	Estimated Cost
d. Sand for Grouting	1.8 metric tons @ $33.08/metric ton (2 tons)($30.00/ton)	$ 60
e. Admixture for Grouting		
Grout #1	45.4 kg @ $6.61/kg (100 lb)($3.00/lb)	300
Grout #2	379 liters @ $0.79/liter (100 gal)($3.00/gal)	300
Grout #3	379 liters @ $0.79/liter (100 gal)($3.00/gal)	300
f. Grout Pressure Testing	50 hours @ $30.00/hour	1,500
g. Grout Connection	150 @ $10.00 each	1,500
h. Core Drilling Center Plug	152 LM @ $19.69/LM (500 LF)($6.00/LF)	3,000
	TOTAL CONTRACT ESTIMATE February, 1973	$105,660
	Actual Costs as Completed September, 1974	$160,930

be capable of withstanding greater pressures. The feasibility of sealing most often will be limited by the ability of the natural mine system to withstand water pressure and prevent water seepage (See Section 2.4).

Technical specifications for the construction of grouted aggregate bulkheads frequently require curtain grouting of adjacent strata to decrease permeability. Grout holes are usually drilled on 3 meter (10 foot) centers on both sides of the seal. Massive leakage, however, can occur along the perimeter of the seal. Due to the settling of concrete and aggregate materials, it is difficult to form a good seal at the mine roof. The sides, top, and bottom of the seal should be well grouted to insure an effective seal around the bulkhead perimeter. Curtain grout holes should then be spaced to insure that the entire space between holes is grouted.

Seals placed in accessible openings may be anchored by chipping a keyway in the perimeter of the mine entry prior to injecting grout or concrete for the center plug. Quick setting bulkheads may be constructed so that they fit tighter in the mine as water pressure increases. The roof, sides, and floor should be cut to form a wedge shape prior to pneumatic placement of the quick setting cement slurry. Sufficient anchoring will allow the seals to withstand a greater hydrostatic head and will decrease leakage around the seal perimeter. Grouting of the seal perimeter and adjacent strata should also be performed.

An emergency discharge borehole should be drilled into the mine to allow gravity discharge when the mine pool approaches its maximum allowable level. A pipe with valve should be constructed through a seal near the lowest elevation of the mine to allow drawdown of the mine pool (See Section 2.4).

The cost of constructing double bulkhead seals will depend upon the size of the opening, the amount of material placed, the expected hydrostatic head, grouting requirements around the seal perimeter, and the amount of site preparation required. Inaccessible seal costs will include drilling required to locate the mine opening and place the sealing materials.

Grouted aggregate seals including curtain grouting will normally range in cost from $10,000 to $30,000 per seal. The amount of curtain grouting required will depend upon subsurface conditions at each individual work site. In some instances the average costs for bulkhead construction and related grouting work may exceed $50,000 per seal. Bids were opened on December 10, 1974 for the construction of two double bulkhead seals under Operation Scarlift Project SL 108-3-1, East Branch Clarion River, Sergeant Township, McKean County, Pennsylvania. The engineer's estimate of unit prices for bulkhead construction, excluding grouting were:

Description	Approximate Quantities	Unit Price Engineers Estimate
Drilling 15.2 cm (6 in) Holes	640 LM (2,100 LF)	$13.12
Coarse Aggregate for Bulkheads	190 metric tons (210 tons)	$49.61 45.00
Class "C" Concrete for Center Plug	38.2 cu m (50.0 cu yd)	$71.93 55.00

Quick setting double bulkhead seals in accessible entries should range between $15,000 and $18,000 per seal excluding grouting. Grouting around the seal perimeter and curtain grouting of adjacent strata may result in construction costs exceeding $20,000 per seal.

REFERENCES

32, 38, 40, 41, 43, 44, 47, 77, 84, 95, 98, 100, 127

2.4-2 SINGLE BULKHEAD SEAL

DESCRIPTION

Single bulkhead seals are generally constructed of poured concrete, quick setting cement material, or grouted aggregate. They can be constructed of other materials, such as masonry block or brick. This type of seal has been demonstrated in both accessible and inaccessible mine entries (45, 127).

Single bulkheads constructed of poured concrete were used to flood abandoned sections of underground coal mines as early as 1926 (45). Such seals were capable of withstanding water pressures as great as 49,217 kilograms per square meter (70 psi), or 49.2 meters (161.5 feet) of water.

Grouted aggregate bulkheads are constructed by placing coarse, dry aggregate in the mine either directly from within the mine opening or through vertical boreholes. The aggregate is then grouted with a quick setting cement slurry to form a solid aggregate plug (127).

Single bulkhead seals have also been constructed in accessible entries by preparing two slurries and blending them together as they are pumped into the mine. The slurries react to give a viscous quick setting cement material which is able to support its own weight as it builds. The completed seal forms a solid plug in the mine opening (47).

The effectiveness of single bulkhead seals most often will depend upon the ability to control leakage around the seal perimeter. Grouting along the top, bottom, and sides of the bulkhead may be required. Curtain grouting of adjacent strata is often performed to increase strength and reduce permeability.

IMPLEMENTATION

Concrete Bulkheads

A 1937 report (45) described the successful and extensive water sealing program at three mines in the midwest coal fields of the United States. These three mines were the Saxton and Dresser, near Terre Haute, Indiana, and the Hegler, near Danville, Illinois. All three of the mines had water conditions that required sealing of abandoned sections. Each of these mines reportedly had over a hundred single bulkhead seals.

Two types of seals, primary and secondary, were constructed in these mines. Primary seals were designed to withstand hydrostatic heads in excess of 49.2 meters (161.5 feet). Secondary bulkheads were designed as temporary, low pressure seals for a safeguard against the sudden break of other seals. Secondary bulkheads were constructed in several different ways of concrete, blocks, and brick, in both straight and curved shapes against the pressure side. The design of a secondary concrete block bulkhead used at the Saxton Mine is shown in Figure 2.4-2-1.

Primary bulkheads were normally constructed of poured or quick setting concrete. These bulkheads were hitched into the ribs and roof to solid unfractured coal. When the floor was of clay, the bulkhead hitching was sunk through to solid stratum. The top of the entry was timbered for a distance of 6 to 12 meters (20 to 40 feet) to prevent roof falls.

Grout pipes were often constructed in the bulkhead for pressure grouting of the seal perimeter. A small diameter pipe for gas testing and water pressure measurements, and a larger pipe 7.6 to 15.2 centimeters (3 to 6 inches) with a strain inside and a gate valve outside were also placed through the seal. The larger pipe was used for draining the flooded section. The design of two primary concrete bulkheads placed in the Saxton mine are shown in Figures 2.4-2-2 and 2.4-2-3.

The costs of constructing these seals will, of course, vary with each installation. At the Dresser Mine, the cost of constructing secondary or low pressure seals in 1937 ranged from $149 to $162 per seal. Based on values of the Engineering News Record Construction Cost Index, the costs of these seals as of January, 1975 would range from $1,300 to $1,500. In 1935, total labor and material costs for constructing two primary bulkheads (Figure 2.4-2-2) in the Saxton Mine were $589.90. The total volume of material placed in the two seals was 55.3 cubic meters (72.3 cu yd). The cost of constructing these seals as of January, 1975 would be approximately $3,200 per seal.

A single bulkhead concrete seal placed in a copper mine near Butte, Montana reportedly withstood a head of 853 meters (2,800 feet) of water. This seal was placed in a 2.7 by 2.1 meter (9 by 7 foot) crosscut to prevent the flow of mine water from an abandoned mine to the active Anselmo Mine, operated by the Anaconda Company. The sides, top, and bottom of the seal were hitched into rhyolite. Information on the costs of constructing this seal was not available. Plan and section views of the completed seal are shown in Figure 2.4-2-4.

Grouted Aggregate Bulkheads

In December, 1967, grouted limestone aggregate seals were placed in two openings of Mine No. 40-016 near Clarksburg, West Virginia. This mine was a small,

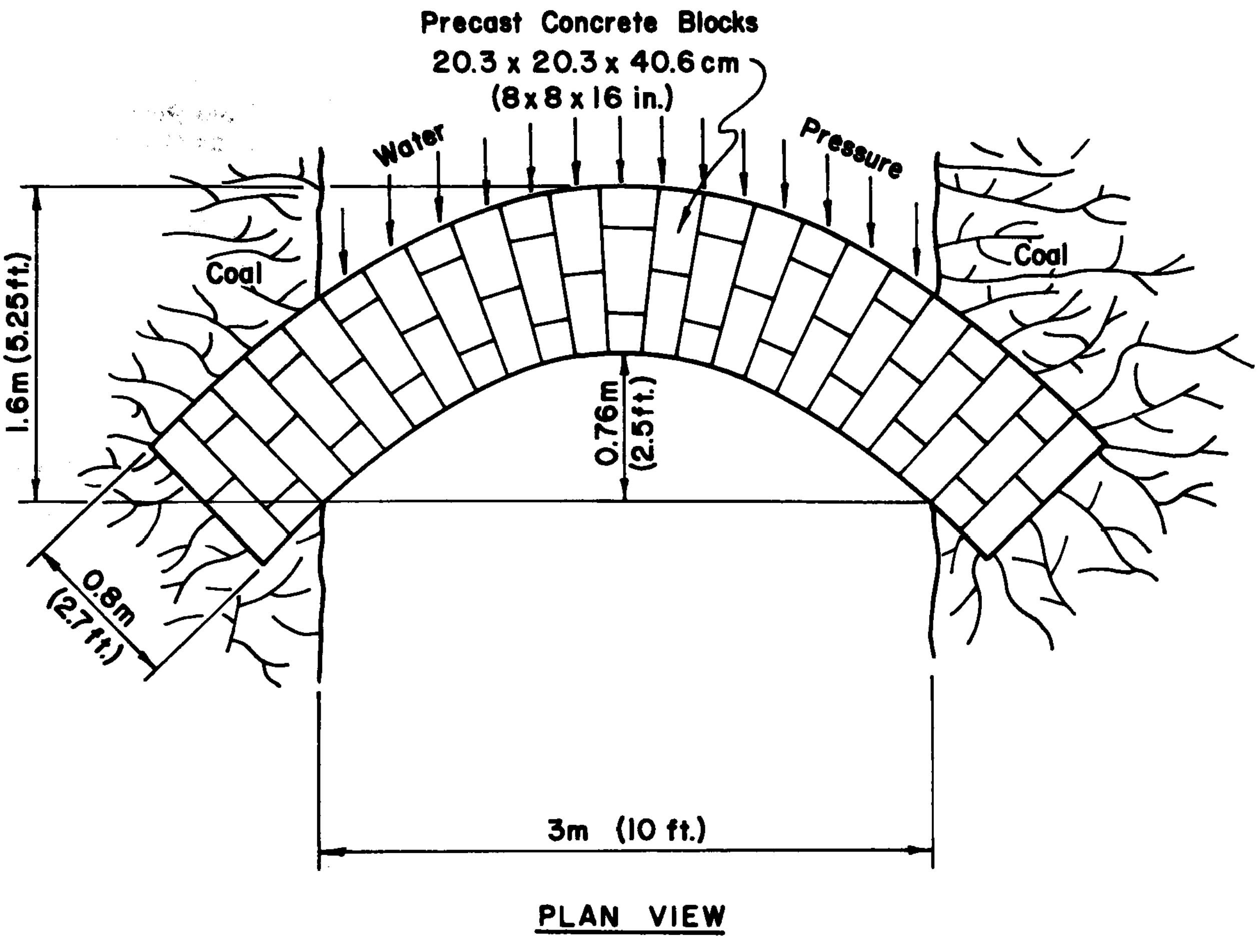


FIGURE 2.4-2-1

SECONDARY CONCRETE BLOCK BULKHEAD, SAXTON MINE

(Adapted from Ref. 45)

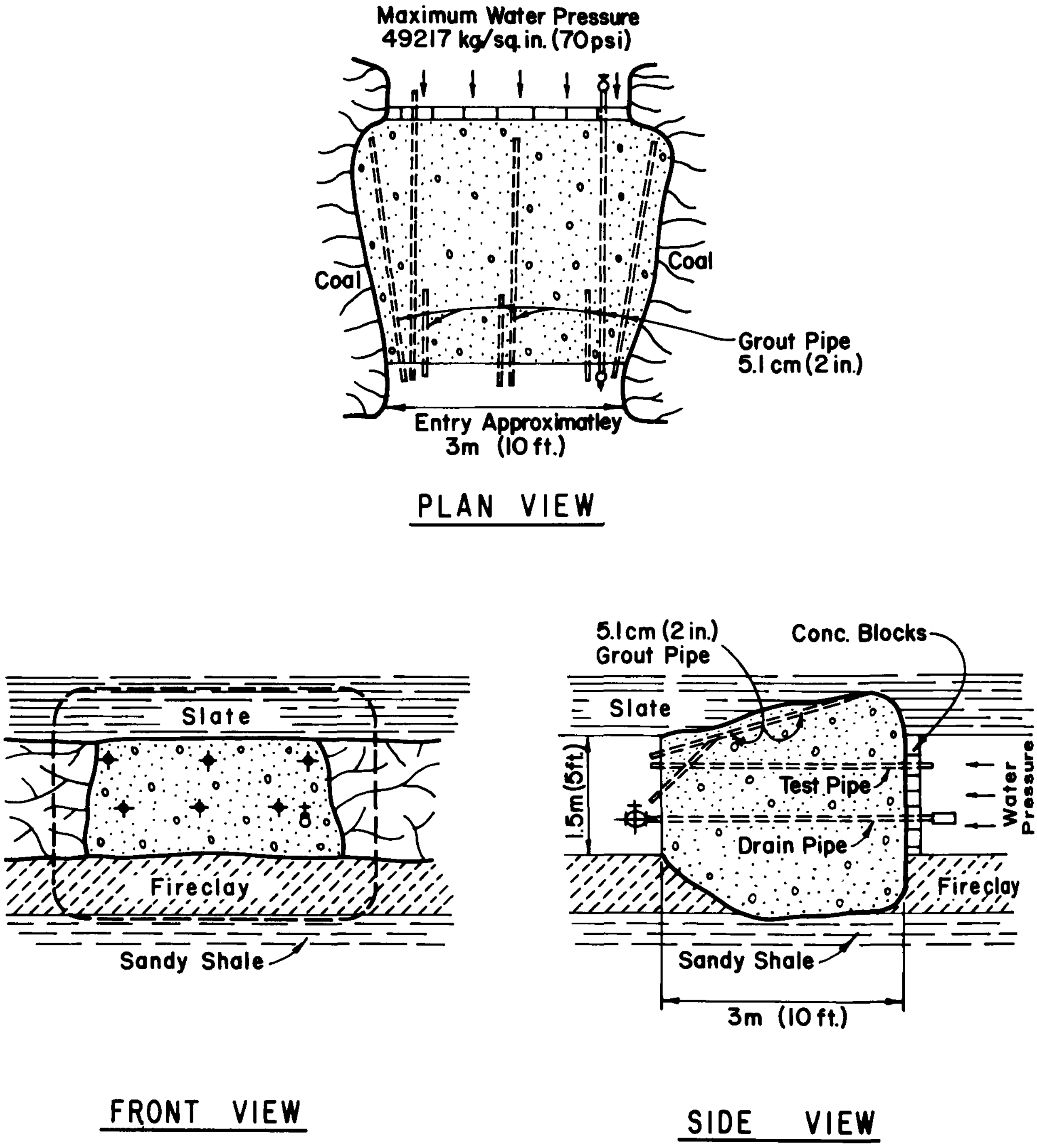
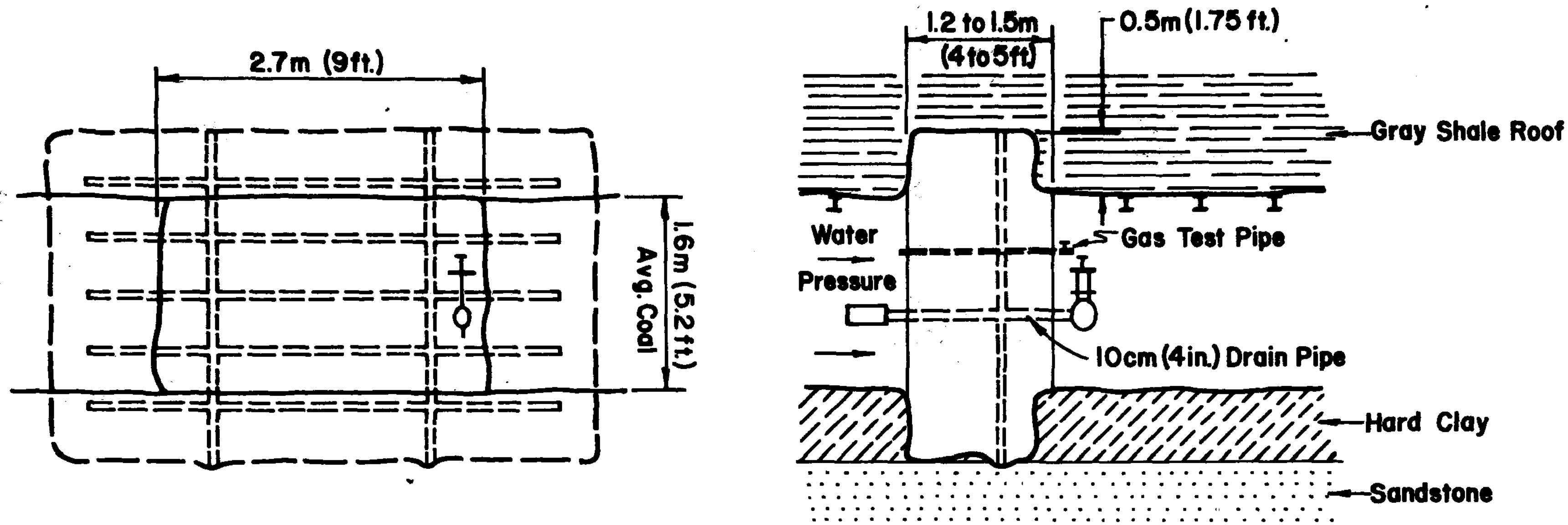


FIGURE 2.4-2-2

DESIGN OF PRIMARY BULKHEAD USED AT SAXTON MINE
(Adapted from Ref. 45)



FRONT VIEW

SIDE VIEW

FIGURE 2.4-2-3

DESIGN OF PRIMARY BULKHEAD USED AT SAXTON MINE
(Adapted from Ref. 45)

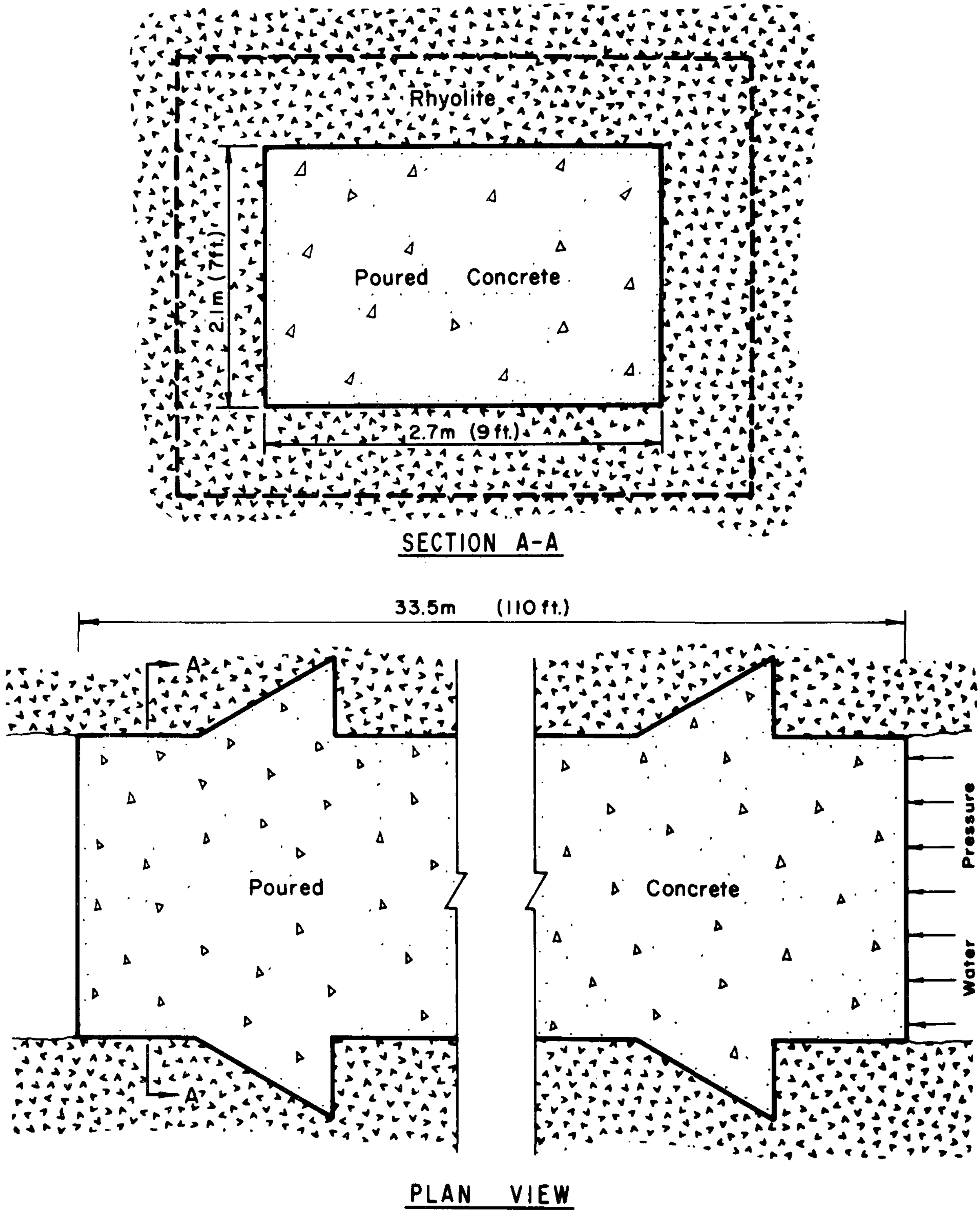


FIGURE 2.4-2-4

SINGLE BULKHEAD CONCRETE SEAL–BUTTE, MONTANA abandoned drift mine in the Pittsburgh coal seam. Construction of the seals and remedial grouting work were performed by the Halliburton Company (47, 98).

The bulkhead seals were constructed by pneumatically placing 1.9 to 3.8 centimeter (3/4 to 1-1/2 inch) graded limestone in the mine. Each of the openings was about 3.7 meters (12 feet) wide and 2.1 meters (7 feet) high. The aggregate was then grouted by injecting a cement slurry through pipes placed in the mine prior to placing the aggregate. Sealing reduced the discharge from the two openings to about 0.44 liters per minute (7 gpm), a reduction of 85 percent. A typical cross section of the seals placed at the mine is shown in Figure 2.4-2-5.

The perimeter of the seals were grouted in an attempt to further reduce the mine discharge. Holes were drilled on each side of the mine entries at an angle extending through the coal outcrop to a point about midway in the grouted aggregate. Various grout mixtures were then pumped through these holes. The remedial grouting reduced the flow rate from the mine to 0.27 liters per second (4.2 gpm).

After sealing, samples of the mine discharge were periodically collected and analyzed between September, 1968 and June, 1971. During this period, flow from the mine varied between 0.08 and 1.1 liters per second (1.3 to 18 gpm). The hydrostatic head behind the seal ranged from 236 to 290 centimeters (93 to 114 inches). Data collected in 1970 and 1971 showed increased pollution loads over previous years because of increased flow, resulting from massive leakage around the seals (98).

The total cost of the sealing project was estimated to be $17,696, or $8,848 per seal. Itemized costs for constructing the two seals were as follows (32):

Cleaning and Site Preparation	$ 387
Aggregate Placement	
Equipment Rental	3,060
Material – 272 metric tons @ $3.64/metric ton (300 tons) ($3.30/ton)	990
Labor	640
Aggregate Grouting	
Equipment Rental	1,322
Material	3,260
Labor	720

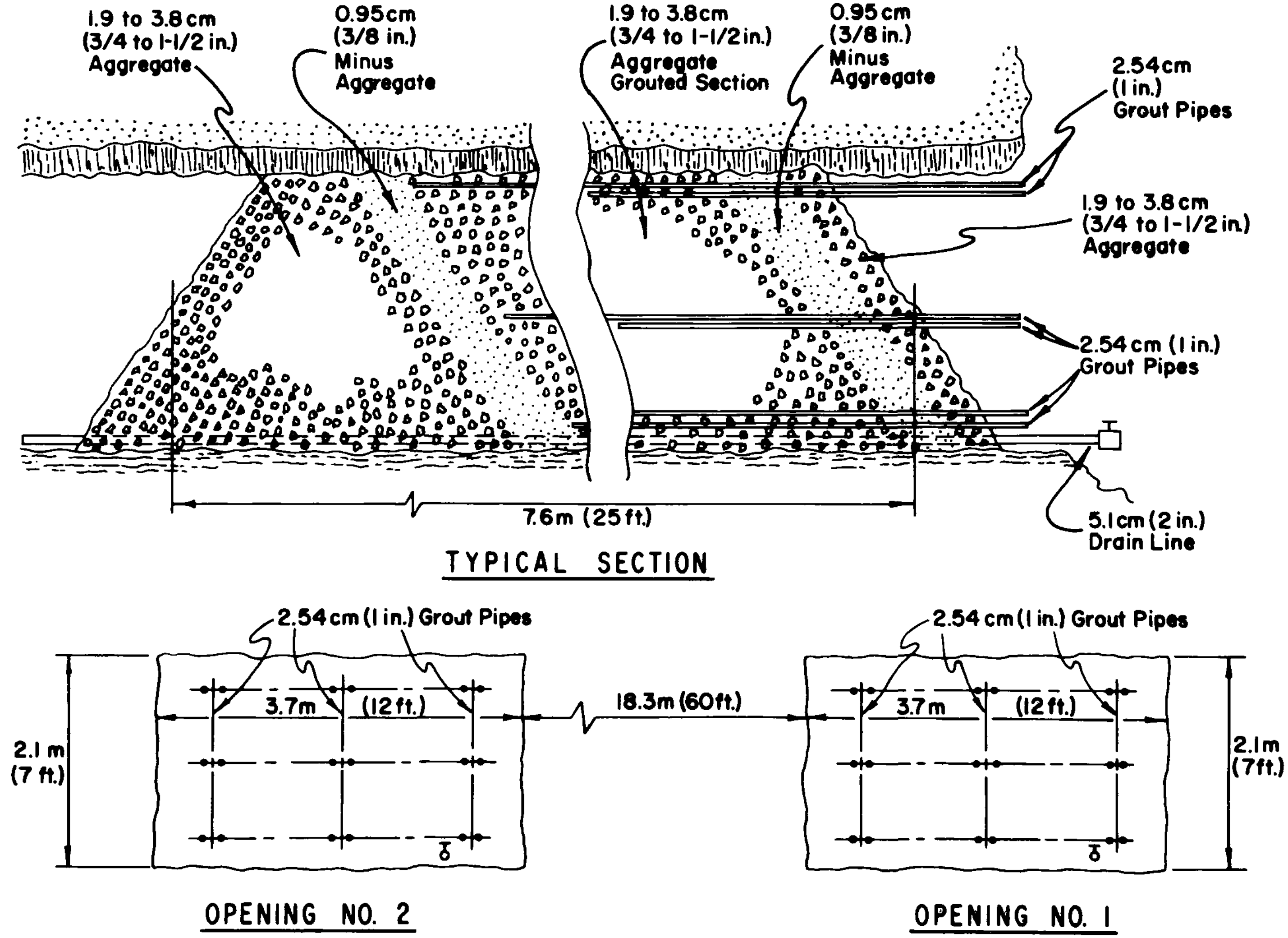


FIGURE 2.4-2-5

GROUTED AGGREGATE BULKHEAD, MINE NO. 40-016
(Adapted from Ref. 47)

Remedial Grouting	
Site Preparation and Restoration	$ 1,310
Equipment, Material and Labor	6,007
TOTAL	$17,696

Quick Setting Bulkheads

In November, 1968, the Halliburton Company under contract to the Federal Water Quality Administration (now Environmental Protection Agency) constructed a quick setting single bulkhead seal in an abandoned mine near Clarksburg, West Virginia. The mine, No. 62-008, was a small drift mine located in the Pittsburgh coal seam. The bulkhead was placed in the main portal, Opening No. 4, which was approximately 3.6 meters (12 feet) wide and 1.5 meters (5 feet) high (47, 98).

The bulkhead was constructed by preparing two slurries and mixing them together as they were pumped into the mine opening. The slurries react to give a viscous quick setting material which is able to support its own weight as it builds. The composition of the slurry was as follows:

Slurry No. 1	Slurry No. 2
Water – 3,293 liters (870 gal)	Water – 3,974 liters (1,050 gal)
Cement – 180 sacks	Bentonite – 318 kilograms (700 lb)
	Sodium Silicate – 1,949 liters (515 gal)

A section of the completed bulkhead seal is shown in Figure 2.4-2-6.

Only limited records were kept on the quality of the water discharging from the mine prior to sealing. Water samples collected and analyzed during September and October, 1968 showed the following (98): average discharge – 0.17 liters per minute (2.7 gpm), acidity – 17.7 kilograms per day (39 lb/day), and total iron – 3.7 kilograms per day (8.1 lb/day).

The bulkhead seal successfully eliminated the mine discharge until September, 1969. At this time massive leaks began to occur between the bulkhead and the surrounding coal strata. Water quality records maintained between September, 1969 and June, 1971 showed the mine discharge varied between 0.03 to 2.8 liters per second (0.45 to 44.9 gpm). Due to the increased flow, acid and iron loads (kg/day) increased significantly. During the period after sealing, the hydrostatic head behind the seal remained constant at 251 centimeters (99 inches).

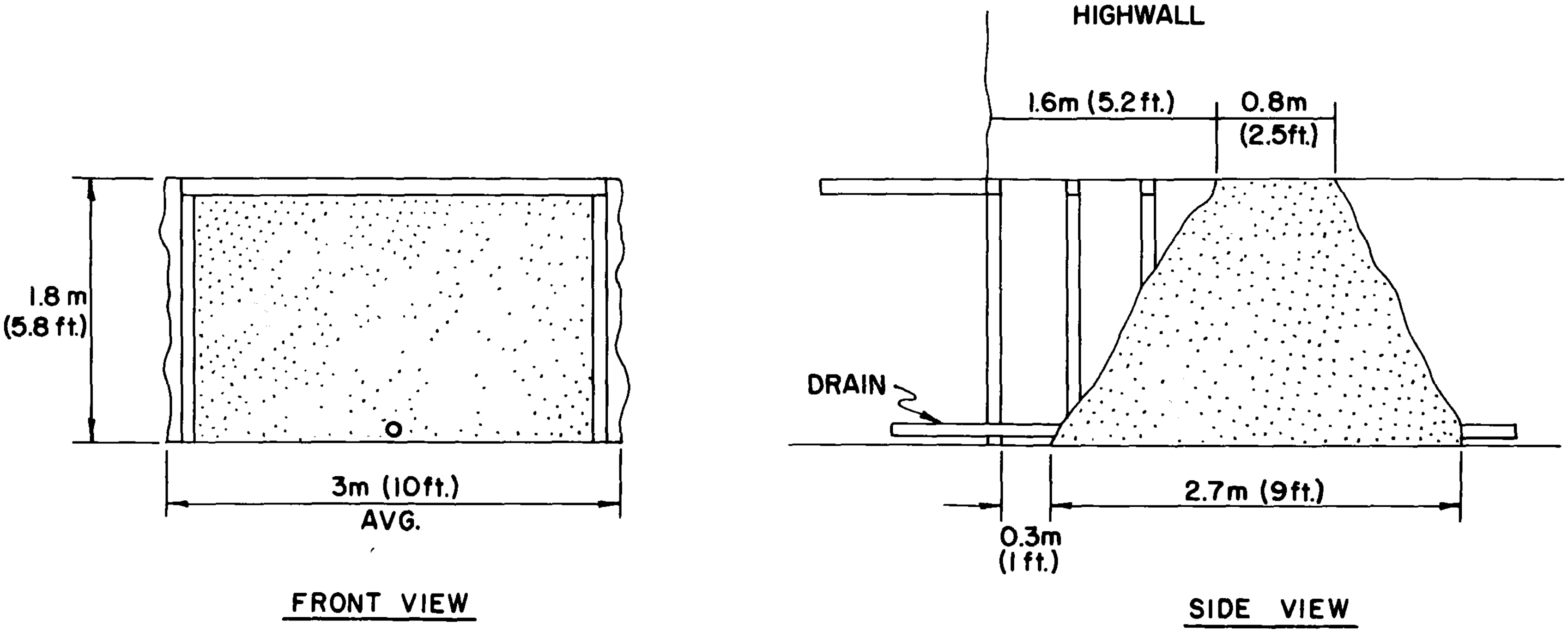


FIGURE 2.4-2-6

QUICK SETTING BULKHEAD SEAL, CLARKSBURG, W.VA.
(Adapted from Ref. 47)

The total cost of constructing the single bulkhead seal in Opening No. 4 was $3,564. This included $647 for site preparation, $1,165 for materials, and $1,752 for equipment and operators (32).

EVALUATION AND RECOMMENDATIONS

The grouted aggregate single bulkhead seal has been demonstrated in both accessible and inaccessible mine entries. Generally, this type seal has been ineffective in controlling mine water discharges. Massive leakage has often occurred due to incomplete grouting of the aggregate or poor anchoring in the mine entry. The maximum head reportedly held by the grouted aggregate bulkhead is approximately 3 meters (10 feet).

Highly permeable zones are often located around the perimeter of the bulkhead. The effectiveness of the seal will depend upon the ability to form a water tight seal along the top, sides, and bottom of the aggregate. Therefore, these areas should be grouted along the total length of the bulkhead. Curtain grouting on both sides of the seal will be required when the adjacent strata is hydraulically unsound.

The use of the grouted aggregate single bulkhead seal should be limited to areas where low pressure is expected. The double bulkhead seal would be better suited for high pressure application (See Section 2.4-1).

The cost of constructing a grouted seal will depend upon the type of opening (accessible or inaccessible), the volume of aggregate placed, and the amount of grouting work required. The cost of a single bulkhead grouted aggregate seal (including curtain grouting 15.2 meters (50 feet) on both sides of the seal) in a 3.7 meter (12 foot) wide by 1.5 meter (5 foot) high mine void at a depth of 15.2 meters (50 feet) would be approximatel $11,000 as follows:

Drill Holes (8)	129 LM @ $13.15/LM (424 LF)(4.00/LF)	$ 1,696
Cement for Grouting	35 sacks @ $4.70/sack	165
Fly Ash for Grouting	35.4 metric tons @ $22.03/metric ton (39 tons)($20.00/ton)	696
Bentonite for Grouting	90.8 kg @ $22.03/kg (200 lb)($10.00/lb)	2,000
No. 2B Stone	27.2 metric tons @ $49.63/metric ton (30 tons)($45.00/ton)	1,350

Curtain Grouting	30.5 LM @ \$163.93/LM (100 LF)(\$50.00/LF)	5,000
	TOTAL	\$10,991

Unit prices for this estimate were based upon the December, 1974 engineer's estimate for constructing two deep mine seals in Pennsylvania under Operation Scarlift Project SL 108-3-1. Total costs of constructing single bulkhead aggregate seals will normally range between \$10,000 and \$20,000 per seal.

Concrete bulkhead seals have been constructed in underground mines since the early 1900's. These seals were used to confine water in abandoned sections of mines, extinguish mine fires, or hold back mine gases. The concept of utilizing these seals to control acid mine discharges from abandoned underground mines has developed in recent years. The hydrostatic head behind a majority of these seals has been less than 61 meters (200 feet). Bulkheads can be designed to withstand water pressures in excess of 305 meters (1,000 feet); however, the maximum hydrostatic head will be limited by the condition of the natural mine system (See Section 2.4).

Bulkheads constructed of poured or quick setting concrete should be anchored by hitching into the roof, sides, and floor of the mine opening. The perimeter of the opening may also be cut to form a wedge shape prior to placement of the concrete. This shape allows the seal to fit tighter in the mine opening as water pressure increases. Sufficient anchoring will allow the bulkheads to withstand a greater hydrostatic head and will decrease leakage around the seal perimeter. Grouting of the seal perimeter and adjacent strata should also be performed.

The total cost of constructing single bulkhead seals will depend upon such factors as size and condition of the opening, expected hydrostatic head, and materials, equipment, and labor required. At \$78.47 per cubic meter (\$60/cu yd) the cost of concrete alone for the seal constructed near Butte, Montana (See Figure 2.4-2-4) would exceed \$15,000. However, the average costs of seal construction including grouting will normally range between \$5,000 and \$10,000 per seal.

Single bulkheads constructed of concrete block are highly susceptible to damage and should not be used where high water pressure is expected. The mine opening should be timbered on both sides of the seal to keep the weight of the roof off the seal. Concrete block wall seals will cost in the range of \$1,500 to \$5,000 each.

Plans and specifications for sealing abandoned underground mines should include provisions for an emergency discharge borehole to allow gravity discharge when the mine pool approaches its maximum allowable level. A pipe should be constructed through at least one bulkhead to allow drawdown of the mine pool (See Section 2.4).

REFERENCES

27, 32, 45, 47, 77, 98, 100, 127

2.4-3 PERMEABLE LIMESTONE SEAL

DESCRIPTION

Sealing of underground mines with permeable seals involves the placement of permeable alkaline aggregate in mine openings where acid water may pass through it. As the acid water passes through the alkaline material, neutralization occurs and precipitates are formed. These precipitates fill the void space in the aggregate and in time the seal actually becomes a solid single bulkhead seal and floods the mine. A section of a permeable seal is shown in Figure 2.4-3-1.

An example of a permeable seal would be the use of limestone as the alkaline aggregate material. Seals of this type have been constructed and successfully demonstrated by the U.S. Environmental Protection Agency and Halliburton Company at sites in West Virginia (47, 98).

IMPLEMENTATION

Laboratory Studies

NUS Corporation, Cyrus William Rice Division and E. D'Appolonia Consulting Engineers, Inc. (87) conducted laboratory studies of self-sealing limestone plugs for mine openings. The purpose of these studies was to determine the optimum limestone material for such a treatment and sealant technique.

Based on previous research by Bituminous Coal Research, Inc., (13) three limestones, Types A, B and C, were selected for the limestone plug study. The limestones were classified according to effective neutralization with Type A – the most effective neutralizing agent; Type B – intermediate; and Type C – the least effective neutralizing agent.

Laboratory studies were performed on six size ranges of each of the three limestones using ferric, ferrous, and ferric/ferrous synthetic mine waters. A summary of the results of these studies follows (86, 87):

1. A 0.95 centimeter (3/8 inch) to dust size Type A aggregate placed at 60 percent relative density was the most satisfactory material tested.

2. Aggregate volume losses can occur due to settling of the stone upon being wetted, erosion, and chemical reactions.

3. Limestone permeable seals will perform best on ferric mine waters.

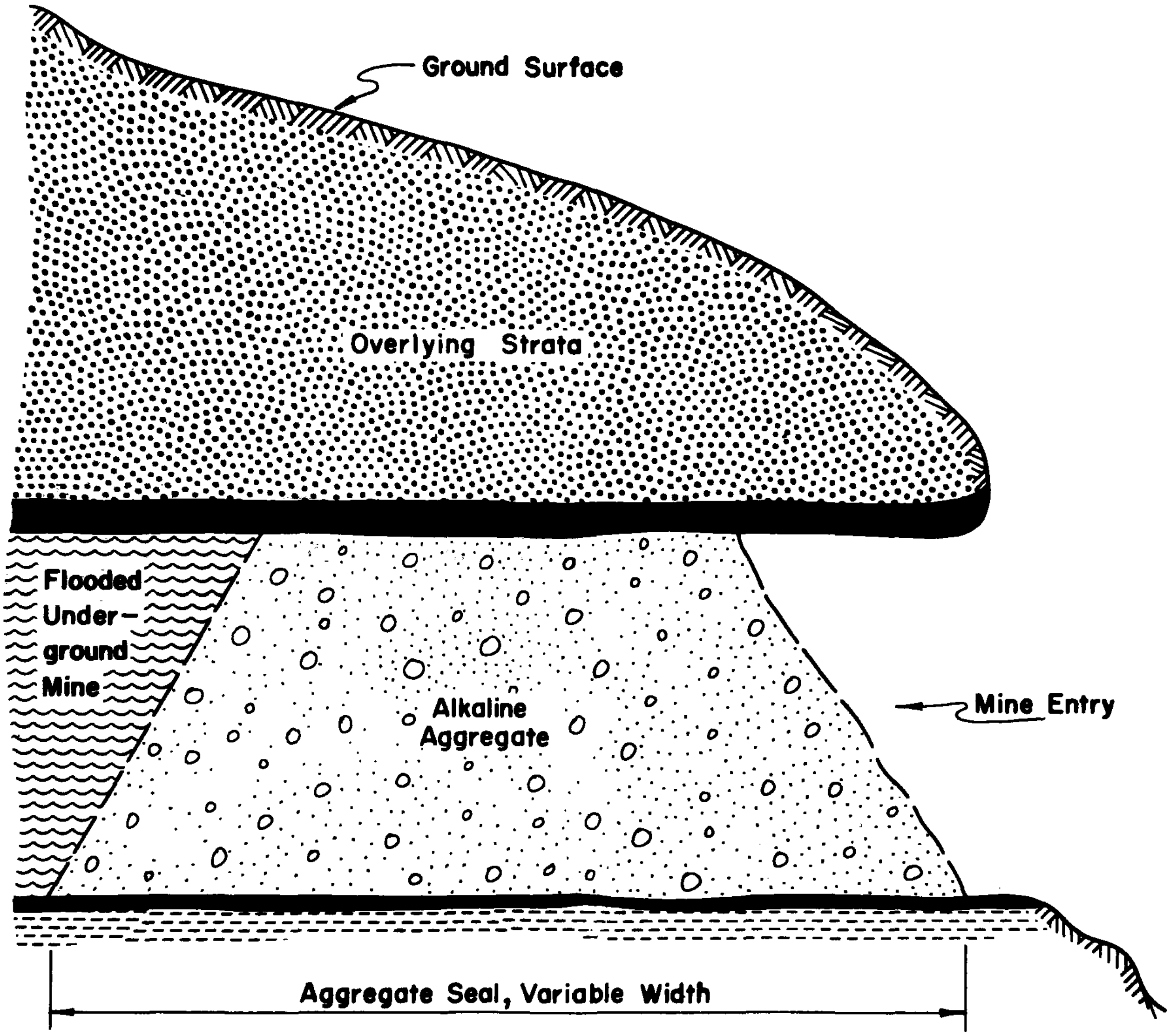


FIGURE 2.4-3-1

TYPICAL CROSS SECTION OF PERMEABLE AGGREGATE SEAL

(Adapted from Ref. 127)

4. Bentonite and fly ash additives improve water flow and treatment properties.

5. Iron is precipitated and trapped in the aggregate but calcuim sulfate is not.

Clarksburg, West Virginia Seal

A permeable limestone aggregate seal was placed in Mine No. 62-008 near Clarksburg, West Virginia by Halliburton Company in June, 1969 (47, 98). A total of 61 metric tons (67 tons) of Harrold No. 12 limestone was pneumatically placed in the 1.3 meter (4.3 foot) by 3.7 meter (12 foot) drift. The finished seal was 11 meters (36 feet) in length at the base and had 7.6 meters (25 feet) of roof contact. Some settling later occurred which left a gap between the roof and aggregate.

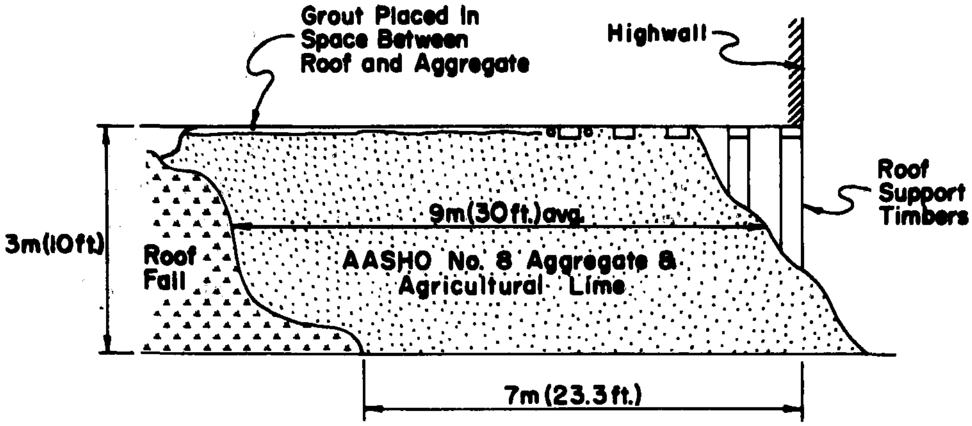
Prior to sealing, water was discharging from the mine at a rate of 0.19 liters per second (3 gpm) and had a pH of 3.0 and mean acidity of 200 mg/l. After sealing, pH increased (6.3 to 6.9) and acidity averaged 150 mg/l, but there was no reduction in flow from the mine. Iron loads were 70 percent higher while sulfate loads did not change appreciably. The evaluation of the effectiveness of this seal was affected by the limited data collected prior to sealing.

The total cost for placing the permeable limestone aggregate seal in Mine No. 62-008 was $3,048. This cost included $756 for site preparation, $237 for materials, and $2,055 for equipment and operators (32).

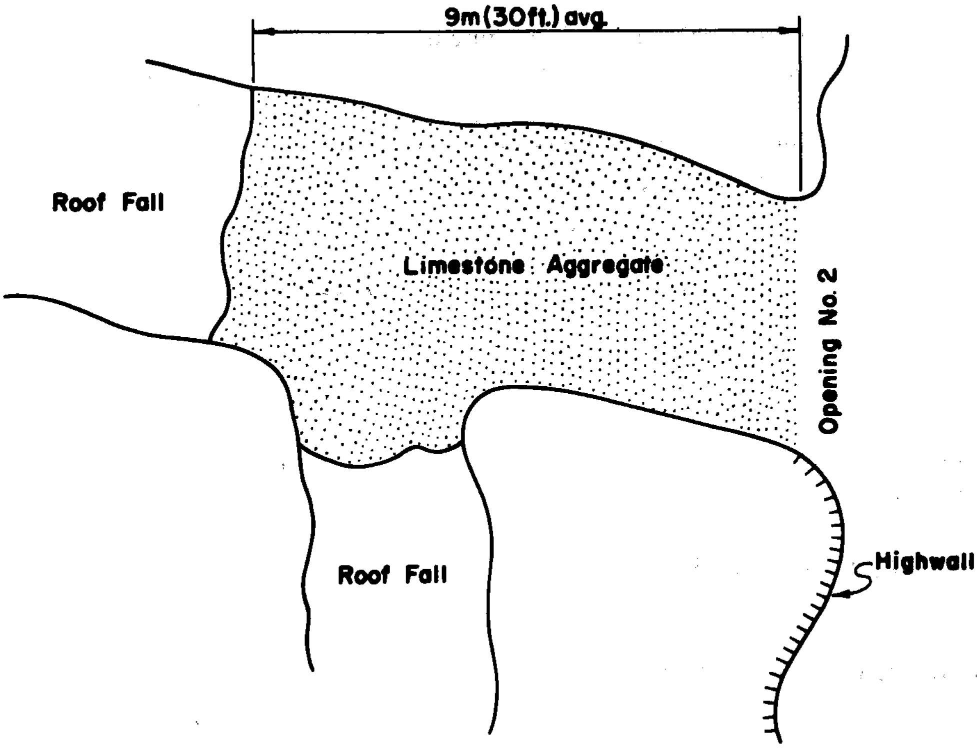
Coalton, West Virginia Seal

In September, 1969, Halliburton Company placed a permeable limestone seal in Opening No. 2 of Mine RT 5-2 near Coalton, West Virginia (47, 98). A total of 150 metric tons (165 tons) of AASHO No. 8 aggregate and agriculture lime were pneumatically placed in the drift. The void space between the roof and aggregate was grouted by pumping 2.8 cubic meters (100 cubic feet) of grout slurry into the upper portion of the aggregate. Plan and section views of the seal are presented in Figure 2.4-3-2.

After sealing mean flow rates decreased better than half and water discharging through the seal was of better quality. Mean acid, total iron, and sulfate concentrations were reduced 99 percent, 98 percent and 94 percent, respectively. Hydrostatic head behind the seal stabilized above 1.8 meters (6 feet) after January, 1970.



SECTION VIEW



PLAN VIEW

FIGURE 2.4-3-2

PERMEABLE LIMESTONE SEAL—MINE RT5-2, Opening No. 2
(Adapted from Ref. 47)

A physical inspection of this seal was made in September, 1971 and the seal was determined to be in excellent condition (98). At that time water was still seeping through the seal, indicating that all voids in the seal had not been filled by the chemical reaction between the mine water and the limestone.

Construction costs for the permeable seal placed in opening No. 2 of Mine RT 5-2 totaled $8,463. The cost included $3,447 for site preparation, $1,690 for materials and $3,320 for equipment and operators. This cost was higher than the Clarksburg seal due to excessive excavation required to prepare the opening, extra grouting materials required for grouting the upper section of the seal, and the corresponding extra equipment required (32).

Stewartstown, West Virginia Seals

In August, 1974, ECI-Soletanche, Inc., under contract with the Environmental Protection Agency, installed four permeable limestone seals and grout curtains in four deep mine entries near Stewartstown, West Virginia (100).

Each mine seal was constructed by pneumatically injecting AASHO No. 8 limestone aggregate and additives into the mine entries (10). The voids between the roof and seal were grouted with a cement, fly ash, bentonite grout mixture. Strata adjacent to the mine seals were pressure grouted for a minimum distance of 9.1 meters (30 feet) on both sides of the mine entries. A plan view of the seals is shown in Figure 2.4-3-3.

An estimate of material requirements for the four seals made by EPA personnel follows (10):

Mine Seals 1A and 1B

AASHO No. 8 limestone – 0.95 cm to 0 (3/8 inch to 0)	245 metric tons (270 tons)
5 weight percent of rock dust	13 metric tons (14 tons)
Bentonite (5 weight percent of final mixture)	13 metric tons (14 tons)

Mine Seal No. 2

AASHO No. 8 limestone – 0.95 cm to 0 (3/8 inch to 0)	118 metric tons (130 tons)

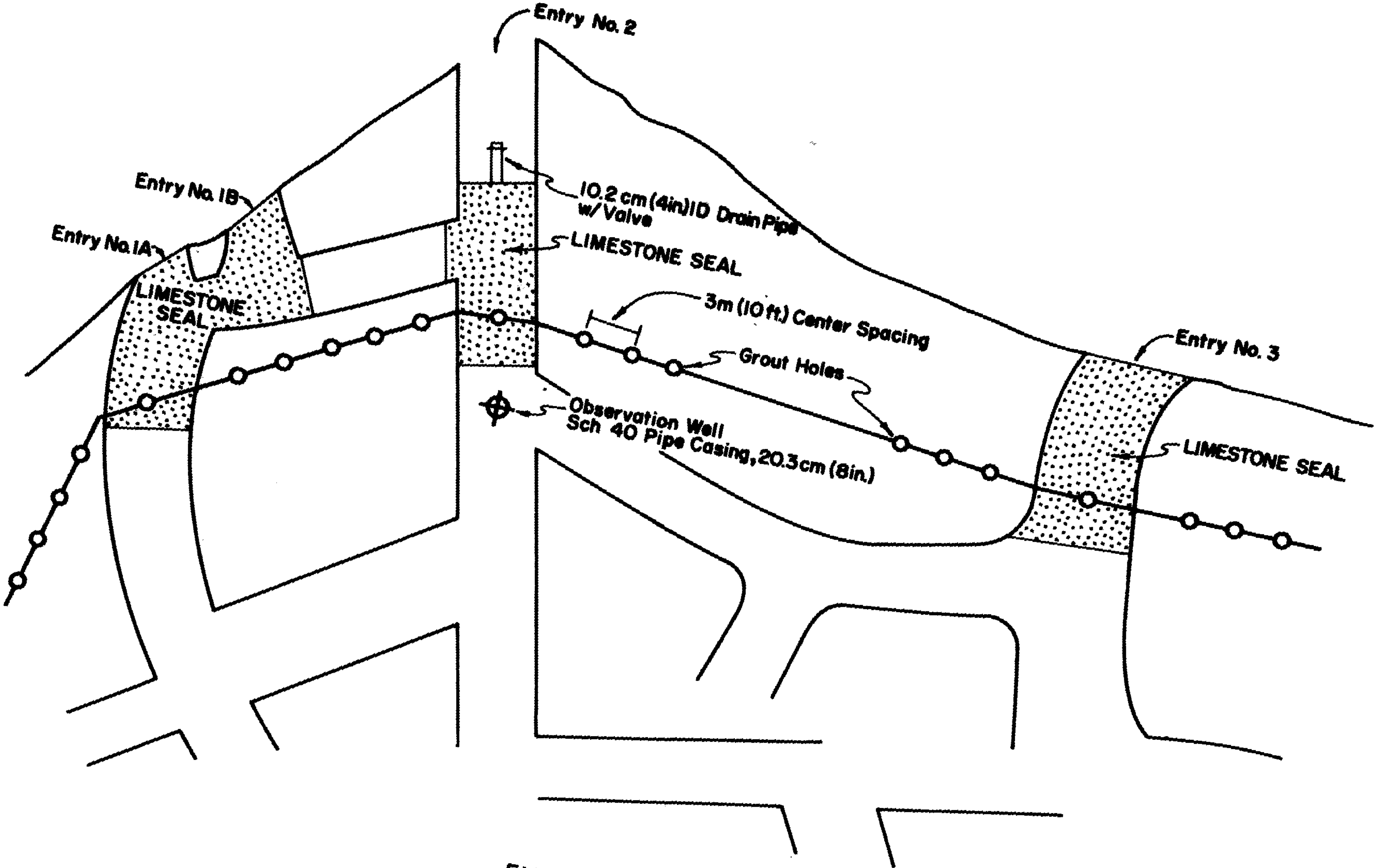


FIGURE 2.4-3-3
PLAN VIEW
PERMEABLE LIMESTONE SEALS—STEWARTSTOWN, W.VA.
(Adapted from Ref. 47)

5 weight percent of rock dust fines	6.3 metric tons (7 tons)

Mine Seal No. 3

AASHO No. 8 limestone – 0.95 cm to 0 (3/8 inch to 0)	136 metric tons (150 tons)
5 weight percent of rock dust fines	7.3 metric tons (8 tons)
10 weight percent of fly ash	13.6 metric tons (15 tons)

Actual material requirements for these seals varied approximately ± 5 percent from the estimate. Grout requirements were 8.7 cubic meters (310 cubic feet) for the pressurized grout curtains and 26.8 cubic meters (958 cubic feet) for grouting of void space between aggregate and roof (100).

EPA personnel are collecting water samples from the mine discharges and will evaluate seal performance. The final evaluation will contain information on the effectiveness of the bentonite and fly ash additives.

An estimated breakdown of anticipated costs for the Stewartstown seals showed the total cost of construction to be $88,500 (33). The cost breakdown is as follows:

Labor Costs	$29,086
Equipment	20,142
Incorporated Materials	14,640
Miscellaneous Cost	5,724
Total Direct Cost	$69,592
Overhead & Profit	18,908
TOTAL BID PRICE	$88,500

Based upon the estimated total bid price, the average cost for placing each seal would be $22,125. The high cost of constructing these seals is partially attributed to equipment utilization. A further breakdown of labor, equipment, incorporated materials, and miscellaneous costs is presented in Tables 2.4-3-1 through 2.4-3-4.

Table 2.4-3-1

Labor Costs
Permeable Limestone Seals
Stewartstown, West Virginia

Classification	No.	Rate/Hour	HEW and Pension	Payroll Taxes 15%	Living Expenses	Total/Hour	No. of Hours	Total
Laborers	4	$ 5.38	$ .53	$ .81	$ 1.50/hr.	$ 8.22	320	$10,521.60
Drill Operator	1	6.08	.64	.90	1.50	9.12	220	2,006.40
Drill Helper	1	5.89	.53	.89	1.50	8.81	220	1,938.20
Equipment Operator	2	6.02	.64	.90	1.50	9.06	320	5,798.40
Truck Driver	1	5.70	.46	.86	1.50	8.52	320	2,726.40
Foreman	1	70.00/day	6.00/day	10.50/day	15.00/day	111.50	40	4,460.00
Engineering	1	150.00/day	6.00/day	22.50/day	25.00/day	203.50	10	2,035.00
								$29,086.00

Table 2.4-3-2

Equipment Costs
Permeable Limestone Seals
Stewartstown, West Virginia

	No.	Days at Job	Value	Rental/Day	Total
Truck Tractors	2	50	$ 20,000	$ 54.00	$ 2,700.00
Bulk Trailers	4	50	30,000	81.00	4,050.00
Hi Lift Crawler MTD	1	60	8,000	21.60	1,296.00
Back Hoe	1	60	6,000	16.20	972.00
Dozer	1	40	10,000	27.00	1,080.00
Dewatering Pump	1	60	4,000	10.80	648.00
Grout Plant With Pump	1	50	10,000	27.00	1,350.00
Stake Bed Truck	1	10	8,000	21.60	216.00
Rotary Drill	1	10	100,000	270.00	2,700.00
Core Drill	1	10	6,000	16.20	162.00
Air Compressor	1	50	8,000	21.60	1,080.00
Auxiliary Pneumatic Blower	1	50	8,000	21.60	1,080.00
Dump Truck	1	50	6,000	16.20	810.00
Winch Truck	1	50	4,000	10.80	540.00
Pick-Up Truck	1	60	4,000	10.80	648.00
Pneumatic Packers, Pipes	1	50	6,000	16.20	810.00
Site and Accessories	Complement				
				TOTAL	$20,142.00

Table 2.4-3-3

Incorporated Materials
Permeable Limestone Seals
Stewartstown, West Virginia

Material	Quantity	Unit Price	Total
#8 Limestone 0.95 cm to 0 (3/8 inches to 0)	499 metric tons (550 tons)	$12.13/metric tons ($11.00/ton)	$ 6,050.00
Bentonite	12.7 metric tons (14 tons)	$75.08/metric ton ($68.10/ton) F. OBB. Pgh. plus $ 5.40/metric ton ($ 4.90/ton) delivery	1,022.00
Rock Dust	36.3 metric tons (40 tons)	$16.54/metric ton ($15.00/ton)	600.00
Fly Ash	90.7 metric tons (100 tons)	$17.64/metric ton ($16.00/ton)	1,600.00
Cement	1,500 bags	$ 2.30/bag	3,450.00
15.2 cm (6 in.) Pipe	76.2 m (250 ft)	6.89/m (2.10/ft)	525.00
10.2 cm (4 in.) Pipe	18.3 m (60 ft)	6.23/m (1.90/ft)	114.00
20.3 cm (8 in.) Sched Pipe	15.2 m (50 ft)	19.69/m (6.00/ft)	300.00
5.1 cm (2 in.) Perforated	91.4 m (300 ft)	3.61/m (1.10/ft)	330.00
Timber 10.2 cm x 10.2 cm (4 in. x 4 in.)	91.4 m (300 ft)	0.82/m (0.25/ft)	75.00
Planking 5.1 cm x 25.4 cm (2 in. x 10 in.)	61.0 m (200 ft)	0.82/m (0.25/ft)	50.00
Posts	20	1.00/each	20.00
Fertilizer and Seeds			300.00
Shut Off Valve	1	150.00	150.00
		TOTAL	$14,640.00

Table 2.4-3-4

Miscellaneous Costs
Permeable Limestone Seals
Stewartstown, West Virginia

Bonds	1%		$ 885.00
Insurance	1%		885.00
Fuel and Lube	$42.50/day	40 Workdays	1,700.00
Utilities & Phone	$20.00/day	40 Workdays	800.00
Small Tools			1,454.00
		TOTAL	$5,724.00

EVALUATION AND RECOMMENDATIONS

Implementation of permeable limestone seals has been limited to demonstration programs sponsored by the Environmental Protection Agency in West Virginia. The long term effectiveness of this type seal has not been demonstrated. The seal has been effective in improving water quality and reducing the volume of mine discharge. Increases in pH and alkalinity, and decreases in acid, iron, and sulfate loads have demonstrated the neutralizing ability of the seal. This neutralization effect, however, is expected to decrease as the limestone aggregate becomes coated with precipitate.

The theoretical end result of the permeable seal is a hydraulic seal. Neither the Clarksburg nor the Coalton seals have been successful in eliminating flow from the mine opening. The seals have attained various levels of mine inundation. Leakage through the seal indicates that precipitates are not plugging the aggregate void or the precipitates are unable to withstand water pressure. The addition of fly ash and bentonite to the Stewartstown seals is expected to further improve sealing effectiveness.

The use of the permeable type seal is limited to accessible mine entries. The limestone aggregate (or other suitable alkaline material) must be properly graded and placed to ensure that the mine water flowing through the seal has sufficient retention time to be neutralized. The completed seal must be capable of withstanding the maximum expected hydrostatic head. To allow drawdown of the mine pool, a pipe should be constructed through the aggregate, and an emergency discharge borehole should be drilled into the mine to allow gravity discharge when the mine pool approaches its maximum allowable level (See Section 2.4).

During construction of the demonstration seals, settling of the limestone aggregate has created a gap between the mine roof and the top of the seal. At Clarksburg, water flowing over the top of the seal resulted in significant increases in iron and acid loads in the mine discharge. Grouting of this void space at the Coalton mine successfully eliminated leakage through this area. To ensure that a watertight seal is formed around the seal perimeter, grouting of the sides and bottom of the seal should also be performed. When strata adjacent to the seal are fractured or hydraulically unsound, curtain grouting will be required.

The costs of constructing permeable seals will depend upon such factors as: size of opening, materials, grouting requirements, site preparation, and proper selection and utilization of equipment. It is difficult to estimate average costs of constructing these seals since only six have been constructed as part of demonstration projects.

Construction costs have ranged from \$3,048 to \$22,125 per seal. As improved methods of construction are developed, costs should generally range from \$5,000 to \$10,000 per seal.

REFERENCES

10, 13, 32, 33, 47, 53, 86, 87, 98, 100, 127

2.4-4 GUNITE SEAL

DESCRIPTION

This seal is constructed by placing successive layers of gunite, a pneumatically placed low slump concrete, in a mine opening until the opening is completely filled. The roof, sides, and floor of the mine opening are cut so that a tapered seal will be formed. This seal must be placed in an accessible entry in areas of sound to reasonably sound adjacent strata. A wood bulkhead is constructed on the inby side to support the initial placement of gunite. Proper adjustment of mix and injection nozzles allows the gunite to stand vertically, thus, eliminating the need for forms (127). Plan and section views of a typical gunite seal are shown in Figure 2.4-4-1.

IMPLEMENTATION

Cherry Creek Watershed, Maryland

Installation of three gunite seals has been proposedfor abatement of acid mine drainage from Mine 902 in the Cherry Creek watershed, Maryland (106). The seals will be placed in entries of an abandoned underground mine in the Upper Freeport coal seam. The mine discharges an average of 15.4 kilograms per day (34 lb/day) acid. Complete flooding of this mine will require that the seals be capable of withstanding 10.7 meters (35 feet) of head. Plans and specifications for these seals were prepared for the Appalachian Regional Commission by Skelly and Loy, and Zollman Associates, Inc. in July, 1973.

The seals will be constructed by excavating the mine opening, shaping the entries, and placing concrete (gunite) pneumatically in layers until the entries are sealed. A 15.2 centimeter (6 inch) borehole will be drilled into the mine for observation and pumping of water from the mine during construction. This hole will also act as an emergency discharge, should the mine pool ever exceed maximum design level.

A 20.3 centimeter (8 inch) drain pipe with manual gate valve will be incorporated in one of the seals to allow for mine pool drawdown in the event of failure or emergency. Grout curtains will be placed adjacent to the seals to prevent mine water leakage through the disturbed area. A section view of one slope entry showing the proposed location of the gunite seal, borehole, and drain pipe is shown in Figure 2.4-4-2.

The gunite mix is to consist of one part expansive type cement, four parts sand, and no more water than is required to maintain satisfactory control over rebound

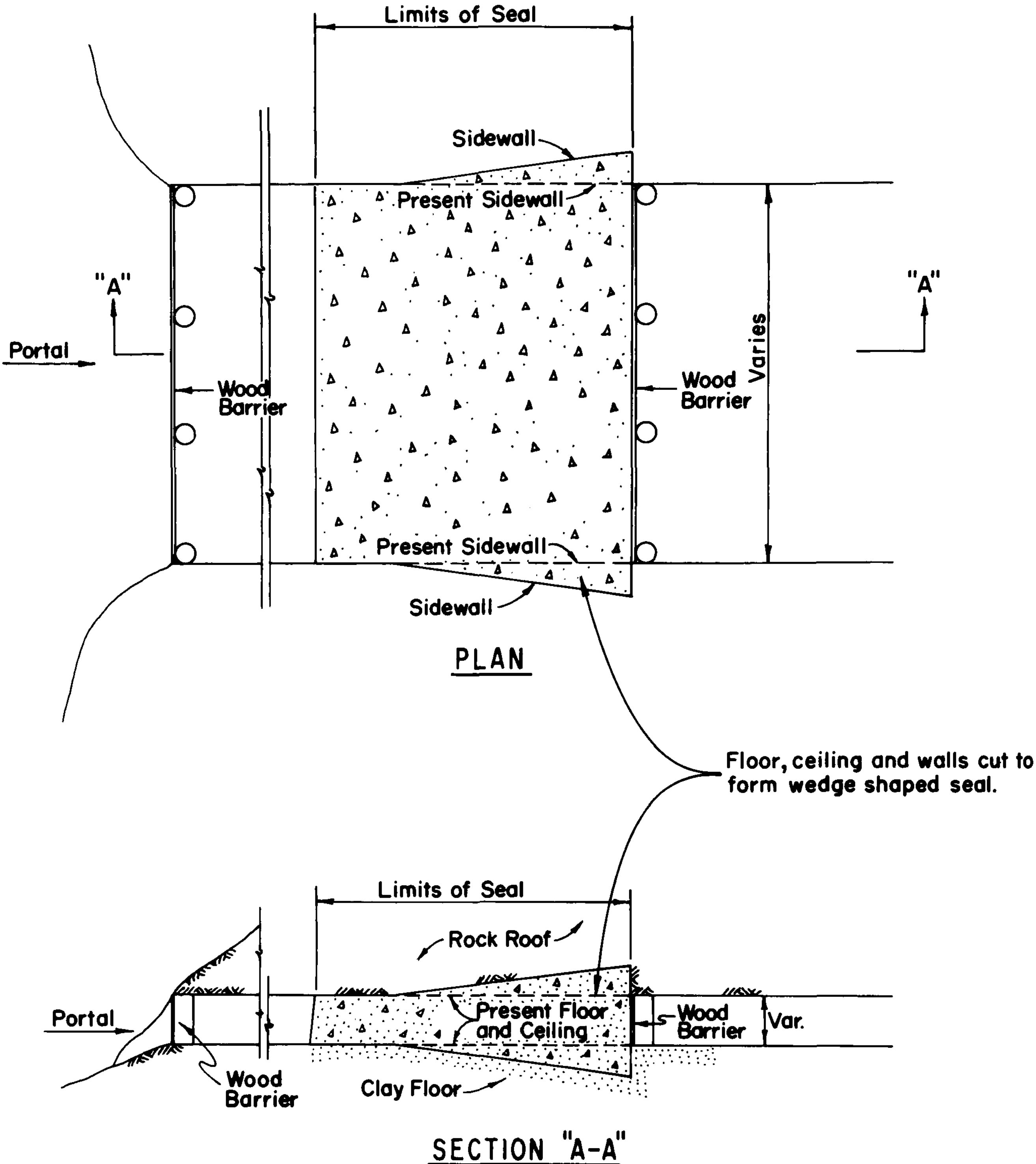


FIGURE 2.4-4-1

TYPICAL GUNITE SEAL
(Adapted from Ref. 127)

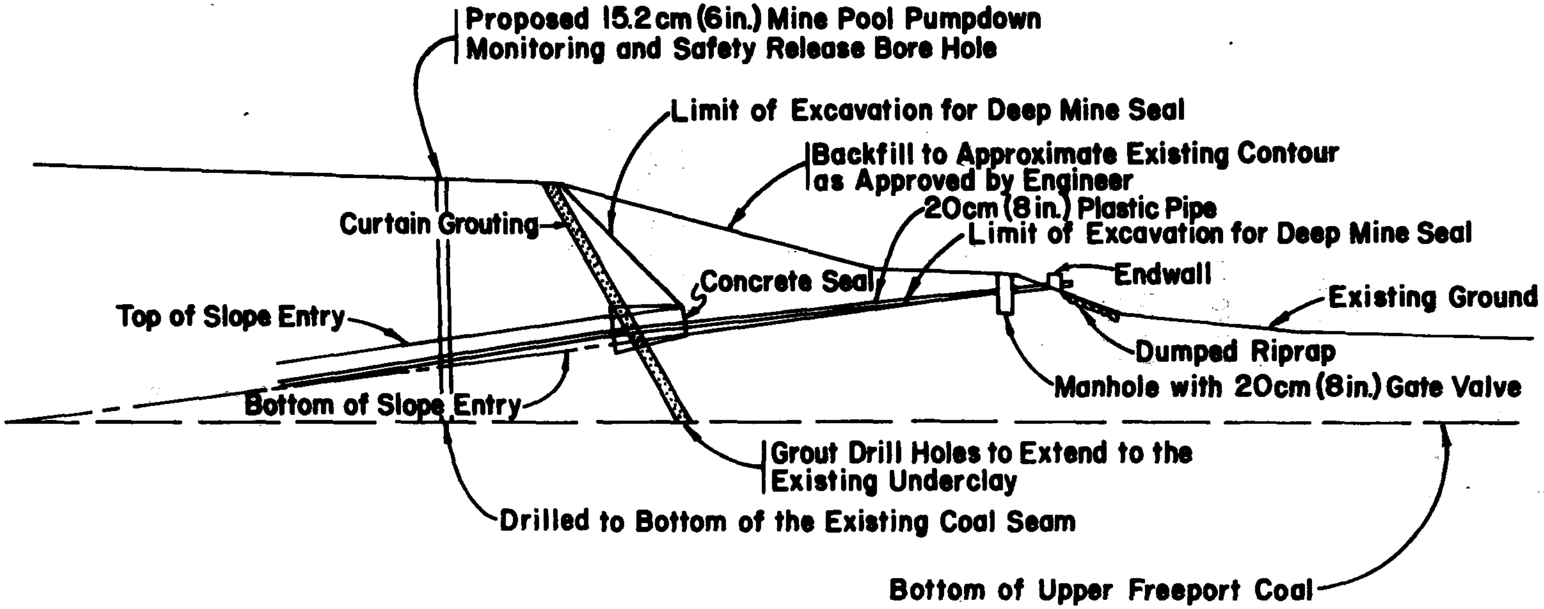


FIGURE 2.4-4-2

PROPOSED GUNITE SEAL, CHERRY CREEK WATERSHED

(Adapted from Ref. 106)

and to obtain proper hydration of the cement. Prior to application of the gunite any unsound material will be removed from the roof, walls, and floor of the entry. The floor is to be maintained in a dry condition during placement of the gunite. The completed seals are to be backfilled and the work area graded and revegetated.

Construction of the gunite seals should begin in the near future. Approximate quantities of material and unit prices have been estimated, and are as follows (106):

15.2 cm (6 in) Borehole	15.2 LM @ $164/LM (50 LF)($50/LF)	$ 2,500
Grout Drilling and Inserting	518 LM @ $13.94/LM (1,700 LF)($4.25/LF)	7,200
Clearing and Grubbing	Lump Sum	400
Excavation for Deep Mine Seals	3,823 cu m @ $0.99/cu m (5,000 cu yd)($0.75/cu yd)	3,800
One Concrete Endwall	Lump Sum	100
Diversion Ditch	61 cu m @ $1.31/cu m (80 cu yd)($1.00/cu yd)	100
Dumped Riprap	49.9 cu m @ $6.54/cu m (60 cu yd)($5.00/cu yd)	300
20.3 cm (8 in) Plastic Pipe	61 LM @ $49.21/LM (200 LF)($15.00/LF)	3,000
One 20.3 cm (8 in) Plastic Gate Valve		800
One Manhole, Frame and Cover		500
Revegetation with Ground	0.4 ha @ $877/ha (1 ac)($355/ac)	400
Concrete Deep Mine Seal	103 cu m @ $285/cu m (135 cu yd)($218/cu yd)	29,400

Curtain Grouting
Materials

a. Cement	175 bags @ $5.00/bag	$ 900
b. Aggregate	45.4 metric tons @ $5.51/metric ton (50 tons)($5.00/ton)	300
c. Fly Ash	650 bags @ $1.50/bag	1,000
d. Sand	16 metric tons @ $36.38/metric ton (18 tons)($33.00/ton)	600
e. Admixtures	227 kg @ $1.10/kg (500 lb)($0.50/lb)	300
Mobilization and Demobilization	Included in Individual Estimates	
	TOTAL	$51,600

EVALUATION AND RECOMMENDATIONS

The gunite seal shows promise of being an effective hydraulic seal for accessible mine entries. The wedge shape allows the seal to become tighter in the mine opening as water pressure increases. Since the gunite is pneumatically placed in the opening, a watertight seal should be formed between the mine and the seal perimeter. This seal is expected to be particularly effective in sealing against higher hydrostatic heads. Similarly shaped seals constructed of poured concrete were placed in Indiana coal mines as early as 1925. (See Section 2.4-2). These seals reportedly withstood water pressures as high as 49,217 kilograms per square meter (70 psi).

This seal will be most effective when located in relatively sound strata. Preparation of the mine opening will include cleaning and shaping of the roof, sides, and floor. When unstable roof conditions are encountered timbering of the entry may be required. The use of an expansive type cement in the gunite mix should create a tight fitting plug in the mine opening.

When seals are located in areas of fractured or hydraulically unsound strata, curtain grouting will be required. In such instances grouting of the seal perimeter may also be deemed necessary. Grout pipes should be placed along the perimeter of the seal prior to injection of the gunite mix.

Since this type seal has not yet been demonstrated, it is difficult to estimate construction costs. The cost of placing gunite seals at Cherry Creek, West Virginia was estimated at \$285 per cubic meter (\$218/cu yd). Additional expenses will include excavation, cleaning, timbering and shaping of the mine opening, and curtain grouting of adjacent strata. The estimated average cost of the Cherry Creek seals, including grouting, is approximately \$13,000 per seal.

REFERENCES

70, 106, 127

2.4-5 CLAY SEAL

DESCRIPTION

Clay may be placed in openings of underground mines to form a hydraulic seal or to control infiltrating water. A good quality plastic clay should be used to ensure impermeability. The seal is constructed by first cleaning the mine opening of debris or any other material that would make the clay seal ineffective. The clay material is placed in layers and compacted to enable the clay to flow into cracks and voids along the walls and roof of the seal area. Earth should be backfilled over the seal to hold it in place and prevent erosion. Under ideal conditions a clay seal constructed in this manner may withstand up to 10 meters (30 feet) of hydrostatic head (127). A cross section of a typical clay seal is shown in Figure 2.4-5-1.

IMPLEMENTATION

Roaring Creek – Grassy Run Watershed

Clay seals were constructed during a demonstration project to evaluate mine sealing in the Roaring Creek – Grassy Run watershed near Elkins, West Virginia. This project was a cooperative effort between Federal agencies and the state of West Virginia. Sealing operations were conducted in an effort to evaluate air sealing of abandoned underground coal mines (101).

A total of 41 openings were sealed with clay during the project. These seals were placed in areas where surface mine highwalls were badly fractured and the stripping operations had intercepted deep mine workings. The seals were constructed by placing 0.6 meter (2 foot) layers of clay against the highwall and compacting with a vibrator sheeps foot roller. In most instances the seals were placed on the updip side of underground mines to prevent the entry of air and water.

During air sealing of a small abandoned underground mine, two clay seals were placed along the outcrop on the downdip side of the mine. Later, as the water level in the mine rose, water near the seal flowed up through the overburden and over the top of the seal. Erosion of the clay seal allowed the mine pool to drain.

The average cost per seal for 10 clay seals placed in Work Areas 1 through 9 was $950. A total of 8,020 cubic meters (10,490 cu yd) of clay was placed at a cost of $1.19 per cubic meter ($0.91/cu yd). At Work Area 10, costs were higher due to greater haulage distance from the borrow pit to the work area. Six seals were constructed at an average cost of $2,360 per seal. The cost per cubic meter of clay was $1.58 ($1.21/cu yd) (101).

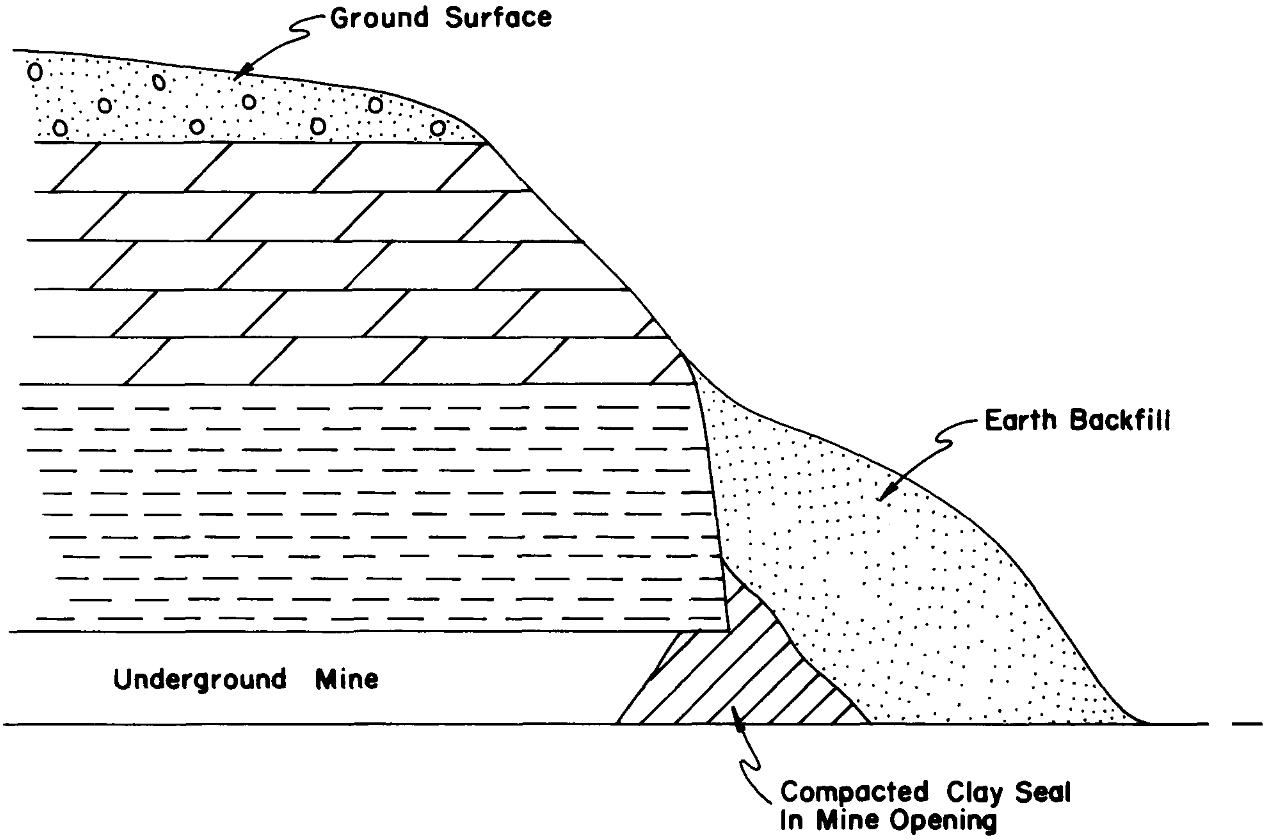


FIGURE 2.4-5-1

CROSS SECTION TYPICAL CLAY SEAL

Shaw Mine Complex, Somerset County, Pennsylvania

Clay seals were installed along the highwall of box cuts excavated at the Shaw Mine Complex, Elklick Township, Somerset County, Pennsylvania (84). In an attempt to hydrologically isolate sections of the Shaw Mine, overburden above the abandoned mine was excavated and the Redstone and Pittsburgh coals removed. After the mining operation was completed, clay barrier seals were constructed in the cut to flood portions of the underground mine. Pennsylvania Projects SL 118-2B and SL 118-3-2 involved reclamation of the excavated cuts which included installation of clay seals, contour backfilling, and planting and seeding. A sketch of the clay seal installed at the Shaw Mine Complex is shown in Figure 2.4-5-2.

Project SL 118-2B involved installing approximately 22,938 cubic meters (30,000 cu yd) of clay along the cut for approximately 274 linear meters (900 LF). The clay was installed in 30.5 centimeter (12 inch) layers and compacted by a dozer running over the clay and/or trucks running over the clay as they traveled to and from the clay pits. The seal was held to a width of not more than 6 meters (20 feet) at the bottom and not more than 4.6 meters (15 feet) at the top.

Approximately 512,282 cubic meters (670,000 cu yd) of spoil were moved during backfilling. Rocks larger than 15.2 centimeters (6 inches) were covered with a minimum of 1 meter (3 feet) of soil. In areas where reclaimed land would be used for farming a minimum of 30.5 centimeters (12 inches) of best soil available was placed over all rocks 15.2 centimeters (6 inches) in size. Backfilling was done coincident with the clay seal installation to keep the seal from becoming too wide.

All areas planted were worked with a disc and/or harrow wherever practical and fortified with 4.5 metric tons of pulverized limestone per hectare (2 tons/acre). Trees were planted on 2.4 meter by 2.4 meter (8 feet by 8 feet) centers for approximately 1,728 trees per hectare (700 trees/acre).

Work under this project was completed in June, 1972 by M.F. Fetterolf Coal Company, Inc. Costs of reclamation were as follows:

Installing Clay Seal – 22,938 cu m (30,000 cu yd)	Lump Sum	$ 54,000
Backfilling, Planting – 512,282 cu m (670,000 cu yd)	Lump Sum	127,300
Liming, Planting Trees – 20.3 ha (50 ac)	Lump Sum	2,500
	TOTAL	$183,800

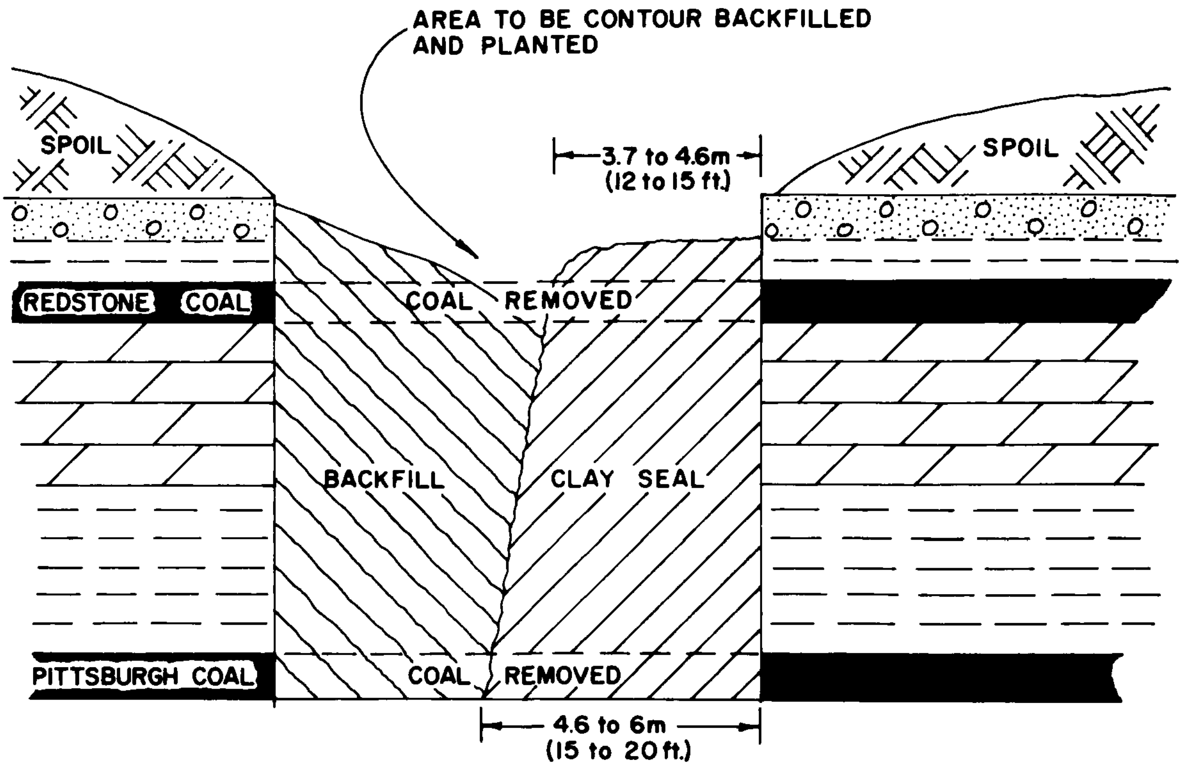


FIGURE 2.4-5-2

CLAY SEAL, SHAW MINE COMPLEX
(Adapted from Ref. 84)

Based on the lump sum values, unit costs of individual work items woud be:

Installing Clay Seal	$2.35/cu m	($1.80/cu yd)
Backfilling	$0.25/cu m	($0.19/cu yd)
Liming, Planting Trees	$123/ha	($50/ac)

Under project SL 118-3-2 approximately 42,053 cubic meters (55,000 cu yd) of clay were installed along 792 linear meters (2,600 LF) of the cut. Backfilling the cut involved moving 856,352 cubic meters (1,120,000 cu yd) of spoil material. The method of seal installation and backfilling was the same as for project SL 118-2B. All areas to be seeded were fortified with 4.5 metric tons of pulverized limestone per hectare (2 tons/acre) and 560 kilograms of 10-20-20 fertilizer to the hectare (500 lb/acre). A mixture of alfalfa, timothy and clover was applied at 22 kilograms per hectare (20 lb/acre).

Work on this project was completed in May, 1973 by Sanner Brothers Coal Company. Costs of reclamation were as follows:

Install Clay Seal	42,053 cu m @ $2.75/cu m (55,000 cu yd)($2.10/cu yd)	$115,500
Contour Backfill	856,352 cu m @ $0.24/cu m (1,120,000 cu yd)($0.18 cu yd)	201,600
Liming, Fertilizing, Seeding	24.3 ha @ $309/ha (60 ac)($125/ac)	7,500
	TOTAL	$324,600

Cherry Creek Watershed, Maryland

Installation of a clay seal has been proposed for abatement of acid mine drainage from Mine 904 in the Cherry Creek watershed, Maryland. The clay seal will be placed in an abandoned slope entry to the Upper Freeport coal seam. This pollution source discharges an average of 2.3 kilograms per day (5 lb/day) acid. Plans and specifications for the seal were prepared for the Appalachian Regional Commission by Skelly and Loy, and Zollman Associates, Inc. in July, 1973 (106).

The discharge from Mine 904 is through an existing subsurface drain. Placement of the clay seal will require excavation of overburden to uncover the mine entry and intercept the subsurface drain. A 15.2 centimeter (6 inch) borehole will be constructed (complete with case and cap) behind the seal for the purpose of monitoring water level and quality in the mine. The clay seal is expected to eliminate the discharge and completely inundate the mine. Plan and section views of the proposed seal are shown in Figure 2.4-5-3.

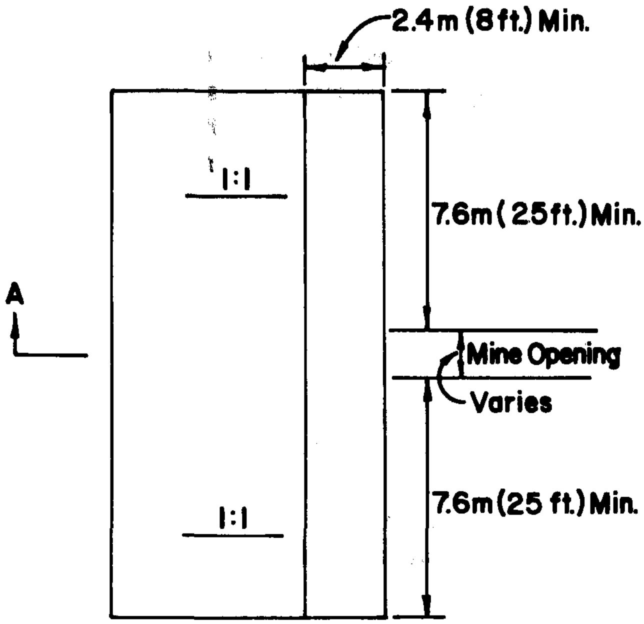
The seal shall be constructed by placing clay in 30.5 centimeter (12 inch) layers, and compacting with available hauling and spreading equipment or other suitable, approved means. The seal is to extend a minimum of 7.6 meters (25 feet) on either side of the slope entry and extend below the mine floor far enough to intercept the existing drainway. Upon completion of seal construction the work area is to be backfilled, graded, and revegetated.

Construction of the clay seal should begin in the near future. Approximate quantities of material and unit prices have been estimated and are as follows (106):

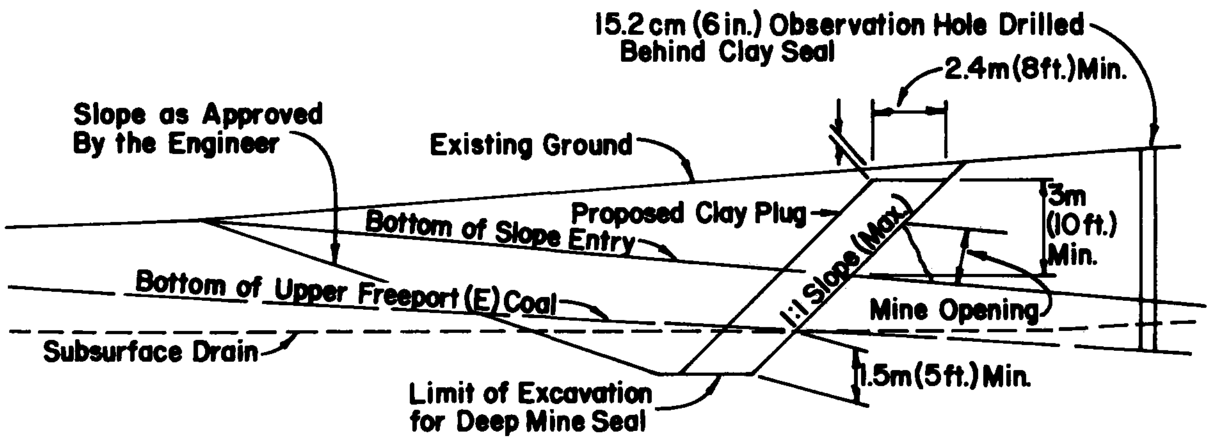
Monitoring Well	7.6 LM @ 27.89/LM (25 LF)($8.50/LF)	$. 200
Clearing and Grubbing	Lump Sum	200
Excavation	2,294 cu m @ $0.98/cu m (3,000 cu yd)($0.75/cu yd)	2,300
Clay Seal	229 cu m @ $4.71/cu m (300 cu yd)($3.60/cu yd)	1,100
Revegetation with Ground Agriculture Limestone	0.2 ha @ $877/ha (0.5 ac)($355/ac)	200
Mobilization and Demobilization	Included in Individual Estimates	
	TOTAL	$4,000

EVALUATION AND RECOMMENDATIONS

Implementation of clay seals should be limited to accessible mine entries where low water pressure is expected. The effectiveness of these seals in controlling mine discharges will depend upon such factors as the quality of clay, method of construction, and type and condition of the mine opening. Clay seals have successfully been placed in mine openings to prevent the entry of air and water into air sealed mines. However, when these seals are properly compacted and backfilled, they are capable of eliminating mine discharges and inundating abandoned underground mines.



PLAN



SECTION A-A

FIGURE 2.4-5-3

PROPOSED CLAY SEAL, CHERRY CREEK WATERSHED
(Adapted from Ref. 106)

Clay seals must be constructed with sufficient internal strength to withstand the maximum expected water pressure. Seals placed in drifts, slopes, highwall fractures, or similar openings should extend beyond the perimeter of the opening. Construction specifications for Cherry Creek require that the clay seal extend a minimum of 7.6 meters (25 feet) on either side of the slope entry, a minimum of 3 meters (10 feet) above the bottom on the entry, and a minimum of 1.5 meters (5 feet) below the entry. Shafts, subsidence holes, and similar vertical openings should be sealed in areas of relatively sound and impermeable strata. Completed seals should be backfilled, graded, and revegetated.

Costs of constructing clay seals will depend upon the type and size of opening; site preparation required; the availiability of suitable clay material; and the amount of backfilling, grading, and revegetation required. The cost of installing clay seals will normally range between \$2.62 and \$5.23 per cubic meter (\$2.00 and \$4.00/cu yd). Total construction costs will range from \$2,000 to \$4,500 per seal.

REFERENCES

32, 38, 70, 84, 100, 101, 106, 127

2.4-6 GROUT BAG SEAL

DESCRIPTION

Construction of a grout bag seal involves the placement of successive layers of expendable grout containers in an accessible mine opening. Nylon or cotton cloth grout retainers are placed on the floor of the mine and inflated with cement slurry to conform to the shape of the mine entry. After the cement slurry sufficiently hardens and is capable of withstanding a load of about 2,109 kilograms per square meter (3 psi) a second row of shorter retainers is placed above it and inflated with cement slurry. This process is repeated until the entire area between the floor and roof of the mine entry is filled by the retainers. A cross section of an expendable grout retainer seal is shown in Figure 2.4-6-1.

IMPLEMENTATION

Clarksburg, West Virginia Seal

In May, 1967, Halliburton Company constructed a grout bag seal in an isolated 2 hectare (5 acre) mine (Mine No. 14-042A) in the Pittsburgh coal seam south of Clarksburg, West Virginia. Prior to sealing a flow of 1.1 liters per second (18 gpm) was discharging from the mine. Analysis of the mine water showed a pH of 2.6, iron – 558 mg/l, acidity – 2,750 mg/l, and acid load 280 kilograms per day (616 lb/day). The floor of the mine was shale and the roof and walls were of coal. The coal was irregular in shape and contained many fractures (47).

The seal constructed in the mine consisted of four expendable grout retainers forming four successive layers. The seal was constructed by placing a 6.1 x 3 x 0.9 meter (20 x 10 x 3 foot) retainer on the floor and inflating it with cement slurry to conform to the shape of the mine. When the first retainer had hardened sufficiently to withstand a load, a second nylon retainer, 4.9 x 3 x 0.9 meters (16 x 10 x 3 feet), was placed on the first. The process was repeated to place a third nylon retainer 4.3 x 3 x 0.9 meters (14 x 10 x 3 feet), and a fourth cotton retainer 3 x 3 x 0.9 meters (10 x 10 x 3 feet), to completely fill and seal the opening. The completed mine seal is shown in Figure 2.4-6-2.

After sealing, leakage around the bag seal was measured at 0.09 liters per second (1.5 gpm), a reduction of 92 percent from flow measured prior to sealing. This leakage was later reduced to 0.02 liters per second (0.33 gpm) by injecting a total of 189 liters (50 gallons) of Halliburton PWG grout fluid around the first and second grout retainers. No further grouting was performed, as the remaining leakage appeared to be coming from coal fractures to the left of the seal (32, 47).

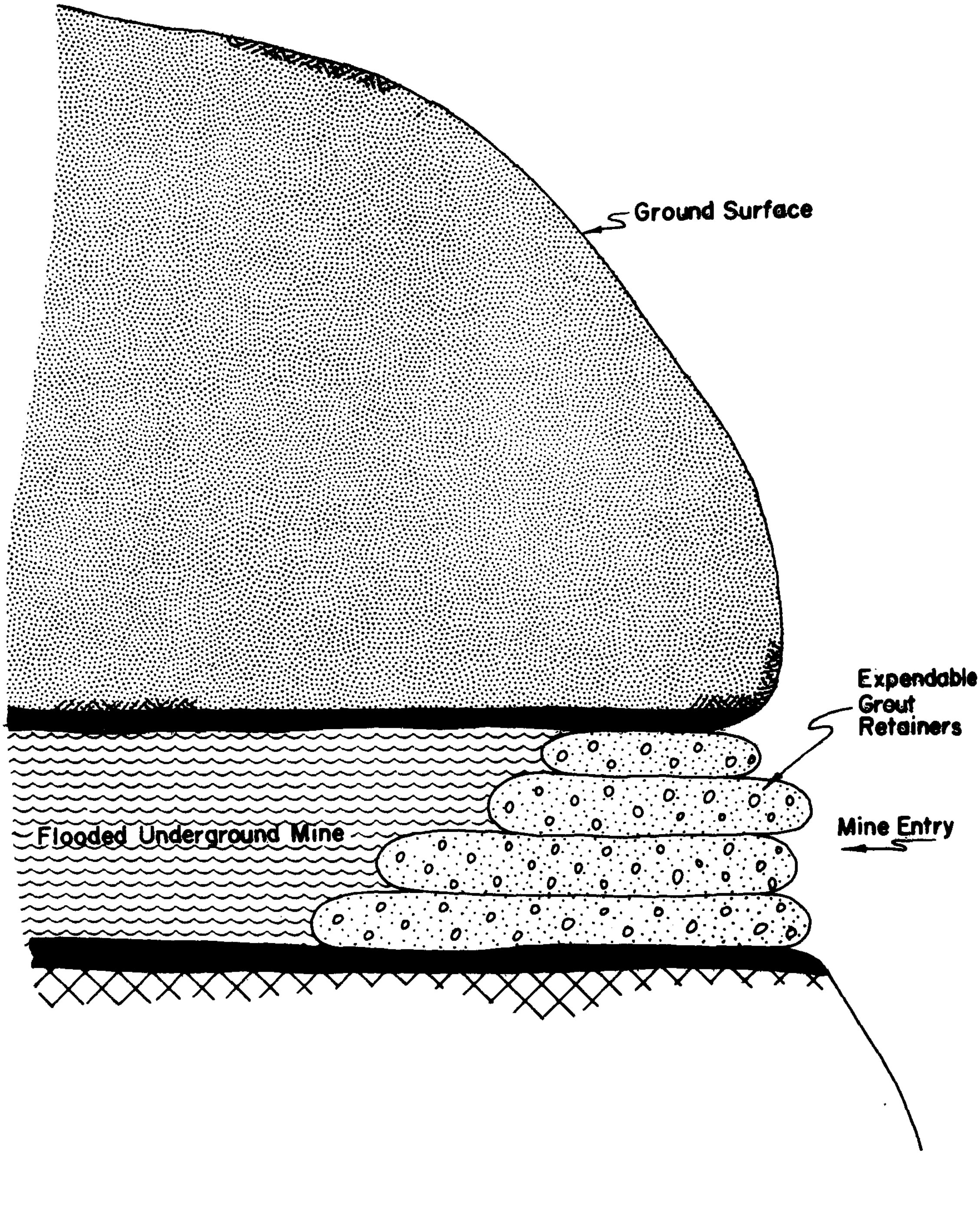
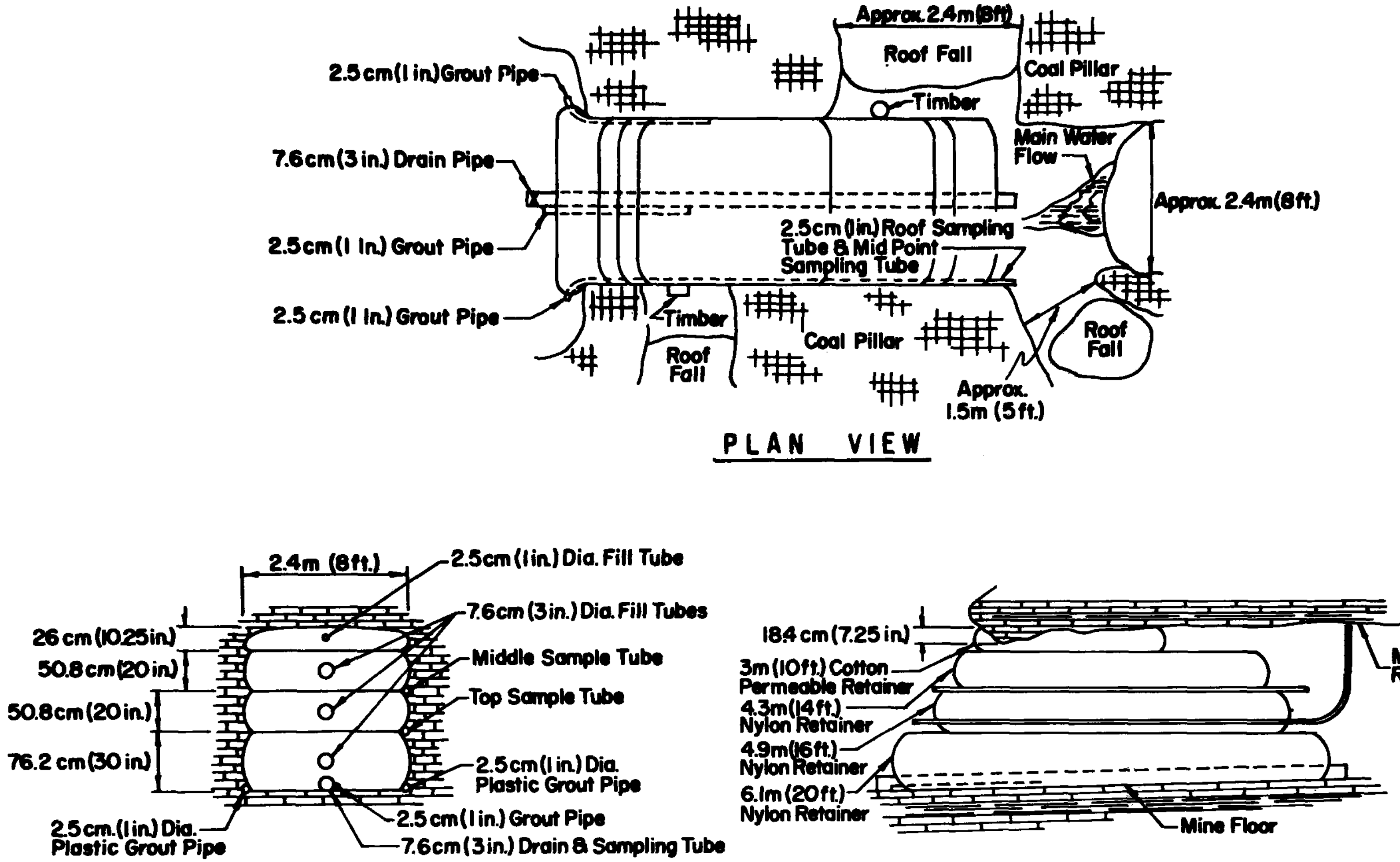


FIGURE 2.4-6-1

CROSS SECTION OF EXPENDABLE GROUT RETAINER UNDERGROUND MINE SEAL

(Adapted from Ref. 127)



FRONT VIEW

ELEVATION

FIGURE 2.4-6-2

GROUT BAG SEAL

Mine No. 14-042A Clarksburg, W. Va.

(Adapted from Ref. 47)

Later an unsuccessful attempt to further reduce flow was made by pumping a gel material of bentonite and shredded cane fiber into the void space behind the mine seal. A total of 156 thousand liters (41,200 gallons) of gel material, utilizing 13,620 kilograms (30,000 pounds) of Wyoming bentonite and 134 kilograms (295 pounds) of shredded cane fiber, were pumped into the mine. After completion of pumping, the flow rate from the mine had increased to 0.03 liters per second (0.55 gpm).

Water quality analyses performed by the U.S. Environmental Protection Agency indicate that ion concentrations of iron, acidity, and sulfates have not changed significantly since sealing. Mean values of samples collected between August, 1970 and June, 1971 were: total iron – 497 mg/l, hot acidity – 1,750 mg/l, and sulfates – 3,210 mg/l. Pollution loads, however, have decreased better than 90 percent due to reduced flow. The mean flow and acid load during the same sampling period were 0.07 liters per second (1.08 gpm) and 10.4 kilograms per day (23 lb/day), respectively (98).

An inspection made four years after seal construction revealed that there was no leakage between the bag layers. The bond between the bags and coal surface had been broken due to deterioration of the coal, and massive leakage was occurring.

Costs for constructing the grout retainer seal and Halliburton PWG grout fluid treatment at Mine No. 14-042A were reported to be $5,000 (130). Materials and equipment used in placing the gel material of bentonite and shredded cane fiber cost $2,771. Access rights and site restoration required additional expenditures of $579 (47). The total cost of construction and remedial work would therefore be $8,350.

A 1967 estimate of the costs of sealing an open drift using 9.1 meter (30 foot) expendable grout retainers was as follows (29):

Site Preparation	$ 500
Entrance Preparation	315
Four (4) Expendable Grout Retainers	1,200
Piping, Valves, Labor	800
Incidental Expenses	200
Water Hauling and Storage	250
Filling Material	2,810
Mixing and Placement Equipment	714
TOTAL ESTIMATED COST	$6,800

If filling material can be economically processed on site, slurry price for filling the retainers could be reduced by as much as 50 percent. The total estimated cost would then be $5,400.

EVALUATION AND RECOMMENDATIONS

Demonstration of this seal type has reportedly been limited to the work performed at the Clarksburg mine. This seal successfully reduced the mine discharge from 1.1 liters per second (18 gpm) to a mean discharge of approximately 0.09 liters per second (1.5 gpm). Although pollution loads decreased, water quality showed little improvement. The hydrostatic head behind the seal was estimated to be 1.8 meters (6 feet).

This seal has limited application in controlling mine drainage pollution from abandoned underground mines. The retainer bags do not form a good bond with the surface of the mine opening. Leakage around the seal perimeter will be difficult to control. Grouting and other remedial work at Clarksburg failed to eliminate the mine discharge. Concrete type bulkheads would appear to be more suitable sealing techniques.

Based upon previous demonstration work and cost estimates the cost of constructing a grout bag seal in an average drift entry would range from $10,000 to $15,000. Grouting of the seal perimeter and curtain grouting of adjacent strata would result in additional expenditures.

REFERENCES

27, 29, 32, 47, 98, 127, 130

2.4-7 SHAFT SEAL

DESCRIPTION

A shaft is a vertical or near vertical entry into an underground mine. Upon abandonment of a mine, shaft entries are commonly filled with miscellaneous materials, covered, or fenced off for public safety. In instances where the shaft has the potential to discharge mine water or to divert water into the mine, an impermeable type seal should be constructed. Discharges of acid mine water from abandoned mine shafts is common in the eastern coal fields.

The placement of shaft seals involves opening the shaft and removing all debris. A suitable sealing zone in the strata is then located. Any water discharging from the shaft is controlled by pumping the mine pool. The shaft is backfilled to the sealing zone with miscellaneous fill and the impermeable seal is placed. A key may be chipped in the adjacent strata to help anchor the seal. The sealing operation is completed by backfilling the shaft to ground level. A cross section of a typical shaft seal is shown in Figure 2.4-7-1.

IMPLEMENTATION

Pennsylvania Sealing Program

Shaft entries were sealed during the Federal Works Progress Administration and Civil Works Administration air sealing projects which began in 1933 (36). When practical the shafts were filled with earth and rock. When this method was impractical or objectional a concrete slab was placed over the shaft and backfilled with earth.

After completion of the Federal sealing program, Pennsylvania continued to seal mines under the State Department of Mines sealing program which initiated with passage of the 1935 Bituminous Mining Law, Act No. 55. Mine entries were sealed in an effort to prevent mine fires and reduce the flow of acid mine water (71).

Abandoned shafts were initially sealed by placing a concrete slab over the shaft opening. It was later discovered that decay of timber in the shaft allowed the shaft to collapse, thereby causing the concrete slab seal to become ineffective. This method of sealing was terminated and shafts were sealed by filling from bottom to top with earth and clay. As of 1952, approximately 150 shafts ranging in depth from 6.1 to 183 meters (20 to 600 feet) in depth had been sealed (71). A sketch of the concrete slab type seal is shown in Figure 2.4-7-2.

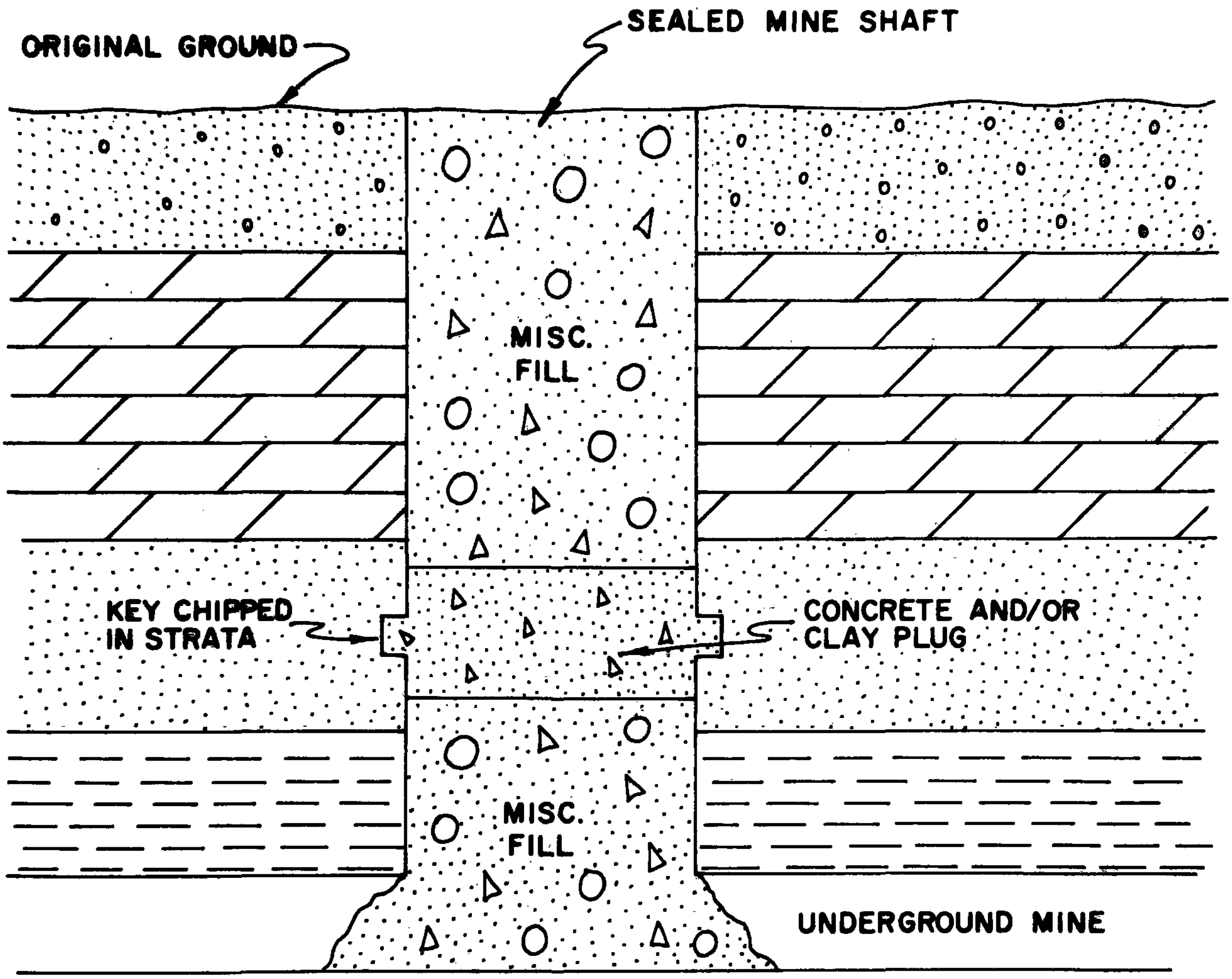


FIGURE 2.4-7-1

CROSS SECTION TYPICAL SHAFT SEAL

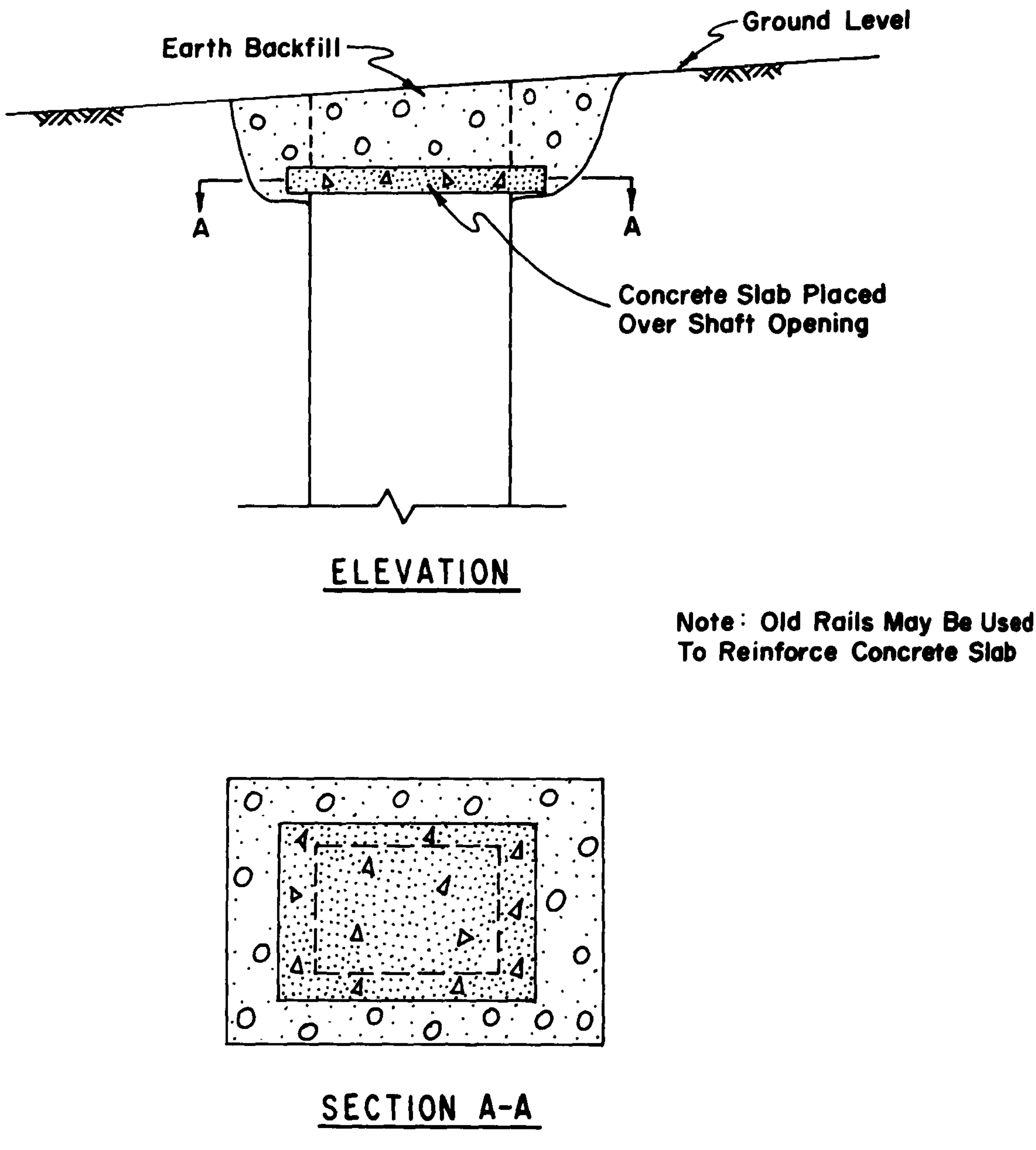


FIGURE 2.4-7-2

SHAFT SEAL WITH CONCRETE SLAB
(Adapted from Ref. 36)

Wildwood Mine, Allegheny County, Pennsylvania

In March, 1971, a discharge of approximately 8,706 cubic meters per day (2.3 MGD) containing 244 mg/l iron occurred from an abandoned air shaft at the Wildwood Mine near Pine Creek, Hampton Township, Allegheny County, Pennsylvania. The mine is in the Upper Freeport coal seam and had been in operation until December, 1968. Upon closure of the mine all boreholes were sealed with concrete, and slope and shaft entries were filled with incombustible materials. As the mine flooded discharges occurred from the air shaft, a slope entry, and a hillside breakout.

Remedial work performed at the mine included placing a concrete seal in the air shaft and grouting the slope and hillside discharges. The sealing operation was performed in the fall of 1972 by Allied Asphalt Company, Inc. under Pennsylvania Project SL 198 (84). Although all funds were expended, the mine was not completely sealed. Two small diameter pipes connecting the mine to the surface were overlooked while sealing the shaft. However, the iron concentration in the air shaft discharge decreased to 70 mg/l.

Work involved in sealing the air shaft included the following:

1. Diversion of drainage from the shaft by pumping.

2. Excavation of the shaft fill and cleaning of the shaft 3 to 4.6 meters (10 to 15 feet) below ground level.

3. Chipping a key in the shaft liner and coating with an expansion agent.

4. Installation of reinforcing rods and pouring a minimum 0.6 meters (2 feet) of concrete.

5. Grouting of any leaks that occurred after the seal cured.

6. Backfilling of the shaft to ground level.

The estimated costs of performing the specified work were:

Excavation and Backfill	765 cu m @ $2.62/cu m (1,000 cu yd)($2.00/cu yd)	$ 2,000
Pumping and Cleanout Labor and Equipment	40 hours @ $60/hour	2,400

Reinforced Concrete (Includes Key)	76.5 cu m @ $196/cu m (100 cu yd)($150/cu yd)	15,000
Cement Grout	100 bags @ $4.50/bag	450
	TOTAL	$19,850

EVALUATION AND RECOMMENDATIONS

Hydraulic sealing of shafts is generally more successful than sealing horizontal or near horizontal entries along outcrops. The extent of leakage around a shaft will be dependent upon the hydrostatic head and the vertical permeability of adjacent strata. In general, very deep underground mines can be successfully sealed. Leakage is likely to occur in shallow underground mines where there is the possibility of the mine flooding to a level above the seal elevation. A complete hydrogeologic evaluation should be made prior to shaft sealing.

In instances where it is determined that shaft discharges will not occur, rock and earth, or concrete cap type seals may be sufficient. However, concrete and/or clay plugs placed in a suitable sealing zone, such as a sandstone bed, are recommended for discharging shafts. The 1969 Health and Safety Act presently requires that all shaft openings in inactive or abandoned coal mines be either capped with concrete or filled for the entire depth of the shaft.

The cost of constructing shaft seals will be highly variable and will depend upon such factors as size and depth of the shaft; excavation, cleaning and backfilling required; type of seal placed; and grouting work required. The cost of backfilling abandoned shafts will generally range from $7,000 to $35,000 for shafts from 30.5 to 152 meters (100 to 500 feet) in depth. Concrete seals will generally range in price from $20,000 to $25,000 per seal.

REFERENCES

36, 71, 84, 127

2.4-8 GEL MATERIAL SEAL

DESCRIPTION

The construction of a gel material seal involves the injection of a chemical grout and filler into a mine cavity through a vertical borehole. The chemical grout has a controllable setting time which allows a stiff, gel-like plug to be formed in the mine cavity without the benefit of retaining bulkheads. The gel material produced must be strong, chemically resistant, impermeable, and capable of withstanding expected water pressure.

IMPLEMENTATION

Laboratory and Field Testing

Laboratory testing of commercially available grouts and filler materials was performed by Dravo Corporation to select materials suitable for constructing a gel material seal (25). Five different chemical grouts with various combinations of fly ash, mine refuse, sand, and gravel as fillers were tested. Of the five chemical grouts tested only AM-9, a vinyl polymer grout, was found to meet the requirements of adequate strength, good gel time control, and resistance to mine acid. A grout slurry of 6.8 kilograms (15 pounds) fly ash to 3.8 liters (1 gallon) of 15 percent AM-9 solution was selected for use in an experimental mine sealing project.

An abandoned deep mine located in Derry Township, Westmoreland County, Pennsylvania, approximately 56 kilometers (35 miles) east of Pittsburgh, was selected for demonstration of the gel material seal. The mine, which was known as the Salem No. 2 mine, is located in Keystone State Park. Of the three openings into the mine only one was discharging acid water. The two non-discharging entries were sealed with double bulkhead aggregate seals with concrete pressure grouted center plugs. The discharging entry was selected for injection of the gel material.

The seal was to be placed through a vertical borehole from the surface. After placement fly ash was to be pumped into the mine side of the seal. The fly ash was to neutralize any leakage that escaped the seal and to help plug any leaks that did develop. A sketch of the proposed seal is shown in Figures 2.4-8-1 and 2.4-8-2. The safety bulkhead is for protection during development and testing of the seal.

Actual injection of the grout material was begun on March 1, 1972. The grout slurry was directed upward and toward the walls through an injection nozzle. The anticipated result of this injection method was the formation of wedges on each side of the corridor which started at the walls and sloped toward the middle where mine drainage was flowing. As the wedges met the flow of mine drainage would be blocked and an effective hydraulic seal would be formed.

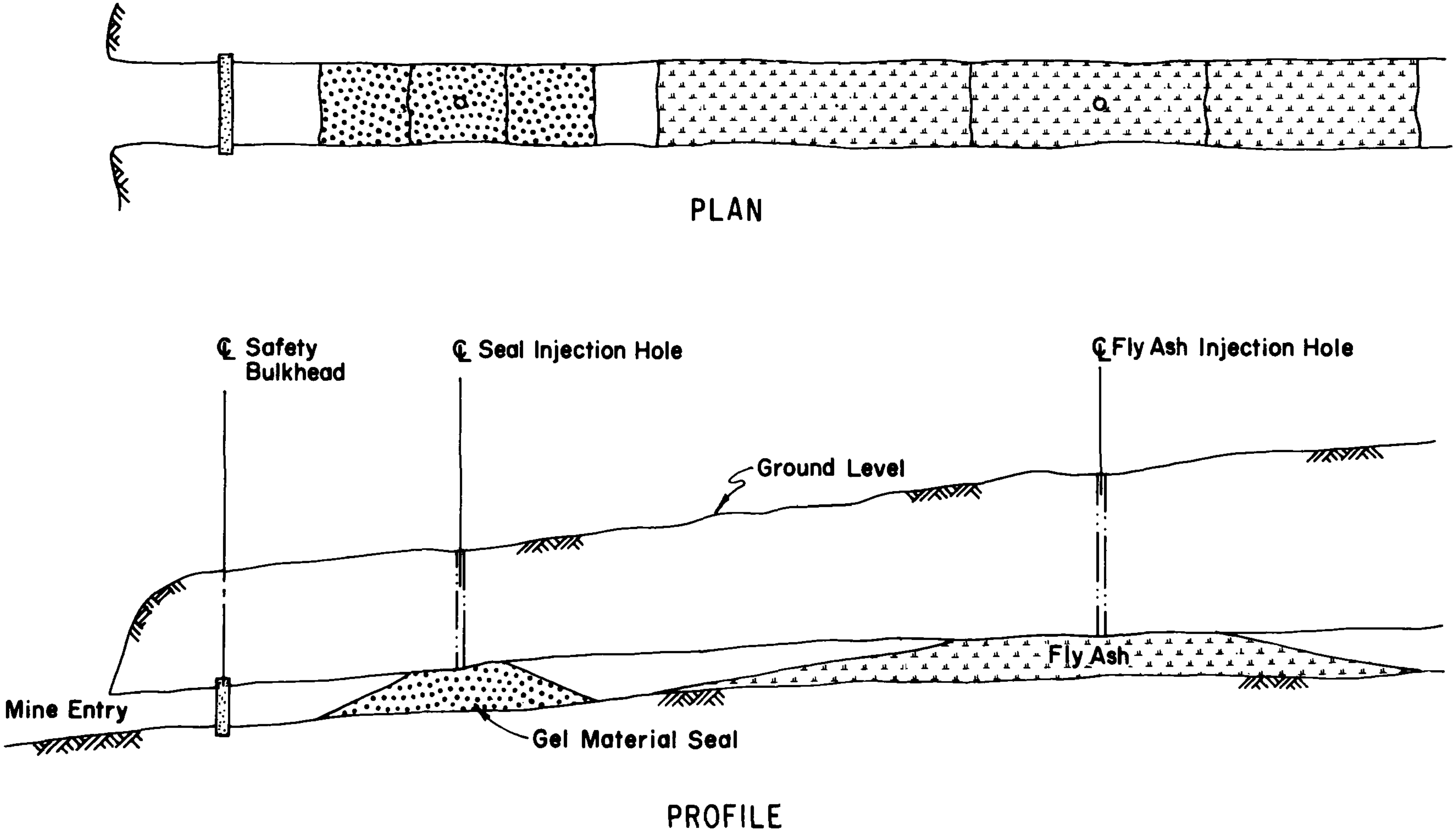


FIGURE 2.4-8-1

ARRANGEMENT OF PROPOSED GEL MATERIAL SEAL
(Adapted from Ref. 25)

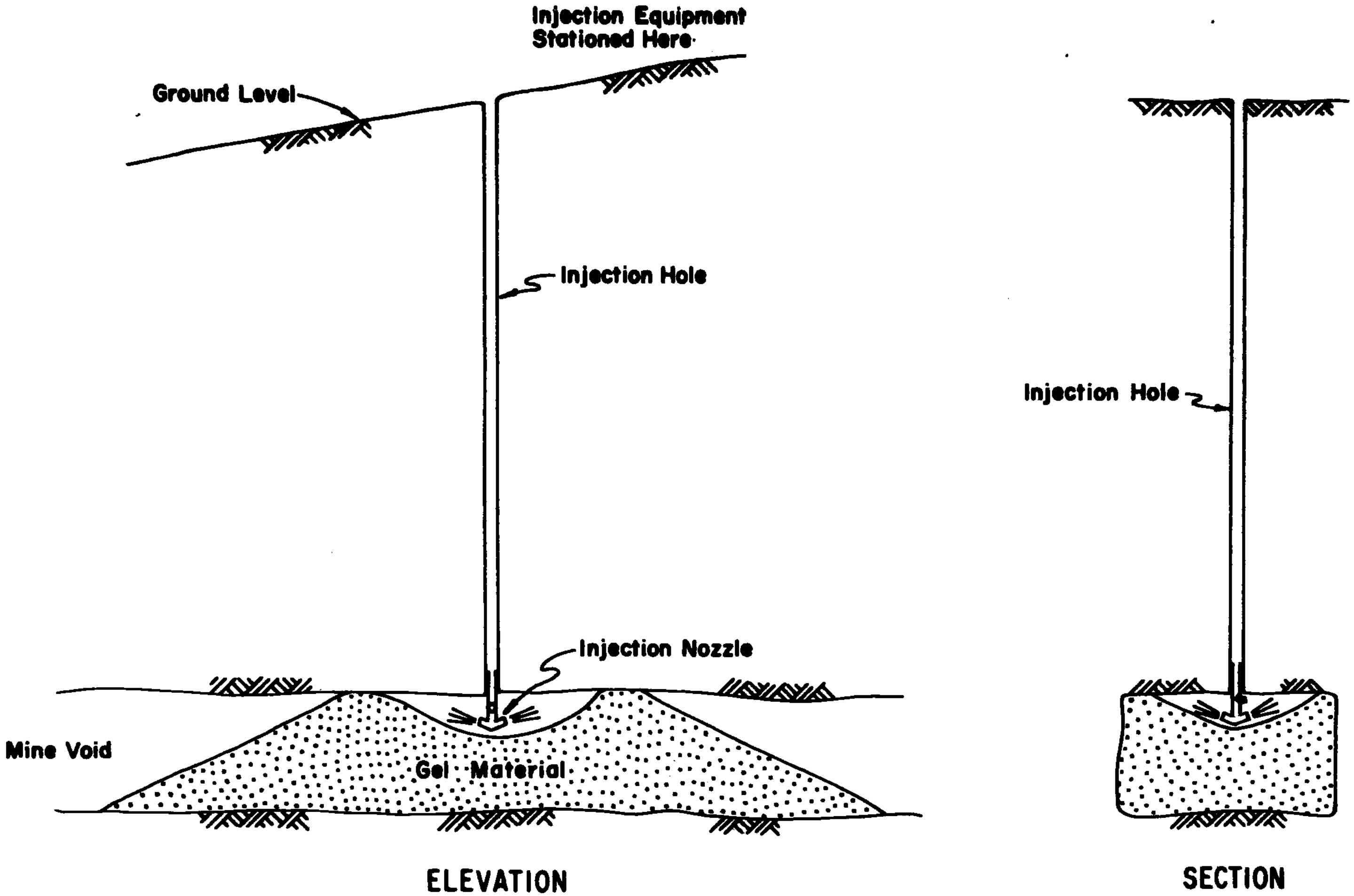


FIGURE 2.4-8-2

INJECTION PROCEDURE FOR GEL MATERIAL

(Adapted from Ref. 25)

The formation of the seal was never completed as the slurry was diluted by the mine drainage before a gel was formed. However, a satisfactory gel was apparently formed on both sides of the entry. The flow from the mine during slurry injection was approximately 9.5 liters per second (150 gpm).

Cost information for a completed gel material is not available. Dravo Corporation did, however, estimate that the cost of grouting materials for a mine seal 3.7 meters (12 feet) wide by 8.5 meters (28 feet) long would be $9,000. This estimate was based upon the use of AM-9 chemical grout.

EVALUATION AND RECOMMENDATIONS

Failure of the demonstration seal was attributed to dilution and erosion of the gel material in the high flow mine. The possible application of this sealing technique in low flow or dry mine entries has not been tested. Based on the estimated cost for the AM-9 grouting materials, this seal type is not competitive with other hydraulic sealing techniques.

Further research and demonstration efforts should be directed to reducing the cost of materials and injection procedures. Reductions in material costs may be achieved by investigating the application of various grout slurry mixtures. Modification of the grout mix with cement as an admixture may produce an acceptable sealing material. Quick setting bulkheads constructed with cement, bentonite, and sodium silicate slurries have been successfully demonstrated in accessible mine openings (See Sections 2.4-1 and 2.4-2). Material costs for these seals have been less than one-third the estimate for the AM-9 grout mix.

RFERENCES

25, 127

2.4-9 REGULATED FLOW SEAL

DESCRIPTION

Underground mine discharge rates are variable and depend upon the response of individual mines to seasonal variations in precipitation. Mines near the surface usually have a short response time. In underground mines having thick cover, precipitation may not affect the volume of mine water discharge for several weeks. Consequently, a mine may discharge maximum pollution loads to a receiving stream during periods of low stream flow. If the receiving stream is unable to assimilate the pollution load, adverse environmental effects can result. The regulated flow seal is designed to release mine water in amounts that the receiving stream is capable of assimilating at any given time (127).

This sealing technique may be used when complete inundation of a mine is impractical. All mine entries must be hydraulically sealed and capable of withstanding the maximum hydrostatic head expected during periods of maximum precipitation. The regulated flow seal is constructed with a pipe drain to maintain an acceptable discharge to the receiving stream.

IMPLEMENTATION

This is a theoretical mine drainage control technique; its use has not been documented.

EVALUATION

The implementation of regulated flow seals should be limited to abandoned underground mine discharges that are major sources of stream pollution. The economic feasibility of this technique can be determined by comparing the cost of treatment plant construction and operation, and mine seal installation.

The technical feasibility of implementing this technique will depend upon the ability to seal the individual mine. The maximum pool elevation that can be safely held by the mine seals and adjacent strata should be determined by performing a complete hydrogeologic study of the mine. A borehole should be drilled into the mine from a surface elevation equal to the maximum allowable mine pool elevation. This borehole would be used for mine pool monitoring and also function as an emergency overflow when the mine pool approaches its maximum safe level (See Section 2.4).

The drain pipe from the regulated flow seal should be equipped with either a manual or mechanical valve to regulate the mine discharge. The pipe and valve system should be capable of completely draining the mine pool in case of emergency or reopening of the mine.

Mechanical valves would be controlled by continuous monitors located in the receiving stream. These monitors would measure various properties of the stream (i.e., pH, flow, etc.) and regulate the mine discharge to maintain acceptable stream water quality. This system could also be operated in conjunction with a treatment plant. The stream monitoring equipment would be programmed to divert the mine discharge to the treatment plant only during periods when the stream was unable to assimilate the pollution load.

The costs of implementing this mine drainage control technique must be developed on an individual application basis. The total cost of hydraulically sealing the mine will depend upon the methods and extent of sealing required. Implementation of the regulated flow seal in conjunction with treatment facilities is expected to result in substantial savings in treatment plant capital and operating expenses.

REFERENCES

127

2.5 CURTAIN GROUTING

DESCRIPTION

Grouting is the process of injecting fluid materials into permeable rock and/or soil formations to fill pore spaces and reduce permeability. Curtain grouting is commonly performed in conjunction with hydraulic sealing of underground mines to control leakage around seals and stabilize outcrop areas. The grout mixtures are pressure injected through vertical boreholes. The injected material sets to form a stiff gel or hardened cement-type material that creates an impermeable barrier in the grouted medium (29).

Grouting mixtures are generally divided into two main categories, true solutions and slurries. Trué solutions are a mixture of soluble monomeric materials in water or other solvent. These solutions have low viscosity and may be injected into permeable zones without fracturing the treated medium. Slurries are suspensions of finely divided cementing materials in a fluid medium. These fluid materials are more viscous than true solutions and cannot be pumped into pores smaller than the grout particles. Slurries which are a combination of true solutions and finely divided solids have also been developed.

IMPLEMENTATION

Grout curtains are commonly utilized to control leakage around bulkhead seals. The grout is normally placed through boreholes drilled from above on 3 meter (10 foot) centers and extending away from the seal for a minimum 15.2 meters (50 feet) on both sides of the mine entry. This method of grouting is presently required as part of many of the mine sealing projects performed under Pennsylvania's Operation Scarlift program. Contract bids for Project SL 108-3-1, East Branch Clarion River, McKean County, Pennsylvania, which included construction of bulkhead seals and curtain grouting, were opened in December, 1974 (84). The engineer's estimate for pressure grouting was as follows:

	Quantity	Unit Price
Drilling 7.5 cm (3 in) holes	1,067 LM (3,500 LF)	$ 10.66 (3.25)
Drilling 15.2 cm (6 in) holes	76.2 LM (250 LF)	13.12 (4.00)
Cement for Grouting	907 metric tons (1,000 tons)	110.25 (100.00)

	Quantity	Unit Price
Fly Ash for Grouting	1,678 metric tons (1,850 tons)	22.05 (20.00)
Sand for Grouting	18 metric tons (20 tons)	44.10 (40.00)
Grout Admixtures		
Grout No. 1	45.4 kg (100 lb)	22.03 (10.00)
Grout No. 2	379 liters (100 gal)	3.96 (15.00)
Grout No. 3	379 Liters (100 gal)	3.96 (15.00)
Pressure Testing	20 hours	35.00
Grout Connections	100	5.00
Core Drilling	61 LM (200 LF)	47.57 (14.50)

Based on this estimate, the total cost for pressure grouting would be $158,275. The bid prices of six contractors for this grouting work ranged from $117,425 to $321,500.

Horizontal grout curtains have also been placed to reduce water infiltration through subsidence areas and other fractured zones. The effectiveness of these seals has depended upon the method of grout injection and the condition of the medium being treated. Minimum and maximum costs per hectare of horizontal grout curtain were estimated by Halliburton Company in1967 and are as follows (29):

Minimum Estimate

	Hectare	Acre
Site Preparation	$ 1,975	$ 800
Four holes – 15.2 meters (50 feet) Deep – Including Moving	1,358	550
Grout Packers	988	400
Piping, Valves, Labor	988	400
Incidental Expenses	494	200
Grouting Material	6,173	2,500
Water Storage and Hauling	1,235	500
Mixing and Placement Equipment	1,556	630
Engineering Service	1,235	500
TOTAL	$16,002	$ 6,480

Maximum Estimate

	Hectare	Acre
Site Preparation	$ 2,469	$ 1,000
100 holes – 15.2 meters (50 feet) deep – Including Moving	2,716	1,100
Packers	12,346	5,000
Piping, Valves, Labor	7,407	3,000
Incidental Expense	1,235	500

	Hectare	Acre
Grouting Material	6,173	2,500
Water Storage and Hauling	1,852	750
Mixing and Placement Equipment	4,691	1,900
Engineering Service	2,716	1,100
TOTAL	$41,605	$16,850

The effectiveness of grouting operations will be difficult to assess. During injection of the grout material there is no way to determine where the grout is going or how effectively it is sealing permeable areas. The effectiveness of curtain grouting has not been documented by monitoring of seepage rates through permeable zones. However, grouting of bulkhead perimeters, subsidence fractures, shaft seals, and aggregate bulkheads has successfully reduced mine water discharges from underground mines.

EVALUATION AND RECOMMENDATIONS

Curtain grouting is a convenient and generally effective method of reducing the flow of water through fissures, fractures, and permeable strata. The placement of grout curtains simply requires the drilling of holes and pressure injection of the grouting material. However, grouting operations require skilled personnel having knowledge of the available grout materials, the equipment used, and the various grouting techniques.

The effectiveness of grout curtains will depend upon the method of injection, the grout material applied, and the type and condition of the geological formation being treated. Grout packers may be utilized to plug the grout hole and allow grouting of individual zones. Alteration of the grout mixture and viscosity will further improve the efficiency of grout injection. A limited subsurface investigation should be performed to obtain information on the character of the strata to be grouted and assist in the estimate of grouting requirements. Grout holes must then be properly spaced to ensure that the total area between holes receives grout treatment.

The following factors must be considered when estimating the cost of placing grout curtains: grout materials and admixtures, drilling and injection equipment, site preparation, labor requirements, water storage and handling, grout packers, and engineering service. The major factors affecting the total cost of placing the grout curtain will be the amount of drilling required and the total volume of grout injected. Vertical grout curtains will normally range in cost from \$115 to \$262 per linear meter (\$35 to \$80/LF) of curtain. The cost of horizontal grout curtains will range from \$29,630 to \$49,400 per hectare (\$12,000 to \$20,000/acre).

REFERENCES

27, 29, 32, 46, 84, 89, 127

3.0

MINING METHODS

3.1 GENERAL DISCUSSION

This section will discuss mining methods that may be implemented to prevent or control the formation of mine drainage pollutants after underground mining is completed. Mining methods discussed will include downdip, longwall and daylighting. Downdip and longwall mining may be incorporated in active underground mines. Daylighting is not a method of underground mining, but is a means of controlling water pollution from abandoned underground mines. These methods will not be universally applicable. Their feasibility will be determined by the characteristics of individual mine sites.

3.2 DOWNDIP MINING

DESCRIPTION

Many of the presently inactive and abandoned underground mines were devloped to the rise. Mine openings were located at a low elevation in the mineral seam and active mining proceeded updip. This method of mining allows easy haulage of loaded mine cars downdip to the mine entrance. It also allows gravity discharge of most water infiltrating into the active workings. However, mines developed to the rise are potential sources of mine drainage pollution. Water entering the mine often becomes polluted and will be free to flow from the mine both during active mining and after abandonment. Sealing of many of these abandoned mines will be extremely difficult due to excessive hydrostatic heads that will develop as the mine floods.

A significant amount of the mine drainage problem we now face would not have occurred if the mine had been developed downdip. This mining method involves the location of mine openings at a high elevation in the mineral seam and development of the mine in a downward direction. After the mine is abandoned flooding will be automatic and the hydrostatic head developed at sealed entries will be minimized (70, 127).

The implementation of the downdip mining method will result in additional costs during active mining. Water collecting in active sections of the mine must be pumped to the surface. These costs will be highly variable and may be prohibitive at times. Hydraulically sound mineral barriers must be left in place around the mine perimeter, so that flooding will occur naturally. Since these barriers consist of in place minerals, they result in a loss of an appreciable amount of potentially recoverable mineral.

IMPLEMENTATION

The downdip method of mining was recently investigated by Skelly and Loy, Engineers and Consultants under contract to the United States Environmental Protection Agency. The project included physical and economic evaluation of updip and downdip mining on both active and abandoned mine sites. A draft report (104) was submitted to EPA in February, 1975.

The pollution control effectiveness of downdip mining was evaluated by comparing two abandoned underground coal mines. These mines were the Shoff and Yorkshire No. 1 Mines which lie in Bigler Township, Clearfield County, Pennsylvania, on opposite banks of Clearfield Creek. These two mines had the following similarities (104): coal seam mined (Clarion coal or "A" seam), coal quality, mine size, mining method, time period of operation, availability of mine history and mapping, geologic controls, hydrologic controls, topographic regime, and measurable discharges. The major dissimilarity was the method of mine development. The Shoff Mine was developed updip while the Yorkshire No. 1 Mine was developed downdip.

To evaluate the effectiveness of mine flooding in controlling or eliminating the production of acid mine drainage, monitoring stations were established at all discharge points of both mines. Five discharge points at the Shoff Mine and two at the Yorkshire No. 1 Mine were sampled eight times between July 30, 1974 and December 2, 1974.

A comparison of the quality of water discharging from the two mines indicates that the Yorkshire No. 1 Mine discharges were of better quality than those of the Shoff Mine. The range in concentrations of various mine drainage indicators during the sampling period was as follows:

	Shoff Mine	Yorkshire Mine
Field pH	2.1 – 5.1	4.4 – 5.8
Acidity (mg/l)	340 – 4,600	16 – 116
Total Iron (mg/l)	12.7 – 1,335	0.3 – 59.4
Sulfates (mg/l)	475 – 3,750	300 – 575
Manganese (mg/l)	3.7 – 18.4	1.5 – 3.4
Aluminum (mg/l)	0.4 – 95.5	0 – 7.2
Specific Conductance (micromhos)	1,025 – 4,550	600 – 1,010

Water quality data clearly shows that the unflooded Shoff Mine is a major source of mine drainage pollution, while discharge quality from the flooded Yorkshire No. 1 mine ranged from marginal to slightly acid. Since the abandoned mines were similar in all other respects, the report concluded that the primary factor controlling water quality was the direction of mine development.

An active mine having both updip and downdip sections was evaluated to determine major advantages and disadvantages of each method of mine development. This mine, the Stott No. 1 Mine is located in Huston Township, Clearfield County, Pennsylvania and operated by Lady Jane Collieries, Inc. The mine is operated in the Lower Kittanning coal seam. Conventional room and pillar mining methods are used and coal is transported from the mine by a conveyor belt system.

The major factors expected to be affected by the method of mine development were production, coal haulage, and pumping. An evaluation of these factors at the Stott No.1 revealed the following (104):

1. During 1973, production from updip and downdip sections was approximately equal, and mining downdip was no more or less advantageous than mining updip.

2. The direction of belt haulage in any mining situation, including downdip mining, does not appear to be a significant economic factor.

3. Pumping costs may be substantially increased by downdip mine development, but they most likely will not reach the point of adversely affecting production economics.

EVALUATION AND RECOMMENDATIONS

The downdip mining method should be considered as an alternative to mine sealing or treatment to maintain acceptable water quality from abandoned underground mines. Since mine entries are located at an elevation above the underground workings, flooding of the mine can occur naturally when mining is completed. Flooding will isolate sulfide minerals in the mine, and thus, control the formation of acid mine drainage pollutants. Since oxidation will be minimized, water discharging from flooded downdip mines should normally be of better quality than discharges from unflooded updip mines.

Mining downdip will also improve the feasibility of sealing mine entries to control mine drainage pollution. The ability to effectively hydraulically seal a mine depends not only upon the strength of the seal, but also on the condition of the natural mine system (See Section 2.4). When mines are developed updip, mine seals and adjacent strata (which is often fractured and unsound) will be subjected to maximum hydrostatic heads. When downdip mining is implemented these hydraulically unsound areas will be subjected to little or no water pressure.

Initial evaluations indicate that there are no technological limitations to the implementation of this mining technique. At the active mine site in Pennsylvania, neither mine production nor haulage and pumping costs were significantly affected. However, due to the variable nature of individual mines, production economics must be evaluated at each potential mine site.

Downdip mining should be implemented wherever significant reduction in pollution discharges will result. This mining technique is expected to be of major economic importance to coal mine operators who will be required to comply with the recently proposed effluent limitation guidelines for the coal industry. These guidlines will require an operator to meet certain effluent standards both during mining and after abandonment, regardless of the mining method employed.

REFERENCES

27, 31, 70, 72, 81, 104, 127, 129

3.3 LONGWALL MINING

DESCRIPTION

Longwall mining is a method of removing a mineral seam in one operation by means of a longwall or working face. The workings advance in a continuous line which is usually 61 to 183 meters (200 to 600 feet) in length, but reportedly, may exceed 305 meters (1,000 feet). Self-advancing powered supports are commonly utilized to keep the longwall face open and prevent roof falls. As mining progresses, the supports are advanced and the roof is allowed to break and cave immediately behind the support line (46, 113). A plan of the longwall mining system is shown in Figure 3.3-1.

At the present time the longwall method is employed primarily for the mining of coal. However, its use may be extended to other sedimentary deposits such as clay, gypsum and salt. The thickness of the longwall cut will be limited by the height of available roof supports. Flat to moderately dipping coal seams may be successfully mined with the longwall system.

IMPLEMENTATION

Longwall mining has reportedly been practiced in at least the following countries: China, England, France, Germany, India, Poland, Russia and the United States. As of 1970, the United States had longwall units operating in 18 coal mines in the states of Pennsylvania, Utah, Virginia, and West Virginia. In these mines seam thickness and length of longwall face ranged from 97 to 213 centimeters (38 to 84 inches and 91 to 182 meters (300 to 600 feet) respectively. The U.S. Bureau of Mines has proposed that longwall methods be used to mine thick seam coal reserves of the western United States.

EVALUATION AND RECOMMENDATIONS

Longwall mining is employed primarily for the advantages achieved during active mining (i.e., increased production and efficient mineral recovery). However, longwalling should also be an effective method of preventing mine drainage pollution after mining is complete. Fracturing and caving of the roof behind the advancing face will reduce void space within the mine. This may result in reduced oxygen-sulfide contact, and thus, the oxidation of sulfides will be inhibited.

Although caving may prevent the production of mine drainage pollution in an abandoned mine, the volume of water infiltrating during active mining may be significantly increased. This water must be pumped from the mine and may require

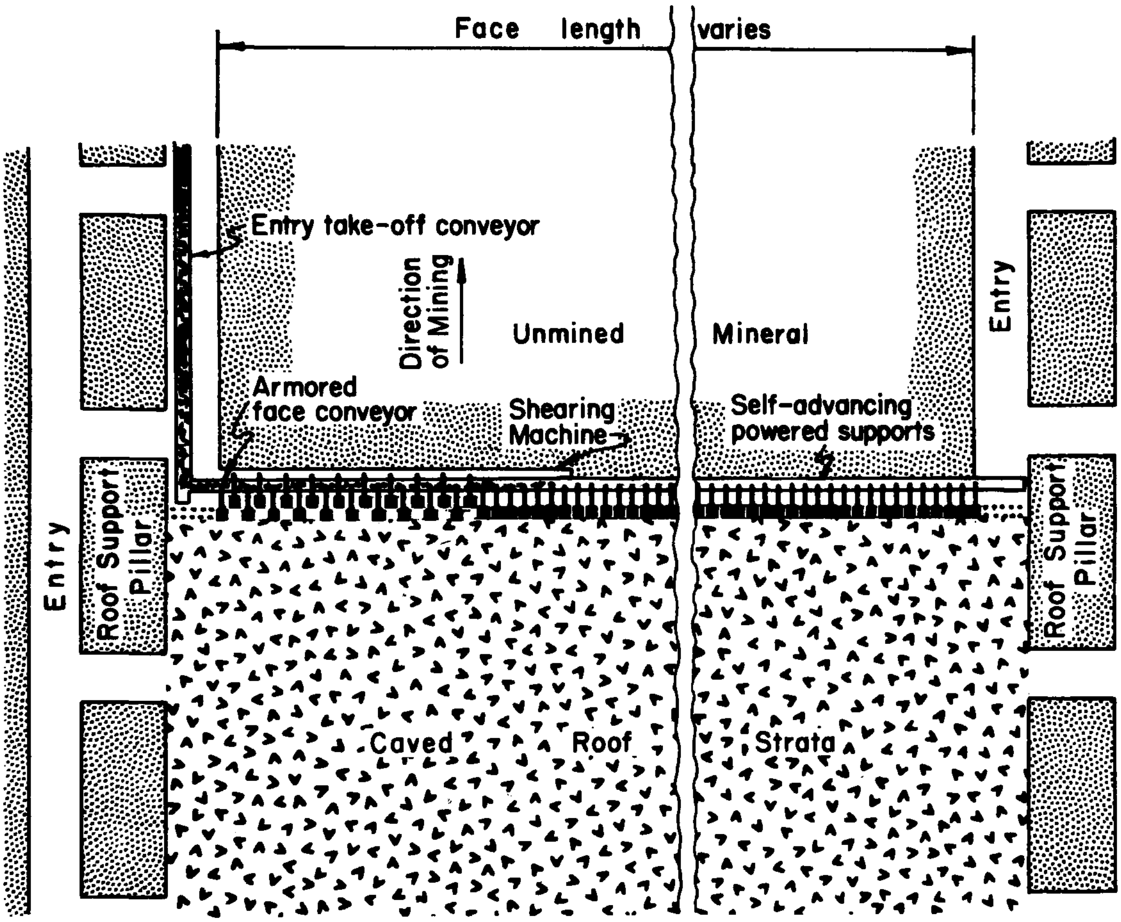


FIGURE 3.3—1

TYPICAL LONGWALL PLAN

treatment prior to discharge on the surface. Increases in pumping and treatment costs will place a financial burden upon the operator during mining. However, since the production of mine drainage pollutants in abandoned sections will be retarded, a reduction in pollution loads discharging from the mine will result.

The implementation of this mining technique should be of major economic importance, especially to coal operators who will soon be required to comply with the recently proposed effluent limitation guidelines for active and abandoned mines in the coal industry.

REFERENCES

46, 113

3.4 DAYLIGHTING

DESCRIPTION

Daylighting is the term applied to the stripping of recoverable mineral reserves in abandoned underground mines. The technique is performed in the same manner asstrip mining. Overburden is removed, mineral reserves are recovered, and the area is backfilled, graded, and revegetated. This technique abates mine drainage discharges by removing pollution forming material and replacing the abandoned mine void with a regraded surface mine.

Two major factors which will determine the feasibility of daylighting a particular area are the thickness and type of overburden material, and the quality and amount of recoverable mineral. The total value of the recovered mineral must offset the cost of the daylighting operation, including mineral and surface rights acquisition. Other factors affecting feasibility are access to the site, topography of the area, and the ability to control erosion and water pollution during operation (31, 127).

As shown in Figure 3.4-1 excavation and mining proceeds in a cut sequence. As each new cut is made, spoil material is placed in the previously mined area to the rear of excavation. Excavating and mining equipment are located on the bench between the highwall and spoil. When topography allows, spoil material from the initial cut may be placed along the outcrop. If this is not feasible, the spoil may be stockpiled in an adjacent area and later returned for backfilling of the mined area. After completion of the final cut the entire mined area is reclaimed by grading and revegetating.

IMPLEMENTATION

Daylighting as a mine drainage abatement technique is presently in the research and development stage. A study was performed to determine the technical and economic feasibility of daylighting an abandoned underground mine in the Lostland Run watershed of the Upper Potomac River basin near Deer Park, Garret County, Maryland (31). The study concluded that daylighting at the project site was feasible and that reclamation would produce usable land and improve present water quality. The completed project should eliminate 227 kilograms per day (500 lb/day) of acid discharging from the 30 hectare (75 acre) site into the North Branch of the Potomac River via Lostland Run.

The coal seam selected for the project demonstration is the 1.3 meter (51 inch) Lower Bakerstown which has a maximum overburden thickness of approximately 16.8 meters (55 feet) at the project site. This coal has been previously surface and

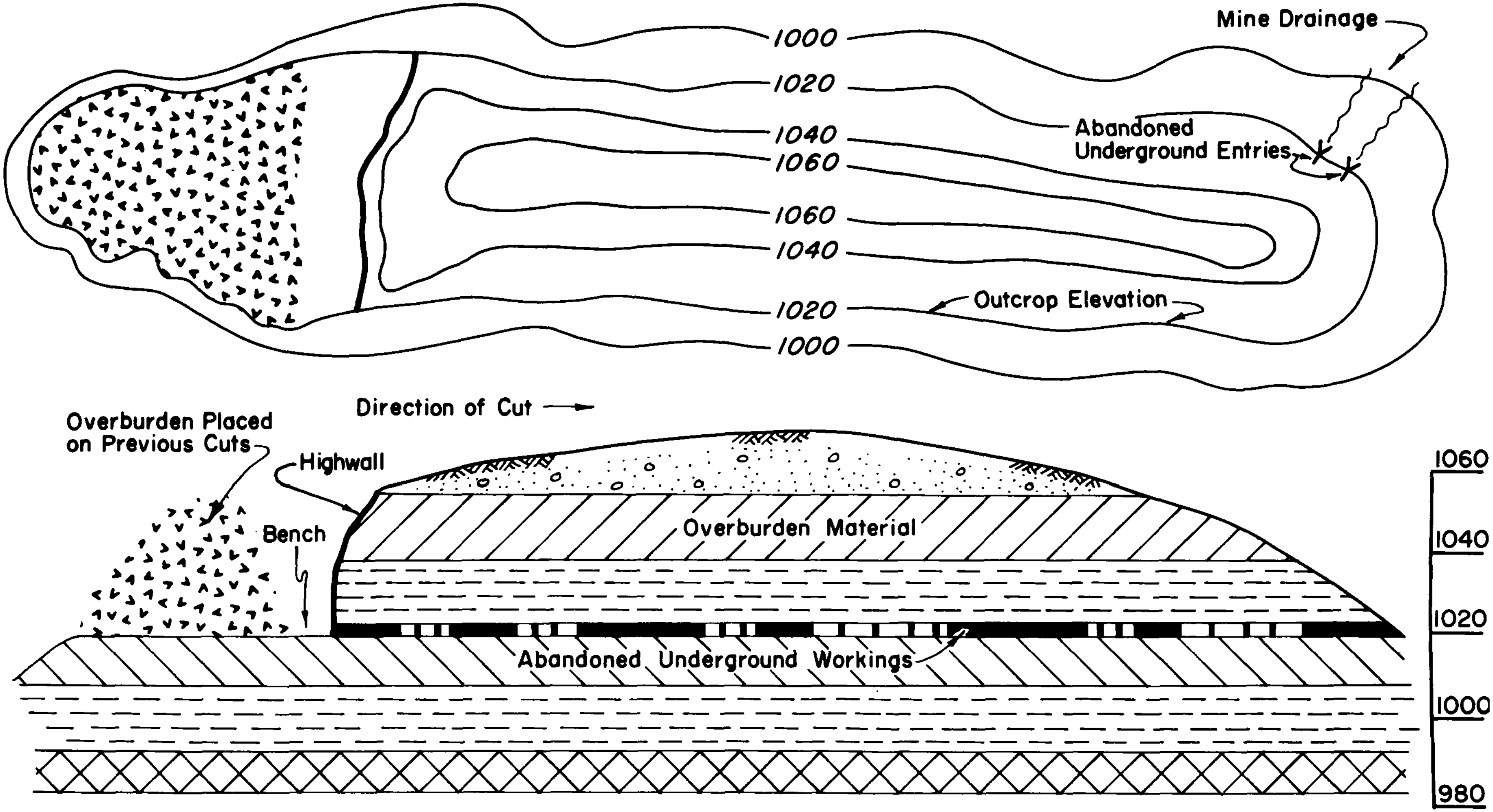


FIGURE 3.4-1

DAYLIGHTING OF ABANDONED UNDERGROUND MINES deep mined. An estimated 30 to 35 percent of the Lower Bakerstown coal remains in-place, underlying the unstripped areas of the site.

The proposed sequence of operation at the demonstration site is as follows (31):

1. Clearing and grubbing of 12 hectares (30 acres) of one growth timber and evergreens.

2. Stockpiling of upper 0.6 meters (2 feet) of topsoil material.

3. Constructing drainage ditches around the site to divert drainage to two siltation ponds.

4. Excavation of overburden material and mining of coal in a cut sequence.

5. Regrading of mined area.

6. Soil preparation, seeding, and mulching of regraded area.

7. Monitoring of site discharges to evaluate effectiveness of project.

Although the feasibility study concluded that daylighting was technically and economically feasible, the project has been delayed by land easement problems since September, 1973. The demonstration project at Deer Park is now expected to begin in the late spring or early summer of 1975.

In September, 1973, the cost of this demonstration project was estimated at $482,735. Credit for the sale of coal was estimated at $191,000. This estimate was based upon a sale price for coal of $4.69 per metric ton ($4.25/ton). Recent increases in coal prices will improve the economic feasibility of the project. An additional $4,500 was credited to the project for reclamation of the 6.1 hectare (15 acre) Buffalo Coal Company strip mine. The total estimate of project costs was as follows (31):

Estimated Cost	$476,760
Credit for Coal	-191,000
Credit for Reclamation	- 4,500
Estimated Net Cost	$281,260
Water Analysis	6,450

Additional Soil Nutrient Analysis Phase II, III	3,800
Engineering plus Fees (Includes Stream Gauging and Sediment Monitoring Stations)	191,225
TOTAL	$482,735

EVALUATION AND RECOMMENDATIONS

Daylighting is a method of mining that can be utilized to eliminate pollution from abandoned underground mines. This method is similar to the mountain top removal method of surface mining which is presently used to remove coal seams that lie high on a mountain and cannot be mined by underground methods. The major difference between these two techniques is the condition of the seam being mined. Virgin seams would be mined by the mountain top removal method, while daylighting would be performed to completely strip out abandoned underground workings.

The feasibility of daylighting will depend upon the total value of mineral reserves that will be recovered during mining. Therefore, a complete resource evaluation will be required to determine the quality and amount of remaining mineral. Mining costs including land acquisition, overburden removal, and reclamation must then be developed. The total cost of mining may exceed the market value of the mineral reserves. In such instances the daylighting operation may be subsidized and the subsidy cost could be partially or completely balanced in terms of pollution abatement benefits.

REFERENCES

31, 38, 108, 125, 127

4.0

WATER HANDLING

4.1 GENERAL DISCUSSION

This section will discuss various methods of reducing the environmental impact of mine drainage pollutants discharging from abandoned underground mines. These techniques may be applied in conjunction with at-source abatement and control techniques (i.e., water infiltration control, mine sealing) or implemented as an alternative to treatment when at-source techniques are technically infeasible or economically unattractive.

Water handling may include methods for conveying water from the mine, regulating mine discharge to the environment, or reducing the pollution load of the discharge. These techniques will not be applicable to all mine drainage situations. The selection and implementation of water handling techniques will depend upon such factors as geology, hydrology, topography, and climatology of the mine area. The techniques discussed in this section will include: evaporation ponds, slurry trenching, alkaline regrading, controlled release holding ponds, and connector wells.

4.2 EVAPORATION PONDS

DESCRIPTION

Holding ponds may be constructed to collect and impound discharges from abandoned underground mines, thus, preventing discharge to the environment. This system is designed to allow evaporation of the mine water to the atmosphere. Therefore, its use will be limited to arid or semiarid areas having high evaporation rates. The impoundment or series of impoundments must be capable of handling peak discharge rates during periods when precipitation exceeds evaporation rates. The impoundment structure must be constructed of materials that will prevent leakage of the impounded water.

IMPLEMENTATION

In the Republic of South Africa, shallow lakes and evaporation areas have been established for the disposal and storage of mine water from underground coal and gold mines (107). These waters may be utilized as cooling water or process water for selected industries requiring low quality water, or for large scale desalination should this process become economically feasible. In the Orange Free State, various shallow lakes are presently being utilized for recreational purposes. Evaporation areas are also designed to collect storm water runoff and mineral pollution from slime dams.

The implementation of these waste water control techniques is expected to reduce effluent volumes from mining activities to manageable proportions. The establishment of large scale projects throughout the Republic of South Africa, however, will require thecooperation and assistance of government, local, and regional authorities.

The impounding of mine drainage has been considered in the United States as a preventative measure in controlling stream pollution from acid mine water (69). Ponds are commonly used for settling of insoluble compounds in mine and treatment plant discharges, regulating the rate of discharge to streams, and impoundment of mine refuse and preparation plant wastes. Documented cases of the utilization of evaporation ponds as a sole water pollution control device were not available in the literature.

EVALUATION AND RECOMMENDATIONS

Evaporation ponds would appear to be an efficient method of controlling discharges from underground mines in semiarid mining regions of the West and Southwest. This system must have the capacity to collect and impound the mine discharge during winter months when evaporationrates will be low and during periods of peak discharge rates. Periodic inspection and maintenance of the impoundment will be required to ensure that the system functions properly. To maintain sufficient storage capacity, settled solids must be periodically removed from the pond.

The planning and construction of evaporation pond systems will require an investigation of the hydraulic and meteorological characteristics of the abandoned mine site. The impoundment must be constructed of materials capable of withstanding the maximum expected water pressure. Lining of the bottom of the pond with clay or other suitable material may be required to control leakage and prevent pollution of ground water. An overflow device should be constructed to prevent erosion or rupturing of the impoundment structure during peak flow periods. If the impoundment is to be utilized for recreational activities, the construction plan should provide access to the area.

The cost of constructing the impoundment structure including materials, compacting, and grading will generally range from $1.31 to $2.62 per cubic meter ($1.00 to $2.00/cu yd). Lining costs will depend upon the material used and the area covered. Clay liners will range in cost from $1.20 to $2.40 per square meter ($1.00 to $2.00/sq yd). Riprap and vegetative cover for slope protection may be required and will result in increased expenditures.

REFERENCES

69, 70, 96, 107, 127

4.3 SLURRY TRENCHING

DESCRIPTION

A slurry trench is a narrow, vertical excavation in unconsolidated material with the sides maintained by a water, clay slurry (usually bentonite). The trench may be excavated with a backhoe, clam shell, dragline or connecting drill holes. The clay slurry is backfilled, when possible, with the previously excavated material or material with suitable grain size distribution. As the slurry dries an impermeable clay is formed in the trench, thus, in effect, forming a ground water dam. The technique has been primarily used for dewatering building foundations and for ground water cut-off trenches below dams placed on unconsolidated material (70, 84, 105, 127).

A slurry trench may be used to control mine drainage discharges from underground mines in areas where discharges are occurring from mine openings, outcrop areas, highwalls, intersected underground workings, etc. In such situations, the placement of a slurry trench with a top level above that of the discharge will result in an increase in water level at the discharge point, and in the underground mine. Acid production will be reduced as the result of inundating oxidizable sulfide minerals. Figure 4.3-1 illustrates the utilization of a slurry trench to control mine drainage from underground mine workings intersected by surface mine operations.

IMPLEMENTATION

Rattlesnake Creek Watershed, Pennsylvania

The final inspection of construction of approximately 412 meters (1,350 feet) of slurry trench in the Rattlesnake Creek watershed, Jefferson County, Pennsylvania was completed in November, 1974. Construction was performed under Pennsylvania Project SL 132-2-101.1 by Trans-Continental Construction Company, Inc. (84). Two trenches were constructed along the highwall of an abandoned surface mine. Trench I begins on the east end of the surface mine and runs along the highwall for approximately 351 meters (1,150 feet). Trench II joins Trench I and continues around the hillside for approximately 61 meters (200 feet) to enclose an abandoned underground coal mine entry. Plan and elevation views of the two slurry trenches are shown in Figure 4.3-2.

The surface mine and underground entry had previously been backfilled. The backfilling of the underground entry resulted in a partial flooding of the mine and a subsequent leakage of mine drainage through the coal seam along the surface mine highwall. The slurry trench was placed in an attempt to increase the water level in the underground mine and control leakage from the highwall. Field investigations of

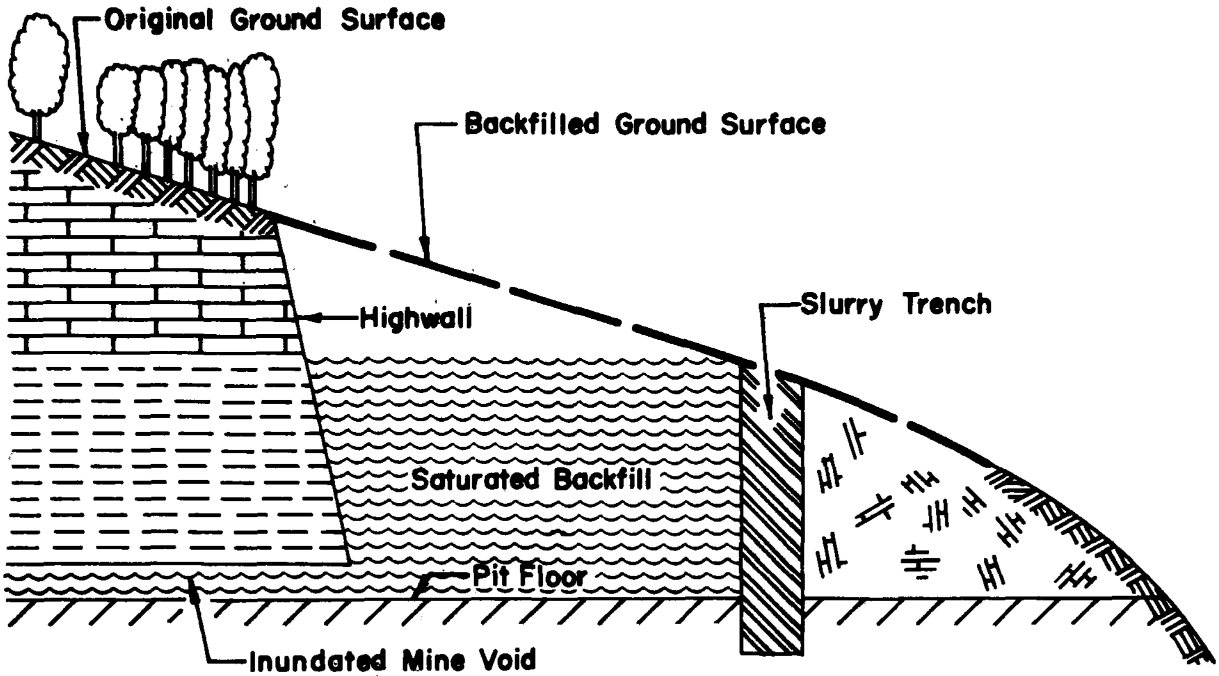


FIGURE 4.3-1

TYPICAL SLURRY TRENCH DETAIL
(Adapted from Ref. 105)

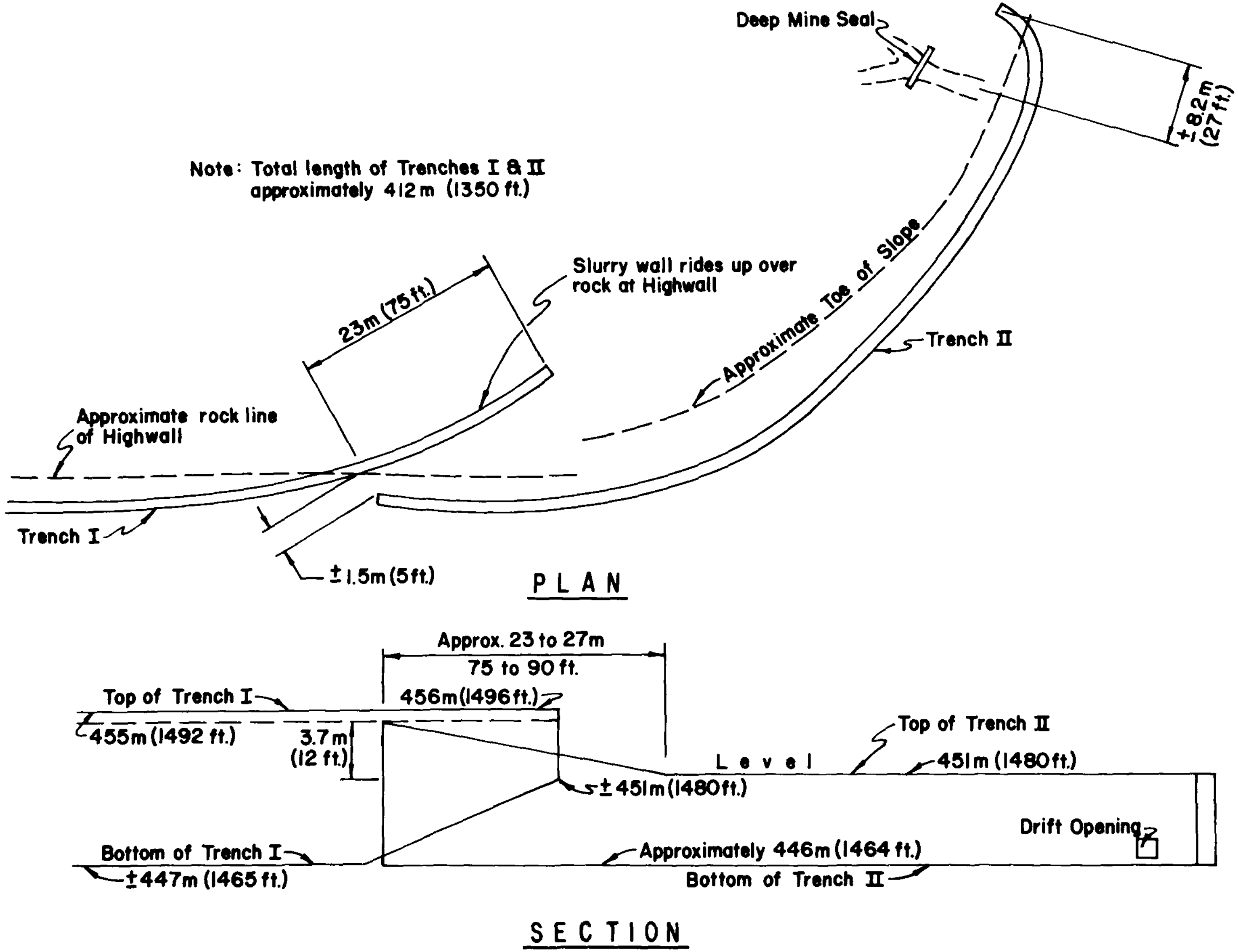


FIGURE 4.3-2
SLURRY TRENCH CONSTRUCTION
RATTLESNAKE WATERSHED, PA.

the completed project indicate that an increase in water level in the underground mine has occurred and water is discharging over the slurry trench.

Work performed in placing the slurry trench, as outlined in the technical specifications, included the following:

1. Clearing and grubbing within the limits of grading.

2. Dewatering of the underground mine so that a reinforced concrete seal could be constructed.

3. Removal and burial of bony and acid forming material on the work area.

4. Grading of the work area.

5. Constructing a diversion ditch above the highwall to divert water away from the graded area.

6. Placing riprap to control erosion.

7. Placing drainage flume and constructing concrete endwall.

8. Placing approximately 2,787 square meters (30,000 sq ft) of slurry trench as measured on a vertical plane through centerline of trench (maximum depth 8.5 meters (28 feet) – Minimum width 0.6 meters (2 feet)).

9. Placing reinforced concrete deep mine seal in the mine opening.

10. Timbering on each side of the mine seal.

11. Revegetation – Liming, treating with soil supplement, seeding, and mulching.

Total costs incurred in constructing the two slurry trenches were $190,835. The cost of placing the estimated 2,787 square meters (30,000 sq ft) of slurry trench was $123,000 which equals a cost per square meter of $44.13 ($4.10/sq ft). Itemized construction costs were as follows:

Clearing and Grubbing	Lump Sum	$ 6,075
Dewatering Deep Mine	Lump Sum	7,500
Removal and Burial of Bony Material	Lump Sum	7,650

Grading	Lump Sum	15,000
Diversion Ditch (Above Highwall)	56.4 m @ $3.28/m (185 ft)($1.00/ft)	185
Riprap	50 sq m @ $24/sq m (60 sq yd)($20/sq yd)	1,200
Drainage Flume	96 m @ $65.62/m (315 ft)($20/ft)	6,300
Concrete Endwall	Lump Sum	1,000
Reinforced Concrete Mine Seal	9.6 cu m @ $130.79/cu m (12.5 cu yd)($100/cu yd)	1,250
Timber Sets	10 @ $200 each	2,000
Revegetation	Lump Sum	14,625
Treatment of Mine Drainage	101 hours @ $50/hr	5,050
Placing Slurry Trench	Lump Sum	123,000

Elk Creek Watershed, West Virginia

Skelly and Loy, Engineers and Consultants has completed pre-design engineering for the demonstration of slurry trenching within the Elk Creek watershed, West Virginia (105). Five sites were evaluated to determine the feasibility of demonstrating slurry trenching in conjunction with alkaline regrading (See Alkaline Regrading, Section 4.4). Each of the demonstration sites lies in an area of past extensive underground and surface mining of the Pittsburgh and Redstone coal seams. The sites are characterized by pollution discharges resulting from breached crop barriers during subsequent strip and auger mining.

The slurry trenches will be constructed into the underclay of the Pittsburgh seam. Limestone and soft claystone above this seam provide large volumes of alkaline rich spoil material. Prior to slurry trench construction this spoil will be regraded to a modified contour or terrace backfill. After regrading the slurry trench will be excavated through the spoil to the Pittsburgh underclay. The completed slurry trench will cause a rise of mine water within the spoil material prior to discharge over the trench. The depth of the constructed slurry trench will be 4.6 to

7.6 meters (15 to 25 feet). The proposed project will demonstrate the neutralization of mine water within the spoil and the decrease in acid production due to deep mine inundation. A profile and cross sections of slurry trench construction proposed for the Elk Creek project are presented in Figures 4.3-3 and 4.3-4.

An estimate of construction costs has been made for each of the five demonstration sites within the watershed. The estimated costs for Site No. 1 including aerial photography, mapping, regrading, revegetation, and constructing 610 linear meters (2,000 LF) of slurry trench are $189,700. Approximately 477 kilograms per day (1,051 lb/day) of acid will be neutralized which equals an estimated cost effectiveness of $398 per kilogram per day ($180 per lb/day) of acid abated. Estimated costs are as follows:

Grading	22,938 cu m @ $0.65/cu m (30,000 cu yd)($0.50/cu yd)	$ 15,000
Slurry Wall 0.6 m thick (2 ft)	3,716 sq m @ $43.06/sq m (40,000 sq ft)($4.00/sq ft)	160,000
Revegetation	2.43 ha @ $1,235/ha (6 ac)($500/ac)	3,000
Contingency	5 percent	8,900
Aerial Photography and Mapping	Lump Sum	2,800
	TOTAL	$189,700

Estimated construction costs at Site No. 2 are $173,000, which includes roof collapse in conjunction with constructing the slurry trench. Elimination of the $10,000 lump sum estimate for mine roof collapse and adjustment of contingency, results in an adjusted estimated cost of slurry trench construction of $162,500. Estimated construction costs excluding mine roof collapse would be:

Grading	45,876 cu m @ $0.65/cu m (60,000 cu yd)($0.50/cu yd)	$ 30,000
Slurry Wall 0.6 m thick (2 ft)	2,787 sq m @ $43.06/sq m (30,000 sq ft)($4.00/sq ft)	120,000

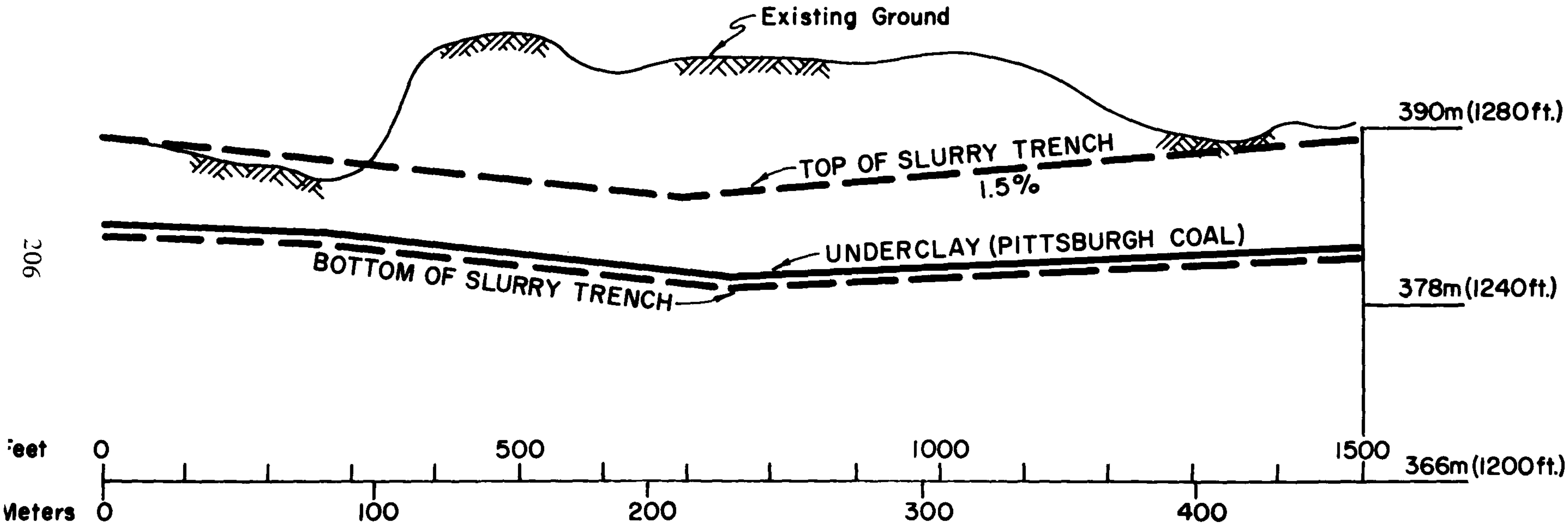
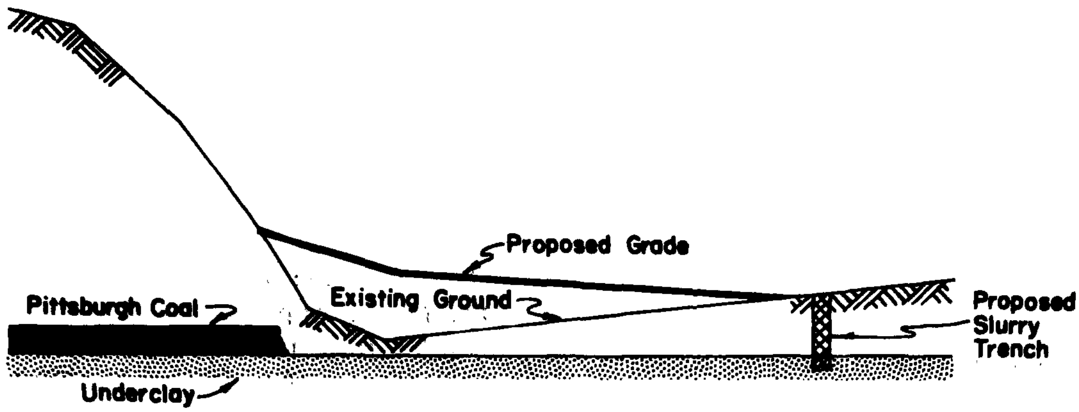


FIGURE 4.3-3

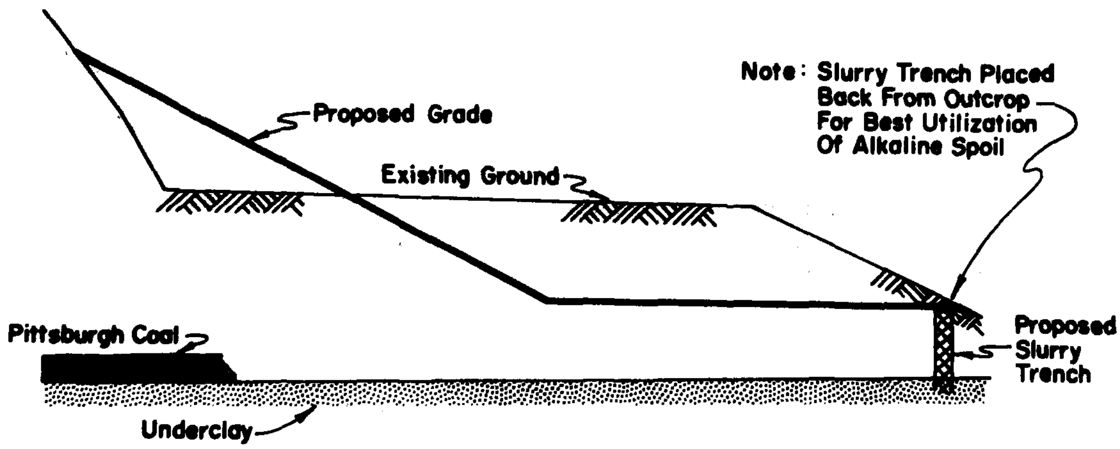
TYPICAL SLURRY TRENCH PROFILE

Elk Creek, W. Va.

(Adapted from Ref. 105)



MODIFIED CONTOUR BACKFILL



TERRACE BACKFILL

FIGURE 4.3-4

TYPICAL SLURRY TRENCH CROSS SECTIONS
ELK CREEK, W.VA.

(Adapted from Ref. 105)

Revegetation	2.03 ha @ $125/ha (5 ac)($500/ac)	2,500
Contingency	5 percent	7,600
Aerial Photography and Mapping	Lump Sum	2,400
	TOTAL	$162,500

Samples collected at Site No. 3 show that an average of 26 kilograms per day (57 lb/day) of acid are discharging into Elk Creek. Approximately 100 percent effectiveness is expected for eliminating pollution from this site. Total estimated construction costs are $171,300 for a cost effectiveness of $6,590 per kilogram per day ($3,005 per lb/day). Estimated construction costs are as follows:

Grading	44,437 cu m @ $0.65/cu m	$ 29,000
Slurry Wall 0.6 m thick (2 ft)	3,047 sq m @ $43.06/sq m (32,800 sq ft)($4.00/sq ft)	131,200
Revegetation	2.43 ha @ $1,235/ha (6 ac)($500/ac)	3,000
Contingency	5 percent	8,100
	TOTAL	$171,300

The total estimated construction costs at Site No. 4 are $62,100. Neutralization of approximately 139 kilograms per day (306 lb/day) of acid equals a cost effectiveness of $450 per kilogram per day ($203 per lb/day) of acid abated. Estimated construction costs are as follows:

Grading	13,304 cu m @ $0.65/cu m (17,400 cu yd)($0.50/cu yd)	$ 8,700
Slurry Wall 0.6 m thick (2 ft)	1,124 sq m @ $43.06/sq m (12,100 sq ft)($4.00/sq ft)	48,400
Revegetation	1.62 ha @ $1,235/ha (4 ac)($500/ac)	2,000
Contingency	5 percent	3,000
	TOTAL	$62,100

Initial chemical analyses of samples collected from Site No. 5 indicated that the flow was acid. However, all analyses following the third sampling round showed net alkalinity and a decrease of acidity concentrations to zero. Subsequently, the site is not deemed feasible for demonstrating acid mine drainage abatement techniques. Estimates of construction costs at the site are as follows:

Grading	12,081 cu m @ \$0.65/cu m (15,800 cu yd)(\$0.50/cu yd)	\$ 7,900
Slurry Wall 0.6 m thick (2 ft)	1,895 sq m @ \$43.05/sq m (20,400 sq ft)(\$4.00/sq ft)	81,600
Revegetation	1.62 ha @ \$1,235/ha (4 ac)(\$500/ac)	2,000
Contingency	5 percent	4,600
	TOTAL	\$96,100

EVALUATION AND RECOMMENDATIONS

The preliminary results of research investigations and demonstration projects indicate that slurry trenching is an effective method of partially inundating abandoned underground mines. The extent of inundation will depend upon the top elevation of the slurry trench and the rise of the mine workings. This technique may be applied to underground mines where the downdip outcrop has been stripped mined or intersected by auger holes and drift mine openings.

Designs for external seals, in which a dam was constructed around a drift mine opening, have been found in records of coal mine sealing projects of the 1930's. The slurry trench is an external ground water dam constructed in unconsolidated material. Various construction projects have demonstrated its effectiveness as an impermeable barrier. Applicable experience related to mine drainage pollution control has reportedly been limited to the work performed in Pennsylvania under Project SL 132-2-101.1. The ability of this water handling technique to control acid production will be further evaluated in the Elk Creek demonstration project.

Construction of the slurry trench will require backfilling, grading, and compacting of suitable material on the work site. The cost of this work will depend upon the availability of material and total volume moved. The costs of placing the slurry wall will range between \$32.30 and \$53.82 per square meter (\$3.00 to \$5.00/sq ft). The estimated cost of constructing 0.6 meter (2 foot) thick slurry trench is approximately \$43.60 per square meter (\$4.05/sq ft). Additional expenses will include clearing and grubbing, and revegetation of the work area. The construction of diversion ditches around the work site may be required to prevent erosion of the graded backfill and slurry trench wall.

REFERENCES

70, 84, 105, 127

4.4 ALKALINE REGRADING

DESCRIPTION

Alkaline regrading is a specialized surface mine reclamation technique for the control of underground mine discharges. Utilization of this technique is limited to areas where alkaline materials lie above a mineral seam and have been intermixed with spoil material during surface mining operations. Regrading of the surface mine with alkaline spoil allows mine discharges along the mineral seam to come into contact with previously inaccessible alkaline material (70, 127). In areas where conditions are favorable, alkaline regrading may be used as a method of neutralizing underground acid mine discharges. A method of alkaline regrading is shown in Figure 4.4-1.

IMPLEMENTATION

Elk Creek Watershed, West Virginia

Alkaline regrading has been practiced in the Elk Creek watershed in West Virginia. The Pittsburgh and Redstone coal seams in this area have been extensively surface and deep mined. The Redstone seam is usually 9 to 12 meters (30 to 40 feet) above the Pittsburgh. The material between the two seams consists of a soft claystone with a thin lense (maximum thickness – 1 meter (3 feet)) of limestone. Discharges are normally acid since mine water does not have access to the alkaline material. Alkaline discharges were observed after the outcrop of an underground mine was surface mined and terrace regraded with spoil material. Prior to surface mining, water discharging from the underground mine was highly acid. Similar conditions have been observed at several strip mines in the area.

This technique will be demonstrated, in the near future, in conjunction with slurry trenching in the Elk Creek watershed (See Slurry Trenching, Section 4.3). Pre-engineering design was completed in November, 1974 by Skelly and Loy, Engineers and Consultants. The slurry trench will increase the water level within the spoil material, thus, more alkaline material will be exposed to acid discharges, retention time in the spoil will be increased, and neutralization will be enhanced. Effectiveness of the demonstration program will be documented by a water quality sampling program (105).

Five sites within the watershed have been evaluated to determine the feasibility of demonstrating alkaline regrading. Each of the sites lies in an area of past extensive underground and surface mining of the Pittsburgh and Redstone coal seams. The

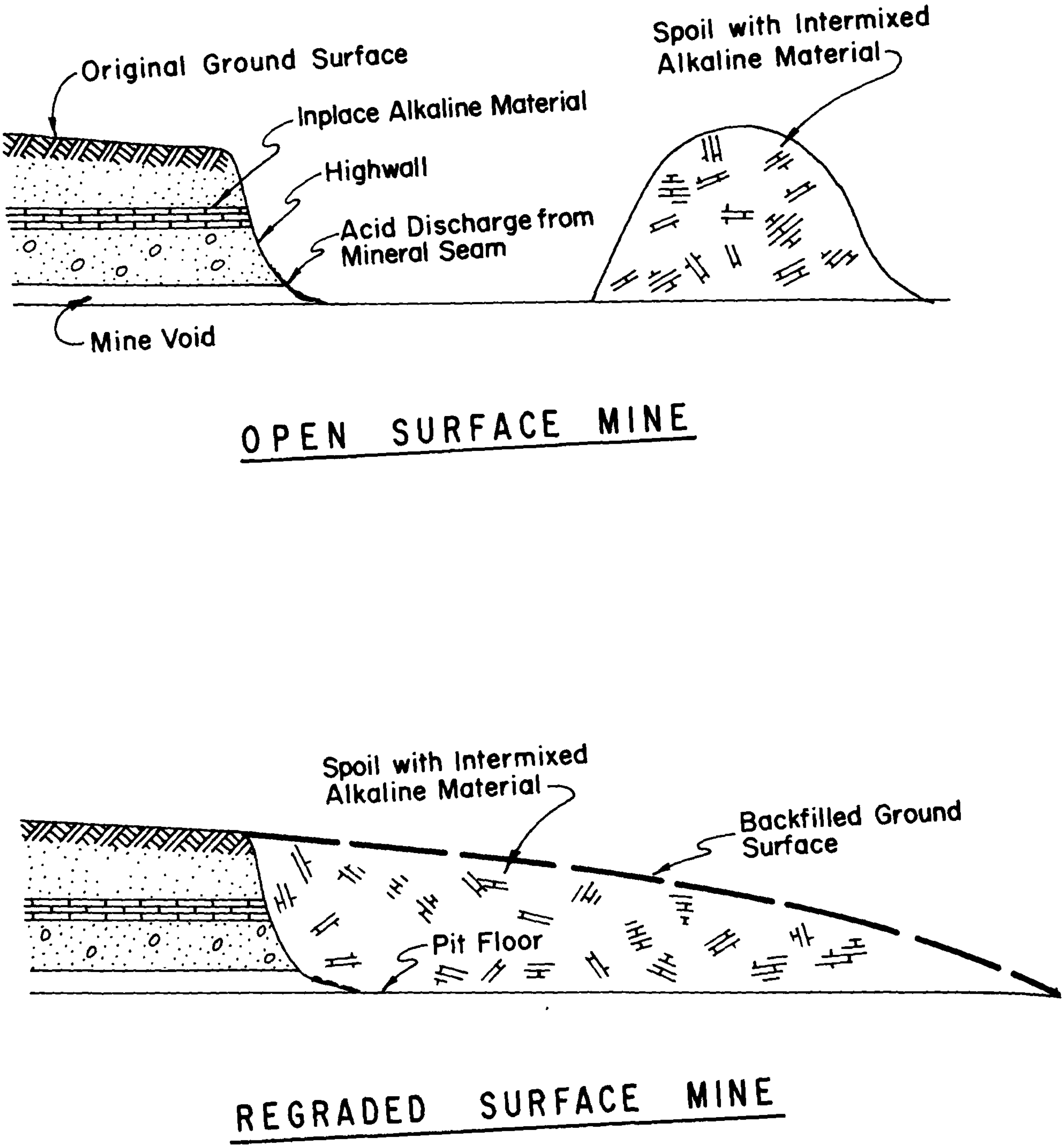


FIGURE 4.4-1

TYPICAL ALKALINE REGRADING

(Adapted from Ref. 70)

sites are characterized by pollution discharges resulting from breached crop barriers during subsequent strip and auger mining. Each of the demonstration sites will be regraded with alkaline spoil to a modified contour or terrace backfill. After regrading a slurry trench will be excavated to the Pittsburgh underclay. The method of alkaline regrading at the Elk Creek sites is shown in Figure 4.4-2.

Alkaline regrading at the five demonstration sites is expected to result in an overall reduction in acidity, iron, manganese, and aluminum concentration in the discharges, with a subsequent increase in alkalinity (therefore, pH). It is estimated that a 25 percent utilization of alkaline material at Site No. 3 will effectively abate acid pollution for 600 years.

Estimates of construction costs for alkaline regrading and slurry trench excavation have been made by Skelly and Loy (105). The unit cost estimates for alkaline regrading are: Grading – \$0.65 per cubic meter (\$0.50/cu yd), Revegetation – \$1,235 per hectare (\$500/acre). Estimated grading and revegetation requirements, and associated costs at the individual sites are:

<u>Site No. 1</u>

Grading	22,938 cu m (30,000 cu yd)	\$15,000
Revegetation	2.43 ha (6 ac)	3,000
	TOTAL	\$18,000

<u>Site No. 2</u>

Grading	45,876 cu m (60,000 cu yd)	\$30,000
Revegetation	2.03 ha (5 ac)	2,500
	TOTAL	\$32,500

<u>Site No. 3</u>

Grading	44,347 cu m (58,000 cu yd)	\$29,000
Revegetation	2.43 ha (6 ac)	3,000
	TOTAL	\$31,000

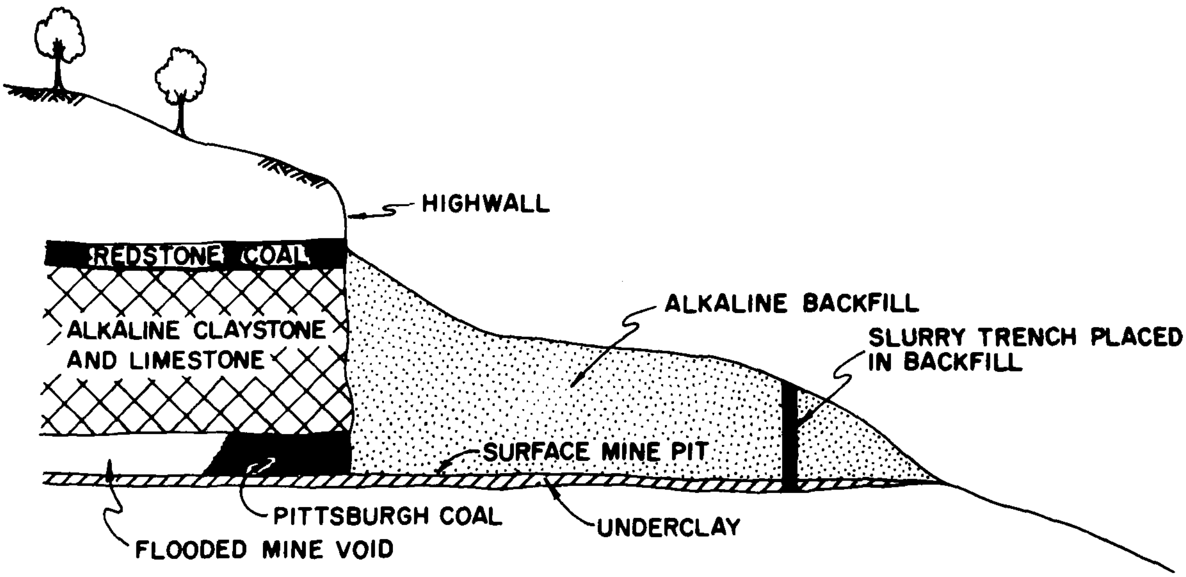


FIGURE 4.4-2

TYPICAL ALKALINE REGRADING, ELK CREEK, WEST VIRGINIA
(Adapted from Ref. 105)

Site No. 4

Grading	13,304 cu m (17,400 cu yd)	$ 8,700
Revegetation	1.62 ha (4 ac)	2,000
	TOTAL	$10,700

Site No. 5

Grading	12,081 cu m (15,800 cu yd)	$ 7,900
Revegetation	1.62 ha (4 ac)	2,000
	TOTAL	$ 9,900

EVALUATION AND RECOMMENDATIONS

Alkaline regrading is classified as a water handling technique because of its ability to neutralize underground mine discharges. The implementation of the specialized surface mine regrading method will be limited to areas where alkaline spoil material is available for neutralization. Regrading with alkaline spoil associated with the Pittsburgh coal seam has effectively neutralized underground mine discharges occurring along surface mined outcrops. This technique would undoubtedly be applicable to other mining areas having similar conditions.

The effectiveness of alkaline regrading will depend upon the volume and characteristics of the available alkaline spoil material. Alkaline materials will be best utilized when they are thoroughly mixed and evenly distributed throughout the surface mine spoil. The construction of a slurry trench in the regraded spoil is expected to result in increased retention time of acid water and more efficient utilization of alkaline material. The ability of the slurry trench to restrict ground water flow and increase water level in regraded spoil has been demonstrated in the Rattlesnake watershed in Pennsylvania (See Section 4.3).

The costs for alkaline regrading will be the same as contour and terrace regrading. The total cost of regrading, including clearing and grubbing, backfilling, grading, and revegetation will normally range from $4,445 to $9,383 per hectare ($1,800 to $3,800/acre) for contour regrading, and $3,704 to $8,395 per hectare ($1,500 to $3,400/acre) for terrace regrading. The selection of the regrading method will depend upon such factors as height and condition of highwall, original slope of ground, volume of available spoil, and available regrading equipment.

REFERENCES

70, 105, 127

4.5 CONTROLLED RELEASE RESERVOIRS

DESCRIPTION

Abandoned underground mines commonly discharge pollutants throughout the year. The rate of discharge will depend upon the response of the individual mine to seasonal variations in precipitation. Therefore, it is possible that a mine may discharge maximum pollution loads during periods when the receiving stream is unable to assimilate large quantities of pollution. This water handling technique involves the construction of large holding ponds or reservoirs to collect mine water discharges. The mine water is released only during periods when the receiving stream will be capable of accepting the water (70, 127).

Controlled release reservoirs may be utilized to regulate abandoned underground mine discharges, effluent flows from treatment facilities, or flows of extensively polluted streams to downstream river systems. The implementation of this technique will require monitoring of various characteristics (i.e., pH, flow, etc.) of the receiving stream. Discharge from the reservoir must be continuously regulated to maintain acceptable stream water quality.

IMPLEMENTATION

A 1942 report (5) advocated the application of flow regulation as a method to control mine drainage pollution of streams of the Ohio River basin. This program was to be implemented, in conjunction with mine sealing, to reduce the environmental effects of various wastes (including mine drainage) during periods of low stream flow. The construction of reservoirs on the Allegheny River having a total capacity of 259 million cubic meters (210,000 acre-feet) was expected to reduce the maximum monthly acidity by 14 parts per million. The implementation of a similar program on the Monongahela River was expected to reduce maximum monthly acidity by 10 parts per million.

Numerous reservoirs have been constructed within the Ohio River basin by the U.S. Army Corps of Engineers for flood control, navigational purposes, and regulation of stream flow volume. The Tygart River reservoir near Grafton, West Virginia is operated primarily for flood control, but, has been successful in reducing down stream acidity. During the period 1930-34 the average monthly stream hardness resulting from mine drainage pollution was reduced 11 parts per million (5, 69).

Controlled release holding ponds have been recommended as a method of control discharges from underground coal mines (2). The mine discharge would be diverted to a holding pond equipped with a constant head, floating outlet which rises and falls with water level. The outlet would be anchored in the pond and connected with a flexible hose to the discharge pipe. This system would provide a constant rate of discharge from the holding pond.

A controlled release holding pond has been utilized to control the discharge of Spring Creek into Keswick Reservoir, Shasta County, California. Pollution of Spring Creek has resulted from the mining of silver, gold, copper, and pyrite in the vast Iron Mountain mining complex. A summary of water quality in Spring Creek follows (125):

	Range
pH	2.0 – 3.0
Specific Conductance (micromhos)	440 – 2,810
Acidity (mg/l)	28 – 1,800
Copper (mg/l)	0.5 – 18
Zinc (mg/l)	0.6 – 136
Iron (mg/l)	27 – 438
Hardness (mg/l)	89 – 100
Sodium (mg/l)	3.9 – 4.4
Sulfates (mg/l)	119 – 401
Chlorine (mg/l)	2 (one value)
Nitrates (mg/l)	1.1 (one value)
Aluminum (mg/l)	20 – 133
Arsenic (mg/l)	0 – 0.32
Chromium (mg/l)	0 – 0.04
Lead (mg/l)	0 – 0.20
Manganese (mg/l)	0.24 – 1.10

The discharge of Spring Creek to Keswick Reservoir had a history of creating fish kills. The controlled release holding pond was constructed in 1963 by the Bureau of Reclamation. This pond was to serve two purposes: (1) store water which was to be discharged at a controlled rate to Keswick Reservoir; and (2) collect metal precipitates and sediment so that they would not enter the reservoir. The system worked well until a 30.5 centimeter (12 inch) rain in 1968 caused an overflow and fish kill. Later studies concluded that the fish kill would not have occurred if the pond discharge had been properly regulated. The cost of constructing this pond was estimated at from $1 to $2 million.

EVALUATION AND RECOMMENDATIONS

This method of handling mine water pollution may be applied to areas where other control and abatement techniques are technically infeasible or economically unattractive. The implementation of this technique should be limited to underground mine discharges or extensively polluted streams that are major sources of pollution in the downstream river system. The reservoir must be designed with sufficient capacity to impound the largest volume of water expected. Efficient and effective operation of the regulated discharge system will require continuous monitoring of water quality and flow in the receiving stream.

Controlled release reservoirs will normally require a greater pool capacity than reservoirs designed solely for flood control. The design of the reservoirs will require a complete hydrologic evaluation of the area, including field sampling and monitoring. Variations in stream acid content and flow volumes must be documented to determine allowable reservoir discharge rates that will maintain acceptable water quality during periods of high, low, and average stream flows.

The costs of constructing a controlled discharge reservoir will be similar to reservoirs constructed for flood control and navigational purposes. This information may be obtained in various forms including cost versus storage area, cost versus volume, and cost versus drainage area. The major factors affecting the total cost of construction will be land acquisition costs and the cost of constructing the impoundment structure and discharge outlet. Initial construction costs will be high; however, benefits such as flood control, recreational use, and decreased treatment costs downstream must be considered.

REFERENCES

2, 5, 8, 29, 69, 70, 96, 107, 125, 127

4.6 CONNECTOR WELLS

DESCRIPTION

This mine water handling technique employs hydrogeologic features of an underground mine to prevent the inflow and contamination of ground water. Wells are drilled from the land surface to the underground mine. These wells tap overlying aquifers and convey water downward to the underground mine. This water may be passed through the mine zone for discharge into underlying aquifers, or conveyed from the mine through a pipe system (81). This method of intercepting aquifers is shown in Figure 4.6-1.

IMPLEMENTATION

This technique is theoretical and will require development and demonstration to determine feasibility. Projects funded by the U.S. Environmental Protection Agency will demonstrate connector wells on both active and abandoned underground mines in the near future.

EVALUATION AND RECOMMENDATIONS

The connector well system appears to be suitable for both active and abandoned underground mines. However, its implementation will not always be technologically or economically feasible. A complete hydrogeological evaluation will be required to determine characteristics of the underground mine and associated aquifers. The connector well system of dewatering aquifers is more complicated than methods of surface water diversion. Therefore, an experienced hydrogeologist will be required to analyze hydrogeologic settings, determine feasibility, and design the system.

The utilization of a pipe system to convey water from underground mines may be limited to active mine sites. In many abandoned mines it will be dangerous or impossible to enter and place pipe systems. In such situations the connector wells may be cased through the mine zone to allow the discharge of water to underlying aquifers. The underlying aquifers, however, must be capable of accepting the expected flow.

Since this technique has not been implemented, cost data is not readily available. The total cost of implementation will include hydrogeologic evaluations, drilling, casing, piping, and possibly grouting to control leakage through the mine

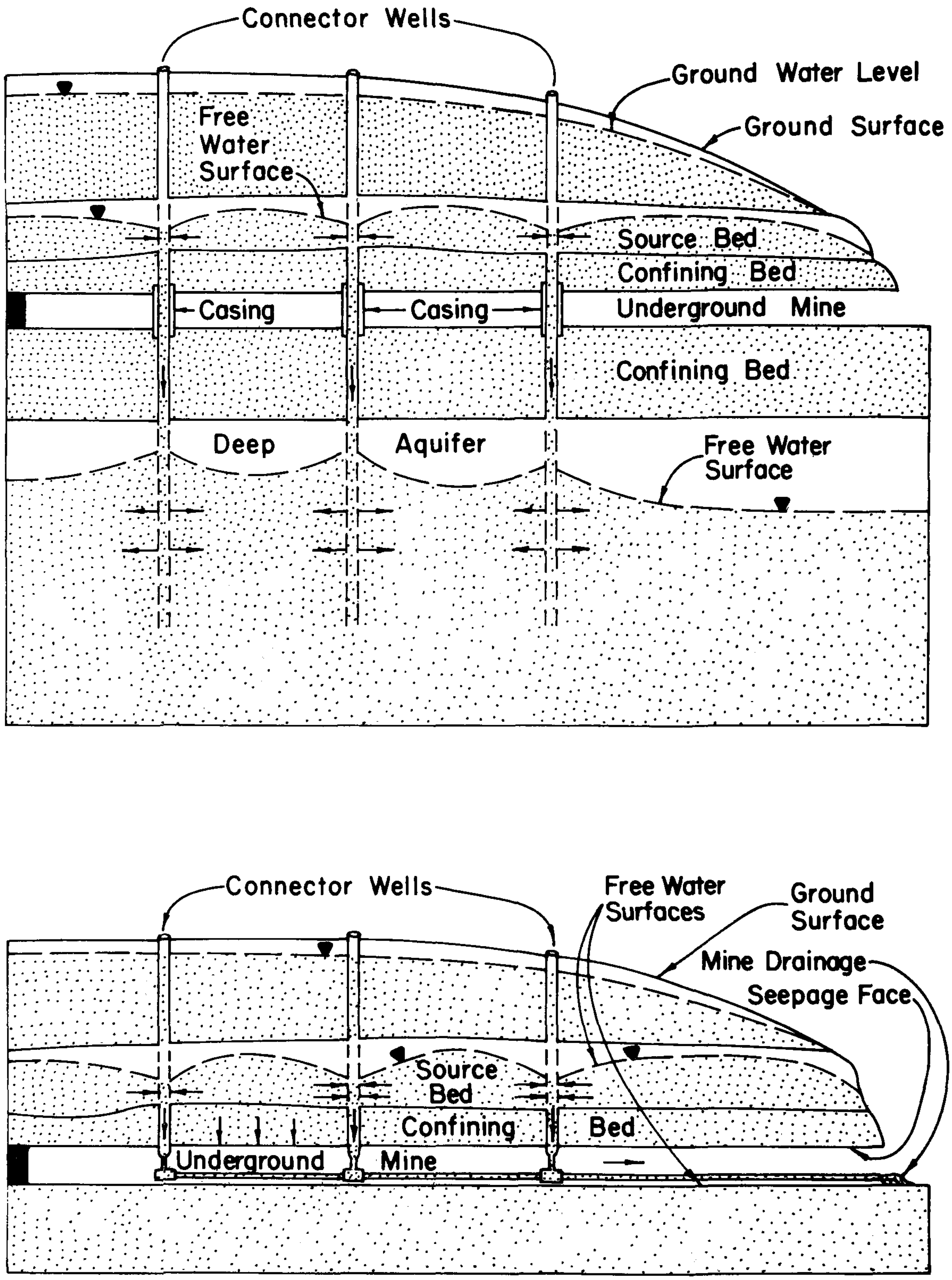


FIGURE 4.6-1

INTERCEPTION OF AQUIFERS BY CONNECTOR WELLS

(Adapted from Ref. 27)

roof. These costs will be variable, and therefore, cost estimates should be developed on an individual application basis.

REFERENCES

27, 68, 81, 125, 127, 129

5.0

DISCHARGE QUALITY CONTROL

5.1 GENERAL DISCUSSION

Sulfide minerals responsible for the formation of mine drainage pollution are commonly associated with ore and mineral bodies. Underground mining exposes these sulfides to sufficient oxygen and water to allow oxidation and flushing of pollutants from the mine. Various methods of sealing abandoned mines to prevent the influx of air and water, and control the quantity of mine water discharge have been described in previous sections of this manual (See Sections 1.0 and 2.0). However, such abatement and control techniques are not universally applicable, and their use will be limited by the technical and economical feasibility of implementation.

The techniques described in this section are designed to control the quality of water discharging from an abandoned mine. Two of these control methods, mine backfilling and pressurizing with inert gas, inhibit the formation of acid mine water by reducing oxygen-sulfide contact. Underground precipitation is an in situ treatment technique that produces a neutralized mine effluent. With the exception of mine backfilling, the demonstration of these techniques has been limited to research and development programs. Further field evaluation will be required to demonstrate their feasibility and practicability.

5.2 MINE BACKFILLING

DESCRIPTION

Underground mine backfilling is a method of disposing of mine and milling wastes. This process had its origin over a century ago in the anthracite coal region of northeastern Pennsylvania. Underground mines were backfilled to control mine fires, arrest the spread of squeezes in coal beds, and protect the overlying ground surface. Backfilling with mine and/or mill waste has been practiced in both active and abandoned underground mines (35).

Abandoned underground mines underlying populated areas have been backfilled to prevent surface damage from subsidence. The degree of mine drainage pollution control resulting from backfilling of abandoned mines has not been demonstrated. However, control of mine roof collapse and subsidence will restrict infiltration of air and water through vertical fractures.

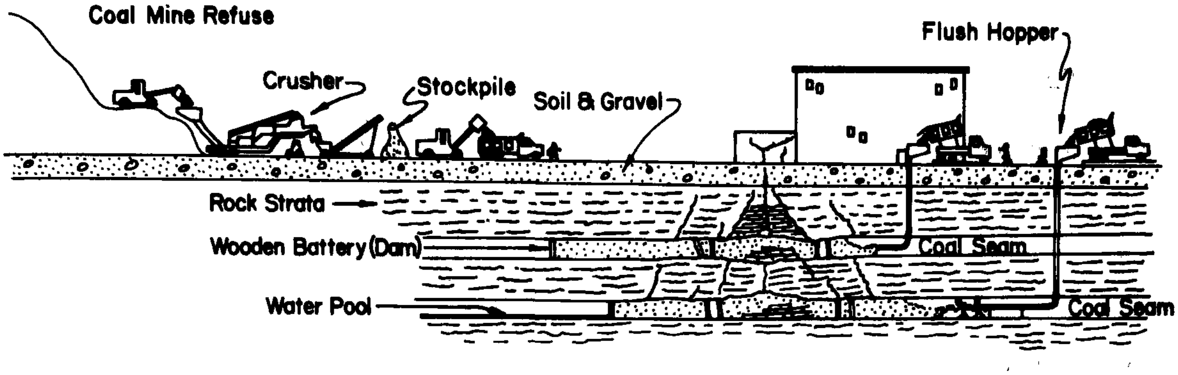
Three methods of hydraulic injection commonly used in underground mine backfilling are: controlled flushing, blind flushing, and pumped-slurry technique. In both controlled and blind flushing, solids are gravity fed from the surface through cased boreholes. Controlled flushing is used in mines that are accessible for the safe entry of workmen. Solids injected through the boreholes are diverted to horizontal pipes and placed by workmen in various sections of the mine. Blind flushing is used in flooded or inaccessible mines. Material is sluiced into a borehole until the mine is filled to the roof. Blind flushing requires more boreholes than controlled flushing and complete filling between boreholes is not achieved (12, 82). The methods of controlled flushing and blind flushing are depicted in Figure 5.2-1.

The pumped-slurry technique is a more effective method of backfilling inaccessible mines. Solids are placed in suspension in a mixing tank and injected as a slurry through a slurry pump into the mine workings via injection boreholes. This technique has resulted in the injection of as much as 144,753 cubic meters (189,319 cu yd) of refuse through one borehole. Quantities injected via blind flushing normally range from 15 to 765 cubic meters (20 to 1,000 cu yd) per borehole.

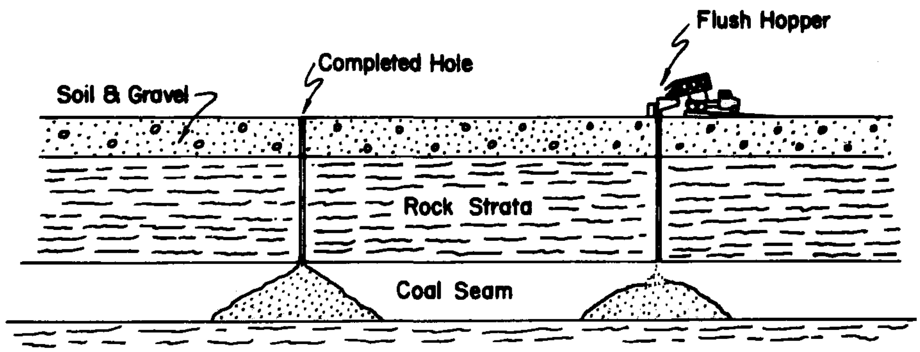
IMPLEMENTATION

Backfilling By Hydraulic Methods

A majority of mine waste disposal in abandoned mines in the United States has been performed throughout the Appalachian region. Since 1962, twelve projects



CONTROLLED FLUSHING



BLIND FLUSHING

FIGURE 5.2-1

BACKFILLING ABANDONED UNDERGROUND MINES WITH COAL REFUSE

(Adapted from Ref. 35)

have been completed, three are presently in progress, and more projects are being planned (35). These projects are conducted to control subsidence damage from abandoned anthracite and bituminous coal mines.

The costs of underground disposal of mining wastes are difficult to evaluate. Average costs of various recent abandoned coal mine backfilling projects in the United States are (35):

Method	Cost Per Unit of Fill Injected
Controlled Flushing (1963-1968)	\$2.41 – 3.11/cu m (\$1.84 – 2.38/cu yd)
Blind Flushing (1965-1967)	\$3.22/cu m (\$2.46/cu yd)
Combined Controlled and Blind Flushing (1966-1969)	\$4.76 – 8.84/cu m (\$3.64 – 6.76/cu yd)
Pumped-Slurry Techniques (1971-1972)	\$6.28/cu m (\$4.80/cu yd)

Rock Springs, Wyoming Demonstration Project

The pumped-slurry technique was developed and first demonstrated by the Dowell Division of Dow Chemical Company at Rock Springs, Wyoming in 1970. The Dowell process (closed system hydraulic backfilling) works on the Venturi tube principle. High volumes of material are injected into the mine by maintaining sufficient particle velocities to transport material to areas beyond the injection point (82).

Three closed system hydraulic backfilling projects have been completed in Rock Springs. In all three projects, underground sub-bituminous coal mines underlying the city were backfilled with sand. Costs for the projects, which include materials, equipment, pumping, and mobilization are shown in Table 5.2-1.

Green Ridge Demonstration Project

Coal mine refuse was used to backfill two anthracite coal seams underlying Scranton, Pennsylvania. Work on this project, the Green Ridge Demonstration Project, was performed in 1972 by Dowell. A total of 12.2 hectares (30 acres) was backfilled with 408,150 metric tons (450,000 tons) of crushed mine refuse. The costs per unit weight of material and unit area backfilled were \$5.27 per metric ton (\$4.78/ton) and \$178,267 per hectare (\$72,198/acre) respectively (116).

TABLE 5.2-1

Costs of Hydraulic Backfilling
Rock Springs, Wyoming

Project/Contractor	Area Backfilled	Cost Per Unit Area Backfilled	Material Cost Per Unit Weight
Project I (Demonstration)/Dowell	1.1 ha (2.8 ac)	$ 158,025/ha (64,000/ac)	$ 7.89/metric ton (7.16/ton)
Project II/Dowell	13.4 ha (33.1 ac)	$ 54,331/ha (22,004/ac)	$ 5.27/metric ton (4.78/ton)
Project III/WHAN Engineering & Construction	22.0 ha (54.2 ac)	$ 52,425/ha (21,232/ac)	$ 3.83/metric ton (3.47/ton)

EVALUATION AND RECOMMENDATIONS

Mine backfilling is an effective method of controlling subsidence damage over abandoned mines and reducing water pollution resulting from the disposal of mine wastes on land. Although this technique has not been utilized exclusively as a mine drainage control technique, it is expected that the oxidation of sulfides within a backfilled mine will be inhibited. The reduction of void space within the mine will result in reduced oxygen-sulfide contact and an increase in the level of water flowing through the mine. The implementation of this technique will be limited by the mining method and characteristics of the mine waste material.

The costs of backfilling abandoned underground coal mines, using the closed system hydraulic backfill method, have ranged from approximately $49,400 to $172,800 per hectare ($20,000 to $70,000/acre). The backfilling of abandoned mines for the sole purpose of controlling mine drainage pollution would be unduly expensive. However, this technique may be economically feasible when performed for the dual purpose of mine drainage control and the prevention of subsidence damage to surface structures. Such a program may be justified when urban areas are involved.

Documentation of the effectiveness of mine backfilling in controlling discharges from abandoned mines will require further research and demonstration. Improved methods of material injection and equipment utilization could result in decreased costs. The mixture of cementing or gelling agents with the backfill material to form hydraulic seals in the mine should be investigated. Controlled flushing methods are less expensive than blind flushing and may be performed during or immediately following active mining operations. Backfilling in this manner would be more efficient and less costly in the long run.

REFERENCES

7, 12, 24, 35, 82, 83, 116, 127

5.3 PRESSURIZING WITH INERT GAS

DESCRIPTION

The pressurizing of abandoned underground mines with inert gas is a mine drainage abatement technique similar to mine inundation. Pollution production is reduced through the reduction of free air oxygen. Experimental laboratory work has shown that a reduction in oxygen content to 0.4 percent or lower will decrease acid production 97 percent over that in air.

Maintaining an inert gas atmosphere in an abandoned mine requires that the pressure within the mine be slightly greater than outside barometric pressure. This positive pressure will result in continuous exhaling from the mine, thus, eliminating the entrance of air during mine breathing, commonly associated with barometric changes in the atmosphere. Inert gas required for pressurization could be obtained from the exhaust of an internal combustion engine driving an electric generator. Power credit would cover operating costs and amortization (90, 92).

IMPLEMENTATION

An experimental program to determine the feasibility of pressurizing with inert gas was initiated in the summer of 1968 by NUS Corporation, Cyrus William Rice Division under contract to the Pennsylvania Department of Mines and Mineral Industries. The objective of Phase I of this program was to determine air injection rates required to pressurize abandoned mines and to develop methods for locating leaks in abandoned mines where the known entries have been sealed (92).

The mine originally selected for Phase I study was the Whipkey Mine located in Stewart Township, Fayette County, Pennsylvania. The calculated minimum air injection rate required to satisfy breathing requirements during rising barometric pressure was 5 cubic meters per minute (180 cfm). Air was injected at the rate of 14 cubic meters per minute (500 cfm); however, a differential pressure could be produced only during periods of falling atmospheric pressure. Attempts to determine the reason for the inability to produce a differential pressure revealed that three original mine entries which had been backfilled with spoil were the sources of leakage.

Operations were switched to an adjacent mine, King Mine No. 2. During an air injection rate of 16 cubic meters per minute (575 cfm) a positive differential pressure was developed which varied from 0.51 to 0.71 centimeters (0.20 to 0.28 inches) of water. After closure of a leak occurring from a subsidence hole, differential pressures up to 2.5 centimeters (1 inch) of water were developed at an air injection rate of 56 cubic meters per minute (2,000 cfm). Although positive differential pressures were successfully developed, a discontinuation of air injection resulted in a rapid fall of pressure within the mine.

Based on results of air pressurization of the King Mine, capital and operating costs were developed for treatment of drainage from the mine and application of inert gas. Calculations were made for lime neutralization of the acid mine drainge, application of inert gas from a simple inert gas generator, and application of inert gas from the exhaust of a natural gas engine driving an electric generator. Power credit from the generator was assumed to be 7 mills per kilowatt hour. Results of the calculations were as follows (90).

	Capital	Operation[3]
Lime Neutralization[1]	$10,000	$5,100/yr
Inert Gas Generator[2]	18,000	7,900/yr
Natural Gas Engine[2]	19,000	3,200/yr

[1] Basis 136 cu m/day (36,000 gpd), 500 mg/l acidity mine drainage

[2] Basis 546 standard cu m/hr (19,500 SCFH) 50 percent of time

[3] Includes 10 year amortization, at 7 percent interest

EVALUATION AND RECOMMENDATIONS

The results of the experimental program conducted in Pennsylvania indicate that positive differential pressures may be established in abandoned underground mines. However, the effectiveness of an inert gas atmosphere in controlling the formation of mine drainage pollution has not been documented. Field demonstrations of this technique will be required to determine practicability of implementation. A major disadvantage will be the periodic inspection and maintenance required during the total period of operation.

The factors that will affect the technical and economic feasibility of implementing this technique will include: volume of the mine, permeability of confining strata, rate of change of barometric pressure, fuel costs for operating inert gas generators, electric power credit, maintenance required, and capital costs of installation. Preliminary economic evaluations have concluded that capital and operating costs for an inert gas installation will be considerably less than neutralization with hydrated lime. The economic advantage realized will greatly depend upon the ability to sell bi-product electric power.

REFERENCES

27, 29, 90, 92, 127

5.4 UNDERGROUND PRECIPITATION

DESCRIPTION

Underground precipitation is accomplished by injecting alkaline water slurries into abandoned underground mines. The alkaline slurry neutralizes mine water within the mine resulting in the precipitation of sludge which fills the mine void. The advantage of filling with sludge is that the sludge is a bulking type precipitate, taking up more volume than that occupied by the unreacted materials.

The technique may be utilized as either a method of sealing drainage openings, or for continuous neutralization of effluent mine water. Sealing drainage openings may be accomplished by injecting slurry behind a rubble barrier and allowing precipitates to flow into the barrier and plug the openings. Continuous neutralization produces a treated effluent while filling the mine voids with sludge, thus, eliminating sludge disposal problems associated with surface treatment operations.

IMPLEMENTATION

The Parsons-Jurden Corporation conducted a study to evaluate underground precipitation in abandoned mines, resulting from the reaction of mine water with hydrated lime and limestone (63, 110). Initial laboratory investigations indicated that underground precipitation would be a feasible mine drainage abatement technique. Laboratory tests revealed that under proper flow conditions, the precipitates formed in the mine would settle in the mine while alkaline water drained from the mine. A sand barrier placed across a simulated mine adit was completely sealed off by precipitates which formed in acid water and flowed to the barrier.

A field demonstration of the technique was conducted during the months of November and December, 1970 at the Driscoll No. 4 Mine, an abandoned mine, near Vintondale, Pennsylvania. Field tests were conducted to: (1) demonstrate the sealing of a rubble barrier by injecting lime slurries on the inby side; and (2) neutralize acid mine drainage behind a bulkhead so that precipitates settle in the mine and neutralized water discharges through a drain pipe. Preliminary work involved placing three bulkheads, a rubble barrier, injection and drainage lines, and weirs in the mine entries. A plan of the mine portal is shown in Figure 5.4-1.

The rubble barrier placed in the No. 1 west entry was 7.6 (25 feet) long and consisted of broken slate, shale, and glacial till. The attempt to seal outflow through the barrier involved alternate injection of hydrated lime and pulverized limestone behind the rubble pile. At the end of 62 hours of slurry injection the flow of water

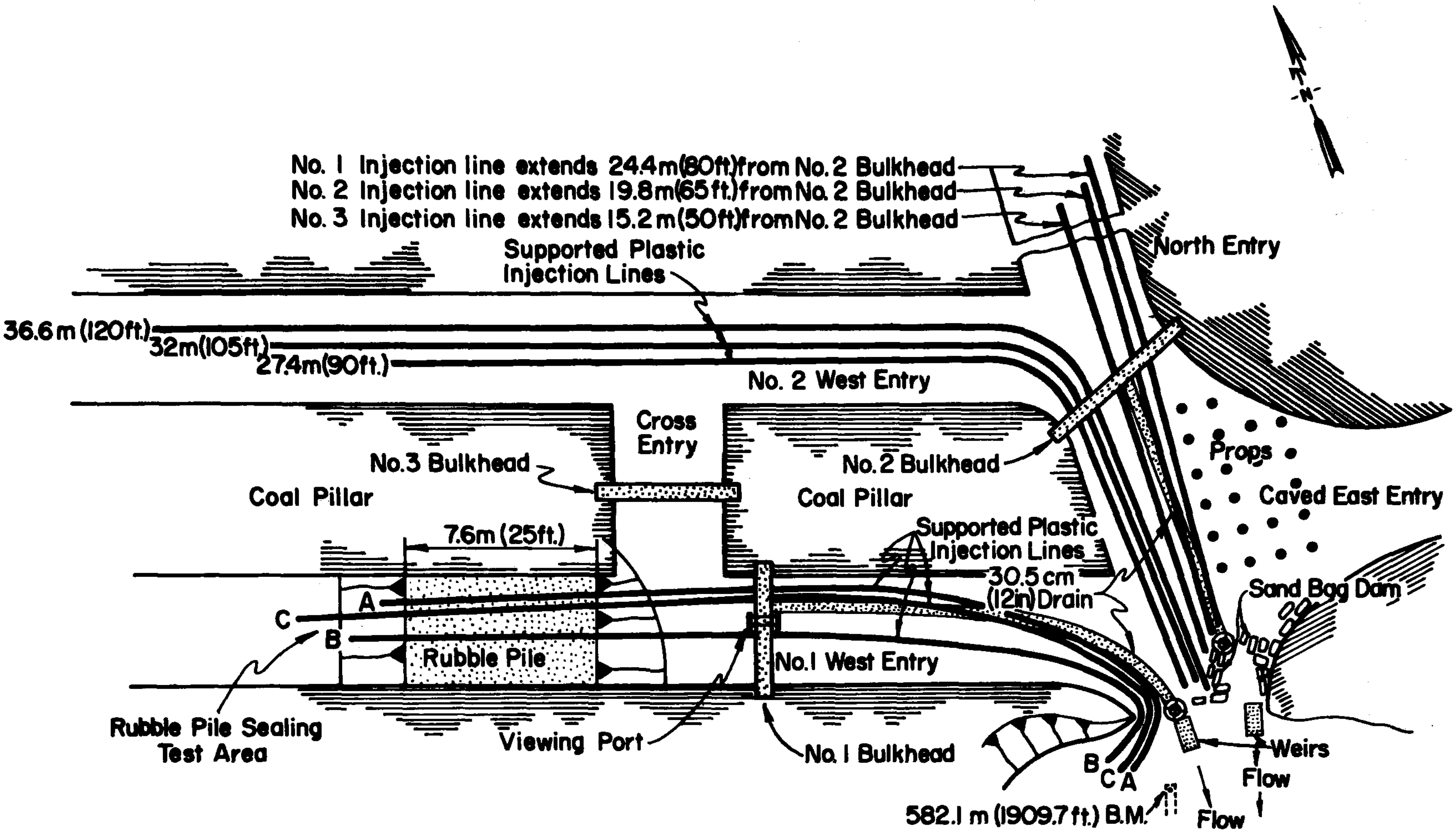


FIGURE 5.4-1

PLAN OF BULKHEADS, PIPING, WEIRS AND PORTAL

DRISCOLL NO. 4 MINE

Vintondale, Pennsylvania

(Adapted from Ref. 110)

through the barrier stopped, indicating that a plug had been formed. A few hours later a small flow of approximately 0.06 liters per second (1 gpm) began. Slurry was again injected but problems with plugging lines resulted in termination of the test after 345 hours. A total of 18,047 kilograms (39,750 pounds) of hydrated lime and 9,775 kilograms (21,530 pounds) of pulverized limestone were injected during this phase of the test.

An attempt was made to re-establish the seal during a second test which lasted 251 hours. During this period 27,422 kilograms (60,400 pounds) of hydrated lime and 8,608 kilograms (18,960 pounds) of pulverized limestone were injected behind the rubble barrier. The flow of water was never stopped; however, the pH of the outflowing mine water increased to the 11 to 12 range during slurry injection.

Although the exact reasons for the failure of the precipitates to seal the rubble barrier are not known, several explanations have been postulated:

1. Shrinkage of gels as they aged may have loosened the plug.

2. Diffusion of mine water into the seal may have caused re-solution of the precipitates.

3. Once the seal was formed there was no flowing force to carry or hold the slurry and precipitates against the rubble barrier.

4. The bulk of the precipitates settled to the floor and were unable to seal areas near the roof and top of the rubble barrier.

The failure to establish and maintain a seal was probably the result of a combination of factors.

Testing of the continuous neutralization of outflowing water was conducted behind the No. 2 bulkhead in the mine. During the first test period of 39 hours 4,249 kilograms (9,360 pounds) of hydrated lime were injected into the mine. Theoretically the slurry should have raised the pH of the effluent mine water to 11.1. Actual pH readings were 3.6 to 4.6. During a second 26 hour test, 7,082 kilograms (15,600 pounds) of hydrated lime were injected. Again the effluent water failed to reach the theoretical pH of 12, having only a pH of 4.4 to 4.8.

Although the injection of slurry behind the No. 2 bulkhead failed to neutralize the effluent mine water, feasibility of the technique was demonstrated during the attempt to reestablish the rubble barrier seal. As previously mentioned the pH of the outflowing water increased to 11 to 12 during slurry injection. When injection was stopped, pH dropped to the normal 3 or 4 range. Presumably, the sludge formed during slurry injection was settling in the mine.

Cost figures for the individual phases of the project are not available. Total project cost estimates have been in excess of $250,000 (32).

EVALUATION AND RECOMMENDATIONS

The major advantages of underground precipitation are the filling of mine voids with sludge, thus, eliminating the need for sludge handling, and the production of a neutralized mine water discharge. This technique appears to be an effective method of controlling polluted discharges from abandoned underground mines when other techniques are infeasible. This in situ treatment technique should be less costly than standard treatment facilities since mixing tanks, settling basins, and sludge storage and handling facilities will not be required. As precipitated sludge fills the mine void, less free air oxygen will be available to further oxidize sulfide minerals and the rate of pollution formation will be retarded.

The cost of implementing the underground treatment technique will include alkaline materials utilized for neutralization, and capital and operating costs for equipment required to inject the alkaline slurry. The slurry may be injected from above the mine through vertical boreholes or through a pipe system within the mine. The construction and maintenance of the injection system will result in additional expenditures. The total cost per unit volume of water treated should approximate costs of conventional treatment methods; however, capital costs should be considerably lower.

REFERENCES

32, 63, 110

III

MINERAL COMMODITIES MINED

This section is divided into: (1) Ferrous Metals; (2) Nonferrous Metals; (3) Nonmetals; and (4) Energy Sources. The information includes principal minerals, types of deposits, location of deposits, location of underground mines, and environmental problems related to underground mining. Included are all mineral commodities for which the United States has mineral resources that are mined currently or may be mined in the future by underground methods.

1.0

FERROUS METALS

1.1 CHROMIUM

The mineral chromite is the sole current source of commercial chromium. Chromite varies compositionally within limits permitted by the formula ($(Mg,Fe,Zn,Mn)(Al,Cr)_2O_4$). No chromite has been mined in the United States since 1961. In the past, almost all the chromite mined in the United States came from Alaska, California, Maryland, Montana, Oregon, and Pennsylvania, with about one-half of all production coming from Montana.

Primary chromite deposits occur only in certain kinds of ultramafic or closely related anorthositic rocks. The two major types are stratiform (layered) and pod-shaped. The Stillwater Complex of Montana is the largest known United States resource. It is a stratiform deposit where several exposed zones of high-iron chromiferous material extend in length. Since there is no commercial chromite mining in the United States, there are no environmental problems related to underground mining.

1.2 COBALT

Cobalt is a major constituent of approximately seventy minerals and a minor constituent of several hundred more minerals. The principal sulfide-arsenide minerals are carrollite ($CuCo_2S_4$), smaltite ($CoAs_{3-x}$), skutterudite ($CoAs_3$), and cobaltite ($CoAsS$). Cobalt formerly produced in the United States was contained in a pyrite concentrate which was a byproduct from beneficiating the magnetite-bearing ore mined at the Cornwall and Grace Mines in Pennsylvania. Both of these mines used a block caving mining method. These deposits are contact metamorphic deposits containing magnetite, chalcopyrite, and cobaltiferous pyrite. United States deposits containing cobalt can be classified geologically as: (1) hypogene deposits associated with mafic intrusive igneous rocks (Pennsylvania, Maine, Connecticut, Massachusetts, New York, Washington, Oregon, California, Minnesota, and Montana); (2) contact metamorphic (Pennsylvania); (3) laterite (California, Oregon, Washington, and North Carolina); (4) massive sulfide (Tennessee, Maryland, Virginia, and Alabama); and (5) hydrothermal (Idaho, Nevada, New Mexico, Connecticut, Virginia, Missouri, Wisconsin, Illinois, and Iowa). Except for the laterite deposits, the cobalt always is associated with iron sulfides and often copper and nickel sulfides. Since cobalt is not produced in the United States, there are no environmental problems related to underground cobalt mining. If cobalt production was resumed as a byproduct or coproduct, the environmental problems related to underground mining of cobalt would be nearly identical to those for iron, copper, and nickel.

1.3 COLUMBIUM

Columbium minerals are chiefly oxides and hydroxides, but include a few silicates. Columbium minerals are not known pollutants and drainage waters from mines should not degrade the environment, except for sedimentation. The United States relies on imports for its primary supply of columbium and domestic mine production is negligible.

1.4 IRON

The iron ore minerals are magnetite (Fe_3O_4), hematite (Fe_2O_3), geothite ($Fe_2O_3 \cdot H_2O$), siderite ($FeCO_3$), pyrite (FeS_2), and pyrrhotite ($Fe_{1-x}S$). The iron oxide minerals are the principal iron ore minerals in the United States. Iron ore deposits can be classified as: (1) bedded sedimentary deposits; (2) deposits related directly to igneous activity; (3) deposits formed by hodrothermal solutions; and (4) deposits produced by surface or near-surface enrichment.

Banded iron formations occur as sedimentary deposits in Precambrian rocks. The most distinctive and economically significant banded iron formations consist of iron oxides (magnetite and hematite) and chert (or its recrystallized equivalent) in alternating thin layers. In some iron formations, siderite occurs with appreciable amounts of manganese, magnesium, and calcium. Iron silicates, such as greenalite, minnesotaite, and stilpnomelane occur in some formations. The occurrance of pyrite and pyrrhotite are rare in banded iron formations. Metamorphism has altered many iron formations and changed pre-existing minerals to silicates, such as cummingtonite-grunerite, pyroxene, and olivine. Silicates in the cummingtonite-grunerite series may contain asbestos-like fibers which represent a possible health hazard when inhaled and/or ingested. Prominent examples of banded iron formations in the United States are the Mesabi, Cuyuna, Gogebic, Marquette, and Menominee Ranges in Minnesota, Wisconsin, and Michigan.

Ironstones, mostly post-Precambrian, occur as bedded sedimentary deposits. Ironstone deposits vary considerably, but commonly are thick bedded rocks containing small pellets (ooliths) of limonite, hematite, or chamosite in a matrix of chamosite, siderite, or calcite. Ironstones may be divided into oxide, carbonate, silicate, and sulfide facies, depending upon the dominant iron mineral. A prominent example of the ironstones is the Clinton Formation, extending from Alabama to New York.

Iron in deposits related directly to igneous activity is believed to be concentrated during recrystallization as a constituent of early formed minerals that may have settled to the base of the magma chamber (magmatic segregations) or as a constituent of fluids (gases and aqueous liquids) which escape the magma chamber and deposit iron minerals in surrounding rocks (pyrometasomatic deposits). Magmatic segregations either can be titaniferous or non-titaniferous. Titaniferous ores occur as layers and segregations in gabbro, pyroxenite, and anorthosite. The gabbro and pyroxenite deposits commonly are layered lenses of magnetite, ilmenite, and silicates, such as pyroxene. Anorthosite deposits are irregular masses and dikes of coarse-grained ilmenite, magnetite or specularite, feldspar, ulvospinel (Fe_2TiO_4), and rutile (TiO_2), such as the anorthosite bodies of upper New York State. Non-titaniferous ores are composed of magnetite and minor amounts of hematite, such as the Pea Ridge and Pilot Knob deposits of Precambrian age in Missouri. Pyrometasomatic deposits encompass a wide variety of igneous deposits. Typical deposits are replacements, usually in limestone, at or near a contact with the parent igneous rock. At Cornwall, Pennsylvania, the ore contains magnetite associated with sulfides, such as pyrite and chalcopyrite. Actinolite and chlorite are the predominant gangue minerals. At the Iron Springs district, Utah, the ore contains magnetite and the gangue minerals include phlogopite and fine-grained calcsilicates, and significant amounts of apatite.

Deposits formed by hydrothermal solutions include replacement deposits in nonferruginous rocks and enrichment of pre-existing non-ferruginous rocks. Small and medium size replacement deposits occurring as pods, veins, and lenses in volcanic rocks, brecciated igneous rocks, and limestone are common in the western United States. Magnetite and hematite are the typical ore minerals and occur mainly in association with pyrite and chalcopyrite. Some veins and bedding replacements consist wholly or largely of siderite. The Benson Mine, New York, is a replacement deposit consisting of magnetite and hematite as ore minerals and quartz, potassium feldspar, sillimanite, garnet, and ferromagnesian minerals as gangue minerals. The enrichment deposits are very high grade deposits approaching 70 percent iron with the ore consisting of crystalline hematite (specularite) as in the Vermilion district of Minnesota.

Deposits produced by surface or near-surface enrichment include laterites and enrichments of low-grade ores. The direct shipping, wash, and semitaconite ores of the Lake Superior region consisting of soft limonite and hematite are products of deep residual enrichment of the primary iron formation, in which oxidation of ferrous minerals was accomplished by partial to complete leaching and replacement of chert. The brown ores of Texas and the southeastern United States were formed by oxidation and enrichment of Tertiary strata containing siderite and glauconite. The hard ores of the Marquette district, Michigan, probably represent in part a former enrichment and in part a clastic accumulation, now modified by metamorphism.

Most United States iron ore is produced in the Lake Superior district in Minnesota and Michigan. There are relatively small but significant mines producing iron ore in Alabama, California, Missouri, New York, Pennsylvania, Texas, Utah, Wisconsin, and Wyoming. In the United States, iron ore is mined principally by open pit methods with only 4 percent of the iron ore mined by underground methods. Underground room and pillar methods are used to mine flat-lying or gently dipping, thin bedded deposits. Caving methods, supplemented by shrinkage and sub-level stoping, are used to mine massive and vein-type deposits.

There are seven underground iron ore mines in the United States. These are located in Michigan, Pennsylvania, Missouri, Wyoming, and North Carolina. The North Carolina mine produces a small amount of high quality magnetite for special uses.

It is estimated that 30 percent of the total iron in the crude ore is lost in the conversion of the crude ore to a usable iron ore concentrate or pellet. This loss occurs because of the inefficiency of benefication processes in recovering fines and different minerals. As examples, fines are lost during gravity processing of hematite ores and nonmagnetic iron (hematite, iron silicates, etc.) is lost during magnetic separation of essentially magnetite ores.

The environmental problems related to underground mining of iron ore are waste water from mines and dumps and subsidence from underground open stopes. Surface and groundwater seepage into operating underground mines require continuous pumping of considerable waste water to maintain dry working areas. Mine waters may be high in suspended solids and either acidic or alkaline. Surface run-off and erosion of mine dumps at abandoned and operating mines are a major source of waste water. These waters usually are turbid and bright red-orange in color. The red-orange color is related to the suspended solids and indicative of the red iron oxide or hematite prevalent in the ore or waste rock. These suspended solids usually can be removed by sedimentation. The suspended solids or silt usually are high in iron content and alkaline, and occasionally contain manganese and silica. These waste waters create an unfavorable environment for fish and wildlife. These waste waters seriously affect the use of swimming beaches, recreational areas, and lakeshore property because they are an aesthetic nuisance. Red silt deposited in shallow lake areas may be resuspended by wind-induced currents and be a source of nuisance for many years. Subsidence is a major environmental problem for underground mines. Surface land will be altered drastically, often causing damage to public and private property. Low subsided areas may collect surface water run-off, which may enter underground workings and then be pumped from underground as waste water.

1.5 MANGANESE

The principal ore-mineral forms for manganese are oxides, carbonates, and silicates. The most important ore minerals are pyrolusite (MnO_2), manganite ($MnO(OH)$), cryptomelane ($(K,H_2O)_2Mn_5O_{10}$), and psilomelane ($(Ba,H_2O)_2Mn_5O_{10}$). In the recent past, almost all the manganese mined in the United States came from Minnesota, Montana, and New Mexico, with the Cuyuna district of Minnesota being the largest producer. Primary manganese deposits can be classifed into four geologic types: (1) sedimentary (including sea floor nodules); (2) hydrochemical; (3) residuals; and (4) metamorphic.

Currently, the United States is dependent completely upon foreign sources for manganese. Domestic resources include deposits in the Chamberlain district of South Dakota, the Cuyuna district of Minnesota, and the manganese nodules in Lake Michigan. Large resources of manganese nodules are known to occur on the deep floor of the Pacific Ocean. There are no environmental problems in the United States related to underground mining of manganese because of the lack of mining. Except for increased sediment loads and siltation, manganese mining is not known to cause water pollution.

1.6 MOLYBDENUM

The ore minerals of molybdenum are molybdenite (MoS_2); ferrimolybdite ($FeMoO_3 \cdot H_2O$); and jordesite (amorphous molybdenum disulfide). In the past, molybdenum also was recovered from wulfenite ($PbMoO_4$) bearing ores. Molybdenum deposits are of five genetic types: (1) porphyry deposits; (2) contact-metamorphic deposits; (3) quartz veins; (4) pegmatites; and (5) bedded deposits in sedimentary rocks. In the United States, molybdenum is mined from porphyry deposits both as a primary product and a by-product. In the porphyry deposits, copper sulfides and/or molybdenite occur as disseminated grains and in stockworks of quartz veins and veinlets in fractured or brecciated, hydrochemically altered granitic intrusive rocks and in the intruded igneous or sedimentary country rocks. Host intrusive rocks range from intermediate to acidic and include diorite, quartz monzonite, and granite, and the porphyritic equivalents. In porphyry molybdenum deposits, molybdenite usually is the only ore mineral, but it is commonly accompanied by pyrite, fluorite, and small amounts of tungsten, tin, lead, and zinc minerals. Porphyry copper or copper-molybdenum deposits usually contain chalcopyrite intimately associated with pyrite and only small amounts of molybdenum which is recovered as a byproduct.

In the United States about 58 percent of the molybdenum produced is recovered as a primary product. About 42 percent is obtained as a byproduct from mining molybdenum-bearing copper, tungsten, and uranium ores with copper ores providing most of this production. The United States primary molybdenum production has come recently from three mines, the Climax and Urad Mines in Colorado and the Questa Mine in New Mexico. The Climax Mine which is the largest United States molybdenum mine uses a block caving mining system. The Urad Mine was closed in 1974 and $5 to $6 million has been allocated for reclamation work. The Questa Mine is an open pit mine which started production in 1966 and produces about 10 percent of the United States molybdenum production. The Henderson Mine near Empire, Colorado, is under development and production is expected to begin in 1976. Development work also is being conducted at the large Thompson Creek deposit near Clayton, Idaho. Molybdenum is recovered as a byproduct from open pit and underground mines in Utah, New Mexico, Nevada, California, and Arizona. Most known United States reserves of molybdenum are associated with currently producing porphyry molybdenum and copper-molybdenum deposits.

The environmental problems related to underground molybdenum mining are mine drainage and subsidence. Pollution of waters by mine drainage can occur because of acidification and heavy metals resulting from sulfides, principally pyrite accompanying the ore. Subsidence occurs when using the block caving underground mining method. Thus, the environmental problems related to United States molybdenum mining are the same as for other large underground mines mining sulfide ores.

1.7 NICKEL

Nickel is mined from both sulfide and nickeliferous laterite deposits. For the sulfide deposits, the principal nickel mineral is pentlandite ($(Fe,Ni)_9S_8$)). Besides pentlandite, nickel may replace iron in pyrrhotite and pyrite. For the laterite deposits, the principal nickel source is garnierite, a nickel-magnesium hydrosilicate.

The nickel sulfide deposits typically consist predominately of pyrrhotite and associated pentlandite and chalcopyrite. The deposits may contain minor amounts of precious metals, cobalt, and selenium. The sulfides occur as disseminations, massive bodies, or veins and stringers in the igneous rocks. The deposits occur in or near peridotite or norite intrusions. The nickeliferous laterite deposits were formed by the weathering of peridotite, dunite, pyroxenite, or serpentinite. Laterites formed from the weathering of serpentinite are rich in iron and are called nickeliferous iron laterites. The nickel most likely is included in the goethite, limonite, and serpentine minerals. Laterites formed from the weathering of peridotite, dunite, and, to a lesser degree, pyroxenite are lower in iron content and are called nickel-silicate laterites. In these laterites, the nickel occurs either as the hydrosilicate garnierite or as nickel-bearing talc or antigorite.

The United States relies on imports for most of its nickel. The only United States primary nickel mine is at Riddle, Oregon, where nickel-silicate laterites are mined. This is an open pit mine which supplies about 8 percent of the United States nickel demand. There are no underground primary nickel producing mines in the United States. A small amount of nickel is produced in the United States as a byproduct of copper mining.

United States nickel reserves consist of: (1) nickel sulfides in the Duluth Gabbro of Minnesota and the Stillwater district of Montana; (2) nickel laterites in California, Oregon, and Washington; and (3) manganese nodules on the deep floor of the Pacific Ocean (large nodule deposits contain 0.8 percent to 1.1 percent nickel). Underground mining could occur in both the Duluth Gabbro and the Stillwater district, resulting in environmental problems similar to those of other nickel sulfide mining districts (Sudbury, etc.).

1.8 RHENIUM

Rhenium is produced in the United States only as a byproduct from the wasting of molybdenite concentrates from porphyry copper-molybdenite ores. Principal rhenium resources are trace amounts occurring in: (1) porphyry copper-molybdenite deposits; (2) porphyry molybdenite deposits; (3) contact metamorphic tungsten-molybdenum deposits; (4) molybdenum-bearing pegmatites; and (5) molybdenite-bearing quartz veins.

1.9 SILICON

Although silica occurs in many minerals, quartz and quartzite are the only minerals adequate in purity and quantity to be mined for silicon. Silica deposits are of three types: (1) primary; (2) secondary; and (3) replacement. Primary deposits result from hydrothermal actions and occur as veins in granite or massive cores in pegmatites. Secondary deposits result from weathering of primary rock. Subsequently, wind, water, and ice action concentrated the silica particles into sandstone beds which then were consolidated and cemented. Some sandstone beds underwent metamorphic changes, resulting in relatively pure quartzite. Replacement deposits result from replacement of the country rock by siliceous solutions.

Silica sand and sandstone are among the more common sedimentary formations in the United States with resources of silica sand being virtually inexhaustable. All mining of silica raw materials for conversion to silicon or its alloys is by open pit methods. Thus, there are no environmental problems related to underground mining of silica.

1.10 TANTALUM

The principal mineralogical source of tantalum is an isomorphous mineral series containing tantalum, columbium, iron, and manganese oxides, often called tantalite. A potential source of tantalum is the microlite-pyrochlore mineral series consisting of complex oxides of tantalum, columbium, sodium, and calcium combined with hydroxyl ions of fluorine. Tantalite and microlite occur principally as primary accessory minerals in granitic rocks. Weathering of these granitic rocks result in tantalite and microlite being concentrated in alluvial or eluvial deposits. Tantalum minerals are not known pollutants and drainage waters from mines should not degrade the environment, except for sedimentation. Past United States production of tantalum minerals has been small. The United States currently relies on imports for its primary supplies of tantalum.

1.11 TUNGSTEN

The principal ore minerals of tungsten are the wolframite series consisting of huebnerite ($MnWO_4$), wolframite ($(Fe,Mn)WO_4$), ferberite ($FeWO_4$), and scheelite ($CaWO_4$).

Other ore minerals commonly occurring with tungsten minerals are molybdenite, cassiterite, chalcopyrite, bismuthinite, native bismuth, fluorite, tetrahedrite, and sphalerite. The principal types of tungsten deposits are: (1) contact-metamorphic deposits (tactites); (2) tungsten-bearing vein deposits; and (3) stockworks and related porphyry-molybdenum deposits. Other types of tungsten deposits are: (1) pegmatites; (2) hot springs; and (3) placers. Tactite deposits result from high temperature replacement and recrystallization of limestone or dolomite at or near the contact of intrusive igneous rocks. These deposits contain calc-silicate minerals, such as garnet, epidote, hedenbergite, and hornblende along with magnetite, quartz, and calcite. Tungsten in tactites occurs only as scheelite or molybdenum-bearing scheelite. Pyrite, pyrrhotite, molybdenite, sphalerite, chalcopyrite, tetrahedrite, stibnite, bornite, and fluorite usually are present. Major tungsten production from tactite deposits comes from: (1) Inyo County, California; (2) Humboldt and Pershing Counties, Nevada; and (3) Beaverhend County, Montana. In addition to these, known tungsten tactite resources are located in Utah, Arizona, Washington, and Idaho.

Tungsten-bearing quartz veins consist of quartz or sometimes quartz-calcite with sheelite and/or one of the wolframite series and minor amounts of other minerals. Other minerals occurring in recoverable quantities in some deposits are sphalerite, galena, chalcopyrite, tetrahedrite, arsenopyrite, and gold. Gangue minerals often are pyrite, pyrrhotite, molybdenite, fluorite, rhodocrosite, and feldspar. Major productive vein deposits are at: (1) Boriana, Arizona; (2) Atolia, California; (3) Boulder district, Colorado; (4) Ima, Idaho; and (5) Hamme, North Carolina. In addition to these, smaller vein deposits are scattered in Arizona, Nevada, Colorado, Washington, Idaho, and Montana.

In deposits of tungsten minerals as fracture fillings and replacements in stockworks and breccia zones, sheelite is the only tungsten mineral, except for the related porphyry-molybdenum occurrences. Deposits of this type occur in Montana, Nevada, and California. In the prophyry-molybdenum ore body at Climax, Colorado, small amounts of huebnerite are disseminated in the ore.

In the United States, tungsten is produced as a coproduct or byproduct of molybdenum and copper mining. About 75 percent of the United States production comes from tactite deposits with the Pine Creek Mine, Inyo County, California, being the largest producer. The Climax ore body, Climax, Colorado, is second in United States tungsten production. Virtually all United States tungsten ore is extracted by underground mining methods. Most known United States resources occur as scheelite in tactite deposits located in California, Nevada, and Montana. Other tactite deposits are located in Utah, Arizona, Washington, and Idaho. Other known United States resources occur as ferberite, wolframite, and huebnerite in quartz veins in Arizona, Idaho, Colorado, and North Carolina and as huebnerite in the Climax porphyry-molybdenum deposit of Colorado.

The environmental problems related to United States tungsten mining are similar to those for other large underground mines mining sulfide ores. A water clarifying chemical system, in which a flocculant-coagulant causes settlement of solid materials in mine water effluent to Pine Creek is in operation at the Pine Creek Mine.

1.12 VANADIUM

The important ore minerals of vanadium are carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$), coulsonite ($(Fe,V)_3O_4$), descloizite-mottramite series ($PbZn(VO_4)OH$-$PbCu(VO_4)OH$), montroseite ($(V,Fe)O \cdot OH$), patronite (VS_4), roscoelite ($K(V,AL)_3Si_3O_{10}(OH)_2$), and vanadinite ($Pb_5(VO_4)_3Cl$). Most vanadium currently produced is recovered from ores with no specific vanadium mineral identifiable.

The five types of vanadium deposits are: (1) deposits of magmatic origin, including both titaniferous and nontitaniferous magnetite deposits; (2) hydrothermal vein deposits; (3) epigenetic deposits, including both vanadate and sandstone deposits; (4) asphaltite deposits; and (5) deposits associated with alkalic igneous complexes. In the past, the uranium-vanadium deposits in the sandstones of the Colorado Plateau have been the most productive vanadium source. Various amounts of uranium and copper are associated with vanadium in these deposits. The principal ore minerals are silicates and oxides of both vanadium (roscoelite and montroseite) and uranium, common copper sulfides, and carnotite as a secondary uranium-vanadium mineral. Vanadium also has been recovered from deposits of phosphatic shales and phosphate rock in Idaho as a coproduct or elemental phosphorous. Vanadium also is mined from the alkalic instrusive complex at Wilson Springs, Arkansas.

The principal United States source of vanadium is the Colorado Plateau uranium-vanadium ores. For these deep, lenslike sandstone deposits, mining is by underground open stope and room and pillar methods. Both Arkansas vanadium ore and Idaho ferro-phosphorous ores were important sources.

Most United States vanadium resources are in deposits that are or will be mined for vanadium as a coproduct or byproduct. Large titaniferous deposits are located in Alaska, Wyoming, and New York. Nontitaniferous magnetite containing vanadium is mined at Buena Vista Hills, Nevada. Uranium ores of the Colorado Plateau and Idaho phosphate rock are expected to produce substantial vanadium. Certain carbonaceous shales, oil shales, phosphatic shales, and graphic schists, such as occur in Idaho and adjoining states, represent large resources of vanadium.

The environmental problems related to underground mining of the uranium-vanadium sandstones are similar to those for uranium mining, including radiation hazards.

2.0

NONFERROUS METALS

2.1 ALUMINUM

The principal minerals in bauxite ore, the principal source of aluminum, are gibbsite ($Al(OH)_3$), boehmite ($AlO(OH)$), and diaspore ($AlO(OH)$). Bauxite is formed by the weathering of aluminous rocks, such as feldspars and clays. During weathering, the bauxite becomes enriched in aluminum by removal of most of the other elements in the parent rock mainly by solution by subsurface water. Conditions favorable for the formation of bauxite are: (1) warm tropical climate; (2) abundant rainfall; (3) aluminous parent rocks of high permeability and good subsurface drainage; and (4) long periods of tectonic stability to permit deep weathering. Since bauxite is formed by weathering, deposits usually lie nearly horizontal close to the surface.

Several types of bauxite deposits occur in the United States. Most of these deposits are composed primarily of gibbsite with the principal impurity being kaolinite. The major deposits, located in Arkansas, were formed by the weathering of nepheline syenite. Other minor lower grade bauxite deposits are located in the southeastern Appalachian region and the states of Washington, Oregon, and Hawaii. United States resources of metallurgical-grade bauxite are limited. Other potential sources of aluminum comprise a variety of rocks and minerals, including alunite, aluminous shale and slate, aluminum phosphate rock, dawsonite, high-alumina clays, nepheline syenite, anorthosite, saprolite, coal, ash, and aluminum-bearing copper-leach solutions.

The United States mines less than 12 percent of its bauxite requirements. Arkansas produces about 90 percent of the United States bauxite and minor amounts are mined in Alabama and Georgia. About 10 percent of the United States production is mined by an underground room and pillar method at the Hurricane Creek Mine in Arkansas. The two major environmental problems related to underground bauxite mining are contamination of streams by sedimentation, and subsidence.

2.2 ANTIMONY

The principal antimony minerals are stibnite (Sb_2S_3), valentinite (Sb_2O_3), senarmontite (Sb_2O_3), stibiconite ($Sb_2O_4.H_2O$), bindheimite ($Pb_2Sb_2O_7{\cdot}nH_2O$), kermesite ($2Sb_2S_3{\cdot}Sb_2O_3$), tetrahedrite ($(Cu,Fe,Zn,Ag)_{12}Sb_4S_{13}$), and jamesonite ($Pb_4FeSb_6S_{14}$). Antimony occurs in epithermal veins, pegmatites, and replacement and hot spring deposits. Virtually all United States antimony production comes from complex deposits as a byproduct of silver, lead, copper, and zinc ores.

Lead-silver mines of the Coeur d'Alene district account for the bulk of the United States antimony production. Antimony also was produced from complex antimony-gold-tungsten ores of the Yellow Pine district, Idaho. Mines in Alaska, Nevada, and Montana also produced minor amounts of antimony. Thus, antimony is a byproduct or coproduct of mining other ores containing relatively small quantities of antimony.

The underground mines of the Coeur d'Alene district are mined by horizontal cut and fill stoping using hydraulic fill. The environmental problems related to underground mining of these lead-silver ores are principally related to mine drainage and include siltation, acidification, and heavy metal contamination.

2.3 ARSENIC

The primary arsenic minerals are arsenopyrite (FeAsS), lollingite ($FeAs_2$), smaltite ($CoAs_{3-x}$), chloanthite ($NiAs_2$), niccolite (NiAs), tennantite ($(Cu,Fe,Zn,Ag)_{12}As_4S_{13}$), enargite ($Cu_3AsS_4$), and proustite ($Ag_3AsS_3$). Arsenic is found primarily in the following types of metalliferous deposits: (1) enargite-bearing copper-zinc-lead deposits; (2) arsenical pyrite-copper deposits; (3) native silver and nickel-cobalt arsenide deposits; (4) arsenical gold deposits; (5) arsenic sulfide and arsenic sulfide gold deposits; and (6) arsenical tin deposits. United States demand for arsenic is met mainly by imports with all United States arsenic production as a byproduct from complex arsenical base-metal ores.

Environmental problems related to underground mining of arsenic-bearing ores are similar to those normally related to base metal mining. In addition, arsenic in sulfide minerals exposed to the atmosphere may form soluble arsenates which can cause surface and ground water pollution.

2.4 BERYLLIUM

The principal beryllium minerals are beryl ($Be_3Al_2(SiO_3)_6$), bertrandite ($Be_4Si_2O_7(OH)_2$), phenakite (Be_2SiO_4), barylite ($BaBe_2Si_2O_7$), and chrysolberyl (Al_2BeO_4), with beryl and sole commercial source of beryllium. Beryllium deposits can be classified into two general types: (1) pegmatitic and (2) nonpegmatitic or hydrothermal. The pegmatitic deposits can be divided into fine-grained unzoned and coarse-grained zoned deposits. The nonpegmatitic deposits can be divided into hydrothermal, mesothermal, and epithermal deposits. The principal commercial sources of beryl are the coarse-grained zoned pegmatites. The pegmatitic deposits are composed of major amounts of quartz, sodic plagioclase, and microcline, with or without spodumene, muscovite, or lepidolite.

The United States imports about 20 percent of its beryllium consumption. Beryl production is essentially a byproduct from mining of feldspar, mica, lithium minerals, columbite, tantalite, and cassiterite. Pegmatitic deposits occur along much of the Appalachian Mountains and in South Dakota, Colorado, New Mexico, and Wyoming, but none of these deposits currently are mined for beryl. Beryllium is mined as bertrandite from a nonpegmatitic deposit at Spor Mountain, Utah. Other non-pegmatitic deposits occur in Utah, Colorado, Alaska, Arizona, Nevada, New Mexico, and New Hampshire, but these are not mined.

Some small pegmatitic deposits are mined principally for beryl by simple open cut methods. The nonpegmatitic deposit at Spor Mountain, Utah, is mined by surface mining methods. There are no environmental problems related to underground mining of beryllium since there are no underground mines.

2.5 BISMUTH

The principal bismuth minerals are bismite (Bi_2O_3) and bismuthinite (Bi_2S_3). Hypogene deposits in the western United States account for most United States bismuth production. Most of the bismuth occurs as a minor constituent in silver, lead, zinc, copper, gold, tungsten, cobalt, and molybdenum ores. Lead-zinc-silver replacement deposits in limestone have been an important bismuth source. Small amounts of bismuth ore have been mined from pegmatite dikes, quartz veins, and contact-metamorphic zones. Because of the low concentration of bismuth, no deposits in the United States are mined for the bismuth content alone. All United States bismuth production is a byproduct of complex base metal ores. Bismuth resources essentially are associated with copper, lead, and zinc ores located in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, and Utah. Environmental problems are the same as related to underground base metal mining, especially lead, which is mined essentially by underground methods.

2.6 CADMIUM

Cadmium occurs primarily as a yellowish earthy film or an oxide coating on zinc minerals, usually spahlerite. All United States cadmium production is recovered as a byproduct during the smelting and refining of zinc. Cadmium resources are closely associated with zinc resources.

2.7 CESIUM

The principal mineral of cesium is pollucite ($H_2O{\cdot}2Cs_2O{\cdot}2Al_2O_3{\cdot}9SiO_2$). Lepidolite ($K_2Li_3Al_3(AlSi_3O_{10})_2(OH,F)_4$), and beryl ($Be_3Al_2(Si_6O_3)$)) occationally contain cesium. Cesium occurs in certain granites and granite pegmatites. Pollucite is recovered as a coproduct in mining pegmatites for lithium minerals and beryl. Cesium also occurs with several other minerals, such as rhodonite, leucite, spodumene, potash feldspar, and related minerals, but cesium is not recovered from these as a byproduct. Currently, no cesium is mined in the United States. However, pollucite has been produced from mines in Maine and South Dakota.

2.8 COPPER

Copper occurs in about twenty common minerals and about 140 less common minerals. The common copper minerals are listed in Table 2.8-1. Chalcopyrite is the most abundant copper sulfide, followed by bornite and chalcocite. The sulfarsenides, enargite and tennantite, and the sulfantimonides, tetrahedrite and famatinite, are rare, but each is a major ore mineral in at least one large ore body. Native copper is abundant in certain types of deposits. Malachite, azurite, and chrysocolla are the common oxidized copper minerals.

Copper deposits can be classified into the five major types: (1) porphyry copper deposits and veins, pipes, and replacement deposits; (2) sedimentary deposits; (3) massive sulfide deposits in volcanic rocks; (4) mafic intrusives forming nickel-copper despoits; and (5) native copper deposits of the Keeweenaw type.

Porphyry copper deposits are deposits of disseminated copper sulfides that are in or near a felsic intrusive body. Porphyry copper deposits have petrologic associations that are dependent on their tectonic environment. Deposits formed in a thin or poorly developed continental crust are associated either with syenite, monzonite, or fennite. Deposits formed on thick continental crust, such as in Arizona, usually are associated with quartz monzonite. The characteristic porphyritic texture of the intrusive occurs because a part of the copper was trapped in disseminated grains by the rapid crystallization of the magma. Another part of the copper escaped from the hot rock mass and was deposited in fractures in the intrusive and wall rocks. Another part may have escaped completely from the intrusive and formed vein and replacement deposits in nearby host rocks. Sulfide minerals in descending order of abundance usually are pyrite, chalcopyrite, molybdenite, and bornite. The Bingham deposit in Utah is the largest United States

Table 2.8-1

Minerals of Copper

Major Minerals	
Native copper	Cu
Chalcocite	Cu_2S
Covellite	CuS
Bornite	Cu_5FeS_4
Chalcopyrite	$CuFeS_2$
Enargite	Cu_3AsS_4
Cuprite	Cu_2O
Malachite	$Cu_2(OH)_2(CO_3)$
Significant Supplementary Minerals	
Tetrahedrite	$(Cu,Fe,Zn,Ag)_{12}Sb_4S_{13}$
Tennantite	$(Cu,Fe,Zn,Ag)_{12}As_4S_{13}$
Famatinite	Cu_3SbS_4
Stannite	Cu_2FeSnS_4
Atacamite	$Cu_2(OH)_3Cl$
Tenorite (melaconite)	CuO
Azurite	$Cu_3(OH)_2(CO_3)_2$
Chrysocolla	$CuSiO_3 \cdot 2H_2O$
Brochantite	$Cu_4(SO_4)(OH)_6$
Antlerite	$Cu_3(SO_4)(OH)_4$
Chalcanthite	$CuSO_4 \cdot 5H_2O$
Kroehnkite	$Na_2Cu(SO_4)_2 \cdot 2H_2O$

porphyry deposit. Numerous other porphyry copper deposits occur in the southwestern United States in Arizona, New Mexico, and Nevada. The principal byproducts of the porphyry coppers are molybdenum, gold, and silver. Economically important amounts of selenium, tellurium, and rhenium are obtained from porphyry copper and molybdenum concentrates. The porpyry copper deposits produce about 90 percent of the United States copper production.

Copper rich veins, pipes, and replacement deposits may be localized: (1) in felsic plutonic rocks with local porphyry intrusions (Butte, Montana); (2) in favorable host rocks near porphyry copper deposits (Bingham, Utah, and Bisbee, Arizona); and (3) near barren felsic intrusive rocks (Magma and Mission, Arizona). Veins are formed when metal-rich solutions deposit minerals in faults or fractures. Replacement deposits form near intrusive contacts or along mineral veins in sedimentary host rocks and may occur in limestone, dolomite, calcareous sandstone, or even diabase sills. The mineralogy of vein, pipe, and replacement deposits is more varied than the mineralogy of the porphyry copper deposits. Copper resources in the vein, pipe, and replacement deposits are small when compared with the related porphyry copper deposits.

Strata-bound deposits in sedimentary rocks include some of the world's largest copper resources. Sedimentary Precambrian deposits in the United States include the White Pine district in Michigan and the Belt Supergroup in western Montana and adjacent parts of Idaho. At White Pine, copper occurs in the Nonesuch Shale with chalcocite the principal sulfide ore mineral. In the Belt Supergroup, copper sulfides occur in beds of quartzite and siltite. Sedimentary red-bed copper deposits are associated with red sandstone. These deposits occur in the southwestern United States and southern Kansas and western Oklahoma. Sedimentary copper deposits also occur where copper dissolved from sulfide-bearing rocks by leaching and then traveled laterally before being deposited in a secondary zone (Wallapai district, Globe-Miami district, and Jerome and Ray, Arizona).

Under various conditions, copper in basalt and andesite may be concentrated to form massive sulfide deposits. Mineralogically, the deposits consist mainly of pyrite and/or pyrrhotite and varying amounts of chalcopyrite, sphalerite, and galena. Chalcopyrite-pentlandite ores occur in mafic intrusives, such as in the Sudbury district, Ontario. In the United States, copper resources occur in mafic intrusives in Maine and Minnesota.

In the United States, native copper deposits occur in the Portage Lake Volcanics on the Keweenaw Peninsula, Michigan. Other United States copper occurrences that resemble the Keweenaw type are the native copper-cuprite-azurite-malachite ores in the Catoctin Formation of Maryland and Virginia.

In addition to the five major types of copper deposits, there are several miscellaneous types of deposits. These include: (1) small and very high grade chalcocite deposits at Kennecott, Alaska, and Mountain City, Nevada and (2) replacement deposits in carbonate rocks at Bornite-Ruby Creek, Alaska, and Missouri.

The porphyry copper deposits of the southwest are the major copper resources of the United States. The sedimentary copper deposits in Wyoming, Idaho, Montana, and Michigan are the next most important United States copper resources.

The leading copper producing state is Arizona with more than 50 percent of the United States production, followed by Utah, New Mexico, Montana, Nevada, and Michigan. About 98 percent of the United States mine production of copper is recovered from ores mined primarily for copper and the remainder is recovered from complex or base metal ores. In addition to copper, important amounts of gold, silver, molybdenum, nickel, selenium, tellurium, arsenic, rhenium, iron, lead, zinc, sulfur, and platinum-group metals are recovered from copper ores as byproducts. About 20 percent of the copper produced in the United States comes from underground mines. These mines are located in Arizona, California, Colorado, Idaho, Michigan, Montana, New Mexico, Tennessee, Utah, and Washington. Underground copper mining is done by both caving and supported stopes. Caving methods usually are block caving or sublevel stoping. Examples of block caving are Miami Copper and San Manuel, Arizona. An example of sublevel stoping is Copper Basin, Tennessee. Supported methods of underground copper mining include room and pillar such as at White Pine, Michigan, and cut and fill such as at Superior, Arizona.

The environmental problems related to underground copper mines are subsidence and water pollution. Subsidence is a major problem in large block caving mines where there is no ground support. Subsidence also may be a problem in supported stopes as the support fails or pillars are recovered. Copper and associated sulfides result in acidification and discharges of heavy metals into ground and surface waters.

2.9 GALLIUM

Gallium is concentrated in sulfide minerals, especially the zinc sulfide minerals, sphalerite, and wurtzite. Gallium apparently replaces zinc in the sphalerite and wurtzite lattice in limited amounts. In addition to zinc ores, gallium is found in bauxite ores. Gallium is produced only as a byproduct from processing zinc and aluminum ores.

2.10 GERMANIUM

Germanium is concentrated in sulfide minerals, especially the zinc sulfide minerals sphalerite and wurtzite. Germanium apparently replaces zinc in the sphalerite and wurtzite lattice in limited amounts. Other sulfide minerals that have major concentrations of germanium are chalcopyrite, bornite, enargite, tennantite, and cinnabar. Germanium is produced only as a byproduct from processing zinc ores.

2.11 GOLD

Gold occurs mainly as native metal, always alloyed with variable amounts of silver and other metals. The only important gold minerals are the tellurides (gold or gold plus silver, copper, or lead combined with tellurium).

Gold deposits can be classified into seven types: (1) gold-quartz lodes; (2) epithermal ("Bonanza") deposits; (3) young placers; (4) ancient (fossil) placers; (5) marine placers; (6) disseminated gold deposits; and (7) gold byproduct deposits. Gold-quartz lodes comprise a wide variety of deposits that are essentially hydrothermal veins of quartz and gold that either replace wall rock or fill open spaces among fractures. Examples of United States gold-quartz lodes are the Mother Lode-Grass Valley, California; Homestake, South Dakota; Central City, Colorado; and Juneau-Treadwell, Alaska. This has been the most productive type of deposit in the United States with Homestake being the most productive gold-quartz lode mine in the world. Epithermal deposits are hydrothermal veins of quartz, carbonate minerals, barite, and fluorite containing gold or gold tellurides and silver. Most epithermal deposits are in highly altered volcanic rocks. Examples of United States epithermal deposits are Goldfield, Virginia City, and Tonopah, Nevada and Cripple Creek, Telluride, Silverton, and Ouray, Colorado. Young placers are composed primarily of unconsolidated or semiconsolidated sand and gravel that contain very small amounts of native gold and other heavy minerals. Examples of young placers in the United States are deposits along the American, Feather, and Yuba Rivers in the Sierra Nevada of California; along Alder Gulch at Virginia City, Montana; on the Yukon River at Fairbanks, Alaska; on or near the beach at Nome, Alaska; and at Boise Basin, Idaho. Ancient (fossil) placers were formed in the geologically distant past and have been lithified to conglomerate and become part of the bedrock. These conglomerates consist of small quartz pebbles embedded in a matrix of pyrite and micaceous minerals and contain gold, uraninite, and platinum-group metals. No fossil placers have been found in the United States. Marine placers consist of ocean floor sediment. The gold was derived from the land, transported by streams to ocean basins, and deposited with clastic sediments on the ocean floor. Marine placers have not yielded significant gold production. Disseminated gold deposits consist of very fine grained gold disseminated in silty and carbonaceous dolomitic limestone. The deposits were formed by hydrothermal replacement of the host rock and the gold is accompanied by silica, barite, and a little pyrite and other sulfide minerals. Examples of United States disseminated gold deposits are Carlin, Cortez, Getchell, and Gold Acres in Nevada. Geologically similar deposits are Mercur, Utah, and Bald Mountain and Deadwood, South Dakota.

Gold byproduct deposits account for about 47 percent of the United States gold production. Of the byproduct gold production, about 80 percent is from copper ores and the remainder is principally from complex ores of lead, zinc, and copper. An example of a United States gold byproduct deposit is at Bingham, Utah.

Lode, disseminated, and placer gold deposits account for 53 percent of the gold mined in the United States with lode and disseminated deposits accounting for almost all of this production. Underground mining produces about 30 percent of this gold production while surface mining of disseminated deposits and placers account for the remaining 23 percent. The Homestake Mine in South Dakota is the major United States gold producer and accounts for almost all of this underground gold production. However, other small underground gold mines are in Arizona, Colorado, Idaho, Montana, and Utah. New underground gold mines now are being opened in the Cripple Creek, Colorado, area. The Homestake Mine uses a cut and fill mining method with shrinkage and blast hole stoping.

Environmental problems related to underground gold mines are similar to those related to other underground base metal mining.

2.12 HAFNIUM

Hafnium occurs as a minor constituent in zirconium minerals, but zircon ($ZrSiO_4$) is the only commercial source for hafnium metal. Hafnium is a byproduct from the production of reactor grade zirconium for zircon. Zircon is a byproduct recovered during processing of dredged heavy mineral-bearing sands to recover titanium minerals.

2.13 INDIUM

Indium is concentrated in sulfide minerals, especially the zinc sulfide mineral sphalerite. Indium apparently replaces zinc in the sphalerite lattice in limited amounts. Some copper-bearing minerals, particularly chalcopyrite and tetrahedrite, have small amounts of indium. Indium is recovered entirely as a byproduct in processing zinc-bearing ores.

2.14 LEAD

The principal lead mineral is galena (PbS). The galena commonly has inclusions of argentite (Ag_2S), argentiferous tetrahedrite ($(Cu,Fe,Ag)_{12}Sb_4S_{13}$), and similar minerals. Many galena ore bodies near the surface are altered to cerussite ($PbCO_3$), anglesite ($PbSO_4$), pyromorphite ($Pb_4(PbCl)(Po_4)_3$), and other minerals. The primary metallic minerals most commonly associated with galena include pyrite, sphalerite, chalcopyrite, tetrahedrite or tennantite, and other sulfides, and locally, marcasite and pyrrhotite. Sphalerite almost always is associated with galena. The primary gangue minerals associated with lead deposits include quartz; calcite, dolomite, and other carbonates; barite; and fluorite.

Lead deposits can be classified on the basis of geologic occurrances as: (1) strata-bound deposits of syngenetic origin; (2) strata-bound deposits of epigenetic origin; (3) volcano-sedimentary deposits; (4) replacement deposits; (5) veins; and (6) contact pyrometasomatic deposits. World wide, strata-bound deposits are the largest and most productive lead deposits. These deposits occur chiefly in limestone, dolomite, or shale. For strata-bound deposits of syngenetic origin, the ore minerals are disseminated finely. These ore minerals consist predominantly of bornite, chalcocite, galena, sphalerite, and tetrahedrite. Accessory elements often include nickel, cobalt, selenium, vanadium, molybdenum, and silver. An example in the United States is the Belt Supergroup of northern Idaho and northwestern Montana where thin beds of galena occur in carbonate rich quartzite and siltite host rocks. The most common host rocks of the epigenetic stratiform deposits are shallow-water marine carbonate rocks. The minerals of these deposits consist predominantly of galena, sphalerite, and pyrite or marcasite. Some deposits may contain chalcopyrite, siegenite, and other sulfides with nickel, cobalt, copper, cadmium, silver, and germanium possibly recovered as a byproduct. The gangue minerals commonly are calcite, dolomite, and jasperoid. In some deposits in Kentucky, Illinois, and Tennessee, barite or fluorite are major coproducts. United States districts containing strata-deposits of epigenetic form include southeast Missouri, Tri-State (Kansas, Missouri, and Oklahoma), Upper Mississippi Valley

(Wisconsin and Illinois), Metaline (Washington), Kentucky-Illinois, central Kentucky, central Tennessee, and Appalachian Valley (eastern United States).

The second most productive lead deposits are lenticular massive sulfide deposits in interstratified volcanic, volcano-sedimentary, and sedimentary rocks. These volcanic-sedimentary deposits and their metamorphic equivalents range from deposits in unmetamorphic rocks to recrystallized massive deposits in metamorphic rocks. At Jerome, Arizona, the ore body is associated intimately with metamorphosed quartz porphyry. The metamorphic deposits commonly consist of intimate aggregates of pyrite or pyrrhotite, sphalerite, galena, and chalcopyrite with minor amounts of quartz, sericite, chlorite minerals, ankerite, and other carbonate minerals. Host rocks include argillite, metavolcanic rocks, schists, shale, and carbonate rocks. At Duckstown, Tennessee, the deposits may have originated as volcano-sedimentary deposits.

The third most productive lead source is the hypothermal replacement deposits. Although commonly occurring in limestone and dolomite, these deposits also occur in quartzite and shale and in igneous and metamorphic rocks. The dominant lead mineral is galena associated with sphalerite, chalcopyrite, and pyrite. Silver, arsenic, antimony, and cadmium occur in many deposits resulting in arsenides, antimonides, and sulfosalts. Oxidation often occurs at depth, resulting in a greater mineral variety. Examples of important massive replacement deposits in the United States include Tintic, Utah; Bingham, Utah; Gilman, Colorado; and Leadville, Colorado.

Lead vein deposits are found in all types of rocks. These deposits may occur as filled veins where ore and gangue minerals occupy open spaces along fractures or as replacement veins, generally in limestone or other reactive rocks. The dominant ore minerals in vein deposits are galena, sphalerite, and pyrite. Some deposits contain argentiferous tetrahedrite, chalcopyrite, silver-lead sulfosalts, and rarely, cobalt, nickel, and uranium minerals. Gangue minerals include quartz, siderite, calcite, barite, and fluorite. Examples of lead vein deposits are the Coeur d'Alene district, Idaho; Butte, Montana; Tintic, Utah; Park City, Utah; Leadville, Colorado; Pioche district, Nevada; and the Kentucky-Illinois district.

Contact pyrometasomatic deposits in the aureoles of granitic plutons are localized chiefly in limy or dolomitic rocks that have become bleached, recrystallized, and silicated. Some deposits occur in calcarious shales, tuffs, and sandstones. The more common metallic minerals are galena, sphalerite, chalcopyrite, pyrite, pyrrhotite, arsenopyrite, and magnetite. Bismuth, molybdenum, tungsten, and gold may occur in some deposits. The gangue minerals include diopside, hedenbergite, garnet, fluorite, epidote, actinolite, ilvaite, tremolite, quartz, and other silicates. Examples of contact pyromatasomatic and similar deposits in the United States are the Central district, New Mexico, and the Darwin Mine, Cerro Gordo, California.

Lead largely is mined by underground methods, although some deposits amenable to surface mining occur in the Tri-State district and Washington. Underground lead ore mines are in California, Colorado, Idaho, Illinois, Missouri, and Wisconsin. These underground mines vary in ore output from a few metric tons per day to over 9070 metric tons per day (10,000 tons/day). Underground stoping includes both open and supported stopes. Underground methods include block caving, room and pillar with and without rock bolts, shrinkage stoping, cut and fill, and timbered stoping.

Southeast Missouri is the leading lead producing district in the United States, followed by Idaho, Colorado, and Utah. Ores mined principally for lead account for about 65 percent of the United States lead production, with the remainder being produced from lead-zinc, zinc, and other complex ores. Most United States lead reserves are located in Missouri with small known reserves principally in Idaho, Utah, and Colorado.

Environmental problems related to underground lead mining are pollution of surface and ground water by acidification and heavy metals. Lead is very toxic and represents a health hazard to humans.

2.15 MAGNESIUM

The principal magnesium minerals are dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), brucite ($Mg(OH)_2$), and olivine ($(Mg,Fe)_2SiO_4$). Dolomite is a sedimentary rock commonly interbedded with limestone. It is formed during diagenesis of limestone by partial replacement of $CaCO_3$ by $MgCO_3$. Dolomite deposits extend over large areas of the United States and are mined in California, Colorado, Illinois, Louisiana, Mississippi, Missouri, Ohio, Pennsylvania, South Dakota, Texas, Utah, and West Virginia. Currently, dolomite is not used as a raw material for producing magnesium metal.

Magnesite occurs mainly in four types of deposits. Crystalline magnesite occurs as replacement deposits in dolomite or in limestone locally altered to dolomite. The principal impurities are calcium, iron, silica, and silicate minerals, such as talc, tremolite, anthophyllite, or enstatite. The two districts in the United States having large deposits of this type are at Gabbs, Nevada, and Stevens County, Washington. Impure crystalline magnesite mixed with talc and with or without quartz occurs as replacement deposits in ultramafic rocks. Bone magnesite deposits are known to occur in Red Mountain, California, Oregon, and Pennsylvania. Deposits of bone magnesite replace bedded rhyolitic tuff in eastern Nevada. Sedimentary magnesite beds and lenses are interbedded with dolomite, clastic rocks, or strata of volcanic origin. In the United States, these deposits are limited to several states in the southwest.

Brucite rarely is found in minable concentrations, however, two minable deposits are associated with magnesite at Gabbs, Nevada. Olivine is a common mineral in quartz-free igneous rocks. The magnesium rich variety, forsterite, forms the rock dunite, which readily alters to serpentine minerals. In the United States, fresh dunite occurs in large masses east of Bellingham, Washington, and in smaller masses in North Carolina and Georgia.

A major portion of the United States magnesium production is obtained from sea water at Freeport, Texas, with well brines in Texas and brines of the Great Salt Lake in Utah supplying the remainder. Dolomite, sea water, and well and lake brines are available in unlimited quantities.

Since all United States magnesium metal is produced from sea water or brines, there are no environmental problems related to underground mining for magnesium.

2.16 MERCURY

The principal mercury minerals are cinnabar (HgS), metacinnabar (HgS), and livingstonite ($HgSb_4S_7$). The common mercury host rocks are limestone, calcareous shales, sandstone, serpentine, chert, andesite, basalt, and rhyolite. Deposits have been formed by replacement, open-space filling, both replacement and open-space filling, and detrital concentration. Mercury deposits usually occur at relatively shallow depths in formations of younger volcanic and tectonic activity. In mercury deposits, silica and carbonate minerals are the common gangue minerals and pyrite and marcasite may be abundant in deposits formed in iron-bearing rocks. Gold, silver, or base metals generally are present in only trace amounts.

At the New Almaden Mine in California, folded and faulted sedimentary and volcanic rocks are intruded by serpentine which was altered along its margins to silica-carbonate rocks. Silica-carbonate rock was replaced by cinnabar along steep parallel fractures to depths of about 610 meters (2,000 feet). The New Idria Mine in California is near the margin of a pluglike serpentine mass that arched upward and pierced through a thick shale-sandstone. Steeply dipping shale near the serpentine has been rendered brittle through induration, and, subsequently, shattered. Cinnabar mostly fills the fractures or coats walls with some cinnabar and metacinnabar occurs in thick carbonate veins.

Mercury is mined by both surface and underground methods with most of the mercury mined by underground methods. Mercury production in the United States comes from a relatively large number of small mines with ore production from underground mines ranging up to 272 metric tons per day (300 tons/day). California is the leading producing state, followed by Alaska and Nevada. Most United States mercury resources are in California. Mercury is recovered as a coproduct from one United States gold mine. Both the New Almanden and New Idria are underground mines. These mines use square-set or modified square-set stoping methods. In some instances, shrinkage and sublevel stoping are used.

The environmental problems related to underground mining of mercury are poisoning of workers by mercury vapors and pollution of ground and surface waters by acidification and heavy metals.

2.17 PLATINUM-GROUP METALS

Platinum, palladium, iridium, osmium, rhodium, and ruthenium comprise the platinum-group metals. Platinum-group metals are found in five major types of deposits: (1) stratiform complexes in mafic and ultramafic rocks, such as the Stillwater Complex in Montana; (2) concentrically zoned ultramafic complexes and associated mafic bodies, such as in southeastern Alaska; (3) alpine complexes in mafic rocks, such as at Burro Mountain, Red Mountain, and New Idria, California, and Twin Sisters and Cypress Island, Washington; (4) copper, nickel, and gold in mafic and ultramafic rocks, such as at the Rambler and Centennial Mines in Wyoming; and (5) placer deposits, such as in Alaska, California, Oregon, Washington, Montana, and Idaho. There also are minor occurrences of platinum-group metals where these metals are associated with syenites (La Plata district, Colorado, and Cooke City, Montana) and gold-quartz (Boss Mine, Nevada).

United States production of platinum-group metals is principally as a byproduct of copper smelting. Significant amounts of platinum-group metals have been produced from placers of the Salmon River of the Goodnews Bay district, Alaska. United States reserves are almost entirely in copper ores with a very small amount in placers. Since most United States mine production of platinum-group metals is recovered as a byproduct of copper mining, environmental problems are incidental to copper production.

2.18 RADIUM

Radium is present in small amounts in uranium ore and the geology of radium and uranium are the same. The United States presently does not produce any radium, but radium has been recovered from high grade uranium (carnotite) deposits in Colorado.

2.19 RARE-EARTH ELEMENTS

The rare-earth elements are the elements having atomic number 57 through 71. These are lanthanum (La), cerium (Ce), praseodymium (Pr), neodyanum (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Le). Yttrium (Y), with atomic number 39, also is classified as a rare-earth. The rare-earths are essential constitutents of more than 100 mineral species. The three most important are monazite ($(Ce,La,Th,Y)PO_4$), bastnaesite ($CeFCO_3$), and xenotime (YPO_4). Other minerals such as allanite ($(Ca,Ce,Th)_2(Al,Fe,Mg)_3 \cdot Si_3O_{12} \cdot (OH)$), gadolinite ($Be_2FeY_2Si_2O_{10}$), euxenite ($(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$), and loparite ($(Ce,Na,Ca)(Ti,Nb)_2O_6$) also are commercial sources. Apatite ($Ca_5F,Cl,OH)(PO_4)_3$), thorgh not a rare-earth mineral, may contain rare-earth elements because of substitution.

Primary concentrations of rare-earth-bearing minerals occur in a wide variety of geologic settings, including veins, gneisses, pegmatites, and alkalic rock complexes and related carbonates. The largest known rare-earth concentration is the bastnaesite deposit in carbonatite at Mountain Pass, California. The gangue minerals are principally barite, carbonates, and quartz. Other deposits of primary concentrations are known to occur in California, Idaho, Montana, Wyoming, Colorado, New Mexico, and New York. Most minable concentrations of rare-earths are found in unconsolidated secondary deposits. These deposits include sea-beach placers, fluviatile placers, and deltaic deposits. Secondary deposits are known in Idaho, North Carolina, South Carolina, Florida, and Georgia.

Except for the Mountain Pass, California, deposit, rare-earths usually are recovered as byproducts. All United States production comes from surface mines.

2.20 RUBIDIUM

Rubidium does not occur in distinct minerals. However, it does occur as an impurity or associate element in various minerals including lepidolite ($K_2Li_3Al_3(AlSi_3O_{10})_2(OH,F)_4$), pollucite ($Ce_4Al_4Si_9O_{26} \cdot H_2O$), microcline ($KAlSi_3O_8$), and biotite ($K(Mg,Fe)_3(AlSi_3O_{10}(OH)_2$) from granites and pegmatites, and carnallite ($KMgCl_3 \cdot 6H_2O$) from saline deposits. The principal united States supply has come from the processing of an alkali carbonate residue resulting from processing imported lepidolite into lithium.

Rubidium also is recovered as a byproduct from pollucite which is recovered as a byproduct from pegmatites mined for lithium and beryl. There are no United States mines producing rubidium, but it does occur sporadically in many New England pegmatites. Rubidium also exists in certain feldspars, brines, and saline deposits.

2.21 SCANDIUM

The minerals of scandium are thortveitite ($(Se,Y)Si_2O_7$), sterrettite ($ScPo_4\ 2H_2O$), bazzite ($Be_3(Sc,Al)_2Si_6O_{18}$), and magbasite ($KBa(Al,Sc)(Mg,Fe)_6Si_6O_{20}F_2$). Many other minerals contain minor amounts of scandium because of substitution. Scandium occurs in four types of geologic deposits. These are: (1) pegmatites such as the occurence of thortveitite in the Crystal Mountain fluorite deposit in Montana; (2) greisen and vein deposits; (3) variscite deposits such as the sparse occurrence of sterrettite in a highly brecciated zone in limestone at Fairfield, Utah; and (4) enrichments in other materials. Scandium is produced only as a byproduct from uranium and tungsten. The United States currently does not produce any scandium.

2.22 SELENIUM

Selenium occurs principally by substitution in sulfide minerals of copper, iron, and lead and is most common in chalcopyrite, bornite, and pyrite. Selenium is principally a byproduct of copper refining. Some selenium also is produced as a byproduct of lead refining.

2.23 SILVER

The principal silver minerals are native silver (Ag), argentite (Ag_2S), polybasite (Ag_9SbS_6), proustite (Ag_3AsS_3), stephanite (Ag_5SbS_4), pyrargyite (Ag_3SbS_3), and cerargyrite (AgCl). Other minerals such as argentiferous tetrahedrite ($(Cu,Fe,Ag)_{12}Sb_4S_{13}$) and argentiferous galena ($(Pb,Ag)S$) have part of their crystal lattice replaced with silver.

Types of silver deposits can be divided into: (1) deposits with byproduct and coproduct silver and (2) deposits with silver as a major constituent. Silver is an important byproduct in nine types of deposits: (1) porphyry copper deposits such as in Utah and Arizona; (2) copper-zinc-lead replacement deposits and vein clusters such as in the Butte district, Montana, and the Superior district, Arizona; (3) massive sulfide deposits; (4) lead-zinc replacement deposits such as the Park City and Tintic districts, Utah; (5) Mississippi-Valley – and Alpine-type lead, zinc, and flourspar deposits and related deposits; (6) copper deposits in sandstones and shales such as White Pine, Michigan; (7) native copper deposits such as the Keweenaw Peninsula in Michigan; (8) gold deposits in veins, conglomerates, and placers such as the Homestake Mine, South Dakota, the Mother Lode Belt in California, and the Colorado mineral belt; and (9) nickel and magnetite deposits such as at Cornwall and Morgantown, Pennsylvania.

The types of deposits with silver as a major constituent are: (1) epithermal veins, lodes, and pipes; (2) epithermal disseminated and breccia deposits; (3) epithermal silver-manganese deposits; (4) epithermal silver-lead-zinc replacement deposits; (5) epithermal silver-copper-barite deposits; (6) mesothermal silver-lead-zinc-copper deposits; (7) mesothermal cobalt-silver, cobalt-uraninite-silver, and cobalt-silver-zeilite deposits; (8) sandstone silver deposits; and (9) sea-floor muds and hot-spring deposits. Epithermal veins, lodes, and pipes were some of the most productive deposits mined during the 19th century, but these currently result in little silver production. Deposits of this type in the United States with notable past silver production are the Comstock Lode in western Nevada; Hornsilver in San Francisco district of Utah; Tonopah and Austin, Nevada; Randsburg, California; and San Juan Mountains and Silver Cliffs district in Colorado. Epithermal disseminated and breccia deposits currently produce little silver. Past districts included the Calico, in southeastern California; Taylor and Success east of Ely, Nevada; and Vipont in northwest Utah. The silver rich manganese carbonate, manganiferous calcite, and manganese oxide deposits also currently produce little silver. The best known districts of this type are Lake Valley, New Mexico; Pioche, Tybo, and White Pine, Nevada; Escalante, southwestern Utah; Tombstone and Aquila, Arizona; Silver Cliff, Colorado; and Modoc, California. Epithermal silver-lead-zinc replacement deposits are not common, but a few have been very productive, such as at Aspen, Colorado, and the Red Mountain district of the San Juan Mountains, Colorado. Epithermal silver-copper-barite deposits are not important in the United States.

The mesothermal silver-base metal veins of the Coeur d'Alene district of Idaho are the major United States deposits with silver as the major constituent. The ore is in replacement veins in weakly metamorphosed argillites, siltites, and quartzites. Ore near the surface occurs in stringers that form wider veins and masses at depth. The principal ore mineral is argentiferous tetrahedrite associated with lead, iron, and zinc sulfides. The gangue is quartz and siderite. Ore has been mined to a depth of 2,438 meters (8,000 feet). The major geologic structure is the Osborn fault which divides the district into a north group and south group of mines. The eastern part of the south group is known as the "Silver Belt" because the ores have a higher silver content.

Mesothermal cobalt-silver, cobalt-uraninite silver, and cobalt-silver-zeolite deposits are known in North America, but not in the United States. Silver chloride deposits disseminated in sandstone occur at Silver Reef in southern Utah. Mineralized sea-floor muds occur near Niland, California, close to the Salton Sea.

Ores mined principally for silver provide about 25 percent of the United States silver production. Thus, 75 percent of the silver production in the United States is produced as a byproduct with base metal ores providing almost all of this production except for about 1 percent coming from gold-silver ores. Almost 99 percent of all the ores mined principally for silver are mined in Idaho's Coeur d'Alene district. This district also produces about 20 percent of the silver produced as a byproduct or coproduct of base metal mining. Thus, the Coeur d'Alene district is the source of almost 40 percent of all silver produced in the United States. Most United States silver resources are in base metal deposits as byproduct or coproduct silver. About three-fourths of these resources are in Arizona, Nevada, Idaho, Montana, and Utah.

All ores mined principally for silver in the Coeur d'Alene district are mined by underground mining methods. The steep terrain of the district permits access to orebodies by adits with development in the ore by winzes and raises. Greater operating depths are achieved by internal or surface shafts. Almost all mining is by horizontal cut and fill stoping using hydraulic fill. Development drifts are driven on the vein or parallel to the vein with crosscuts at regular intervals. Level intervals vary from mine to mine.

The environmental problems related to underground silver mines are principally associated with mine drainage. In the Coeur d'Alene district, gross pollution of the Coeur d'Alene River and tributaries has resulted from siltation, acidification, and heavy metals contamination. These mine drainage problems are similar to the environmental problems related to base metal mines.

2.24 TELLURIUM

Tellurium is widely distributed in nature as a constituent of at least 40 minerals. Tellurium rarely occurs in the native state and is usually associated with gold, silver, copper, lead, mercury and bismith ores. Present United States production is a byproduct of electrolytic copper refining. Tellurium resources of the United States are related with porphyry deposits. There are no known deposits which can be mined only for tellurium. Care must be exercised in handling tellurium, since several tellurium compounds are very toxic.

2.25 THALLIUM

Thallium is a relatively rare element. Characteristic thallium sulfide, selenide, and oxide minerals occur in nature, but they are extremely rare. Most thallium occurs as a trace element in other minerals. All thallium production in the United States occurs as a byproduct of the base metal smelting industry, especially zinc and lead smelting. United States resources principally are associated with zinc deposits.

2.26 TIN

The tin mineral of major commercial importance is cassiterite (SnO_2); although, small amounts of other tin sulfide minerals are mined such as stannite (Cu_2FeSnS_4), cylindrite ($Pb_3Sn_4Sb_2S_{14}$), and teallite ($PbSnS_2$). There are no major tin mines of commercial significance in the United States. However, a very small amount of tin is recovered from placer deposits in Alaska and New Mexico and as a byproduct of molybdenum at the Climax Mine in Colorado. Both the United States resource base and foreseeable potential production are negligible, and virtually all primary tin requirements will be met by importing.

2.27 TITANIUM

The principal titanium minerals of commercial importance are ilmenite ($FeTiO_3$) and rutile (TiO_2). Small quantities of other titanium minerals such as anatase (TiO_2) and brookite (TiO_2) often are associated with ilmenite and rutile. Many other minerals, including sphene ($CaTiSiO_5$), perovskite ($CaTiO_3$), and pyrophanite ($MnTiO_3$) are abundant locally in some deposits, but these have not been mined commercially.

Both ilmenite and rutile occur in primary and secondary deposits. Primary rutile deposits occur in alkalic igneous rocks, in alkalic noritic-anorthositic complexes, and in granitic and syenitic veins and pegmatites with all economic deposits in the noritic-anorthositic complexes. Most primary rutile is recovered as a byproduct of ilmenite mining. Primary ilmenite deposits occur as ilmenite-magnetite deposits in gabbro and anorthosite at Tahawus, New York. Secondary deposits of rutile are derived from weathering of primary rutile occurrences. These deposits consist mainly of marine placer sands, stream sands and gravels, and lag saprolite deposits. Deposits of this type occur in Virginia and Arkansas. Secondary deposits of ilmenite occur as branch fossil placer deposits and as residual deposits formed by lateritic weathering. Important placer deposits in the United States occur in northern Florida and near Lakehurst, New Jersey.

Ilmenite forms most of the economic secondary deposits of titanium. Ilmenite placer deposits commonly contain rutile and leucoxene, along with other heavy minerals such as zircon and monazite. Some deposits are worked principally for other minerals and titanium minerals are a byproduct. The known economic titanium resources of the United States occur as: (1) ilmenite rock deposits in New York and Virginia; (2) ilmenite beach sands in Florida, New Jersey, and Georgia; (3) rutile rock deposits in Virginia; and (4) rutile sand deposits in Florida, South Carolina, Tennessee, and Georgia. Additional uneconomical ilmenite resources are known to occur in California, Colorado, Minnesota, Montana, New York, Rhode Island, Wyoming, Oregon, and Oklahoma. Most of the known titanium resources in the United States are ilmenite deposits.

Ilmenite is produced from seven operations in New York, Florida, Georgia, and New Jersey. Rutile is produced at one mine in Florida where ilmenite and zircon are coproducts. All mining for titanium is by dredging or surface mining methods. Thus, there are no environmental problems related to underground titanium mining.

2.28 ZINC

The principal ore mineral of zinc is sphalerite (ZnS). Occassionally, sphalerite is intergrown with wurtzite (ZnS). Zinc sulfides oxidize to secondary minerals such as smithsonite ($ZnCO_3$) and hemimorphite ($Zn_4(OH)_2Si_2O_7 \cdot H_2O$). Franklinite ($(Fe,Zn,Mn)(Fe,Mn)_2O_4$), willemite ($Zn_2SiO_4$), and zincite (ZnO) are the ore minerals of the unique deposits at Franklin Furnace and Sterling Hill, New Jersey. Sphalerite commonly is associated with iron, lead, and copper sulfides such as pyrite, galena, and chalcopyrite, and gold and silver minerals.

Zinc deposits occur in many diverse geologic environments and can be classified into seven broad categories. These are: (1) contact-metamorphic deposits; (2) irregular replacement deposits and associated fissure fillings; (3) vein deposits; (4) stratabound deposits in metamorphic rocks; (5) strata-bound deposits in carbonate rocks (Mississippi Valley and Alpine-type deposits); (6) stratiform deposits; and (7) deposits formed by supergene enrichment or laterization. Zinc deposits also may be classified by the associated metals as: (1) zinc; (2) zinc-lead or lead-zinc; (3) zinc-copper or copper-zinc; and (4) base metal if zinc, lead, and copper all are present.

Contact-metamorphic zinc deposits are those contained in metamorphosed sedimentary rocks adjacent to igneous intrusives. These occur principally in carbonate rocks that have been altered metasomatically. Common minerals are chalcopyrite, pyrite, pyrrhotite, sphalerite, and molybdenite. There are many small deposits of this type in the United States including the Central district of New Mexico and the Darwin district of California. Irregular replacement deposits and associated fissure fillings often replace contact metamorphic deposits. In addition to lead and zinc, these deposits often contain appreciable quantities of copper, silver, and gold. Typical deposits of this type in the United States are the silver-lead-zinc deposits in the Park City, Bingham, and Tintic districts of Utah; in the Eureka district of Nevada; and at Leadville and Gilman, Colorado. Zinc bearing vein deposits commonly occur in igneous rocks or in rocks near igneous contacts. Zinc veins may have significant amounts of lead, copper, silver, and gold. Important zinc vein deposits have been mined in the Coeur d'Alene district of Idaho; at Butte, Montana; and at many locations in Colorado.

The major known deposits of zinc-lead and lead-zinc ores occur in metamorphic rocks. These consist principally of pyrrhotite and pyrite accompanied by sphalerite, galena, and chalcopyrite. Significant deposits of this type occur in the United States in the Ducktown district of Tennessee; Jerome district of Arizona; Balmat-Edwards district of New York; and Franklin Furnace-Sterling Hill district of New Jersey. Zinc deposits in carbonate rocks (Mississippi Valley – type deposits) also are of major importance. Zinc and usually lead sulfide minerals may occur as open-space fillings in breccias or be formed by replacements. This type of deposit occurs in the East and Middle districts of Tennessee; Tri-State district of Kansas, Missouri, and Oklahoma; Upper Mississippi Valley district of Wisconsin and Illinois; Friedensville district of eastern Pennsylvania; and the Metaline district of northeastern Washington.

Stratiform deposits, where the zinc-bearing stratum is interbedded with other strata, are not common in the United States. Supergene enrichment of silver-bearing base metal deposits occurs because of weathering of primary ore deposits. Most of these deposits were formed by weathering of sulfides in the bedrock, with the metals redeposited as secondary carbonate, silicate, oxide, or sulfide minerals. Major districts with this type of deposit include Friedensville, Pennsylvania; Austinville, Virginia; Mascot-Jefferson City, Tennessee; Leadville, Colorado; and Tintic and Ophir, Utah.

The major identified zinc resources of the United States (80 percent) occur in the Appalachian and Mississippi Valley regions. The Appalachian region includes the Franklin Furnace – Sterling Hill district of Pennsylvania; Friedensville district of Pennsylvania; Balmat-Edwards district of New York; Austinville district of Virginia; and the East Tennessee district. The Mississippi region includes the Tri-State district of Kansas, Missouri, and Oklahoma; Upper Mississippi Valley districts in Wisconsin and Illinois; Central and Southeast Missouri lead belts; and the Middle Tennessee district.

Zinc ores provide almost 60 percent of the United States zinc production with the remaining production coming from zinc-lead ores, lead-zinc ores, copper-zinc and copper-lead-zinc ores, and other sources. Zinc was produced in 18 States with New York being the leading producer, followed by Missouri, Tennessee, Colorado, Idaho, and New Jersey. These six States accounted for about 80 percent of the total zinc production. Almost all zinc ores are mined by underground methods with mines in New York, Tennessee, Colorado, New Jersey, Pennsylvania, Virginia, Wisconsin, Maine, and California. The underground mining is by square-set, room and pillar, and cut and fill stoping methods. The near flat lying deposits of the Tri-State, Upper Mississippi Valley, Metaline, Tennessee, and Virginia districts are mined by room and pillar methods.

The environmental problems related to underground zinc mining are mine drainage and subsidence.

2.29 ZIRCONIUM

The important zircon minerals are zircon ($ZrSiO_4$), baddeleyite (ZrO_2), and eudialyte ($Na_4(Ca,Fe)_2ZrSi_6O_{17}(OH,Cl)_2$), with zircon being the more important commercial source. Zircon occurs in both primary and secondary deposits, but primary deposits are rare. In secondary placer deposits, zircon is concentrated with other heavy minerals, such as rutile, ilmenite, monazite, and garnet. These placer deposits are in stream terraces, along beaches, and in sand dunes. Phosphatic sediments and lithified titanium-rich placers in sandstone or metamorphosed sandstone also form secondary zircon deposits. The United States has the world's largest known zircon resources with most of this resource located along the Atlantic Coastal States of Florida, Georgia, South Carolina, and New Jersey.

Zircon currently is recovered from mineral sands by dredging at Starke and Green Cove Springs, Florida, and near Folkston, Georgia. There are no environmental problems related to underground mining of zirconium.

3.0

NONMETALS

3.1 ASBESTOS

Asbestos is a term applied to naturally fibrous silicate minerals. The principal asbestos mineral is chrysotile ($Mg_6(Si_4O_{10})(OH)_8$) with other commercial varieties being amosite ($(Fe,Mg)SiO_3$), crocidolite ($NaFe(SiO_3)_2 \cdot FeSiO_3 \cdot H_2O$), tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$), and anthophyllite $(Mg,Fe)_7Si_8O_{22}(OH)_2$).

Chrysotile asbestos occurs in two geologic settings: (1) large stockworks of veins in serpentinized peridotite, pyroxenite, and dunite of the "Quebec type" and (2) veins of thin serpentine layers in limestone of the "Arizone type." The Quebec type deposits occur in ultra-mafic rocks dominated by peridotite where the rocks have been altered almost completely to form serpentinites. Additional alteration resulted in the formation of talc schist, steatite, and massive quartz-carbonate in shear zones and margins. An example of the Quebec type deposit is the Belvidere Mountain deposits of northern Vermont. Numerous small to large serpentinite masses occur along the Pacific Coast in Washington, Oregon, and California. The Arizona type deposits occur where cherty or siliceous magnesian limestones were metamorphosed adjacent to igneous intrusions. These deposits usually are small but the asbestos content of the ore usually is high.

Anthophyllite and tremolite asbestos deposits occur in ultramafic intrusions and in association with greenstones and amphibolites. Many small deposits of amphibolite asbestos occur in western North Carolina and northeastern Georgia. Crocidolite and amosite only occur in certain fine grained cherty ferruginous metasediments and asbestos deposits of these minerals are not known in the United States.

California is the leading United States producer with 54 percent of the production followed by Vermont, North Carolina, and Arizona. All asbestos mining in the United States was by surface mining methods except for one underground mine north of Globe, Arizona. The known asbestos resources occur principally in Vermont, California, and Arizona.

There are environmental problems related to underground mining of asbestos. Asbestos and asbestos type fibers are a known health hazard in air and possibly water. Fibrous laden mine dust is a health hazard in the mine and fibrous emissions from mine ventilation would represent an environmental hazard to areas surrounding the mine. Efforts continued in 1974 to establish an acceptable level of asbestos dust fibers in the atmosphere of both mines and general environment. Where occurring, mine drainage waters can contaminate surface and ground waters, resulting in a possible health hazard due to ingesting fibers in drinking water.

3.2 BARIUM

The principal barium minerals are barite ($BaSO_4$) and witherite ($BaCO_3$). Witherite is of minor importance and is produced commercially only in England. Barite resources are large and widely distributed. Barite is commonly associated with quartz, calcite, dolomite, siderite, rhodochrosite, celestite, fluorite, and various sulfide minerals, such as pyrite, chalcopyrite, galena, sphalerite, and their oxidation products. Barite is a common gangue mineral in lead, zinc, gold, silver, fluorite, and rare-earth vein deposits.

Barite occurs in sedimentary, igneous, and metamorphic rocks. Commercial deposits can be classified as: (1) vein and cavity-filling; (2) residual; and (3) bedded. Vein and cavity-filling barite deposits are not significant commercially. Residual barite deposits are formed by weathering of primary deposits. Small amounts of pyrite, galena, and sphalerite may occur with the barite. These residual deposits lie within the clayey residuum derived from limestone and dolomite, especially in southeastern Missouri and the Appalachian region. These include deposits in Washington County, Missouri; Sweetwater district, Tennessee; and Cartersville district, Georgia. In bedded deposits, barite occurs as a principal mineral or cementing agent in stratiform deposits of layered rock sequences. Barite beds commonly are interbedded with chert, siliceous siltstone, and shale. The principal gangue mineral is fine-grained quartz and small amounts of clay and pyrite are common. Deposits of the bedded type include Magnet Cove, Arkansas; Toquima and Shoshone Ranges, Nevada; and New Castella, California.

Approximately 40 mines in eight states produce barite, with 50 percent of the production coming from Nevada. Other leading states are Arkansas and Missouri. Most barite is mined by surface mining methods but there is some barite production from an underground mine in Arkansas. Environmental problems related to underground mining of barite is pollution of streams by mine drainage such as the Ouachita River in Arkansas.

3.3 BORON

The principal commercial boron minerals are the sodium borate minerals borax ($Na_2B_4O_7 \cdot 10H_2O$) and kernite ($Na_2B_4O_7 \cdot 4H_2O$). Boron minerals currently mined occur chiefly as deposits in non-marine Cenozoic rocks. The borate deposit at Boron, California, is a large, bedded, thick, slightly deformed, lacustrine deposit. Shale beds containing colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$) and kernite ($CaNaB_5O_9 \cdot 8H_2O$) lie directly over and under the borate deposits. Near Death

Valley, California, colemanite is mined from formed mudstone and sandstone. At Searles Lakes, California, sodium borate is produced as a byproduct from brines pumped from the interstices of mineralogically complex salt layers beneath the dry lake surface. The total United States boron production comes from mines at Boron and Death Valley and brines from Searles Lake in California. All mining currently is by surface mining methods; although, there has been underground mining in the past. Currently, there are no environmental problems related to underground boron mining.

3.4 CLAYS

The principal clay minerals are kaolinite ($Al_4Si_4O_{10}(OH)_8$), halloysite ($Al_4Si_4O_{10}(OH)_8 \cdot 4H_2O$), montmorillonite ($(Al,Mg)_8(Si_4O_{10})_3(OH)_{10} \cdot 12H_2O$), palygorskite ($Mg_5(Si_4O_{10})_2(OH)_4 \cdot 4H_2O$), and illite ($K_2(Si_6Al_2)Al_4O_{20}(OH)_4$). Kaolinite and halloysite are formed by hydrothermal, weathering, and sedimentary processes, either alone or in combination. Hydrothermal clay is formed by solutions dissolving the country rock and precipitating kaolinite. Residual clay is formed by chemical weathering and the altering of feldspars and muscovites to kaolinite or halloysite. Unconsolidated and consolidated sedimentary deposits are formed by the weatherbed debris being eroded, transported by streams, and then deposited in lakes. After deposition, leaching may remove iron, potassium, and other ions. Montmorillonite usually is formed by the devitrification and alteration of volcanic ash or tuff. Palygorskite is believed to be formed as a chemical precipitate from the reaction of hydrothermal solutions with sea water having a high magnesium and silica content. Illite can be formed in many ways, but it usually is found in residual shale deposits.

Clay deposits are classified into six categories: (1) kaolin; (2) ball clay; (3) fire clay; (4) bentonite; (5) fuller's earth; and (6) miscellaneous clays. Kaolin clays consist principally of kaolinite. Kaolin is produced in 17 states, with the primary producers being Georgia and South Carolina, followed by Arkansas, Alabama, and Texas. Ball clays are composed principally of kaolinite, but have a higher silica-to-alumina ratio and more impurities and are finer grained than kaolins Tennessee is the primary ball clay producer, followed by Kentucky, Mississippi, Texas, California, Maryland, New York, and Indiana. Fire clay also consists principally of kaolinite, but usually includes other clay minerals and impurities. Clays are designated fire clays based on their refractory property. Fire clays commonly occur as underclay below coal seams with the major producing states being Missouri, Ohio, Pennsylvania, and Alabama. Bentonites are composed principally of montmorillonite group minerals with the principal producing states being Wyoming, Montana, and South Dakota. Fuller's earth is essentially montmorillonite or palygorskite with Georgia and Florida the principal producing states. Miscellaneous clays include all clays not included in the other five classifications. These miscellaneous clays are mined in almost all states.

Most clays are mined by surface mining methods. There are a few underground mines, principally mining underclays in coal mining areas. These underground mines, which are located in Colorado, Ohio, Pennsylvania, Utah, and West Virginia, use a room and pillar mining method. The possible environmental problems related to underground clay mining are sedimentation and discoloration of surface waters because of mine drainage.

3.5 CORUNDUM AND EMERY

Corundum (Al_2O_3) is the second hardest known natural substance. The United States has no corundum production, no known reserves, and poorly known resources.

Emery consists of corundum and magnetite with admixed spinel, hematite, garnet, and other minerals. Emery is produced in West Chester County, New York, and Linn County, Oregon. All mining is by surface mining methods.

3.6 DIAMOND

Diamond is the hardest known natural substance. Natural diamond normally occurs only in an unusual type of peridotitic igneous rock known as kimberlite which was injected into overlying rocks as pipes. Two kimberlite pipes occur in Arkansas; one containing no diamond and the other uneconomical amounts of diamond. Thus, the United States has no known commercial deposits of industrial diamond.

3.7 DIATOMITE

Diatomite is a sedimentary rock consisting mainly of the siliceous remains of diatoms, single-celled aquatic organisms. All United States production comes from surface mines in California, Nevada, Washington, and Oregon.

3.8 FELDSPAR

Feldspar is a general term to designate a group of anhydrous aluminim silicate minerals that contain various amounts of potassium, sodium, and calcium. The principal feldspar minerals are orthoclase and microcline (both $KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_3O_8$). Feldspars are important rock-forming minerals and occur in significant amounts in most igneous and some sedimentary rocks. Commercial feldspar deposits are widely distributed. Pegmatite deposits are a source of massive feldspar crystals. However, most United States production is from feldspar bearing rocks such as alaskite and from beach sands. Feldspar is mined in eight states: North Carolina, California, Connecticut, Georgia, South Dakota, Arizona, Wyoming and Colorado. Almost all feldspars are mined by surface mining methods, but small deposits can be mined by underground methods. There are no known environmental problems related to underground feldspar mines.

3.9 FLOURINE

The principal flourine minerals are flourite (CaF_2), cryolite (Na_3AlF_6), fluorapatite ($Ca_5(PO_4,CO_3)F$), and topaz ($Al_2SiO_4(F,OH)_2$). Flourspor, the ore of the mineral fluorite, is the principal commercial source of fluorine.

Fluorine occurs in deposits associated with igneous, sedimentary, and regionally metamorphosed rocks and in hydrothermal deposits. Deposits associated with igneous rocks include accessory fluorine minerals disseminated through the igneous rock and fluorine minerals in pegmatites, carbonatites, and contact aureoles of intrusive rocks. The flourspar deposits at Crystal Mountain, Montana, are mainly fluorite with minor amounts of biotite, quartz, feldspar, sphene, rare-earth-bearing apatite, amphibole, fergusonite, thorianite, and thortveitite. Fluorine deposits associated with sedimentary rocks include deposits in volcaniclastic and lacustrine sedimentary rocks and in evaporite, marine-carbonate, and marine-phosphorite rocks.

The principal commercial sources of fluorine are deposits of hydrothermal origin. These include deposits in veins and mantos, pipes and stockworks, and zones of alteration. These deposits occur in almost any type of host rock but are most common in carbonate, silicic igneous, and silicic metamorphic rocks. In addition to fluorite, other common minerals are quartz, chalcedonic quartz, opal, barite, manganese oxides, calcite, clay minerals, and lead and zinc sulfides. Hydrothermal deposits are located in the Illinois-Kentucky district; at Jamestown, Colorado; and near Spor Mountain, Utah.

The Illinois fluorspar district accounts for more than 50 percent of the United States fluorine production. Other producing states are Colorado, Montana, Nevada, Texas, Utah, Arizona, New Mexico, and Kentucky.

Most fluorspar is mined by underground methods in Illinois, Colorado, Nevada, Utah, and Kentucky. In New Mexico, underground mines are being developed and drilling is continuing at other properties. These mines range in size from very small to large fully mechanized mines. Bedded deposits usually are mined by a room and pillar system. Other deposits commonly are mined by top slicing, cut and fill, shrinkage, and open stoping methods. Underground fluorspar mining is not known to produce any unusual environmental problems. However, some fluoride compounds are toxic and harmful to both plant and animal life and the Environmental Protection Agency is proposing stringent water quality standards for mine water discharges.

3.10 GARNET

Commercial garnet occurs primarily as almandite ($Fe_3Al_2(SiO_4)_3$). Commercial sources of garnet occur almost exclusively in metamorphic rocks and in placer deposits derived from these primary rocks. Garnet deposits are reported in more than half the states. Currently, all United States production comes from two states, New York and Idaho. In New York, garnet is produced as a primary product by surface mining at North Creek and as a byproduct of wollastonite underground mining at Willsboro. In Idaho, garnet is produced from placer deposits by dragline at Emerald Creek.

3.11 GEM STONES

Gem minerals are rare and occur in most of the major geologic environments. Gem minerals usually are silicate, alumino-silicate, or oxide minerals. These minerals are formed principally by precipitation from aqueous solutions, crystallization of magmas, and metamorphism. Igneous rocks are the source of many gem stones including diamond, ruby, sapphire, tourmaline, and topaz. Metamorphic rocks are the source of ruby, sapphire, and emerald. Placer deposits are formed by the weathering of primary gem stone deposits. Most gems are dense, resistant to abrasion, and chemically inert.

Gem stone mining in the United States is essentially by amateur "rock hounds". However, placer deposits are mined commercially by surface mining methods and a small underground mine is located near Utica, Montana.

3.12 GRAPHITE

Graphite is pure crystalline carbon. Natural graphite occurs in three geologic environments. Graphite occurs as (1) vein graphite in igneous and metamorphic rocks; (2) flake graphite disseminated through layers of metamorphosed carbonaceous sedimentary rocks; and (3) amorphous graphite in thermally metamorphosed coal beds. The only active graphite mine in the United States is the surface mine at Burnet, Texas, which produces flake graphite. Similar graphite deposits occur in other areas of Texas and in Alabama, Alaska, New York, and Pennsylvania.

3.13 GYPSUM

Gypsum ($CaSo_4{\cdot}2H_2O$) and its anhydrous form anhydrite ($CaSO_4$) occur widely and abundantly in virtually all marine evaporate basins. Deposits were formed as chemical precipitates from marine waters of high salinity. Gypsum usually predominates over anhydrite at or near the surface and then grades into anhydrite deeper in the deposit.

Gypsum is mined in 22 states from 57 surface mines and 12 underground mines. The states leading in production are California, Michigan, Texas, Iowa, and Oklahoma. Underground mines are in Indiana, Iowa, Michigan, Montana, New York, Ohio, and Virginia. Underground mining generally is by room and pillar methods; although, steep dipping beds may be mined by shrinkage stoping. The environmental problems related to underground gypsum mining are negligable.

3.14 KYANITE AND RELATED MINERALS

Kyanite and related minerals are known as the kyanite or sillimanite group and include kyanite, sillimanite, and andalusite, all having the same chemical composition ($Al_2O_3{\cdot}SiO_2$). The kyanite group minerals occur in nearly all large areas of metamorphic rocks. These minerals are contained principally in micaceous schists and gneisses, but they also may occur in quartzose rock and in quartz veins and pegmatites. Almost all United States production comes from three hard rock surface mines in Virginia (Willis Mountain and Baker Mountain) and Georgia (Graves Mountain). Some kyanite-sillimanite was obtained as a byproduct from a titanium and zirconium sand deposit at Trail Ridge, Florida.

3.15 LITHIUM

Lithium is mined from pegmatites with the principal lithium minerals being spodumene ($LiAlSi_2O_6$), lepidolite ($K_2Li_3Al_3(AlSi_3O_{10})(OH,F)_4$), and petalite ($LiAlSi_4O_{10}$). Pegmatites containing spodumene are mined by surface mining methods at Kings Mountain and Bessemer City, North Carolina. Lithium also is obtained from brines at Silver Peak, Nevada, and Trona, California.

3.16 MICA

Mica is the general name for several complex hydrous aluminum silicate minerals including muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$), and phlogpite ($KMg_3(AlSi_3O_{10})(OH)_2$). Mica occurs in pegmatites, granite, and mica-rich metamorphic rocks. All mica produced in the United States is flake mica with North Carolina the largest producing state followed by Alabama, Arizona, Connecticut, Georgia, New Mexico, and South Carolina. All mica mining is by surface mining methods and mica usually is produced as a coproduct with other mineral commodities such as feldspar and kaolin.

3.17 PERLITE

Perlite is a metastable amorphous aluminum silicate with minor impurities and inclusions. It is a form of volcanic glass associated with surface flows or shallow igneous intrusives. Perlite deposits of the United States are restricted to the western states where volcanism was more recent, since alteration of the deposit occurs after formation of the perlite. Crude perlite is produced from 12 mines in seven states with New Mexico the principal producing state followed by Arizona, California, Nevada, Colorado, Idaho, and Texas. Mining is by surface mining methods except for one underground mine in Lincoln County, Nevada. There are no known environmental problems related to this underground perlite mine.

3.18 PHOSPHOROUS

The principal commercial phosphorus minerals are phosphates in the apatite group ($Ca_5(F,Cl,OH)(PO_4)_3$). Minable concentrations of phosphate, called phosphate rock, occur in igneous rocks, as guano and related deposits, and as sedimentary phosphorite. Apatite occurs in igneous rocks as intrusive masses or sheets, as hydorthermal veins or disseminated replacements, as marginal differentiations, or as pegmatites. Largest are the intrusive masses commonly associated with alkaline igneous rocks. Apatite occurring in igenous rocks and guano and related deposits currently are not mined and United States resources in these types of deposits are small.

Sedimentary phosphorite deposits are of four different types. Deposits caused by divergence upwelling of sea water are characterized by black shale, phosphatic shale, phosphatic sandstone, phosphorite, dolomite, chert or diatomite, and saline deposits and red or light-colored sandstone or shale. The phosphate is carbonaceous and consists of pellets, nodules, and phosphatized bone material and shell. Examples of this type of deposit include the Permian Phosphoria Formation in the western United States, the Miocene Monterey Formation of California, the Mississippian and Triassic deposits of northern Alaska, and the Mississippian deposits of Utah. Deposits formed in warm currents along the eastern coast of the United States in Florida, Georgia, and North Carolina consist of phosphatic limestone or sandstone. Deposits formed on stable shelves or in continental interiors are associated with limestone, dolomite, shale, and glauconitic sandstone. The phosphate occurs as nodules or grains. Examples of this type of deposit include the Oreskany Sandstone in New York, Pennsylvania, and Virginia; sandstone in Tennessee and Arkansas; black shale in Missouri; shale in Arkansas; several beds associated with limestone in Alabama and Georgia; and beds associated with glauconite in Tennessee, Alabama, and New Jersey. Marine deposits concentrated and enriched by secondary processes are the richest phosphate deposits. Deposits in the Bone Valley Formation of Florida were formed by submarine reworking of phosphate-rich residuum, followed by leaching and weathering. River pebble deposits occur in the flood plains of streams that drain phosphate areas of Florida, South Carolina, and Georgia. Chemical weathering of phosphatic limestone, such as in Tennessee and Kentucky, results in phosphate enrichment. Phosphate lake beds occur in Wyoming and Utah.

Florida and North Carolina produce over 80 percent of the phosphate in the United States. The western states (Idaho, Missouri, Montana, Utah, and Wyoming) and Tennessee produce the remainder. Most of the known phosphate resources of the United States occur in Florida and North Carolina with lesser reserves in Idaho and Montana. Surface mining methods are used in Florida, North Carolina, Tennessee, and western states. Underground mining is limited to one mine at Warm Springs, Montana, where phosphate rock is mined by adit. Production from Missouri is from apatite recovered from Pea Ridge iron ore mine tailings. Underground mining methods used to recover high-grade phosphate beds are top slicing, sublevel stoping, and open stoping. There are no known environmental problems related to underground phosphate mining. However, the United States Departments of Interior and Agriculture have called for an environmental impact study covering federal western phosphate lands in northern Utah, western Wyoming, southern Montana, and eastern Idaho. No new operations will be approved until this study is completed.

3.19 POTASSIUM

The principal commercial potassium minerals are sylvite (KCl) and langbeinite ($K_2SO_4 \cdot 2MgSO_4$). Potassium also occurs in large and early pure deposits of polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$), but these deposits are not mined. Potassium or "potash" occurs in two main types of deposits: (1) crystalline deposits of saline rocks containing sylvite, langbeinite, and related potassium minerals and (2) concentrated brines in relect lakes and lacustrine sediments of continental origin in arid regions. The crystalline bedded deposits occur as tabular bodies which may be primary or replacement in origin. The potassium minerals occur within the sodium-rich (halite) facies of the evaporite. Most United States potash production (83 percent) comes from these type deposits in southeastern New Mexico and eastern Utah. The remaining United States production comes from brines in California and Utah. California production is from alkaline near-surface brines of Searles Lake. Utah production is from the nearly neutral waters of the Great Salt Lake.

The deep bedded potash deposits are mined by underground methods with eight mines in Eddy County, southeastern New Mexico, and one mine near Moab, Utah. In New Mexico, deep shaft underground mining is by room and pillar methods, with pillars being robbed after initial mining. Thicker deposits are mined by large continuous equipment while thinner deposits are mined by smaller conventional equipment. At the Utah deposit, a conventional room and pillar underground mine was converted to a solution mine. Potash is recovered by dissolving the potash in water underground and pumping to the surface for recovery.

The environmental problems related to underground potash mining are pollution of surface waters by mine dewatering. This problem is of particular concern at the Utah operation near the Colorado River.

3.20 PUMICE

Pumice is essentially aluminum silicate of igneous origin with a cellular structure formed by explosive or effusive volcanism. Volcanic action ejects material into the air, which is then transported horizontally before deposition to form pumice. Due to metamorphism, only areas with relatively recent volcanism have commercial pumice deposits. The principal producing states are California, Oregon, and Arizona with significant production also from Hawaii, Nevada, and New Mexico. All current mining is by surface mining methods.

3.21 SALT

The salt mineral is halite (NaCl). Bedded salt deposits are formed by evaporation of sea water until salts are partially or entirely deposited. These deposits may be large horizontal beds or large vertical domes. The domes result from deformation of deeply buried salt beds under great pressure. Dolomite, shale, anhydrite, and other evaporites usually occur as impurities.

In the United States, salt is produced by: (1) solution mining; (2) underground mining; and (3) evaporation of natural brines and sea water. Louisanna and Texas are the leading salt producing states, followed by New York, Michigan, and Ohio. Solution mining of salt deposits produces almost 60 percent of the salt produced in the United States. Underground mining accounts for almost 30 percent of the United States salt production. The room and pillar method is used for underground mining of bedded and dome deposits. Underground salt mines are located in Kansas, Louisanna, Michigan, New York, Ohio, and Texas.

There are no known environmental problems related to underground salt mines. Most mines are at considerable depth and subsidence is negligible.

3.22 SAND AND GRAVEL

Sand and gravel are unconsolidated rocks and minerals ranging in size from silt to boulders. These deposits consist predominantly of silica, but other minerals usually are present. Deposits are formed by the breakdown, erosion, and transport of bedrock by ice, water, and wind. The principal commercial sand and gravel deposits are along existing or ancient river channels and in glaciated terrains. These deposits include flood-plain, outwash-plain, stream-terrace, alluvial-fan, esker, kame, delta, and moraine deposits. Sand and gravel deposits of different types are located throughout the United States, but the industry tends to be concentrated geographically in the large, rapidly expanding urban areas. California leads in production followed by Michigan, Ohio, Illinois, Wisconsin, Texas, and Minnesota. All known mining is by surface methods.

3.23 SODA ASH

Soda ash (Na_2CO_3) occurs naturally as evaporite and brine deposits. Soda ash resources of the United States are immense. Mose soda ash produced in the United

States is manufactured synthetically from sodium chloride, ammonia, and carbon dioxide by the Solvay process. Natural soda ash is obtained from brines and trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) deposits. Soda ash is mined by deep shaft underground methods from an immense deposit of bedded trona in southwestern Wyoming. These three mines are highly mechanized and use a room and pillar mining system. There are no known environmental problems related to underground soda ash mining.

3.24 STONE

Stone is a commercial term which includes all consolidated rock used for construction and roads, in agriculture, in chemical and metallurgical industries, cement manufacture, etc. Stone may be classified further into dimension and crushed stone. Terminology for the dimensional stone industry differs from standard mineralogical rock descriptions. In addition to true granite, the term granite includes other types of igneous and metamorphic rocks such as quartz diorites, syenites, quartz porphyries, gabbros, schists, and gneisses. Dimensional marble includes true marble and any limestone that will take a high polish and sometimes serpentine, onyx, travertines, and granite. Hard sandstone sometimes is called quartzite. For the crushed stone industry, all coarser grained igneous rocks usually are called granite. Traprock is dense, dark, fine-grained igneous rock. Quartzite may be any siliceous-cemented sandstone.

Stone is produced in almost all the states. Almost all dimensional stone is quarried with production methods varying from antiquated to modern. Dimensional stone is produced from one underground mine in Franklin County, Alabama. Crushed stone is produced primarily by surface mining, but large scale underground mining also is used in many areas. About 5 percent of the crushed stone production in the United States is by underground mining, usually a room and pillar system. Underground stone mines are in California, Illinois, Indiana, Iowa, Kentucky, Ohio, Pennsylvania, Tennessee, and West Virginia. There are no known environmental problems related to underground stone mining.

3.25 STRONTIUM

The principal commercial minerals of strontium are celestite ($SrSO_4$) and strontianite ($SrCO_3$). Small quantities of strontium commonly occur in igneous rocks and traces may be found in sedimentary rocks. Potentially commercial strontium deposits occur as beds, veins, veinlets, nodules, or irregular masses in or near sediments or sedimentary rocks. These deposits are known to occur in Texas, California, Washington, Arizona, and Ohio. Strontium minerals have not been mined in the United States since 1959.

3.26 SULFUR

Sulfur is produced commerically from four major sources. Elemental sulfur is recovered from deposits in evaporite rocks using the Frasch hot-water process. These deposits in Texas and Louisianna occur as anhydrite ($CaSO_4$) cap rock lying on salt domes and as thick bedded anhydrite. Elemental sulfur also is recovered as a byproduct from natural gas and petroleum refining operations. Sulfur is recovered as byproduct sulfuric acid at copper, lead, and zinc roasters and smelters. The fourth source is sulfur recovered from pyrite which is produced as a byproduct of copper production at three mines in Arizona and Tennessee.

3.27 TALC

Talc refers to rock composed mainly of magnesium-rich silicate minerals and having the mineral talc ($Mg_3(Si_4O_{10})(OH)_2$) as an important constituent. The mineral content of industrial talc may range from pure talc to predominantly tremolite ($Ca_2Mg_5(Si_8O_{22})(OH)_2$). Talc deposits of commercial importance occur mainly in metamorphosed dolomite and altered ultramafic igneous rocks. Most of the major talc deposits in the United States occur in regionally metamorphosed dolomite. The talc, tremolite and serpentine rocks occur in carbonate and siliceous sedimentary rocks as in St. Lawrence County, New York. Similar deposits occur in North Carolina, Montana, and California. Deposits in Georgia and Texas also occur in metasedimentary rocks, but these are associated with phyllites, schists, and quartzites and required extensive metasomatism. Talc deposits associated with serpentinized ultramafic rocks occur in regionally metamorphosed and folded sedimentary and volcanic rocks. Deposits of this type occur in Vermont, California, Texas, and Virginia. Talc deposits are formed by contact metamorphism when granite plutons and diabase dikes intrude favorable dolomitic sedimentary strata such as in southern California.

The leading talc producing states are Vermont, New York, Texas, Montana, California, and North Carolina. Talc is mined by both surface and underground methods. Almost 50 percent of the production comes from underground mines in California, Georgia, New York, North Carolina, and Vermont. Underground mines usually require timbering for stope support. Dust is a major environmental problem related to underground talc mines. Medical research has shown a positive correlation between incidence of lung disease and working with or near asbestos which is similar to the asbestiform minerals tremolite and anthophyllite ($(Mg,Fe)_7(Si_8O_{22})(OH)_2$) occuring in talc deposits.

3.28 VERMICULITE

Vermiculite is a micaceous ferromagnesium-aluminum silicate mineral. Vermiculite deposits generally are associated with ultra-basic igneous host rocks such as pyroxenite or serpentine. Vermiculite is produced at two mines in South Carolina and one mine in Montana. All mining currently is by surface mining methods, but there has been past production from underground mines.

4.0

ENERGY SOURCES

4.1 COAL

Coal is ranked according to fixed carbon and heat content, determined on a mineral-matter-free basis. In ascending order of rank, coals are classified as lignite, subbituminous, bituminous, and anthracite. Coal also is classified by grade based on the content of ash, sulfur, and other deleterious constituents.

Coal is formed by the compression and lateration of plant residue in ancient fresh or brackish water swamps. Accumulated plant residues were first transformed into peat containing sand, silt, and mud that was washed into the peat swamps. Plant growth on the peat swamps was then terminated by trangressing seas. The submerged peat swamps were then overlayed by sand, silt, and mud from eroding land masses. These sequences of deposition may have been repeated many times, forming several sedimentary beds. Weight of the overlying sedimentary formations, heat produced by depth of burial, structural deformation, and time all contribute to the progressive compaction and devolatization of peat to form the higher ranks of coal.

Coal contains widely varying amounts of ash, sulfur, and other deleterious constituents. Ash is from sand, silt, and mud washed into the peat swamps during deposition. Most of the sulfur occurs in pyrite and marcasite. Sulfur also occurs as hydrous ferrous sulfate ($FeS_4 \cdot 7H_2O$), gypsum, and organic sulfur. Coal also contains small quantities of virtually all metallic and nonmetallic elements. When the coal is burned, most of these elements are in the ash, but a few may be volatilized and emitted to the atmosphere.

Coal-bearing rocks are found in 37 states, underlying about 13 percent of the land area of the 50 states. Bituminous coal is the most abundant and widespread rank of coal in the United States with the largest resources in Illinois, West Virginia, Kentucky, Colorado, and Pennsylvania. Lignite is the next most abundant rank of coal with the largest resources in North Dakota and Montana. Subbituminous coal resources almost are equivalent to lignite resources. Major subbituminous coal resources are in Montana, Alaska, and Wyoming. Anthracite resources are small and principally in Pennsylvania.

Bituminous coal and lignite are mined at approximately 4,500 mines in 24 states. The principal producing states are Kentucky, West Virginia, Pennsylvania, Illinois, Ohio, and Virginia. These states account for almost 80 percent of the bituminous coal and lignite produced in the United States. Bituminous coal is mined by both underground and surface mining methods with underground and surface mining methods accounting for about 50 percent of the bituminous coal and lignite production. Underground mining has occurred in all of the major bituminous coal producing states.

Anthracite coal is mined in northeastern Pennsylvania by both underground and surface mining methods. Underground mining accounts for 11 percent of the anthracite coal production.

Underground coal mining is by room and pillar method and longwall method. In steeply dipping beds, the room and pillar is modified to a breast and pillar method. Loading in room and pillar mines can be by continuous miners, mechanical loaders, and hand loading. Longwall mines use longwall cutting units and conveyors. In the United States, continuous miners and mechanical loaders produce 62 percent, and 34 percent, respectively, of the coal produced.

The major environmental problem related to the mining of coal is the production of acid mine drainage resulting from the oxidation of iron sulfides. Acid production from abandoned eastern underground coal mines is the largest single source of acid mine drainage in the United States. In Appalachia alone, more than 16,100 kilometers (10,000 miles) of streams have been affected by coal mine drainage. Of the sources inventoried in Appalachia, abandoned underground mines accounted for more than 50 percent of the acid production.

Mine drainage pollution resulting from coal mining has also been reported in the following states: Illinois coal region (Illinois, Indiana, and western Kentucky); Western Interior coal region (Iowa, Kansas, Missouri, and Oklahoma); and Rocky Mountain coal region (Colorado and Montana). However, a majority of the coal mine drainage pollution occurring outside the Appalachian region reportedly results from surface mining operations.

4.2 THORIUM

The principal thorium minerals are monazite ($(Ce,La,Th,Y)PO_4$), thorite ($ThSiO_4$), thorianite (ThO_2), uranothorite (isomorphous mineral containing uraninite and thorianite), and brannerite ($(U,Ca,Fe,Th,Y)_3Ti_5O_{16}$). Thorium deposits are of four types: (1) vein deposits; (2) placers and residual deposits; (3) deposits in sedimentary rocks; and (4) deposits in igneous and metamorphic rocks. Vein deposits occur in steeply dipping fractures cutting across the structure of the host rocks. Thorite is the principal ore mineral. Vein deposits occur in the Wet Mountains, Colorado and at Hall Mountain, Idaho. Beach and stream placers were formed from the debris of metamorphic and granitic rocks. These placers often occur on active beaches where monazite and other heavy minerals are concentrated in a narrow belt along the shoreline. Important deposits in the United States are in

Florida and North Carolina where monazite is recovered as a byproduct of ilminite. Deposits in sedimentary rocks consist of indurated placer sediments such as sandstones and conglomerates. Thorium mineral deposits occur in some igneous and metamorphic rocks such as potassic igneous rocks (especially granitic and alkalic complexes) and carbonatites.

Thorium is produced at two mines in the United States, one at Folkston, Georgia and the other in Green Cove Springs, Florida. Both of these operations recover monazite from placer deposits. Thus, there are no environmental problems in the United States related to underground mining of thorium minerals.

4.3 URANIUM

The principal unoxidized uranium ore minerals are uraninite (UO_2) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$). The massive form of uraninite is called pitchblende. The oxides brannerite (oxide of uranium, titanium, thorium, rare earths, and other elements) and davidite (oxide of titanium, iron, and uranium) occur in some unoxidized ores. The principal oxidized uranium ore mineral is carnotite ($K_2O{\cdot}2UO_3{\cdot}V_2O_5{\cdot}nH_2O$).

Uranium occurs in six types of deposits. These are: (1) peneconcordant deposits; (2) quartz-pebble conglomerate deposits; (3) vein deposits; (4) uraniferous igneous rocks; (5) uraniferous phosphatic rocks; (6) uraniferous marine black shales. The principal United States minable uranium resources occur as peneconcordant masses in continental and marginal marine sandstone and associated rocks. The uranium minerals mainly occupy pore spaces of the sandstone, but also may replace sand grains or carbonized plant fossils. Most of the host sandstone beds are quartzose, but some are arkosic derived mainly from granitic rocks. Peneconcordant deposits occur in (1) tabular bodies that are nearly concordant with the gross sedimentary structures of the sandstone and (2) roll bodies that are crescent-shaped and discordant to bedding in cross section and nearby concordant to bedding on the long axes. Tabular type deposits occur in the San Juan Basin, New Mexico, and Uravan Mineral Basin in the Colorado Plateau. Roll type deposits occur in the Shirley Basin of Wyoming and the Texas Coastal Plain.

Uranium-bearing veins occur in many kinds of rock. Common types of alteration associated with uranium veins are sericite, argillic, chloritic, and hematitic. Base metal sulfides may occur with uranium such as the Schwartzwalder mine in Colorado. Fluorite occurs in the deposits in Marysvale, Utah. Only small amounts of uranium have been mined from uraniferous igneous rocks such as pegmatites. Uranium has not been mined in the United States from igneous rocks such as granite, deposits in quartz-pebble conglomerates, phosphatic rocks, and marine black shales.

Uranium is presently mined at 114 operations in seven states. Wyoming and New Mexico are the leading producers with 75 percent of the United States production. Underground mining accounts for almost 50 percent of the United States production. These underground mines are in Wyoming, New Mexico, Colorado, and Utah. Production of many small underground mines is by adit or incline. Larger shaft mines use room and pillar or modified room and pillar mining systems.

Uranium reserves of the United States are primarily in the Colorado Plateau and Wyoming Basins. New underground uranium mines are being developed at Mount Taylor near Grants, New Mexico; Paguate mines near Laguna, New Mexico; and Powder River Basin, Wyoming.

The environmental problems related to underground uranium mines are radioactive dust and mine water drainage. Ventilation in mines is closely monitored and must meet standards to prevent excess accumulations of radon-222, a radioactive gas. Uranium miners may be subject to an increased risk of lung cancer due to radon-222 and its daughter products. If airborne radioactive dust is discharged into the environment at ventilation shafts, there may be a health hazard to the public. Mine water drainage may contain dissolved chemical constitutents which represent a possible health hazard, and therefore, must be monitored closely. Uranium is recovered from mine water by ion exchange prior to discharge at several underground mines.

REFERENCES FOR PART III – MINERAL COMMODITIES MINED

6, 22, 26, 30, 48, 49, 64, 80, 88, 91, 94, 96, 119, 120, 121, 122, 126, 130

IV

GLOSSARY OF TERMS

Abandoned Mine – A mine that is not producing any mineral and will not continue or resume operation.

Abatement – The lessening of pollution effects.

Acidity – A measure of the extent to which a solution is acid.

Acid Mine Drainage – Any acidic water draining or flowing on, or having drained or flowed off, any area of land affected by mining.

Acre-Foot – The quantity of water that would cover an area of one acre, one foot deep.

Adit – A horizontal or nearly horizontal passage driven from the surface for the working or unwatering of a mine.

Alkaline – Having the qualities of a base (i.e., a pH above 7).

Alkalinity – A measure of the capacity to neutralize acids.

Alluvial, Alluvium – Sedimentary (clay, silt, gravel, sand, or other rock) materials transported by flowing water and deposited in comparatively recent geologic time as sorted or semisorted sediments in river beds, estuaries and flood plains, on lakes, shores, and in fans at base of mountain slopes.

Anorthosite – Igneous origin rock composed almost entirely of plagioclase; monomineralic equivalent of gabbro, but lacking in essential monoclinic pyroxene.

Anticline – A configuration of folded stratified rocks in which the rocks dip in two directions away from a crest or fold axis.

Auger Hole – A hole driven into a mineral seam with a power-driven auger for the purpose of extracting the mineral-bearing material.

Aureole – Zone in country rock surrounding an igneous intrusion and in which zone contact metamorphism of the country rock has occurred.

Backfilling – The transfer of previously moved material back into an excavation such as a mine, ditch, or against a constructed object.

Barrier – Portions of the mineral and/or overburden that are left in place during mining.

Bench – The ledge, shelf, table, or terraces formed in the contour method of surface mining.

Bentonite – A montmorillonite-type clay formed by the alteration of volcanic ash.

Borehole – A hole formed with a drill, auger, or other tools for exploring strata in search of minerals, for water supply, for blasting purposes, for proving the position of old workings, faults, and for releasing accumulations of gas or water.

Breccia – Rock formation essentially composed of uncemented or loosely consolidated, small, angular-shaped fragments.

Bulkhead – A tight partition of wood, rock, or concrete in mines for protection against gas, fire, and water.

Chert – Very hard glassy mineral, chiefly silica.

Clastic – Consisting of rock fragments or of organic structures that have been moved individually from their places of origin.

Conglomerate – A cemented clastic rock containing rounded fragments of gravel or pebble size.

Daylighting – A term to define the procedure of exposing an entire underground mined area to remove all the mineral underlying the surface.

Deep Mine – An underground mine.

Diabasic – Texture of igneous rocks in which discrete crystals or grains of pyroxene fill the interstices between lath-shaped feldspar crystals.

Diagenesis – Any change occurring within sediments subsequent to deposition and before complete lithification that alters mineral content and physical properties of the sediments.

Dike – Discordant tabular body of igneous rock that was injected into a fissure when molten, cutting across the structure of the adjacent country rocks and usually having a high angle of dip.

Dip – The amount of inclination in degrees of a mineral seam or rock bedding plane from the horizontal. True dip is measured perpendicular to the strike of the bed.

Downdip – Lying down-slope along an inclined mineral seam or rock bedding plane.

Drift – A horizontal or near horizontal passage underground which follows a vein and may be driven from the surface.

Effluent – Any water flowing out of the ground or from an enclosure to the surface flow network.

Eluvial – A residual ore deposit almost formed in situ but mostly displaced by creep.

Epigenetic – Mineral deposits of later origin than enclosing rocks, or deposits of secondary minerals formed by alteration.

Epithermal – Applied to hydrothermal deposits formed at low temperature and pressure.

Esker – Long, winding gravel ridge deposited in the bed of a subglacial stream.

Fault – A fracture or a fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture.

Felsic – Light-colored rocks containing an abundance of one or all of feldspar, lelands or feldspathoids, and silica.

Flume – An open channel or conduit on a prepared grade.

Fly Ash – All solids, ash, cinders, dust, soot, or other partially incinerated matter that is carried in or removed from a gas stream and usually is associated with coal-fired electric generating plants.

Fracture – A break in a rock formation due to intense folding or faulting.

Gabbro – A fine to coarse, dark colored crystalline igneous rock composed mainly of calcic plagioclase, clinopyroxene, and sometimes olivine.

Gangue – Undesired minerals associated with ore, mostly nonmetallic.

Glauconitic Sandstone – A quartz sandstone or an arkosic sandstone rich in glauconite grains.

Gneiss – A metamorphic rock of coarse grain size, characterized by a mineral banding in which the light minerals (quartz and feldspar) are separated from the dark ones (mica, and/or hornblende); the dark mineral layers are foliated and the light bands are granulitic.

Ground Water – That water of atmospheric origin which saturates rock openings beneath the water table.

Grout – A fluid mixture of cement, sand (or other additives) and water commonly forced into a borehole to seal crevices in rock to prevent ground water or mine water seepage or flow.

Hard Rock Mining – Loosely used to designate mining in igneous and metamorphic rock.

Highwall – The exposed vertical or near vertical wall associated with a strip or area surface mine.

Hydrology – The science dealing with water standing or flowing on or beneath the surface of the earth.

Hydrostatic Head – The pressure exerted by a column of fluid usually expressed in kilograms per square meter (lb/sq in).

Hydrothermal – Applied to magmatic emanations high in water content.

Hypogene – Mineral deposits formed by ascending hot waters.

Inactive Mine – A mine that is not producing any mineral but may continue or resume operation in the future.

Inby – Toward the working face or interior, and away from the entrance of a mine.

Induration – Process of hardening sediments or other rock aggregated through cementation, pressure, heat, or some other agency.

Infiltration – The act or process of the movement of water into soil.

Intrusive – Body of igneous rock which while molten penetrated into or between other rocks, but solidified before reaching the surface.

Joint – A divisional plane or surface that divides a rock and along which there has been no visible movement parallel to the plane of surface.

Kame – Rounded hill or oblong ridge terminating abruptly in a high mound and composed of sand and gravel and having its major axis transverse to the drift movement.

Kimberlite – Highly serpentinized periodite, usually a breccia because of inclusion of surrounding rock it has penetrated, occurring in vertical pipes, dikes, and sills.

Lacustrine – Produced by or belonging to lakes; deposits which have been accumulated in freshwater lakes or marshes.

Lateritic – Extreme type of weathering common in tropical climates where iron and aluminum silicates are decomposed and silica (along with most other elements) are removed by leaching.

Lattice – Orderly geometric structure in which a crystal's atoms are arranged.

Leaching – The removal in solution of the more soluble minerals by percolating waters.

Lenticular – A mass of rock thinning out from the center to a thin edge.

Leucoxene – Brown, green, or black variety of sphene or titanite ($CaTiSiO_5$) occurring as monoclinic crystals.

Lithification – Complex of processes that converts a newly deposited sediment into an indurated rock.

Mafic – Pertaining to or composed dominantly of ferro-magnesium rock-forming silicate.

Mantos – Blanketlike replacement of rock by ore.

Mesothermal – Applied to hydrothermal deposits formed at intermediate temperature and intermediate pressure.

Metamorphic – Characteristics of, pertaining to, produced by, or occurring during the metamorphism of certain rocks.

Metamorphism – Any process by which consolidated rocks are altered in composition, texture, or internal structure by conditions and forces such as pressure, heat, and the introduction of new chemical substances which do not result simply from burial and the weight of the subsequently accumulated overburden.

Metasediment – A partly metamorphosed sedimentary rock.

mg/l – Abbreviation for milligrams per liter which is a weight volume ratio commonly used in water quality analysis. It expresses the weight in milligrams of a substance occurring in one liter of liquid.

Micaceous – Occurring in thin plates or scales like mica.

Mineral – An inorganic substance occurring naturally in the earth and having a consistent and distinctive set of physical properties and a composition that can be expressed by a chemical formula. A mineral is commonly defined as a substance obtained by mining.

Mine Spoil – The overburden waste material removed or displaced from a surface mining operation that is not considered a useful product.

Monzonite – An aluminum silicate of alkalies.

Moraine – An accumulation of earth and stones carried and finally deposited by a glacier.

Nepheline Syenite – A coarse-grained igneous rock of intermediate composition, undersaturated with regard to silica, and consisting essentially of elaeolite, a varying content of alkali feldspar, with soda-amphiboles and/or soda-pyroxenes.

Neutralization – The process of adding an acid or alkaline material to waste water to adjust its pH to a neutral position.

Noritic – Like a coarse-grained igneous rock of basic composition consisting essentially of plagioclase and orthopyroxene.

Outby – Away from the face or toward the entrance of a mine.

Outcrop – The part of a rock formation that appears at the surface of the ground.

Packer – A device lowered into a borehole which automatically swells or can be made to expand at the correct time by manipulation from the surface to produce a watertight seal against the sides of the borehole or the casing.

Pegmatite – Coarse-grained igneous rock; irregular in texture and composition, occurring in dikes or veins, sometimes containing valuable minerals.

Peridotite – General term for essentially non-feldspathic plutonic rocks consisting of olivine, with or without other mafic minerals.

Permeability – The measure of the ability of a material to transmit underground water.

pH – The negative logarithm of the hydrogen-ion activity which denotes the degree of acidity or of basicity of a solution. Acidity increases with decreasing values below 7 and basicity increases with increasing values above 7.

Phlogopite – Brown magnesium mica, near biotite in composition, but containing little iron.

Phyllite – An argillaceous rock intermediate in metamorphic grade between slate and schist.

Pit – Any mine, quarry or excavation area worked by the open-cut method to obtain material of value.

Placer – Alluvial or glacial deposit of sand or gravel containing particles of valuable minerals.

Pollution Load – The amount of pollutants that a transporting stream carries during a given period of time (usually expressed as kg/day).

Porphyry – All rocks containing conspicuous phenocrysts in a fine-grained or aphanitic groundmass.

Portal – Any entrance to a mine.

Pyrometasomatic – Formed by metasomatic changes in rocks, principally in limestone, at or near intrusive contacts, under influence of magmatic emanations and high temperature and pressure.

Pyroxene – Mineral group, $ABSi_2O_6$ where A is chiefly Mg,Fe^{+2},Ca or Na, and B is chiefly Mg,Fe^{+2}, or Al.

Pyroxenite – Coarse-grained, holocrystalline igneous rock consisting chiefly of pyroxenes.

Quartzite – Quartz rock derived from sandstone.

Raise – A vertical or inclined opening driven upward from a level to connect with the level above, or to explore the ground for a limited distance above one level.

Reclamation – The procedures by which a disturbed area can be reworked to make it productive, useful, or aesthetically pleasing.

Regrading – The movement of earth over a surface or depression to change the shape of the land surface.

Riprap – Rough stone of various sizes placed compactly or irregularly to prevent erosion.

Schist – Crystalline rock that can be readily split or cleaved because of having a foliated or parallel structure.

Sediment – Solid material settled from suspension in a liquid medium.

Serpentinite – Rock consisting almost wholly of serpentine minerals derived from the alteration of previously existing olivine and pyroxene.

Shaft – An excavation of limited area compared with its depth made for mineral exploration, or for lowering or raising men and materials, removal of ore or water, and for ventilation purposes in underground mining.

Shear Zone – Zone in which shearing has occurred on a large scale so that the rock is crushed and brecciated.

Sill – Flat bedded strata for sandstone or similar hard rocks.

Slope – An inclined shaft for access to a mineral seam usually developed where the seam is situated at a distance beyond the outcrop.

Stockwork – Solid mass of one vein or a rock mass so interpenetrated by small veins of ore that the whole must be mined together.

Stratum – A section of a rock formation that consists of approximately the same kind of material throughout.

Strike – The direction (course or bearing) of the line of intersection of an inclined plane (such as a rock unit bedding plane) with an imaginary horizontal plane.

Stringer – Narrow vein or irregular filament of mineral traversing a rock mass of different material.

Subsidence – A sinking down of part of the earth's crust.

Supergene – Ores of minerals formed by downward enrichment.

Surface Water – Water from whatever source that is flowing on the surface of the ground.

Syenite – Any granular igneous rock composed essentially of orthoclase, with or without microcline, albite, hornblende, biotite, augit, or corundum.

Syncline – A configuration of folded stratified rocks in which the rocks dip downward from opposite directions to come together in a trough.

Syngenetic – Mineral deposits formed contemporaneously with the enclosing rocks.

Tactite – Rocks of complex mineralogy formed by contact metamorphism of limestone, dolomite, or other carbonate rocks into which foreign matter form intruding magma has been introduced by hot solutions.

Tectonic – Pertaining to rock structures and topographic features resulting from deformation of the earth's crust.

Topography – The physical features (i.e., relief and contour) of a district or region.

Ultramafic – Some igneous rocks containing no less than 45 percent silica.

Underground Mining – Removal of the mineral being mined without the disturbance of the surface (as distinguished from surface mining).

Updip – Lying up-slope along an inclined mineral seam or rock bedding plane.

Urethane Foam – A rigid, cellular, acid resistant foam that is formed by mixing isocyanate and a polyether polyol containing a halogenated hydrocarbon agent which may be used to protect mining and pollution abatement equipment and structures.

Winze – A vertical or inclined opening, or excavation, connecting two levels in a mine, differing from a raise only in construction; a winze is sunk underhand and a raise is put up overhand.

V

LIST OF MINERALS

actinolite
$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$

albite
$NaAlSi_3O_8$

allanite
$(Ca,R)_2(Al,Fe,Mg)_3Si_3O_{12}(OH)$

almandite
$Fe_3Al_2(SiO_4)_3$

alunite
$KAl_3(SO_4)_2(OH)_6$

amosite
$(Fe,Mg)SiO_3$

anatase
TiO_2

andalusite
Al_2SiO_5

anglesite
$PbSO_4$

anhydrite
$CaSO_4$

ankerite
$Ca(Mg,Fe)(CO_3)_2$

anorthite
$CaAl_2Si_3O_8$

anthophyllite
$(Mg,Fe)_7Si_8O_{22}(OH)_2$

antigorite
$Mg_6Si_4O_{10}(OH)_8$

antlerite
$Cu_3(SO_4)(OH)_4$

apatite
$Ca_5(F,Cl,OH)(PO_4)_3$

argentiferous galena
$(Pb,Ag)S$

argentiferous tetrahedrite
$(Cu,Fe,Ag)_{12}Sb_4S_{13}$

argentite
Ag_2S

arsenopyrite
$FeAsS$

atacamite
$Cu_2(OH)_3Cl$

azurite
$Cu_3(CO_3)_2(OH)_2$

baddeleyite
ZrO_2

barite
$BaSO_4$

barylite
$BaBe_2Si_2O_7$

bastnaesite
$CeFCO_3$

bauxite
$Al_2O_3 \cdot 2H_2O$

bazzite
$Be_3(Sc,Al)_2Si_6O_{18}$

bertrandite
$Be_4Si_2O_7(OH)_2$

beryl
$Be_3Al_2Si_6O_{18}$

bindheimite
$Pb_2Sb_2O_7 \cdot nH_2O$

biotite
$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$

bismite
Bi_2O_3

bismuthinite
Bi_2S_3

boehmite
$AlO(OH)$

borax
$Na_2B_4O_7 \cdot 10H_2O$

bornite
Cu_5FeS_4

brochantite
$Cu_4(SO_4)(OH)_6$

brookite
TiO_2

brucite
$Mg(OH)_2$

calcite
$CaCO_3$

carnallite
$KMgCl_3 \cdot 6H_2O$

carnotite
$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$

carrollite
$CuCo_2S_4$

cassiterite
SnO_2

celestite
$SrSO_4$

cerargyrite
$AgCl$

cerussite
$PbCO_3$

chalcanthite
$CuSO_4 \cdot 5H_2O$

chalcocite
Cu_2S

chalcopyrite
$CuFeS_2$

chamosite
$Fe_6(Al,Si)_4O_{10}(OH)_8$

chloanthite
$NiAs_2$

chlorite
$(Mg,Fe,Al)_6(Al,Si)_4O_{10}(OH)_8$

chromite
$(Mg,Fe,Zn,Mn)(Al,Cr)_2O_4$

chrysoberyl
Al_2BeO_4

chrysocolla
$CuSiO_3 \cdot 2H_2O$

chrysotile
$Mg_6(Si_4O_{10})(OH)_8$

cinnabar
HgS

cobaltite
CoAsS

colemanite
$Ca_2B_6O_{11} \cdot 5H_2O$

columbite
$(Fe,Mn)Nb_2O_6$

corundum
Al_2O_3

coulsonite
$(FE,V)_3O_4$

covellite
CuS

crocidolite
$NaFe(SiO_3)_2 \cdot FeSiO_3 \cdot H_2O$

cryolite
Na_3AlF_6

cryptomelane
$(K,H_2O)_2Mn_5O_{10}$

cummingtonite
$(Fe,Mg)_7Si_8O_{22}(OH)_2$

cuprite
Cu_2O

cylindrite
$Pb_3Sn_4Sb_2S_{14}$

dawsonite
$NaAl(OH)_2CO_3$

descloizite-mottramite series
$PbZn(VO_4)OH-PbCu(VO_4)OH$

diaspore
$HAlO_2$

diatomite
siliceous remains of diatoms

diopside
$CaMgSi_2O_6$

dolomite
$CaMg(CO_3)_2$

enargite
Cu_3AsS_4

enstatite
$MgSiO_3$

epidote
$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$

eudialyte
$Na_4(Ca,Fe)_2ZrSi_6O_{17}(OH,Cl)_2$

euxenite
$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$

famatinite
Cu_3SbS_4

ferberite
$FeWO_4$

fergusonite
$(Y,Er,U,Th)(Nb,Ta,Ti)_2O_6$

ferrimolybdite
$FeMoO_3 \cdot H_2O$

fluorapatite
$Ca_5(PO_4,CO_3)F$

fluorite
CaF_2

franklinite
$(Fe,Zn,Mn)(Fe,Mn)_2O_4$

gadolinite
$Be_2FeY_2Si_2O_{10}$

galena
PbS

garnet
$(Fe,Mg,Mn,Ca)_3(Al,Fe)_2(SiO_4)_3$

garnierite
$(Ni,Mg)SiO_3 \cdot nH_2O$

gibbsite
$Al(OH)_3$

glauconite
$K(Fe,Mg,Al)_2(Si_4O_{10})(OH)_2$

goethite
$Fe_2O_3 \cdot H_2O$

greenalite
ferrous silicate isomorphous with serpentine

grunerite
$(Fe,Mg)_7Si_8O_{22}(OH)_2$

gypsum
$CaSO_4 \cdot 2H_2O$

halite
NaCl

halloysite
$Al_4Si_4O_{10}(OH)_8 \cdot 4H_2O$

hedenbergite
$CaFeSi_2O_6$

hematite
Fe_2O_3

hemimorphite
$Zn_4(OH)_2Si_2O_7 \cdot H_2O$

huebnerite
$MnWO_4$

illite
$K_2(Si_6Al_2)Al_4O_{20}(OH)_4$

ilmenite
$FeTiO_3$

jamesonite
$Pb_4FeSb_6S_{14}$

jordesite
amorphous molybdenum disulfide

kaolinite
$Al_4Si_4O_{10}(OH)_8$

kermesite
$2Sb_2S_3 \cdot Sb_2O_3$

kernite
$Na_2B_4O_7 \cdot 4H_2O$

kroehnkite
$Na_2Cu(SO_4)_2 \cdot 2H_2O$

kyanite
Al_2SiO_5

langbeinite
$K_2SO_4 \cdot 2MgSO_4$

lepidolite
$K_2Li_3Al_3(AlSi_3O_{10})_2(OH,F)_4$

leucite
$KAlSi_2O_6$

limonite
$FeO(OH) \cdot nH_2O + Fe_2O_3 \cdot nH_2O$

livingstonite
$HgSb_4S_7$

lollingite
$FeAs_2$

loparite
$(Ce,Na,Ca)(Ti,Nb)_2O_6$

magbasite
$KBa(Al,Sc)(Mg,Fe)_6Si_6O_{20}F_2$

magnesite
$MgCO_3$

magnetite
Fe_3O_4

malacite
$Cu_2(CO_3)(OH)_2$

manganite
$MnO(OH)$

marcasite
FeS_2

metacinnabar
HgS

microcline
$KAlSi_3O_8$

microlite
$Ca_2Ta_2O_7$

minnesotaite
ferrous silicate isomorphous with talc

molybdenite
MoS_2

monazite
$(Ce,La,Y,Th)PO_4$

montmorillonite
$(Al,Mg)_8(Si_4O_{10})_3(OH)_{10}\cdot 12H_2O$

montroseite
$(V,Fe)O\cdot OH$

muscovite
$KAl_2(AlSi_3O_{10})(OH)_2$

niccolite
NiAs

olivine
$(Mg,Fe)_2SiO_4$

palygorskite
$Mg_5(Si_4O_{10})_2(OH)_4$

patronite
VS_4

pentlandite
$(Fe,Ni)_9S_8$

perovskite
$CaTiO_3$

petalite
$LiAlSi_4O_{10}$

phenakite
Be_2SiO_4

phlogopite
$KMg_3(AlSi_3O_{10})(OH)_2$

pollucite
$Ce_4Al_4Si_9O_{26}\cdot H_2O$

polybasite
Ag_9SbS_6

polyhalite
$K_2MgCa_2(SO_4)_4\cdot 2H_2O$

proustite
Ag_3AsS_3

psilomelane
$(Ba,H_2O)_2Mn_5O_{10}$

pyrargyite
Ag_3SbS_3

pyrite
FeS_2

pyrochlore
$NaCaNb_2O_6F$

pyrolusite
MnO_2

pyromorphite
$Pb_4(PbCl)(PO_4)_3$

pyrophanite
$MnTiO_3$

pyrrhotite
$Fe_{1-x}S$

quartz
SiO_2

rhodochrosite
$MnCO_3$

rhodonite
$MnSiO_3$

roscoelite
$K(V,Al)_3Si_3O_{10}(OH)_2$

rutile
TiO_2

scheelite
$CaWO_4$

senarmontite
Sb_2O_3

sericite
fine grained muscovite

serpentine
$Mg_6Si_4O_{10}(OH)_8$

siderite
$FeCO_3$

siegenite
$(Co,Ni)_3S_4$

sillimanite
Al_2SiO_5

skutterudite
$CoAs_2$

smaltite
$CoAs_{3-x}$

smithsonite
$ZnCO_3$

soda ash
Na_2CO_3

sodic plagioclase
$Na(Al,Si)AlSi_2O_8$

sphalerite
ZnS

sphene
$CaTiSiO_5$

spinel
$MgAl_2O_4$

spidumene
$LiAlSi_2O_6$

stannite
Cu_2FeSnS_4

stephanite
Ag_5SbS_4

sterrettite
$ScPO_4 \cdot 2H_2O$

stibiconite
$Sb_2O_4 \cdot H_2O$

stibnite
Sb_2S_3

strontianite
$SrCO_3$

sylvite
KCl

talc
$Mg_3Si_4O_{10}(OH)_2$

tantalite
$(Fe,Mn)Ta_2O_6$

teallite
$PbSnS_2$

tennantite
$(Cu,Fe,Zn,Ag)_{12}As_4S_{13}$

tenorite
CuO

tetrahedrite
$(Cu,Fe,Zn,Ag)_{12}Sb_4S_{13}$

thorianite
ThO_2

thortveitite
$(Se,Y)Si_2O_7$

topaz
$Al_2SiO_4(F,OH)_2$

tremolite
$Ca_2Mg_5Si_8O_{22}(OH)_2$

tremolite-actinolite
$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$

ulexite
$CaNaB_5O_9 \cdot 8H_2O$

ulvospinel
Fe_2TiO_4

uraninite
UO_2

valentinite
Sb_2O_3

vanadinite
$Pb_5(VO_4)_3Cl$

variscite
$AlPO_4 \cdot 2H_2O$

willemite
Zn_2SiO_4

witherite
$BaCO_3$

wolframite
$(Fe,Mn)WO_4$

wulfenite
$PbMoO_4$

wurtzite
(Zn,Fe)S

xenotime
YPO_4

zincite
ZnO

zircon
$ZrSiO_4$

VI

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16. ABSTRACT

This report is prepared in response to the requirements of P.L. 92-500, Section 304(e)(2)(B). It was prepared for use by planners, engineers and resource managers and provides information on the chemistry and geographic extent of mine drainage pollution in the U.S. from inactive and abandoned underground mines; underground mining methods and the characterization of mine drainage control techniques.

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