PREDICTING WATER QUALITY AND QUANTITY TO BE DISCHARGED FROM A PROPOSED UNDERGROUND URANIUM MINE

Popielak, R.S., Taylor, M.J., Olsen, R.L.
D'Appolonia Consulting Engineers, Inc.
Denver, Colorado, U.S.A.

ABSTRACT

The quality and quantity of water flowing into the shaft and headings of a planned underground mine has been effectively predicted for non-standard hydrogeologic conditions using currently available techniques and equipment applied in a creative and unique manner. In particular, inflow was determined for a proposed uranium mine in the western United States in which the following conditions exist:

- The mine workings will be situated in an active recharge area.
- The only aquifer saturated through its entire thickness consisted of arkosic conglomerate.
- No zones of elevated secondary permeability such as faulting and depositional/erosional discontinuous were detected.
- The shaft will be approximately 1066 meters (3500 feet) deep with headings located at depths of 847 meters (2780 feet) and 1027 meters (3370 feet) below the surface.

To gather data for prediction of inflow, water quantity and quality, a large number of drill stem tests (DST) were conducted with test interpretation performed electronically during testing. At depths preselected from geophysical logs, the hydrodynamic properties of the aquifer of interest were measured and water samples were collected during the flow periods of DSTs. The unique electronic in-situ analysis of formation behavior was made possible by the use of down hole piezoelectric transducers interfaced with surface located data processing equipment.

The geochemical characteristics of the mineralized zones and associated chemical characteristics of the formation water were determined by analysis of water samples obtained from the DST. Emphasis was placed on parameters that may effect the quality of surface waters when discharge on mine water occurs.

The following data procurement, an aquifer profile was constructed and analyzed in conjunction with the mine development schedule. An inflow hydrograph for various stages of mine development was generated. A geochemical/lithologic profile was also constructed to calculate the concentration of selected chemical parameters in the inflow at various stages of mine development. Graphs of chemical parameters versus time showed that the concentration of radionuclides and other elements in discharge water may exceed allowable limits. Treatment may be required to reduce concentrations of gross alpha radioactivity, uranium, zinc and arsenic prior to discharge. Methods and construction schedules for such treatment processes could be estimated based upon the calculations of water quality and quantity with time.

INTRODUCTION AND SITE CONDITIONS

Inflow of water into the underground openings of a mine can have a profound effect on the progress and cost of mining. The presence of water in the formations to be penetrated by mine workings and the quality of the water may dictate the method of mining and may necessitate measures to mitigate water hazards. A prognosis concerning the extent to which a future mine development and operation is going to be affected by mine inflow must be provided to mine planners prior to the commencement of conceptual design efforts.

The quantity and quality of mine inflow from layered deposits is often governed by a small number of strata which have significantly different hydrodynamic and geochemical properties than the surrounding formation. Those features which can dominate the overall hydrologic and chemical characteristics of the formation under investigation can be further classified as:

- Beds which have significantly higher or lower permeabilities than surrounding strata.
- Zones of different hydrostatic pressure.
- Mineralized zones which cause the chemical composition of the water to differ from surrounding strata.
- Oxidized or reduced zones which cause the composition of the water to change.

Accordingly, predictions of the anticipated quantity and quality of mine inflow require that strata displaying hydrological properties different from those existing in surroundings be identified in terms of their position within the stratigraphic profile, areal extent, and hydrodynamic properties. These requirements in turn, dictate testing methods which are able to produce high resolution hydrogeological data. In other words, the method must provide information on the hydrodynamic and geochemical characteristics of all strata to be influenced by mining. A method which meets these requirements is the drill stem testing (DST) method.

A potential uranium mine where the DST tests were applied is discussed in this paper. The mine is located on Green Mountain in south central Wyoming in the northwestern United States.

Initially, exploratory drilling has been performed with the purpose of defining mineralization for development of a full scale underground mine. This proposed mining project involved the development of a shaft and horizontal headings in the saturated part of the aquifer. The shaft is expected to be sunk to a depth of 1066 meters (3,500 feet) and headings are to be driven at depths of 847 meters (2,780 feet) and 1027 meters (3,370 feet) below the surface. The shaft and headings will encounter water and the resultant inflow will be discharged at the surface (after appropriate treatment). The limited impact on the groundwater regimes adjacent to the shaft and headings is of interest as a regulatory issue, although the impact is anticipated to be small.

Geologic Setting

The rock units composing Green Mountain are the Battle Spring Formation (lower unit) and Crooks Gap Conglomerate (upper unit). Lithologically, the units are composed of arkosic conglomerates, sandstones, conglomeratic sandstone, and silty lenses, all of Eocene age. Contacts between beds are generally gradational. No tectonic or erosional discontinuities were identified within the area considered for underground development. Sediments are continuous and most of the strata can be traced for the entire area under consideration (approximately 1600 meters). A three-dimensional fence diagram illustrating subsurface geology within the Green Mountain project and configuration of exploratory mine workings is shown in Figure 1.

Hydrogeological Setting

The hydrologic system of concern is within the Battle Spring Formation and consists of a unconfined aquifer starting at approximately 280 meters (920 feet) below the surface. The water table of this system slopes away from Green Mountain indicating that the top of the mountain is a recharge area. The Battle Spring Formation aquifer will be a main contributor of inflow into the mine workings. The hydrogeology of the project site is unique and includes:

- Significant depth to the water table in excess of 274 meters (900 feet).
- Thickness of the aquifer reaching 1220 meters (4000 feet).
- Aquifer stratification in terms of primary permeabilities.
- Aquifer stratification in terms of water composition.
- Aquifer recharged from surface infiltration as the primary recharge mechanism.

These characteristics dictated that the drill stem test should be the primary method of use for hydrogeological investigations. The basis for this testing decision, the results obtained, and the application of results are discussed in the following section. Reference is also made to the supporting testing and analysis to obtain the desired quantity and quality of mine inflow.

METHODS OF ACQUISITION OF HYDROLOGICAL DATA

To assess mine drainage and its impact on future mine operations at the Green Mountain mine, it was necessary to identify and test water-bearing strata to be affected by mining. Identificaiton of water-bearing strata in terms of their location within the stratigraphic profile, areal extent, and lithological character is usually accomplished during the exploratory drilling program. Determination of other aquifer properties such as the permeability, undisturbed formation pressures, drainability, temperature, and water composition require special hydrological testing in the formation under consideration. Two testing methods, the pumping test and the drill stem test were used to acquire the required data at the Green Mountain site. A synoptic presentation of the implementation of these methods and their advantages and disadvantages are described and compared in the following section.

Pumping Test

Numerous testing methods are available to investigators. The most comprehensive data on aquifer characteristics, however, can be derived from a pumping test. Data obtained from a pumping test represent aquifer characteristics averaged over the total volume of the formation tested. The composition of water samples obtained during a pumping test represent an average value from all layers producing inflow into the pumping well.

Pumping tests became less accurate for inflow assessments under conditions of:

- Distinct formation stratification in the form of lithologic and hydrodynamic properties as well as water quality characteristics.
- Limited recharge capacity such as a recharge zone.

For these conditions, the pumping test is not sensitive enough to identify the stratification and may give erroneous results.
In a situation where the aquifer is stratified and deep and recharge is limited, drill stem testing provides definite benefits.

Drill Stem Testing

The DST method was developed by the petroleum industry to test pressures and permeabilities of hydrocarbon reservoirs. In the DST, sections of predetermined thickness of an aquifer are either allowed to produce water or recover their pressure. Conceptually, DST is a short-term modification of the pumping test with all its components such as pumping and recovery periods.

In the DST method, a substantial smaller volume of the system is investigated. However, the high resolution of results obtained by this method is often essential when the quality and quantity of water draining from different strata are to be predicted. However, relatively high hydrostatic pressures are required to provide good results; i.e., use in shallow aquifer provides dubious results.

Technique of Drill Stem Testing

During the drill stem test, the stratigraphic interval of interest is isolated in the hole by the use of a packer (or packers) attached to the drill pipe and allowed to yield fluid into the drilling pipe under the influence of the formation head. A typical drill stem test setting is shown in Figure 2. Drill stem testing consists of periods during which the formation produces fluid (flow periods) followed by periods when the formation is shut-in to allow the pressure to recover (pressure build-up periods). Figure 3 illustrates a distribution of these periods which consist of the following:

- Prior to initiation of drill stem tests, all fluid from the drill pipe is evacuated by swabbing. By opening the shut-in valve, the formation is allowed to yield fluid into the drill pipe for a short period of time. This part of the test is termed the "first-flow period" (FFL) and usually lasts, depending upon the formation permeability, 5 to 30 minutes.

- Following the flow period, the shut-in tool is closed, causing the formation pressure to recover. This part of the drill stem test is called the "first build-up period" (FBU). The first build-up period usually lasts 15 to 90 minutes.

- After the initial flow and build-up periods, the shut-in tool is opened again and the formation fluid flows into the drill pipe. Commonly, this production period, called the "second flow period" (SFL), lasts from 30 minutes to 2 hours.

- After the second flow period, the shut-in valve is closed again isolating the formation and allowing the pressure to recover. This so-called "second build-up period" (SBU) concludes the typical drill stem tests.

Pressures within the tested formations are recorded throughout the test with a bottom hole transducer/recorder. Figure 3 shows each phase of the test described above (identified by its pressure response on the graph).

A wide variation is possible in the combination of operation and components of test settings. It is, for example, fairly common that a drill stem test as described above is followed by a long-term slug test. During the slug test, the formation is allowed to flow until practically full recovery is achieved. If the difference between formation and atmospheric pressure is too small to allow for sufficient duration of all production, and recovery periods, injection tests can be performed. Such a modified version of DST, however, excludes the opportunity to collect water quality samples.

HYDROGEOLOGIC INVESTIGATIONS AT GREEN MOUNTAIN

Hydrological investigations were conducted to provide the following information:

- A pre-mining baseline for documentation and comparison with conditions during and after exploration.
- Aquifer parameters necessary for evaluation of potential drawdown and other effects during exploration.
- Prediction of groundwater inflow into mining workings and impact to the groundwater and surface water regimes.

Investigations were conducted between 1979 and 1981, including geological exploratory drilling, geophysical logging, pumping tests, drill stem tests, and laboratory permeability testing. During the initial stage of hydrological investigations, the pumping tests were regarded as the most suitable hydrological testing method. Two pumping tests were performed in Wells TW-1 and TW-3, both in the Battle Spring Formation aquifer (see Figure 1). The pumping tests performed in these wells produced different sets of aquifer characteristics. The transmissivity values differed by a factor of 7 and the water chemistry was distinctly different in both wells. Specifically, waters from TW-1 contain significantly higher concentration of radionuclides than water from TW-3. Such a difference in permeability values and water composition for the same aquifer tested with the same method, although quite acceptable in hydrological investigations, first appear somewhat disquieting when it came to the assessment of mine inflow. A possible explanation for such differences in aquifer characteristics is that different parts of aquifers displaying different hydrodynamic properties were tested because the pumping wells were screened at different intervals. Well No. TW-3 was fully screened and derived water from an upper more permeable part of the aquifer where concentration of radionuclides were small. TW-1 was extracting water from a lower part of the aquifer which has a lower permeability and higher concentrations of radionuclides due to mineralized zone.

To determine where the most prolific and, from the mining standpoint, potentially troublesome zones were located, the drill stem testing (DST) method was selected. DST can also delineate sections of inferior water quality. Acquisition of this information allowed proper modification of planning procedures, and proper selection of remedial and mitigating measures.

Drill Stem Testing Program

Drill stem testing was conducted in two wells, TW-5 and TW-6. These wells were located in the southern and northern portions of the proposed exploration workings (see Figure 1). TW-5 was drilled in the proximity of the proposed shaft location to a depth of 1128 meters (3700 feet). This depth is slightly lower than the projected shaft depth. Fifteen drill stem tests were performed in this well throughout the entire saturated thickness of the Battle Spring Formation aquifer.

TW-6 was drilled in the northern portion of the proposed exploration workings. Five drill stem tests were performed in this well at the depth of the uranium mineralization and the proposed headings.

The criteria for selection of depths of the drill stem tests in each hole were:

- High or low permeabilities as preliminarily assessed from effective porosity logs.
- Location of zones of uranium mineralization.
- Location of proposed mine workings.

DST Instrumentation

The downhole instrumentation consisted of a modified Lynes "Treat and Test Tool" packer assembly. As shown in Figure 2, the downhole assembly consisted of the following major components:

- Water-inflatable rubber packer (elements A in Figure 2): The inflatable packer conformed very well to borehole walls. When expanded by a differential pressure of 67 bar (1,000 psi) above the existing downhole pressure, this packer provided an excellent seal.
- "J" slot tool (element B in Figure 2): Essentially, this component is a valve which either (a) hydraulically connects the inflatable packer with a drill pipe, thus allowing its inflation or deflation or (b) seals the packer off in an inflated position allowing the DST to be performed. The "J" slot tool is operated by lifting and rotating the drill pipe.
- Shut-in tool (element C in Figure 2).: This component is a valve which operates between the tested section of the borehole and the drill pipe. In the open (or flow) position, the valve allows the formation water from the tested section beneath the packer to enter the drill pipe. In the shut-in position, the connection is cut off and formation pressure allowed to recover ("build-up"). The shut-in valve is operated by rotating the drill pipe while the packer is inflated and the "J" slot tool is locked into the testing position.

Depending on sensing instrumentation system, the pressure and temperatures in the tested intervals were either monitored and recorded at the surface-located computer system (Conducting Wireline System), or recorded onto the downhole memory recorder (Digital Memory Recorder System) . In the Conducting Wireline System (CWL), three, 0 to 345 bar (0 to 5,000 psi) quartz pressure transducers were used to monitor pressure and temperature readings in the tested zone below the packer as well as pressures and temperatures in the borehole above the tested interval. Transducers located in the sensor carrier were connected with the surface-located data processing equipment through a single conductor wireline cable.

A schematic representation of the downhole and surface instrumentation is provided in Figure 2.

The CWL system has several advantages over standard DST methods employing downhole recording devices:

- Immediate data evaluation. Examination of data during acquisition facilitates early detection of system malfunction. Often deficiencies, for example, leakage around the packer, can be corrected without the removal of the instruments from the borehole. Initial evaluation of aquifer response also allows for modification of testing procedures as testing progresses.

- On-site data analysis during testing. Parameters which determine aquifer characteristics such as permeability, formation pressure, and temperature are obtained as testing progresses. No additional time for data reduction and calculation is required.

- Monitoring above, within, or below the tested inverval. Detection of leakage around the packer and also radial flow through the formation pores and fractures is possible.

- Monitoring packer inflation. Packer inflation can create a "squeeze" or overpressure on the tested interval. In low permeability formations, this can create delays and interpretation problems. In the medium to high permeability sections, however, the overpressure dissipation can be treated as a "pulse" test providing preliminary transmissivity values for the testing zone.

- Higher resolution pressure data. The transducer has a resolution $\pm$ $7x10^{-4}$ bar (0.01 psi) and an accuracy of $\pm$ 0.17 bar (2.5 psi). The accuracy may be improved with further transducer calibration.

The CWL system also has some limitations and disadvantages. The limitations should be addressed and identified during the process of selecting a testing method. The main disadvantages of the CWL system are:

- External wireline cable. This component is the most frequent source of breakdowns. Special care is required in cable handling and maintenance. To prevent the cable from being caught between tubing and the borehole walls, tubing centralizers are required. In poorly consolidated or unstable formations, the centralizers may aggravate sloughing and caving problems. This, in turn, may results in delays or loss of downhole instrumentation.

- Dedicated 110 AC power. Additional power generating units used exclusively for the CWL system instrumentation and data processing equipment are required.

- Equipment cost. Cost of the CWL system including downhole instrumentation and surface data processing is high and usually exceeds $3,000 per day for long-term projects. Short-term arrangements are usually much more expensive. Cost of a single test is in the vicinity of $6,000.

Digital Memory Recorder System

When the aquifer response to DST can be predicted to some extent, it may be more practical to use the downhole pressure and temperature recording probes (DMR-Digital Memory Recorder) rather than the CWL system. The DMR system utilizes the same basic transducers as the CWL system. They are, however, not connected with the surface-located data processing equipment. Hence, the monitoring of formation response as the test progresses and modifications to testing procedures are impossible. The selection of the time interval at which pressure and temperature readings are taken must be selected prior to insertion of the instrumentation in the hole.

Upon completion of the test, the probe is retrieved and connected to the surface electronic instruments for data access and evaluation. The data recovered by the DMR must be entered manually into the data processing equipment which requires a significantly higher amount of technical personnel time. The savings, however, on the rig time as well as the relatively trouble-free operation may easily offset the increased man-power cost.

For depths not exceeding 1220 meters (4000 feet), the rig time required for a single DST test was typically 10-16 hours with a modest allowance for contingencies. If the CWL system was employed, the time demand was usually 20 percent higher due to cable handling, placement of centralizers, and periodic stops for system checkup.

PREDICTIVE ANALYSIS OF MINE INFLOW

Distribution of Aquifer Properties

The final product of the drill stem tests (DST) are diagrams illustrating the distributions of permeability and formation hydraulic pressures along the vertical profile of the Battle Spring Formation aquifer. These diagrams are presented in Figures 4A and 4B. Appendix A contains the method used to calculate the transmissivity and permeability of the formation.

The distribution of water quality with depth can also be plotted. For example, Figure 5A, shows the concentration of gross alpha radio activity at the different tested intervals in TW-5. Such diagrams were also generated for major anions and cations, metals, radionuclides and total dissolved solids. Appendix B discusses the methodologies used and the evaluations performed.

Examination of these diagrams, particularly permeability and hydrostatic pressure profiles, reveals two phenonema which influence the predicted mine inflow. First, the most permeable part of the aquifer is located close to the water table at depths of 274 to 488 meters (900 to 1600 feet). The quality of water in this part of the aquifer is good with most of the concentrations below allowable standards. From 488 meters (1600 feet) downward permeabilities show a slight shift toward lower values with depth which can be explained by increased compaction. The quality of water from the lower part of the aquifer shows significant increases in concentrations at radionuclides and metals. These increases are typically located just below the mineralized zones.

Second, hydrostatic pressures for the part of the aquifers above the low permeability stratum at a depth of 884 meters (2900 feet) are responding directly to the saturated thickness of the aquifer above the tested zone. Below the low permeability stratum, pressures are much lower than could be expected in static or "no-flow" system. The departure from an earlier trend is typical of aquifers with stratification in permeability values located in the recharge zone.

Quantity and Quality of Mine Inflow

The permeability and hydrostatic pressure values used in conjunction with information concerning the rate of advancement of underground workings enable development of the shaft inflow hydrograph. This hydrograph, shown in Figure 6, displays a strong correlation between the permeability and hydrostatic pressure profiles. The anticipated inflow into the shaft, being a product of both of these parameters, varies from a few gallons per minute at depths of 335 meters (1,100 feet) to more than 0.025 m^3/sec (400 gallons per minute) at a depth of 1066 meters (3,500 feet).

The quantity of shaft inflow does not present particular concern. The mine is to be located in the active recharge area and the maximum inflow of 0.025 m^3/sec (400 gallons per minute) is not expected to jeopardize the regional and local environmental systems.

To predict the quality of water to be discharged at the surface during shaft advancement, the calculated inflows are combined with the measured concentrations of selected chemical species at specific depths. The resultant quality of water (in terms of gross alpha activity) to be discharged is shown graphically in Figure 5B. Analysis indicate that the concentration of alpha activity in the waters discharged from the shaft after completion of construction may reach 17.8 pCi/1. As shown in Figure 5B, the concentration of gross alpha radioactivity to be discharged during shaft construction is above the allowable standard of 15 pCi/1. Appendix B contains additional remarks on the assessment of water quality.

Based on these assessments, the water will probably have to be treated before discharge into surface waters. Similar calculations indicate that arsenic, zinc, uranium and radium may also exceed standards and require treatment before discharge. The water treatment, although technologically simple and of proven efficiency, impose a financial demand because of remoteness of operation and the high expected volume of water to be treated. As a consequence, a sealing of the zones from which the water of inferior quality is expected is being considered.

Summary

Owing to the implementation of DST methods, the strata of uranium mineralization and overburden were well defined in terms of their location, thickness, drainability, permeability, porosity, hydrostatic pressure, and chemical makeup. These data, in turn, were analyzed by the engineering design staff to select the best preventive method. The personnel responsible for the economic analysis of this project utilized these data to effectively plan preventive measures and assess impacts.

LIST OF REFERENCES

1. American Society for Testing and Materials, 1979, Annual Book of ASTM Standards, Part 31, Water, Philadelphia, Pennsylvania.

2. Bouwer, H., 1978, "Groundwater Hydrology," McGraw-Hill Book Company, New York, N.Y.

3. Cooper, H., Jr., Bredehoeft, J.D., Papadopulos, I.S., 1967, "Response of a Finite-Diameter Well to an Instantaneous Charge of Water," Water Resource Research, Vol. 3, No. 1.

4. Hockbarth, D.A., 1978, "Application of the Drill-Stem Tests to Hydrogeology," Ground Water Vol. 16, No. 1, Jan.-Feb. 1978.

5. Horner, D.R., 1951, Pressure Build-up in Wells, Proceedings of Third World Petroleum Congress, Section II, pp. 503-521.

6. Ramey, H.J., I. Martin, and R.G. Agarwal, 1975, "Analysis of 'Slug Test' or DST Flow Period Data," in Canada Petroleum Technology, July-Sept., 1975, pp. 37-47.

7. U.S. Environmental Protection Agency, 1979, "Methods for Chemical Analysis of Waters and Wastes," EPA-600/4-79-020, Cincinnati, Ohio.

8. U.S. Environmental Protection Agency, 1976, Quality Criteria for Water, EPA-440/9-76-023, Washington, D.C.

9. Wyoming Department of Environmental Quality, Water Quality Division, 1980, Water Quality Rules and Regulations, "Quality Standards Wyoming Ground Waters, Chapter No. 8.

APPENDIX A
TECHNIQUES OF DATA ANALYSIS

Two methods were used to analyze the DST data. One method was used for the flow period data analyses (FFL, SFL, SLUG); the other method was used to analyze the buildup period data (FBU, SBU).

Flow Period Analysis

Cooper et al. (1967) [3] introduced a method for calculating the hydraulic conductivity and storage coefficient of a homogeneous, isotropic artesian aquifer of uniform thickness which is fully penetrated by a well. A hydraulic gradient is established around the well by instantaneously removing from or injecting into the well a known amount of water. The problem is described mathmatically by:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad \text{(Eq. 1)}$$

where:

- h = hydraulic head at radius r, and time t.
- r = radius from well center
- t = time
- S = formation storage coefficient
- T = formation transmissivity

This equation describes nonsteady, radial flow of groundwater.

The solution to this equation is presented by Cooper et al. (1967) in the form of curves of $\frac{P(t)-Ps}{Ps-Pi}$ versus the dimensionless time parameter $\beta = Tt/rc^2$ for each of several values of $\alpha = rs^2S/rc^2$.

where:

- P(t) = head or pressure data as a function of time
- Ps = static head or pressure
- Pi = initial head or pressure (when flow begins)
- rs = radius of borehole
- rc = inside radius of tubing string

The use of these type curves is similar to the Theis graphical method of pump test analysis. A plot of the quantity [P(t)-Ps/ Ps-Pi] versus t is made on semilogarithmic paper of the same scale as the type curves. The type curves are then placed over the test data and translated horizontally (with the horizontal axes coincident) until a best fit is achieved. In this position a match point is chosen, and the coordinates of this point, α and β are read from the type curve, and t is read from the data plot. The values of transmissivity (T) and storage coefficient (S) are then calculated from the following rearrangements of the equations just presented using the coordinates of the match point.

$$T = \frac{\beta rc^2}{t} \qquad \text{(Eq. 2)}$$

$$S = \frac{\partial rc^2}{rs^2} \qquad \text{(Eq. 3)}$$

Two other plotting methods were also used to analyze the flow period data (See Ramey et al, 1975) [6]. These techniques were specifically designed to accentuate either early or late time data and to indicate borehole-storage affected data. Because the Cooper et al. plotting technique gives a more even accentuation of the early and late data, it was used to calculated the reported T and S values.

Buildup Period Analysis

A second solution to the aforementioned radial groundwater flow equation was developed by Horner (1951) (5) and is useful for buildup period analysis. Horner's solution is:

$$H(t) = H_s - \frac{2.3q}{4\pi T} \log \frac{t + \Delta t}{\Delta t} \qquad \text{(Eq. 4)}$$

where:

$H(t)$ = head inside the well bore at time t

H_s = static head

q = production rate of previous flow period (assumed to be constant)

t = time since shutin (buildup time)

T = test zone transmissivity

Δt = length of previous flow period (all consistent units)

This equation is solved graphically by plotting H(t) versus $\log \frac{t + \Delta t}{\Delta t}$, drawing a straight line through the data and measuring the change in H(t) on this line over one log cycle. The above equation then reduces to

$$T = \frac{2.3q}{4\pi\Delta h} \qquad \text{(Eq. 5)}$$

where Δh = change in head on the line over one log cycle. T is then calculated.

The semilog plot used in the Horner analysis can also be used to estimate the static formation pressure head. The axis where $\log \frac{t+\Delta t}{\Delta t} = 1$ represents infinite recovery time, and the value of H(t) at this time should equal H_s unless the reservoir has been permanently depleted.

From the results of both the flow data analysis and the pressure buildup analysis, values of the test interval transmissivity were obtained. The hydraulic condictivity of the rock in the test intervals was calculated using the following equation:

$$K = T/b \qquad \text{(Eq. 6)}$$

where:

b = thickness of the test interval.

K = hydraulic conductivity.

APPENDIX B

TECHNIQUES OF WATER QUALITY ANALYSIS

Sample Collection and Analyses

Water samples were taken from all DST zones, representing water quality from depths of 335 to 1066 meters (1,100 to 3,500 feet) below the surface. Water was removed by swabbing prior to sample collection until specific conductance measurements were approximately constant. Typically, a water volume of about three times the testing volume was removed. A testing volume is equal to the length of the tested interval times the cross sectional area of the open borehole. Both field and laboratory measurements were performed in accordance with standard methods. [1,7]

Shaft Discharge Water Quality

Most major constituents and trace elements in the water quality samples collected during DST testing did not exceed any of the government criteria [8,9] for domestic use. Certain parameters which exceeded standards at a few depths in TW-5 and TW-6 will not present problems because the waters coming from the bottom of the shaft will be mixed with waters from all levels prior to discharge. These parmameters include iron, lead, aluminum, copper and manganese. Other parameters which exceeded the allowable standards at the majority of the elevations or contained extremely high concentrations at a particular elevation include:

- Gross alpha
- TDS (Total Dissolved Solids)
- Uranium
- Ammonia
- Zinc
- Arsenic
- TSS (Total Suspended Solids)

For these parameters, calculations were performed to predict changes in concentrations in water from the shaft during its sinking and to determine if mixing of waters flowing into the shaft was sufficient to dilute the concentrations to levels which did not exceed the standard.

Gross Alpha Activity Evaluations

To determine how the gross alpha activity (or concentration of any of the investigated chemical species) would change during shaft construction, the following data were used:

- Inflow into the shaft from a 40 foot unlined interval located at the base of the shaft. This inflow was determined at different periods of construction corresponding to different depths within the shaft.

- Seepage into the shaft from the lined section of the shaft at various times during shaft construction.

- The total inflow into the shaft. This number is equal to the summation of the previous two inflows.

- The gross alpha concentration of different elevations.

The concentration of gross alpha activity or a particular chemical species in the water to be discharged when the shaft reaches the nth level is equal to:

$$D = \frac{C_n \cdot q_n + \sum_{i=1}^{n-1} q_i C_i}{q_n + \sum_{i=1}^{n-1} q_i} \qquad \text{(Eq. 7)}$$

where:

- D = concentration of chemical species in discharge water
- C_n = concentration of chemical species in water from unlined base of shaft
- C_i = concentration of chemical species in water from lined section of shaft
- q_n = inflow rate from unlined base of the shaft
- q_i = inflow rate from lined section of shaft

By calculating D at each interval as the shaft is sunk, an estimate of variation of gross alpha levels in the water is obtained based on progress of shaft construction. It is also possible to see if dilution will reduce the levels of activity which were described for each depth in Figure 5A. Figure 5B provides a graphical presentation of the resultant discharge water quality.

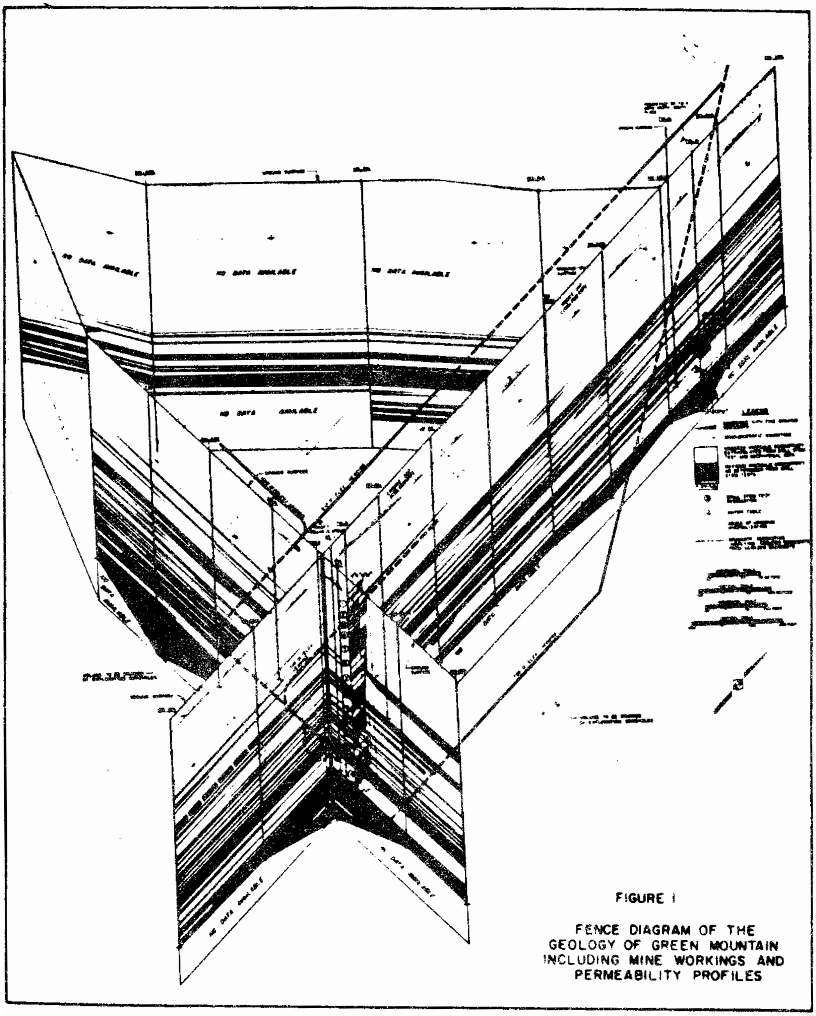

FIGURE 1

FENCE DIAGRAM OF THE GEOLOGY OF GREEN MOUNTAIN INCLUDING MINE WORKINGS AND PERMEABILITY PROFILES

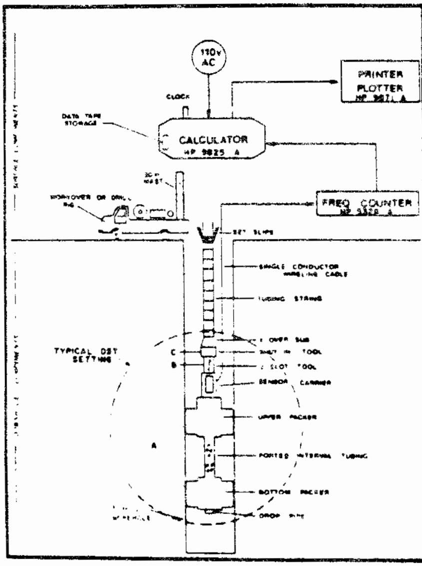

FIGURE 2

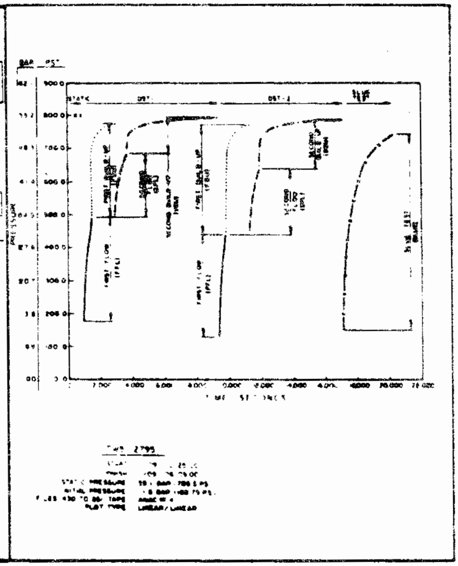

FIGURE 3

DST INSTRUMENTATION SYSTEM SCHEMATIC

EXAMPLE FOR DST SEQUENCE

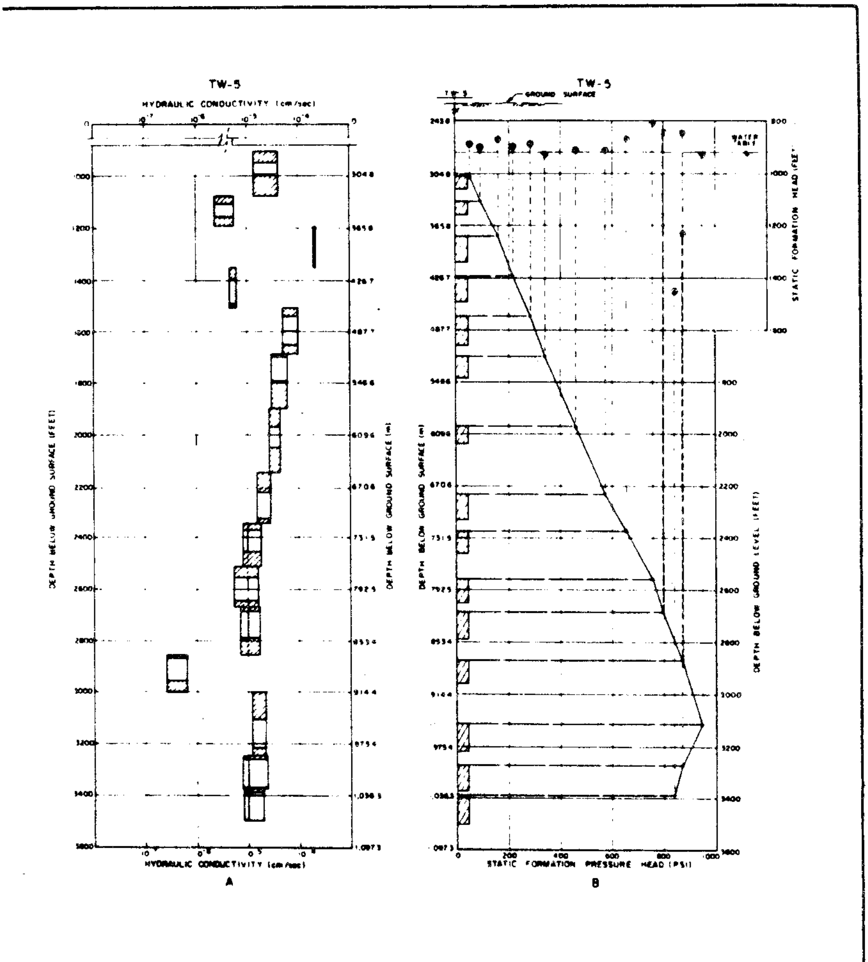

FIGURE 4
DISTRIBUTION OF PERMEABILITIES AND HYDROSTATIC PRESSURES WITHIN THE BATTLE SPRING FORMATION AQUIFER

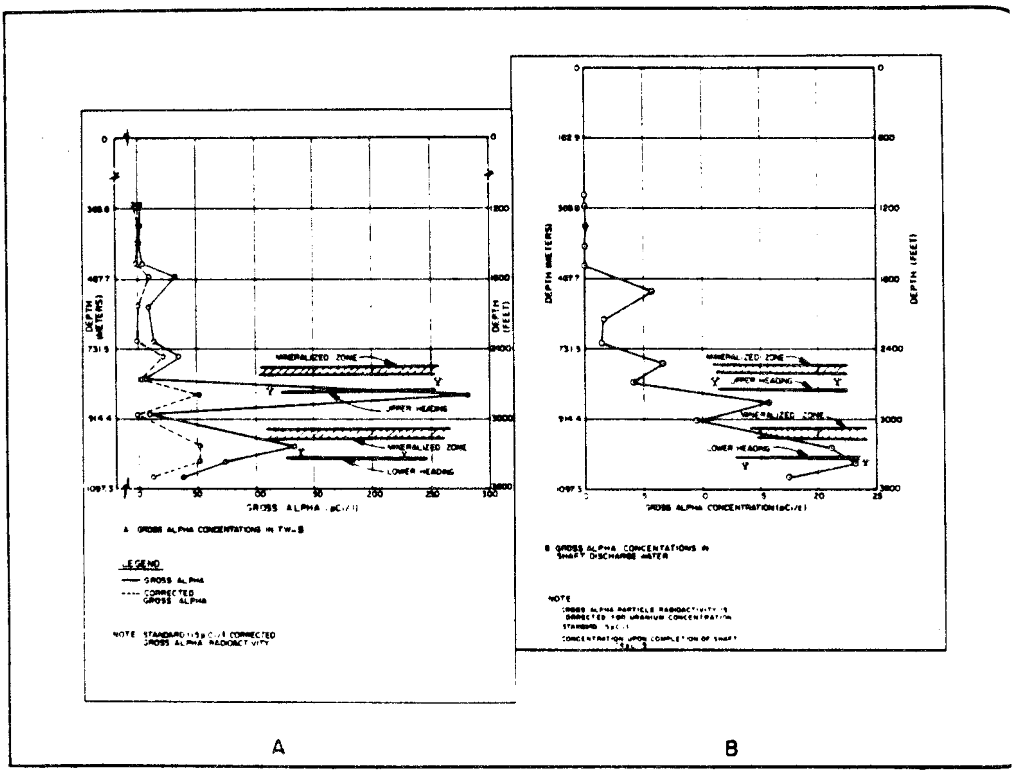

FIGURE 5

GROSS ALPHA CONCENTRATIONS IN BATTLE SPRING FORMATION AQUIFER AND IN DISCHARGE WATER DURING SHAFT CONSTRUCTION

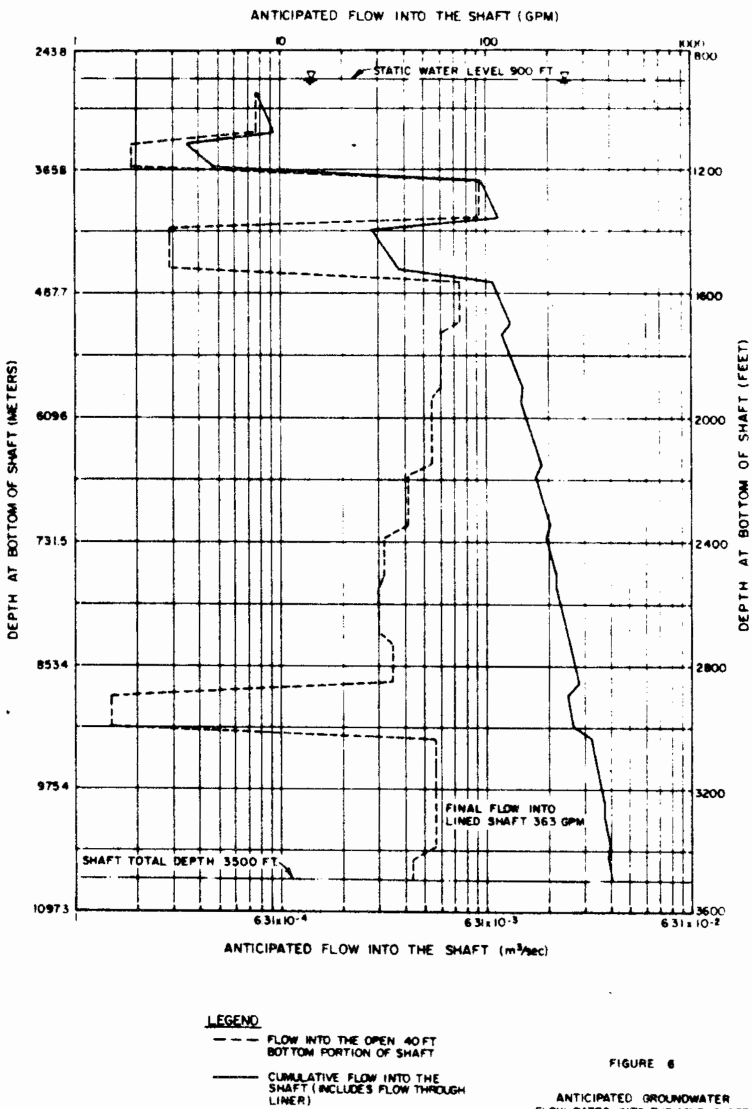

FIGURE 6

ANTICIPATED GROUNDWATER FLOW RATES INTO THE MINE SHAFT