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WATER CONTROL FOR SHAFT SINKING

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INTRODUCTION

As the search for minerals leads to deeper mines the need to control water inflow into mine shafts and mine workings will grow. As shallower more readily available minerals are exploited, ore bodies which were previously uneconomic be cause of their depth will now become attractive targets. In known mining districts new ore bodies are being discovered down dip of existing ones. In the west many metal deposits are being developed in rocks of the mountain front pediments, frequently covered by several hundred feet of saturated alluvium. Greater depth often means that workings are developed well below existing water tables, creating high hydrostatic heads adjacent to mine workings.

The purpose of this paper is to review some of the methods available for determining if water control will be necessary and to present some of the techniques for locating water bearing zones and the amount of water to be expected. The paper will concentrate on problems associated with water control in mine shaft development, although many of the exploratory techniques are similar to those needed for assessing overall mine water inflow problems. A brief case history on water control problems in mine shafts in the Grants mineral belt of northwestern New Mexico is presented.

Water control during shaft sinking presents some unique features. First, the problem is a relatively short term one, since water control is often necessary only while the shaft is being sunk. Control measures may be necessary only while the shaft is open into the water bearing zone and the lining installed and cemented. Secondly, limited working space within the shaft area presents difficulties in handling large amounts of water inflow. The presence of water in the shaft working area increases sinking time and the potential hazard to miners. Finally, there is the economics of shaft sinking. While the shaft is being sunk no ore is being produced and there is every incentive to minimize costs.

IMPORTANCE OF WATER CONTROL

The importance of controlling water inflow during shaft development has been well known to those faced with the problem. Depending on the amount, temperature, and quality of the water, the extra costs of working in wet conditions can easily be several times that for the same work under dry conditions. I have heard estimates of cost increases from 25 percent to 300 percent. The actual cost increase can be controlled if the water inflow is expected and if adequate control measures are employed prior to encountering the water.

Table 1 lists some of the problems that can be associated with working under wet conditions. The more obvious of these effects are considered direct, that is directly associated with pumping or controlling water inflow. Usually most mining projects will have taken these into account at feasibility stage. However, there are also indirect effects which are not always fully accounted for during the early feasibility stages. These include such items as muddy conditions, freezing of water in the shafts, added equipment maintenance, reduction in ground stability and washed ground, problems with explosives and scaling of pipes. These are indirect effects which occur within the shaft itself. Others may occur outside the shaft area including the effect on surrounding water users of drawing down local water tables during pumping from the shaft and the discharge of potentially poor quality water to surface drainages.

DETERMINING THE NEED FOR WATER CONTROL

The first question to be answered is whether or not water control during shaft sinking will be necessary. Ground water occurs to some degree or another in nearly all rocks below a few tens of feet below the ground surface. Whether or not water is present in sufficient quantity or is of such poor quality as to warrant control measures must be determined prior to selection of the shaft sinking method.

One of the best indicators is previous experience. If the mine is located in an area of previous or existing mining activity, it is relatively simple matter to evaluate whether water will be a problem or not. Even in this case, however, care should be taken to determine if the new shaft will be in a hydrogeologic setting that is the same as the surrounding existing shafts. It is best to carefully review what is known of the existing geology of the area in order to evaluate known or suspected aquifers or waterbearing zones in the new shaft area.

Whether the shaft is located in an existing mining district or not, data from exploration borings can be very valuable, especially if at least some are designed to evaluate hydrogeologic conditions. Usually borings are drilled without regard to hydrogeologic parameters. Detailed logs are often only kept on the portion of the hole that penetrates the suspected ore horizon. No attempt is made to locate or measure water levels in borings. This is unfortunate because it is usually possible, at very little additional cost, to add hydrologic parameters to the geologic parameters normally considered during an exploration program. It is an investment which can produce a very high rate of return in terms of early identification of potential water problems and can reduce the need to essentially re-drill footage once a water problem is identified.

ASSESSING THE LOCATION AND AMOUNT OF WATER

Once it is determined that the potential for significant water inflow into the shaft exists, detailed knowledge of the subsurface conditions must be obtained. The exact level of detail required is dependent upon the specific geohydrologic conditions in the shaft area. In areas where the geology is relatively uniform and water movement is not controlled by fractures and faulting, much useful information can be obtained from other mines, exploration boreholes, and a general knowledge of the site hydrogeology. However, when water movement is thought to be predominately fracture controlled, detailed knowledge of the specific shaft site is needed, as water inflows can vary by several orders of magnitude if a significant fracture or other zone of high permeability is encountered in the shaft. The following paragraphs discuss some of the available field techniques to assess the hydrogeologic character of subsurface materials.

Field Methods

A number of field methods are employed to locate potential waterbearing zones and to estimate their water yield to the shaft. As in all engineering studies, a balance between costs and expected results must be maintained. Field methods can be divided into two broad categories, direct and indirect. Direct methods involve coring, in-hole testing, and laboratory testing. Indirect methods include geologic mapping, preparation of cross sections, and geophysical logging. Direct methods generally produce more accurate and reliable results but also cost more. Table 2 compares some of the advantages and disadvantages of the various field methods in general use.

The results of the field program must allow a reasonable estimate of the parameters necessary to calculate: 1) the hydrostatic head in the shaft area, 2) anticipated inflow rates with time, and 3) the ground water velocity across the shaft area. Specifically, the following data must be known:

1. Location, depth, thickness and extent of known aquifers and confining beds.
2. Tranmsmissivity and storage coefficient of aquifers and confining beds.
3. Whether aquifers are under water table or artesian conditions.
4. Head relationships.
5. Location and attitude of faults.
6. Nature of fault zones (impermeabile barriers or conduits for water movement).
7. Position of proposed shaft within the areal hydrologic system (recharge, discharge, or horizontal flow area).
8. Water quality.

Predicting Water Inflow

Relative to the larger problem of mine dewatering, estimates of probable water inflow to a shaft are simplified by the fact that a shaft is essentially a large diameter well and there is an extensive body of theory governing flow to wells. Once the above design parameters for each potential water-bearing horizon are known, the approximate water inflow at any given time can be estimated with the following equation:

$$Q/s = \frac{T}{264 \log \left[\frac{Tt}{1.87\, r_w^2\, S}\right]} - 65.5$$

where r_w is the radius of the shaft, in feet, S is the storage coefficient, T is the transmissivity, in GPD/FT, t is the time after pumping started, in days. This equation yields the theoretical full-penetration specific capacity (Q/s) of the shaft in gallons per minute per foot of drawdown (GPM/FT). The inflow rate is found by multiplying the available drawdown (s) by the specific capacity.

Depending upon the type of shaft construction and the aquifer thickness, a given water-bearing horizon may not be exposed throughout its entire thickness at any given time. Such would be the case for a thick aquifer where the shaft is excavated 10 to 20 feet ahead of the lining. In this case, the theoretical full penetration specific capacity would overestimate the actual quantity of water that will flow into the shaft. If the amount of partial penetration at any given time is known, the reduced specific capacity can be calculated from the following equation:

$$Q'/s' = Q/s \left[\frac{L}{M}\left(1 + 7\sqrt{\frac{r_w}{2L}} \cos \frac{\pi L}{2M}\right)\right]$$

where Q'/s' is the specific capcity of the partially penetrating shaft, L is the length of the open hole, and M is the aquifer thickness. The adjusted specific capacity (Q'/s') is then multiplied by the total available head to estimate water inflow. This equation is valid only under near steady state conditions.

SELECTION OF WATER CONTROL METHOD

Once a determination is made that water control techniques will be required, it remains to select the optimum control system. Common systems include installation of water rings, sump pumping, grouting, freezing, and pumping from deep wells outside the shaft perimeter. It is not the purpose of this paper to compare advantages and disadvantages of various water control methods. However, a few general observations can be made.

Collecting water that flows into the shaft and pumping it to the surface is the most time honored method of water control. Water rings can be installed as the shaft liner advances allowing for better control of the inflowing water. This is probably the least cost method, however, it is not effective where large water inflows, especially in poor ground, are encountered.

Grouting is probably the second most popular method. Water-bearing zones can be grouted from the surface or from various levels within the shaft as it advances. In addition to reducing rock permeability, grouting can also increase strength in weak ground. Grouting is not without its difficulties, however. It is as much an art as a science and works best when there are well defined isolated fracture systems that contribute most of the water. Grouting may be less effective in fine-grained materials or in fractured areas where clay may be present along openings.

Freezing is a technique that has gained popularity in soft ground areas. Unlike grouting, freezing is undertaken from the surface and may require relatively deep very closely spaced holes ringing the perimeter of the shaft. In some cases, the time to freeze the ground may be a factor in considering this technique. It is generally recognized as one of the most expensive methods of water control.

Deep dewatering wells can be used to reduce hydrostatic pressures and water inflow rates. Wells are often used in conjunction with sump pumps and grouting. In many cases, dewatering wells will only reduce water inflow into the shaft, not completely stop it. Wells are only effective when there is a continuous, sufficient flow of water to allow continuous pumping.

The remainder of this paper presents a typical case history of a water control method that is gaining acceptance in the deep uranium mine shafts in northwestern New Mexico.

CASE HISTORY

Introduction

Uranium mining in northwestern New Mexico began in the 1950's. Early mines were generally less than 800 feet in depth and water was removed from shafts and workings with sump pumps. New ore discoveries at depths of 2,000 to 4,000 feet and the presence of aquifers with water under 1,000 feet or more of hydrostatic head have necessitated new methods of water control.

Hydrogeology

The Grants Mineral Belt is located in the San Juan Basin, a structural depression that occupies a 25,000 square mile area in northwestern New Mexico and adjacent parts of Colorado, Arizona and Utah. Approximately 15,000 feet of sedimentary rock are present in the deepest part of the basin.

Geology of the southern and western parts of the basin, in which the Grants mineral belt is located, is characterized by a thick sequence of sandstones and shales generally dipping to the northeast. The basin was formed during late Cretaceous to Eocene time. A typical geologic column is shown on Figure 1.

The area is relatively free of major structural activity. Locally some faulting and folding has been detected but displacements are relatively small. In general, permeability is primary, or through the rock interstices.

The ore is located in the Westwater Canyon Member of the Morrison Formation (Late Jurrasic). Depending on the precise location within the basin, overlying units consist of interbedded sandstones and shales of Cretaceous age and unconsolidated alluvium. Existing mines in updip portions of the Westwater Canyon formation are known to produce significant quantities of water. Some overlying sandstones are also known to be waterbearing. In some of the deeper mine areas, exploration boreholes exhibit artesian conditions with water flowing at the surface.

The following case history is a composite of several studies performed by the author over the past few years. The data presented do not apply to any particular site, but is representative of the general area.

Determination of Water Producing Zones

Usually shaft investigations are concerned not only with water control but also rock conditions which could effect shaft sinking. Therefore, the field program is designed to develop pertinent data for both the hydrologic and geotechnical studies. All studies have included a bore hole drilled from the surface to below the ore horizon. The core obtained from this hole is analyzed for rock strength and engineering characteristics as well as hydrologic properties. The hydrologic properties included stratigraphy, lithology, fracture intensity, and cementation. Representative samples of the sandstone were tested in the laboratory for permeability and grain size distribution. A set of geophysical logs are usually obtained from the core hole. These include caliber, density, temperature, self-potential, resistivity, porosity and 3-D velocity.

Potential water-bearing zones are identified from the hydrologic properties log and from the geophysical logs. Depending upon the location within the basin up to six major aquifers have been identified. These include, in descending order, some of the thicker sandstones in the Menefee Formation, the Point Lookout Sandstone, the Hosta Sandstone Tongue of the Point Lookout Sandstone, the Dalton Sandstone, the Gallup Sandstone, the Dakota Sandstone, (including the Two Wells member), and the Westwater Canyon sandstone of the Morrison Formation.

Since the presence of fractures, joints, or faults can significantly affect permeability it is desirable to obtain an indication of the presence of major discontinuities. In addition to logging fractures in the core, a knowledge of areal jointing, fracturing, and faulting can be obtained by a combination of surface mapping and the construction of cross-sections. Surface outcrops in the vicinity of the shaft site are mapped and the orientation of joints and fractures analyzed statistically. As is typical of thinly bedded sedimentary rock, two prominent dividing plains are commonly noted in the San Juan Basin. These are approximately perpendicular to the bedding and to each other. Both joints sets are predominately subvertical.

Cross-sections, utilizing geophysical logs from nearby exploration boreholes, can be constructed across proposed shaft site areas. These cross-sections are useful in determining whether significant faulting or folding occurs in the vicinity of the proposed shaft.

Estimation of Hydrologic Properties and Water Inflow Rates

Following the identification of the potential water-bearing zones a test program must be designed to determine the major hydrologic parameters. These parameters include transmissivity, storage coefficient, water levels and boundary conditions. An ideal test program would consist of the installation of a pumping well and at least one observation well in each major water producing zone. However, from a practical standpoint it is not always cost effective to drill two or more wells to each zone and some alternative methods have been devised that represent a compromise between cost and information obtained.

One such compromise involves the installation of observation wells in the most prolific of the aquifers, with the remaining zones being tested in a single well that penetrates all aquifers. Typically, observation wells are located in the

Point Lookout, Dakota, and Westwater Canyon Sandstones. Where wells flow at the surface hydraulic coefficients can be determined for each observation well by utilizing constant drawdown testing procedures. Where wells do not flow a pump must be installed. In either case, a test well is installed and designed to test all identified aquifers, including those with observation wells. Since the head and expected flow from each aquifer usually varies greatly, the pumping system must be flexible to accomodate these expected variations. A system utilizing compressed air or nitrogen eliminates the cost of purchasing, installing, and removing several different pumps in order to test all the zones. Construction of a typical test well is shown on Figure 2. In this case the well is drilled to the lowermost aquifer and casing installed and cemented to the surface. The well is then pump tested. Overlying formations (starting with the Gallup Sandstone) are tested by installing a wireline bridge plug below each zone and perforating the casing over the entire aquifer thickness. Following pumping of the perforated zone a second wireline packer is set below the next overlying zone and the perforating-pumping sequence repeated for each zone going up the hole.

Field test results, laboratory permeability and grain-size determinations, and visual examination of rock core are used to select design parameters. Transmissivity and permeability values normally vary considerably, reflecting the complex depositional pattern of the deposits. Normally, the results of field pumping tests are given the most weight in parameter selection, as these tests indicate any secondary as well as primary permeability effects and a much greater volume of aquifer is tested. Pump test results are analyzed for evidence of recharge or discharge boundaries, and leakance through the confining beds calculated. Since shaft sinking is a relatively short-term operation, it is not necessary to conduct long-term pumping tests. Typically, tests are run from between 24 and 72 hours on major aquifer zones and as short as four hours on minor zones. The ability to define boundary conditions during tests less than 24 hours is limited, however.

Following the selection of design parameters, estimates of water inflow rates from each aquifer can be made utilizing the formula presented earlier. The results of a typical study in a deeper portion of the San Juan Basin are shown on Table 3.

Design of Deep Well Water Control System

Recent deep shafts in the Grants mineral belt have utilized a system of grouting, sump pumping and pumping from deep wells. Wells are installed and pumped for some time period prior to the penetration of each aquifer by the shaft.

The sandstone aquifers in the San Juan Basin cannot be completely dewatered with wells. The aquifers are artesian, deep, relatively thin, and have low tranmissivities. If the water level is drawn down below the top of the aquifer in the pumping well, very little additional drawdown at the shaft (compared to the total available drawdown) is gained and it is readily offset by a decrease in transmissivity at the pumping well due to the reduction of the saturated thickness of the aquifer. The principle benefit to be obtained from pumping from wells is a major reduction in hydrostatic pressure; and while the flow into the shaft is not eliminated it is significantly reduced. Since the wells are not designed to dewater the aquifers they are referred to as "depressurizing" rather than dewatering wells.

If grouting is to be conducted while depressurizing wells are in operation, it is desirable to prevent excessive migration of the grout away from the shaft by minimizing ground water velocities in the shaft area. A ground water velocity less than two feet per day is considered optimum.

Design alternatives for a depressurizing system involve comparison of well construction procedures, number of wells, field geometry, duration of pumping, and ground water velocity across the shaft area. Consideration must be given to the feasibility of completing each depressuring well in more than one aquifer and of deepening wells to lower aquifers when depressurization is no longer required.

Multiple completions (in more than one aquifer) involve pumping larger quantities of water and are more complicated to construct. If the pumping level is drawn below the upper aquifer, cascading water will occur and larger diameter casing may be needed for a pump shroud in order to provide adequate pump cooling. A screen and possibly gravel packing of the upper aquifer may be necessary to elimate sand inflow and caving which could result in the loss of the well or pump. Also, if entrained air in the cascading water is significant a gas separater may be required to prevent the pump from excessive corrosion and cavitation. Multiple aquifer completions where the pumping level is not drawn below the top the upper formation are favored, as these avoid the problems of partially dewatered aquifers and cascading water.

Deepening of wells is feasible if sufficient time is available for deepening between the end of the pumping period required for the upper aquifer and the required start of pumping in the lower aquifer. The time available is dependent upon the grouting and sinking schedule which is, in part, a function of the depth between aquifers. In some cases there is insufficient time to deepen wells from any one aquifer to the next deepest one, however, it is frequently possible to deepen wells from a shallow aquifer to the deeper aquifers.

The selection of pumping duration prior to entering the aquifer with the shafts must allow for sufficient time to work out any problems in the mechanics of the pumping system and provide a reasonable reduction in head of the shaft. The time required to reduce the head can be estimated from aquifer properties determined by the field test program. Typically, in the San Juan Basin, a 60-to 100-day pumping period prior to shaft sinking provides adequate time for both head reduction and resolution of any system problems.

Various symmetrical well arrangements with the number of wells varying from two to eight are usually evaluated. A minimum distance of 100 feet from the center line of the shaft is usually required in order to reduce congestion of the drilling equipment with the head frame and other construction equipment near the shaft collar. Utilizing a computer program to solve the well flow equation; a comparison of the various well systems and their respective pumping rate, head reduction, and associated ground water velocity can be made.

Figure 3 shows a plan view of a depressurizing system for a six aquifer system. Table 4 gives a summary of each system and its predicted results.

SUMMARY

This paper has attempted to review some of the techniques available to assess the need for water control, estimate the location and amount of water inflow expected, and briefly outline the techniques commonly in use. The application of these techniques to a practical problem is illustrated by recent work in the uranium mines of northwestern New Mexico.

While the shafts studied by the author are still under development, it appears that a combination of depressurizing wells and grouting is successful in controlling water inflow during sinking. Available data indicate that head reductions in excess of seventy percent are possible. Water inflow rates during shaft sinking are less than one-half that estimated to occur without depressurization.

The use of these techniques does not eliminate the water problem, however, they can make the problem more predictable and consequently manageable. Good planning is possible only if the conditions to be encountered during shaft sinking are known in advance.

TABLE 1. EFFECTS OF WET CONDITIONS

(After Loofbourow, SME Mining Engineering Handbook)

1. Direct Effects
   - Costs of pumping
   - Failure to handle inflow may interrupt sinking and could damage the shaft, perhaps beyond recovery, perhaps with loss of life.

2. Indirect Effects in Shaft
   - Freezing water in cold areas.
   - Reduced efficiency of crews and equipment
   - Added equipment maintenance.
   - Reduced stability of walls and potential for washed ground.
   - In areas of hot water, increased heat and humidity.
   - Interferes with certain explosives.
   - Scale in pipes and pumps.

3. Indirect Effects outside Shaft
   - Drawdown may effect surrounding water wells.
   - Poor quality water may pollute surface waters.

TABLE 2. FIELD TECHNIQUES

	Advantages	Limitations
Coring	- Excellent Stratigraphic Control - Visual Log of Subsurface - Samples for Testing - Record for Use During Sinking	- High Cost - Time to Drill - Small Area Examined
Geophysical Logging	- Good Stratigraphic Control - Low/Moderate Cost - Rapid - Continuous Record - In-situ Properties	- No Samples - Affected by Borehole Fluid - Results Relative - Required Skill Interpreter
Drill Stem Tests	- Rapid - Moderate Cost - Evaluate Borehole Effects - Samples - In-situ Properties	- Low/Moderate Premeabilities - Possible Leakage Around Packers - Limited Area Investigated
Injection Tests	- Rapid - Moderate Cost - Good Grouting Data - In-situ Properties	- Low/Moderate Permeabilities - Possible Leakage Around Packers - Usually Underestimate Permeability - No Samples - Affected by Borehole Condition
Pumping Tests	- Large Area Investigated - Assess Boundary - Water Samples - Simulate Actual Dewatering - Experimental Design Data	- High Cost - Control Water Discharge - Temporary Effect on Surrounding Wells - Time to Drill and Test

TABLE 3. ESTIMATED WATER INFLOW 22-FOOT DIAMETER SHAFT

Aquifer	Transmissivity (Gallons/Day/Foot)	Penetration (Feet)	Average Flow Rate (GPM) (@ 90 Days)
Menefee*	200	40	25
Point Lookout	2000	10	250
		20	400
		30	500
Hosta*	500	86	400
Dalton	100	10	75
		20	100
		30	125
Upper Gallup*	500	40	650
Lower Gallup*	200	80	300
Dakota	600	10	400
		20	600
		30	750
Westwater Canyon	1000	10	450
		20	700
		30	900

*Thin aquifers not analyzed for partial penetration.

TABLE 4. DEPRESSURIZING SYSTEM PERFORMANCE

AQUIFER	NO. WELLS	HEAD REDUCTION @ SHAFT %	SHAFT INFLOW (GPM)		AVERAGE WELL PUMPING RATES (GPM)
			WITHOUT	WITH	
Point Lookout	3	77	780	200	150
Hosta	3	71	425	100	75
Dalton	3	73	160	50	30
Gallup	3	73	780	250	100
Dakota	3	73	1,750	500	320
Westwater Canyon	4	79	2,500	550	400

GEOLOGIC COLUMN

DEPTH		STRATIGRAPHIC UNIT	ROCK TYPE (% OF FORMATION)
	MESA VERDE GROUP		
	MESA VERDE GROUP	MENEFEE	SANDSTONE (30%)
	MESA VERDE GROUP		SILTSTONE (35%) SHALE (30%)
500	MESA VERDE GROUP	POINT LOOKOUT	SANDSTONE (100%)
	MESA VERDE GROUP	SATAN TONGUE	SILTSTONE (70%) SHALE (25%)
1000	MESA VERDE GROUP	HOSTA TONGUE	SANDSTONE (95%)
	MESA VERDE GROUP — CREVASSE CANYON FM	MULATTO TONGUE	SANDSTONE (45%) SILTSTONE (20%) SHALE (35%)
1500	MESA VERDE GROUP — CREVASSE CANYON FM	DALTON	SANDSTONE (95%)
	MESA VERDE GROUP — CREVASSE CANYON FM	DILCO	SLST, SDS, SH, COAL
	MESA VERDE GROUP	GALLUP	SANDSTONE (100%)
2000 2500		MANCOS (MAIN BODY)	SHALE (85%) SILTSTONE (10%)
		DAKOTA	SANDSTONE (80%)
	MORRISON FORMATION	BRUSHY BASIN	SHALE (90%)
3000	MORRISON FORMATION	WESTWATER CANYON	SANDSTONE (85%)
	MORRISON FORMATION	RECAPTURE	SANDSTONE (85%)

FIGURE 1

SCHEMATIC OF TEST WELL CONSTRUCTION

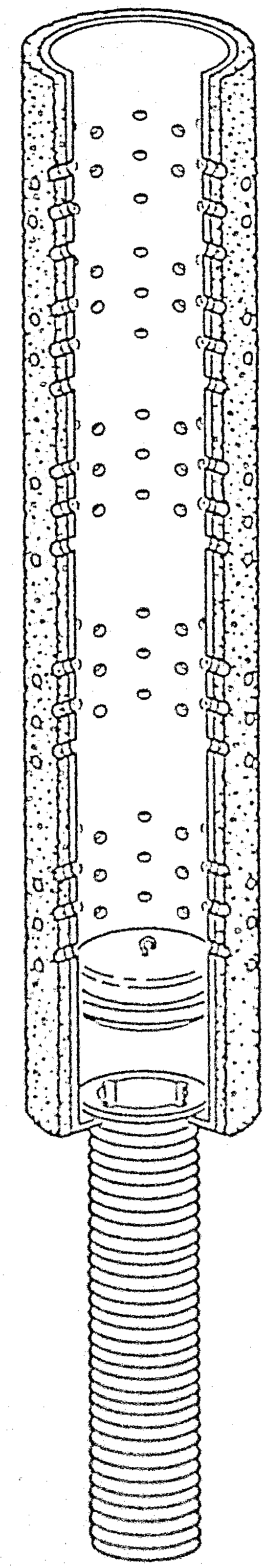

FIGURE 2

DEPRESSURIZING WELL LAYOUT

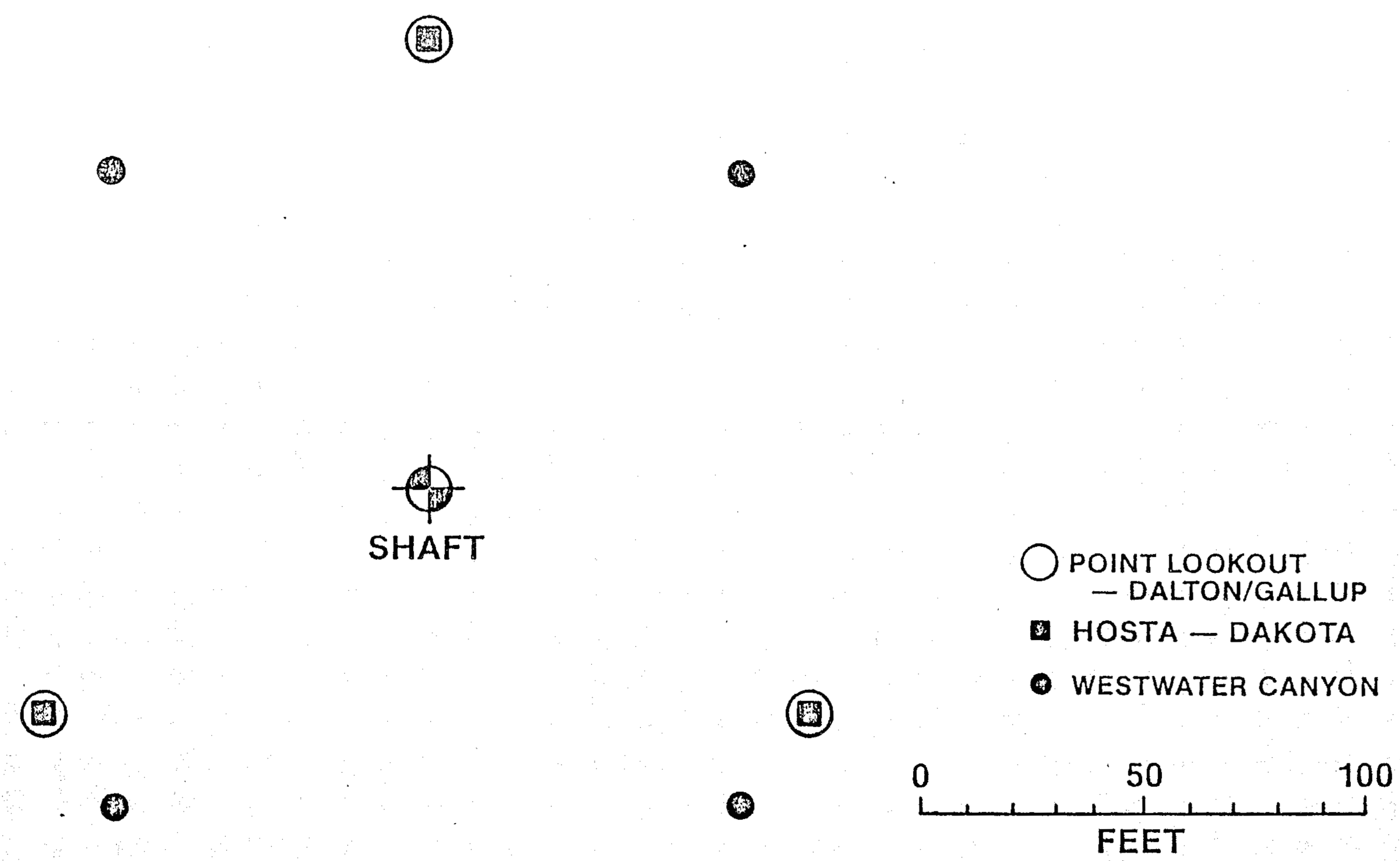

FIGURE 3