Section 26

Ground Water and Ground-Water Control

J. Richard Lucas

Lawrence Adler

Coordinating Editors

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Ground Water and Ground-Water Control

R. L. LOOFBOUROW

26.1—WATER FLOW, USE, EFFECTS, CONTROL

Sec. 4 discusses ground water as a mineral resource. This section deals with its control.

26.1.1—IMPORTANCE

Flows of water have an important effect on the cost and progress of many deep excavations. The existence of water limits the methods which can be used in some and presents hazards in others. Lowering the water table may reduce the flow of springs and wells, with legal liability. Some mine water is used directly, some must be treated before discharge, and some contains dissolved solids which can be recovered profitably.

Loss of life, property and production from flooding is grim, yet scores of mines have worked safely for generations under ground-water reservoirs, lakes and even the sea.

The need for better control of mine water is measured by the severity of recent floodings, concern with the quality of the effluent, and direct and indirect costs of working wet ground. There are improvements in freezing in shaft sinking, pumps and their controls, treatment of mine water before it is pumped, bulkhead construction and certain efforts to reduce inflow.

26.1.2—PUMPING COST VS. COST OF WET WORK

Direct operating and capital costs of pumping are more evident than indirect items, such as provision of extra standby power and maintenance facilities. The total of all these items is the cost of pumping water from an excavation. This is only a part of the extra cost of working wet as compared to dry ground. Less productive methods, less efficient equipment and more expensive explosives may have to be used in wet work. Wet rock plugs certain equipment. Maintenance is higher and labor less efficient. The cost of any means of keeping work drier should be weighed against the higher cost of working wet. The true difference in the cost of working wet ground, compared with dry, probably is known at only a few places (see checklist of cost items, Sec. 26.4.13).

An extreme comparison of mining wet and dry ore is available from Ambrosia Lake, N.M. (Fig. 26-1). Between 1963 and 1967, a wet and a dry mine were worked by the same company under conditions otherwise comparable. Average operating cost at the wet mine, pumping 1,600 to 1,800 gpm, was $16.06 per ton of ore. The comparable figure for the dry mine was $7.50. Principal differences included the fact that the wet mine was worked from drainage levels below the ore with rail haulage, the dry mine in the ore with off-track equipment loading and hauling to the shaft. In the wet mine, ore packed in chutes, cars and skips and froze in surface bins, stockpiles and trucks. Wet-mine costs included drilling drain holes, building and maintaining ditches and pumping water containing abrasive solids.

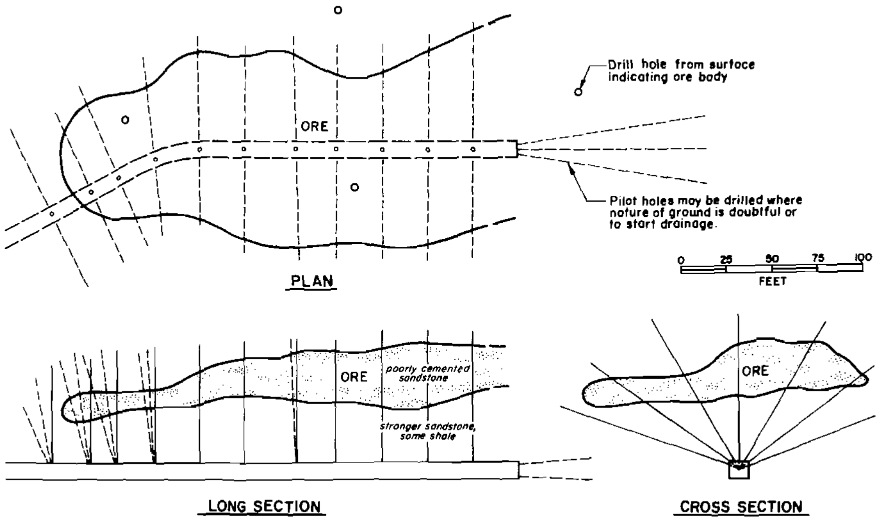


Fig. 26-1—Longholes to drain and delimit Ambrosia Lake ore.

The extra costs and hazards of tunnels and shafts in wet, weak and wet, hot and wet ground can be several times those for corresponding work in tight, competent rock.[1-5]

26.1.3—OBJECTIVES OF WATER CONTROL AND COMPARISON OF MEANS

The general objective in the control of water in deep excavations is to permit efficient safe work with side effects at least acceptable. The most common method of control is pumping. The differences between direct pumping costs and total costs of wet work have been emphasized in the preceding. However, if $0.10 is taken as a rule-of-thumb *direct* cost of pumping 1,000,000 ft-gal, the direct outlay for pumping this much water each minute for a year is $52,560. Where it is possible to reduce the pumping load by this amount, the present worth of the saving over a period of 15 yr. interest at 6%, is about 10 times the annual cost, or approximately $0.5 million. When consideration is given to the likelihood that inflow will increase as the mine is deepened and extended, and to the many possible indirect savings from working a drier mine (Sec. 26.4.13), the reason for reducing inflow becomes even more apparent.

Where an impervious cover above a mineral deposit can be maintained and shafts gotten through still shallower wet ground by freezing or by boring and casing (Sec. 10) the water level need not be disturbed. Many European salt, potash and coal mines are of this type. Potash mines developed in Saskatchewan in the 1960s are prime examples.

Pregrouting with cement slurries at sites of deep shafts has reduced hazards of serious water inrushes and minimized delays during sinking (Fig. 26-2). In tunnels, grouting has been used more as a remedy. Fine sand and very small fractures can be consolidated and sealed with "chemical" grouts. Clay grouts are used increasingly to reduce leakage under dams. A similar material has been useful in controlling large water flows through fractured cavernous dolomite. Means of controlling water inflow are outlined in Sec. 26.2.3. As more difficult work is undertaken, there will be greater need to use and improve them.

26.1.4—COMPARISON OF PUMPING FROM WATER-SUPPLY WELLS AND MINES

Water wells should produce a designed quantity of acceptable water efficiently—i.e., with least drawdown. If more water is needed than can be supplied efficiently

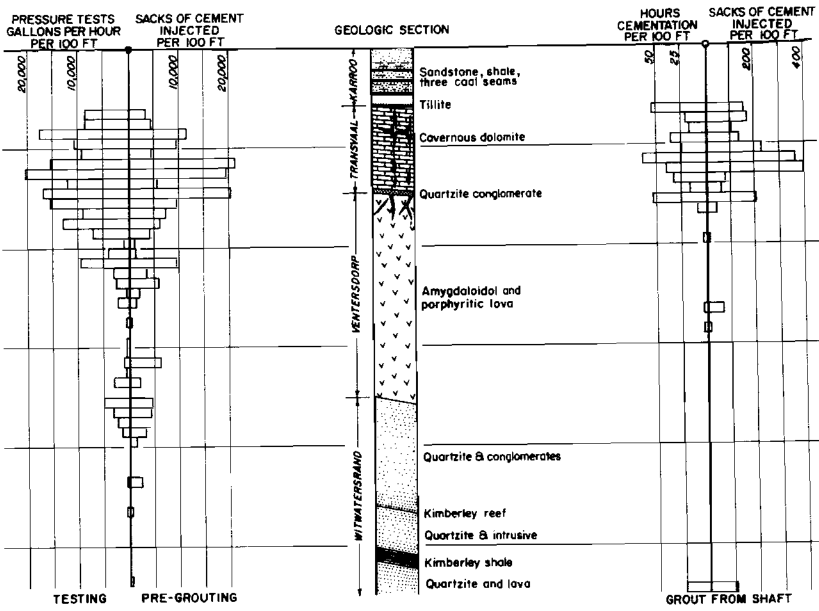


Fig. 26-2—Water occurrence and cement injection, Kinross Mines, Ltd. (after Munro Craig and Pritchard Davies[54]).

from existing wells the usual course is to drill another well at such a distance that pumping from the new well will not add appreciably to the drawdown in existing wells. Most water wells are cased to shut out undesirable water and draw from beds of sand, gravel or sandstone, which may be rather uniform over a large area. In many respects, oil-well pumping is similar. Fluid movement is slow to moderate, and laminar flow (yield proportional to drawdown) is the rule. Pumps normally are operated at designed capacity for long periods, but may be shut down for repair as convenient.

Dewatering wells are close-spaced so that cones of dewatered ground overlap amply. The usual objective is to dewater rapidly. While water is being lowered, pumping interruptions are avoided or reduced by every means. Drawdown usually

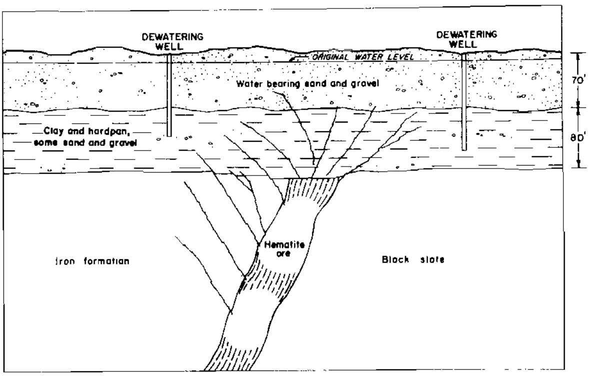


Fig. 26-3—Dewatering wells, HomerWauseca mines, Iron River, Mich. (after Mahon[22]).

is maintained until a shaft can be sunk and lined, until more permanent pumping facilities are provided or until an ore body has been mined. Usually, all water which flows to dewatering wells is pumped (Fig. 26-3).

A conventionally sunk mine shaft or a mine (open-pit or underground) is like a great well on the bottom of which men work. Before the well reaches the water level there is no inflow. A number of means are used to extend the well below the natural water table, the choice being limited by the conditions (see Sec. 26.2.1). Below the water table, water will flow into the well through any conduit open to it. If the permeability is low and the well is deepened rapidly, the water table will slope steeply toward the well.

Pumping from an accessible place in the mine has some characteristics of dewatering through wells, but sumps and water clarification can be provided, pumps of larger capacity and greater head can be used and they are more readily serviced.

26.2—MINE-WATER OCCURRENCE, EFFECTS AND CONTROL—IN OUTLINE

26.2.1—OCCURRENCE

Occurrence of water in deep excavations shows the diversity of geological conditions plus some imposed by man. Many sites present only minor ground-water problems to deep excavating, some are obviously difficult, and others are downright deceptive. Even at untested unworked sites, much evidence may be visible to the experienced eye. Opinion can be based on rainfall, topography, drainage, lithology and structure, but some conditions are difficult to appreciate with boring and testing and even when excavation has been well advanced. Understanding water occurrence helps in evaulating the problems.

Type of Water Occurrence	Examples
1. Inrushes from the sea, lakes, rivers, swamps, clay deposits, wet cover	Sunro,[6] River Slope,[7] United Paracale, Josephine,[8] Beattie,[9] Milford
2. Inrushes from caverns in carbonate rocks	S.W. Indiana gypsum, Friedensville (Fig. 26-16),[2,4] San Antonio,[10] Venterspost,[1] (West Driefontein indirectly)[11]
3. Inrushes from isolated water pockets	Buena Tierra-El Potosi (Chihuahua)[12]
4. Inrushes from fault conduits	W. Driefontein,[11] Jefferson City,[13] Naica (Fig. 26-12,)[14] Birmingham,[15] Deep Ruth,[16] Josephine,[8] Divide and Rokko tunnels[23]
5. Flow from primary (inherent) permeability	Saskatchewan (above Paleozoic),[3] Gas Hills,[17] Ambrosia L. (Fig. 26-1),[18–20] Bancroft (h.w.),[21] Homer-Wauseca (Fig. 26-3),[22–23] Garsdorf[24,101] and many European coal, potash shafts
6. Flow from secondary (fracture) permeability	Butte, Saskatchewan (Paleozoic)[3,25,26] Bancroft (footwall),[21] Tombstone, Park City Consolidated,[27] Ahumada
7. Magmatic water (perhaps at least in part)	Limón,[28] Sta. Francisca (Nicaragua)[28]
8. Sources—conduits at least partly man-made:	
a. Inrushes from adjacent flooded mines	Saxewell 8, mines near River Slope[7]
b. Incompletely drained hydraulic fill	Kerr Addison
c. Columns of broken rock or sand, with clay or slimes	Mufulira,[121] Atlas, Philex, Bancroft,[21] Nchanga, Balatoc
d. Subsidence fractures in tight rock	Many deep gold mines in South Africa[29]
e. Open boreholes in shaft or ore body	Some shafts, ore bodies
9. Combinations:	
a. Pri., sec. permeability, caverns	Bancroft[21]
b. Pri., sec. perm., weak ground	Ambrosia Lake (Fig. 26-1)[18–20]
c. Subsidence, fault conduit, caverns	West Driefontein[11,30]
d. Natural sources, artificial conduits	Philex, Sunro,[6] River Slope,[7] U. Paracale, S. Antonio,[10] Beattie,[9] Milford

26.2.2.—EFFECTS OF MINE WATER

Indirect effects even within the mine are easily overlooked. Most lead to cost items, some to hazards.

Effects	Examples
1. Direct effects of water in the mine:	
a. Cost, perhaps becoming a principal item (though in some cases water is used in treatment or otherwise)	W. Driefontein,[11,30] Bancroft,[21] Tecolote,[5] Casapalca, Penn. anthracite,[31] Friedensville,[2,4] Eureka (Nev.),[32] Kentau,[33] Naica[14]
b. Inrushes or other failure to handle inflow may interrupt production and damage the mine, perhaps beyond recovery, perhaps with loss of life	Mufulira,[121] W. Driefontein,[11,30] Saxewell 8, Philex, Sunro,[6] Jefferson City,[13] S.W. Indiana (Fig. 26-15), River Slope,[7] U. Paracae, Josephine,[8] San Antonio,[10] Beattie,[9] Milford
2. Indirect effects of water in the mine:	
a. Freezes in cold shafts, is hazard to shaftmen, corrodes hoist rope	Some effects in all wet shafts[34]
b. Reduces efficiency of crews, equipment, hinders materials handling	Probably all wet mines, Bancroft,[21] Tecolote,[5] Nchanga, Knob Lake,[35] Balatoc
c. Adds to maintenance of equipment, tires, cost or hazard of using electricity	Especially where water is corrosive and rock abrasive, Ambrosia,[18–20] Casapalca[36]
d. Washes weak ground into mine openings	Ambrosia Lake,[18,20] Gas Hills, many shafts, tunnels[23] and pits[35,40]
e. Flows of hot water heat and humidify ventilating air	Naica,[14] Limón, Santa Francisca,[28] Casapalca,[36] Tecolote and Graton tunnels,[5,37]
f. Carries dissolved gas into some mines	S.W. Indiana, Detroit-Windsor (H_2S),[38] Orange Free State (methane), Osceola[39]
g. Promotes deterioration of some rock and caving in blastholes, reduces stability of rock walls and dumps	Shales and clay shales Many open-pit mines and cuts[35,40,43,56] and some underground—White Pine[62]
Dissolves soluble minerals	Salt, potash and gypsum mines
h. Washes fines from conveyances, increasing work on accessways, ditches	May be costly where valuable mineral is friable or haulages long
i. Interferes with certain explosives	Wet open-pit and underground mines[40]
j. Mud makes some products unacceptable	Kimballton limestone (early work)[41]
k. May form scale in pipe, pumps	Butte (ochre),[42] Star-Morning (siderite)
l. Rapid inflow is peril if power fails	W. Driefontein,[11,30] Naica,[14] any wet mine
m. May add "wet," "waterproof" pay items	Many shafts and wet mines
3. Indirect effects outside the mine:	
a. Moisture in product increases shipping, treatment, handling costs	All direct-shipped ores,[35] those processed dry, tending to be sticky and those exposed to low temperatures[35]
b. Effluent may pollute surface water	Many wet coal mines,[44] iron mines
c. Drawdown may take water from wells and lower quality of water remaining, or improve it	Friedensville, Tri-State and Middle Tennessee Zinc Dists.[63]
d. Drawdown may be apparent cause of surface subsidence, sometimes violent	Oberholzer, Doe Run sinkholes
4. *With regard to time, prime effects may:*	
a. Exist only during shaft sinking	Salt, potash, some coal, metal mines
b. Increase during life of project	Most wet mines
c. Persist after mining is stopped	Pollution from some mines through which water flows by gravity

26.2.3—MEANS OF CONTROL

Means of control are limited by circumstances and objectives. Their rational bases are study and testing begun with the first indication that mining is likely and continued as long and as vigorously as costs and hazards justify. Some controls can be applied in emergency, as to prevent a mine from being flooded by an inrush or to recover it after a flood. Some cannot be used unless previous work is suitable and other conditions favor. Some require time. Controls can be used singly but are more effective in combination.

Type of Control	Example
1. Reduce, postpone or avoid trouble, e.g.:	
a. Locate shafts or excavations in best ground, and protect from direct inflow from surface	Naica (Fig. 26-2),[14] Kimballton,[41] San Antonio[10]
b. Use methods which favor control and reduce hazards	Wabana,[45] other submarine mines,[46] most salt, some coal, metal mines[123]
c. Leave pillars along fissures to reduce or delay subsidence	Some deep gold mines in S. Africa,[29] Nova Scotia coal mines[123]
d. Work under water as by dredging, mining with draglines, leaching in place	Alluvial gold,[47] tin,[47] platinum, sand,[47] gravel[47] Shirley Basin (Wyo.)[48,49]
2. Divert or drain water at or near surface:	
a. Divert rivers, drain lakes (including clay), clear and straighten streams to reduce direct inflow and recharge	Griffiths,[50] Black Lake,[47] Caland,[47] Bancroft,[21] Steep Rock Lake,[47] Biwabik,[51] Josephine,[8] Hazelton
b. Cover intakes with ponded slime, concrete	Bancroft,[21] Leadwood[52]
c. Intercept water in shallow wells	Homer-Wauseca (Fig. 26-3)[22]
d. Catch water in water rings in shafts	Most wet shafts
e. Clear slopes, build drains	Bancroft[21]
f. Plant trees in low, flat areas to increase evapo-transpiration	Bancroft[21]
3. Keep water from shafts with impervious linings placed as follows:	
a. Pregrout from surface, test and grout progressively from shaft bottom	Kinross,[53,54] Hartebeestfontein,[55] Saskatchewan (Paleozoic),[25,26] Meramec[107] Friedensville,[2,4] Venterspost[1]
b. Freeze, sink, set lining and thaw	Saskatchewan (above Paleozoic)[3] many European coal, salt, potash shafts
c. Bore, usually with mud-supporting hole until casing is set	Beatrix Shafts,[57] S.E. Missouri,[58] Ambrosia Lake, Carlsbad
d. Drop shafts (little used)	
4. Reduce permeability of rock mass by:	
a. Grouting with cement slurry	Port Radium,[59] Deep Creek[60]
b. Plugging solution channels and grouting	Leadwood[52]
5. Drain water through adit	Graton tunnels,[37] Pennsylvania anthracite project,[31] Sutro tunnel, Monteponi[61]
6. Compartment wet or potentially wet areas to confine water or possible damage	Leadwood,[52] Nova Scotia coal mines[123]
7. Case or cement exploration drill holes	Mid Tennessee,[63] required many places
8. Dewater bedrock at depth by pumping:	
a. Deepwell pumps from surface	Pine Point,[64,65] N.C. phosphate,[66] Huber,[67] Garsdorf,[24,101] Nyirad,[68] Lisbon, Grace[69]
b. Deep-well pumps from underground	Park City Consolidated[27]
c. From shaft	Fad Shaft,[32] Jarbridge[70]
d. From lowest working heading or from a still lower drainage drive	Most wet mines, Bancroft,[21] Naica,[14] Friedensville,[2,4] Bancroft,[21] Ambrosia Lake
e. From drainholes drilled into conduit or wet ore body	(Fig. 26-1),[18–20] Naica (Fig. 26-12),[14] Friedensville[2]
f. From bottom of open pit	Knob Lake,[35] most pits
9. Use special design in pumping system(s):	
a. Abrasion-resistant pumps	Jefferson City,[13] Ambrosia Lake

Type of Control	Example
b. Corrosion-resistant pumps, pipe; protect from stray currents, galvanic corrosion	Copper mines with "oxide" ore,[42] many coal mines, Casapalca[36]
c. Treat, underground, to remove solids, reduce scale or corrosion	Sudbury,[71,72] Butte,[42] South Africa,[73] Ambrosia Lake, Pea Ridge[74]
d. Keep hot water in pipe	Naica,[14] Limon, Sta. Francisca[28]
e. Pump to subterranean conduit	*Chief Consolidated*[75,76]
f. Use water in hydraulic hoisting	Lengede,[77] American Gilsonite Co.
g. Use water to remove heat from mine	Butte[42]
h. Automatically control, supervise pumps	Butte[42]
i. Use high-lift pumps	Butte,[42] South Africa[73]
10. Use special practices aiding control:	
a. Regularly plot, record pertinent data	Bancroft,[21] Friedensville[2]
b. Regularly get informed outside opinion	
c. Use test holes, pilot holes	Bancroft,[21] Naica,[14] Friedensville[2]
d. Blast only after shift	Many mines
11. Anticipate emergencies with, for example:	
a. Extra water-handling capacity	W. Driefontein,[11] Naica,[14] Friedensville[2]
b. Doors or bulkheads to protect pumps or use submersible or deep-well types	Bancroft,[21] W. Driefontein,[11] Naica,[14] Casapalca,[36] Friedensville[2]
c. Emergency space for water storage	West Driefontein[11]
d. Compartments confining damage	S.W. Indiana gypsum, Nova Scotia coal[123]
e. Plans of action with equipment, material, trained crew on call, escape procedures	West Driefontein,[78] Friedensville,[2] Port Radium[59]
12. Procedures used in emergency:	
a. Remove crews through large boreholes	Lengede[77]
b. Isolate inflow with bulkheads	West Driefontein[11,30]
c. Plug a large conduit, working in mine	Anneville limestone mine
d. Plug a large conduit, working on surface	S.W. Indiana (Fig. 26-15), Friedensville (Fig. 26-16)[2,4]
e. Locate a large intake and plug it	Moodie, Levant (Cornwall)[79]
13. Reduce effects outside the mine:	
a. Treat water to improve quality, in some cases recovering a product	Mines with "oxide" copper,[42] many coal and metal mines
b. Reduce-flow through the mine	Some coal mines
c. Minimize change of water level	

26.3—FORECAST OF INFLOW

26.3.1—GENERAL

Rational forecast of water inflow is based on understanding the geological factors plus any existing man-made conditions, such as abandoned wells and nearby flooded mines, plus the effects of the work planned, such as subsidence. Many sites present no water problem but the inadvisibility of assuming it has been demonstrated. In most cases, it is extremely difficult to forecast inflow with confidence. Methods are discussed very generally here and references to more detailed work are given. The following points may help:

1. Water study should begin when the likelihood of work is first apparent. It should be broad, be conducted by experienced people, and be adequate to guide later work.

2. Care and cost of the study should be in proportion to the total effect, including hazards to health and life, investment, continuity of work, neighboring property and the environment.

3. Continued vigilance is needed as long as hazards exist, which is throughout the life of some work. Under much easier water conditions, informed study of the geology and observation of drilling may be enough.

4. Low precipitation, dry surface and topographic relief generally point to a comparatively deep water table. They don't prove the absence of water. Consider the rush of 100,000 gpm into the San Antonio mine (Chihuahua) in 1945.[10]

5. Without downgrading efforts to limit the effects of flooding and to recover the work thereafter, prevention must be the prime objective.

6. Qualitative appraisal of water occurrence may be enough. For example, where the potential rate of inflow is great, a method like dredging under water may be chosen to avoid the problem altogether.[47]

26.3.2—FACTORS AFFECTING ESTIMATES

Each of the types of water occurrence outlined in Sec. 26.2.1 involved a hazard. In spite of the diversity of occurrence, all problems of inflow have common elements: a source of water above an excavation (or at higher pressure), and a connection between the sources and the excavation. The source may be an aquifer, a body of surface water or, even, a normally dry canyon in which there is an upstream cloudburst. Among criteria which may be useful in judging the degree of hazard presented by these elements are:

1. Relation between the volume of the source and the volume the mine can take; if the source is recharged, the extreme rate of recharge.
2. Capacity and location of any connections, natural or artificial, and their susceptibility to enlargement by scour, solution or other means.
3. Available driving potential (pressure difference).
4. Complications such as release of gas, e.g., H_2S dissolved in the water.[38,39]
5. Hazards presented by existing and planned work.

Some of these criteria can override others. Experience teaches the hazard of a small squirt of gritty or even muddy water, for example.

Confidence in estimates is likely to be highest where:

1. Lithology and geologic structure are comparatively simple, uniform and well known.
2. Hydrologic data such as recharge-discharge, storage and the permeability of the rock masses and structures are known.
3. Nature of the work to be done is well defined and the effect of work and water on the rock masses is known.

Water occurrence may be deceptive because:

1. Even in arid places flows of ground water may be large.
2. An inrush at a point and an occasion of weakness can flood perfectly sound connected workings.
3. Test holes may pass within a few inches of a conduit without indication. They may cross one in a tight place or where it is tightly plugged with clay.[2]
4. Important indirect effects of water may be overlooked.
5. Surface drill sites generally are above the static water level where the penetration of conduits is not obvious.
6. Evaluation of the water occurrence is not certain to be of prime interest to those who plan and supervise the test drilling.
7. During early stages of work, inflow generally is least burdensome; it may receive scant attention. When it has become a serious problem, work already done may prevent the use of some methods of control. Others may be ruled out for lack of time.

26.3.3—SUGGESTED STAGES OF INVESTIGATION

For efficiency, study of water can be staged.

1. The earliest stage,[30] which can preceed detailed drilling may include observations of:

A. Topography, drainage, precipitation, snow melt, evapo-transpiration, runoff, recharge-discharge, local water supply and use.

B. Gains or losses in stream flow, highest water levels.

C. Lithology and structure of the rock masses with special emphasis on their permeability and storage capacities.

D. Water occurrences in any nearby excavations.

E. Study of similar occurrences.

F. Consideration of indirect effects inside and outside the mine.

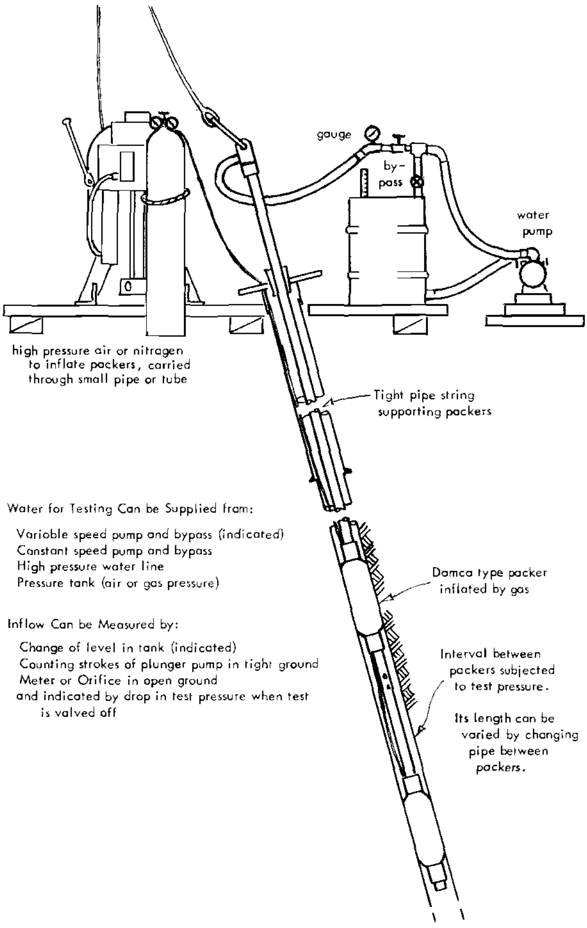


Fig. 26-4—Pressure tests with pneumatic packers.

G. Relation of water to possible mining methods.

H. The suitability of mine water to meet expected plant or other requirements.

I. Indications of water quality and temperature.

At this stage, effort should be to anticipate the water problems, indicate their gravity and plan any further investigation recommended.

2. Observations during drilling may include:

A. Water levels in drill holes and other points, and changes as drilling progresses, with notes of fluid loss and mud weight.[122]

B. Quality and temperature of water from various sources.
C. Stability of rock at critical places on exposure to moist and dry air.
D. Nature and spacing of fractures or other conduits.
E. Electric logs, borehole-camera photos.
F. Permeability of various rock units as measured by tests with packers, by "swabbing" or, more elaborately and usually later, by pumping tests (Fig. 26-4).
G. Movement of water, perhaps using tracers.
H. Special attention to the capacities of sources and any existing or potential connecting conduits.
I. Continued effort to learn the conditions and to anticipate potential hazards and ways to minimize them.
3. While excavation is in progress (where problems exist or are expected):
A. Take steps listed in outline (Sec. 26.2.3) as may be appropriate.
B. Regularly solicit informed outside opinion.
C. Seek to defray costs of pumping by making use of water.
D. Continue to seek means of reducing inflow.

The relative importance of these observations depends on the circumstances. For example, a prime concern in open-pit planning is likely to be the evaluation of maximum precipitation and runoff in the immediate pit area and the storage and recharge of shallow aquifers near it. These would also be important considerations in planning any underground mining which creates open fractures to the surface. They would be of secondary concern if mining were to be done beneath a uniformly impermeable bed sure to be kept intact.

26.3.4—COMMENTS ON ESTIMATING INFLOW

In testing aquifers for water supply, hydrologists[81] are advised to:
A. Accept dispersion of data as a measure of departure from the ideal.
B. Plan test procedures to conform as nearly as possible to theory.
C. Be prepared to learn that an aquifer is too complex for clear evaluation.

The conclusion that a water occurrence is not predictable with reasonable accuracy may lead usefully to (a) attempts to avoid the water, (b) a most flexible approach, or (c) reconsideration of that project.

Tests—e.g., pressure tests—reflect existing water conditions. They don't forecast the effect of changes, such as the opening of conduits which may follow subsidence over a mined area.

Hydrologists,[81-86] petroleum engineers[87,88] and civil engineers[89,90] all start with Darcy's 1856 observation that velocity of laminar fluid flow through sand is directly proportional to the permeability of the medium and the pressure gradient. Hydrologists find pumping tests useful in predicting the performance of water wells. Petroleum (reservoir) engineers test within very much deeper wells and on cores taken from them to forecast production of oil and gas. Civil engineers concentrate on soil moisture and the effects of pore pressure on stability. Efforts have been made to calculate flow to tunnels and shafts[89,91,92], open pits[64,65] and underground mines.[29] Such attempts have been complicated by complex geology, by several conditions usually not fully determinable and differences in the nature and speed of work. Some general guides are available.[35,40,80,93]

General Means—In undisturbed bedded rocks the interpretation of electric logs shows where water should be expected and where its occurrence is likely to be insignificant. Use of these logs to indicate water in fractures or other discrete conduits is not well established.[94]

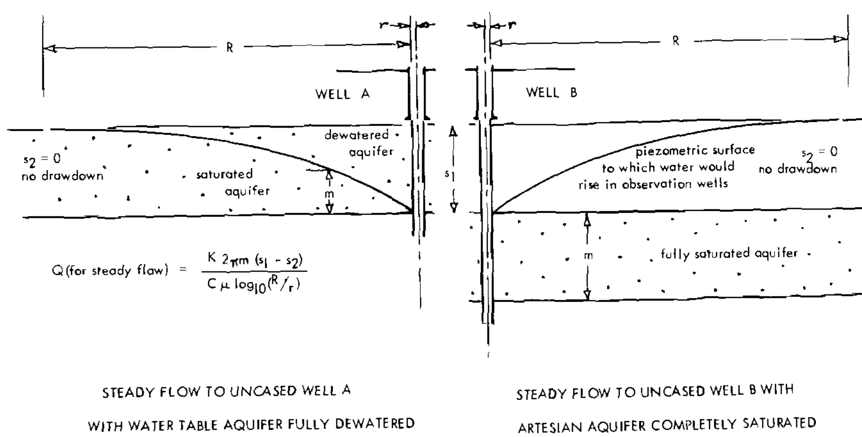
During drilling, observations appropriate to the conditions should be made. These may include items such as those listed in Pt. 2, Sec. 26.3.3.

In some cases a very rough approximation of potential inflow can be made by subtracting from the total precipitation on a drainage basin an amount lost by evaporation and outflow. Streamflow records may furnish clues to water yield.

Where the degree of similarity can be judged correctly, analogy is a great help.

Referring to general observations of topography, drainage and recharge-discharge, LeGrand[30] says although attempts to show values of storage and transmitting capacity of rocks in mining areas must be applied with caution, "adherence to some concepts of ground water used by hydrologists in the study of . . . wells should be helpful to mine operators."

Fig. 26-5—Showing of irregular multiple aquifers in pit wall (darker parts); lensing beds of clay, silt and sandstone.



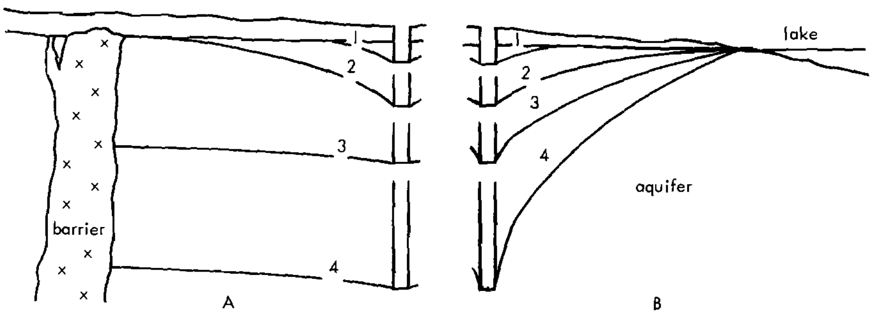
Note that in Well A, 100% dewatering is, in fact, impossible; if water is to continue flowing to the well, there must be some saturated wall through which it passes.

Fig. 26-6—Comparison of flow to wells in dewatered and saturated aquifers.

Concepts—In simplest form, the water table, below which ground is saturated, is nearly a horizontal plane. In a succession of layers of diverse permeability there may be multiple water tables. Artesian water is trapped under a layer of comparatively low permeability. In a well it rises to the piezometric surface. Where permeability is irregular or discontinuous the water table is similarly erratic (see Fig. 26-5). Where water feeds into the ground the water table is higher and ground water flows from such points to lower points of discharge. The slope of most natural water tables is gentle and motion slow.

The water table or piezometric surface is depressed by pumping a well. The resulting gradient causes flow toward the well. Analysis of flow is based on an ideal aquifer, homogeneous, isotropic and horizontally infinite, and a perfect well, open to the full thickness of the aquifer, toward which water flows horizontally and radially. The depression is an inverted cone, symmetrical around the well. Its slope decreases logarithmically to the radius of effect where there is no measurable depression. If permeability is not uniform the cone is distorted. Where water is only in fractures, it is discontinuous.

As a well is pumped, the drawdown increases until the well is dewatered or until, because of the steepening gradient, the rate of inflow balances the pumping and flow becomes steady. As the cone expands its shape may be changed by masses of higher or lower permeability or by recharge. Schematic profiles in Fig. 26-7A show the extreme effect of a barrier surrounding a shaft being deepened. Those in B show the effect of an irreducable recharge, e.g., on a shaft being



THE CONE AROUND A SHAFT EXPANDS NORMALLY AS THE SHAFT IS DEEPENED IN STAGES 1 AND 2 BUT ITS SHAPE IS CHANGED BY A) A BARRIER, AND B) A CONTINUING RECHARGE. THE CONE AROUND AN OPEN PIT OR AN UNDERGROUND MINE, DEEPENED OR EXPANDED HORIZONTALLY, COULD BE AFFECTED SIMILARLY

Fig. 26-7—Extreme effects of barrier and continuing recharge.

sunk in the center of an island. If either shaft is not surrounded, nonradial flow will reduce the effects.

Almost all natural ground-water movement and most in efficient water-supply wells is by laminar flow, gradient being in proportion to the velocity. Where velocity is sufficient flow may be turbulent.[95] Head loss in turbulent flow increases as some power of Q, the quantity of flow to the well. Where there is no unwatering, observed values are between Q^2 and Q^3. Observed powers of 3.5 seem to be related to a combination of dewaterng and turbulance.[84] The effect of the size and shape of the passages through which water flows is not fully understood, but turbulence is unlikely in rock having only fine pores. A shell of turbulence probably surrounds many heavily pumped wells of small diameter, and some deep shafts. However, as an opening is enlarged its perimeter increases much faster than the inflow. If turbulence exists around large openings its effect is less (Fig. 26-8A).

In the analysis of ground-water movement, flow is usually assumed to be horizontal and radial. In mines opened extensively, vertical flow can be important, as illustrated by Fig. 26-8B. The effect of this flow can be calculated.[81]

Units—The three most commonly used units of pemeability are:

Darcy and *millidarcy,* used by petroleum engineers. Through a rock of 1 darcy, a fluid of 1 centipoise viscosity (water at 68° F) moves at the rate of 1 cm per sec under a pressure gradient of 1 atm per cm (1,034 cm of water at the same temperature.)[86]

Velocity of flow is used in civil engineering, engineering geology and soil mechanics. Through a rock of unit permeability, water of 1 centipoise viscosity moves 1 cm per sec at 100% gradient. Note that this rate of flow is the same as stated in defining the darcy, though in this case the gradient is 1:1 rather than 1,034:1.

Meinzer units are used by hydrologists and civil engineers in the U.S. Through a rock of unit permeability, 1 gpd of water at 60° F moves through each square foot of cross section at a 100% gradient. The related term "transmissibility" or, sometimes, "transmissivity," is the flow in gallons per day, at prevailing temperature, through a vertical strip 1 ft wide and the full saturated height of the aquifer at unit gradient.

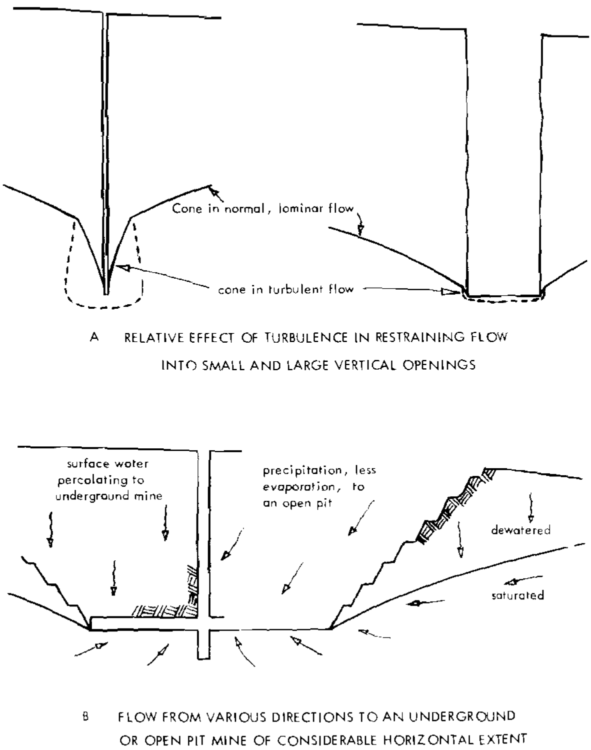


Fig. 26-8—Effects of turbulence and vertical flow.

These units, means of determining permeability and its relation to flow, are discussed in the context of hydrology in Refs. 81–86, of petroleum engineering in Refs. 87, 88 and API Codes, and of civil engineering in Refs. 89 and 90.

The viscosity of water varies with the temperature from 1.792 centipoises at 0° C to 1.005 at 20°, 0.506 at 55° and 0.299 at 95° C.

The interrelation of the units and the range of a few materials are shown in Table 26-1.

The coefficient of storage, the volume of water which drains from a unit volume of dewatered ground, is usually expressed as a decimal fraction. The term "effective porosity" has similar meaning. The absolute porosity of many shales and clays, for example, is 25% but the intergranular spaces are typically so small that movement of water under usual conditions is negligible unless huge areas are considered. Most of the porosity of coarse sandstones is effective as storage. Close-spaced open fracturing can give dense rock important storage capacity but it is rare. Solution cavities can provide storage in otherwise dense limestone and dolomite. Some lava contains ash, erosion surfaces and tubes with high permeability and more or less storage. Weathered surfaces of most strong rocks are likely to carry water. Induration closes pores and fractures.

Tests for Permeability and Storage Capacity (see Table 26-2)—Pumping tests are made by pumping water from a well at a sufficient rate long enough to lower the water table measurably in several observation wells, which should be at prescribed locations with respect to the pumped well. The pumped well should penetrate the entire aquifer and, in usual tests, receive water freely from all of it.[81,82,85] Attempts have been made to use this practice to forecast flow to dewatering wells and deep excavations, but even where the ground and the water occurrence are favorable, the

TABLE 26-1—Approximate Ranges of Permeability and Comparison of Three Units*

Description of Ground	Permeability Unit		
	Darcy[1]	Meinzer[2]	Cm per Sec[3]
Clay shale or dense rock with tight fractures, considered impermeable in most excavations	0.0001	0.0018	9.7×10^{-8}
Dense rock, few tight fractures, approximate lower limit for oil production..............	0.001	0.018	9.7×10^{-7}
Dense rock, 0.005 in. fracture each sq ft......	0.5	9.0	4.8×10^{-4}
Silt or clay, silt, fine sand. Few water wells in less permeable ground....................	1.0	18	9.7×10^{-4}
Dense rock with high fracture permeability...	2.0	36	19.4×10^{-4}
Clean sand, medium and coarse (0.25 and 1.0 mm).................................	500	9100	0.48
Clean gravel (70% larger than 2.0 mm)......	1250	22750	1.2

* This table compares the permeability of ground described in the first column, by showing the measure of its permeability in each of the three commonly used units, i.e., the same silt with some sand and clay, having a permeability of 1 darcy, has permeability of 18.2 Meinzer units and 9.7×10^{-4} cm per sec.

1. 1 millidarcy = 0.001 darcy.
2. Transmissibility or transmissivity: T = Meinzer unit × saturated thickness in feet.
3. Because this is a high rate, a velocity of 1 cm $\times 10^{-4}$ per sec also is used.

difference in objectives calls for modifications.[64,89,91,92,96,97] Uncertainty in the use of pumping tests for these purposes would be reduced by continuing the test to complete drawdown.

The time and cost of pumping tests generally limit stringently the number that can be made on a project.[97] Hence, it is difficult or impossible to (a) determine properties of more than one part of a complex rock mass, (b) indicate uniformity of any part of the mass or (c) establish averages which can be used with confidence. Where these points can be determined in other ways and where the test can be set up to provide the information needed, there is no better source of data.

Pressure tests with packers are water-injection tests, in some ways the reverse of pumping tests, but they can be made in holes of usual diamond-drilling size, the packers can be set to test any interval of open hole, and can be reset repeatedly. Generally, water pressure, at the section under test, can be between 1.1 and 2.5 times the hydrostatic head without danger of opening fractures.[63] Where permeability is high, there is advantage in testing at a low pressure difference to limit pipe friction and the likelihood of turbulence. Where it is low, a higher pressure difference provides a measurable inflow with less time (Fig. 26-4).

TABLE 26-2—Comparison of Methods for Testing Hydraulic Properties of Ground

	Pumping Tests	Pressure Tests	Drill-Stem Tests	Lab Tests on Rock Core
Required minimum diameter, open hole or casing, inches	To admit pump of capacity needed—usually at least 6 in.	At depths to 750 ft, 1.5-in. dia: deeper tests need 1.75 in. (smallest standard packers)	4.625 in. (with smallest standard tool)	Sufficient to get sample at least 1 in. in dia. × 1 in. long; larger preferred
Tests show	Permeability, storage coefficients, drawdown time; may indicate radius of drawdown in bed(s) connected to pump	Permeability of interval between packers or below them	Permeability of interval between packers or below them, bottom hole pressures, sample of fluid	From many determinations, calculate permeability and porosity of intergranular openings as in sandstone, silt
Preparation needed for single test	Usually drill pumped well, perhaps observation wells also. Provide pump of enough capacity, power, discharge, measuring device	Provide packers and means to expand them, water for test and way to measure it; may need to clean wall of hole	Provide DST tool, packers and means to expand them	Special lab apparatus and procedures
Time for each test	To forecast water production from ideal aquifer several hours may do, but for dewatering test should get deep drawdown, perhaps several weeks	For tests in series, need time to lower or raise packers plus 20 to 45 min for each test	Time to lower and raise tool, set packers, test for 0.5 to several hours, come out and reset tool (for full test)	Time to prepare samples and test, all in lab
Steps required for multiple tests in the same hole	Provide connection from each new test interval to pump and close off other intervals	Deflate, move and reset packers	Raise tools, reset DST, lower to new interval and reset packers	
Approximate cost or range of cost, (thousands of $ (M) per test)	Including cost of well usually drilled for the test, a brief shallow test may cost $10M. An extended dewatering test at 1,500 ft, $100M	Not including cost of hole (d. drill holes can be used), multiple tests to 600 ft, $15 to $75 each. Deeper, $40 to $200 each	Purchase tool or rent, with operator, by hour and mileage. Not incl. hole, may cost $1M each at 1,000 ft, $1.5 to $2.5M at 3,000 ft	$5 to $15 per sample for porosity and permeability

Packers may fail to seat where erosion of weak rock has enlarged the hole and water can leak around them through fractures or connected pores. Such leakage can be reduced by using long packers, by making successive tests below a single packer near the bottom of the hole as it is deepened, and by testing below double packers. A series of tests can be checked by a single test of the same section of the hole. Leakage around packers or through pipe joints leads to over-estimating inflow. However any mud or grease caked on the walls of the hole would have the opposite effect.

Holes can be cleaned by "swabbing," i.e., pumping by repeatedly lifting a column of water above plastic cups on a wire line inside a string of casing or tubing which extends several hundred feet below the water level in the hole. Measurement of the rate of water-level recovery after swabbing is a negative-pressure test. The swab can be run inside tubing on which packers are set to determine inflow from the interval between them and sample it.[97,98]

Shallow pressure tests may be made most conveniently between pneumatic packers (Damco) inflated from a cylinder of compressed air or nitrogen. These packers are made to work in the usual diamond drill holes. At more than 750 ft, oil field open-hole-type (Leynes) packers are better (no separate high-pressure gas hose is needed).[97] They are sturdier and can be used at any depth in test holes 1.75 in. or more in diameter.

A series of tests between packers efficiently expanded and contracted from the surface can be made at the rate of 1 to 3 tests per hr. Tests below packers take time for lowering and recovering the packers and setting up for each test.

Drill-stem tests are made with a special "tool" lowered into the hole on a string of drill pipe. Above the tool is a packer, which can be expanded to close off the bottom of the hole. The tool can be placed between two packers to test the section enclosed. A recording pressure gage shows pressure increase as the tool is lowered, the shut-in pressure in the test section, pressure changes during the test, and pressure decrease as the tool is being removed. To start the test, a valve is opened permitting fluid to flow from the ground through the tool into the empty pipe. A sample is recovered. Potential production can be calculated from the rate of flow and the recorded bottom hole pressures.

Each normal drill-stem test calls for a trip into and out of the hole with a string of tight pipe. The smallest standard tool requires a hole of 4.625 in. ID.

Laboratory tests on core are used by petroleum engineers to determine intergranular permeability and storage capacity in sandstone, silt and similar rock. They do not indicate properties of fractures as in-hole tests do. These tests and the apparatus are described in API codes.

Combinations of the general means and tests can be useful. Goodman[89] proposes the use of pressure tests with calculations specially adapted to tunnels. Venter[29] says that knowledge of the permeability and storage capacity, as indicated in early stages of mining in the Orange Free State, can be used with nonequilibrium formulas to forecast changes in inflow. It must be noted that structure is regular and that the water occurrence and changes which accompany mining are very well known.

Early investigation of the water occurrence in the new north-central Tennessee zinc district included pertinent aspects of regional and local geology, topography and drainage, as well as pressure tests in many exploration drill holes and observation of the temperature, quality and level of the water in them. Subsequently, the amount pumped from exploratory workings and the effect of this pumping in observation holes is noted. Broad combinations of various types of observations provide a promising basis for estimating inflow.[63]

Calculations—Most calculations are intended for use in conditions uncommon in mine-water control. A comparatively direct equation attributed to Theim[83] (p. 461) is based on dewatering the aquifer and has several applications. Assumptions are that flow is steady, horizontal and radial through an aquifer which is uniform, isotropic and of great horizontal extent into a well without entrance loss penetrating the full aquifer.

$$Q = \frac{K 2\pi m (s_1 - s_2)}{C\mu \log_{10} (R/r)}$$

Symbol	U.S. Hydrology Units	Petroleum Engr. Units
Where Q is rate of inflow:	U.S. gallons per min	ml per sec
K, permeability	Meinzer	Darcy
m, average saturated thickness of aquifer at two observation points	Feet	Centimeters
R, radius to farther observation well or radius of effect	These radii can be measured in any consistent units	
r, radius of nearer observation well or well radius		
C, constant	528	2.30
μ, viscosity	Centipoise	Centipoise
s_1, drawdown at farther observation well or static reservoir pressure	Feet	Atmospheres
s_2, drawdown at nearer observation well or flowing pressure at bottom of well	Feet	Atmospheres

In dewatering it is important to note that m is the average saturated thickness at the two points of observation. With reference to Fig. 26-6, compare an uncased fully dewatered well at A with another into which the full aquifer discharges, B. With other conditions equal, if R is the radius of effect where s_2 is 0, and r is the radius of the well, note that with complete dewatering in A, m is only half the thickness of the aquifer. The Thiem formula shows that flow into this completely dewatered well will be only half that to Well B in which none of the aquifer is dewatered and m is its full thickness. Fig. 26-9 shows the relation of percent of maximum inflow to the percent of drawdown in an uncased well calculated by the same formula. Fig. 26-10 shows the steady flow into completely dewatered uncased wells of various diameters. If there is turbulence, its effect will be more pronounced in openings of smaller diameter and the left-hand part

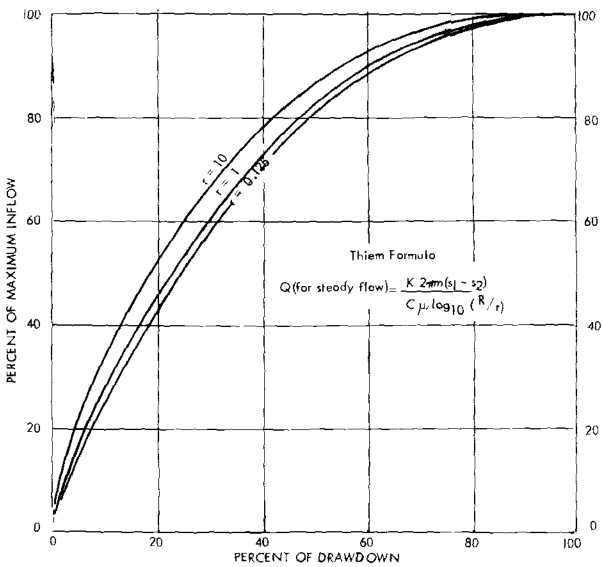


Fig. 26-9—Flow to well in a water-table aquifer as well is dewatered.

of the curve will be steeper. Fig. 26-11 shows the steady inflows which would be expected as wells or shafts are deepened progressively in a uniform aquifer, However, in dense rock, through which water moves in fractures, the spacing between fractures is likely to increase and their width to decrease with depth, permeability decreasing correspondingly. There is no assurance of such a decrease. In many places, there are local increases of permeability on fracture zones. They can be troublesome.

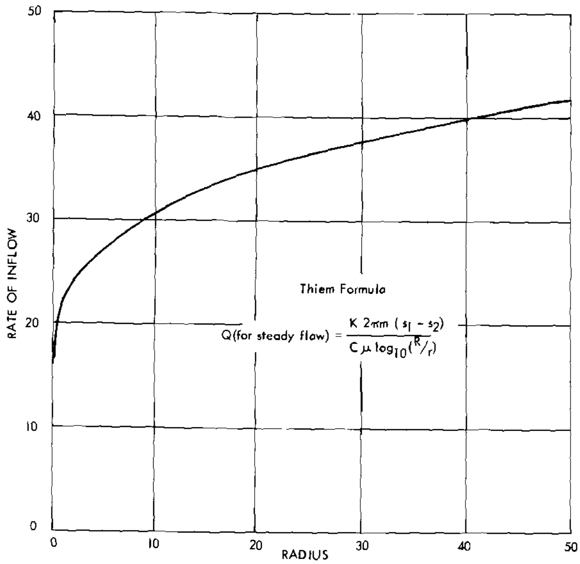


Fig. 26-10—Flow to well in a water-table aquifer as radius is increased.

Where drawdown should be related to pumping rate and time, nonequilibrium formulas—Theis,[99] in some cases as modified by Cooper, Jacob and others—are best selected and applied by hydrologists specialized in this work, with guidance in the conditions and objectives. The use of equally specialized and somewhat similar techniques of petroleum engineers merits consideration in deep work, for which their methods were devised.

26.4—PUMPING, DRAINAGE

26.4.1—GENERAL

Pumping is the most common means of water control. It has inherent advantages where:

1. Dewatering is the most practical way to sink shafts and excavate saturated rock masses.
2. Depressing the water table adds to stability or security of work in a way or to a degree which could not be attained more advantageously otherwise.
3. The pumped water is needed or carries sufficient recoverable mineral.
4. Inflow is small and pumping may be preferable to seeking, establishing and maintaining an alternative.

The design of pumping systems of even moderate capacity presents complications which need specialists but they should be guided by those who are fully acquainted with broader plans and objectives of the work.

The cost of standard water ends of horizontal centrifugal mine pumps generally is 30 to 50% of the total cost of the pump-motor-starter unit, and may be 5 to 15% of the pumping plant, including sumps, clarification, power supply, ventilation, suction, discharge and the required excavations.

Need to pump inflow of water with complete reliability means that there must be at least one pumping unit capable of doing it, and one equal spare. In a three-unit system, any two should be able to pump the maximum inflow. The

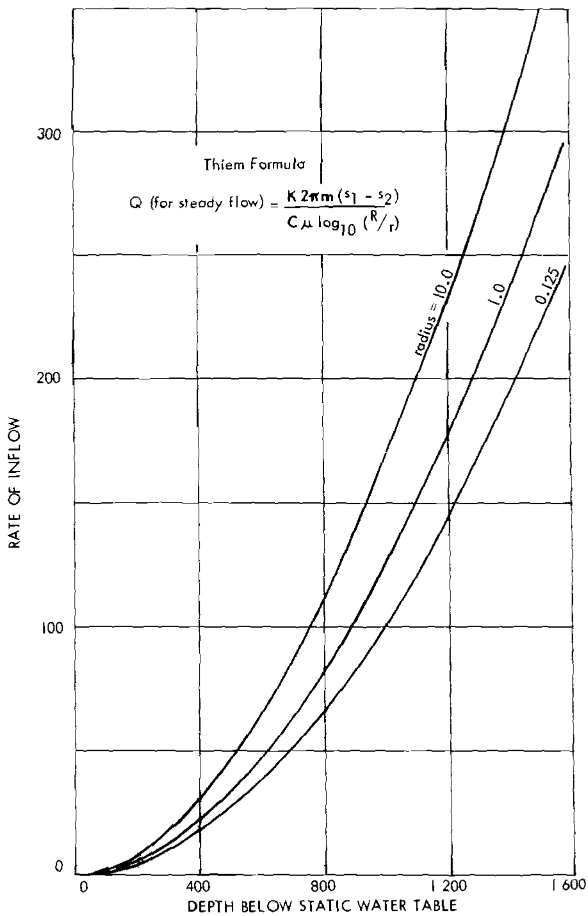


Fig. 26-11—Flow to a well in a water-table aquifer as well is deepened.

greater the number of units the less the percentage of spare capacity but beyond some point a larger number of smaller units will cost more and will have lower efficiency (Allan,[73] p. 240). Where only brief pumping interruptions can be permitted, duplicates of all essential parts must be provided, including power supply, pipe and valving.

Modern high-speed centrifugal pumps are capable of high efficiency providing close tolerances are maintained. They are vulnerable to wear by grit, and essentially are clear-water pumps. Means to remove suspended solids before pumping therefore have become an important consideration in sizable installations. In some of these treatments, acid water is neutralized.

26.4.2—DEWATERING THROUGH WELLS

The possibility of dewatering through wells depends on meeting, to a reasonable degree, each of these conditions:

1. Volume must be within reasonable limits and head must be such that the volume can be pumped efficiently.
2. There should be a degree of uniformity of water yield.
3. There must be no bar to lowering the water table over an area which may be irregular and, even in some comparatively shallow work, extensive.
4. The occurrence must be reasonably well known.
5. Sufficient time must be provided.

The desirability of dewatering through wells depends on how well the foregoing conditions are met and may be influenced by some of these factors:

1. The cost of drilling, casing and completing adequate wells.
2. Clarity of water inflow at extreme drawdown (ground should have some cohesion).
3. Possibility of using the water produced.
4. Availability of power, equipment and needed services.
5. Continuity of the work and the extent of the area to be dewatered.
6. Comparison of this and other methods of control at the job.

To dewater effectively requires enough wells, properly located, pumping at a sufficient rate for sufficient time. The importance of understanding water occurrence, and of providing sufficient time for lowering the water level the necessary amount cannot be overemphasized.[35,40,93]

Effective advanced dewatering confers a number of advantages, among which are:

1. Work areas are free of sumps, pumps and pipelines.
2. Stability of walls is likely to be better than if water were pumped from a sump at the lowest excavated elevation.
3. Maintenance of accessways and equipment is easier because work is kept drier.
4. Danger of sudden flooding is reduced.
5. Accumulations of water, mud and ice are reduced.
6. Product is drier.
7. Cleaner water is produced.

Disadvantages include:

1. Adequate testing and planning require time and cost.
2. The preproduction investment in wells, pumps and power distribution is likely to be substantial and the drawdown period may be many months.
3. The water level is depressed deeper, sooner and, generally, more extensively.
4. Results may be disappointing except where conditions are favorable.

Dewatering wells commonly are contracted. If the type of well and range of sizes and depths are foreseen, bids can be solicited from contractors with appropriate equipment and experience.

Where churn drilling (with cable tools or spudders) is suited to the ground and can make wells of the diameter and depth desired, it may result in lowest cost. Rotary drilling (with rolling cutters or rock bits) generally is a good deal faster and, except where circulation cannot be maintained, the walls of the hole can be supported by mud until casing is set. With equipment of sufficient size, deep holes and holes of larger diameter can be drilled with assurance. Where ground is suitable, compressed air can be used instead of mud, usually with savings of time and cost. In large-diameter holes, there may be advantage in reversing the circulation, bringing cuttings up through the drill pipe.

Generally the objective is to pump all water which will flow to the well and casing may be perforated throughout. However, there may be advantage in casing off upper beds to exclude grit, especially if these beds drain to a main lower nongritty aquifer.[66] If the main aquifer is reasonably stable it can be left uncased.[65]

Well screens with various sizes and shapes of slots are used to exclude sand

and gravel. In dewatering where rates of flow must be high, if the well is to be effective, screens should be large enough so that entrance losses will be no more than moderate.

Generally, the productivity of wells as ordinarily completed can be improved by surging with plungers (swabbing) or compressed air to clean loose sand, subsequently bailed.

"Gravel-packed" wells can be especially useful in dewatering. They are bored oversize or under-reamed through a principal aquifer to diameters to 2 m. Clean gravel is pumped into the annulus between the casing and the wall of the hole. For any given pumping rate from a given well, the rate of flow in the aquifer immediately outside the well is inversely proportional to the well diameter. In dewatering, where the objective is to lower the water table between wells efficiently, gravel packing has important consequences: (a) if turbulence is not eliminated its effect is greatly reduced and the cone is flatter, (b) the tendency of rock fragments or grit to be moved into the well is reduced and (c) the gravel acts as a settler to catch any fragments which may move.

26.4.3—TAPPING WATER AT HIGH PRESSURE

In some cases, there are advantages in making initial openings in tight ground to drain conduits or masses of wet rock. Procedure may be complicated by one or more of the following conditions:

High pressure water, hot water, dissolved gas.

Weak ground, unstable in contact with water flowing under high pressure.

Mud and grit causing or increasing erosion.

Uncertain location of wet ground or conduits.

Uncertain rate of inflow.

To indicate where the water is, its pressure and perhaps something of the rate of flow, pilot holes usually are drilled ahead of large openings (Sec. 26.7.2).

Tapping can be accomplished by:

1. Driving an opening into the water source. Where water occurs in small conduits in a rock strong enough to resist erosion, the heading can be continued until the desired inflow is obtained. If water is carried by a well-defined, clean conduit, this may still be a good approach, but drilling and blasting the last round is tricky and, unless a pressure door has been built, only friction in the conduit and in the heading restrain the inflow.

2. With more time and cost, tapping can be controlled by driving to within 25 to 75 ft of the wet ground, cutting a drill station and drilling many radiating holes. Where high pressure must be expected, and especially where the collars of the holes could be eroded by it, work must be protected by drilling 5 to 10 ft of oversize hole and cementing a collar pipe with a bypass tee and a full-opening valve. Drilling is completed through this valve. Water is drawn from many points throughout a sizable rock mass. This may be important to minimize erosion (Fig. 26-12).[2] Because these holes are short, head losses of 10 to 40 ft per hundred may be acceptable. In this range, each 2-in. hole may produce 60 to 120 gpm and each 3-in. hole, 180 to 360.

It may be worthwhile to utilize the pressure of tapped water to reduce the pump head. This can be done by piping water under pressure directly, or through a settling tank, to the pump suctions (Fig. 26-12).[2]

26.4.4—DITCHES, PIPE

Mud and silt from blasthole drilling, from fill decant water, and from flow through caved or weak ground, are problems in many mines, even where natural permeability of rock is low. The choice of remedies may be affected by the uniformity of flow, the nature of the suspended solids, the recoverable value of suspended and dissolved solids, sources of water and mud and their location, and the expected life of the work.

Benefits of controlling mud and water may include:
Easier maintenance of track ballast, road surfaces.
Neater, cleaner, safer travel for crews.
Less water percolating to any lower work.
Lower cost, less congestion, less loss of time for cleaning.
The following remedies may be considered:
1. Mechanical ditch cleaning, flushing.
2. Full or partial ditch lining with wood, concrete, precast or other half-culvert segments.

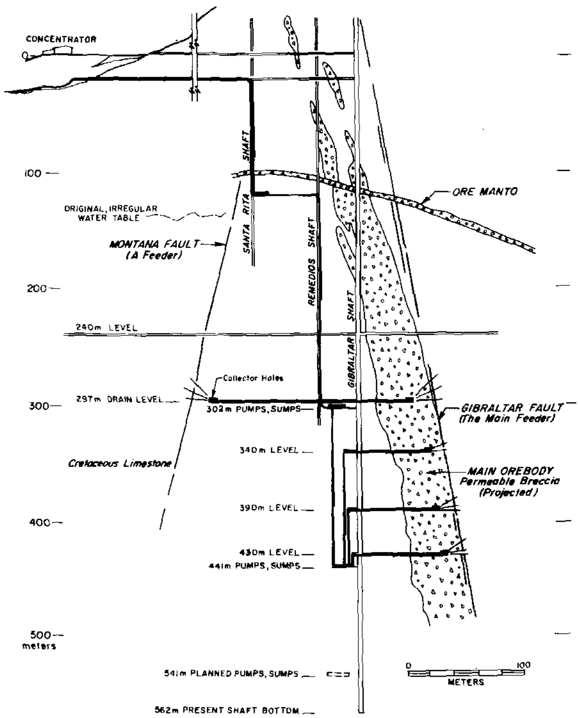


Fig. 26-12—Naica mine drainage (schematic).

3. Control of grade to minimize the amount of solids settling in the ditch.
4. Small settling sumps near sources of mud.
5. Pipe to carry water from workings above a level to sumps or settlers.
6. Ditches located under chutes and other discharge points.
7. Cars with solid bodies rather than doors where rock is sloppy.

An approximation of the amount of water flowing in a ditch may be obtained by a "standing wave" weir, a constriction in the walls of the ditch which raises the level of the water surface at the throat.

26.4.5—CLARIFICATION, OTHER TREATMENT, SUMPS

Sumps are (a) accumulators to partially equalize the continuously changing rate of inflow and increase the regularity of pump operation, (b) reserve storage, unless it is provided otherwise, in which water can be held during short power interruptions and periods of suddenly increased inflow, and (c) settlers in which some suspended solids can be removed.

Where pumping is substantial, the higher efficiency of separate settlers or clarifiers is advantageous because:

1. Modern high-speed pumps are highly efficient when worked with close tolerances. They are vulnerable to suspended solids.
2. Generally, pumping loads increase.
3. Some useful mining practices, such as placing sand fill hydraulically and longhole drilling, tend to increase the volume of sludge.
4. Generally, effluent must be treated eventually.

Sumps and settlers may provide facilities for other treatment, such as neutralizing acid. Usually they are planned to have somewhat more than the capacity required and for enlargement, if needed. Width of openings may be limited by the stability of the ground.

In response to diverse conditions several different trends are noted.

1. Quartzite beds in which South African gold ore occurs have very low permeability but, as the gently dipping reefs are mined, fractures are opened by subsidence and water flows through them. In the early 1950s, 40,000 gpm was pumped, much of it from more than 3,000 ft below the surface. The use of high-speed centrifugal pumps motivated search for ways to clarify water most efficiently before pumping. Suspensions of fine particles in water drained from dolomite generally are treated by flocculation. Acid water in other mines is neutralized with lime. In all cases, water contains some suspended quartzite grit, most of which can be removed in settlers. Many varieties were tried on pilot and full scale (Evans[73], p. 59). There is general agreement that:

A. With unassisted settling, surface area of settlers is the prime design control. At least 1 sq ft of settler area should be provided for each gpm through the settler. Where raw water is introduced at the bottom of the settler, this results in a rising velocity of about 1.6 ipm.

B. With flocculation, area is less important than mixing, and detention time which should be at least 2 hr. Good results have been obtained by causing inlet water, after thorough mixing with reagent, to rise through a "floc blanket."

C. Eight mines reported (1955–1959 papers) separation of at least 60% of suspended solids—seven of these, 80%, and 6, 90% or more.

D. Inlet design is important. It should minimize currents in the settler. Cold water tends to "dive."

E. At many of these mines, much of the sludge is 5 μ (0.0002 in.) or smaller. At about 3% solids, it can be pumped by centrifugal pumps at heads of as much as 3,000 ft if clear gland water is used. Sludge also can be settled to about 50% solids and hoisted in cars, which eliminates the need for separate pumps and discharge columns. The sludge is trammed to the concentrator.

2. At its magnetite mine in S.E. Missouri, Meramec Mining Co. pumps from 2,275 ft. Raw mine water contains 1,108 ppm by weight of abrasive suspended solids. Unassisted settling in a rising-current settler of about 2,000 sq ft area reduces this to 155 ppm, or about 14% of the original content. Volume is reported as 530 gpm;[74] 92% of the sludge is −325-mesh.

3. At the Kelley shaft, Butte, Mont., Anaconda Copper Corp. recently has established a central pumping plant where mine water is gathered, treated and pumped against a 4,100-ft head to the surface.[42] Sulfuric acid is added to decrease the pH from about 2.8 to 1.9. This prevents deposition of ochre. Water contains dissolved copper and on the surface, is used in leaching a dump, where the extra acid is beneficial. All concrete is protected and wetted metal parts are stainless steel or similarly resistant.

4. From its Sudbury mines, International Nickel Co. of Canada pumps about 5,000 gpm, in some cases from below 5,000 ft. Water is from natural inflow, drilling and, in several mines, decant from sand fill. All contains abrasive solids. Some is acid. From one mine, 49% of the sludge is reported as −1,600-mesh.[71,72] To meet the increasing problem, simple rectangular sumps were replaced by cone settlers, and later rectangular rising current clarifiers. With adequate size, these produced good overflow but with difficulties in maintenance and handling sludge. Use of hydraulic fill, with added cement in some mines, increased the volume of sludge and made it more gelatinous. Most recent practice was developed to produce a satisfactory effluent, recover copper, nickel and iron, reduce pump maintenance and improve sludge handling.

Treatment of the hydraulically placed fill with a flocculant reduces the suspended solids in the decant water. In the most recent installation, this and other mine water goes to a 40-ft-dia, 12-ft-deep thickener with a deep flocculating central feedwell, V-notched overflow weir and extra discharge rakes in a deep discharge cone. Lime is added. Thickener underflow goes to a vacuum belt filter. Although procedure has not become fixed, results indicate thickener underflow of higher solids content than attained with other settlers. This increases filtration speed and produces a cake which is handled without difficulty in cars, belts and bottom-dump skips.

26.4.6—PUMP STATIONS

Objectives usually include:

1. Provide enough units of all essential components that any one can be repaired while others handle greatest expected flow. Ordinarily, this requires spare units with appropriate valving and crossovers and a crane or crawl capable of moving the heaviest.

2. Protect pumps and all electrical equipment from being flooded:

A. Provide sufficient storage in sumps or otherwise.

B. Use vertical pumps to take water from sumps, or

C. Protect the pump room with an adequate pressure door and a raise for access and ventilation.

3. Provide for adding to capacity if needed.

4. Provide sufficient controls, usually at least automatic start-and-stop; alarms for high water, and minimum protection for pumps and motors (Sec. 26.4.8).

5. Provide positive suction head if reasonably possible by:

A. Pumping from sump with vertical pumps.

B. Locating pump room lower than sump.

6. Protect, as much as possible, high-tension items from accidental jets and splashes. Slope floor and provide drain.

7. Ventilate as needed for normal and emergency operaton, discharging hot air to mine or returning it to the surface or, if both are objectionable, cooling it mechanically, adding to the temperature of water discharged.

26.4.7—PUMPS

Centrifugal pumps of several types predominate. Unlike positive displacement pumps, including plunger and most "rotary" pumps, centrifugal pumps can be rotated without fluid flow. Because the power demand is least when no water is pumped, large pumps generally are started with discharge valves closed. Flow also is limited or stopped if (a) discharge pressure is not sufficient to force water into discharge pipe (as from extreme impeller wear), (b) passages anywhere in the pump system are plugged, or (c) pressure in the suction is insufficient. "Cavitation" develops in the intake of impellers if pressure there drops below the vapor pressure of the fluid. Formation of bubbles reduces capacity and efficiency and their collapse damages the pump. Suction head is important in the efficient operation of centrifugal pumps and is a factor in priming them, on which, in turn, automation depends. Typical relations of suction head, total dynamic head and specific speed $\left(\text{rpm}\,\frac{\sqrt{\text{gpm}}}{H^{0.75}}\right)$ for single- and double-entry single-stage centrifugal pumps handling clear 85°F water at sea level are shown in Fig. 26-13A. Fig. 26-13B shows the various power losses typical of centrifugal pumps in relation to specific speed (Kewley,[73] 172).

Relations of capacity, discharge pressure and power requirement of the various types of centrifugal pumps to impeller peripheral speed are similar. Generally these are approximately:

Capacity or rate of discharge varies with peripheral speed at exit of impeller.

Maximum discharge pressure varies with the square of peripheral speed.

Power imput varies with cube of peripheral speed.

To a degree all pumps can be fitted to resist corrosion and abrasion, with added cost (see further discussion, Sec. 26.4.11). Except in special circumstances modern practice is to treat water before pumping.

Commonly Used Mine Pumps—Types, distinguishing characteristics and uses of common mine pumps are briefed in the following:

1. Small portable or semiportable pumps for special uses:

A. Sump pumps powered by compressed air, electricity.

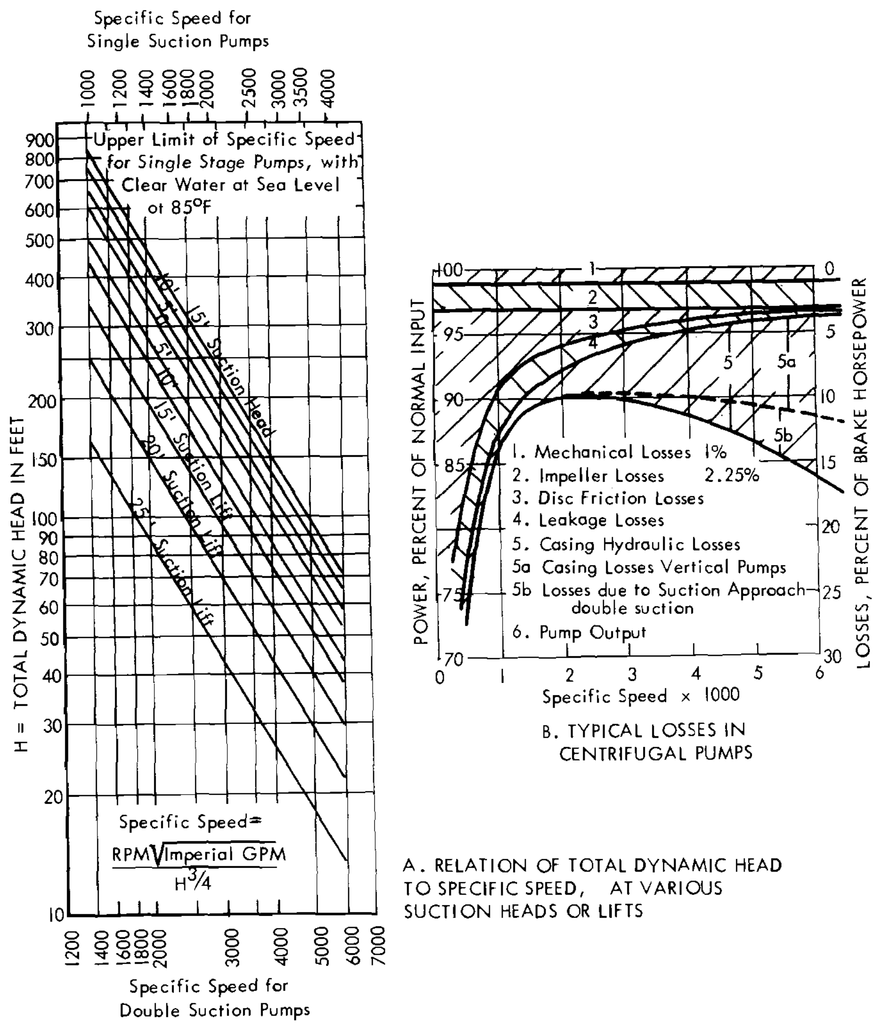


Fig. 26-13—Suction and losses, single-stage centrifugal pumps (after Kewley[73]).

Characteristics: vertical centrifugal pumps with open impellers and abrasion resistance; less commonly, diaphragm and displacement pumps. They are hand-moved to and from sumps where they normally work submerged but can run dry without damage. Air pumps are limited to heads of about 100 ft, with capacities of up to about 100 gpm. Electric pumps exceed these limits.

Used to clear small inflows from shaft bottoms, clean sumps, etc., where high portability is desirable.

B. Contractor's pumps, usually powered by small internal-combustion engines or electricity.

Characteristics: usually horizontal centrifugals, on wheels or skids, with suction hose and foot valve; otherwise, like sump pumps.

Used for dewatering trenches, foundations, other shallow excavations where portability is important.

2. Mud pumps, slurry pumps, grout pumps powered by compressed air or connected to other power source by belts or gears.

Characteristics: plunger pumps with high abrasion resistance and low to moderate capacity, but capable of high discharge pressure. Valves are accessible for cleaning, and usually are partly rubber. Most have replaceable cylinder liners. Air-powered pumps commonly used in grouting have complete speed regulation and are not damaged by stalling.

Used for grouting, pumping sludge, pumping drill mud and, in larger sizes, adapted to pumping into long-distance pipelines.

3. Single-stage sand pumps, dredge pumps, usually direct-connected electric drive; small and moderate sizes generally 1750 rpm, larger sizes slower.

Characteristics: Horizontal centrifugal pumps with high abrasion resistance, many with large impeller clearance or open impellers for passing comparatively coarse material and dense suspensions at high capacity and low to moderate discharge pressure. Most use clear gland-water to protect bearings.

Used for transferring slurried solids in treatment plants, commonly of small and moderate capacity for heads generally less than 200 ft, but larger high-pressure models go to 1,300. Capacity of dredge pumps for moving mixtures of cobbles, pebbles, sand, silt and clay through pipelines several miles long can be very large.

4. Small centrifugal motor-and-pump units with common frame, bearings and shaft, for horizontal mounting as on skids or vertical as in slings. Generally 1,750 and 3,500 rpm, up to about 50 hp and 3-in. discharge. Most are single-stage.

Characteristics: adaptable to a variety of conditions with moderate head, small to moderate capacity.

Uses: intermittent work and use in plants. Sling-mounted single-stage units are useful in shaft bottoms and sumps.

5. Single-stage horizontally split centrifugal pumps, usually direct-connected to electric motors for compactness, dependability and ease of control. Discharge sizes from a few inches to about 12. Generally furnished with close clearances for clear water. Smaller sizes, 1,750 and 3,500 rpm; larger, 1,750 rpm.

Characteristics: with close tolerances, these pumps can work with high efficiency to capacities of about 3,500 gpm and heads to about 500 ft. Pumps are made for larger capacity at somewhat lower heads. Installation and maintenance are simpler than for multistage pumps.

Uses: excellent station pumps for clear water at heads to about 500 ft. Dirty water can be pumped, with or without modification of the pumps, but for long-lived installations there generally is a cost advantage in treatment before pumping.

6. Horizontal multistage centrifugal pumps, usually direct-connected to electric motors for compactness, dependability and ease of control. Discharge sizes, 3 to 8 or 10 in.; 2 to 10 stages with heads as great as 1,000 ft per stage; most, 3,500 to 3,550 rpm.

Characteristics: Although best total efficiency is likely to be less than that of single-stage units, efficiency per stage may be higher. Heads range from about 500 to 5,000 ft; with some models, to 7,000 ft.

Uses: high-head station pumps with clear water. Although the first cost of these pumps generally is higher than cost of single-stage pumps of similar power, their use may save capital and operating cost of duplicate facilities.

7. Vertical turbine (deep-well) pumps—essentially vertical centrifugal pumps made in comparatively small diameters to work in water wells and similar narrow but high spaces. Water ends are essentially similar whether close-coupled to a vertical electric motor, connected by a shaft several hundred feet long to a motor at the top of a well casing, or connected to a submerged motor in the well.

Small sizes are turned at 3,500 rpm; larger at 1,750 and 1,170. Vertical turbines are made with as many as 20 or more bowls (stages) for heads of 15 to 100 ft per stage. Pumps are made in diameters from about 6 in. to several feet.

Characteristics: Because pump intakes normally are submerged, priming is not a problem. Motors of close-coupled pumps can be well above normal water levels. Impellers can be removed if a pump is to work at less head, or more bowls and impellers can be added for greater head.

For lifts up to 300 ft, open-impeller vertical-turbine pumps can be used. This approximate limit is set by stretch between the thrust bearing at the top of the shaft and the vertical reaction of water against runners. Closed-impeller vertical-turbine pumps are free of this limitation because the vertical reaction is against the bowls. Settings to 400 and 500 ft are common. They can be at twice these distances but at greater cost for shafting and longer time for pulling and replacement. Deep-well vertical turbine pumps can be equipped with water-lubricated rubber shaft bearings or with the shaft and metal-to-metal bearings enclosed in a small oil-filled pipe centered in the pump casing. This oil-lubricated arrangement generally is preferred in dewatering pumps because it protects the bearings from any suspended grit.

Vertical turbine pumps are made to work in casings from 6 in. ID to several feet, and with motors as large as several thousand horsepower. Their dependability is high, and efficiency compares with that of horizontal centrifugals. They can be fitted to resist corrosion and abrasion, and, with enough suction pressure, will pump hot water.

Submersible pumps have water ends similar to vertical turbines but are driven by special small-diameter motors below the pumps. Power is supplied by submarine cable. Submersibles can be used in holes not sufficiently straight for deep-well pumps. Generally, they are likely to be preferred for depths of more than 400 to 500 ft. Power cable is less expensive than shafting, and submersible pumps can be lowered and raised faster. Their repair, however, is more complicated and generally is done by the manufacturer. Because the motor is cooled by the water moving past it, submersible pumps are at a disadvantage where hot water must be handled.

Submersible pumps up to 500 hp are made in the U.S.; sizes up to 1,000 kw for 1,000-ft head are used in Europe (see additional data, Sec. 26.5.3).

Submersible pumps are available for use in casings of 4 in. and up.

Submersible pumps are used in oil wells at as much as 12,000 ft but their pumping rate, like that of the admirably simple down-hole plunger (sucker-rod) pump is too low for any usual dewatering.

Uses: Both deepwell and submersible pumps are well pumps especially useful in water supply and dewatering. Close-coupled pumps are good on shaft bottoms where inflow is too large for lighter pumps.

8. Vertical centrifugal pumps are made in one and two stages with proportions like those of horizontal centrifugals. They are direct-connected below vertical motors by short shafts. Because the pump always works submerged, priming is not a problem. Usual speeds are 1,750 and 3,500 rpm.

Characteristics: They have the simplicity and high capacity of horizontal centrifugals and in many uses approach or equal the convenience of vertical turbines. They are made for capacities up to 15,000 gpm and heads to 800 ft with motors as large as 1,250 hp.

Uses: within the range of heads available, vertical centrifugals are well suited to pumping directly from underground and open-pit sumps to the surface. They can be mounted on platforms directly over the sump. In deeper mines, they can be used to raise water from a lower to an upper sump, from which it can flow with positive suction head to horizontal centrifugals. They also can pump to emergency storage.

9. Other types are especially useful in work infrequently undertaken, viz.:

A. Air lifts. Their efficiency is low at best, yet there is no simpler unwatering installation—nothing but two strings of pipe is submerged and anything which can get into and through the larger pipe is pumped without damage done. They are especially good in unwatering partially blocked shafts.

B. Progressing cavity pumps with abrasion-resistant rotors in rubber stators will pump any mud which can be drawn into them.

C. Axial-flow and mixed-flow pumps handle water at very high rates and good efficiencies for low heads.

A checklist of factors which may be considered in selection of pumps follows:

General:
- Life of work, of installation, likelihood of reusing pumps, salvage
- Objectives, continuity of work
- Sequence of work at various elevations
- Effluent requirements
- Comparison of various adequate pumping systems

Environment:
- Type and location of installation, any hazards or unusual conditions and means of protection available, such as bulkheads, emergency storage, protection from freezing, etc.
- Power system, including dependability of service, power factor, capacity of feeders
- Any limits on transporting equipment
- Possible ways to provide high suction head, priming
- Restrictions on size of excavations imposed by ground stability or other condition
- Cost of pump room, transformer room, control room, clarification, sumps, bulkheads, doors, etc., as needed
- In wells, their productivity, diameter, straightness, type of completion, equipment and crews for boring and servicing
- Means of ventilation, heat removal

Duty:
- Range of inflow expected
- Number of units and arrangements for repairing each while others are in use, spares
- Uniformity, predictability of inflow
- Water quality and possible improvement before pumping (suspended and dissolved solids and resulting abrasion, corrosion, scale, possible metal recovery)

Pumps, Drives:
- Dependability, durability under conditions of work
- Ease of maintenance (time and cost)
- Relation of pump speed to that of preferred driver
- Suction head, priming requirement
- Efficiency
- Space required to move pump horizontally and vertically for repair, replacement
- Accessories required and advisable
- Adaptability to automatic control
- Possibility and effectiveness of abrasion, corrosion resistance and their cost
- Lubrication requirement
- Leakage of water, oil
- Need for cooling, ventilating, protection from moisture
- Adaptability to any forseen changes
- Vibration, pulsation and their control
- Means to measure performance for maintenance planning
- Availability of parts, services
- Cost of pump, drive, starter, controls and auxilliary equipment
- Cost of required valving, piping
- All installation costs
- Weight, size of largest component in relation to entries

26.4.8—PUMP MOTORS, STARTERS, CONTROLS

The selection of motors and starters for large pumping installations is a specialized undertaking linked with other special functions such as mine planning, including the evaluation of water occurrence and inflow expected during the life of the work, the details of the drainage system and finally, the mine power system.

Because most modern units are direct-connected, the motor generally is selected to match the speed needed by the pump. The starting torque required by centrifugal pumps is moderate. Choice of voltage depends on the size of the motor and also on the voltage at which power is brought into the mine and, for smaller motors, the cost of reducing that voltage.

Each starter protects the motor to which it is connected from certain abuses, such as overloads and low voltage. Circuit breakers usually are needed to protect the motor against larger faults. Some very large motors can be started by circuit breakers.

Low operating cost and dependability are likely to be prime objectives. Low first cost, sturdiness and compactness are important in most cases. Squirrel-cage induction motors started across the line meet these objectives very well. The four types of squirrel-cage induction motors made in U.S., with different built-in rotor resistance, afford a degree of choice of the relations between starting torque and starting current, speed, slip and load, and, to a lesser extent, efficiency.

Advantages of squirrel-cage induction motors are:

1. Lowest first cost, installation and maintenance costs because of simplicity, sturdiness and compactness.
2. Greatest dependability because of sturdiness and simplicity.
3. Highest availability.
4. Ready adaptability to automatic control.
5. Speed of large motors on usual frequency matches that of more efficient large clear-water pumps.
6. Adequate starting torque.

Disadvantages are:

1. Squirrel-cage induction motors started across-the-line draw about six times full-load volt-amperes. Specially designed motors larger than 200 hp can be designed to reduce power inrush.
2. Induction motors cannot be used, as synchronous motors are, to correct the power factor.

Limitation of surges may be required by the capacity of a local generating plant, by the capacity of the supply cable and transformers or by high demand charges. Motors usually are started one at a time, the largest first, and discharge valves are opened after all are up to speed. A small pump can be started and stopped as needed to accommodate changes in flow. Large sump capacity makes it easier to accommodate the variations. There are several kinds of reduced-voltage starters for use with squirrel-cage motors if circumstances justify the extra cost.

The power-factor of squirrel-cage motors can be improved by capacitors where the added cost is justified.

Across-the-line starters have the advantages of simplicity, dependability, compactness and least first cost. For economy in motor-starter cost alone, 440 v would be chosen for motors of 500 hp and less. In consideration of the voltage of the mine supply cable and the need for transformers, higher voltages might be preferable on units of this and even somewhat smaller sizes.

Usual duties of controls are to:

1. Stop and start pumps at preset water levels.
2. Signal if water rises abnormally.
3. Signal if a pump is stopped for any reason other than low water.
4. Protect pumps from being started or continuing to work under conditions which might damage them, such as hot bearings and insufficient water.
5. Protect motors from trouble such as overload, heated bearing, or electrical faults in the motor or in the power supply.
6. Record certain data to indicate performance and for use in planning maintenance.

Controls do not think but they react faster than people who do, and their vigilance can be made extremely high. Controls should fail safe—i.e., if any protective device fails, dependent equipment should be stopped, an alarm given and, except in emergency, equipment prevented from being restarted until the fault is corrected.

For the smallest installation, controls may be no more than a start-stop float switch and a high-water alarm. A large recent pumping plant, on the other hand, has controls which verify nineteen conditions, such as gland-seal water pressure, suction pressure, oil pressure, oil level and motor-winding temperature, which must be normal before that pump can be started.[42] Controls are neither simple nor cheap but engineering design has been much improved and better use is made of them. The advantages of simplicity still are recognized but the cost of labor and more common use of larger equipment units promote automation.

Some controls provide special protection—e.g., automatically putting a small current through the windings of a stopped motor to keep them 5° to 10° above ambient temperature to prevent condensation.

Controls can also provide records of performance, such as total quantity of water pumped each day, and other records of individual pumps, such as suction and discharge pressures and individual flow needed to plan maintenance.

26.4.9—DISCHARGE PIPE IN SHAFTS AND PITS

Fundamental considerations include:

1. **Pressure**—Normal working pressures may be increased considerably by the pulsations of reciprocating pumps or by surging and water hammer. Special steels or extra wall thickness may compensate for pressure or corrosion but with added cost or weight.

2. **Subsidence**—Where significant subsidence is likely, the discharge pipe should be able to survive some misalignment.

3. **Need to Remove and Replace Sections**—If it is likely that individual lengths or sections of a discharge line must be removed to clean scale or repair accidental damage, pipe should be coupled and supported accordingly. Repair by cutting and welding is difficult in some places.

4. **Corrosion, Inside and Outside**—In some cases, there are reasons for not treating water underground and protection of the outside of steel pipe is likely to be incomplete.

5. **Location and Related Factors**—The angle of the pipe, its exposure to accidental damage, working room and service facilities also are factors in selection of pipe and couplings and how it is supported. Because many of these factors are difficult to evaluate, continuous dependable service is most important and repair can be highly inconvenient, innovation in high-pressure design pipe is uncommon.

Preference for seamless steel pipe for high-pressure lines has decreased with better welding and use of centrifugal pumps. Welded pipe has been used increasingly in South Africa for 25 years (Johnson,[73] p. 296). High-pressure lines usually are no larger than 10 in. to limit weight of long steep columns, facilitate placement and repair in limited shaft compartments, reduce the number of centrifugal pumps discharging to the same line and make it easier to provide a spare line. Wall thickness needed for any pressure is calculated from the minimum ultimate tensile stress with a good factor of safety; 5 is frequently used.

There is much more latitude in choice of pipe for lower pressures, such as discharge from single-stage pumps. Where volumes are large, 20-in. pipe has been installed. Chief Consolidated used numerous submersible pumps in winzes, hung on 12- and 18-in. spiral-weld pipe with Victaulic couplings.[76]

On high-pressure lines, practice is to join pipe with flanges. Simple flanges generally are preferred, but gasket material must resist extrusion by strength or by retention (Anderson,[73] p. 284). These long strings generally are assembled from the bottom up by adding one or several lengths. With the use of a cage with extensible crawls to handle the pipe and decks where crews work, more than 300 ft of pipe can be placed in a shift (Martin,[73] p. 300).

Weight usually is carried on steel bearer beams or brackets concreted into the shaft wall at intervals of 400 ft or less. The provision of an expansion joint below each bearer assists in equalizing weight, adds vertical flexibility and makes it unnecessary to raise an entire string to replace a length.

The four 10-in. 3,900-ft stainless-steel lines recently installed in Butte[42], were supplied in 60-ft lengths with a sleeve on one end and the other turned for close fit. Lengths were joined by welding as each length was added at the surface, like well casing. Strings 500 ft and more long were assembled in this manner. These were lowered and welded into the last-placed component. Guides 20 ft apart prevent side movement but all weight bears on a concrete bridge at the elevation of the pumps. An expansion joint is provided at the surface.

The usefulness of expansion joints in long lines is questioned because of their tendency to "freeze" with scale and rust. An increasing tendency to omit them seems to prove that they are unnecessary. Where they are used, it is likely that periodic maintenance is needed to keep them functioning (Anderson, Gimkey,[73] pp. 290, 294).

In inclined shafts, pipe commonly is hung from steel posts or from rock pins at intervals of a pipe length or less. Lines up pit walls are similarly set on piers—if possible where exposure to flyrock and likelihood of pit expansion are least. In some cases, both hazards are avoided by pumping through nearby shafts.

Gate and check valves are placed in the discharge of each centrifugal pump for use in starting and for protection during the repair of a pump connected to an active discharge line.

26.4.10—TESTING PERFORMANCE OF PUMPS

Well-equipped manufacturers have extensive facilities for testing large pumps with precision. Comparable test facilities are uncommon in deep mines and construction, yet records of performance are essential to evaluate the results of pumping and to guide maintenance. Serviceable data can be obtained by such means as the following:

1. Measure the total output by a weir on the surface. This can be integrated and recorded. In some cases, it is possible to measure rate by pumping into or out of a large sump or tank, but usually with less satisfaction. Inflow can be estimated by adding the water removed with ventilating air and subtracting any water piped into the mine for drilling and washing, and decant water from hydraulic fill.
2. Measure pumping rate of each pump by any of several means including magnetic flowmeters, venturis, or orifices, weirs or pumping from or into a sump. Provision of these measuring devices in the discharge of each pump makes it possible to check each periodically with little labor and loss of pumping time.
3. Measure individual discharge and suction heads with calibrated Bourdon-type gages placed appropriately. In view of the close relation between high suction head and efficiency, it may be better to measure these heads with a mercury manometer.
4. Mechanical input can be determined from a calibrated watt-hour meter, subtracting the motor loss as taken from the manufacturer's test data. Various torque dynamometers can be used for a more fundamental determination of power input.
5. Pump speed is most readily measured by a calibrated tachometer and stopwatch, and this is generally adequate.

The rate of discharge of a pump and discharge pressure can decrease with time because of:

1. Scale formed in the discharge or other change increasing the dynamic head.
2. Decrease in suction head, as by scale, obstruction of intakes, etc.
3. Decrease in effective diameter of the runner or other severe pump wear.
4. Blocking or other obstruction of the runner passages.
5. Wear causing excessive leakage between stages of multistage pumps and across wear rings in single-stage.

All pumps discharging into a single line should be kept "balanced" to operate together efficiently. In an extreme case, the head of one pump could decrease until flow is reduced to the degree that the pump bearings seize (Low,[73] p. 219).

26.4.11—COST OF PUMPS

In most cases, half a dozen of the pump characteristics in the check list given in Sec. 26.4.7. are likely to be more significant than the first cost of the pump.

The cost of standard water ends of horizontal centrifugal mine pumps generally is 30 to 50% of the total cost of the pump-motor-starter unit. It may be only 5 to 15% of the cost of the pumping plant including sumps, clarification, power supply, ventilation, suction, discharge and required excavations. The construction of the pump influences the cost of the station—e.g., vertical pumps require less floor space and no suction. Efficiency is important because power ordinarily is the largest part of operating cost. Where planning makes it practicable, a single high-head pumping installation can be more efficient as well as simpler than a series of pumping stations each working at a lower head.

Minimum estimating list prices of pump-motor-starter units are shown in Fig. 26-14 in relation to capacity in million foot-gallons per minute. These are for the least expensive combinations of pump metal, motor and starter. Additions should be made if special drives or special protection against corrosion or abrasion are planned.

The approximate motor input horsepower shown in Fig. 26-14 is based on assumed efficiency of 60% (motor × pump) for small units, 75% for larger pumps and up to 80% for units of large capacity. Large units, in which both motor and pump are excellently matched to the pumping duty, may go higher—e.g., 90% pump × 93% motor (see discussion of motors and starters, Sec. 26.4.8).

Prices of submersible and deep-well pumps include the cost of the pump column pipe and cable or pump shaft, and are based on the assumption that water is discharged to atmosphere at the surface. Small-capacity well pumps are designed to be used in small wells. Many stages are required for high heads. Hence, these pumps tend to cost more than well pumps of large capacity.

If Fig. 26-14 is used to compare costs of well pumps and horizontal centrifugals, consideration should be given to discrepancies in foundations, suctions, valves and discharge pipe.

The prices of horizontal centrifugal pumps in 316 stainless steel (pump only) can be approximated by multiplying the price of the standard pump by factors. For the water end (pump only), these are:

	Factor
Horiz. centrif. pumps, heads to about 600 ft	1.75
Horiz. centrif. pumps, heads to about 1,200 ft	1.9
Horiz. centrif. pumps, heads to about 4,000 ft	2.5

Because Fig. 26-14 shows prices of complete pump-motor-starter units, the factors for use against prices shown by that table should be:

Low-Head, about	1.4
High-Head, about	1.75

Corrosion resistance can be provided for close-coupled vertical turbine, deep-well and submersible pumps. Price multipliers are approximately:

Vertical turbine (pump only), all-bronze bowls, 416 stainless-steel shaft	2.2
Niresist bowls, 304 stainless-steel shaft	2.6
Submersible pump motor, combinations noted, all-bronze bowls, standard steel motor	2.0
Zincless-bronze bowls, stainless-steel motor	3.5
Niresist bowls and stainless-steel motor	4.0
316 or 304 stainless-steel with 316 stainless-steel motor	5.5

26.4.12—COST OF PUMPING

Conditions which make for low unit pumping cost include:

Large, nearly uniform volume—say several million foot-gallons per minute.

Dependable power at moderate cost.

Clear cold noncorrosive water.

Well-designed dependable system.

Easy write-off with life of 15 or more yr for all major units of the system.

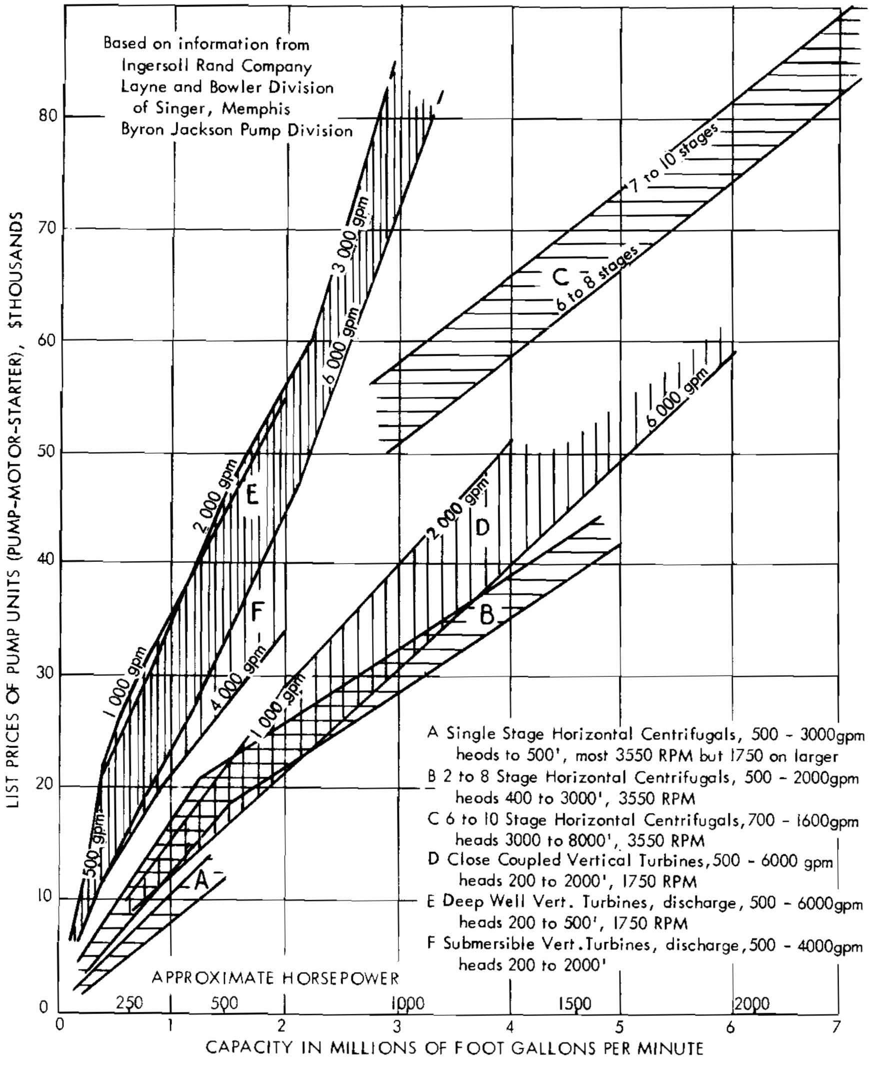


Fig. 26-14—Minimum estimating prices of pump units, 1970—standard iron construction for clear noncorrosive water, with drip-proof squirrel-cage induction motor and across-the-line starter at 480 v to 450 hp and 2,300 v from 500 hp up.

Where all these favorable conditions exist, a basic pumping cost may be made up of:

	Per Million Foot-Gallons, $
Power, 4 to 5.5 kw-hr	------------
Write-off, pumps, drivers	0.01
Write-off, other parts of system	0.02
Maintenance	0.005–0.01
Total (add power at appropriate rate)	0.04

Not only is there a large variation in power cost but at some mines having ample storage and pumping capacity, pumping can be done during periods of low demand at much less than normal rates. In some places, use of water or the recovery of dissolved mineral might be considered to justify a credit against pumping. Under unfavorable conditions especially in combination, unit pumping costs can be very much higher.

26.4.13—COSTS OF WORKING WET GROUND AS COMPARED WITH DRY

The added cost of working in wet ground, compared with dry, can be much more than the total pumping cost. This is true in open pits as well as underground. The basis for the statement is given in the following checklist of items which may increase the cost of working wet ground (Note: effective advanced dewatering eases or eliminates all but the last four items).

1. Higher labor costs from lower efficiency, more absences, wet pay, waterproof-clothing allowance, increased hazards to shaftmen, electricians and operators.
2. Lower efficiency of equipment such as belts, bins, passways and chutes, skips, cars, trucks, feeders, screens, fine crushers.
3. Inability to use certain equipment, such as rubber-tired vehicles, on wet, soft floors.
4. Inapplicability of certain low-cost methods of development or mining, such as entry through undulating ore bodies, methods depending on off-track equipment in some cases.
5. Inapplicability of certain low-cost explosives.
6. Caving in wet blastholes.
7. Loss of friable minerals, such as sulfides washed from passways, chutes, cars, trucks.
8. Damage to product, such as to limestone by mud washed in.
9. Cost of cleaning ditches and excavating or supporting ground which would have stood if kept dry.
10. Higher cost of shipping a wet product.
11. Cost of drying a wet feed, as in a dry-process cement plant.
12. Increased cost of digging frozen ground, of handling, and of thawing or prevention of freezing.
13. Increased cost of installing and maintaining the mine power system with acceptable safety in wet environment.
14. Increased cost of building and maintaining roads, track, ditches.
15. Increased cost of maintaining mechanical equipment against abrasion and corrosion, and tires against cuts.
16. Increased cost of providing and maintaining standby facilities, such as bulkheads, water doors, accessways to pumps and sumps, and supplying power to pumps.
17. Cost of any interruption caused by inflow, cost of crew, equipment or supplies for emergency control.
18. Increased cost of maintaining cooling power of ventilating air.
19. Cost of maintaining a stockpile and a financial reserve to continue work in case production is interrupted by flooding.
20. Cost of pumping during any work stoppage.
21. Cost of any treatment given water before discharge.
22. Cost of any liability attributable to dewatering, effluent discharge or preventing it.
23. Cost of engineering, planning, consulting attributable directly or indirectly to water.

26.5—WATER IN SURFACE MINING

26.5.1—GENERAL

Water is not likely to be as spectacular a problem as in underground mining, but still it is an important factor in costs and output of many pits. Dewatering costs of $0.18 per ton of ore are noted at a sizable open pit. Maintenance of equipment which must be worked in mud and grit generally is more than normal and its output less. Advanced dewatering increases the stability of pit walls below the static water level. In most pits, maintenance of roads calls for a degree of water control. Twenty of the examples in the outline, Sec. 26.2.1, are open pits.

Probably all the effects of water noted underground are seen, to some degree, in open pits. In addition, there may be greater difficulty in protecting pump installations from blast damage, fluctuations of inflow are likely to be greater and more sudden, the area of rock exposed is likely to be much greater, the effect of water on stability may be more important,[35,40,43,56] but pumping heads generally are less. For direct and indirect effects, see Secs. 26.2.2 and 26.4.13.

As to water, pits might be classified as follows:

1. Pits needing sloped working levels, ditches and small pumping plants to control minor inflow, rainfall and snow-melt. Among these are mines above the water table, on steep slopes, in rock of very low permeability, in areas of low precipitation. Pumps, if needed, generally are in the pit bottom.

2. Pits with moderate to large inflow, probably the majority, perhaps needing some diversion of surface water and pumping, not only to keep the pit dry but for efficiency, maintenance, stability or to keep products drier. Pumps may be in the pit bottom but dewatering through wells offers distinct advantages, which may justify additional preproduction time and cost.

3. Pits which cannot be mined under water and are in ground so wet and, in some cases, weak also, that dewatering appears to be a necessary preparation. Pumping rates can be as large as 53,000 gpm at Nyirad bauxite, Hungary,[68] and 175,000 gpm from the Garsdorf lignite mine, Rhineland.[24]

4. Pits below rivers, lakes or swamps opened by a combination of pumping or river diversion and stripping. Quantities may be huge, as at Caland, Ont., where 162 million cu yd of overburden was moved as far as 30,000 ft and lifted as much as 472 ft. Hydraulic cutterhead dredges have been used.[47]

26.5.2—DITCHES, SUMPS AND PUMPS IN THE PIT

Unless ground is highly permeable, some of the precipitation in hillside pits can be caught in adequate ditches and diverted. Floors should slope away from faces enough to drain them.

The simplest pumping is from a small sump at an initial low elevation on each newly opened working level. If inflow is minor, a small submersible pump discharging through a hose to the lowest sump is convenient. Larger flows can be handled by skid-mounted pumps set up beside the sump. These pumps require more attendance, as need for priming complicates automatic control and neither maintenance nor efficiency are likely to be good.

A float-mounted pump can be moved more easily. It can be a vertical pump with submerged intake, easily automated. Vertical pumps also can be mounted on simple platforms eliminating discharge hose. Stubbins[75] comments on these arrangements with special reference to protection required for cold-weather operation.

26.5.3—DEWATERING WELLS FOR OPEN PITS

Dewatering though wells is discussed generally in Sec. 26.4.2. Remarks here are limited to their use for open pits. As in underground mining, there are cases in which advanced dewatering probably is the most practical, and indeed in some, the only apparent course.

In cold places advanced dewatering offers special advantages noted in the checklist, Sec. 26.4.13 and Table 26-3. Except for part of the spring runoff, pits at Knob Lake, Quebec-Labrador, are dewatered by wells in the pit bottoms. Masses of low permeability are found in complex relation with more permeable rock. Wells drilled outside pits would be considerably deeper and more expensive and would not be certain to drain ground to be mined. About 16,000 gpm was pumped in 1964.[35] At Pine Point, NWT, pits in nearly horizontal comparatively stable dolomite are dewatered by wells outside the pits. About 27,000 gpm was pumped in 1969–70.[64,65] Some 35 to 40 wells are pumped at each mine from about 100 ft below planned pit bottoms.

In kaolin pits at Huber, Ga.,[67] and the Neyveli lignite mine, India,[100] deep wells are pumped to lower the artesian pressure in aquifers below the ore.

At Nyirad, Hungary, advanced dewatering was begun in 1957 because progressively larger inflows from solution cavities in limestone, encountered above, in and below the bauxite being exploited, made it impossible to plan. About 53,000 gpm was pumped in 1968 by submersible pumps set in wells of 2 m in dia about 200 m deep. Wells are bored because inrushes made conventional sinking slow, costly and hazardous. Drawdown is expected as far as 20 km from the wells.[68]

TABLE 26-3—Comparison of Three Open Pit Pumping Systems

<table>
<tr><th>A
Sumps and Pumps in Pit</th><th>B
Deep Wells in Pit</th><th>C
Deep Wells Outside Pit</th></tr>
<tr><td rowspan="2">Most flexible, needs least planning, least preparatory expense and time
Effect on regional water table is minimized and deferred as long as possible. Rate and total volume pumped generally are minimized
Pumps are grouped at sumps
Where water is a minor problem, pumping from the pit is likely to result in lowest cost
Also good application where there is large inflow in pits of large area so that cost of each settler-sump-pump installation is well spread
Easiest way to handle surface water</td><td>Wells are not as deep as wells outside pit limits, as in Col. C
Pumps are not as scattered as if outside pit, as in Col. C
Where drilling is difficult may be lower cost than with wells outside pit, as in Col. C
Can take advantage of any topographic relief to minimize lifting water out of pit
Where drawdown cones are steep, wells in pits are more effective than outside</td><td>Wells can be pumped without interruptions for blasting and loading
Wells can be drilled without interference with work in pit bottom and are not in the way of blasting
Wells are less shaken by blasting
Pit is clear of pumps, power and discharge lines
Discharge lines can be short and easily drained
Although wells are scattered, service is likely to be easier and the pumps are more accessible than if in the pit</td></tr>
<tr><td colspan="2">Pit is free of sumps; digging and cleaning ditches is minimized
Pumps do not freeze if stopped
Water table can be lowered so that pit does not begin to fill soon after a power interruption or other stoppage, and is not so likely to flood in heavy storms
Rock near toes, sumps, new cuts can be dewatered
Walls are more stable
Road maintenance can be better
Rates of pumping are more uniform than with Col. A arrangement
Water is likely to be cleaner and may be better chemically than Col. A arrangement</td></tr>
</table>

At the Garsdorf mine in Nordrhein-Westphalia, an average of about 175,000 gpm is pumped by submersibles capable of lifting up to 4,000 gpm from 1,050 ft. Water is in thick severely faulted weak silt beds above the coal. The operators believe that there is no other practicable way of maintaining acceptable pit slopes. As mining goes deeper, they expect to use pumps of as much as 2,000 kw in wells as deep as 1,600 ft. Wells are gravel-packed. In the entire Rhine Dist., more than 600 wells were pumped in 1965, feeding some 750,000 gpm into the Rhine or its tributaries.[24,101]

In dewatering, the importance of understanding the water occurrence, appropriate planning and allowance of sufficient time cannot be overemphasized.

26.5.4—COMBINATIONS, MODIFICATIONS OF SYSTEMS

At Knob Lake, heavy snow-melt is caught in and pumped from sumps, though dewatering wells are pumped all year.

Water from open pits at Ruth, Nev., and Jeffrey Mine, Que., is collected in adjacent underground workings and pumped from underground sumps through shafts to the surface.[40,102]

Walls and floor of the Lucky Mc mine, Wyo., are drained by a peripheral ditch dug and maintained to at least 8 ft below the pit floor by backhoes.[17]

26.5.5—PUMPS FOR OPEN PITS

Many open-pit pumping systems can tolerate more suspended solids and acid than can those for deep underground mines. This is especially true of shallow pits and strip mines, and pits which are deepened rapidly and where inflow is small. In these cases, the tendency is toward abrasion- and corrosion-resistant pumps. Vertical centrifugal pumps are especially useful. Set on rafts or platforms, motors are well above water yet the pump unit is sumberged and automatic control is provided readily. They can be fitted to resist abrasion and corrosion. For repair, they must be pulled out of the water but otherwise maintenance is not difficult.

Dewatering is discussed in Sec. 26.4.2 and pumps and controls generally in Secs. 26.4.7 and 8.

26.5.6—COMPARISON OF OPEN-PIT PUMPING SYSTEMS

Table 26-3 is a comparison of three pumping systems.

Because preproduction time and expense are lower and flexibility is high, pumping from sumps in pit bottoms is likely to be favored in strip mining and comparatively shallow pits, where inflow is not large and where there are no special advantages in dewatering through wells.

Comparison of costs of pumping directly from a pit bottom and dewatering through wells is difficult. Complete comparison should include any applicable indirect items such as those shown at the bottom of Cols. B and C, Table 26-3. However, in some cases, a few more readily obtained items may be sufficient. At a Quebec-Labrador iron mine, the production of ore with 2% less moisture is credited with saving $0.12 per ton on the cost of shipping the product.[35]

In selection of a water-handling system, dependability, ease of maintenance and durability are prime considerations. Where large numbers of pumps are to be used, especially in remote locations, standardization also may be important.

26.6—MINE-DRAINAGE POLLUTION CONTROL

The most important type of pollution resulting from mining activities is acid mine drainage. Although primarily a problem associated with the coal industry, the acid-mine-drainage problem potentially exists wherever sulfide minerals, particularly iron sulfides, are associated with the ore body. As yet there is no positive or complete solution known, but means have been found for eliminating or minimizing the pollution load in many instances.

26.6.1—THE PROBLEM

Oxidation of the exposed surfaces of the sulfide minerals associated with the ore body is the initial step in the formation of mine acid. As oxidation continues, acid salts are formed, and the parent materials disintegrate and expose new surfaces to oxidation and further acid formation. Time thus becomes an important factor in the amount of acid formed. The longer the acid-producing materials are exposed to the atmosphere, the greater the amount of acid which will be formed.

Water invades almost every mine in the form of direct precipitation, surface runoff and underground percolation. Atmospheric moisture also is present, which hastens the oxidation process. As the water flows over or through mined material it becomes mine drainage, whose quality at any time is the net result of the alkaline and acid materials dissolved in it. When water comes in contact with acid material in the mine, it becomes the transporting agent for any acid that has been formed. If the acid thus picked up exceeds the alkaline component, the mine drainage will be acid in character.

Chemical reactions which follow are an oversimplification of a complex series on which principal investigators do not yet altogether agree:

$$FeS_2 \text{ (pyrite)} + H_2O + 7O \rightarrow FeSO_4 + H_2SO_4 \quad (1)$$

This probably is the initial step in the production of acid. The rate at which it proceeds is variable and depends on such factors as pyrite properties and composition, temperature, and pH of the water.

The second step also depends on aeration and temperature and may involve bacterial oxidation by an iron-oxidizing bacterium.

$$2FeSO_4 + O + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O \quad (2)$$

The ferric sulfate hydrolyzes, forming more acid and precipitating ferric hydroxide and basic sulfates. The approximate formula for the reaction is:

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4 \quad (3)$$

26.6.2—CONTROL PRACTICES

The practices in mine drainage control can be divided into two categories. The first includes those aimed at preventing the formation of mine drainage; the second, the various processes for treating acid mine drainage once it has been formed. Prevention is preferred over treatment as it is less expensive and is permanent in nature.

Prevention—Preventive practices are based on eliminating one of the three reactants (acid-forming mineral, oxygen and water) that combine to form acid mine drainage.

The diversion of surface waters and ground waters to prevent entry or reduce the flow of water into and through workings has been discussed. In surface mining, diversion ditches also should be maintained above the highwall to minimize entrance of runoff water into the pit. Slope of the ditches should be limited to 1 to 3% and, if possible, they should not exceed 1,500 ft in length.

Water that does gain entry to the workings should be handled in a manner that will reduce the flow through or over acid-producing materials. To accomplish this, mine water should be removed as quickly as possible or accumulated for later removal in sumps or other storage facilities located as near as practicable to the point of inflow into the mine. Local depressions in the bottom which permit the accumulated water to spread out over a relatively large area are not suitable sumps. Sumps should be kept free of acid-forming materials and should be pumped continuously to maintain a static water level. Mine water should be conducted in acid-resistant pipes rather than ditches, unless such ditches can be kept free from acid-producing materials. If gravity flow cannot be relied on, local pumping stations or suction pickup stations should be employed. These techniques are applicable in both underground and surface mining.

Refuse from the mining and processing of coal and other minerals represents a potential source of acid mine drainage and should be handled and disposed of in a manner which will minimize drainage. In constructing a refuse pile, care should be taken to insure that all refuse is compacted to reduce oxidation and infiltration of water into the pile. Where the "size consist" of the refuse is such as to prevent effective compaction, a suitable consist should be obtained by crushing or other suitable means as necessary. Runoff water from the area surrounding refuse piles should be diverted around the piles by suitable ditches or conduits. If such runoff must pass through a pile, it should be contained in a conduit large enough to carry the maximum anticipated flow.

Probably the most effective protection against oxidation and the formation of acid in refuse piles is permanent submergence under water. This often can be accomplished by disposal in strip-mine pits where the refuse will be inundated following completion of mining. If submergence is impossible, consideration should be given to covering the refuse with suitable nonacid-producing material.

Upon discontinuance of mining operations all practicable mine-closing measures, consistent with safety requirements, should be employed to minimize the formation and discharge of acid mine drainage.[124] This provision is based on the principle of eliminating oxygen from the acid-forming material.

In underground mines below surface drainage, flooding following completion of mining will eliminate the oxygen and normally will eliminate future acid formation.

In underground mines at elevations that will permit gravity drainage to the surface, effective application of this provision requires careful preplanning of mine openings to avoid, wherever practicable, numerous openings to the surface and locations that would render sealing impossible. It should be recognized that mine sealing by the use of bulkheads, unless all fractures and subsidence cracks to the surface are effectively sealed, has limited effectiveness in preventing oxygen from entering the mine. Prevention of the formation of acid mine drainage can only be insured if the coal seam and/or other acid-producing strata and materials are submerged. Where practicable, therefore, bulkheads should be designed to be watertight seals and be constructed to withstand the water and earth pressures which may be imposed on them.

Detailed construction of bulkheads is treated in Sec. 26.7.4. If a masonry seal is constructed, a concrete footer is recommended in lieu of hitching the block directly into the bottom clay. The perimeter of the seal should be sealed with concrete and both the inby and outby surfaces of the seal should be covered with bitumastic coating, urethane foam or other acid-resistant coating. In addition to protecting the seal from corrosion by contact with acid water, the coating also decreases the permeability of the seal. To prevent fracturing of the masonry seal, adequate roof support must be provided on both the inby and outby sides.

Upon the permanent abandonment of strip pits, or the completion of auger mining, all acid-producing refuse should be removed, buried or submerged. The face of the coal seam in the bottom of the pit should be covered or submerged, and proper provisions for handling water should be established.

Treatment—The principal methods for treating mine water are designed to neutralize acidity and remove iron by processes involving the use of lime or limestone, and by demineralization.

Most mine water treatment processes involve lime neutralization. Lime generally is available and has a high basicity. Its cost, while high, is less than that of all other bases except limestone and waste material. Complete lime-treatment processes include neutralization using hydrated lime, aeration to oxidize the iron from a ferrous (if present) to a ferric state, sludge settling and sludge disposal.

Neutralization costs are dependent on the quantity of water to be treated, the total acidity of the water and the ferrous iron content. For example, costs for treating one highly acidic water (acidity, 2,800–4,000 ppm; ferrous iron, 900–1,200 ppm) ranged from $0.48 per 1,000 gal for a plant with a capacity of 8,000,000 gpd to $0.62 per 1,000 gal for a plant with a capacity of 300,000 gpd.[103] Costs of neutralizing weak acid water (acidity, 600 to 700 ppm; ferrous iron, 300 ppm) ranged from $0.19 per 1,000 gal for an 8,000,000-gpd plant to $0.28 per 1,000 gal for a 30,000-gpd plant.

Because of its low cost, limestone treatment is most appealing. However, unless sufficient oxidation is provided, this type of system is not satisfactory for treating ferrous-iron waters as the oxidation rate is too slow at the pH level attained. Another problem with the use of limestone is that, other than with low-iron waters, the limestone becomes coated with ferric-oxide hydrates and calcium sulfate and loses its neutralizing effectiveness. This problem was overcome at one mine site, by constructing a single stage-limestone treatment plant consisting of a 3 × 30-ft horizontally mounted rotating drum in which is placed approximtely 5,000 lb of 1 × 3-in. limestone.[104] The entire mine discharge of approximately 150 gpm flows through the drum, which rotates between 10 and 20 rpm. The resulting particle abrasion is sufficient to remove the coating from the surface of the stone and permit the carbonate reaction to continue.

The volume of water that can be treated using limestone can be increased if the rotating drum is used as an autogenous wet grinder to produce a —400-mesh limestone slurry that is mixed with the mine discharge. Neutralization in this process is followed by air sparging, to remove excessive CO_2, and settling.[105]

Based on a 20-yr depreciation of equipment, treatment costs involving the use of limestone can be expected to range from $0.04 to $0.60 per 1,000 gal of mine water, depending on the quality and quantity of the mine discharge and the degree of treatment required.

Demineralization treatment processes include the many saline-water-conversion processes for producing potable water.[106] Saline-water conversion theoretically can be applied to mine effluent to produce potable water. However, under present conditions, these processes do not have application to acid mine waters except in cases where a municipality needs an additional supply of potable water to meet Public Health standards. The cost of the treatment of mine water by the saline-water processes range from $0.36 to $4.05 per 1,000 gal, depending on feed rate, operating factors and water composition.

26.7—SPECIAL CONSTRUCTION FOR WATER CONTROL

26.7.1—TREATMENT OF EXPLORATION DRILL HOLES

Exploration drill holes must be cemented in some areas to prevent migration of water. There are a number of considerations.

1. If the hole is left unsupported, any soil or weak rock soon caves, partly plugging the hole and hiding it, after which treatment from the surface is at least difficult.

2. If an underground working is connected to a hole to which water has access, it may come in, perhaps with gas, at such volume and pressure that sealing from below is very difficult. Practice at a salt mine is to leave a 45,000-ton pillar centered on the mapped location of each hole. The capacity of high-pressure water to ravel weak rock and, if it carries grit, to erode strong rock and metal, must not be overlooked.

3. Without being connected to workings, wet holes can decrease stability by permitting water to saturate and weaken clay shales, and raise pore pressure.

4. Some holes, if kept open, could be used for observation of water levels, treatment, geological testing, telephone or electric lines, driving raises, etc.

Water freely supplied to vertical boreholes falls through them with head loss of 100%. Flows through clean holes of diamond-drill sizes are approximately:

Diameter, In.	Gpm
1.5	90
1.875	180
2.375	315
3.0	610
6.0	3,600

Exploration holes generally should be plugged securely before abandonment, or if they may be needed for communcation or observation, pipe or casing should be set through all weak or wet ground.[63]

26.7.2—PILOT HOLES

Wherever there may be sudden inflows at rates initially or potentially inconvenient, pilot holes should be drilled in advance of work. The use of tungsten-carbide percussion bits, jointed steel and longhole machines has greatly increased the convenience of drilling pilot holes. With this equipment, it is possible to drill 100- to 200-ft holes efficiently in most directions in most ground.

Where water may come in with sufficient force to erode the walls of a hole or in other ways make it difficult to stop inflow, holes should be drilled through a full-opening valve on a cemented-collar pipe. Use of fast-setting cement usually is desirable. For added assurance, the collar pipe can be rock-bolted.

If rock to be traversed is in homogeneous layers, one or two pilot holes should be enough. Because this assurance is uncommon, at least two, more often four and, in some cases, as many as 12 to 20 holes are drilled at angles diverging 10° to 20° from the direction of advance. A symmetrical pattern is common, though holes could be pointed to intersect conduits of known orientation. Under most favorable conditions, pilot holes provide something less than 100% assurance. Deception may arise from irregular configurations of conduits, from clay which keeps water from pilot holes, or other variations in permeability. Secondary protections may be provided by serviceable water doors, and by training crews in plugging inflows and supplying materials for doing it promptly.

26.7.3—GROUTING

Objectives may include:

1. Facilitating or permitting sinking and tunneling, rarely stoping, in weak wet ground by avoiding inrushes, reducing delays or assisting placement of tight concrete.[1,2,4,23,25,26,52–55,59,60,107,108,112,113]
2. Reducing or stopping flow past underground plugs and bulkheads.[78]
3. Reducing leakage from reservoirs, especially under dams.[109]
4. Consolidating and strengthening ground.[110,111]
5. Plugging a conduit through which work has been flooded.[2,4,79]
6. Making concrete for plugs, etc., with or without preplaced stone.[2,4,11,78]

Limitations are notable. The grout operator controls the nature of grout and the rate at which he injects it into the hole he has prepared. He can limit the pressure and, in some cases, influence the movement of water in the spaces he plans to fill. Generally, his picture of these voids and what happens in them is vague. After it has left the pipe into which he pumps it, the grout goes where it wants to go, unseen. The existence of clay in voids interferes with cement grouting. Appreciable water movement interferes with all kinds. New grout materials have increased the range of conditions in which grouting can be used, but a degree of uncertainty persists.[112]

Usual procedure is to drill the ground through casing anchored sufficiently to withstand the pressure to be used, test permeability and inject a grout, which should be chosen and used in accordance with the conditions and objectives. Conduits below the water table should be grouted before a heading reaches them. Thereafter water movement is much more difficult to control. Deep holes usually are grouted in stages: i.e., the hole is drilled until a degree of permeability is found, then grouted. After the grout has set, the hole is drilled out, deepened and again grouted. A method of stage grouting from the bottom up has been developed for grouting alluvium.[109,112]

Where walls are to be built, grouting should preceed walling, if at all possible. If not, grout pressure must be kept as low as possible.[25] Pressure against the ground must exceed hydrostatic; ordinarily, it is not allowed to exceed the vertical stress. In special work it may be desirable to open fractures by pressure exceeding the vertical stress (Sec. 26.7.4). Once grout pumping is begun it usually is continued without interruption until the planned sealing-off pressure is reached.

Dyes can be mixed with grout to "tag" various stages of injection. Effectiveness of grouting is tested by drilling new holes between or near holes which have been grouted. The degree of confidence in the result depends partly on the uniformity of the ground and partly on the nature of subsequent work.

Cement grouts do not enter the smallest fractures or pores finer than those of coarse sand. Prior treatment of the ground and admixture of sodium silicate and bentonite improve penetration but, even with this help, pores of medium sand are a limit.[112,114] Bentonite decreases strength but improves the "pumpability" of cement slurries and gives body. It also acts as a dispersant, reducing or preventing "bleed" or separation of water. Neat cement slurries do not set unless the cement particles are brought together at a specific gravity of about 1.5.[112]

Set time is reduced by use of high early strength (Type 3) cement, by the addition of as much as 2 lb of calcium chloride per sack, and somewhat more by the use of special fast-set additives. High pressure and temperature also shorten setting time. Sawdust, shredded plastic and similar materials can be added to help plug large openings. As far as the delivery system and the size of the openings permit, fly ash, sand and fine gravel can be added to reduce cost without sacrificing strength. Powdered aluminum reduces or counteracts shrinkage but where the grout sets under high pressure its effectiveness is questioned. (Table 26-4.)

The water-cement ratio is important in controlling the behavior of cement slurries. In grouting deep holes which cut openings of various widths, usual practice is to start with thin slurry, say 5 water to 1 cement, or even 10:1 by weight, in the expectation that this will get into the smallest possible openings. Average slurry on one series of shaft pregrouts was 4:1 and water was reduced to 1:1 where possible. Cement slurries of about 0.5:1 can be pumped. Slurries can be made to stand under water at 20 to 30° from horitontal. Trial runs should be made with unusual mixtures.

Acceptance of a large quantity of grout without pressure increase generally is considered to indicate that grout is running through a sizable conduit out of the ground intended. Remedies may include thickening the slurry, adding bridging materials, such as sand or chopped plastic, reducing the rate of pumping, and letting the hole stand for several hours.

At Friedensville, Pa.[2,4] and at a southwestern Indiana gypsum mine, openings were flooded by flows of approximately 20,000 and 25,000 gpm from solution cavities. Specially designed cement grout was placed through holes bored from the surface, plugging the conduits, which were 400 to 450 ft below the surface in each case (Figs. 26-15 and 26-16).

Where large quantities of cement grouts are to be used for an extended time, labor may be saved and slurry quality improved by mixing at a central plant with bins, weighing devices, water meters, agitators and pumps. With pressure, slurry can be pumped through a mile of 1- to 2-in. pipe. This plant and the grout operator are connected by telephone. For short jobs, a batching plant and truck mixers are useful.

Reciprocating simplex or duplex grout-fitted slush pumps are usual. Compressed air drive is convenient because of its flexibility. Centrifugal pumps can be used for low pressure. Pumps usually are fed by gravity from agitators.

Practice for pregrouting sites of deep shafts has developed progressively in Orange Free State and Transvaal. Pregrouting costs on four large deep shafts sunk since 1954 range from $51.5 to $73 per ft of shaft.[53] On two shafts, pregrouted and sunk to 5,500 ft concurrently between October, 1963 and March, 1966, 40 and 45% of the total pregrouting cost went for cement, the remainder for diamond drilling, cementation and supervision. Total pregrout cost was $3.30 per sack with 181,645 sacks used on both. Drilling and grouting from the surface required 16.5 mo. Delays for drilling and grouting from the shaft bottoms were only 16.5 days, during which 2,164 sacks were used.[53,54]

Clay and clay-cement grouts are used in very large quantities with, wherever possible, local clay—in part at least. Moderate strength can be obtained with the use of 50 to 60% cement but in many cases low-strength is adequate. Because they do not bleed, clay grouts do not introduce water into native clay and are likely to bond to it.[112]

Before 1949, St. Joseph Lead Co. injected some 450,000 tons of desanded tailings into 763 diamond drill holes, most drilled for exploration, in a 300-acre tract near Leadwood, Mo. An earlier attempt to mine this ground had met fracture zones,

TABLE 26-4—Typical Conditions and Objectives in the Use of Four Grouts and Comparisons of Material Cost

Clay Grouts	Cement Slurries	Acrylamides and Chrome Lignins	Resorcinol Formaldehydes
Commonly used to fill very large total volumes of small voids in weak ground such as alluvium to resist low pressure gradients. In many places local clay or mixed local and treated clay is suitable. Colloidal suspensions can be used to fill voids as small as 0.1 mm,[114] about 0.01 cm per sec, in medium sand. Clay grouts bond with native clay. They are especially useful where ground must remain tight in spite of subsidence or other movement as below large dams. Setting time is indefinite; some clays are thixotropic.	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. Cement slurries enter fractures and pores larger than about 1 mm, about 0.3 cm per sec, in coarse sand though penetration is said to be improved with sodium silicate or clay lubrication.[112] 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 slow and inexact.	Advantages are lowest viscosity, acrylamide about 2 cp until just before set. Setting time, determined rather accurately by admixture 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,[114] about 0.001 cm per sec. Strength is moderate; gels can be extruded from sizable openings but AM9 has been used to resist gradients of more than 15 psi per ft in fine sand.[107] Both gels lose water and shrink where exposed to dry air. Acrylamide also shrinks where exposed to brines. Viscosity and cost of solution pumped and set strength vary with concentration.	Advantages are moderately low viscosity and rapid set to a strong stable elastic-plastic material resembling bakelite. Resorcinol formaldehyde can be squeezed into openings almost as small as those entered by AM9. It can 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. Viscosity and cost of solution pumped and set strength vary with concentration.
Approximate Cost of Materials Only, Subject to Large Variation, Depending on Location, Volume Purchased, Etc., $ per Cubic Foot of Space Filled			
Cost of local clay with minor treatment is in some cases less than ..... $0.20 Bentonite 0.50	Neat cement slurry ..... $1.30 Sand-cement 1:1 ..... 1.00 Sand-cement-fly ash, Clay-fly ash-cement, Clay-cement ..... 0.80 to 0.50	Acrylamide ..... $5.00–$9.00 Chrome lignin 2.50– 4.50	Resorcinol formaldehyde ..... $20.00–$60.00

Close control of setting times may increase effectiveness of "Chemical Grouts," in some cases requiring less material; equipment needed to place them is more easily moved.

enlarged by solution, making as much as 5,000 gpm. The treatment reduced inflow to 5 to 10%, which was controlled by small grout injections.[52]

On limited work, substances like hot asphalt, and bentonite suspended in diesel fuel, have been used effectively.

"Chemical" grouts are liquids rather than suspensions. With sufficient pressure and time they can be forced into the smallest openings. Modern grouts are mixed before injection to set at a time chosen by the oprator. Acrylamide and a methyl derivative (AM-9) form a translucent gel which is stable in saturated air and fresh water but dries and shrinks in contact with dry air or brine. The viscosity of the mixed solutions continues to be only a little more than that of water until the set, which is sudden.[114] Chrome-lignin (Terranier) is a dark-brown liquid available in several grades of viscosity. It shrinks if exposed to dry air. Its set

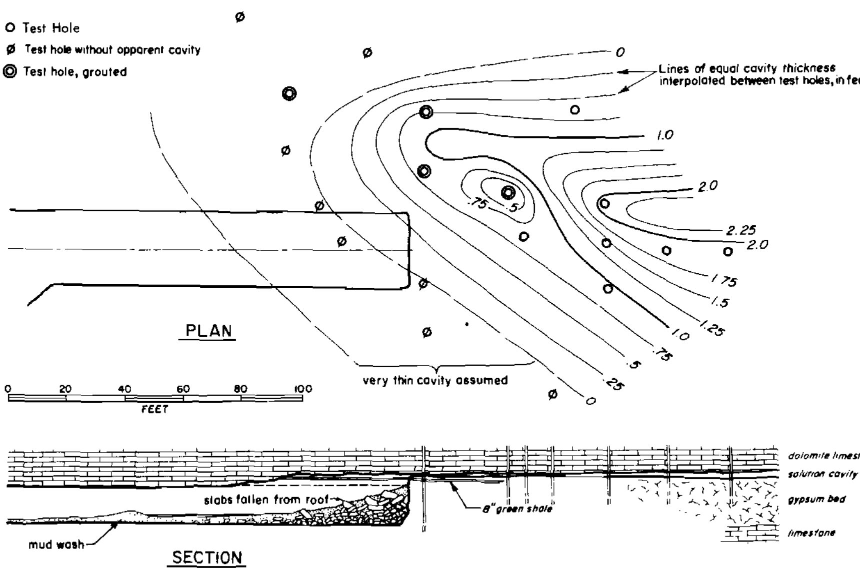


Fig. 26-15—Heading in gypsum bed, grout placement.

is more gradual. The strength of these gels depends on the concentration, but is not high. Either can be extruded from large openings by water pressure but develops greater strength in cementing sands or silts. AM-9 was used to seal a 15-ft bed of fine sandstone (average particle size, 0.25 mm, with 10% voids) against 310 psi, permitting a 19-ft shaft to be extended through the bed without difficulty. Sinking was delayed only 6 days for grouting, during which 5,500 gal of chemical was injected in 50 holes.[107]

A reddish-brown resorcinol formaldehyde resin forms a very strong stable solid resembling bakelite. Viscosity is somewhat higher than AM-9 and set is more gradual, but its time is fully controllable.

Equipment for "chemical" grouting is comparatively easy to move. With AM-9, two separate positive displacement pumps are driven so as to deliver the two components in a chosen volumetric ratio, although the rate of flow is variable. Discharges are connected by short hoses to a Y at the collar of the hole. Grout can be mixed to set in a few minutes.

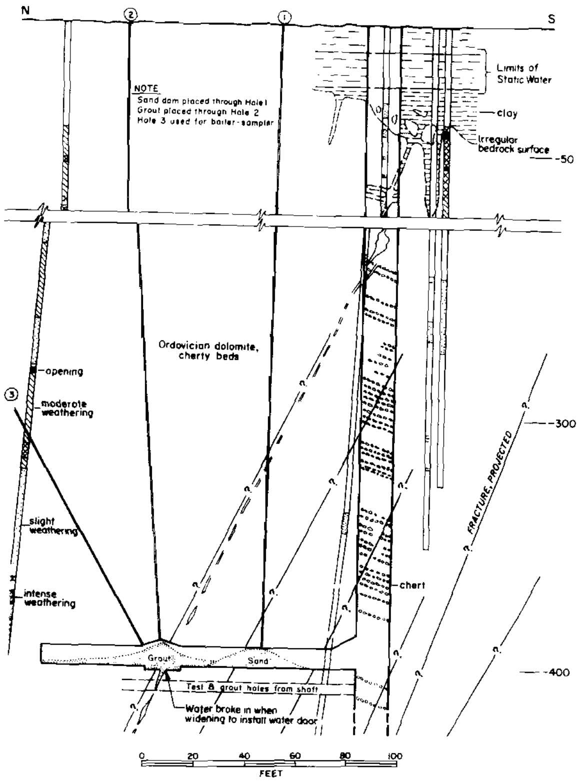


Fig. 26-16—Section across Fridensville shaft showing procedure for plugging 400-ft-level breakout (geology from New Jersey Zinc Co.).

26.7.4—UNDERGROUND BULKHEADS AND PLUGS

Deep gold mines in South Africa have developed outstanding practice, demonstrated in tests and in both routine and emergency construction.

Garrett and Campbell Pitt[78] show data on 22 plugs or bulkheads, including one enclosing a small test chamber pressured to 6,800 psi. Generally, these plugs were built in hard strong quartzite, impermeable except on fractures. Culmination of this development came with the four plugs placed in the West Driefontein mine in November, 1968. Two at a depth of 3,472 ft and two at 3,830 ft prevented the complete flooding of the mine. They were completed 20 days after the inrush, in 10 × 12-ft crosscuts. Work was undertaken with water flowing 3 to 4 ft deep on each level. Valves to stop bypassing water were closed on the 23rd day, and the lower plug withstood a head of 3,661 ft of water on the 26th day.[11,30]

Conclusions from South African practice:

1. Generally, it is more difficult to stop leakage past a bulkhead than to make it strong enough to resist thrust. Passage of water through rock fractures is related to the pressure gradient, which should be moderate.

2. More than half the 26 plugs described were neither hitched, tapered nor reinforced. Reliance was placed in the strength of the concrete bearing against the usual irregularities of the rock surface. Ten of these "parallel" bulkheads withstood pressures of more than 1,000 psi, one 2,250. No indication of structural failure resulting from thrust was noted (for typical design see Fig. 26-17).

3. Leakage is likely along the floor and roof, even at low pressure, where mud and honeycomb, laitence and air pockets commonly weaken the rock-concrete contact. These leakages sometimes are sealed acceptably by one stage of grouting.

4. At higher pressures water is likely to break through rock fractures. This appears to result from rock movement induced by pressure on rock surfaces. Part of the water entering the fractures may not appear outside the bulkhead. Much of this leakage can be sealed by several stages of cement grouting at pressures to at least 2.5 times the hydrostatic head, in holes drilled as far as 30 ft into the rock. The effect of each stage of grouting seems to be to fill the fractures, perhaps post-stressing the ground around the bulkhead, increasing its resistance to the entrance of water.

5. The loss of several bulkheads subjected to more than 1,000 psi is attributed to failure of gaskets, threaded plugs and other fittings.

6. The possibility that even the smallest leakage through fractures may be enlarged by high pressure erosion should not be underestimated.

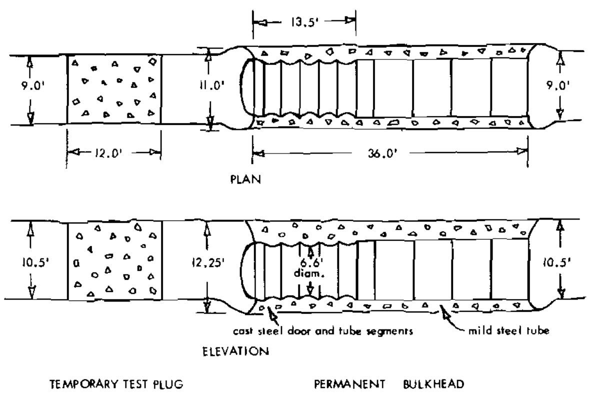


Fig. 26-17—Plug and bulkhead at Virginia Merriespruit boundary. The longer bulkhead was designed for 1,800 psi and the short temporary plug was built to test it. After an initial application of cement grout around both plugs, at as much as 2,000 to 3,000 psi, leakage increased to pump capacity (80 gpm) without sufficient increase of pressure. After two more successively deeper stages of grouting to pressures of 4,500 psi, a test pressure of 1,425 psi was reached with a leakage of 20 gpm (after Garrett and Campbell Pitt[78]).

7. Preferred construction is by injecting cement-sand grout into clean strong angular rock previously packed between timber forms. This generally results in better concrete, easier logistics and, in some circumstances, less time and cost than direct concrete placement. Type 1 portland cement usually is used but rapid-set cement can be required by urgency. Concrete should reach at least 2,500 psi in 28 days. The four recent plugs at West Driefontein were made of cement-sand slurry only. Slurry can be mixed under good control at a central plant and pumped several thousand feet through small pipe. Horizontal cold joints should be avoided by all means.

Recommendations from this work:

1. Seek sites in tight sound rock. In good ground, at least, keyways are unnecessary, but note the length next recommended.

2. Make the plug long enough that the pressure gradient is moderate. In one test, a gradient of 400 psi per ft was reached after several stages of rock grouting, but for working bulkheads designed gradients of 25 to 40 psi per ft have proved effective (i.e., for each 1,000 psi, allow between 40 and 25 ft of plug).

3. Remove all mud and loose rock, stop water flow across floor and vent high spots in roof.

4. Test pipe, gaskets, valves and fittings at a pressure somewhat greater than that to be withstood.

5. Plan several stages of grouting to reduce leaks. The first, through pipes at concrete-rock contacts, can be at a few hundred psi, later stages through holes drilled successively deeper into rock can be at successively higher pressures up to at least 2.5 times the expected hydrostatic head.

Comparable experience in other rock is unknown but several inferences seem to deserve consideration:

1. In any strong rock which can be grouted effectively, similar practice seems applicable.

2. In weaker rock, or one with seams which do not take grout well, it appears prudent to work to lower pressures and lower pressure gradients to reduce the risk of uncontrollable leakage through erosion and enlargement of rock permeability or defects.

3. No large excavation should be subjected to pressure greater than the maximum hydrostatic head unless after full study and evaluation of rock stresses.

4. Although no test is known, the use of "expanding" cement in any rock seems promising.

26.7.5—TRACERS

Tracers are put into a ground-water system at some point and used to indicate the direction of water movement and, in some cases, its approximate rate, by being recognized at a point or points downstream. None of the many tracers is ideal under all conditions.

A tracer should:

1. Be recognizable after dilution, generally with portable equipment, in some cases in test holes.

2. Be unimpaired by physical, chemical or bacteriological reaction with the water being tested or rock in contact with it—at least until recognized.

3. Move with the water.

4. Be convenient to use, reasonably available at moderate or low cost, easily soluble in water, and requiring no elaborate equipment or procedure.

5. Present no hazard or cause anxiety to anyone.

Fluorescein, an extraordinarily intense coal-tar dye, usually is purchased as a red-orange powder. When dissolved in water it is a brilliant green. One part in 40 million ordinarily is recognized by eye. One part of good quality fluorescein in 5 to 10 billion parts of clear water can be recognized in a colorless tube about 1 cm or less in diameter by 1 m long, with a black rubber stopper or other black bottom. A number of tubes can be mounted side by side in a rack. Examination should be made by good white light in front of a white reflecting surface. Tubes containing 0 to 0.002 ppm of fluorescein can be used comparatively. Fluorescein is not affected by carbonic acid but is made colorless by contact with peat, acetic acid and mineral acids. It is unaffected even by long contact with limestone, sand, silt, montmorillonite and other common clays.[115–117] Its vivid color gives fluorescein a special advantage where it is desired to make results evident to all observers. Other dyes—fast crimson, congo red, methylene blue, etc.—may be used similarly.

Chloride ion or salt is recognized in test holes by decreased resistance to electric current or chemically, providing dilution is not too great. Dense solution may be trapped in low spots. Otherwise, salt solution seems to move at the same rate as the water. It is obscured by any natural brine and changes the permeability of some clays. Nitrates and other ions are also used.

Dextrose, recognized chemically, is not adsorbed and moves at the same rate as water but is attacked by soil bacteria and is more easily lost in dilution than radioactive isotopes.

Radioactive isotopes, detected by a geiger counter, are said to be recognizable[115] in concentrations of 10^{-18}. Abnormal background may interfere. In addition, forms of cations may be taken out of action by ion exchange, and anions by adsorption. Even tritium, a hydrogen isotope, apparently can be lost by exchange reactions with natural water. To be of any use, an isotope having sufficient half-life must be chosen, yet to minimize environmental effects the shortest half-life would be desirable. Finally, operators must be trained to observe special precautions. Use must be licensed by AEC and generally by local authorities, now becoming more vigilant, and always is likely to arouse indignation.

The normal application is to place the tracer in a possible water source and watch for it to appear in the mine. For example, a tracer may be added to mine water discharge to show whether it is returning into the mine. This may be impossible if the suspected source is a very large body of water. If the mine is flooded, the tracer can be put in the mine and water pumped behind it to cause the tracer to be observed at the surface.[79]

26.7.6—MINING UNDER BODIES OF WATER

In several parts of the world, coal and iron ore in comparatively thick gently dipping sedimentary beds are mined 3 to 5 mi out under the sea by methods which produce subsidence. The substantial importance, extent and life of the work, plus a degree of uniformity in water occurrence, have made it possible to build up instructive regulations.

Steep ore bodies in crystalline rock also have been mined but here the conditions are diverse. Formal regulation would be more difficult. None is known.

Nova Scotia—The Sydney coalfield extends 45 mi along the coast of Cape Breton Island and dips under the sea for an unknown distance. Coal measures are gently folded into five synclines which diverge seaward. Between two mines, there is evidence of a sharp flexure.[118] In 1970, coal was mined between 1,400 and 2,900 ft below sea level. Least cover over longwall mining has been 681 ft. Shallower coal was mined room-and-pillar. Pillars were extracted under cover as thin as 700 ft below sea-level. No inrush has been experienced. Requirements of the Province of Nova Scotia (1947) include:[123]

1. At least 100 ft of cover over any undersea passage and at least 180 ft over any extraction work.
2. A barrier at least 50 yd wide along the boundary of each submarine lease and a barrier at least 30 ft wide against any fault on which the throw is more than 30 ft or whose walls are more than 2 ft apart.
3. Written plans, approved by the chief inspector, before any undersea work is begun and any changes made.
4. Where cover is less than 500 ft, levels, taken at least each 3 mo, and soundings at reasonable intervals to show depth of water; results and thickness of cover shown on a plan.
5. Where ground has not been probed by work in another shallower seam, and where mining is by longwall or where pillars are being removed less than 1,000 ft below the sea bottom, and where the existence of a fault is suspected, an exploratory heading must be driven at least 150 ft ahead of any extraction.

National Coal Board (Great Britain)—The Durham undersea coalfield extends about 15 mi along the coast of the North Sea. At the shoreline, coal is from a few hundred to more than 1,000 ft below the surface. Regional dip is about 1.5 to 2° seaward. Several seams are minable over much of the field. Permian magnesian limestone above the coal measures is highly permeable in places. Occasional "feeders" carry water to the coal seams but the rock is not readily eroded. Static pressure of water in feeders and test holes drilled upward from mine working generally is as from sea level. Flow of most feeders is less than 100 gpm. Half a dozen normal faults displace the coal seams, one by almost 500 ft.[46] Carboniferous beds are about half shale, and generally faults act as barriers.

Coal Board precautions against inrushes[119] include requirements that:

1. No work approach within 150 ft of the surface unless the manager has sufficient information to know if intermediate material is hazardous nor approach within

150 ft of any peat moss, sand, gravel, silt or any rock or stratum likely to contain water unless with sufficient information to know its nature and position and to determine that it is not dangerous. No working in situations noted shall exceed 10 ft wide without specific approval of the district inspector.

2. Except to preserve the mine or for sinking, no work be within 60 ft or 10 times the height of the work, whichever is greater, of hazards noted except under special regulations applicable to that mine.

3. No work approaching and within 120 ft of any of the hazards noted be wider than 8 ft and preceeded by test holes kept at least 15 ft in advance of the center of the work and not more than 15 ft apart on each side.

For undersea mining NCB requirements include the following:[119]

1. No work be done except with layout approved by the chief mining engineer of that area.

2. Longwall not be used where cover between roof and seabed is less than 105 m, and tensile strain not exceed 0.01 (10 mm per m) cumulatively; in case several seams are mined, stability of old pillars and staggering of working edges considered. (A table of maximum room height vs. cover is provided.)

3. Room-and-pillar not be used where thickness of cover is less than 60 m or Carboniferous thickness less than 45 m. Where extraction is not wider than 6 m and height not over 2 m, least pillar dimension shall be 0.1 depth; where floor becomes plastic when wet, 0.167 depth. Where pillars are extracted, cover and tensile strain shall be as for longwall.

4. Development plans show all available information on (a) levels of top and bottom and nature of potentially dangerous aquifers and the likely effect of subsidence on their permeability, (b) seabed elevations and estimated thickness of seabed drift and buried channels, (c) position of faults known or suspected which could critically reduce the thickness of Carboniferous cover, intersect the seabed or a known aquifer.

Coal Board regulations provide for special consideration where circumstances justify.

Newfoundland—In the 73 yrs before closure in 1966, 80 million long tons of crude and beneficiated ore was taken from Wabana mine; 50 million tons remain in pillars and proven reserve is said to be 36 million tons. There are three beds of minable ore in unmetamorphosed Ordovician sandstones and shales dipping about 8° to the northwest from Bell Island under Conception Bay. Numerous faults displace beds as much as 90 ft. Ore tends to break in rhombs because of two steep joint systems and bedding plane partings. Neither grade nor thickness of ore is uniform but the lowest bed, 15 to 40 ft thick, has produced the most ore. Above it is 5 to 12 ft of strong sandy conglomerate, which makes a good roof. In mining out more than 3 mi, inflow is about 250 gpm, ascribed to surface runoff and drill water.[120]

All mining has been room-and-pillar, generally with rooms 26 ft wide on 65-ft centers. Surface mining took ore from the outcrop to "heavy cover." From there to shore, about 75% was recovered. Nothing was extracted from shore to a line above which there is 200 ft of rock cover. Below that line, extraction has not exceeded 63% in the most competent ground.[45]

Tightness of the mine is ascribed to:

A. Leaving 200 ft or more of solid cover and consistently conservative mining in good ground.

B. The absence of valleys or channels in the sea bottom.

C. Several 80-ft shale beds above the ore.

D. Coatings of calcite and siderite on joints.

E. Absence of natural steep conduits.

Steep Ore Bodies in Crystalline Rock—Such ore bodies are mined under bodies of water in some places. In eastern Canada, glaciation generally has removed weathered rock and many ore bodies and their enclosing rocks are strong. The narrow gold-quartz Siscoe mine was worked from an island barely large enough for the surface plant.

Several Cornish tin mines worked steep veins in granite. The Levant extended a mile west of the shore and 2,000 ft deep. It was flooded by sea water but only after having been abandoned and permitted to fill, some 60 yr after small inflows of sea water had first come into shallow submarine workings. After 6 yr of sustained effort, the breach was plugged in 1966, some of the work and much of the control being done by divers working from small boats in 45 ft of water at low tide. New mining is to approach the sea bottom no nearer than 240 ft.[79]

26.8—SOME LEGAL ASPECTS OF GROUND-WATER CONTROL

Because of the diversity of applicable law and changes introduced periodically, detailed comment is impractical. Among considerations are:

1. Effect of pumping on the use of ground water by others.
2. Effect of water discharged by reason of its quality, quantity or variation in quantity.
3. Possible encroachment of undesirable water as a consequence of dewatering.
4. Possible damage from any other changes in the flow of ground water.
5. Possible indirect effects of dewatering, such as subsidence.

Possible liabilities of this sort should be considered as a part of any extended feasibility study. Where question arises, competent legal counsel should be sought.

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References:

1. Allen, W., and Crawhall, J. S., "Shaft Sinking in Dolomite at Venterspost," *Journa of the South African Institute of Mining and Metallurgy*, Apr. 1937, pp. 502–523.
2. Hastings, W., Kane, F. J., and Wright, F. D., "Methods and Costs of Sinking a Shaft Through a Fractured Water-Bearing Formation at Fridensville, Pa.," IC 7680, May 1954, Bureau of Mines.
3. Scott, S. A., "Shaft Sinking Through the Blairmore Sands and Paleozoic Water-Bearing Limestones," *Transactions* Canadian Institute of Mining and Metallurgy, Vol. LXVI, 1963, pp. 48–57.
4. Wright, F. D., Loofbourow, R. L., and Kane, F. J., "Water Problems in Shaft Sinking at Fridensville, Pa.," *Mining Congress Journal*, Nov. 1951, pp. 25–29.
5. U.S. Bureau of Reclamation, Tecolote Tunnel, Sept. 1959.
6. Loofbourow, R. L., and Lehmann, E. K., "A Mine Flood, Vancouver Island," SME-AIME Preprint 68AG346, 1968.
7. Rachunis, W., and Fortney, G. W., "Report of Major Mine Inundation Disaster, River Slope Mine, Port Griffith, Pa., Jan. 22, 1959," Dist. A., Bureau of Mines.
8. Gallie, A. E., "Mining Methods and Costs at the Josephine Mines," *Transactions* Canadian Institute of Mining and Metallurgy, Vol. L, 1947, pp. 589–636.
9. Bake, W. W., and Haflidson, R. S., "Rehabilitating Lower Levels, Beattie Mine," *CIM Bulletin*, Mar. 1951, pp. 139–144.

10. Signer, C. M., and Hewitt, W. P., "San Antonio Mine—Landmark on the Path of the Conquistadores," *Mining Engineering*, May 1952, pp. 459–463.
11. Cousens, R. R. M., and Garrett, W. S., "The Flooding at the West Driefontein Mine," *Journal* of the South African Institute of Mining and Metallurgy, Apr. 1969, pp. 421–463.
12. Hewitt, W. P., "Geology and Mineralization of the Main Mineral Zone of the Santa Eulalia District, Chihuahua, Mexico," *Trans. SME-AIME*, Vol. 241, Jun. 1968, pp. 228–260.
13. Miller, H. W., and Jolley, D. H., "Flooding and Recovery of the Jefferson City Mine," *Mining Congress Journal*, Jan. 1964.
14. Bogert, J. R., "Naica Battles Water and Costs as Lead-Zinc-Silver Mining Goes Deeper," *Mining World*, Aug. 1963, pp. 26–29, 38.
15. Simpson, T. A., "Geologic and Hydrologic Studies in the Birmingham Red-Iron-Ore District, Alabama," Prof. Paper 473C, 1965, U.S. Geological Survey.
16. Huttl, J. B., "Grouting Solves Water Problem at Kennecott's Deep Ruth Shaft," *Engineering and Mining Journal*, Nov. 1953, pp. 94–95.
17. Anderson, D. C., "Lucky Mc Mine," *Case Studies of Surface Mining*, H. L. Hartman, ed., AIME, 1969, pp. 275–286.
18. Argall, G. O., Jr., "Water Makes Mining Tough and Sloppy," *Mining World*, Aug. 1958, pp. 30–33.
19. Argall, G. O., Jr., "How Miners Solve Tough Problems at Ambrosia Lake's Wet Mines," *Mining World*, July 1959, pp. 34–38.
20. Argall, G. O., Jr., "Miners Beat Ambrosia Lake Problems," *Mining World*, July, 1960.
21. Whyte, W. J., and Lyall, R. A., "Control of Ground Water at Bancroft Mines, Ltd., Zambia," *Proceedings* 9th Commonwealth Mining and Metallurgical Congress, 1969.
22. Mahon, R. C., "Draining and Mining a Wet Mine," Tech. Pub. 1834, July, 1945, AIME, pp. 1–16; "Ground-Water Control in Underground Mining," *Mining Engineering*, June, 1954, pp. 632–634.
23. "Divide Tunnel: Quite a Little Difficulty," *Engineering News-Record*, Nov. 28, 1968, pp. 64–66; "Miners Drain Mountain for Rail Tunnel," same publication, Apr. 2, 1970, pp. 22–23.
24. Gartner, E. H. E., "Garsdorf Lignite Strip Mine," Ref. 17, pp. 12–35.
25. Annett, S. R., "The Chemical and Physical Aspects of Grouting Potash Mine Shafts," *CIM Bulletin*, July, 1969, pp. 715–721.
26. York, L. A., "Grouting the Prairie Sediments," *CIM Bulletin*, Jan. 1964, pp. 63–67.
27. Wiles, G. M., "Development and Dewatering Practices at Park City Consolidated Mines," *Trans.* AIME, Vol. 153, 1943, pp. 115–120.
28. Anderson, D. L., "Shaft Sinking and Development Under Hot-Water Conditions," *Mining Engineering*, June, 1959, pp. 592–593.
29. Venter, P. P., "The Problem of Underground Water in Mines," Symp. on Ground Water in Southern Africa, Pretoria, Apr. 10, 1969.
30. Cartwright, A. P., *West Driefontein—Ordeal by Water*, Ince & Sons (Pty.) Ltd., South Africa.
31. Dierks, H. A., Eaton, W. L., Whaite, R. H., and Moyer, F. T., "Mine Water Control Program, Anthracite Region of Pennsylvania, July 1955-Dec. 1961," IC 8115, 1962, Bureau of Mines.
32. Mitchell, G. W., and Johnson, A. C., "Shaft-Sinking Methods and Costs at Fad Shaft, Eureka, Nevada," IC 7495, Apr. 1949, Bureau of Mines.
33. Argall, G. O., "Soviets Recover Lead and Barite From Wet Mine," *World Mining*, July, 1969, pp. 16–20.
34. "Investigations Regarding the Safety of Hoisting Equipment and Hoisting Practice in Ontario Mines," Bulls. 138 and 138A, 1947, 1949, Ontario Dept. of Mines.
35. Stubbins, J. B., and Munro, P., "Open-Pit Mine Dewatering, Knob Lake," *Transactions* Canadian Institute of Mining & Metallurgy, Vol. LXVIII, 1965, pp. 229–237.
36. Clarke, C. D., and Reinberg, G., "Corrosion Problems in Pumping Acid Mine Water," *Trans.* AIME, Vol. 205, 1956, pp. 821–825.
37. Graton: "Tunneler's Nightmare Complete With Scalding Deluge," *Engineering News-Record*, Nov. 26, 1970, pp. 22–25.
38. Gail, C. P., "The Application of the Freezing Method to Shaft-Sinking at the Ojibway Mine of the Canadian Rock Salt Co., Ltd.," *CIM Bulletin*, Sept. 1954 p. 586.
39. Kromer, A. S., Marcotte, R. J., Campbell, C. A., Spencer, R. R., and Ostlender, P. H. "Underwatering the Osceola Lode," *Mining Engineering*, Apr. 1956, pp. 375–381.
40. Stubbins, J. B., "Dewatering and Flood Control, *Surface Mining*, E. P. Pfleider, ed., AIME, 1968, pp. 750–761.
41. Eilertson, N. A., "Mining Methods and Costs, Kimbalton Limestone Mine, Standard Lime & Cement Co., Giles County, Virginia," IC 8214, 1964, Bureau of Mines.

42. Corbett, R. P., and Ralph, F. E., "Dewatering With a 4,1000-Ft-Head Pumping Plant," *Mining Congress Journal*, Sept. 1968, pp. 33–43.
43. Brawner, C. O., "Three Big Factors in Stable Slope Design," *Mining Engineering*, Aug. 1969, pp. 73–77.
44. "Mine Drainage Abstracts," Commonwealth of Pennsylvania (bibliography prepared by Bituminous Coal Research Inc., Monroeville, Pa.).
45. Southey, V. J., "History and Problems of the Wabana Submarine Iron Mines," *Transactions* Canadian Institute of Mining and Metallurgy, Vol. LXXII, 1969, pp. 45–70.
46. Saul, H., "Current Mine Drainage Problems," *Transactions* Sec. A, Institution of Mining Engineers, London, 1970, pp. 1e–9e.
47. Davis, C., and McKay, C. E., "Mine Planners See Wider Use of Dredging," *Engineering and Mining Journal*, Jan. 1969, pp. 68–71.
48. Anderson, J. S., and Ritchie, M. I., "Solution Mining of Uranium," *Mining Congress Journal*, Jan. 1968, pp. 20–26.
49. Sievert, J. A., et al., "In-Situ Leaching of Uranium," SME-AIME Preprint 70AS334, 1970.
50. Morawski, F. P., et al., "The Griffith Mine Story," *CIM Bulletin*, Nov. 1970, pp. 1271–1282.
51. Stuart, J. R., "Developing Mesabi Orebodies Under Lake Beds," *Trans.* AIME, Vol. 190, 1951, pp. 777–779.
52. Weigel, W. W., "Mine Drainage, Southeast Missouri Lead District," *Trans.* AIME, Vol. 153, 1943, pp. 74–81, and "Grouting in the Southeast Missouri Lead District," *Trans.* AIME, Vol. 181, 1949, pp. 320–323.
53. Van den Bosch, L. W. P., "Pregrouting of Shaft Sites," 9th Commonwealth Mining and Metallurgical Congress, 1969.
54. Munro, R. D. R., Craig, A. J. J., and Pritchard-Davies, E. W. D., "Initial Water Control by Grouting at Kinross Mines, Ltd.," Association of Mine Managers of South Africa, Nov. 1966.
55. DeVilliers, G. S., "Pregrouting of the Dolomite at No. 4 Shaft, Hartebeestfontein," papers and discussions, 1960–61, Association of Mine Managers of South Africa, pp. 129–139.
56. Merrill, R. H., "The Factors That Influence the Design of Slope Walls in Rock," 6th International Mining Congress, 1970, I-C.2.
57. Weehuizen, J. M., "Sinking Two Shafts at Beatrix Mine by Drilling," *Trans. SME-AIME*, Vol. 220, 1961, pp. 311–321.
58. Kreuger, H. A., "Shaft Drilling in Southeast Missouri," *Mining Congress Journal*, Apr. 1968, pp. 46–53.
59. Nancarrow, W. C., "Control of Underground Water at Port Radium Mine," *CIM Bulletin*, Jan. 1957, pp. 28–35.
60. Quine, A. V., "Pressure Grouting at Deep Creek," *Mining Engineering*, Mar. 1954, pp. 279–281.
61. Argall, G. O., Jr., "Montepone-Monteveccio Train Speeds Driving of Sartori Level," *World Mining*, Oct. 1965, pp. 38–41.
62. Parker, J., "Temperature and Humidity Affect Strength of Rock Structures at White Pine," *Trans. SME/AIME*, Vol. 247, 1970, pp. 142–144.
63. Fischer, F. T., and Hoagland, A. D., "Hydrologic Investigation of the Middle Tennessee Zinc Districts," Vol. 1, *Mining & Concentrating of Lead Zinc*, D. O. Rausch, B. C. Mariacher, eds., AIME, 1970, pp. 95–107.
64. Brashears, M. L., and Slayback, R. G., "Pumping-Test Methods Applied to Dewatering Investigations at Pine Point Mines," NWT, Canada, AIME Preprint 71AG90.
65. Calver, B., and Farnsworth, D. J. M., "Open-Pit Dewatering at Pine Point Mines," *Trans.* Canadian Institute of Mining and Metallurgy, Vol. LXXII, 1969, pp. 341–347.
66. Hird, J. M., "Control of Artesian Ground Water in Strip Mining Phosphate Ores—Eastern North Carolina," *Trans. SME-AIME*, Vol. 250, 1971, pp. 149–156.
67. Oxford, E. F., "Development of a Kaolin Body Under Hydrostatic Pressure," SME-AIME Preprint 68AG358.
68. Horiszt, G., "Hydrogeology of the Nyirad Bauxite Region and the Results of Active Water Protection," ICSOBA, Budapest, 1969.
69. Biemesderfer, G. K., and Leske, R. H., "Ground-Water Control at Grace Mine," *Mining Congress Journal*, Oct. 1961, pp. 39–44.
70. Camozzi, R. O., "How a Tough Water Problem Was Handled at Jarbridge," *Engineering and Mining Journal*, July, 1942, pp. 45–48.
71. Conibear, J. K., "The Use of Alluvial Sand and Improvements in Hydraulic Filling Operations at the Mines of the International Nickel Co. of Canada, Ltd.," Ontario Div., SME-AIME Preprint 70AU45.

72. Ferguson, C., and Morris, M., "Mine-Water Treatment, Inco Sudbury Operations," Ontario Water Resources Commission, 1970.
73. Symp. on Pumping, *Institution of Certified Engineers of South Africa*, June 1952–Jan. 1955; reprinted, Hortors, Ltd., Johannesburg.
74. Monroe, H. L., "Design of a Water Settler at Pea Ridge," *Mining Engineering*, Dec. 1965, pp. 81–84.
75. Hall, J. G., "History of Pumping at the Chief Consolidated Mine, Eureka, Utah," *Trans.* AIME, Vol. 184, 1949, pp. 229–234.
76. Young, W. E., "Mining and Water-Control Methods at the Chief Lead-Zinc Mine, Chief Consolidated Mining Co., Juab Co., Utah," IC 7828, May 1958, Bureau of Mines.
77. Wyllie, R. J. M., "How West German Iron-Ore Miners Use Continuous Miners to Tear Out Nodular Brown Ore From Flat Bed and Slurry With Water for Pumping to Surface," *World Mining*, June 1969, pp. 26–30.
78. Garrett, W. S., and Campbell Pitt, L. T., "Design and Construction of Underground Bulkheads and Water Barriers," 7th Commonwealth Mining and Metallurgical Congress, Johannesburg, Vol. 3, 1961, pp. 1283–1301.
79. Batchelor, D. H., and Wardle, Lt. Cdr. H., "Sealing of the Undersea Breach Into Levant Tin Mine, Cornwall," *Transactions*, Sec. A, Institution of Mining and Metallurgy, 1969, pp. 65–89.
80. LeGrand, H. E., "An Overview of Problems of Mine Hydrology," SME-AIME Preprint 72AG5, 1972.
81. Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., "Theory of Aquifer Tests," Water Supply Paper 1536 E, U.S. Geological Survey, 1962.
82. Bruin, J. and Hudson, H. E., Jr., "Selected Methods for Pumping Test Analysis," 3d ptg., 1961, Illinois State Water Survey.
83. Meinzer, O. E., *Physics of the Earth-IX, Hydrology*, McGraw-Hill, New York, 1942.
84. Rorabaugh, M. I., "Graphical and Theoretical Analysis of Step-Drawdown Test of Artesian Well," *Proceedings*, Hydraulics Div., American Society of Civil Engineers, Vol. 79, Separate 362, Dec. 1953.
85. Walton, W. C., "Selected Analytical Methods for Well and Aquifer Evaluation," Bull. 49, 1962, Illinois State Water Survey.
86. Wenzel, L. K., "Methods of Determining the Permeability of Water-Bearing Materials," Water Supply Paper 887, 1942, U.S. Geological Survey.
87. Craft, B. C., and Hawkins, M. F., *Applied Petroleum Reservoir Engineering*, Prentice Hall, Englewood Cliffs, N.J., 1959.
88. Muskat, M., *The Flow of Homogeneous Fluids Through Porous Media*, McGraw-Hill. New York, 1937.
89. Goodman, R. E., Moye, D. C., van Schalkwyk, A., and Javandel, I., "Ground-Water Inflows During Tunnel Driving," *Engineering Geology* (AEG), Vol. 2, No. 1, Jan. 1965, pp. 39–56.
90. Terzaghi, K. and Peck, R. B., *Soil Mechanics in Engineering Practice*, John Wiley, New York, 1948.
91. Dudley, W. W., Jr., "A Technique for Predicting Water Inflow to Large Underground Openings," SME-AIME Preprint 71AG70.
92. Worley, M. T., "Ground-Water Influx Into a Vertical Mine Shaft," *Trans. SME-AIME*, Vol. 223, 1962, pp. 428–431.
93. Loofbourow, R. L., and Brittain, R. L., "Dewatering Through Wells Before Mine Development," *Mining Congress Journal*, July 1964.
94. Patten, E. P. Jr., and Bennett, G. D., "Application of Electrical and Radioactive Well Logging to Ground-Water Hydrology," Water Supply Paper 1544-D, 1963, U.S. Geological Survey.
95. Smith, W. O., and Sayre, A. N., "Turbulence in Ground-Water Flow," Prof. Paper 402E, 1964, U.S. Geological Survey.
96. Stuart, W. T., "Pumping Test Evaluates Water Problem at Eureka, Nevada," *Trans.* AIME, Vol. 202, 1955, pp. 148–156.
97. Blankennagel, R. K., "Hydraulic Testing Techniques of Deep Drillholes at Pahute Mesa," open-file report in cooperation with AEC, 1967, U.S. Geological Survey.
98. Marine, I. W., "The Permeability of Fractured Crystalline Rock at the Savannah River Plant," Prof. Paper 575B, 1967, U.S. Geological Survey, pp. B203–B211.
99. Theis, C. V., "Relation Between the Lowering of the Piezometric Surface and the Rate of Discharge of a Well Using Ground Storage," *Transactions*, 16th ann. mtg., American Geophysical Union, Pt. 2, 1935.
100. Brealy, S. C., "Ground-Water Control in Opencast Mining, *Proceedings* Symp. on Opencast Mining, Institution of Mining and Metallurgy, Nov. 1964, pp. 390–415.
101. Tilman, W., "Brown Coal, West Germany," Ref. 40.

102. Grosz, R. W., "The Changing Economics of Surface Mining," Ref. 17, pp. 195–209.
103. Corsaro, J. L., Holland, C. T., and Ladish, D. J., "Factors in the Design of an Acid Mine Drainage Treatment Plant," 2d Symp. on Coal Mine Drainage Research, May, 1968, pp. 274–290.
104. Calhoun, F. P., "Treatment of Mine Drainage with Limestone," Ref. 103, pp. 386–391.
105. Mihok, E. A., Deul, M., Chamberlain, C. E., and Selmiczi, J. G., "Mine Water Research—The Limestone Neutralization Process," RI 7191, Bureau of Mines.
106. Schroeder, W. C., and Marchello, J. M., "Study and Analysis of the Application of the Saline-Water Conversion Process to Acid Mine Water," R. & D. Progress Rpt. No. 199, 1966, Office of Saline Water, Dept. of the Interior.
107. Bilheimer, L., "Chemical Grout Technique Solves Meramec Shaft-Sinking Problem," *Engineering and Mining Journal*, Nov. 1959, pp. 107–108.
108. Atherton, F. G., and Garrett, W. S., "History of Cementation in Shaft-Sinking," Symp. on Shaft-Sinking, 1959, Institution of Mining Engineers, London.
109. Bowman, W. G., "Record Grout Curtain Seals Nile's Leaky Bed," *Engineering News-Record*, Feb. 29, 1968, pp. 22–24.
110. Bogert, J. R., "San Manuel Lowers Cost by Grouting Bad Ground," *Mining World*, Sept. 1961, pp. 22–25.
111. Goss, J. W., and Coolbaugh, M. J., "Use of Pressure Grouting to Stabilize Ground in the San Manuel Mine," *Trans. SME-AIME*, Vol. 220, 1961, pp. 326–332.
112. International Society of Soil Mechanics and Foundation Engineering, *Grouts and Drilling Muds in Engineering Practice*, London Symp., May 1963, Butterworths.
113. Munro, R. D. R., "Longhole Drilling With a Percussion Machine During Shaft-Sinking," Association of Mine Managers of South Africa, Aug. 1966.
114. Caron, C., "The Development of Grouts for the Injection of Fine Sands," Ref. 112, pp. 136–141.
115. Kaufman, W. J., and Orlob, G. T., "An Evaluation of Ground-Water Tracers," *Transactions* American Geophysical Union, Vol. 37, No. 3, June 1956, pp. 297–305.
116. Thatcher, L. L., "Evaluation of Hydrologic Tracers," Geological Survey Research 432, 1961, U.S. Geological Survey, p. D-396.
117. Kent, D. F., "Techniques Used in Mine-Water Problems of the East Tennessee Zinc District," Cir. 71, 1950, U.S. Geological Survey.
118. Zorychta, H., MacFadgen, D. W., and Smith, F., "Strata-Control Measurements in the Sydney Coal Field," *Transactions* Canadian Institute of Mining and Metallurgy, Vol. LXX, 1967, pp. 38–48.
119. National Coal Board of Great Britain, Mines & Quarries Act, 1954; Coal and Other Mines, Precautions Against Inrushes, *Regulations*, 1956; App. to Pl/1968/8.
120. Coughlan, W. K., "Geology of the Wabana Deposit," *CIM Bulletin*, Feb. 1966, pp. 171–175.
121. "Mufulira Disaster Prompts Strict Regulations in Zambia," *Engineering & Mining Journal*, Dec. 1971, pp. 40, 102.
122. Shuter, E., and Johnson, A. I., "Evaluation of Equipment for Measuremet of Water Level in Wells of Small Diameter," Circular 453, 1961, U.S. Geological Survey.
123. Nova Scotia Coal Mines Regulation Act, 1947, Part VIII, Submarine Areas.
124. Moebs, N. N., and Krickovic, S., "Air-Sealing Coal Mines to Reduce Water Pollution," RI 7354, Mar. 1970, U.S. Bureau of Mines.