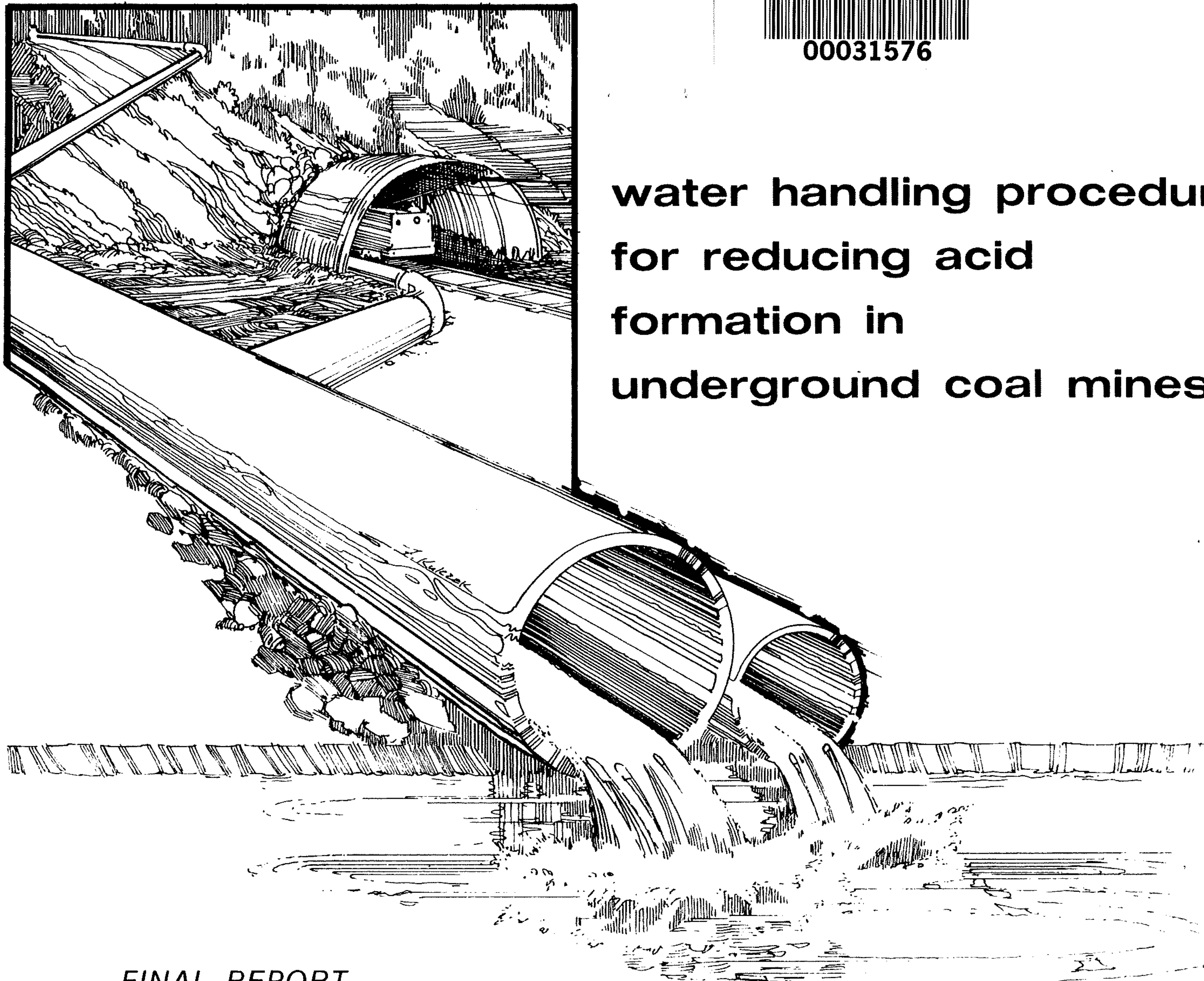

water handling procedures for reducing acid formation in underground coal mines

Open file Skelly & Loy

FINAL REPORT

Contract Number J0199027

Submitted to:

U.S. BUREAU OF MINES

Pittsburgh, Pennsylvania 15236

Submitted by:

SKELLY AND LOY
ENGINEERS-CONSULTANTS
Harrisburg, Pennsylvania

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16. Abstracts The treatment of acid mine drainage can amount to a considerable expense over the life of a mine where highly pyritic materials are present. Two possible options to reduce costs are reducing inflow to the mine or collecting and transporting the water once it has entered the mine so as to minimize its contact with acid producing material. Planning the water handling system ideally should be part of the initial mine design. Adequate geologic and hydrologic data are necessary to avoid areas where high inflows may occur, or to plan for handling and treating the inflows.

This report discusses several methods to reduce or prevent inflows, including surface and stream diversions, dewatering of aquifers, grouting and sealing, and leaving barrier pillars between adjacent mines. Mine closure and down-dip mining are also considered in reducing acid mine drainage formation. The design of water handling systems in the mine is covered in detail. The system must be integrated throughout the mine. Methods of determining pump requirements, pump size and pipe sizing is discussed. Various types of acid mine drainage treatment is also discussed.

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FOREWORD

This report was prepared by Skelly and Loy, Engineers and Consultants, Harrisburg, Pennsylvania, under USBM Contract No. J0199027. The contract was initiated under the Environmental Control Program. It was administered under the technical direction of the Pittsburgh Research Center with Noel N. Moebs as Technical Project Officer. Sylvia Brown was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period September 4, 1979, to July 1, 1980. This report was submitted by the authors on October 1, 1980.

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INTRODUCTION

Water handling poses a critical problem to mine operators in northern Appalachia for several reasons. First, there can be a large volume of water inflow into some mines often requiring that five or more tons of water be handled for each ton of coal mined. Second, inflowing water often reacts in the oxidizing environment with materials within the seams and overlying strata to produce acid which mining companies must then treat to meet water quality standards. Further, it has been determined that time is one of the major factors in the formation of acid mine water. Any water handling system must, then, be designed capable of efficiently handling the volume of water generated while integrating the flow with the treatment facility.

Decreasing the influx of water by utilizing more effective infiltration control techniques can also be important and deserves consideration, since once water enters the mine, it must be gathered and removed from the oxidizing/acid forming environment as quickly as possible. In the case of large concentrated inflows, inflow reduction can be cost effective compared to handling and treating the water.

The purpose of this manual is to offer an outline of the possible water handling methods which can be used to deal with groundwater inflows in conjunction with AMD treatment. Acid formation reactions have been treated in a number of publications as have the treatment techniques required once the water has been delivered from the mine. This manual highlights the methods by which inflows can be reduced, and the water that does inflow can be gathered and moved within the mine to achieve both efficient movement and reduction of acid formation.

Acid reactions and treatment processes are discussed only insofar as they relate to water handling and to provide a means of understanding the mechanics or chemistry involved. Infiltration control is discussed as an alternative to the need to develop massive water handling systems. The scope of this manual does not allow an intensive technical treatment of water handling, but serves instead to direct attention to potential options and guidelines that can be used for basic design of water handling systems.

ACID MINE DRAINAGE (AMD) FORMATION REACTIONS

ACID MINE DRAINAGE (AMD) FORMATION REACTIONS

The development of acid mine drainage results from a series of naturally-occurring, chemical, biological, and physical steps in which the insoluble mineral pyrite, iron disulfide (FeS_2), is converted to various unstable, soluble reactive substances. Pyrite is present in most coals and in the rock units above and below the seam. This degradation of water quality so often associated with coal mining activities would not manifest itself if the coal and associated strata in which the pyritic materials are contained were allowed to remain in the reducing environment under which they were formed. Within an underground coal mine, as the working face advances, the coal seam and associated strata are subjected to a very significant change from a chemically reducing environment in which they were formed (one which is characterized by the absence of oxygen) to an oxidizing one.

The oxidation process takes place initially on the exposed surfaces of the pyritic materials associated with the coal seam and is the first step in the formation of mine acid. As oxidation continues, acid are formed, and the oxidized materials dissolve and expose new surfaces to oxidation and acid formation. Time is therefore an important factor with regard to the amount of acid formed. The longer the pyritic acid-forming materials are exposed to the atmosphere, the greater the amount of acid that is formed. The oxidation process is accelerated during warm weather months when atmospheric moisture within underground coal mines is present at or near saturation.

Bacteria also play an important role in the oxidation proccess. The bacteria act as a catalyst in speeding up the rate of acid formation. Laboratory research has been directed towards eliminating or reducing the effects of these bacteria, but the results have not been effective when applied in the mines. Controls on these microbes may eventually be developed to combat the formation of acid mine drainage.

Heavy metals other than iron such as lead, chromium, mercury, boron, and manganese which may also be present in the form of sulfide compounds. These will oxidize in the same manner as pyrite, releasing trace quantities to the water in the mine and affecting water quality.

The acid formation process is initiated when water at or near neutral pH percolates through the overlying cover and infiltrates the coal seam. As this water flows over and through the mined material and workings, acidic salts that have oxidized, such as iron or sulfate, become part of the mine drainage. Thus, the three ingredients necessary for acid mine drainage formation are pyrite, oxygen, and water. This initial chemical reaction in simplified form is as follows:

$$2\ FeS_2 + 7O_2 + 2\ H_2O \longrightarrow FeSO_4 + H_2SO_4$$

The rate of this initial step is variable depending on temperature, pH of the water, pyritic composition, oxygen content, and area of surface which is saturated with water. It is important to note that the rate of the oxidation reaction is controlled by the conditions at the pyrite surface.

The second step is also dependent upon aeration and temperature and is believed to involve bacterial oxidation by iron-oxidizing bacteria.

This reaction is as follows:

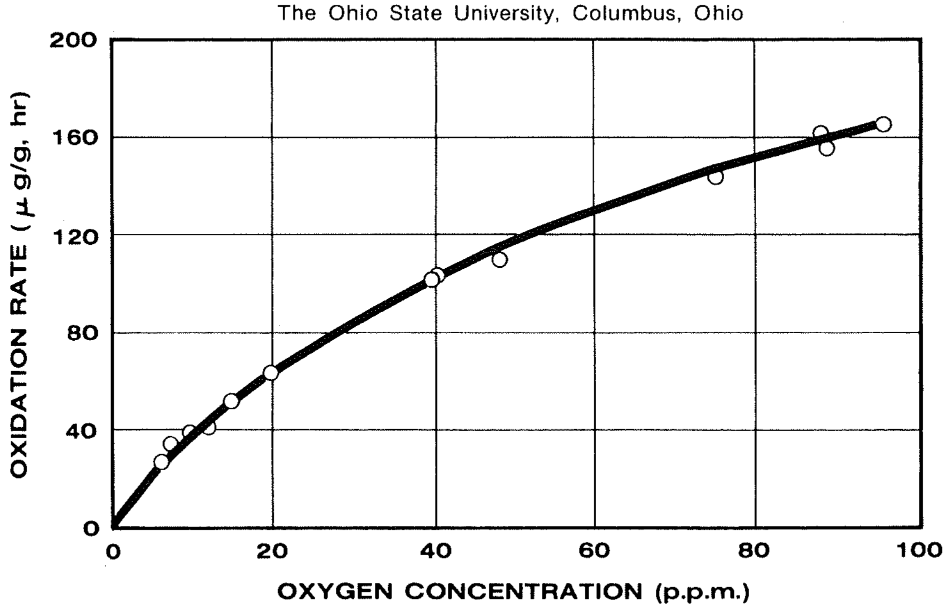
$$4\ FeSO_4 + 2_2O_2 + 2\ H_2SO_4 \longrightarrow 2\ Fe_2(SO_4)_3 + 2\ H_2O$$

The ferric sulfate then hydrolizes, thus forming more acid and precipitating ferric hydroxide and basic sulfates as shown below:

$$Fe_2\ (SO_4) + 6H_2O \longrightarrow 2Fe(OH)_3 \downarrow + 3H_2SO_4$$

Ferric hydroxide precipitates as an orange deposit known as "yellowboy." The important kinetic features of this reaction are illustrated by the following figures.

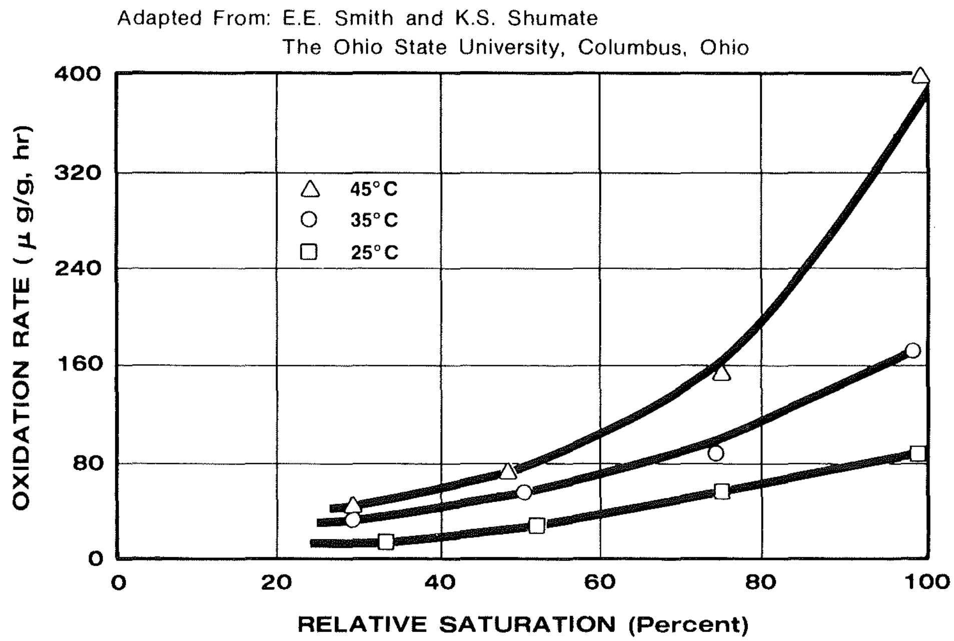
Adapted From: E.E. Smith and K.S. Shumate
The Ohio State University, Columbus, Ohio



OXIDATION RATE vs OXYGEN CONCENTRATION IN AQUEOUS PHASE

FIGURE 1

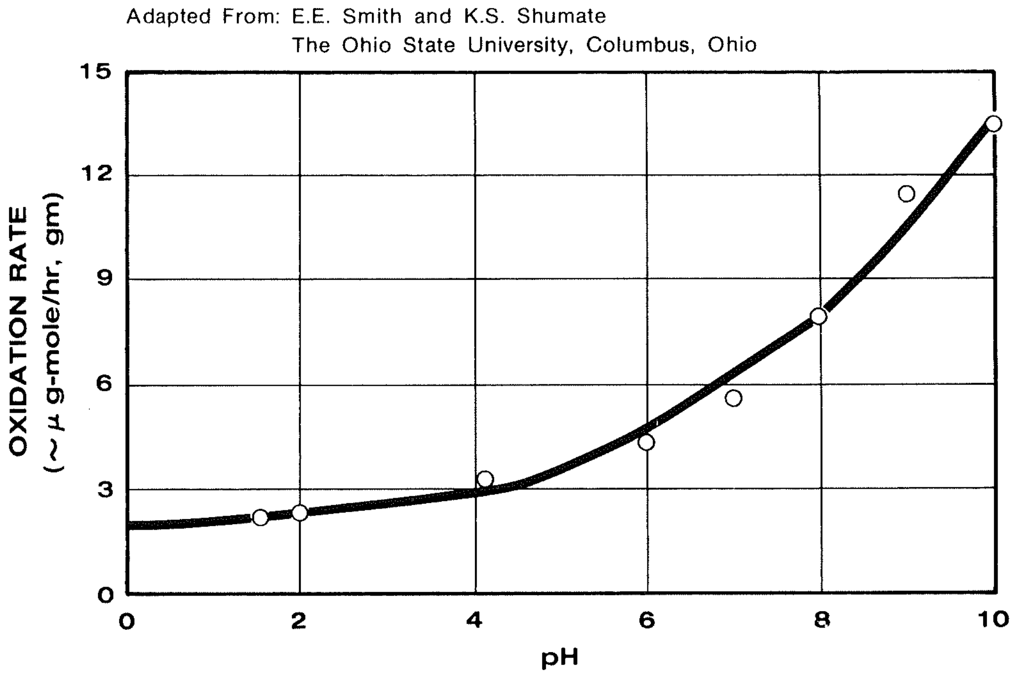
Figure 1 illustrates the effect of oxygen concentration upon pyrite oxidation rate. By halving the oxygen concentration of water, which is about the best to be expected from air-sealing an underground mine,



OXIDATION RATE vs PERCENT RELATIVE SATURATION
FIGURE 2

Smith and Shumate found that the oxidation rate of exposed pyrite was reduced to approximately 60%. Further, the oxidation rate does, for all practical purposes, go to zero in the absence of oxygen. The oxygen concentrations shown are given in terms of oxygen dissolved in the aqueous phase on the surface of the pyrite.

Figure 2 illustrates findings regarding the relation of pyrite oxidation to the degree of saturation of the pyrite surface, which reaches a maximum when the surface becomes completely wet. This does not mean complete immersion in liquid water - the oxidation rate of pyrite exposed to air of 100% relative humidity was found to be essentially the same as pyrite immersed in oxygen-saturated water. Figure 2 also illustrates the effect of temperature upon the oxidation rate. For each 10°C rise in temperature, it was found the rate approximately doubled, which is generally characteristic of most chemical reactions.



OXIDATION RATE vs pH

FIGURE 3

Figure 3 illustrates findings by Smith and Shumate pertaining to the influence pH has on the oxidation rate of pyrite. As pH increases (i.e., the solution in contact with pyrite becomes more alkaline) the oxidation rate increases, and it decreases as the solution becomes more acidic. However, generally it has been observed that if alkaline water is infiltrating through pyritic materials, there is likely to be less acid mine drainage produced. Alkaline water results from percolation through alkaline overburden which does exist in many areas. For instance, glacial tills tend to be alkaline and some seams of coal have overlying layers of limestone which raises the pH of infiltrating the water. These seams include the Pittsburgh and Clarion seams in Pennsylvania.

Data obtained through Ohio State University's pilot scale research facility, a small drift mine in Vinton County, Ohio, indicated that the reaction sites extend behind the working face as far as oxygen can diffuse before it is consumed in oxidation reactions. The extent of pyrite oxidation is limited by the rate of oxygen transport.

Pyrite is contained in a porous matrix through which oxygen must infiltrate. The critical acid formations take place in a vapor environment in which the pyrite is moist and in contact with a continuous supply of air. This concept can be visualized by a thin film of water vapor saturated with oxidation products at the surface areas of the pyrite.

After these sulfide compounds have been oxidized, the products collect in local spots of standing water. Sulfates, iron, and heavy metals are soluble at low pH's. Whenever passing water encounters these oxidation products, they are flushed out and are reflected by the water's quality. For this reason, it is imperative to avoid the uncontrolled flow of drainage through the underground workings because of the drainage's ability to pick-up and flush acid and iron compounds.

DETERMINATION OF WATER QUANTITY AND QUALITY

DETERMINATION OF WATER QUANTITY AND QUALITY

The design of a mine's water handling system should consider all pertinent data on the geology, hydrology and ecology of the mine site. This initial information will be implemented in the design of the system and are the most important factors to be considered. The geology and topography of the mine site will influence the layout of the mine workings, which naturally dictates the layout of the water handling system including the basic head conditions, power requirements, discharge piping and boreholes, location of sumps, etc. The data collected must be as accurate as possible to assure that the system design will be adequate throughout the life of the mine. Where the geology is complex, such as where folding or faulting of rock units is common, more data is required for decision making, than in areas of flat lying, structurally simple rock formations.

A good drilling program is necessary at the planning stage and should be designed to provide maximum information for the cost involved. Drill hole information should not only include the geologic strata, but should record the depths at which groundwater is encountered and the relative quantities which are flowing into the hole. The drill holes should be later checked to determine the static water table at various times of the year. Groundwater samples can be taken from the holes for water quality analyses required by federal regulations. Casing or packs can be placed in some selected drill holes to perform pumping and permeability tests on the various aquifers. These can be left in place in critical locations for monitoring during the life of the mine. The holes should be properly cased and grouted to prevent contamination of one aquifer by another. Once the holes are no longer needed, they should be permanently sealed to prevent contamination from surface inflow and aquifer mixing. Core samples can be taken while drilling to be used in overburden analysis where required for acid mine drainage prediction. Judicious planning at the onset of the drilling program can save added expense later.

A good visualization of coal seam dip and relief or structure makes it possible to choose the most effective solutions to water handling problems. Geologic maps of the area are invaluable to early planning of the drainage system, especially coal structure contour isopach maps, which are developed from drill hole data. These will depict possible natural drainage patterns concurrently with mine layout plans. Structural characteristics can be taken advantage of; i.e., structural lows can be utilized as large, permanent natural drainage sumps. Since the geology of every mine environment is unique, a good perception of underground conditions will result in effective planning and engineering.

The quantity of water which the system must handle is determined by the hydrological conditions that exist and the mining system used. Proper consideration given here to the required capacity assures cost effectiveness of the system since the size (and consequently the cost) of equipment such as pumps, pipes, and power supply is dependent upon required capacity. Fluctuations in hydrologic conditions often occur with the seasons and should be considered for capacity requirements. Studies should be conducted for at least a year prior to designing the system so that seasonal parameters can be determined. In most areas the highest flows and groundwater levels occur in the early spring, but this may vary from year to year.

The following sections will review the various stages implemented during the planning phase of water handling systems.

INFLOW ESTIMATES

It is important to predict inflow to a mine in the planning and design of its water handling system. However, the nature of groundwater flow in the coal regions is complex and adequate data seldom exists. The typical rock units overlying coal seams consist of thinly bedded sandstones, shales and siltstones. Intergranular porosity is low and most groundwater flow is through joints (fractures), and along bedding planes - between layers.

Water can exist under both water table and confined (artesian) conditions. Often perched aquifers will exist on top of impermeable shale layers. Identifying perched water tables prior to interception by mining is important. These are often identified by springs which are found where the impermeable layer outcrops on the sides of hills. Perched water tables may be unaffected during mining advance, but may be drained during retreat as fractures propagate upward from the mine as a result of subsidence.

Groundwater flow tends to flow along paths sub-parallel to the surface with the water table closer to the surface under valleys and deepest under hills. However, geologic structure can modify flow, particularly where the dip of the rocks is greater than a few degrees. The water may then flow downdip along bedding planes or in confined layers. Thus, greater quantities of water are more commonly found in the bottoms of synclines (structural troughs) than in anticlines. (Miller and Thompson 1976). Where a seam has been mined, the mine acts as a large underdrain carrying the water off in the downdip direction.

Water encountered in coal mines may originate from several different sources. In mines with a shallow cover and without an impermeable, solid roof, or in deeper mines where pillar extraction has broken the roof to the surface, rainfall can seep directly into the mine. Old strip mines may be intersected by the underground mine allowing water to enter by that route. Where there are direct connections to the surface, or the mine is not deep, there is more inflow during rainy season and less in the dry season. Thus, the deeper the mine, the longer it takes for inflow rate to change in the mine.

Water may also enter through natural fracture zones, often identified on aerial photographs as lineaments or straight-line features. Streams and valleys are usually associated with higher densities of fracturing either because the valleys form along fracture zones or because of stress release occurring as erosion unloads the rocks. When the mine workings intersect these zones, high water inflows as well as bad roof often result. Often these inflows decrease with time, either as the zone is dewatered or the joints seal themselves by chemical precipitation of minerals.

Another common point of groundwater entry to a mine is where an overlying sandstone layer changes into siltstone or shale. Water traveling downdip through the sandstone encounters the lower permeability shale and is forced into the mine openings along fractures or bedding planes.

The coal seam itself may act as an aquifer and water will enter through the face or the ribs, often under artesian head if adjacent layers are clays and shales. If there are adjacent mines updip which have been flooded, the high head may force water into the mine. A very common situation is for water to come into mines through the floor.

In estimating inflow to a coal mine, the determination should be made according to water input as influenced by rainfall, subsurface percolation, and rock permeabilities.

First, the water available for inflow depends on rainfall. A review of groundwater records in northern Appalachia and published articles in the Annual Coal Mine Symposia (Miller and Thompson, 1976) indicate that annual precipitation ranges from 34 to 50 inches, with an average of 36 to 42 inches per year. A convenient figure to use in this area is 40 inches/year which converts to a water supply of roughly 2 gallons/ minute per acre.

Secondly, the available water depends upon the amount that escapes runoff and evapo-transpiration, and percolates into the subsurface.

Base runoff is indicative of the amount of groundwater available to subsurface flow and averages about .6 gal./minute per acre in the northern Appalachian region. This implies that roughly 30% of the rainfall is available to enter a mine where rock permeabilities are representative of the area. (Miller and Thompson, 1976.)

The third factor governing inflow is the permeability of the rock, both intergranular (primary porosity) and that which is due to rock fractures (secondary porosity). Permeability tends to decrease with depth, as rock freactures close under pressure. In areas of shallow residual and transported soils, such as northern Appalachia, the first 50-150 feet of depth is the zone within which most water table levels occur. When using well yield data to determine permeability, it should be kept in mind that this zone has high water yields which distort the value of the data when applied to water handling problems.

The following table lists typical permeabilities of rocks normally encountered in coal mining.

Material	Permeability Range gal. per day/ft^2*
Clay	0 to 10
Shale	1 to 100
Limestone	1 to 100
Sandstone	10 to 1000

*As defined by Meinzer, the rate of flow in gallons per day through a square foot of the cross section of material, under 100 percent hydraulic gradient, at a temperature of 60° F.

In most areas, the horizontal permeabilities exceed the vertical permeabilities by a factor of 10 to 1 or even 50 to 1 (Parizek, 1972). However, vertical permeabilities increase where fracture zones, faults, old wells, subsidence cracks or shafts intercept the impermeable layers which serve as aquitards (layer which transmit relatively less water than the aquifers).

A commonly used procedure for identifying areas of probable inflow and roof fall areas is the fracture trace or photo-lineament study. A photo-lineament is a natural straight-line feature visible on aerial photographs or satelite imagery. These features could be alignments of stream valleys, straight stream segments, or tonal differences in soils and vegetation. Many geologists feel these lineaments frequently represent fracture and fault zones in the earth, where jointing in the rocks are of a higher density than in the surrounding bedrock. These zones may extend through many layers of rock, and may be capable of transmitting large quantities of water. Where a mine entry intersects a fracture zone, inflow may result, especially if the zones connect to a high yield aquifer or to a stream or lake.

To calculate inflows to a mine from the permeable rock masses surrounding it, several basic equations can be applied which treat an underground coal mine as a large well.

A useful equation on which most calculations are based is Darcy's Law:

$$Q = KiA$$

Q = flow rate in ft^2/min
K = hydraulic conductivity (proportionality constant)
i = head gradient
A = area of flow through medium

This equation simply states that the volume of fluid flowing through a porous medium is proportional to the head gradient times the area of the medium through which flow occurs. (The medium in this case might be a sandstone formation.) Actual inflows may be less than this equation yields but it gives an upper limit to mine inflow and environmental effects.

A number of methods for determining the permeabilities or the transmissivity (the number of gallons per day passing through a unit width of aquifer under 1 unit of head) of an aquifer are discussed in several publications including Parizek (1971) and Brown (1979), where examples are given of calculating inflow into mines. These methods are more generally treated in any of the many standard texts on groundwater hydrology on the market. Aquifer tests (pumping tests) are used to determine the aquifer characteristics and predictions of mine inflow may be made from the results. Because of the complex and varying nature of hydrologic conditions in the eastern coal region, it is recommended that a hydrogeologist who is familiar with the area be consulted in making these determinations.

Computer programs are increasingly used in hydrogeologic studies. Some of these could be useful in determining inflow into mines. For instance, a hydrology simulator program put together by The Pennsylvania

State University's Department of Mineral Engineering is able to incorporate data on precipitation, infiltration, runoff, evaporation, evapotranspiration, and interflow, and also considers unsaturated zones which allows application to perennial watersheds. It should be kept in mind that the reliability of this method of predicting inflows is dependent upon the accuracy and completeness of the input data used and should always be verified by comparing it to anticipated theoretical results. As with all methods, often the best predictions which can be expected are within a range of an order of magnitude; however, such information can still be useful in planning a water handling system.

ACIDIC CONCENTRATION ESTIMATES

An important stage of water system planning is the determination of the mine area acid-base relationship. A survey of this relationship must be conducted to enable the planner to calculate the potential for the formation of acid mine drainage. The acid-base relationship is determined by two parameters: 1) pyritic sulfur and 2) neutralization potential. Thus, the formative potential of acid drainage equals the difference between the maximum possible acidity and the neutralization potential.

To perform such a determination, samples which are representative of the overlying strata and coal seam must be obtained. Possible sources of representative samples include core borings, fresh strip mine highwalls, nearby mines, and core data from available previous geological investigations of the immediate area. Groundwater samples from the coal seam can also give an estimate of the reactivity of the pyrite and the neutralization potential of the water. Carrucio (1979) collected water samples in his study of the relationship of coal depositional environments to acid formation. He states:

> The exact nature of the geochemical system of the coal seam and overlying strata from which the water sample was collected can be quickly ascertained if sulfate data are related to and examined in conjunction with hardness, acidity and pH. If, for example, a sample has high sulfate, hardness and acidity content, coupled with a low pH, it could be readily assumed that that particular stratigraphic section is generating acid mine drainage and contains abundant amounts of reactive pyrite. If, on the other hand, the sample contains low sulfate concentrations coupled with high hardness, low acidity and high pH, it could be assumed that the water flowed through strata containing calcareous material and a paucity of reactive pyrite. Finally, if a sample has high sulfate, high hardness, low acidity and high pH, it could be assumed that the geochemical system is such that acidity is being generated by reactive pyrite, but is subsequently neutralized by the alkalinity produced by calcareous material present in the selection.

Various methods of overburden analysis have been developed to predict acid mine drainage, but these have been mainly applied to surface mines. Coal varies greatly in its sulfur content within short distances, so a number of samples would have to be analyzed to provide for average data. Groundwater samples give a general idea of the geochemistry for the wide area of rocks through which the water has passed.

Prior to mining, acid-base accounts, analyses can be made on samples taken from core drillings. Most important in predicting potential AMD would be those layers of rock most likely to be disturbed and exposed to water and oxygen, that is the coal, the floor material, and the roof rock.

Volume and pollutant loading in deep mine drainage generally increase proportionally to:

1) Total disturbed area
2) Roof caving, which may lead to increased strata permeability, increased strata fracturing, and increased pyrite content
3) Amount of water
4) Reactivity of the pyrite

After volume and chemical characteristics of the mine drainage have been established, the next step will be the selection of the reagent for treatment. This is covered in a later section on treatment.

CONTROL OF INFLOW

CONTROL OF INFLOW

Some bituminous underground coal mines in the United States at times produce as much as 5 or more tons of water for each ton of coal mined. For many mines even this figure is highly conservative due to poor hydrogeologic conditions and/or inefficient water handling. Other mines handle little or no water because of favorable hydrologic conditions or because they have planned and implemented water handling procedures which are systematic and highly effective.

By far the best method of controlling the amount of acid mine drainage which an underground mine might produce is by controlling the amount of water which enters the mine either as vertical or horizontal flow.

Water that is prevented from entering an underground mine does not require expenditures for its constant removal and treatment. That which does enter the mine can be handled effectively at a minimum cost by collecting it rapidly (to reduce contact with acid-forming materials) and transporting it efficiently to a proper disposal area.

Although it is not possible to completely eliminate the influx of water into a coal mine, it is practical to control the quantity in many situations.

There are various methods of controlling infiltration. For vertical flow these are: 1) diversion of surface waters from around mine openings such as shafts, slopes, and boreholes; 2) dewatering either aquifers surrounding the coal seam to be mined or existing underground workings which have accumulated water; or 3) grouting and sealing fractures and cracks that permit flow of subterranean water into the mine. For horizontal flow, adequate coal barriers must be left around the mine, especially along the outcrops and adjacent old works. In most cases a combination of these practices is the most efficient means of controlling inflow and should be implemented only after the sources of such inflow have been properly identified.

SOURCES OF INFILTRATION

Following is a list of various sources of infiltration which should be identified in planning a water handling system for a mine.

- Water bearing strata above or below the coal seam, or the coal seam itself.
- Fractures in roof rock which extend to the surface - usually only important where the mine is close to the surface. These include fracture zones identified on aerial photographs.
- Areas where there is a change in rock type such as from sandstone to shale.
- Previously mined sections in the same seam or in overlying seams - this is one of the major sources of acid mine water. Old workings are often allowed to accumulate water by companies who abandon them for one reason or another often to reduce acid mine drainage. When attempts are made to mine virgin coal in adjacent areas, it can seep above, below or through barrier pillars and enter new workings. Extreme hydrostatic heads can develop in these old works, posing the threat of inundation to the new mine.
- Areas under streams and valleys which are relatively shallow and fractured. These areas are known to be prime sites for roof falls.

- Fractures or openings caused by mine subsidence - again where the mine is close to the surface. In any case, fractures resulting from subsidence are an important source, and can intercept overlying aquifers.

- Mine openings - slopes, shafts, drifts - slopes and shafts particularly may allow infiltration either directly through the opening or indirectly along the casing or collaring.

- Direct connections to surface mines or auger holes.

- Exploratory drill holes - either as surface inflow resulting from poor plugging or as groundwater flow where uncased or improperly grouted. Old gas and oil wells may also be encountered.

The first seven situations can be known before planning new mines or new sections. Areas where serious problems can occur may be avoided. If the mines or conditions already exist, engineering solutions may be used to eliminate or reduce inflow in most cases. Every situation will be unique and will take good planning and creativity to solve the problem. Again, it cannot be stressed too much that good data is necessary to insure proper design and save money in the long run.

INFILTRATION CONTROL

Water Bearing Strata Above or Below the Coal

When aquifers exist above the coal and are infiltrating into the mine, little can be done to stop it. Wells placed above the mine can be pumped to reduce the head in the aquifer. This can reduce the inflow, since groundwater flow is proportional to the hydraulic gradient (head x distance). The U.S. Environmental Protection Agency (1979) conducted a well dewatering study at the Barnes and Tucker Lancashire No. 20 Mine where high quality water was entering the mine roof near the face. By pumping they were able to reduce inflow by 37% (Wahler, 1979). In other situations higher reductions may be possible. The theory is discussed by Parizek (1972) and may be cost effective where highly acid-producing materials are present in the mine. Parizek also proposes another system where gravity wells would extend from the overlying strata to an aquifer below, acting as drains and reducing the hydrostatic head above the mine. This system would only work where the natural movement of groundwater is in a downward direction. The Bureau of Mines is currently investigating another possible method of controlling water entering the roof: draining the roof with angled drillholes in fracture zones where water is entering the mine, and pumping the water to the surface through pipes. This will eliminate the contact of the good quality water with the acid-forming materials in the mine and allow it to be discharged without treatment. With all these schemes there is the problem of low transmissivity in coal-bearing formations. Since most of the permeability is due to fractures, for such a system to be successful the well or drillhole must intersect most of the fractures. Permeabilities are often so low that pumping one well will not effect another seven feet away. Closely spaced wells would be a necessity in this case.

Groundwater Sealing

Generally groundwater flows by either of two separate mechanisms, either through fractures or as porous flow through the pore structure of rocks such as sandstone. The use of grouting techniques is most highly applicable to fracture related flow although judicious use of pressure grouting techniques may also be used in slowing porous flows. The techniques are based on a determination of groundwater flow patterns followed by injection of grout into those flow areas which could cause inflow into the mine. Successful grouting operations therefore require a thorough understanding of the geologic structure of the area - an understanding which can be gained through detailed exploration, including visual inspection, geophysical sensing, test drilling, and aerial photointerpretation.

Pressure tests on boreholes are always made during the packing of a grouting program. Results are based on open hole tests, or single and/or double packer holes. A packer is a device used in the drill hole to segregate a part of the hole for grouting. Double packers are considered best when the walls of the hole do not cave or when the rock is not blocky or open, because seating two packers at a fixed distance is difficult. If the hole needs casing or cementing, pressure tests are made prior to doing so. Tests using water should be run at the same pressures considered safe for grouting, a rule of thumb being one psi/foot of depth. Higher pressures may be safe in more structurally sound rock that is not horizontally stratified.

There are various types of grouts which have been used in mining applications. The selection of the best material(s) and method(s) of injection are decisions which depend upon the geologic characteristics of the area to be grouted. Following is a brief outline of materials which have been used in the past. Generally, these grouts fall in either of the two main categories of cement grouts and chemical grouts.

Cement Grouting

Much of the grouting used in mining applications has been experimental with cement grouting by far the most popular and widely used. The most popular cement grouts are Portland Cements - type III having the fastest set-up time. Other grout materials include:

- Slag cement which is used because of the economics of its use
- Resin gypsum cement which is used because of its rapid set
- Lumnite cement used for its extra high strength gain in a short set time
- Combinations of these and Portland Cement

Certain desired characteristics may be imparted to the grout through the use of additives:

- Retarders to delay set-time
- Accelerators to speed set-time
- Lubricants to increase flowability
- Colloids to minimize segregation
- Expansion to minimize shrinkage
- Water reducing materials for reducing water to cement ratio

Cement slurries are commonly used to fill moderate or large volumes of voids of any size in competent rock, preferably free of clay to which neat cement and cement-sand grouts do not bond. Sand-cement and sand-cement-fly ash slurries develop good strength. Clay-cement grouts bond with native clay, are pumped more readily, have more body, and have lower permeability, but develop less strength. Setting times are also slow and inexact.

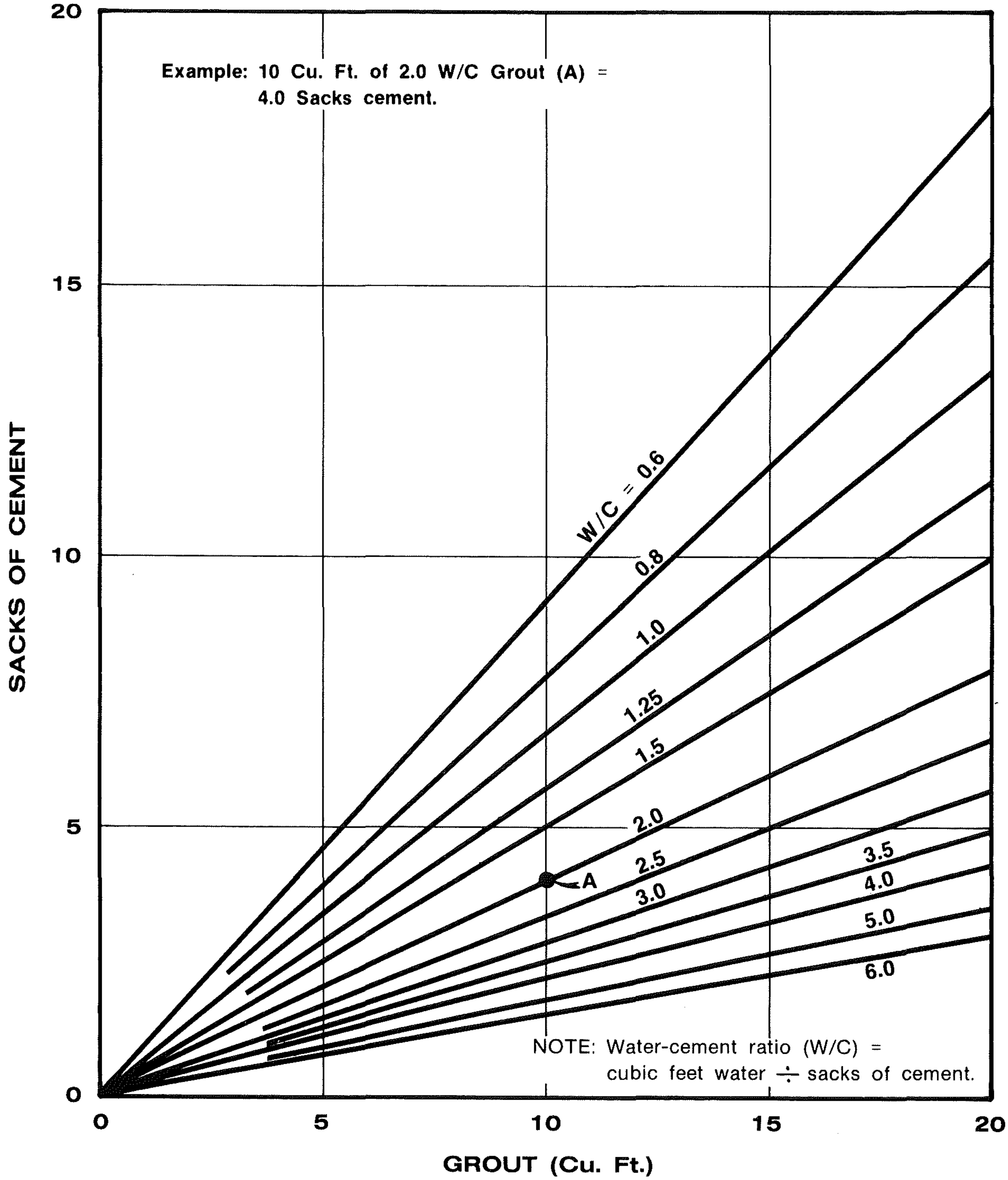
The water to cement ratio is the ratio of cubic feet of water/ cubic feet (1 ft = 1 sack) of grout. The ideal water content compensates for absorption losses into the rock and still keeps the mixture fluid enough to fill cracks and voids and remain pumpable. The following charts, (Figures 4 through 6), taken from the Corps of Engineers Manual on grouting, August 19, 1963, describe proper grout mixtures.

In proper grouting, the rate of injection is such that a maximum amount of grout is pumped in the hole, without displacement of surrounding rock, which would indicate excessive waste. Acceptance of large quantities of grout without an increase in pressure indicates the occurrence of large openings, a situation which may be corrected by:

- Thickening the slurry
- Reducing pumping pressure and rate
- Letting the hole stand for several hours
- Adding bridging materials, e.g., sand, chopped plastic, etc.

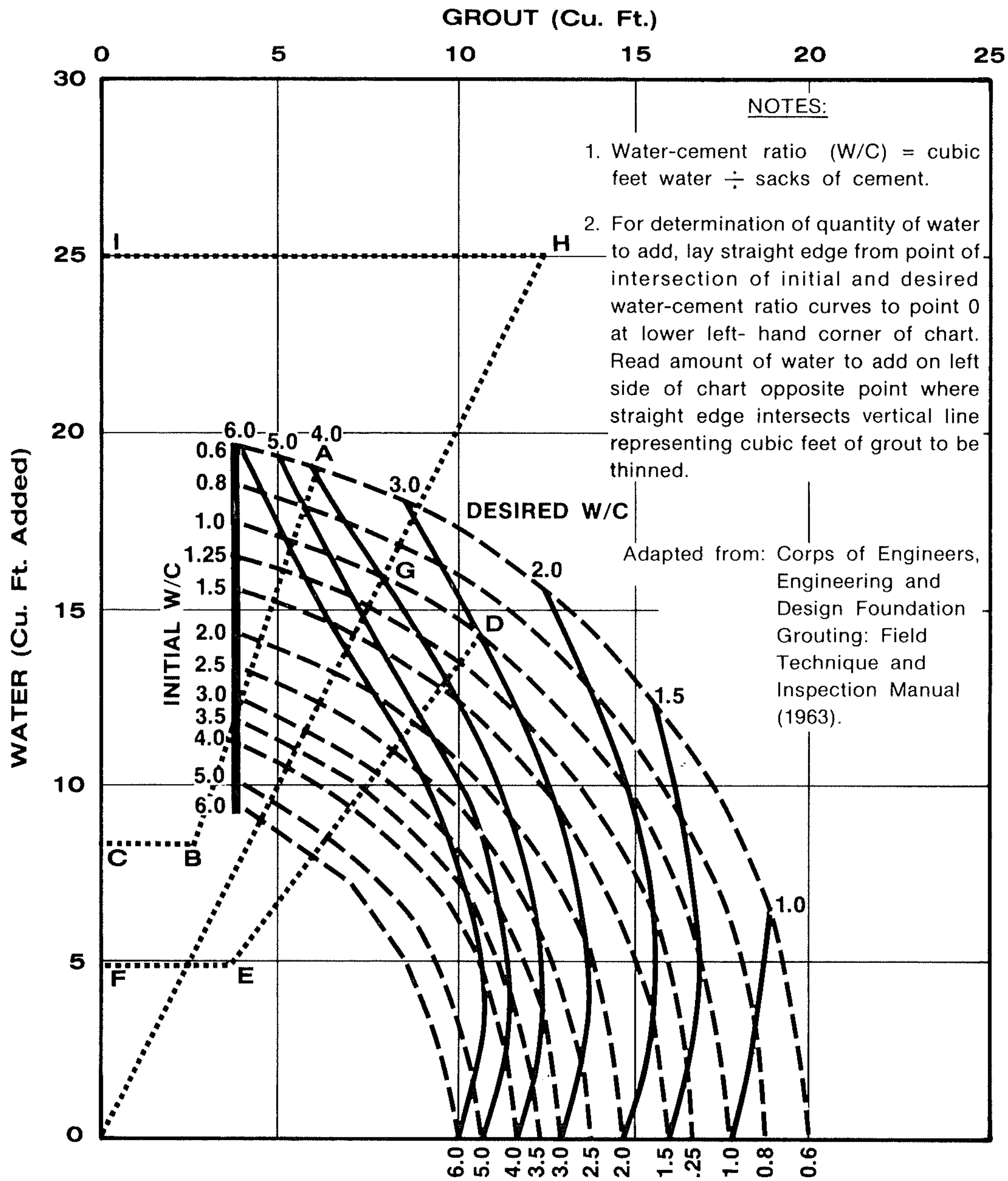
Cement grouts will not penetrate fractures of pores smaller than coarse-medium sand. Bentonite improves penetration and acts as a dispersant to prevent bleeding or separation of the water and increases pumpability, but with some decrease in strength.

Adapted from: Corps of Engineers, Engineering and Design Foundation Grouting: Field Technique and Inspection Manual (1963).



CEMENT CONTENT OF GROUT MIXES

FIGURE 4



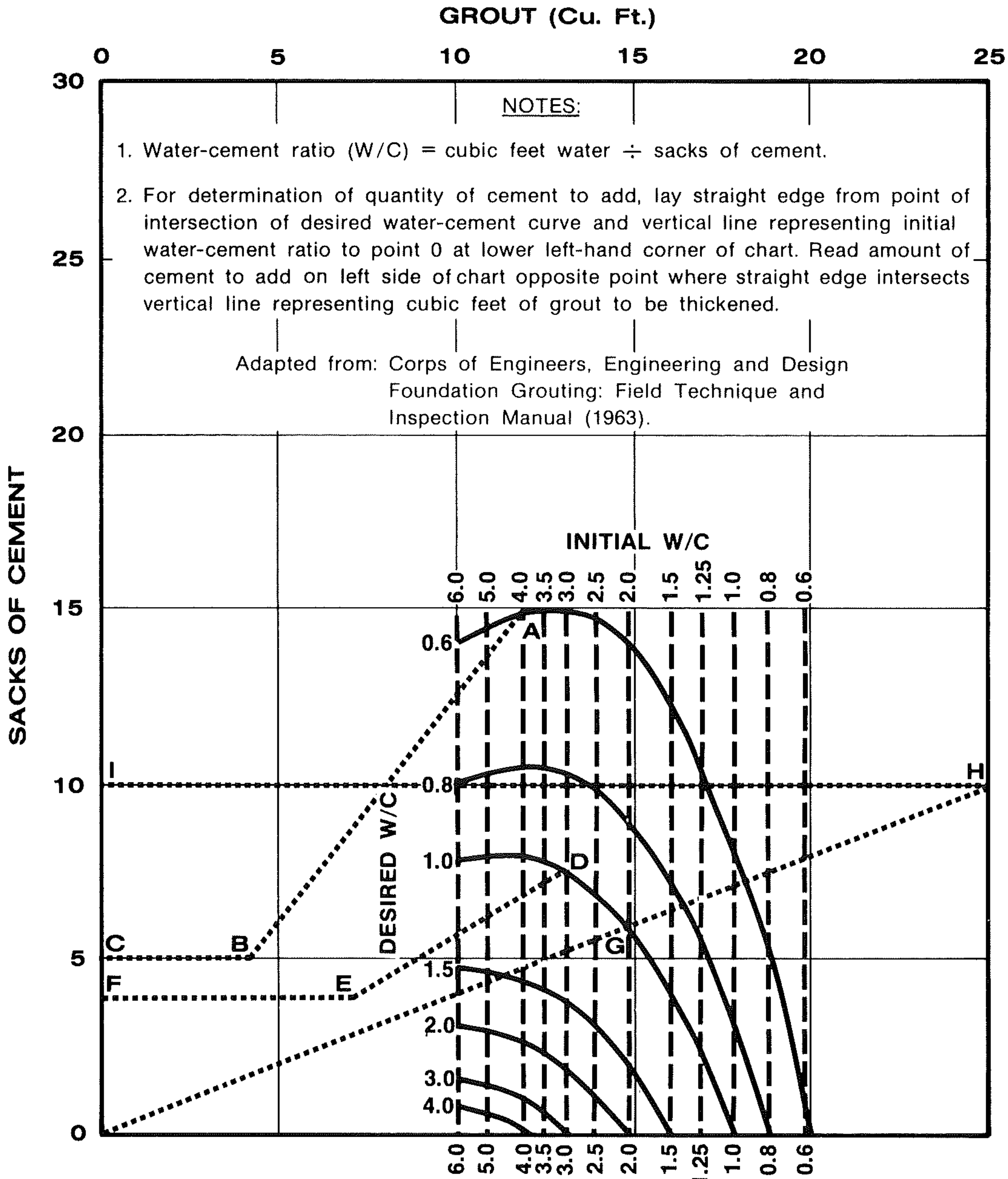
Example 1: Water required to thin 2.7 cu. ft. of 0.6 W/C grout to 4.0 W/C (ABC) = 8.3 cu. ft.

Example 2: Water required to thin 3.7 cu. ft. of 1.0 W/C grout to 3.0 W/C (DEF) = 4.9 cu. ft.

Example 3: Water required to thin 12.5 cu. ft. of 1.0 W/C grout to 4.0 W/C (GHI) = 25 cu. ft.

GROUT THICKENING CHART

FIGURE 5



Example 1: Cement required to thicken 4.0 cu. ft. of 4.0 W/C grout to 0.6 W/C (ABC) = 5.0 sacks.

Example 2: Cement required to thicken 7.0 cu. ft. of 3.0 W/C grout to 1.0 W/C (DEF) = 4.0 sacks.

Example 3: Cement required to thicken 25 cu. ft. of 2.0 W/C grout to 1.0 W/C (GHI) = 10.0 sacks.

GROUT THINNING CHART

FIGURE 6

As a type example, in one Pennsylvania limestone quarry an estimated inflow of 7 million gallons per day created problems and caused very high power costs from pumping. Detailed exploration (visual inspection, aerial photo interpretation, geophysical sensing, and drilling) determined the hydrogeologic regime of the mine site. A well developed fracture system in the mining area intersected a stream and provided a conduit for the excessive inflow. This inflow source and underground flow paths were confirmed by injecting tracers, NaCl, into boreholes in the fracture zone with tracer detection by use of automatic water samplers at various points on major suspected inflow routes.

Pumping a grout curtain between the stream channel and the mine workings was determined to be a more viable method than other options such as lining the stream channel with a plastic liner or constructing an earth fill dam. Four to six inch diameter holes were drilled, at 20 foot intervals, along a 450 foot linear front. On pumping the cement grout mixture into the holes, it was decided to bisect the first set of holes with a secondary set resulting in a pattern which effectively stopped inflow to the mine. In all, 7,000 yards of concrete was pumped into the boreholes at a material cost of 220,000 dollars.

From inside the mine, cracks and crevices which provided inflow of the water, were sealed with "hot plugs," mixtures of cement and "antihydro" (calcium chloride) which, when plugged into the openings, form a gel which then hardens into a very effective, water-tight seal. A similar method, called the Joosteen process, accomplishes the same task. The process utilizes a mixture containing calcium chloride and sodium silicate (water glass) to form an impermeable seal. Chemical grouts such as these will be discussed in a following section. Where slow water seepage occurred in the mine, gunite was sprayed on the roof and ribs to reduce the seepage and to add structural strength to the rock.

In all, this combination of infiltration control methods greatly improved mining conditions and caused a significant decrease in power consumption for pumping.

Chemical Grouts

Chemical grouts consist of two or more chemicals in water solutions which react to form a gel or solid precipitate. The advantage of using chemical grouts is their ability to penetrate smaller openings then possible with cement grouts. Chemical grouts are more expensive than portland cement and require special pumping and blending equipment. Examples of them are:

Acrylamides and Chrome Lignins - advantages are lowest viscosity-acrylamide has a viscosity of about 2 cp until just before set. Setting time, determined rather accurately by a mixture of accelerator before injection, can be from a few minutes to many hours. They can be pumped into narrow fractures and pores of very fine sand, and even silt, larger than about 0.01 mm, at a rate of about 0.001 cm per sec. Strength is moderate; gels can be extruded from sizable openings but an acrylamide known as AM-9 has been used to resist gradients of more than 15 psi per ft. in fine sand. Both gels lose water and shrink where exposed to dry air. Acrylamides also shrink where exposed to brines. The viscosity and cost of solution pumped and set strength vary with concentration.

Resorcinol Formaldehydes - advantages are moderately low viscosity and a rapid set to a strong stable elastic-plastic moderate material resembling bakelite. Resorcinol formaldehyde can be squeezed into openings almost as small as those entered by AM-9. It can, therefore, be used to fill shrinkage cracks in cement grout and in other places where very small openings are to be filled with a material of high strength and permanent stability. Again, viscosity and cost of solution pumped and final set strength vary with concentration.

Chemical grouts, such as AM-9, have been used in the past in mining applications, but have not advanced to much more than the experimental stage. One successful grouting project using a chemical grout was undertaken in a deep mine in western Pennsylvania's Upper Freeport seam. Intense water inflow was created when a slope was driven through an underground aquifer. To locate the exact point source, a fluorescent yellow-green dye (calocid uranine) was injected into selected boreholes near the suspected source of water leakage. The time lapse between injections and dye content of the inflowing water were measured and used in determining the precise location of the water source and in determining the required gel time of the chemical grout to provide effective sealing. 220 gallons of 10% AM-9 was pumped into 15 boreholes effectively eliminating water inflow.

Chemicals such as AM-9 (currently out of production) are rarely used today because they have been found to be highly toxic and can contaminate drinking water supplies. Warnings abstracted from the Corps of Engineers Design Manual, 1 July, 1966, state the dangers of using chemical grout and specify that only highly experienced persons should run such operations.

If fracture traces are identified on aerial photographs, they should be checked in the field to determine if they are natural or man-made. If conditions warrant the costs, drilling or geophysical surveys, using electrical resistivity or seismic equipment, could be performed to determine the extent and nature of the fracture zone. If water inflow into the mine is determined to be highly probable, mine plans can be drawn to avoid these areas. If the area cannot be avoided, it would be best to cross fracture zones at right angles to intersect the zone with the smallest area exposed in the entry.

Surface Flow Diversions

Since much of the inflow to underground coal mines is from the percolation of surface water, this infiltration process is greatly reduced by increasing the runoff of surface water on land areas above the mine. This may be especially true where abandoned surface mines intersect the coal seam near the mine. If the overland flow can be diverted away from possible openings of the underground works, it can be channeled away from the mine site and disposed of in a controlled manner.

Often underground mines intersect old surface mines or approach so close that an inadequate barrier exists. Often auger holes extend from the surface mine bench several hundred feet into the coal seam. In these cases, clay or other impermeable material should be placed against the coal seam to prevent passage of water. The surface mine bench should be properly graded and diversion ditches used to keep water off of the back-filled slope so it will not infiltrate down to the coal seam. If the spoil material is acid, lime will have to be used for neutralization.

Diversions are designed based on maximum runoff flow calculations these can be calculated by several methods such as the Soil Conservation Service method or the rational method. Diversion runoff is a function of depth, flow, % grade, slope configuration, and texture of the soil.

The rational formula for estimation of peak flows from various storm events is:

$Q = ciA$, where:

Q = Peak flow in cfs
c = Runoff coefficient
i = Storm intensity - in./hr. for duration of time (t)
A = Drainage area, in acres
t = Time of concentration

The rational formula has been widely used for design purposes on smaller watersheds or drainage areas, but is not recommended for use with areas in excess of 15 acres, since results become less reliable. For a complete discussion of rational formula usage and computations, refer to the Pennsylvania Department of Highway's Design Manual, Part II, Chapter 12.

The Soil Conservation Service has developed a procedure for estimating runoff which is becoming increasingly popular and provides greater accuracy than the rational formula for large areas. This approach involves examination of precipitation, soils, vegetative cover, conservation practices and topography, and is described in full detail in the Engineering Field Manual for Conservation Practices (USDA, 1969).

When constructing drainage diversions - swales, ditches, dikes, flumes, etc. - standard engineering practices should be applied for each individual site. The economic feasibility of constructing such drainage features will be limited by the steepness of slope, area of the contributing watershed and the availability of a safe, non-erodable outlet. Decisions are also necessary on the required service life of the structures, because temporary ones can be built very cheaply but may not last through the required life of the mine.

Generally, the approach taken in diverting surface runoff depends on the amount or concentration of that runoff. Dikes may be used in certain very limited situations but they are easily eroded and offer little resistance to percolation unless carefully constructed. Ditches are generally a more effective means of diversion because of their ability to act as a more positive control device. Whereas a dike may be infiltrated by water, a ditch may be more effectively lined and sloped to not only collect the water but also carry it away.

Mine Subsidence Fractures and Mine Openings

Where streams are losing water to subsidence features or into mine openings, stream diversions have been successfully used in the past. One must keep in mind that special permits are required for any changes in streams.

Many projects using techniques such as these have been undertaken in the past and have resulted in considerable reductions of mine water inflow. As an example, one such project was undertaken at Catawissa Creek in Pennsylvania to restore a streambed and prevent water from flowing into deep mine workings. An alternate streambed had been constructed previously by the deep mine operator to prevent water from entering his mine. Later, a surface mine operator had moved the stream back to the mine openings to facilitate his mining operations. He neglected to return the stream to the alternate location and a large acid loading to the stream occurred as water flowed through the old workings. As part of Pennsylvania's Department of Environmental Resources "Operation Scralift," the alternate streambed was reconstructed making it deeper and clearing it of debris. The job was completed in 1970 at a cost of $30,529.68. Seventeen hundred feet of new streambed was designed to carry the maximum flow of record. Since its construction, it has been highly successful and has needed no maintenance. The acid load to the creek was reduced by 1,830 lbs. per day. (Klingensmith, et. al. 1976.)

In another project under the same program, a new channel was built on Little Sandy Run where significant stream loss into mine workings has been determined to exist. The area was cleared and grubbed and a new channel was excavated and lined with an impermeable layers of sand and bentonite. A riprap cover was placed to protect the impermeable membrane. Subsidence areas near the channel were filled so that drainage would be into the channel rather than into the depressions. The total costs for the project completed in 1974 are as follows:

Item	Quantity	Cost
Clearing and Grubbing	3.00 Acres	$ 3,000.00
Channel Excavation	1,600.00 Cu. Yds.	3,995.00
Channel Lining		
a. Bentonite and Sand	2,914.44 Sq. Yds.	58,288.80
b. Quarry Stone	2,914.44 Sq. Yds.	5,887.17
Embankment	7,500.00 Cu. Yds.	16,875.00
Seeding and Soil Supplements	5.00 Acres	5,000.00
Anti-Pollution Measures	Job Job	500.00
Underdrain System	Job Job	3,000.00
	Total =	$96,545.97

Since diversion structures cause concentrated flows that can become serious erosion problems at their outlets, runoff control and soil stabilization are important factors to consider in planning the proper control and disposal of these concentrated flows. This may be accomplished by decreasing the flow gradient, increasing the flow distance, or destructing the flow. In most cases, these three techniques must be used in some combination to most effectively control erosion.

Proper disposal of concentrated flow involves spreading the water into nonerosive sheet flow by using a level spreader (dam or other barrier) and energy dissipators at discharge points. Flow barriers such as a dam or depression excavated out of the channel bottom not only decrease the flow rate but also settle out solids. These types of impoundments tend to increase cross sections across the flow and also build up water heads which can cause downstream erosion. This energy may be dissipated through use of flumes and flow destructers such as riprap and large mid-stream boulders. Placement of these flow energy dissipators should be at points below grade control structures and outfalls.

Another means of flow energy control is to directly increase flow distance through construction of meanders. Decreases in flow gradient with this method is equivalent to the increase in flow distance thereby spreading the water head or kinetic energy along a longer stretch of channel. Energy dissipators are still required but to a much smaller extent and only along the outsides of meanders. Vegetation growth may be encouraged to accomplish the same results.

Where mine subsidence depressions exist on the surface, water may be infiltrating into the mine through fractures below. These depressions can be filled with clay or other impermeable material and graded so that runoff cannot enter the subsidence fractures.

Adjacent Mine Workings

An adjacent abandoned mine which has accumulated water may be a major source of infiltration. Effective control may require an analysis of the potential seepage of impounded waters through barrier pillars.

The three major variables governing the volume of water flowing through any saturated rock strata are permeability, gradient, and cross-sectional area perpendicular to the direction of flow. The permeability and the hydraulic gradient determine the velocity of seepage, an essential quantity in identifying the possibility of piping. Piping is a crucial consideration in water retaining structures because failure can be caused by eroding away material. To avoid piping failure, coal pillars must be undisturbed and not fractured. Seepage analysis is conducted by separately calculating seepage through the overlying strata, the coal barrier itself and the underlying strata, because all three will have different permeabilities and therefore will transmit water at a different rate.

To determine the permeability values necessary to compute the seepage analysis, tests can be made at the mine site by either forcing water into the material or removing it under controlled conditions. Forcing the water into the strata from a drill hole is usually the least expensive method. The test is then based on measuring the amount of water which the strata accepts through the open bottom of a pipe or through an uncased section of the hole. Clear water must be used to prevent misleading results. A hole is drilled to the strata which is to be tested. The procedure is to clean the hole to the proper depth and add clear water through a metering system, either by gravity or pressure flow, until a constant rate of flow and head differential is obtained. Injection of water for 5 minutes under these steady state conditions is satisfactory to determine permeability by using the relation:

$$K = C\ Q/H$$

K = permeability (ft./yr.)
C = constant depending on size of casing or borehole
Q = constant rate of flow into the hole (gpm)
H = differential head of water (ft.)

The values of C for given pipe diameters are:

Diameter of Casing I.D.	C
1 1/2 inches	204,000
1 23/32 inches	160,000
2 3/8 inches	129,000
3 inches	102,000

The value of H for gravity tests of the water table is the difference between the level of water in the casing or boreholes and the level of groundwater. If the test is conducted above the water table, H is the depth of water in the hole.

Another type of permeability test is known as a pressure test. For pressure tests, the applied pressure in feet of water (1 psi = 2.31 feet) is added to the gravity (differential) head to arrive at H. A more detailed treatment of permeability tests can be found in the Soil Conservation Services Engineering Field Manual (USDA, 1969).

Example: Field test for permeability.

Given: Casing size - 3 inch I.D.
Q = 1.1 gallons per minute
H = 46.0 ft.

Solution:
$$K = C\,Q/H$$
$$= (102{,}000)(1.1/46.0) = 2{,}440 \text{ ft./yr.}$$
$$= 6.7 \text{ ft./day}$$

Permeability can also be determined by well pumping tests. There are several types of tests. These can be expensive to perform and require the services of a hydrogeologist.

The standard practice in hydrologic engineering is to complete the seepage analysis through use of a flow net construction. The barrier situation is drawn to scale and flow through the separate strata is visualized by determining flow lines (horizontal lines) paralelling the movement of the groundwater. Then equipotential lines (vertical) are drawn such that rectangular spaces are created as much as is possible. Two hypothetical situations are illustrated in Figure 7. There are a number of additional rules to be followed in the construction of flow nets. These are discussed thoroughly in Cedergren (1967).

Cedergren presents the following relationship:

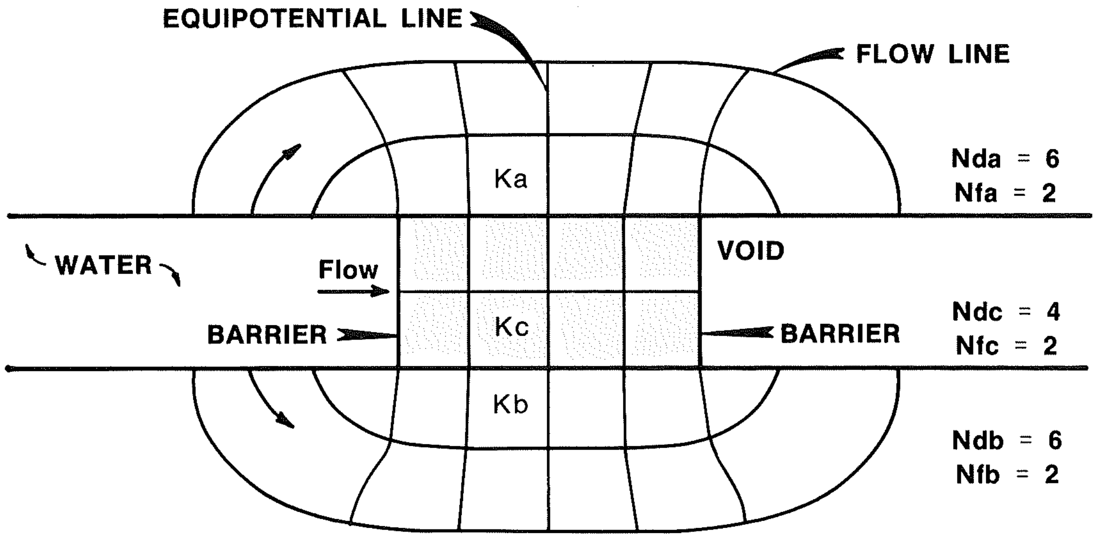
Q = K h Nf/Nd to apply flow nets to seepage analysis

Nf = number of flow paths in the system
Nd = number of equipotential drops
h = head
K = permeability

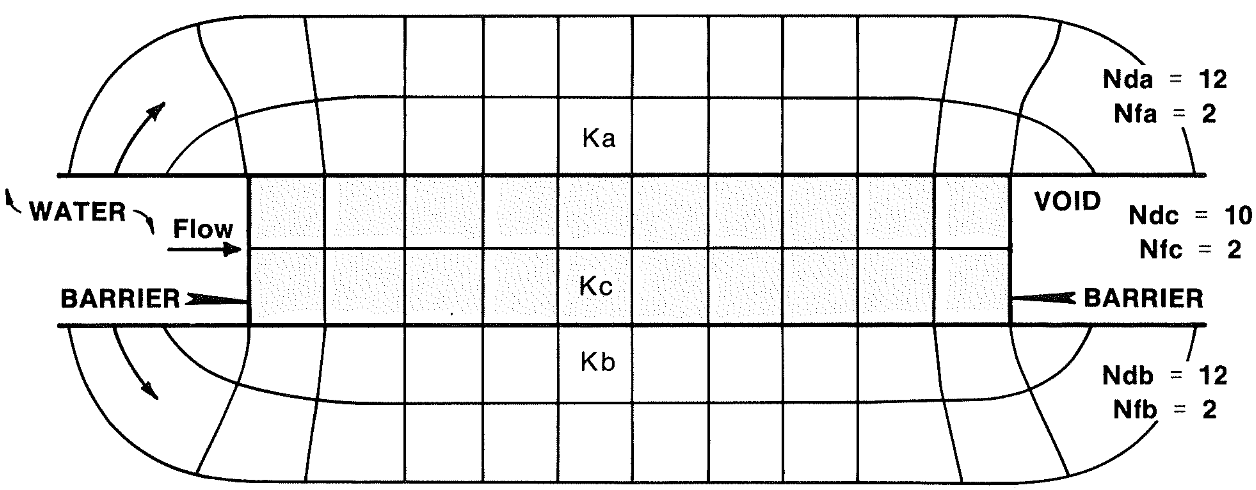
This equation is based on Darcy's Law.

As an example of a flow net analysis to barrier seepage, assume a flow system consisting of two entries in a 10 ft. thick coal seam approaching each other but separated by a 20 ft. thick barrier of coal (Figure 8). Assume consistent permeability throughout the coal and surrounding strata, although the permeabilities usually vary from one layer of rock to another. Hydrostatic head provides the energy of flow from left to right. Water is impounded in the abandoned workings on the left. To illustrate the concept of the Nf/Nd ratio, construct two flow paths through the thickness of the coal (any number could be used, and visualize the system as limited to two flow paths above and two flow paths below the coal. The equipotential lines are drawn such as to create rectangles. The ratio of Nf/Nd = 2/6 above the coal, 2/6 below the coal, and 2/4 through the coal.

In the equation A = K h (Nf/Nd), K is a constant. Assuming h to be 100 feet at the middle elevation of the coal, it can be seen that the



COAL BARRIER 20 FT. WIDE: Ka = Kc = Kb



COAL BARRIER 50 FT. WIDE: Ka = Kc = Kb

COAL BARRIER SEEPAGE FLOW NETS

FIGURE 7

average h above the coal diminishes, while the opposite is true below the coal. Further, assuming the change in average h above and below the coal to be 9 feet, the flow above the coal is Qabove = K (100-a)(2/6) = K(33-a), Qbelow = K(100+a)(2/6) = K(33+a) and Qcoal = K (100)(2/4) = K(50). The units for K are ft/day and h is in feet, so the solutions of the relationships yield units of ft/day/lineal foot of barrier length.

The effect that is caused by widening the pillar to 50 feet changes the ratio Nf/Nd to 2/12 above and below the coal and 2/10 through the coal, therefore the seepage above and below the coal is decreased 50% and seepage through the coal is decreased by 60%. Increasing the width to 100 feet yields Nf/Nd ratios above and below the coal to 2/22 and 2/20 through the coal. Seepage above and below is decreased by 73% and 80% through the coal. Keep in mind that the barrier pillar must be undisturbed and intact. This means that such an intact condition might require an additional 2 thicknesses of the coal on each side of the 20 foot barrier and as much as 4 thicknesses on each side of the 50 foot pillar due to deformation from the vertical load.

The effectiveness of the barrier can be increased by one of two factors: decreasing the permeability of flow through the pillar or increasing the length of flow path around the pillar, i.e., lining the roof and floor of the mine adjacent to the barrier with an impermeable blanket. To decrease permeability through the pillar, place impermeable material adjacent to the exposed faces of the pillar.

If the seepage analysis indicates that a massive pillar is required to reduce seepage, an economic evaluation should be made to determine alternate methods of prevention.

Down-Dip Mining

While not actually reducing inflow into the mine, mining down-dip can be beneficial in reducing acid mine drainage, after an area is mined out. The mains are driven to the lowest point in the coal seam and then the sections are worked up-dip, allowing the lower sections to flood. The coal barrier impounds the water, so that sealing is not necessary. Less oxygen is available to create acid mine drainage in the inundated sections. Mentz and Warg (1975) determined that haulage and pumpage up-dip increased production costs by only a few percent. Down-dip mining is presently required by the Office of Surface Mining to control post-closure acid discharge.

Mine Closure Methods

Mine closure does not actually control the inflow of water but can be useful in reducing acid mine drainage once a section or the entire mine is worked out, as in down-dip mining. A variety of mine or section closure and sealing methods have been implemented by the mining industry over the years including: dry seals/air seals, hydraulic seals (single and double bulkhead), and multipurpose seals. Their purposes range from sealing off a mine heading to eliminate ventilation or drainage requirements to closing an entire mine (drift mine) once it is worked out.

Dry seals are described as those which require the seal to withstand little or no hydraulic head. The dry seal is constructed by grading earth over a mine opening or it may consist of clay or block wall bulkheads. The objective of dry seals is to prevent the entrance of air and water into the mine. As discussed earlier, dry seals have not been found to be successful in reducing acid mine drainage.

Air seals are structures constructed in a mine which permit the discharge of water but which are so designed to prevent the exchange of outside ambient air into the mine as this would expedite pyrite oxidation.

Closures which create an impoundment underground are categorized as hydraulic seals. Single bulkhead seals are normally constructed of a grouted or aggregate bulkhead which is placed either through vertical boreholes or directly in the mine opening. Single bulkhead seals are usually used where the predicted water pressure will be low.

Double bulkhead seals are used when high pressures are expected as a result of the barrier construction and consequent high water heads. The construction of double bulkhead seals is normally accomplished by one of two methods. The first method involves the placement of two crushed stone barriers in the mine tunnel, followed with grouting of the stone bulkheads, and the addition of cementing materials into the void between the bulkhead to create an airtight seal. Another method used, which is very similar, excludes the grouting of the bulkhead so as to retain the center plug. The most commonly used materials for the construction of the bulkhead seals include poured concrete, masonry block or bricks, grouted aggregate, and quick settling gel materials. Other hydraulic seal methods include clay seals, gunite seals, and grout bag seals. As with any type of constructed seal or barrier, seepage through the surrounding coal barriers must still be accounted for using techniques described above.

Multipurpose seals are those barriers which are designed to not only close the mine entrance but to provide additional functions such as allowing outflows of mine water. Two such structures are the permeable limestone seal and the regulated flow seal. The permeable limestone seal is a hydraulic closure in which a permeable alkaline aggregate is placed in the mine so water will pass through it. The alkaline material helps neutralize the acidic water and induce the formation of a precipitate which will eventually fill the voids in the aggregate creating a solid single bulkhead seal.

The regulated flow seal consists of a hydraulic seal with a regulated flow valve installed in the seal. The drainage rate of the mine discharge may be regulated to reduce the effect of shock-loading upon the receiving stream.

The effectiveness of mine closures in preventing acid mine drainage is controversial. In some cases, it does seem to have an appreciable effect, as high as 80%. It is the most common method of controlling mine drainage in abandoned mines. In active mines, it could be effective in closing off mined-out areas to reduce the amount of water which needs to be treated. Safety regulations must be considered, especially if the sections to be sealed off are up-dip to working areas. With seals, there is always the problem of maintaining the seals. They must be properly constructed so that piping does not occur around the edges of the seal, causing its eventual destruction. Grouting of the bedrock may be necessary. Seepage and strength analyses should also be performed on the coal barriers which will also be impounding the water. Often seals have been constructed which have been adequate, but the coal barriers have been too thin or may have high permeabilities so that the mines have not held water. Fracture-trace studies may be useful in pinpointing areas where high permeabilities may exist which could transmit water through or around the barriers at excessive rates.

HANDLING METHODS

HANDLING METHODS

Since the introduction of environmental regulations on mine drainage, the emphasis on water handling methods in underground coal mines has changed. In the past, the major concern was to economically remove any water from the mine that would inhibit production. Environmental regulations prohibiting discharge of acid mine drainage (AMD) or otherwise polluted waters into streams has added to the concern that waters be removed in such a way as to minimize pollution. Contamination can arise from many sources including equipment fuels and lubricants and solids. However, the most important in most coal mines is acid formed by the oxidation of pyritic formations. (See the section, "Acid Mine Drainage (AMD) Formative Reactions.")

Implementation of the more recent concern of water handling - to economically remove water from the mine that will inhibit production and to minimize surface and groundwater contamination - is accomplished in two major ways. The most desirable way is to minimize or prevent water from entering the mine. This method, as discussed in the "Control of Inflow" section, is quite effective in reducing contamination, but in many cases can have risky chances for success or is not practical. The second, somewhat less desirable but most prevalent way is to effectively remove the water from the mine after inflow and treat the water, if needed, to remove or neutralize any contamination. This section provides a discussion of methods for handling the water from the infiltration point to the surface and contains some guidelines for the design of in-mine water handling systems.

SYSTEM COMPONENTS

Water handling systems constructed in a mine for the purpose of removing water are comprised of a variety of components including sumps, ditches and pipes, boreholes, and pumps. The following sections present a brief discussion of the function of these components and how they relate to one another.

Sumps

A sump is nothing more than a water storage reservoir that holds water until it is pumped to another location. The reason for constructing sumps is to allow enough water to accumulate so that a pump can be primed and operated at highest possible efficiencies.

A secondary function of a sump is to provide detention time to allow some suspended solids to settle out prior to pumping. This not only increases water quality of the discharge but reduces wear on pump parts and pipes. It should be noted that because of this function of a sump, all sumps in a mine should be periodically examined for accumulated sediment. A failure to detect and remove these settled solids will reduce the sump volume resulting in reduced time between pumping periods (which may overheat pump motors) and in reduced clarification properties (which will increase pump and pipe wear).

Sumps may be constructed by either excavating a pit or by constructing dams and using mined out areas for water storage. Excavated pits can be cut in the underlying strata using mining techniques. Care should be taken to check this material for pyritic content and take preventive measures if there is potential acid formation. Dams are typically constructed of wood, concrete, or masonry and must be designed to meet safety standards.

Mine sumps can be classified into three types:

Collection sumps are constructed at the source of infiltration and hold water before pumping by small submersible pumps. These sumps are typically found at the working face and advance along with the face. Water is drained into the sumps by ditches or the sumps are located at a fracture seep.

Transfer sumps collect flow from one or more collection sumps and are necessary when the head required to pump water from the collection to the main sump is too great for the small pumps used in collection sumps. The transfer sump can also act as a collection sump if infiltration occurs in that area of the mine.

Main sumps are the final stage in the underground network prior to pumping to the surface. Very large mines may have more than one main sump, but most mines have just one.

Ditches and Pipes

Water can be moved within a mine by gravity or pressure flow. Gravity drainage is nearly always used when possible because gravity is doing the work that would have to be done by a pump. Pressure flow is needed, however, to lift water to higher elevations and to get water out of sumps.

Gravity flow can be accomplished using ditches when the material being used is non-pyritic. If a pyritic material is below the coal seam, pipes or ditch linings may be used to prevent formation of acid waters. Pipe materials that are typically used in mining operations include PVC, fiber-wound, and other similar materials. These materials are selected for their lightweight, corrosion resistance, and ease of installation.

Pumps

Electrically driven centrifugal pumps are typically used in underground mines. The pumps may be single or multiple stage submerged or unsubmerged. The number of stages in a pump is a function of the amount of head that the pump must supply and the space available for installation. The selection of submerged versus unsubmerged pumps is also a function of space. Often a submerged pump is used at a sump to prime an unsubmerged pump. The best way to select the proper pump for your situation is to define network, head and discharge requirements and characteristics and call several pump manufacturers to examine the information and specify a pump. More disccussion on the types of information to assemble and how to assemble it are discussed later in this chapter.

Boreholes

Discharge of water from the mine can be accomplished in several ways. The most common way is by pumping the water through a pipe located in the entrance shaft or slope. A second method that is often considered is pumping the water through a borehole directly above the main sump. When used this method can sometimes save costs by reducing the length of pipe and lowering the head required.

Some mines that are located in seams over old working have used boreholes to drain water from the active mine into the old workings below by gravity. The old working may hold the water, discharge at a controlled location, or act as a sump and be pumped. It should be kept in mind that the Federal Regulations issued under the Surface Mining Control and Reclamation Act prohibit such discharge to inactive mines unless the miner can demonstrate that the environment will be protected, safety is maintained and MSHA regulations are met.

DESIGN AND OPERATION CONSIDERATIONS

Water handling network components must be planned as an integral part of an overall system. Each component is dependent upon other components and should be designed and selected as such. The following sections present information that should be considered when designing a water handling network for a mine that will effectively remove excess water that may limit production and will minimize the formation of acid waters.

Sump Design and Operation

Location of Sumps

One of the most important aspects of water handling network layouts is the location of sumps. Pumping water uses electricity and thus economics enters into the location of sumps. Collection sumps must, of course, be located at the mine face and at other water sources and transfer sumps must be located where pumping heads from the collection sump pumps become limited. This leaves the designer with the location of the main sumps.

Main sumps may handle large volumes of water and should be logically located where they can be most efficient. In many cases the main sump may be moved during development of the mine to avoid excess energy consumption. The following considerations should be used when selecting sump locations:

- Locate sumps as close as possible to the major source(s) of water.
- Locate sumps in convenient sites that are out of the way of active mining but that are accessible for maintenance.
- Collect water at the highest point practicable to minimizing pumping head.
- Try to locate transfer sumps so that they can handle water from more than one collection sump.

Sump Sizing

Sumps should be sized for two primary reasons: collection of water over a period of time and retention of sediment. Proper sizing ensures sumps that reduce pump wear and may also be used so that pumps can be operated during off peak electrical use. To retain sediment, sumps should be sized to detain sediment laden waters long enough to remove some of the suspended solids that can result in excessive pump and pipe wear. Another factor to keep in mind when sizing sumps is whether or not the sump in question will be critical to production or safety during pump breakdown or power failure. Such may be the case especially for main sumps in mines with high inflow rates.

Collection sumps and transfer sumps can often be sized using the following rule of thumb: sump capacity draw-down should be equal to at least 15 minutes times the rated pump capacity in gpm. "Capacity draw-down" is the volume contained between the high level and low level pump stops within a sump equipped with flat arrangements. The pump should be selected based on head and flow requirements as discussed later. This rule of thumb assures that a pump in a collection or transfer sump will operate continuously for 15 minutes plus the time required to pump inflow that occurred during operation (usually very little) and then shut off until the sump refills. Quite often construction of one of these sumps, particularly collection sumps involves the sumping in of the continuous miner into the rib and material below.

Sizing of main sumps is typically much more involved than for collection or transfer sumps. This is primarily because of the cost of the high head/flow pumps that are often required for pumping water out of the mine. The sump should be designed to minimize pump wear and to prevent overheating caused by too continuous operation and/or inadequate cooling time between shutdown and start-up. Some good design considerations to follow when sizing main sumps were examined by Karassik, et. al., in Pump Handbook and are summarized as follows:

1. Attempt to get a complete analysis of the water (from another portion of the mine or from an adjacent mine if necessary).

2. Analyze the sample for corrosive properties to determine the proper materials of construction for the pump.

3. Analyze the sample for possible scale buildup in the pipeline and pumps. Check the velocity effect, if any, on the buildup rate.

4. Examine the sample for percentage of suspended solids, the screen analysis and the settling rate for various fractions. Determine the sump dimensions for removal of all solids and then for progressively larger solids in order to select the most economical size.

5. Compare the sump size above with the size required for physical storage capacity for: (a) continuous pumping, (b) off-peak power pumping, (c) programmed pumping, and (d) storage for estimated maximum length of power interruption.

6. Calculate practical sump dimensions, considering the geologic conditions.

7. Consider methods for cleaning the sump. Compare mechanical cleaning methods with cost of parallel sumps.

8. Install grit traps ahead of the sump to remove large, heavy solids. Consider methods for cleaning the grit traps.

9. Install trash screens to prevent wooden wedges, etc., from entering the sump.

10. Review sump-cleaning methods and program. The best designed sump is of no value if it is not cleaned.

11. Review the suction requirements of the pumps to be used.

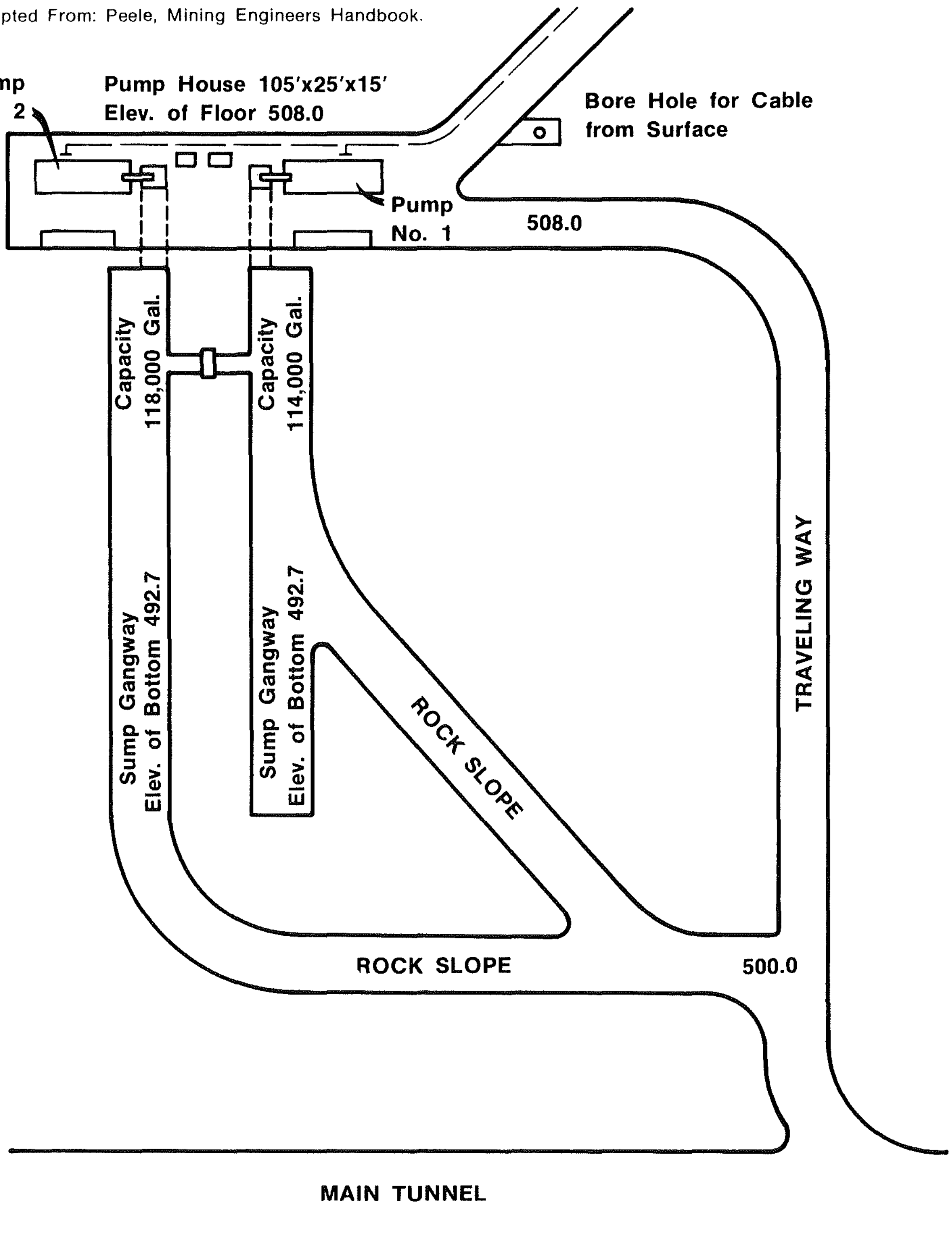
12. Determine the final design based on a compromise between the mine engineer (who wants maximum output), the electrical engineer (who wants small starting load), the geologist (who wants small sump dimensions), and the mechanical engineer (who wants the most reliable and easily maintained equipment).

An example of a well designed main sump is that which was used at an anthracite underground mine which was examined in Peele (See Figure 8). Two 2,000 gpm centrifugal pumps were installed, one for each of two sump rooms. The two sumps were connected to maintain equal water level in both. Pump operation was set up by float arrangement such that pump #1 would operate with pump #2 starting only when pump #1 could not handle the flow. The sumps were driven down rock slopes below the coal seam. This technique effectively prevents standing water from coming in contact with pyritic material. Cleaning of either sump was accomplished by closing the connecting tunnel and diverting further inflow to the other sump.

<u>Using Dams for Sumps</u>

An alternative to using sumps cut into the material beneath the seam is to construct a dam that will impound water in worked out areas.

Adapted From: Peele, Mining Engineers Handbook.



EXAMPLE OF A MAIN SUMP/PUMP CONFIGURATION

FIGURE 8

Two important things to remember when utilizing this technique for sumps are:

- The dam must be able to safely hold the maximum possible water head without failure.

- If there are any soft or highly pervious materials adjacent to a dam, the material should be cut back to ensure stability or another location should be used.

Just as in surface water impounding structures, there are a variety of types of dams that can be used in underground mines. Dams can be constructed of concrete, block, steel, or timbers with clay cores although timber dams should only be used for temporary low head structures. When the side material is of high stability, arch dams can be used and will require less material because much of the resisting force provided by the adjacent material. Straight or flat dams are easier to construct and are safer in less stable material. The required thickness of a flat dam is computed by examining a one inch wide portion of the dam using the following equation:

Where:

t = Thickness of dam in inches

W = Total load in pounds/square inch

L = Length of dam in inches

b = Breadth of unit being investigated in inches (1 inch)

s = Allowable unit stress in extreme fibers in pounds/square inch (for standard concrete an s of 50 psi takes into account a factor of safety equal to 8)

As an example, assume that a dam is to be constructed of standard concrete 5 feet high and 12 feet wide. Compute the required thickness.

1. The dam must hold 5 feet of water pressure therefore:

$$w = \frac{(5\ ft)(62.4\ lbs/ft^3)}{144\ in^2/ft^2} = 2.2\ psi \quad t = \frac{w\,L^2}{2bs}$$

2. Length = 12 feet = 144 inches
   breadth = 1 inch
   strength = 50 psi

   therefore:

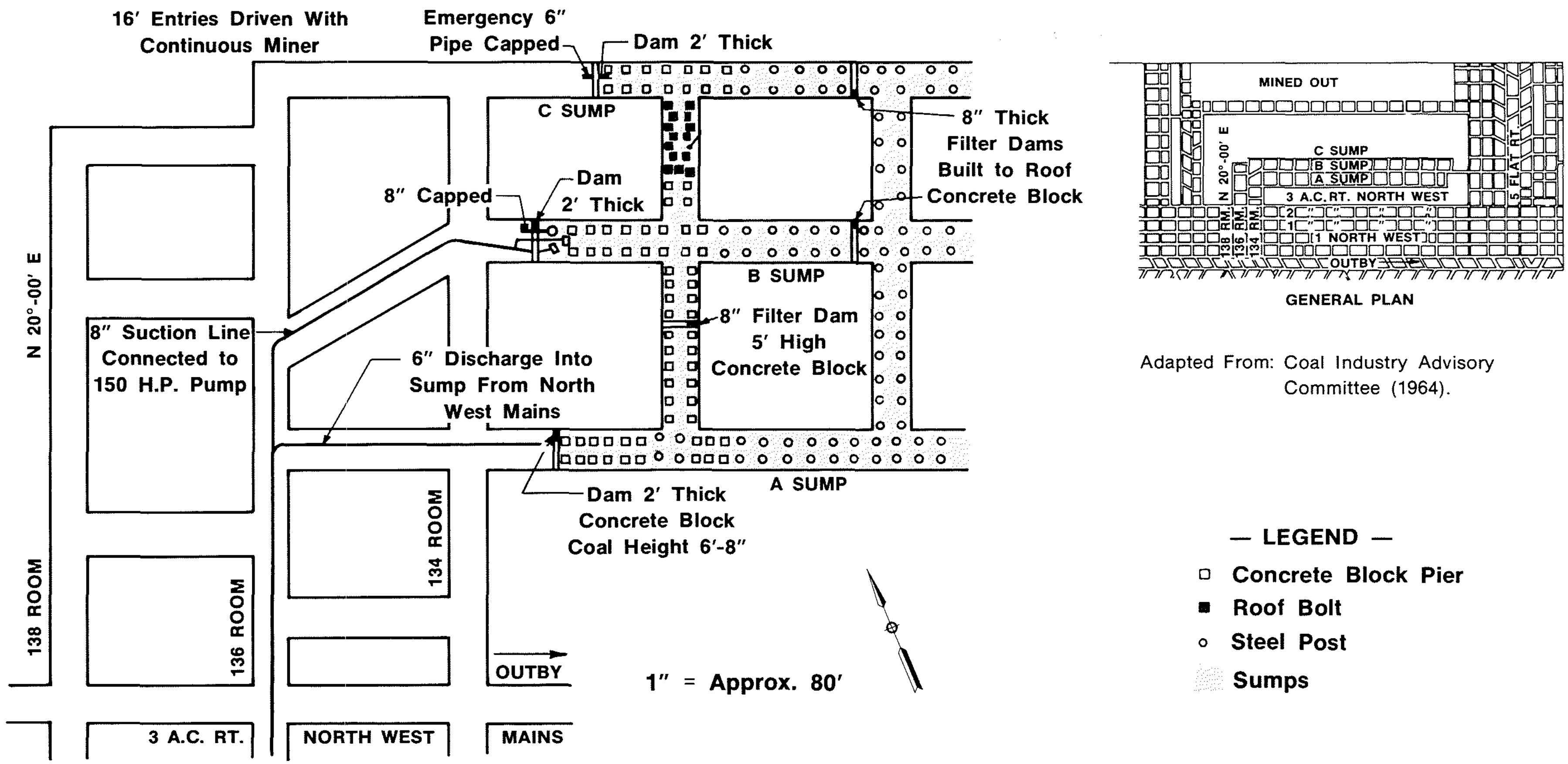
$$t = \frac{2.2\ (144)^2}{2\ (1)(50)} = 21\ \text{inches}$$

When attempting to use dams to form sumps, keep in mind that MSHA and the state agencies regulate such activities closely because of the potential life hazard present. An example to a mine that has used dams for sump construction is shown in Figure 9. In this case the entries were driven specifically for sumps and provide some AMD prevention.

Minimizing Pollution with Sumps

Sumps that are properly designed and constructed will help to minimize the potential pollution of waters receiving mine discharge. Because sumps are usually designed to remove some suspended solids they will have a positive impact on this contaminant. Sumps can also have a positive effect on fuels and lubricants, also identified as a potential pollutant. Most of these pollutants float on water and pump intakes continually remain under the surface resulting in trapping of the pollutants.

Another important factor in using sumps to minimize pollution is to take care either to not construct sumps in pyritic material or to mitigate the acid formation if other sump locations are not possible. One way of preventing AMD if the sump is in a pyritic material is to line the sump



UTILIZATION OF DRIVEN ENTRIES AND DAMS FOR SUMPS

FIGURE 9

with an impervious liner such as rubber or clay. A liner should be compared to the cost of treating the AMD either at the surface or in the sump itself. In many cases liners will be impractical because of the temporary nature of many sumps. Treatment methods are discussed in the next chapter.

If good quality water is entering the mine through the roof, it might be practical to rig a system of metal, plastic or cloth sheets from the roof which would direct the water directly to a lined ditch or sump. The water could then be pumped to the surface and discharged without the need for treatment.

Sump Maintenance

Sump maintenance is very important to the efficient operation of a water handling system. Poorly maintained sumps may cause undue damage to pumps and pipes and reduce the quality of mine discharge. The settling and floatation functions of a sump must be remembered during active mining and the proper steps should be taken to assure that settled solids and floating liquids and debris are removed and properly disposed of. This can be best accomplished through a scheduled maintenance plan (i.e., sumps are checked for sediment etc. on a set schedule and have sediment removed when necessary).

A routine maintenance schedule is particularly important if sumps are used for AMD treatment. This technique is usually only used in mines where mine drainage is highly acidic and would be very corrosive to pumps and pipes. These sumps should be examined at least daily or every shift to assure proper treatment occurs and precipitated sludges are removed when the sump volume begins to be altered. Sludges and sediment should be removed before it reaches pump intakes.

Pipe/Ditch Design and Operation

Pipes and ditches are used to convey water through a mine - ditches by gravity flow and pipes by either gravity or pressure flow. The principles of gravity flow and other information on materials and maintenance are discussed in this section. The proceeding section on pump design discusses pressure flow.

Computations of Gravity Flow

When designing a ditch or pipe for gravity flow in a mine, the primary concern is to assure that the ditch or pipe has sufficient capacity to carry the maximum expected flow. Flow capacity and velocity in gravity flow situations is usually calculated using the Manning Equation:

$$Q = \frac{1.49}{n} AR^{.67} S^{.5}$$

$$\text{or } V = \frac{1.49}{n} R^{.67} S^{5}$$

Where:

Q = Flow in cubic feet/second

V = Velocity in feet/second

n = Manning's roughness coefficient (See Table 1)

A = Cross sectional area in square feet

R = Hydraulic radius (area divided by wetted perimeter) in feet

S = Slope of the hydraulic grade line which is approximated by the ditch on pipe slope in feet/foot

TABLE 1

SUMMARY OF MANNING'S ROUGHNESS COEFFICIENT (n)

Channel Material	n
Plastic pipe	0.009
Smooth cement or metal	0.010
Planed timber, asbestos pipe	0.011
Wrought iron, welded steel	0.012
Ordinary concrete, asphalted cast iron	0.013
Unplaned timber, vitrified clay	0.014
Cast-iron pipe	0.015
Corrugated metal pipe	0.022
Natural channels in good condition	0.025
Very poor natural channels	0.060

Designers should compute the capacity of the pipe or ditch selected and compare the full capacity with the expected flow to assure that the flow can be carried. As an example, assume that a "V" shaped ditch cut in rock is one foot deep with 2h:1v side slopes on a 1% grade and is to carry an expected flow of 2,000 gpm. Is the ditch satisfactory?

$n = 0.025$

$A = 1/2\ [(4)(1)]\ (1) = 2$ ft.

$$R = \frac{A}{P} = \frac{2\ \text{ft.}^2}{2\ (\quad (1)^2 + (2)^2)} = 0.45\ \text{ft.}$$

$S = 0.02$ ft./ft.

$$Q = \frac{1.49}{0.025} (2) (0.45)^{.67} (0.01)^{.5} = 7.0 cfs = 3,100 gpm$$

Ditch is satisfactory.

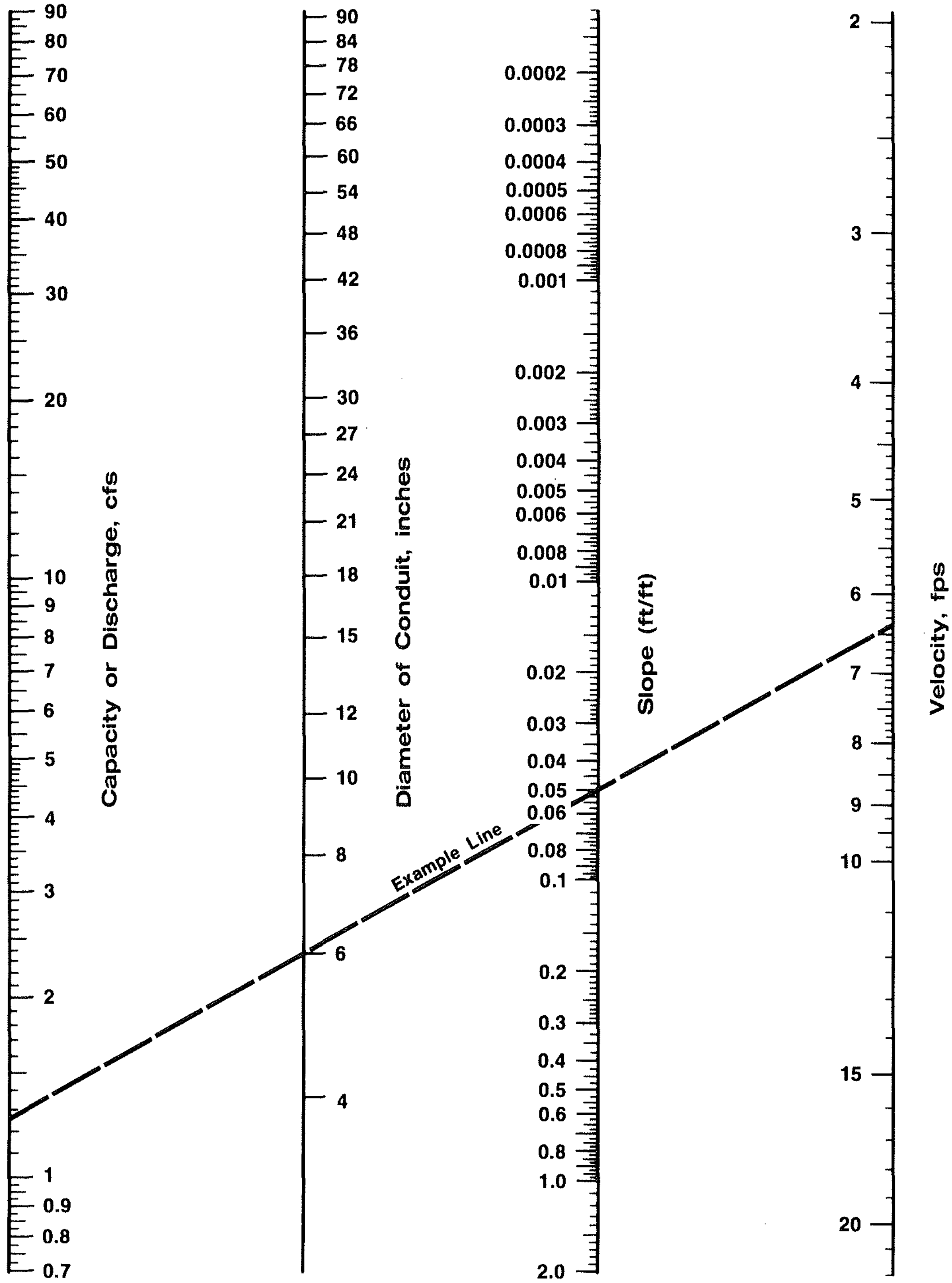
Manning's Equation for circular pipes flowing full is represented by the nomograph in Figure 10. Note that the nomograph is for pipes with an n=0.013, for flow values when n≠0.013 multiply the flow by 0.013/n. For example, if the above problem had a 1 foot PVC pipe (n = 0.009) instead of a ditch:

Q = 3.6 cfs (from nomograph)

$$Q = 3.6 cfs \frac{0.013}{0.009} = 5.2 cfs = 2,300 gpm$$

Pipe is satisfactory.

Because mine flows are usually very stable and do not fluctuate, and because ditches and pipes are sized to carry these flows at a full or near full capacity, maintaining a velocity of flow for scour of sediment is not usually a problem. However, if there is a great fluctuation of flow, the designer should check to be sure that scour velocities are maintained. Typically, if velocities exceed 2 feet/second there will not be a problem. To check velocity of flow during lower flows, use the equation (not the nomograph as it is for full flow only) to find the depth of flow by trial and error. Then compute the velocity of flow and check versus 2 feet/second minimum. If the velocity does not exceed the minimum, try altering channel/pipe size or slope or be sure that sumps are good clarifiers.



Example for using Nomograph - based on n=0.013. A 6" dia. conduit has a slope of 5%. Place a straight edge from the 6" dia. point to the 5% point. Continuing this straight line you can then determine the loss of head and velocity. In a like manner with any two values the other values can be determined.

NOMOGRAPH FOR MANNING FORMULA, FOR CIRCULAR PIPES FLOWING FULL BASED ON n = 0.013, GRAVITY FLOW

FIGURE 10

Materials

Ditches are usually cut in the underlying rock material with mine equipment or can be constructed along the top of the floor as a wood or other material flume. The flume technique is much more practical for the prevention of AMD. However, flumes and sometimes cut ditches are more difficult to erect than pipes. For this reason, pipes are the primary type of transport mode for water in mines.

An additional factor in the selection of pipes is their use for pressure flow conduits. The most common materials used for mine pipes are PVC and fiberglass. These two materials are lightweight, easy to install, non-corrosive, and relatively long lasting. If exceptional long life is required for a particular case, aluminum pipe may be used; however, aluminum can be quite costly.

Valves and Supports

Whenever the flow in a pipeline is changed, the resulting change of velocity causes a surge. The common causes of pipeline surges are:

1. Closing or opening a valve
2. Starting and stopping a pump
3. Movement of air pockets in pipeline

Most pipelines are designed and operated to minimize surges from valves and pumps. Many times, however, due consideration is not directed to the potential for accumulation and resulting movements of air pockets within a pipeline. The seriousness of entrapped air is generally not realized. When an air pocket suddenly dislodges, the change in fluid velocity and the subsequent pressure are much more than for most other sources of surge (pressures of several hundred psi). It is therefore essential to control the formation of air pockets in pipelines.

Air valves which permit the escape of air on filling, and entrance of air on emptying, are placed at every summit and at shut off valves because air collects at all summits and must be removed. Blow-off valves are placed at low points in pipelines for emptying the pipe when necessary and for removal of sediment. These blow-off valves usually consist of gate valves placed on a waste pipe leading to a discharge in a stream or channel. A waste pipe, 1/3 the diameter of the pipeline, is usually sufficient. Shut-off or gate valves are placed at the end of a pipeline, and, in long pipelines, at intervals of 1 to 2 miles. This practice allows for inspection and repair of any section, without draining the entire line. These valves are usually placed at summits with an air valve on each side. The cost of gate valves increases rapidly with the size; a savings in cost at a slight loss in head usually can be obtained by decreasing the diameter of pipe at valve locations by using suitable reducers and tapers.

Check valves are utilized on pump lines at points where a large backward flow of water would occur on pump shut-down. The use of non-slam or slow closing check valves are recommended to reduce water hamper.

Pipe supports are needed when pipe is placed above ground (as around a pump). Distance between supports is roughly estimated by considering the pipe as a continuous beam, loaded with its own weight plus the weight of water, and using a low-fiber stress. Anchorages are necessary for exposed pipe at all bends where the resultant pressure may throw it out of line, at valves subjected to heavy static or water hammer pressures, and on steep slopes.

Maintenance of Pipes and Ditches

Just as with sumps it is very important to maintain pipes and ditches, primarily from sediment or scaling that may occur. Ditches can be cleaned by digging the material, but pipe maintenance is not so easy.

Pipe cleaning is usually done by forcing a "pig" (an object the same size as the inside diameter of the pipe) through the pipe to scrape off scale and push out sediment. Gravity flow pipes must be disconnected and cleaned in one or several lengths while pressure flow pipes may be able to force the pig through by pressure. This maintenance should be conducted on a set schedule depending on the quality of water and system characteristics.

Pump Design and Operation

The work horse of a mine water handling system is the pump. Most pumps used in mine applications are centrifugal pumps - meaning that they have an impeller that allows water to enter at its center and by rotation uses its veins to impart centrifugal force to the water. A centrifugal pump can be either submerged or non-submerged which simply is a descriptor that indicates if the pump is located above or below the water surface. The following sections discuss the location, operation, selection, specifications, and operating costs of handling system pumps.

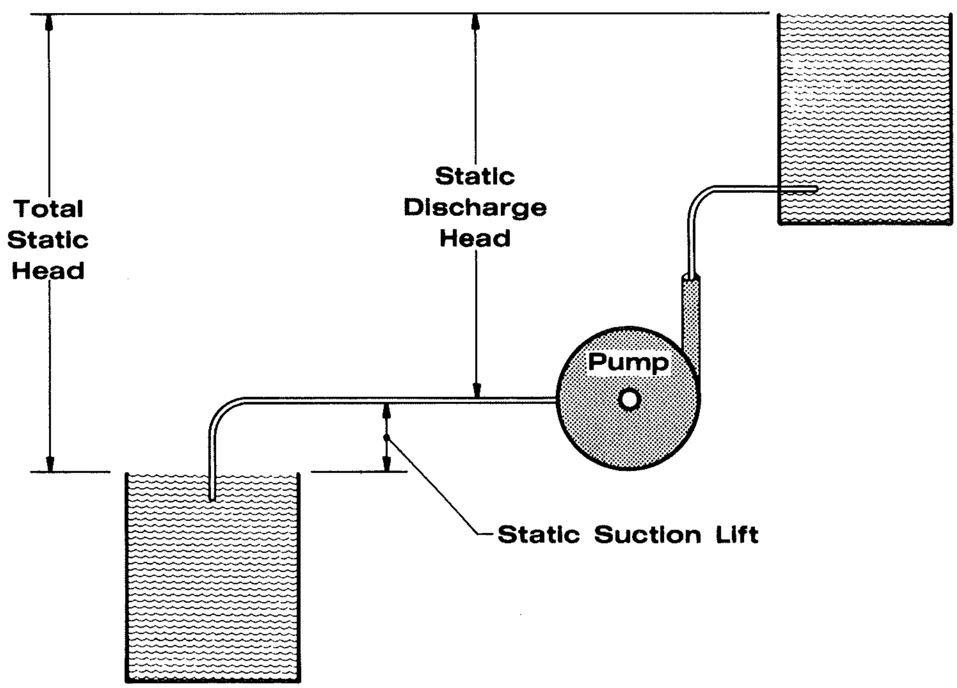
Pump Arrangement

Submerged pumps are located beneath the water surface and are typically lower head and flow pumps. The advantage to a submerged pump is that they can be easily primed just by starting the pump and will usually remain primed once submerged. Priming is an operation used to fill the pump with water and remove air that would keep the pump from operating. Submerged pumps are also often used to prime non-submerged pumps that are located above the water surface.

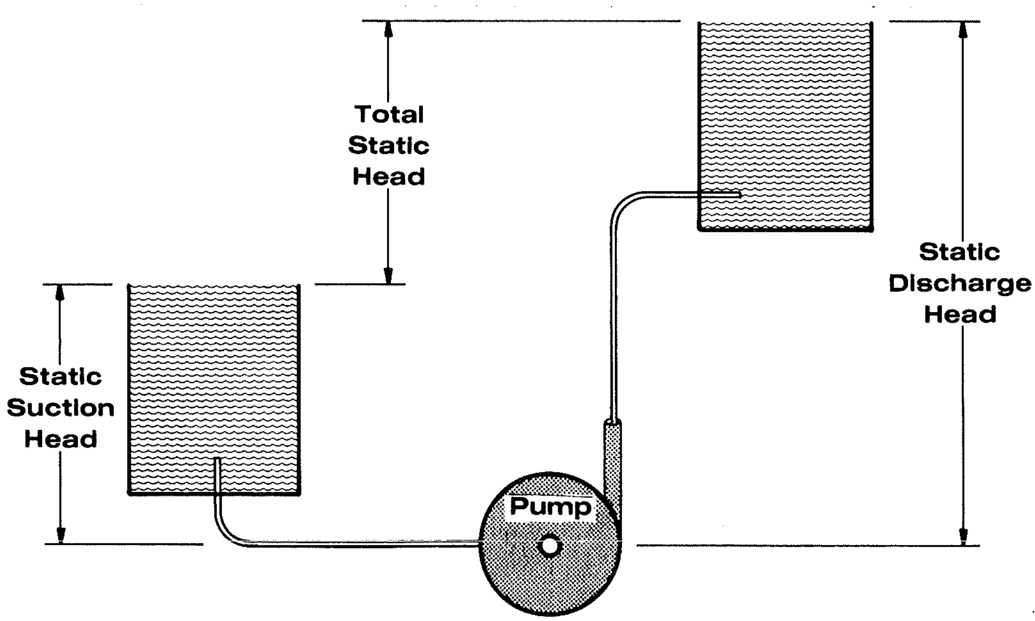
Acting in a like manner as submerged pumps are non-submerged pumps that are located below the water surface, but are not in the water. These pumps as well as sub-merged pumps operate with a suction head - meaning that the suction side of the pump has a positive pressure because of the water body. Pumps located above the water surface operate with a suction lift - meaning that the water on the intake side of the pump has a negative pressure and must be drawn to the pump by suction.

Figure 11 illustrates the two types of pump arrangement and the concept of static head. Total static head is the difference in elevation between the water level in the sump and the discharge elevation while static discharge head is the difference in elevation between the pump center line and the discharge. Pump above the water surface must create static suction lift while submerged pumps has a built in static suction head.

Both types of pumps do have their avantages. As mentioned before submerged pumps are easy to prime. Non-submerged pumps are typically used



PUMPING SYSTEM WITH STATIC SUCTION LIFT



PUMPING SYSTEM WITH STATIC SUCTION HEAD

PUMPING SYSTEM VARIATIONS

FIGURE 11

for higher heads and flows and are usually easier to reach for maintenance. In mine operations submerged pumps are usually used in collection and transfer sumps while non-submerged are used for main sumps where high head conditions typically exist.

System Head Curves

Once a flowrate has been determined and the sump and pipe network has been identified, a particular pump can be selected using a system head curve. A system head curve is a graphical plot of the total dynamic head (TDH) that must be applied to a system to overcome static, pressure, and friction heads versus flow rate. Static head was discussed in the last section - it is a constant value for all flow rates. Pressure head applies when pumping to or from closed tanks that contain water at pressure other than atmospheric (this value usually does not apply to mining situations). Friction head is the amount of head that must be applied to overcome losses due to friction in the system - this value is a function of flow rate, fluid density, pipe size, and pipe material.

The basis behind the development of system head surves is the Bernoulli Equation which uses the conservation of energy principle:

$$\text{Velocity Head}_1 + \text{Pressure Head}_1 + \text{Elevation}_1 + \text{Pumping Head} = \text{Velocity Head}_2 + \text{Pressure Head}_2 + \text{Elevation}_2 + \text{Friction Head Losses}$$

In mine applications the velocity head and pressure head are the same at points one and two; therefore, the equation becomes:

Pumping Head (TDH) = $\text{Elevation}_2 - \text{Elevation}_1$ + Friction Loss (H)

The difference in elevation is static head (H_s)

therefore:

$$TDH = H_s + H_f$$

where:

TDH = total dynamic head or pumping head (feet)

H_s = static head or elevation the water must be lifted (feet)

H_f = friction head loss (feet)

Friction head losses in pipes under pressure can be computed using the Hazen-Williams Equation:

$$Q = 1.318\ CAR^{0.63} H_f^{0.54}$$

where:

Q = flow rate in cfs

C = Hazen-Williams coefficient (140 for PVC and fiberglass pipe, 100 for cast iron and concrete, and 130 for aluminum)

A = cross sectional area of pipe in square feet

R = hydraulic radius (area divided by circumference) in feet

H_f = hydraulic grade line or friction head loss in feet/foot

Friction head loss is often expressed in terms of feet of loss per 1,000 feet of pipe and flow in terms of gallons per minute, to solve for H_f the Hazen-Williams Equation can be written:

$$H_f = \left(\frac{8.17\ Q}{CAR^{0.63}}\right)^{1.85}$$

H_f in feet/1,000 feet

Q in gpm

A in feet^2

R in feet

The Hazen-Williams Equation is also represented in nomograph form by Figure 12. Note that this nomograph is for C=100. For other values of C multiply the resulting value of H_f from the nomograph by the following multiplier:

C	Multiply By
140	0.537
130	0.616
120	0.714
110	0.838
90	1.22
80	1.51
70	1.93
60	2.57

To construct a system head curve, follow the following steps:

1. Compute the static head by taking the difference in elevation of the intake water surface and discharge.

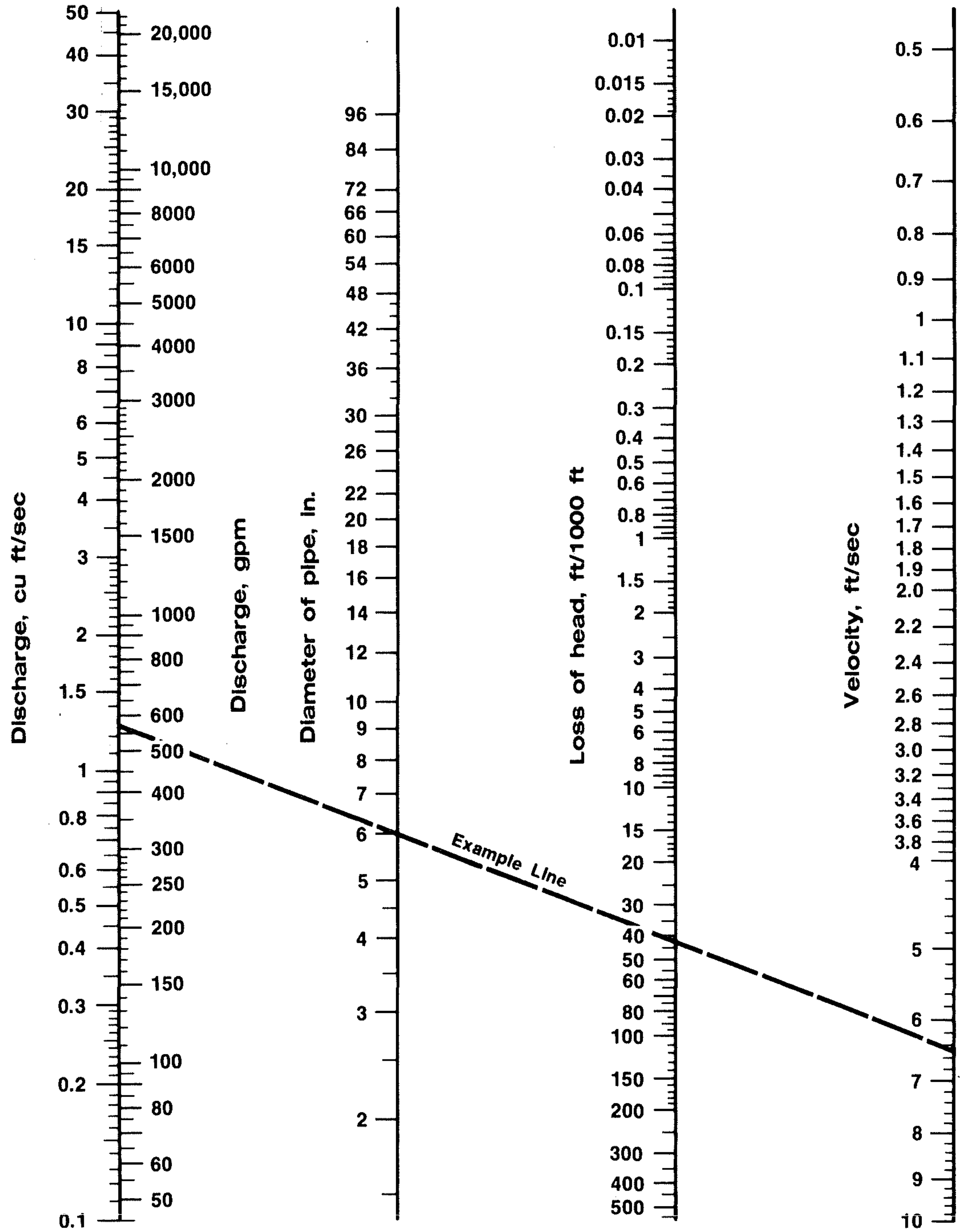
2. Determine the equivalent length of pipe by converting all valves, elbows, etc., into a pipe length based on Figure 11 and then adding this to the actual length of pipe.

3. Compute the friction head loss in feet/1,000 feet of pipe as a function of roughness, pipe size, and flow.

4. Compute friction head by multiplying Hf times the equivalent length of pipe.

5. Compute total dynamic head equal to the friction head plus the static head.

6. Repeat steps 3, 4, and 5 for a variety of flows to compute the system head curve.

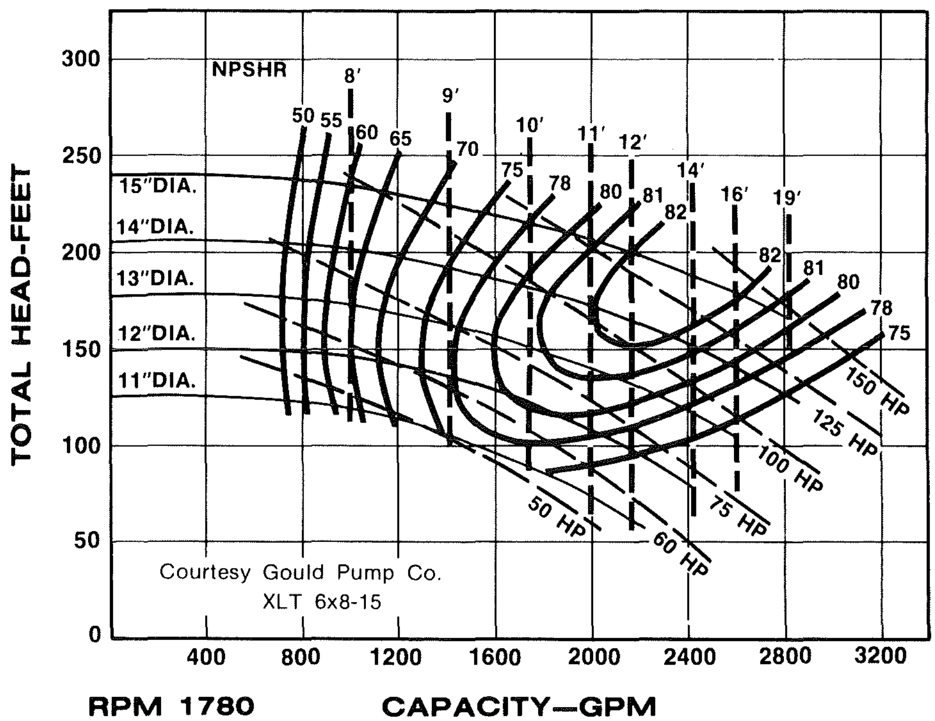


Example for using Nomograph - based on C=100. A 6" dia. pipe and 1000 ft. long is to carry 1.3 cu. ft./sec. Place a straight edge from 6" dia. point to 1.3 cu. ft./sec. point. Continuing this straight line you can then determine the velocity and discharge. In a like manner with any two values the other values can be determined.

NOMOGRAPH FOR HAZEN-WILLIAMS FORMULA, FOR CIRCULAR PIPES FLOWING FULL BASED ON C = 100, PRESSURE FLOW

FIGURE 12

With the system head curve constructed, a pump can be selected by superimposing pump curves over the system head curve, and the proper pump will have a pump head curve that intersects the system head curve at the specified flow rate. This assures that the pump and system will operate at utmost efficiency. A series of pump curves for a given pump with different drivers (various horsepower) is represented in Figure 13. Each different pump will have a series of curves such as this.



SAMPLE PUMP CURVES

FIGURE 13

For example, consider a system with a sump elevation of 450 feet and a discharge elevation of 598 feet. The desired flow rate is 2,000 gpm, and the system consists of 3,000 feet of 12 inch PVC pipe with (1) gate valve, (1) check valve, (3) 90° elbows, and (2) 45° elbows. Determine system head curve. (The equivalent lengths of valves and fitting is shown in Figure 14.)

1. Static Head

H_s = Elevation discharge - elevation sump
= 598 - 450
= 148 feet

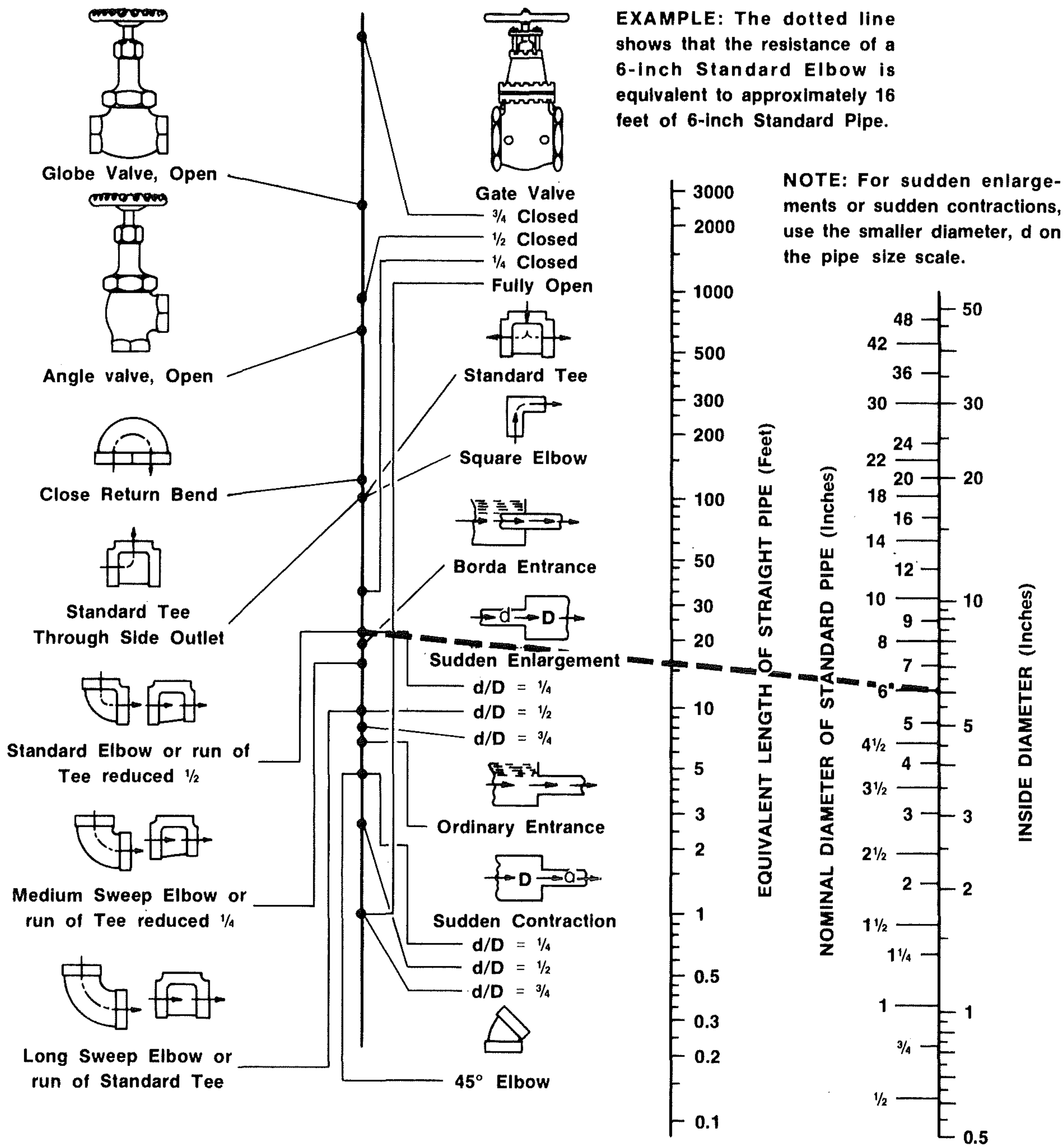
2. Equivalent Length of Pipe

Description	Equivalent Length (ft)
3,000' pipe	3,000.0
(1) check valve (open) (use 1/2 closed gate)	180.0
(1) gate valve (open)	8.0
(3) 90° elbows at 32.0	96.0
(2) 45° elbows at 15.0	30.0
entrance (Bordo)	30.0
exit (use entrance)	30.0
	3,374.0 ft

3, 4, and 5 - Set up table for computation

Flow (gpm)	H_s (feet)	H_s (feet/ 1,000 ft)*	H_f (feet)	TDH (feet)
0	148	0	0	148.0
500	148	0.64	2.2	150.2
1,000	148	2.3	7.6	155.6
1,500	148	4.6	15.	163.0
2,000	148	7.8	26.	174.0
2,500	148	12.	41.	189.0
3,000	148	16.	54.	202.0

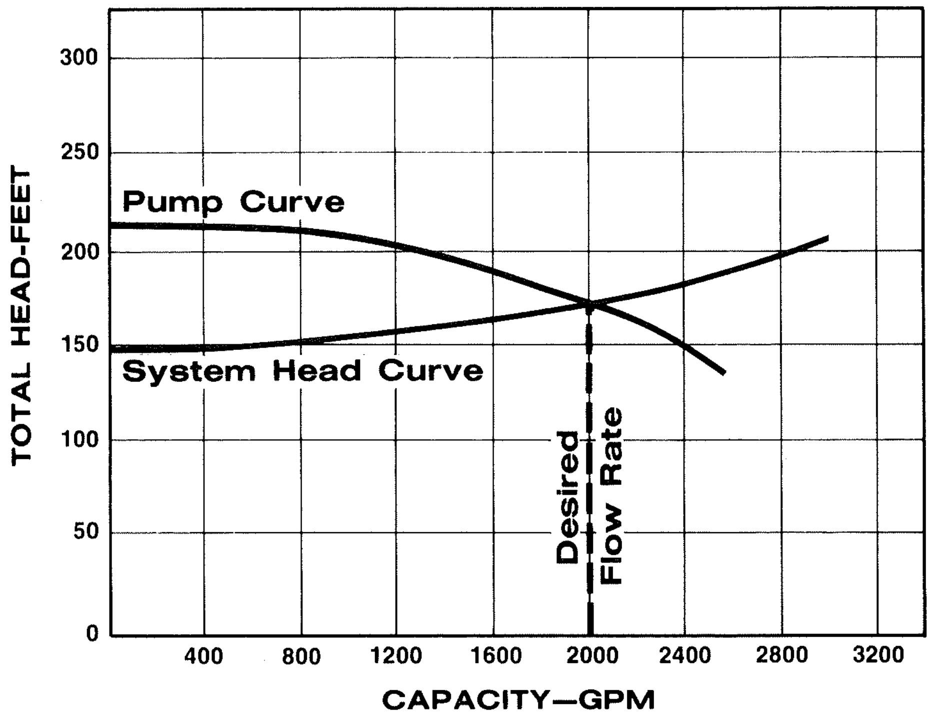
*From nomograph (Figure 12) and multiplied by 0.537 to correct for C = 140.



EQUIVALENT LENGTH OF PIPES FOR VALVES AND FITTINGS

FIGURE 14

The system head curve represented by the TDH in this table is plotted in Figure 15, which also shows how the proper pump curve should superimpose on the system head curve. It may be most practical to construct a system head curve and then ask manufacturers to recommend a pump.



SYSTEM HEAD CURVE AND PUMP SELECTION

FIGURE 15

Specifications

When contacting a pump manufacturer to recommend a pump for your system, a variety of information is required. The most important of which is the system head curve and desired flow rate. However, other less obvious information may be just as important to receiving an efficient pump that will fit the situation and provide long and dependable service. This other information includes material specifications and pump application. Some of this information may include the following:

- Special requirements for water quality, especially if AMD or high suspended solids are expected. This will limit the material from which the pump can be constructed.
- Type of pump requested or situation in which to be used (i.e., submerged or non-submerged).
- Space requirements in the mine.
- Power limitations, if any exist.

Operation Costs

Operation costs for pumps can sometimes become quite high, and therefore the water handling system designer may want to compute operating costs of several options for network layout for comparison. An operator may also want to estimate the cost of pumping in an installed system. Operating costs can be estimated by the following equation:

$$OC = \frac{0.00315\ (TDH)(\$/KWH)}{e_p\ (e_m)}$$

where:

OC = operations cost (\$/1,000 gallons pumped)

TDH = total dynamic head (feet)

\$/KWH = cost of electricity (\$/kilowatt hour)

e_p = pump efficiency (if unknown, use 0.8)

e_m = motor efficiency (if unknown, use 0.8)

TREATMENT

TREATMENT

The design of the treatment facility is based primarily on the following factors:

1) Drainage flow
2) Concentration of pollutants
3) Neutralizing reagent
4) Reaction formation

The best method for treatment of mine drainage is evaluated on a site specific basis and will depend on the quality of the mine discharge and the ultimate use of the water.

Conventionally, the treatment of AMD has been accomplished by neutralizing the acid water through addition of an alkaline reagent. Regardless of the treatment process, a combination of all of the following stages may be incorporated in the system:

a) Flow equalization
b) Neutralization
c) Iron oxidation
d) Settling
e) Sludge disposal

Variations to the conventional AMD treatment process, such as aeration and sedimentation processes for the removal of excessive concentrations of iron and suspended solids, have been used where neutralization is not required. Other variations include:

1) Ion exchange
2) Reverse osmosis
3) Freezing
4) Flash distillation
5) Electrodialysis
6) Foam separation
7) Submerged coal refuse combustion
8) Neutradesulfation

The following is a review of the various stages of the treatment process.

FLOW EQUALIZATION

Surface holding ponds or underground sumps are frequently utilized as flow equalization structures. These structures are normally designed to provide one or more days storage capacity for the acid drainage if the treatment facility is inoperative. A constant head for gravity flow through the treatment facility may also be provided by the equalization structure. If discharge from the mine varies greatly with rainfall, holding ponds should be designed for the 10 year 24 hour storm. Federal regulations do not require that runoff from storms greater than this meet water quality standards.

NEUTRALIZATION

The neutralization or mixing process involves the addition of alkaline material to the acid water to neutralize the acid and to precipitate the contaminating metal salts, and removal of the precipitate by filtration and/or sedimentation. Treatment normally requires rapid mixing when adding the neutralization agent to the raw water for uniform dispersion of the agent which may be in a liquid or solid form. The design of the mixing devices, speed, and horsepower requirements depend upon the type of reagent used and the specific application.

The selection of the neutralization reagent for the treatment process is a vital segment of the treatment process and the particular reagent selected tends to dictate the overall process utilized.

Several alkaline materials are available for the treatment of AMD including hydrated lime, limestone, caustic soda and soda ash. Prior to selection, an evaluation of the various alkakis must be conducted and factors such as cost, reactivity, availability, volume of sludge produced, ease of handling and water quality effluent required must be considered.

Bench-scale testing should be conducted on raw water samples using various neutralization agents. Determination of reaction time, settling rate, clarity of supernatant, volume and density of the sludge should be completed. The tests should be performed on samples containing the maximum ferrous iron concentration and at the lowest anticipated operating pH, the desired pH and at several other pH reference points for comparison of results. Additional chemical parameters which should be measured on raw water samples include pH, acidity, iron (total, ferrous and ferric), aluminum and sulfate.

Bench-scale laboratory test results yield information valuable in designing the various unit process stages and the overall treatment facility. After the bench-scale tests have been conducted and the criteria for reagent selection have been determined, the most appropriate neutralization agent may be selected.

Types of mixers used in AMD treatment facilities are categorized according to the flow pattern they produce, such as axial or radial patterns. Propellers, axial turbines, fan turbines, and pitched paddles are examples of mixers inducing axial flow. Radial flow impellers (certain turbines and paddles) induce currents perpendicular to the drive shaft. The rate at which the neutralizing agent is added is determined from a nomograph using flow and acidity of raw water.

Over 90 percent of all AMD treatment facilities utilize lime or a lime by-product. A cost comparison of several alkalis is presented in the table below.

Agent	Basicity Factor (a)	Cost $/Ton (b)	Cost $/Ton of Basicity
Quick Lime (Calcium Oxide)	1.786	$49.50	$27.72
Hydrated Lime (Calcium Hydroxide)	1.351	$48.00	$35.53
Limestone, Rock (Calcium Carbonate)	1.000	$ 3.80	$ 3.80
Limestone, Dust (Calcium Carbonate)	1.000	$11.50	$11.50

a) Grams of calcium carbonate ($CaCO_3$) equivalent per gram of alkaline agent

b) F.O.B. costs at Philadelphia, Penna., June 1980

These alkakis, in addition to neutralizing acidity, also intensify removal of iron, manganese, and other soluble metals through the formation of their insoluble hydroxides.

AERATION

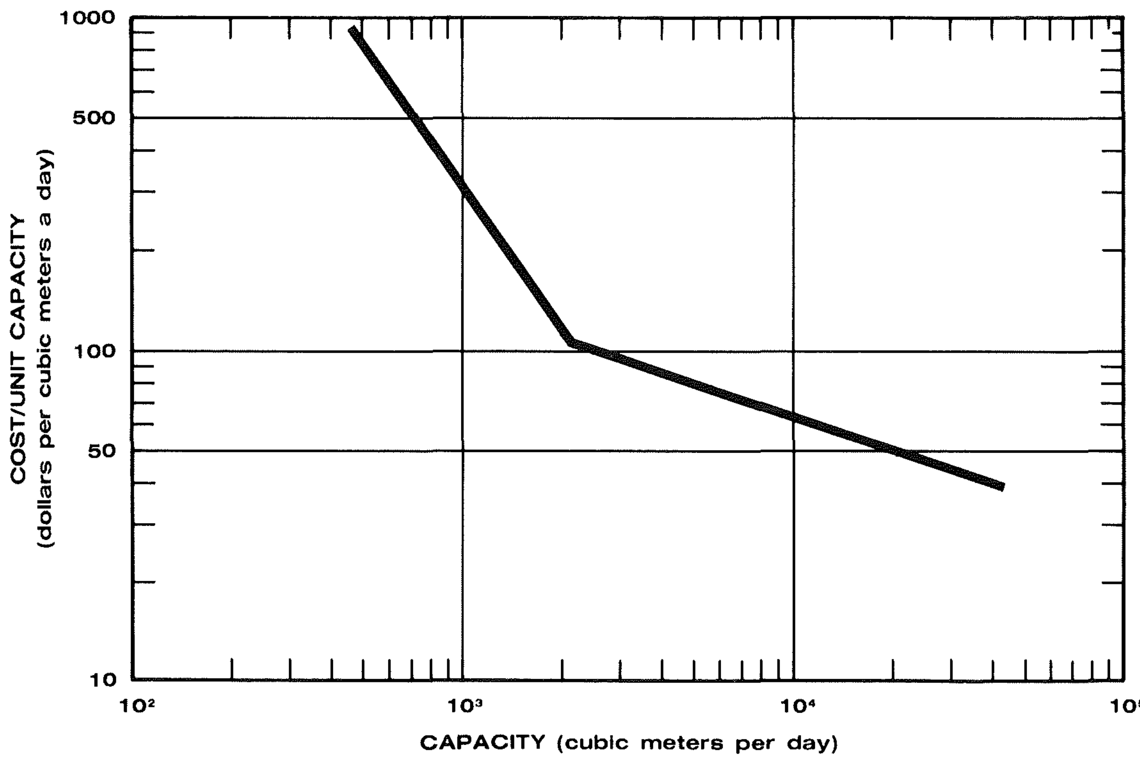
Large quantities of iron may be present in the AMD as a result of pyritic exposure to ambient mine air promoting oxidation to soluble ferrous salts and sulfuric acid. The ferrous iron can be oxidized to the ferric form in the presence of oxygen. The oxidation is pH dependent and is extremely slow (days) at a pH of 3.0, slow in the pH range of 3.0-6.0, and moderate to fast in the pH range of 6.0-8.0 and above. If proper conditions are provided, the oxidation may be accomplished within 15-30 minutes.

Aeration of AMD is accomplished by either natural or mechanical means and chemical or biological oxidation. Regardless of the aeration system utilized the design must be capable of 1) supplying the demand of oxygen for ferrous iron oxidation; and 2) suspending the ferric hydroxide. The process equipment required for the aeration system consists of the aeration basin and mechanical equipment, including blowers, diffusers, and turbines. A guideline for estimating the capital cost as a function of the plant capacity is shown in Figure 16.

SETTLING

The sludge produced as a result of the neutralization process will vary according to the raw water quality and the neutralization process employed. The most desirable end product is a dense sludge which reduces volumetric handling and cost of disposal.

Mechanical clarifiers and earthen settling basins are used for the removal of the suspended solids. Earthen settling basins are most often used because of their initial low capital and operating costs. When



CAPITAL COST vs CAPACITY
CONVENTIONAL NEUTRALIZATION PROCESSES
FIGURE 16

designing these basins, the following criteria must be evaluated.

1) Site location
2) Soil conditions
3) Foundation conditions
4) Embankment construction
5) Volume requirements

The basin design volume may be calculated as:

$V = Qd$

where V = volume of settling basin without sludge storage, gal.

Q = design flow, gal./min.
d = detention time, min.

Sludge storage volume can be predicated as 5-10 percent of the average daily volume treated.

Earthen basins may be classified as either settling ponds or impoundments. Settling ponds are usually small and employed for settling with either frequent or continuous sludge removal. They are usually designed with two day detention time. Impoundments are large ponds designed for both settling and final stage sludge disposal. The detention time for impoundments is normally greater than two days. However, they are usually constructed without regard to detention time and as large as possible.

The storage capacity in a settling basin is dependent upon the frequency of sludge removal. Ponds without removal devices or sludge collectors should provide a minimum of one month sludge storage volume. Settling basins which will have sludge removal devices installed should be designed to allow sufficient volume for sludge storage between withdrawal operations. Only minimal storage capacity is required for ponds which implement continuous sludge removal.

Settling basins are often designed in a series of one or more basins. This provides sufficient storage capacity of the sludge when cleaning and/or sludge removal takes place in the various ponds.

Mechanical clarifiers or thickeners are employed where the area available limits the size of earthen settling bains. As an alternative, they also offer the operator more control over the treatment system and improve sludge densities. There are three basic types of mechanical clarifiers used in existing acid drainage treatment plants: 1) flocculator-separators, 2) conventional clarifiers, and 3) thickeners.

SLUDGE DISPOSAL

The two most frequently used methods of sludge disposal are lagoons and abandoned deep mines. Lagoons designed in either a series or a parallel arrangement offer the most economical method of sludge storage and dewatering where land is available. The basic problem associated with lagooning of sludge is deactivation of the ponds after their storage capacity has been exhausted. Capping lagoons by chemical fixation and spread burial of lagoon contents in surface mining reclamation or coal preparation tailing disposal have been used by the coal industry, but this is sometimes not feasible.

The disposal of sludge in abandoned deep mines is feasible if the iron contained in the sludge is in the ferric state. Ferric iron is soluble at a pH less than 4.0. Therefore, any drainage from the proposed section of mine to be used must have a pH above 4.0, or it will redissolve iron from the sludge. A pH of 7.0 or above is preferred. The sludge removal operation involves removal from the settling basins and injection into boreholes leading into the deep mines. To do this, permitting requirements for the disposal of sludge in abandoned deep mines must be considered and all legal and environmental consequences must be evaluated.

Other methods of sludge disposal include vacuum filtration, pressure filtration, porous bed drying, and centrifugation. Regardless of the sludge disposal method utilized, substantial costs will be incurred; however, the pumping of sludge into abandoned deep mines offers an increasingly more practical and economical method of sludge disposal.

AMD TREATMENT FACILITY - CASE HISTORY

Acid drainage is treated at a west central Pennsylvania mine using a facility which has been in operation since 1973 and which currently handles approximately 50,000 gal./day. The basic plant process stages are:

1) Water collection - surge storage in underground mine sump. Continuous gravity discharge supplemented by manually controlled pumping.

2) Lime neutralization using hydrated lime (95% $Ca(OH)$)

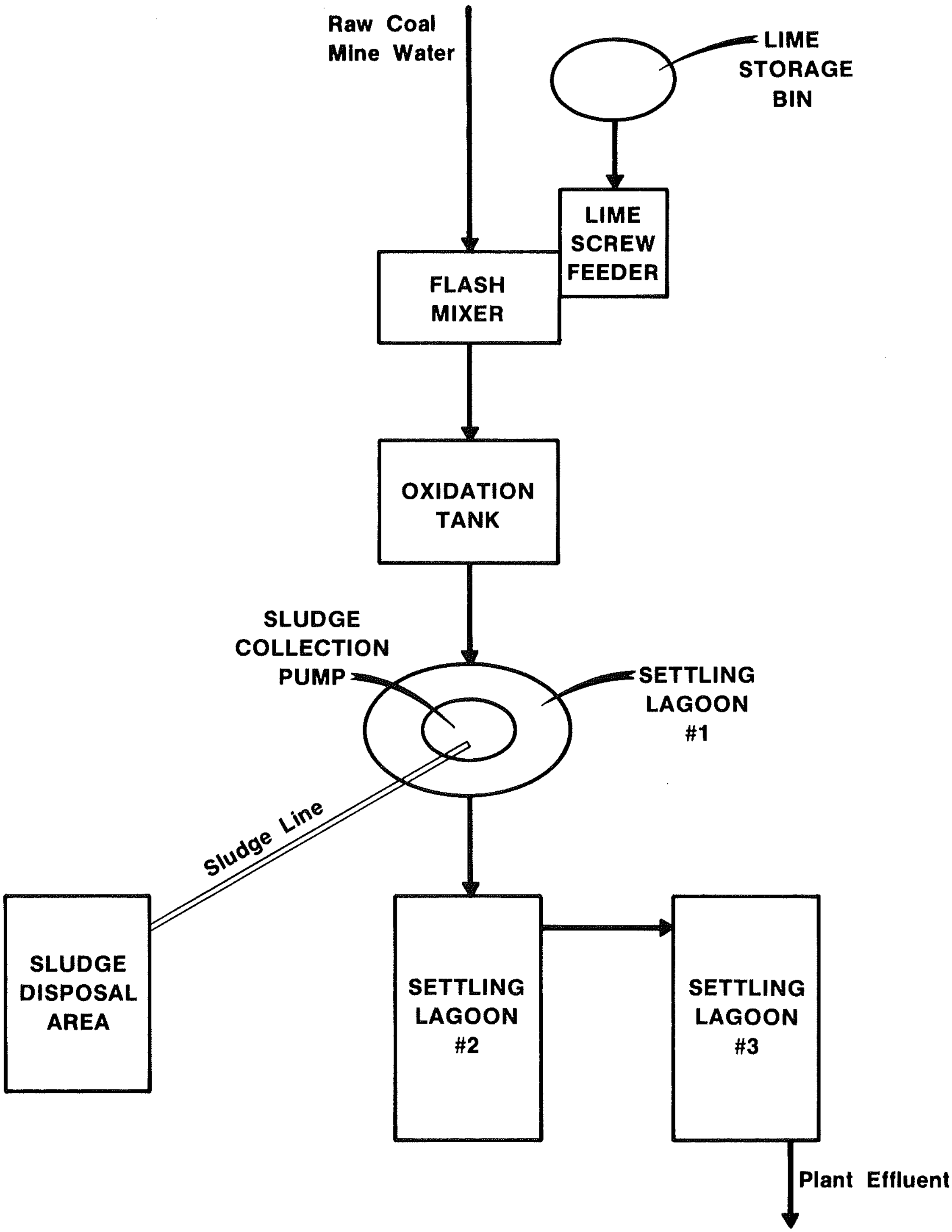
3) Air-oxidation of ferrous iron

4) Solid-fluid separation in settling lagoon of sludge with use of flocculants as necessary.

5) Sludge disposal - pump settled sludge to sludge storage pond (see flow diagram, Figure 17).

Submersible pumps are installed as needed to pump water, which collects in the area of the working face, approximately 1,000 feet to a transfer area. From this point, the water flows by gravity through previously worked out areas to the main sump area close to the portal. A lift pump which is located at the portal controls the drainage from this main sump to the first stage of the treatment facility.

Water from the main sump is directed to a flash mixer where a screw feeder adds the lime. From the mixer, the water flows to the oxidation tank which is capable of transferring 6 lb. oxygen/hour with an average 2 hour retention time. The water is then transferred from the oxidation tank to a series of three settling lagoons which have a total combined storage capacity exceeding 1 million gallons. A submersible pump



FLOW DIAGRAM OF HYDRATED LIME TREATMENT PROCESS FOR ACID MINE DRAINAGE

FIGURE 17

located in pond #1 transfers settled sludge to the sludge storage pond. The treated water flows through two additional ponds and the effluent is discharged into a local stream if established pH and iron requirements have been met.

A comparison of chemical analysis results conducted on various water quality data obtained from 1973 through 1979 are as follows:

	Chemical Parameters		Hot	Total
	pH	Alkalinity	Acidity	Iron
Before Treatment (mean value)	3.02	26.3	428.2	76.1
After Treatment (mean value)	8.90	42.9	39.1	.39

Water quality samples were collected on two separate dates at various sections of the mine and stages of the treatment process. Results of the sampling program are recorded in Table 2 as mean values unless otherwise indicated.

The iron oxidation rate is controlled by the pH level and is normally monitored by pH meter located in the aeration basin.

The sludge pumping rate is normally maintained at a continuous pre-determined rate during plant operation. The rate may be manually increased during lagoon clean out periods.

The plant effluent is pH controlled by continuous electronic monitors with automatic value control for terminating the discharge of pH values deviate beyond preset pH limits.

Mounted pumps are frequently used to recycle water to a flash mixer when necessary, and the pumps are normally automatically controlled.

Any secondary and final settling pond levels are maintained at low levels to provide emergency storage capacity.

The process control system implemented at the treatment facility will vary according to the design of the plant and their applications.

TABLE 2

MEAN WATER QUALITY PARAMETERS FOR A CASE HISTORY MINE

CHEMICAL PARAMETERS	SAMPLING LOCATION									
	A	B	C*	D	E	F	G*	H	I	J*
pH	7.75	5.1	2.7	2.7	4.7	3.1	9.4	8.3	8.1	10.0
Acidity (hot) mg/l	-127	1,427	1,340	1,255	44	202	-13	-4	-3.5	-4,830
Alkalinity (total) mg/l	137	52	0	0	7.0	0	34	24	22	6,000
Nonfilterable Residue mg/l	172	1,199	1,670	20.5	29.5	720	8	6.5	7.5	180,800
Iron (total) mg/l	.35	82.5	163	353	28.3	56.9	1.41	1.1	2.1	354
Iron (ferrous) mg/l	.14	76	140	108	5.02	32.9	.05	.095	.05	1.20

A. 400' from the face
B. Face #1
C. Face #2
D. Pump at previous work-out section
E. Main sump
F. Discharge from mine
G. Pond #1
H. Pond #2
I. Pond #3
J. Sludge storage pond

*Sample only collected once (grab analysis)

SUMMARY

SUMMARY

Water inflow into underground mines can be expensive for the mine operator not only because the water must be transported outside the mine, but also because the water must often be treated upon discharge for acid mine drainage to meet water quality standards. The longer that groundwater is in contact with pyritic materials in the mine, the more acid, iron and other dissolved solids are picked up as the water flows through the mine. The best solution is to prevent water from entering the mine. However, this is only possible in limited cases. Once water has entered the mine, steps should be taken to keep the water from coming in contact with the floor of the mine by utilizing lined sumps, ditches pipes and pumps to transport the water out to the surface, instead of letting it flow along the floor in sloping entries.

The design of a water handling system requires adequate planning before the mine or new section is started. The following steps are recommended in the planning stages of a mine to minimize inflow problems and provide for an economical water handling system:

1) Collect as detailed geologic information as is economically possible. This includes a drilling program designed to maximize hydrologic input. The acid-producing potential of the coal and adjacent rock layers should be determined.

2) Photo-lineament studies should be performed to determine fracture zones. These areas often have large inflows and bad roof, and can be avoided in the layout of the mine.

3) A hydrogeologist should make an estimation of the quality water that will enter the mine and where the largest quantities will be found. Pumping tests or permeability tests may be made to calculate hydrologic parameters of the various rock units.

4) The mining engineer should plan for controlling water inflows which may be encountered. If areas of high inflow cannot be avoided, some options are: dewatering aquifers with wells, leaving pillars in place to avoid fracturing, stream diversions, regrading the surface, sealing and grouting. Adequate barriers should be left between adjacent flooded mines to reduce seepage.

5) Abandoned sections can be sealed and flooded to reduce acid mine drainage by reducing oxygen on the pyritic surfaces. Mining should be down-dip, so that on retreat natural coal barriers will impound the water. This may reduce acid discharge and lower treatment costs.

In all cases, an economic analysis should be made as to whether it is more cost effective to use a control measure to reduce inflow or to handle and treat the water.

The water handling system should be integrated throughout the mine. The main components of the system are sumps, pipes and pumps. An economic analysis should be made during the planning stage also to determine the costs of treatment vs. installing a system which minimizes the contact of the water with the pyritic materials. Engineering principles can be used to design the most cost effective and efficient system.

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