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CIVILIAN RADIOACTIVE WASTE MANAGEMENT SYSTEM

Management and Operating Contractor

Contract #: DE-AC01-91-RW00134
LV.PA.CEB.2/93-007

WASTE ISOLATION EVALUATION

UE-25 UZ#16 (VSP#2) DATA ACQUISITION PHASE

PRELIMINARY DRAFT

by

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March 9, 1993

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Waste Isolation Evaluation

UE-25 UZ#16 (VSP#2) Data Acquisition Phase

SUMMARY

This waste isolation evaluation considers the impact of data acquisition and sealing borehole UE-25 UZ#16 (VSP#2) on waste isolation at the potential Yucca Mountain repository in Nevada. It is shown that geophones can be stemmed and grouted in the borehole to form a viable seal. Supporting bounding calculations and computer analyses are presented, and some recommendations are made: 1) Seal the inside of the support tube before the hole is abandoned; 2) investigate alternative grouts; and 3) maintain a standoff distance of 50 ft between boreholes and mobile sources during vertical seismic profiling (VSP) activities.

1. INTRODUCTION

1.1 Purpose

UE-25 UZ#16 (VSP#2) is one of two vertical seismic profile (VSP) boreholes at the Yucca Mountain site. Due to its depth and proximity to the repository conceptual perimeter drift boundary (CPDB), activities at UZ#16 could impact waste isolation of a potential repository. A request was made to evaluate the potential waste isolation impacts for the vertical seismic profiling data acquisition phase of this borehole (Dyer, 1992). An additional oral request was made by M. Tynan of the Yucca Mountain Site Characterization Project Office (YMPO) on December 23, 1992, to provide an independent assessment of the data acquisition phase and subsequent sealing of UZ-16 in light of conflicting requirements by the United States Geological Survey (USGS) and Sandia National Laboratories (SNL). Following meetings on UZ#16 (February 9-10 and 26, 1993 in Las Vegas), the M&O was directed to consider alternative modes for emplacing the geophones in the borehole.

1.2 Proposed Activities

As stated in the Study Plan for Characterization of the Percolation in the Unsaturated Zone-Surface-Based Study, "Lateral and vertical percolation of water in the unsaturated zone are presumed to be strongly influenced by the stratigraphic layering of units with markedly different storage and hydraulic-conductivity properties, and by faulting which may give rise to the formation of perched water, or which may have introduced preferred pathways for diverting flow either vertically or laterally" (USGS, 1991a, p. 2.2-8). The VSP study is designed to give the three-dimensional stratigraphic information necessary to evaluate flux and ground-water travel time through the unsaturated zone of Yucca Mountain.

Upon completion of the drilling, UZ#16 will extend 24 m (80 ft) below the water table, an approximate total depth of 515 m (1690 ft). Hydrologic and geologic testing within the borehole will take about five months (DOE, 1992b). The borehole will then be instrumented with a string of geophones which are stemmed and grouted in place to support a VSP study across the central section of Yucca Mountain (USGS, 1991a). The instrumentation process is expected to last one month.

Present plans call for a stemming and grouting program similar to that used in the existing borehole USW UZ-1 (USGS, 1991a). Figure 1 shows the various layers and instruments of the stemmed and grouted borehole USW UZ-1 (McBride, 1984). Initially, UZ#16 was to be stemmed and grouted using only one medium (a cement-based grout) and different instrumentation will be installed than in USW UZ-1. Recently, alternative emplacement strategies have been proposed.

Because it is desirable to have the option of removing the instrumentation from the borehole prior to final sealing, Long (1993) suggested a composite sand and grout seal around the instrumentation. It would be comprised of 6' intervals of soft grout centered across each geophone (on 16' centers) and 10' intervals of sand or beads between the grout intervals. This fill configuration is softer than the surrounding tuff, and therefore it allows for the possibility that the instrumentation may need to be drilled out at a future date.

Rousseau, USGS, observed that the ratio of strengths between the welded tuffs and "soft" (compressive strength ~ 1000 psi) grout is approximately 40 to 1 (UZ#16 Meeting, February 26, 1993). Thus, he proposed that in the welded units the geophones would be continuously grouted in place. In the other geologic units, Long's configuration would be used.

Using either Long's or Rousseau's geophone emplacement, the option of removing part or all of the instrumentation is maintained. High performance grouts can then be placed at selected locations, probably a combination of (1) from the top of the borehole into the Tiva Canyon welded unit, (2) across the Paintbrush unit into the Topopah Spring unit, and (3) in the Calico Hills unit. SNL's proposed sealing configuration (Fernandez and Case, 1992) consists of all three of these seals.

The geophone package consists of a fiberglass support tube with three geophone cable assemblies, each consisting of electrical cable with 32 sets of three geophones spaced approximately every 5 m (16 ft) sealed inside a heavy plastic jacket. The geophones extend most of the length of the borehole. The package will then be stemmed and grouted as described above (USGS, 1991a).

Once the geophones are stemmed and grouted in place, the VSP study will proceed. Mobile seismic sources (thumpers) will be placed at various points along the lines designated A through F in Figure 2 (Statton, 1993). The signal will be received by the geophones emplaced in UZ#16.

Data collection will occur intermittently for about a year (DOE, 1992b).

Contingent upon successful VSP studies at UZ#16, additional tests may be conducted at or near USW UZ-6, along the western boundary of the potential repository.

1.3 Location of UZ#16

· Eastern end of Whale Back Ridge (Scott and Bonk, 1984).

· Staked at Nevada Central Zone coordinates N 760.535 feet, E 564,857 feet (DOE, 1992a).

· About 430 m (1400 ft) SE outside the nearest point on the repository conceptual perimeter drift boundary (CPDB) and about 4.5 km (2.8 mi) inside the conceptual controlled area boundary (CCAB) (per Figure 3 and EG&G, 1992b and 1993).

· About 1.3 km (0.8 mi) WNW inside the potentially useable area 6 (per Figure 3 and EG&G. 1992e and 1993).

· At least 750 m (2500 ft) from all proposed testing in the Exploratory Studies Facility (ESF) (M&O, 1992).

· About 38 m (125 ft) from proposed borehole UZ#9, 26 m (86 ft) from proposed borehole UZ#9a, and 20 m (65 ft) from proposed borehole UZ#9b. Existing boreholes USW UZ-N53, -N54, -N55, and UE-25 UZN#56 and proposed boreholes USW SD-8, -10, -11, -12, and UE-25 SD#9 are also nearby (per Figures 4 and 5 and EG&G, 1992a and 1992b).

· Within 250 m (820 ft) of at least eleven inferred faults (per Figures 4 and 5 and EG&G, 1992d and 1993).

· About 730 m (2400 ft) east of the Ghost Dance Fault (Scott and Bonk, 1984).

· Within a probable maximum flood zone (Costin, 1992a) and within the 500-year flood zone (per Figures 4 and 5 and EG&G, 1992c and 1993).

1.4 Relevant Elevations

In order to give some perspective on the spatial relationship of UZ#16 to other planned activities, the elevations (rounded to nearest meter and foot) above mean sea level (m.s.l.) of some relevant locations are shown below:

	Meters	Feet
Ground Elevation of UZ#16 (RSN, 1992b)	1220	4001
Water table at UZ#16 (RSN, 1993)	728-729	2387-2392
Projected bottom of UZ#16 (RSN, 1993)	703-705	2307-2312
North ramp at surface (YMP, 1991)	1124	3687
North ramp at Topopah Springs level (YMP, 1991)	988	3240
South ramp at surface (YMP, 1991)	1198	3930
South ramp at Topopah Springs level (YMP, 1991)	1140	3741
Calico Hills drift north end (YMP, 1991)	824	2702
Calico Hills drift south end (YMP, 1991)	955	3134

1.5 Stratigraphy

Figure 6, compiled by Doyle (1993), shows the stratigraphy of UZ#16, including the depths, the fracture frequency, and the welding of the various units. The elevations of some of the more significant layers are:

Rock Unit	Elevation of the top of rock unit (ft)
Alluvium	4001
Tiva Canyon member	3961
Bedded Tuff	3839
Yucca Mountain member	3835
Bedded tuff	3825
Topopah Spring member	3772
Tuffs of Calico Hills	2800

1.6 Quality Assurance

The proposed activity will affect natural barriers at the Yucca Mountain site, which are listed in Appendix A of the Q-List (YMP, 1990). Accordingly, this report was prepared as a quality-affecting activity according to CRWMS M&O Quality Administrative Procedure QAP-3-5 "Development of Technical Documents" and QAP-3-9 "Engineering Calculations and Analyses." Guidance for the format and content of waste isolation evaluation reports, in lieu of a document development preparation plan, was provided by Younker (1992). The computer codes that were used in Appendix A have not been verified and validated, and thus have not been approved for M&O quality-affecting analysis. Some of the referenced data may not have been approved for quality-affecting activities and the referenced analyses may not have been performed as quality-affecting activities or under software QA requirements. The extent and possible effects of non-qualified data and analyses on the evaluations, conclusions and recommendations of this report were not determined, but are not expected to be significant.

2. EVALUATION

2.1 Evaluation Approach

This is a largely qualitative evaluation of the data acquisition phase of UZ#16 based on the best available information in the referenced documents and supplemented by personal communications. New quantitative analyses include quantitative comparisons of available information. supporting computational analyses (Appendix A), and bounding calculations done by hand (Appendix B). A checklist (see last page) was used as guidance to ensure that no potential activities and impacts were overlooked.

2.2 Relative Locations and Elevations

Borehole UZ#16 is located about 430 m (1400 ft) SE (stratigraphically downdip) outside of the nearest point on the conceptual perimeter drift boundary (CPDB) and about 4.5 km (2.8 mi) inside the conceptual controlled area boundary (CCAB) (per Figure 3 and EG&G, 1992e). UZ#16 lies about 1.3 km (0.8 mi) WNW inside potentially useable area 6 (per Figure 3 and EG&G, 1992e). UZ-16 is situated within 250 m (820 ft) of at least eleven inferred faults (EG&G, 1992d). Also, the borehole is within the 500-year flood zone (EG&G, 1992c) and near many other proposed and existing boreholes (EG&G, 1992a; EG&G, 1992b).

UZ#16 will extend from 1220 m to about 704 m (4001-2310 ft) above m.s.l. (RSN, 1992b; RSN, 1993). Thus, the borehole extends above and below the potential repository, of which the conceptual horizon elevations are 988 m (3240 ft) at the north end and 1140 m (3741 ft) at the south end of the planned ESF Topopah Spring level drift (YMP, 1991).

2.3 Relevant Hydrology and Hydrogeology

Borehole UZ#16 is located within the probable maximum and 500-year flood zones of the lower reaches of Drillhole Wash (Costin, 1992a; EG&G, 1992c). Water in Drillhole Wash flows in an easterly direction, which is away from the conceptual repository area. According to Fernandez and Case (1992), "Calculations show potential flooding and inundation of the borehole with one or two feet of water potentially flowing across the borehole." A probable maximum flood is estimated to last about 14 hours (Bullard, 1986).

Stratigraphically, borehole UZ#16 is located downdip of the conceptual repository (Scott and Bonk, 1984). Borehole UZ#16 is planned to be drilled about 24 m (80 ft) below the water table, which at this location is at an elevation of about 728 m (2390 ft) above m.s.l. or about 491 m

(1611 ft) below ground surface. Saturated-zone ground-water flow in this vicinity is expected to be in a southerly direction (DOE, 1988a), away from the conceptual repository area.

Although UZ#16 is far from any major fault, approximately 730 m (2400 ft) east of the Ghost Dance Fault, the borehole lies in an area inferred to contain many small faults, which are generally oriented in the north-south direction (Scott and Bonk, 1984). As of January 6, 1993 (approximately 1200 ft drilled), UZ#16 intersects three significant faults and many fractured zones. It is not yet known how much water travels through these faults (personal communication from J. Rousseau, USGS, December 23, 1993).

2.4 Previous Evaluations

Although there is a large literature base on the various aspects of sealing boreholes, the authors found very little information published regarding the methods of sealing boreholes with instruments grouted in place. The approach taken by SNL requires that all grout, instrumentation, and other materials be removed from the borehole prior to permanent sealing. SNL does not address the possibility of sealing a stemmed and grouted borehole (Costin, 1992b; Fernandez and Case, 1992). Although SNL is developing a borehole sealing strategy, it has not yet been published. In the meantime, SNL recommends that "no grout should be placed in selected sealing areas which contain fractures" (Costin, 1992b). As can be seen in Figure 6, most layers drilled through at UZ#16 have at least 10 fractures for every ten ft interval. Based on this, SNL's recommendation is incompatible with a grouted geophone configuration.

SCP section 8.3.3.2 gives a reference design for borehole plugging and sealing (DOE, 1988b), and this is the design which SNL follows. However, there are two alternatives for an unsaturated-zone borehole that is stemmed and grouted: (1) show that the stemmed and grouted configuration forms a viable seal, or (2) demonstrate that stemmed boreholes can eventually be drilled out for sealing (USGS, 1991a).

2.5 Specific Evaluations and Conclusions

2.5.1 Water Flowing from UZ#16 to Conceptual Repository UZ#16 is located in a flood-prone draw (see Figures 4 and 5), and there is the potential for water to flow into the drillhole. If the borehole is not sealed or the seal fails, then there is the possibility that water flowing into the borehole may reach the conceptual repository. In their analysis of UZ#16, Fernandez and Case (1992) stated, "Preliminary results indicate that a borehole located in a flood prone area has the potential for introducing quantities of water greater by orders of magnitude into the underground workings when compared to a borehole located outside [a probable maximum flood area]." However, it is unclear from their analysis how this could impact waste isolation.

Some bounding calculations (see Appendix B) were performed to estimate the amount of water that could enter the borehole during a probable maximum flood. The conclusions are:

1) Up to 0.83 m^3 of water will infiltrate through a highly degraded backfill matrix.
2) Up to 1.9 m^3 of water will infiltrate through fractures and a degraded matrix.

These numbers are extremely conservative for the following reasons: 1) the matrix is assumed to have a hydraulic conductivity of sand; 2) the fractures are assumed to extend the entire length of the borehole; 3) steady flow is assumed, which is much more rapid than infiltration into an unsaturated matrix; 4) no evapotranspiration is assumed; 5) no credit is taken for a ground level seal: and 6) a high number of fractures is assumed. It should be noted that these calculations are for a probable maximum flood, which should occur no more than twenty times in the 10,000-year period of interest at the site.

Computer analyses have been performed to evaluate the impact of matrix and fracture flow of water on the conceptual repository (see Appendix A). Using very conservative assumptions of a backfill with a hydraulic conductivity of sand, a 14-hour flood duration, no evapotranspiration, level stratigraphy, and a fracture which extends the length of the borehole, the conclusions are:

1) Approximately 0.03 m^3 of water will infiltrate the borehole for a 500-year flood.
2) Approximately 0.0135 m^3 of water will infiltrate the borehole annually.
3) The capillary-pressure barrier effectively prevents borehole flow below the top 7 m of the Tiva Canyon.
4) The borehole does not affect rock saturations, other than a disk at the top of the borehole measuring 15 m in radius and 7 m in depth.

It should be noted that the difference, compared to Appendix B, in the amount of water that infiltrates the borehole for a flood event is due mostly to different values of permeability for the sand. When the hand calculations ((Appendix B) incorporated the same permeability as the computer simulation, the results were almost the same.

As can be seen from the above analyses, the potential volume of water flowing into the borehole, and subsequently from UZ#16 to the conceptual repository, is negligible and therefore insignificant to waste isolation.

2.5.2 <u>Water Flowing from UZ#16 to Potential Repository Expansion Areas</u> UZ#16 is located near the center of potential repository expansion area 6 (see Figure 3). As discussed in SCP Section 8.4.3.3.1.2, a standoff distance of at least 30 m (100 ft) will be maintained between boreholes and emplaced waste (DOE, 1988c). Because UZ#16 is located in a flood-prone area, there is potential for water to accumulate in the borehole. Furthermore, the borehole extends from the surface through the expansion area to the water table. If the borehole is not sealed or the seal loses integrity, then water in the borehole could reach the expansion area.

Computer analyses (see Appendix A) have shown that the inflow of water and subsequent rise in saturation is limited to a disk of tuff with a radius of 15 m and a depth of 7 m. The assumptions used in the analyses are extremely conservative, so the 30 m (100 ft) standoff distance should be sufficient.

2.5.3 <u>Saturated Zone Ground-Water Travel Time</u> If the borehole is not sealed or the seals fail, surface water flowing into the borehole may reach the water table and could potentially affect saturated flow direction and velocity. Some bounding calculations were performed to estimate the effects of seal failure (see Appendix B). The extremely conservative calculations show that the maximum inflow is small relative to the regional saturated zone ground-water flow, and the subsequent rise of the water table is 3.3 x 10^{-6} m at the edge of the conceptual repository boundary. Consequently, the infiltration of water through the borehole is judged to be insignificant to the saturated zone ground-water travel time.

2.5.4 Aqueous Radionuclide Transport UZ#16 lies downdip of the potential repository. Since the borehole extends to the saturated zone, it is a possible pathway for aqueous radionuclides to be released to the accessible environment. For this reason, it is prudent that the seal be maintained at depths beneath the repository.

Fernandez and Case (1992) considered flow from a flooded drift and concluded, "For the UZ-16 location, the projected lateral distance from the repository boundary is 100 m, and the plume would not intersect the borehole." Their calculations are conservative as they considered only fracture flow and did not account for fracture-matrix interactions. The effect of the matrix on fracture flow would be to draw water out of the fracture, further limiting the extent of the fracture flow.

Costin (1992) summarized the results with a caveat, "The analysis indicates that, while it is unlikely that a contaminated plume would reach UZ-16, if perched water occurs at material contrasts beneath the repository, there is a limited possibility that contaminated fluids could enter UZ-16." However, the borehole is almost completely drilled (the water table was reached in late February), and there is no evidence of perched water in the vicinity of UZ#16.

If the potential repository expansion area 6 is used in the future, these analyses indicate that there may be the potential for aqueous radionuclides to be transported to the water table via UZ#16. Although it is possible that the mandatory 30 m standoff distance between boreholes and emplaced radioactive waste (DOE, 1988c) is sufficient to avoid adverse impacts on the site, more analyses are necessary prior to the development of expansion area 6. These analyses should consider the effect of fracture-matrix interaction on fracture flow.

The present instrumentation plans call for leaving the central support pipe empty in order to allow access for various tests. There are no plans to eventually fill the pipe. If the pipe is not sealed with an expansive grout, the tube would not impede the transport of aqueous radionuclides to the water table. We do not feel that it is necessary to fill the interior of the tube during instrumentation, only before the hole is abandoned.

2.5.5 Gaseous Radionuclide Transport Fernandez and Case (1992) analyzed diffusive transport of gaseous radionuclides through fractures at Yucca Mountain. Two cases were considered: 1) a base case with no general orientation to the fractures, and 2) a case where the general northeast-southwest orientation of the fractures was considered. They concluded,

> "For the isotropic [base] case, the lateral spreading would be limited to several hundred meters from the edge of the repository. This is a conservative estimate because the dominance of the vertical fracture system could force flow to be more narrowly confined around the perimeter of the repository....In the second case, lateral spreading is

directionally controlled by the dominant northeast-southwest trending fractures. The figure [our Figure 7] shows that the borehole falls within 600 meters for the first case and slightly outside the zone of gaseous radionuclide diffusion for the second case."

In an analysis which included thermal effects, Ross *et al.* (1992) analyzed rock-gas flow in Yucca Mountain. For a conceptual repository which is heated to 330 K, gas in the area of UZ#16 would flow westward, be heated by the repository, and rise vertically out of the mountain (see Figure 8). In such a scenario, gaseous radionuclides which are released from their waste packages reach the accessible environment by migrating vertically through the repository. Thus, UZ#16 is an unlikely pathway for gaseous radionuclides from the potential repository.

However, if the potential repository expansion area 6 is used, the borehole could act as a pathway for gaseous radionuclide transport to the surface. The most likely route would be up the support pipe, the sealing of which is not planned. If the pipe is not sealed with an expansive grout, the tube would not impede the release of gaseous radionuclides and the borehole could be a preferential pathway for release to the accessible environment. We conclude that the inside of the tube should be sealed before the borehole is abandoned.

If the support tube is sealed, then the most likely route for transport of gaseous radionuclides is through fractures. As can be seen from the bounding calculations in Appendix B, for a scenario where a fracture forms between the grout and the tuff over the entire depth of the borehole, the fracture porosity of the borehole would then be of the order of the fracture porosity of the host tuffs. Consequently, we conclude that if the inside of the support tube is sealed with an expansive (non-shrinking) cement, then the borehole probably will not be a preferential path for gaseous radionuclide transport from the potential repository expansion area 6.

2.5.6 Thermo-Mechanical Effects Due to its proximity to the repository conceptual perimeter drift boundary, UZ#16 and the instrumentation contained therein may experience thermal effects from the potential repository. The magnitude of the thermal effects depends on the thermal loading of the repository. Various alternatives are being considered, ranging from a "cold" repository to a "hot" repository. The latter is the only one of concern here, as the "cooler" scenarios would have negligible thermal effects on the borehole.

For a "hot" repository, different heat transport phenomena can yield different repository temperatures. Ross (1992) summarized three scenarios. In the most likely model, the waste containers reached a peak temperature of approximately 200°C twenty-five years after waste emplacement, thereafter gradually cooling. However, "the area in which the temperatures exceeded the boiling point extended only about 10 m from the canisters." Thus, the borehole is not expected to experience temperatures above 100°C. For the other scenarios, the waste packages remain at or below the boiling point of water.

The thermal effects of a hot repository on the instrumentation and grout in UZ#16 are discussed in the next two sections, which are dedicated to materials analysis. It is concluded that for temperatures below boiling, the materials to be used in the stemming and grouting of the borehole are stable.

Two mobile seismic sources will be used in the survey: "1) a medium frequency source (250 Hz maximum).... and 2) a small, lightweight high frequency source (such as the Oyo vibrator)" (Hayes and Chaney, 1992). The first is truck-mounted and will be used far from the borehole, while the second can be hand-carried and will be used closer to the borehole. The mobile transducers ("thumpers") are not expected to impact the rock on which they are set (personal communication from L. Thompson, SAIC, January 15, 1993). If the thumpers are used on alluvium, shallow depressions may be formed (Hardage, 1983), but due to their small size (less than three feet across) these depressions are not expected to affect site performance. Vibratory sources can be a source of Rayleigh wave ground roll, which can impact the entrances of boreholes (Hardage, 1983). As the ground roll amplitude decreases with propagation distance, it is prudent to maintain a standoff distance between the seismic sources and the boreholes. A conservative standoff distance is estimated to be 50 feet from existing boreholes and other tests (Statton, 1993). Thus, if the standoff distance is observed, the surface activities related to the seismic study are not expected to adversely impact site performance.

The borehole is being drilled, not blasted, so mechanical effects on rock materials are expected to be negligible. The stresses exerted by the expansive grout are also expected to be insignificant to waste isolation. In fact from a sealing standpoint, an expansive grout is preferable to a nonexpansive grout.

2.5.7 Fluids, Tracers and Materials No unusual fluids or tracers will be used. Since none of the materials to be used for activities on the surface will remain permanently at the site, they will not adversely impact siter performance. Adequate controls exist to prevent adverse impacts to site performance from dust-control water and from potential spills of vehicle and equipment fluids.

As the initial plan called for permanently stemming and grouting the geophones in place, it is important that we consider the possible effects this may have on site performance. The materials of interest include the fiberglass central support pipe, the centralizers, the geophones and their cables, and the grout to be used for the geophone emplacement. Some fiberglass tape may be used to secure the cables to the support pipe, but the small quantity is not considered significant.

The fiberglass central support pipe that will be used is SDT 1010HP Downhole Tubing by Smith Fiberglass Products. It has a thickness of 0.125 in and an outer diameter of 2.375 in. The fiberglass is stable at temperatures below boiling, and there is substantial evidence that it is long-lived in hot, dry environments (personal communication from Phil Ellsworth, Smith Fiberglass Products, February 4, 1993).

According to the original criteria letter, three-arm centralizers will be attached to the central support pipe every 48 feet. Originally, about 36 centralizers would be needed (USGS, 1991b), but according to Rousseau (USGS, verbal communication, January 20, 1993), no more than five or six centralizers will be used. They would be either fiberglass or iron. The small quantity of relatively inert material is not considered significant to site performance.

The geophone assembly consists of three polyurethane encased cables of 0.89-in diameter (0.16 in jacket thickness). Each cable has approximately 100 conductors of 26 TCS (tin-copper strand), and the space between the strands is filled with the water blocking compound V-726 (Craig, 1993; personal communication from Ezra Wasson, RSN, on January 15, 1993). The polyurethane is rated to 90°C and does not melt below 160°C, so the cable is thermally stable at the relevant temperatures (personal communication from Zafar Jafri of Philatron. Inc., on January 6, 1993). It is unlikely that polyurethane or the blocking compound would be a significant source for colloid formation and radionuclide transport due to its relatively small quantity and moderate distance from the repository CPDB. However, there is some concern that the polyurethane may react with the grout and infiltrating water. Currently, we do not have sufficient data to evaluate the longevity of the polyurethane or its reactivity with the grout.

The metallic geophones are of sufficiently small mass that they are considered insignificant to waste isolation. Chemical aspects and materials considerations of the grout will be discussed in the next section on sealing considerations.

2.5.8 Sealing Considerations As can be seen from the analyses above, UZ#16 is not likely to adversely impact site performance. Thus, the method used to seal UZ#16 is flexible. The analyses presented in Appendix A show that although the final sealing plan of a borehole may have multiple high-performance seals, the important seal is the top seal that extends into the Tiva Canyon unit. This seal can significantly inhibit infiltration of water into the borehole, while the other two seals do not. If the proposed repository expansion area 6 is used, then a more rigorous sealing program may be necessary, as described in this section.

Roy *et al.* (1979) defined some *a priori* criteria for stable borehole plugging and sealing. These seem reasonable and are listed below:

(1) The plug must seal boreholes at least as effectively as the rock strata it penetrates.

(2) The plug must be stable in the host rock environment.

(3) Any changes in the plug or plug-rock unit due to host-rock environment as a function of time must not be detrimental to the quality of seal.

(4) The plug must be able to withstand natural long-term geologic processes at least as well as the competent rock strata it penetrates.

(5) The plug must withstand natural catastrophic processes at least as effectively as the rock strata it penetrates.

These criteria imply that the sealant should have good compressive, shear, and tensile strengths, low hydraulic conductivity, high thermal stability, and a bulk chemistry similar to that of the host rock. Fernandez *et al.* (1987) also indicate that the seal components of a borehole plug should have high strength and density to prevent settlement and gap formation. Furthermore, Jeffry (1980) advises that the inclusion material should be less compressible and stiffer than the host rock, in order to minimize critical radial and tangential tensile stress concentrations which could lead to fractures in the grout.

Of all the materials, the grout that couples the geophones to the borehole wall is the feature that has the greatest potential impact on waste isolation for two reasons. First, the ability of the grout to form a good seal will determine the integrity of the borehole seal. Second, the grout is volumetrically the major component in the borehole.

Although the USGS has not selected a final grout composition, it will probably be a calcium sulfate mix design. According to Rousseau of the USGS (verbal communication, January 5, 1993), the concern is that a calcium carbonate mix would interfere with ongoing and planned tests measuring carbon dioxide. The USGS is planning to use a grout with a compressive strength of approximately 1,000 psi to allow for the possibility that the grout and instruments might be drilled out (Craig, 1993; Craig, verbal communication, January 6, 1993). However, the borehole is deviated, and it is estimated that the final deviation might be as much as 45 ft to the southwest (Wright, 1993). According to Wright (RSN, verbal communication, February 8, 1993), the technology necessary to drill out a 1600 ft borehole which is deviated by 2-3°, like UZ-16, has not been demonstrated. Consequently, the incentive for a relatively soft grout is not as great, and we feel that stronger grouts should be investigated, particularly for the proposed high performance seals mentioned in section 1.2. These grouts could be used as a grout-sealant that would couple the geophones to the borehole wall and seal the borehole permanently. Alternatively, the high-performance grouts could be used after some or all of the instrumentation, soft grout, and sand is removed.

For a long-term seal, it is generally suggested that the sealant should have a composition which is similar to the host rock: "It is presumed that the closer the bulk chemistry of a material is to its emplacement environment, the lower is the potential for the modification of the material bulk chemistry. Therefore, the potential modification of its physical and mechanical properties will also be lower" (Licastro *et al.*, 1990).

In an evaluation of potential mortar and grout formulations, Licastro *et al.* (1990) chose three for further study: expansive mixtures 82-22 and 82-30 and nonexpansive mixture 84-12. All three have low permeabilities (less than 10^{-8} darcy) and are less permeable than the tuff, which is expected to have a permeability greater than 10^{-6} darcy (Daemen *et al.*, 1983). Furthermore, these "dense, pumpable grouts suitable for borehole and fracture/fault sealing" have good bond, tensile, and compressive strengths, positive expansion under confining stress, relatively low porosities and conductivities, and chemistries which are similar to the host rock. Mixtures 82-22 and 84-12 (see Figure 9) show promise as sealants. The first, 82-22, is the closest to the bulk composition of the nonwelded and welded tuffs, and the latter, 84-12, has a similar composition (see Figure 10).

Mixture 84-12 has a reduced sulfate content and high silica, so that an intermediate pH is maintained and there is a lessened potential for the sulfate to react as a radionuclide complexing agent. It was noted by Sheetz and Roy (1986) that aluminum substitution into the tobermorite structure increases the thermal stability of the mixture. In fact, tobermorite was observed at temperatures as high as 300°C, well above its expected stability. Mixture 82-22 has the highest alumina content of the three listed above, and therefore more Al-substituted tobermorite could be formed. Also, when there is coupled alkali plus aluminum substitution in tobermorite, material is generated which has ion exchange properties favorable for radionuclide sorption.

Jeffry (1980) concluded that it is "important to establish a good bond between the plug and the rock not only to provide an effective seal but also to help control the development of adverse stresses." In support, Fernandez *et al.* (1987) observe, "Laboratory and field studies indicate, however that the interface between the rock and cementitious materials may be more permeable than either the seal or rock and may be a preferred flow path." The interface permeability associated with mixture 82-22 was consistently lower or comparable to the interface permeabilities associated with the other mixtures tested (Licastro *et al.*, 1990).

The mixtures considered by Licastro *et al.* were quite strong relative to the sulfate-based sealants presently considered. As mentioned above, the sulfate-based sealant will probably have a compressive strength of 1000 psi, or about 6.9 MPa. In contrast, the experimentally measured 7-day compressive strengths for the 82-30 grout (no sand included), 82-22 mortar (with sand), and 84-12 mortar (with sand) are 99.1 MPa, 77.5 MPa, and 86.9 MPa, respectively, an order of magnitude stronger than the sulfate-based sealant.

The durability of cement sealants over 10,000 years is an important issue. In an examination of ancient cements which have survived to the present day, Roy and Langton (1983) found that hydraulic hydrated lime based materials and lime-pozzolanic cements are more durable and workable than gypsum (hydrous calcium sulfate) or hydrated lime cements. They also tend to have wider particle size distributions, allowing higher density of packing and permitting lower water/cement ratios. Some coarser materials showed excellent grading of coarse to fine fractions, which appeared to be responsible in part for their mechanical stability. The composition of the SNL mixtures is similar to the alkali-rich calcium silicate compositions of the pozzolana cements, which also contained aluminum. "Finally, it is apparent that their exposure to surface and near-surface conditions in a warm relatively dry climate resembles to a certain extent the prospective exposure conditions for candidate borehole and shaft sealing materials for near-surface application in a nuclear waste repository as currently conceptualized for the NNWSI" (Roy and Langton, 1983). Consequently, the long-term durability of the SNL mixture 82-22 at Yucca Mountain seems good.

Some preliminary studies (Hinkebein and Gardiner, 1993; Gardiner *et al.*, 1991) indicate that ettringite, the component of 82-22 which is responsible for the expansive nature of the grout, may exhibit preferential leaching and react to form gypsum. However, saturated conditions are assumed, and the time span over which this occurs is not discussed. For the unsaturated conditions expected at the borehole, it is probable that the reaction occurs at a significantly slower rate, if at all. The effect of the decomposition of the ettringite is to open up the concrete structure, but "the permeability changes...are estimated to be small" (Hinkebein and Gardiner, 1992).

Mixture 82-22 seems to be a prime sealant because of the following properties: 1) expansive; 2) strong; 3) bulk chemistry is similar to the host tuff composition; 4) therefore, it is expected that it will react minimally with the host rock; 5) low hydraulic conductivity and interface hydraulic conductivity; 6) high alumina content and good thermal stability; 7) durable and has a long expected lifetime; 8) relatively little sulfate, and thus it will not be a likely radionuclide complexing agent. However, it is unclear whether or not mixture 82-22 can be transported downhole before the tremie pipes bridge off. Before 82-22 could be used at UZ#16, its workability would need to be shown. Also, further stability analyses of ettringite and 82-22 is advisable.

Alternative sealants such as backfill and clay (e.g., bentonite) have been considered. However, emplacement of these materials in small-diameter boreholes is neither simple nor very effective. Roy et al. (1979) summarized the status of earthen seals: "After extensive feasibility testing at MIT, it was determined that, although compacted earthen materials might possess some desirable properties and appear promising, they could not be relied upon as primary sealants. However, as a potential inter-strata layer or zone which could expand upon contact with water (partially dehydrated clay) and extrude into any cracks in the interfacial region or plug itself, they hold quite a bit of promise." The present emplacement configuration does not include earthen materials, but in highly fractured zones such as the partially welded and nonwelded tuffs below the Topopah Spring Member vitrophyre, clay may be useful. It should be noted that calcium leaching from the grout can decrease the swelling pressure of Na-K swelling clay. To avoid this problem, Fernandez (1991) suggests using a calcic form of clay.

A total of approximately 800 gallons of water will be used to clean out the tremie pipes between grout batches (Boak, 1992). This quantity is sufficiently small that it is not a significant waste isolation consideration.

SCP section 8.3.3.2 gives a reference design for borehole plugging and sealing (DOE, 1988b). There are two alternatives for an unsaturated-zone borehole that is stemmed and grouted: (1) show that the stemmed and grouted configuration forms a viable seal, or (2) demonstrate that stemmed boreholes can eventually be drilled out for sealing (USGS, 1991a). For the reasons given above, a stemmed and grouted configuration is acceptable for a long-term sealing program at UZ#16, whereas it is highly impractical and expensive to drill out and seal the borehole after the VSP study is completed. Furthermore, the drilling technology necessary to drill out a deviated borehole of almost 1700 ft has yet to be demonstrated.

3. CONCLUSIONS AND RECOMMENDATIONS

This analysis is a result of conflicting requirement for UZ#16 given by the USGS (the stemmed and grouted geophone configuration described in USGS, 1991b) and SNL (no grout would be left in the fractures as per Costin, 1992). We conclude that grouting geophones in place is an acceptable sealing program for this borehole. Certain controls should be observed in the instrumentation of the hole and subsequent data acquisition.

The surface activities associated with the planned seismic profiling are not expected to adversely impact site performance, provided existing controls for tracers, fluids, and materials are observed. The materials that are planned to be used in the instrumentation of the borehole are not expected to impact site performance. However, as an added measure of certainty, we suggest that an alternative grout be used for the sealing of the borehole (Recommendation 2).

Analyses to estimate the potential impact of surface water inflow into the borehole if it could not be sealed effectively or if the seals deteriorate in the future indicate that the planned activities, including the permanent grouting of geophones in the borehole, can proceed if the following recommendations are implemented:

Recommendation 1. The interior of the central support pipe should be sealed. We suggest an expansive cement, as backfill is impractical due to the narrow dimensions of the pipe and sand would not impede the travel of gaseous radionuclides up the tube, or water and aqueous radionuclides down the pipe. It is not necessary to seal this pipe at the time of instrumentation, but it should be permanently sealed before the hole is abandoned. In the meantime, reasonable care should be taken so that water or other foreign materials do not get into the pipe.

Recommendation 2. A different grout composition should be considered. The present sulfate-based grout is relatively soft, a possible radionuclide complexing agent, and of unknown thermal stability or durability. SNL (notably Fernandez, Roy, Licastro, and Scheetz) has done extensive work on possible grout formulations, and we recommend consideration of Sandia's 82-22 mixture for the reasons given above in section 2.5.8. Further investigation is necessary to determine 82-22's longevity and ability to be transported downhole.

Our recommendation of 82-22 is based on the information we were able to obtain. Other grouts which exhibit 88-22's high strength, low porosity, low hydraulic conductivity, chemical compatibility with the host tuff, expected longevity, thermal stability, positive coefficient of expansion, and low interface hydraulic conductivity would be just as acceptable. In their upcoming sealing report, SNL will probably recommend some specific grouts for use in sealing boreholes. If UZ#16 has not been grouted at that time, we would advocate evaluating Sandia's suggested grouts for use in UZ#16.

Recommendation 3. During VSP, a standoff distance of at least 50 ft should be observed between the seismic sources and any boreholes.

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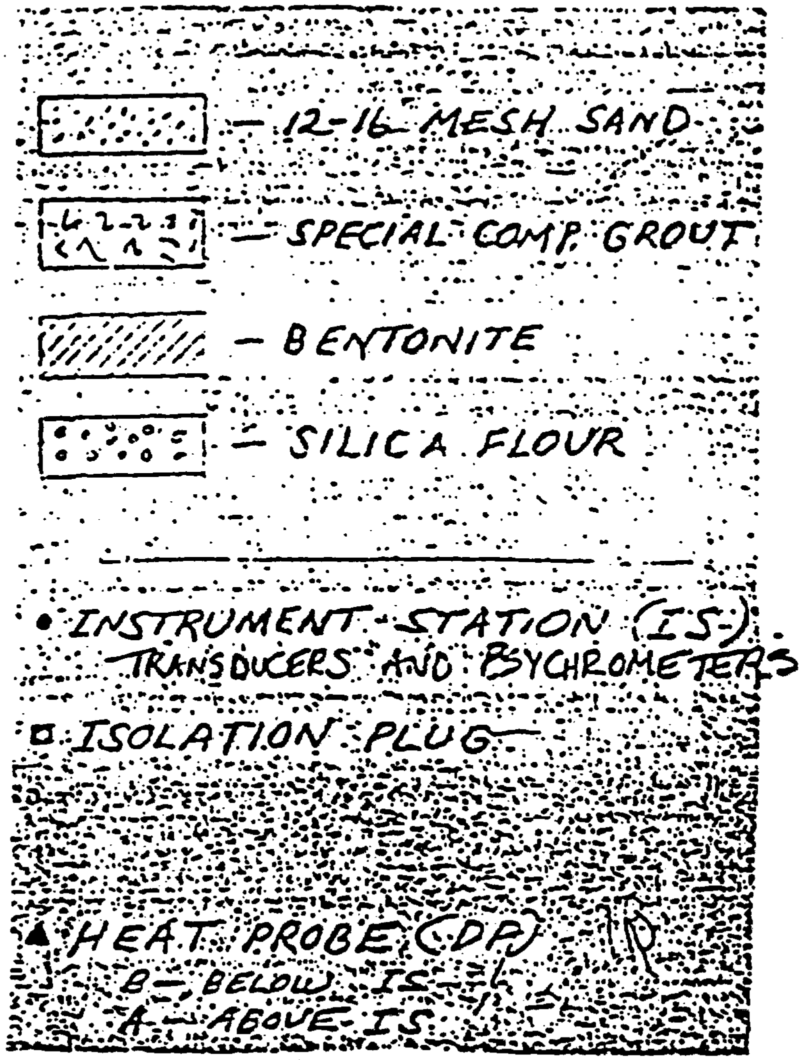


Figure 1 Diagrammatic cross-section of the stemmed and grouted borehole UZ-1 showing the distribution of instruments and isolation plugs (McBride, 1984).

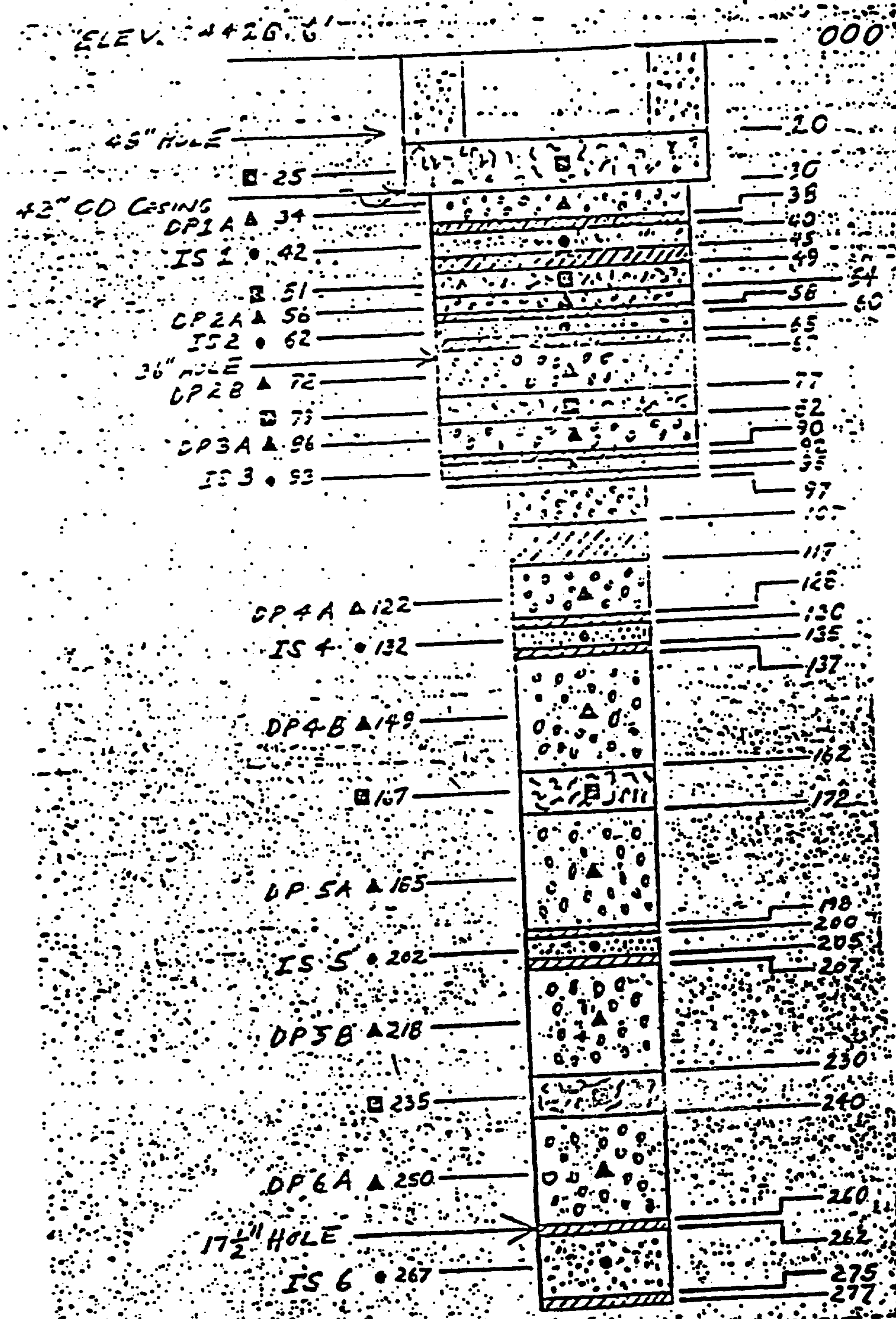

ELEV.
45" HOLE
42" OD CASING
DP1A ▲ 34
IS 1 ● 42
DP2A ▲ 56
IS2 ● 62
36" HOLE
DP2B ▲ 72
DP3A ▲ 86
DP4A ▲ 122
IS 4 ● 132
DP4B ▲ 149
DP 5A ▲ 165
IS 5 ● 202
DP5B ▲ 218
DP 6A ▲ 250
17 1/2" HOLE
IS 6 ● 267
000
20
30
35
40
45
49
54
58
60
65
77
82
90
97
117
130
137
162
172
200
205
207
230
240
260
262
275
277

Figure 1B

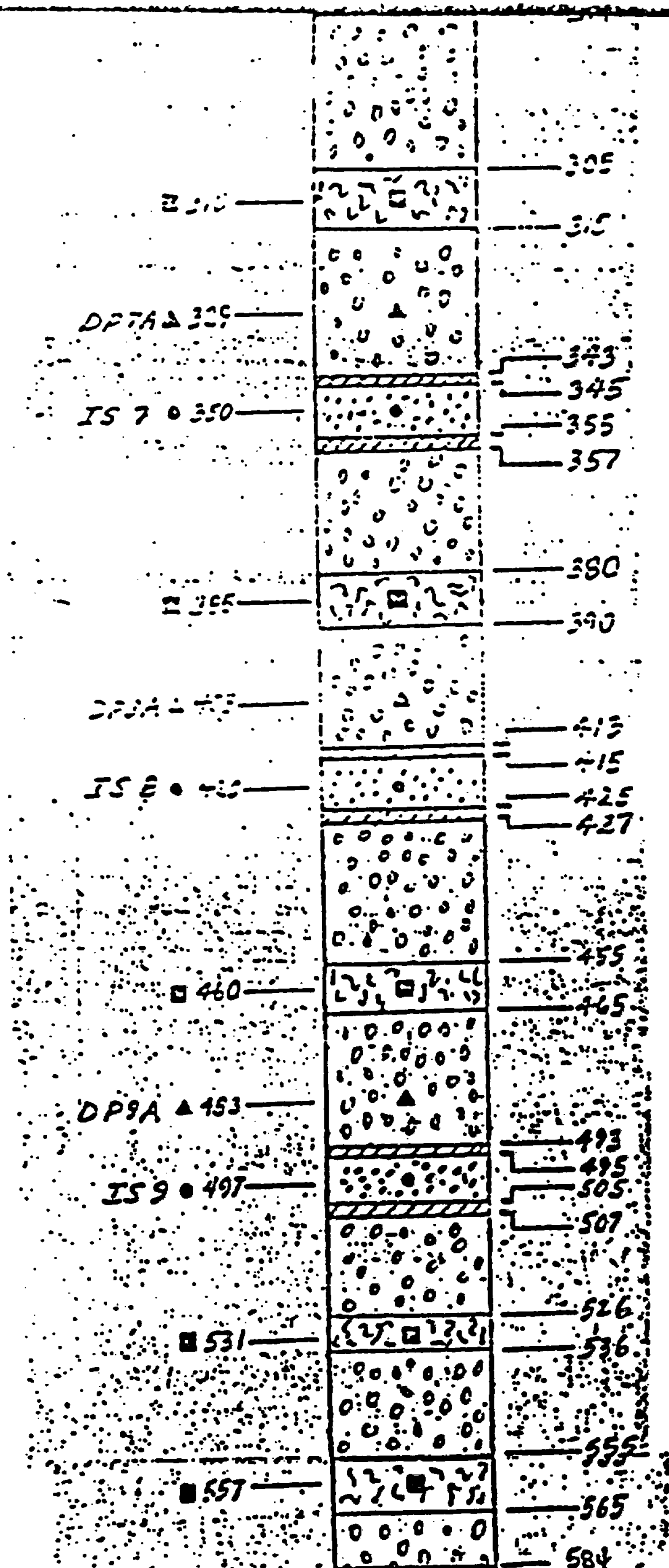
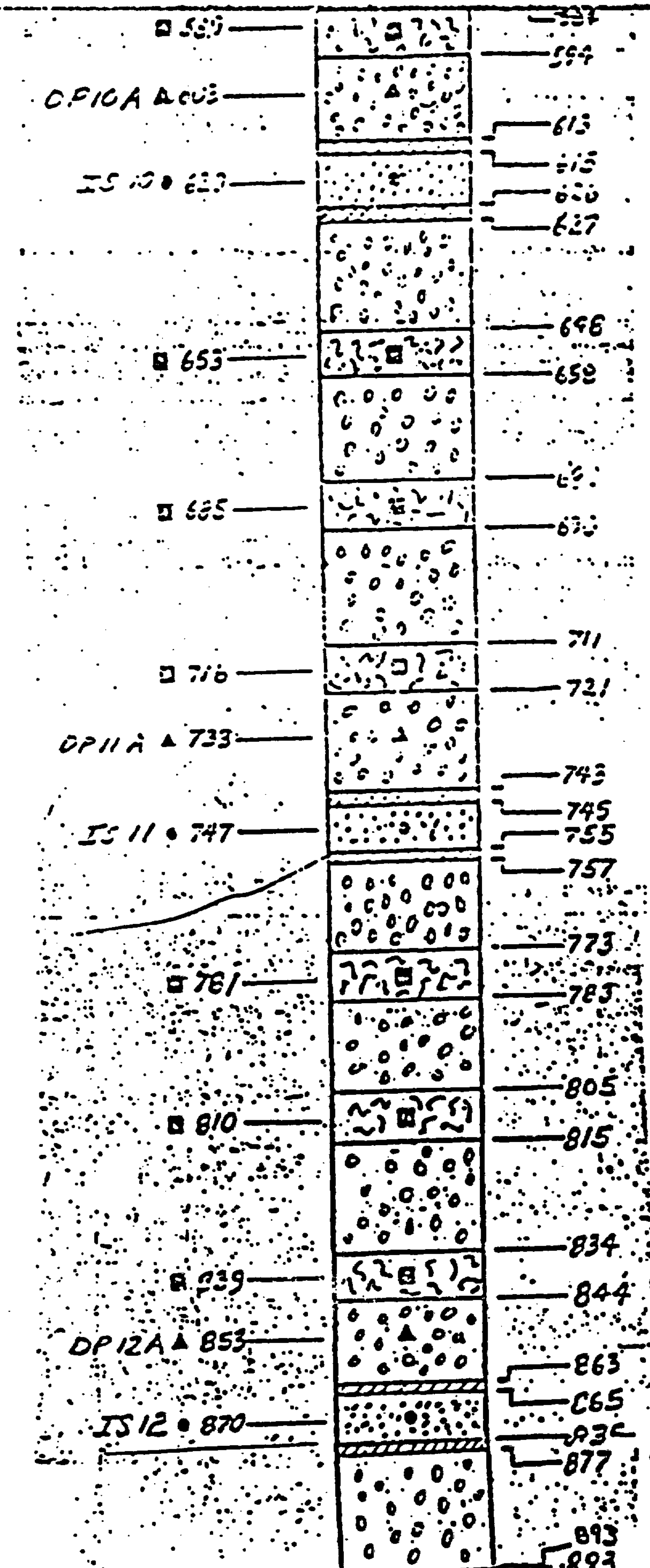
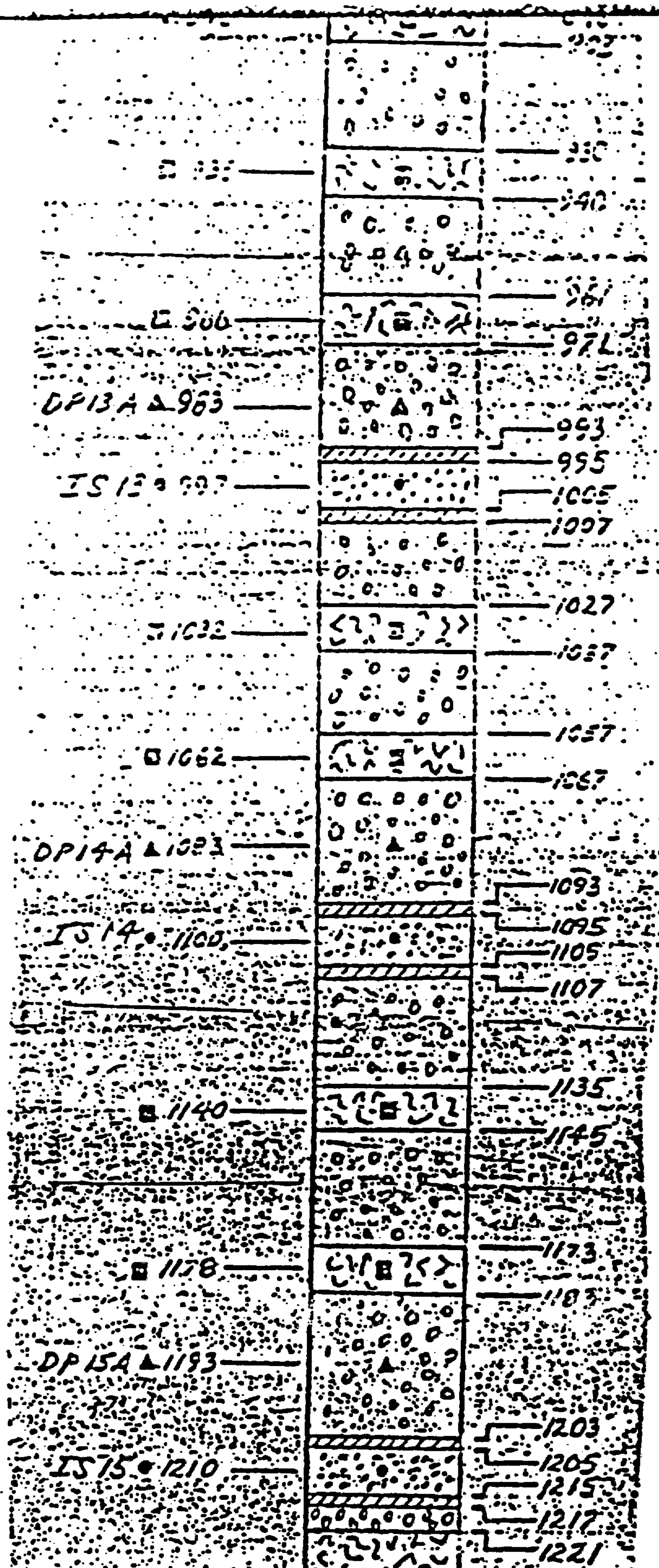

305
310
DP7A ▲ 329
343
345
IS 7 ● 350
355
357
380
385
390
413
415
IS 8 ● 420
425
427
455
■ 460
465
DP9A ▲ 483
493
495
IS 9 ● 497
505
507
526
■ 531
536
555
■ 557
565
584

Figure 1C



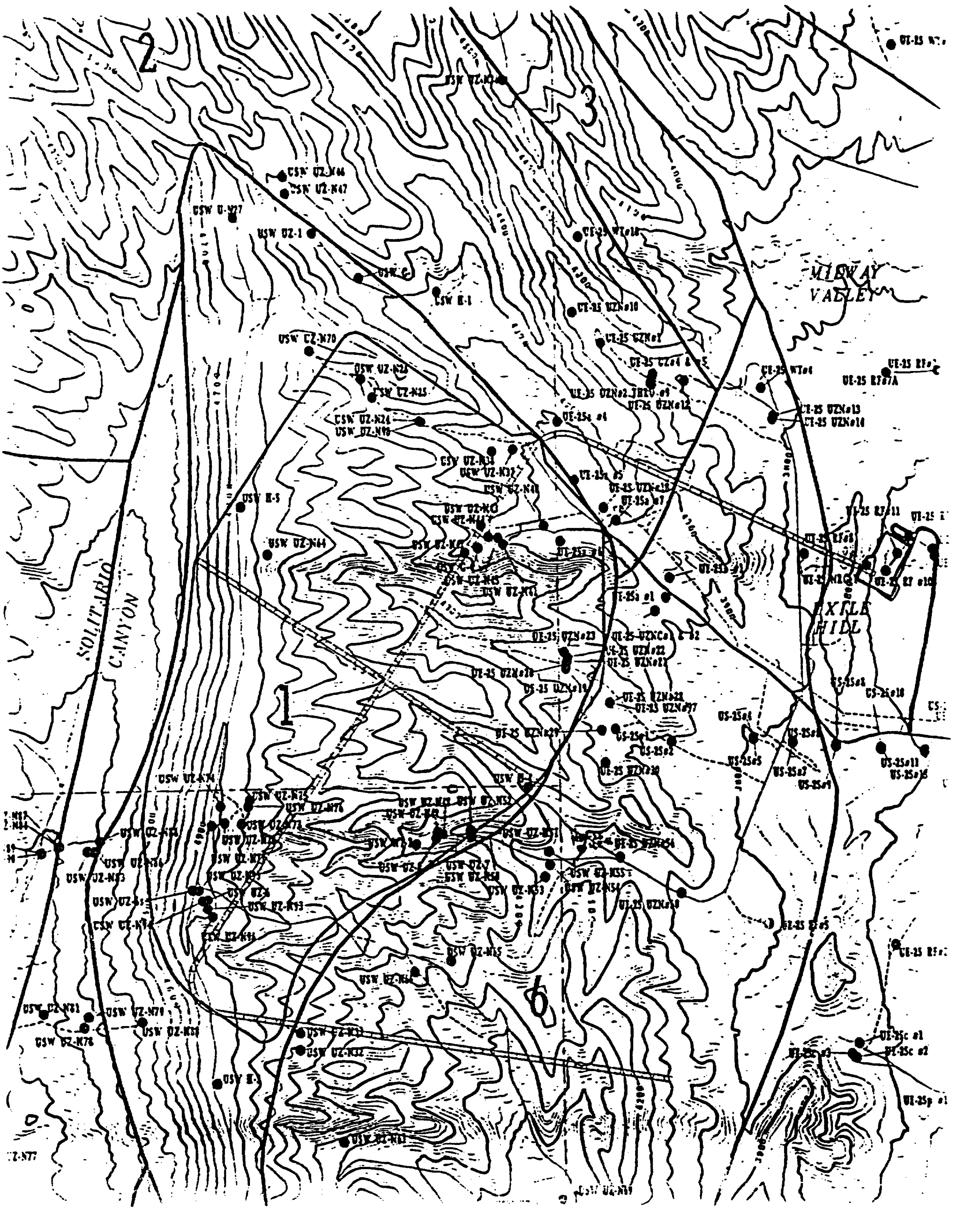
DP10A ▲ 603
IS 10 ● 620
653
685
716
DP11A ▲ 733
IS 11 ● 747
781
810
839
DP12A ▲ 853
IS 12 ● 870
594
613
615
620
627
648
658
711
721
743
745
755
757
773
785
805
815
834
844
863
865
877
893

Figure 1D



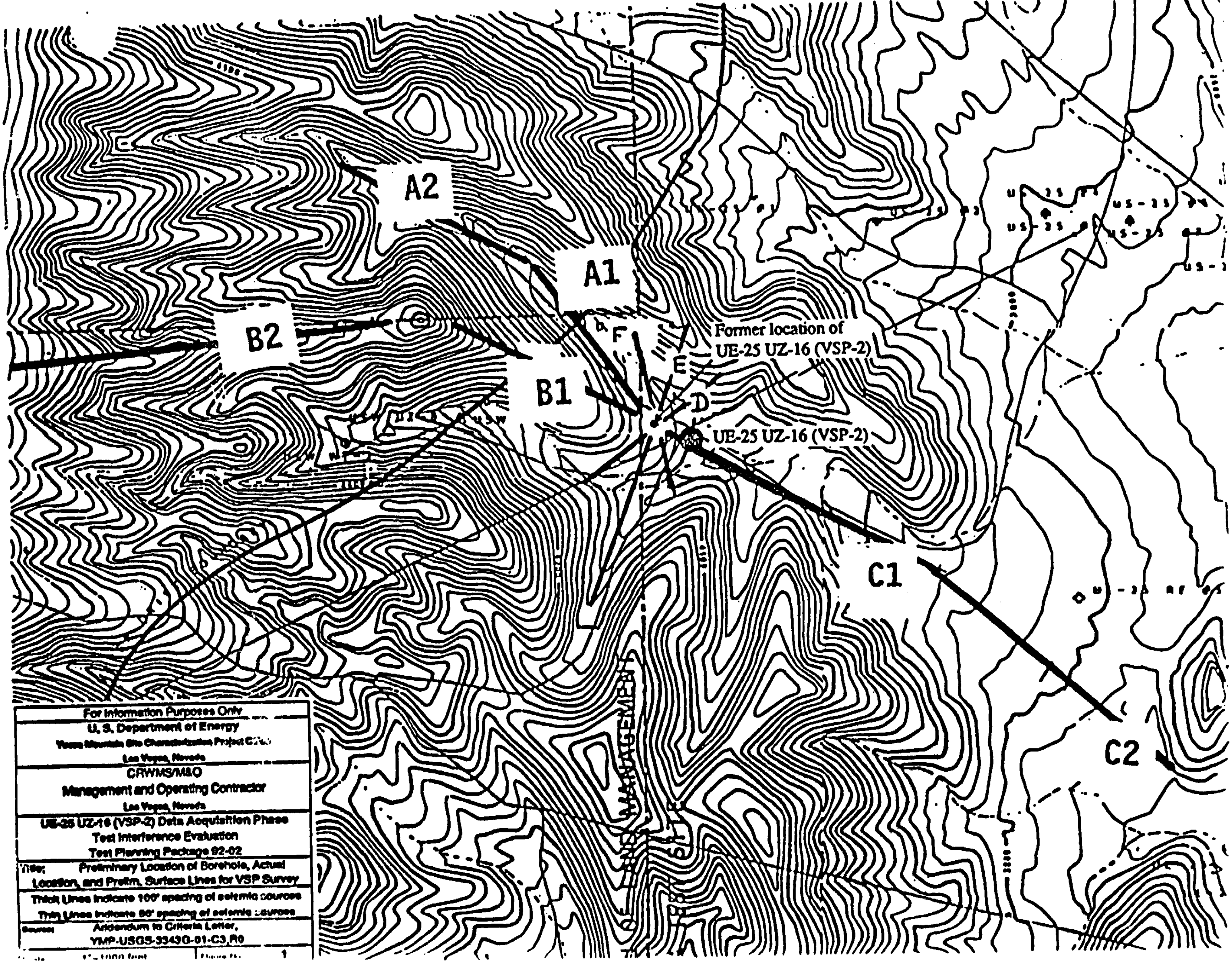
961
971
DP13A ▲983
993
995
1005
1007
1027
□1032
1037
1057
□1062
1067
DP14A ▲1083
1093
1095
IS14 ● 1100
1105
1107
1135
□1140
1145
1173
□1178
1183
DP15A ▲1193
1203
1205
IS15 ● 1210
1215
1217
1221

Figure 1c



2
3
1
6
MIDWAY VALLEY
SOLITARIO CANYON
EXILE HILL
USW UZ-1
USW UZ-N46
USW UZ-N47
USW UZ-N70
USW UZ-N64
USW UZ-N15
USW H-5
USW H-1

... of UE-25 UZ#16 (VSP#2), actual location, and preliminary



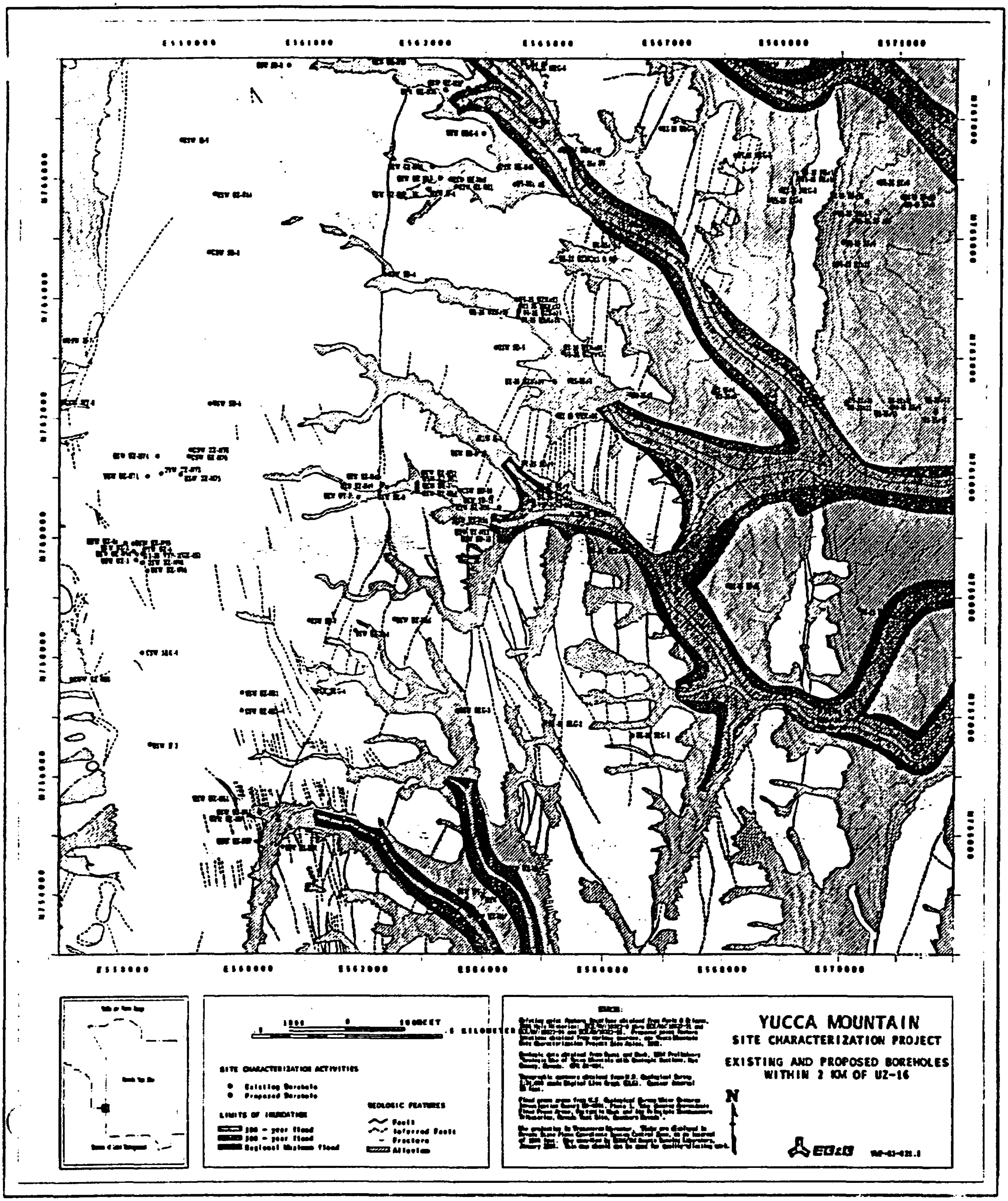
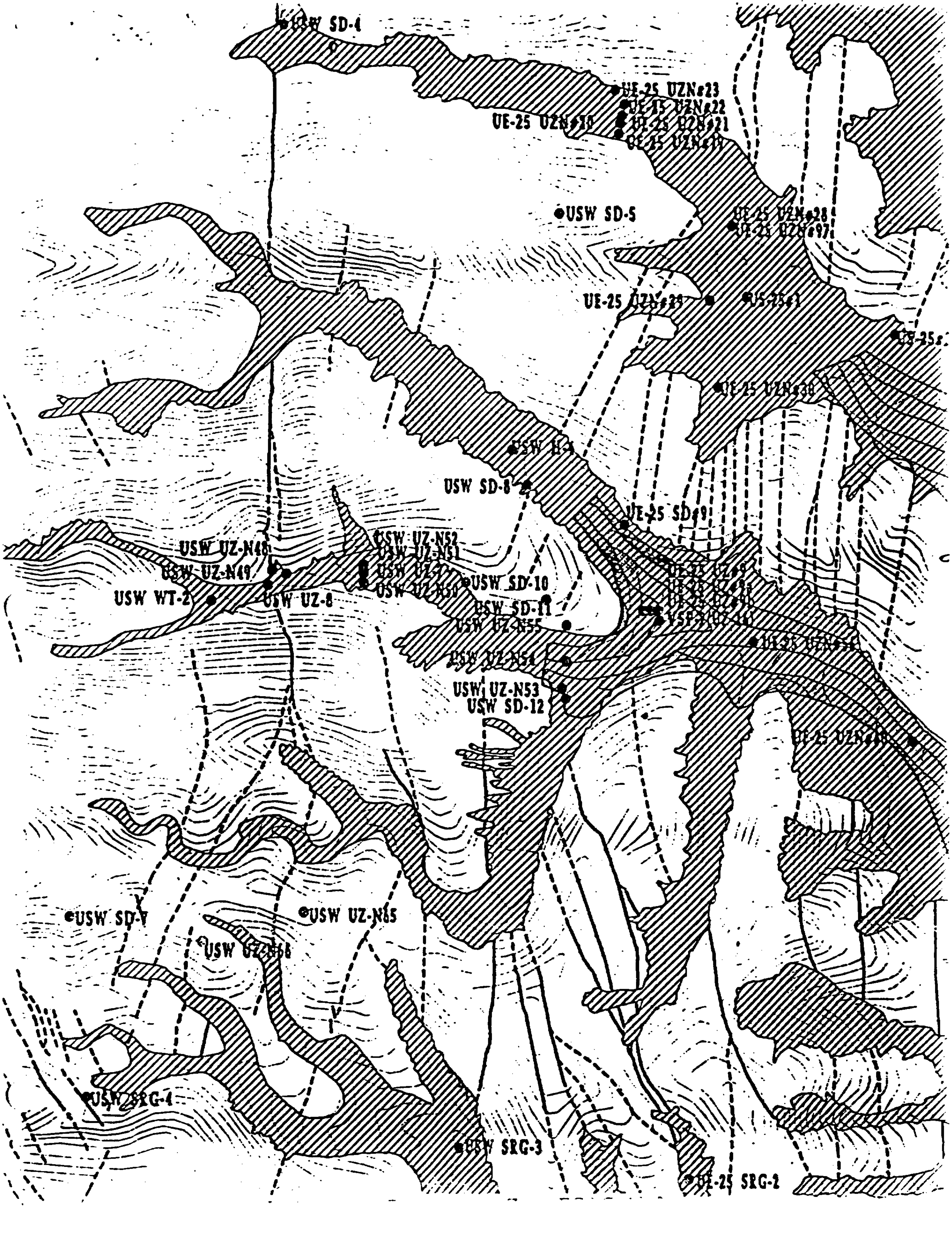
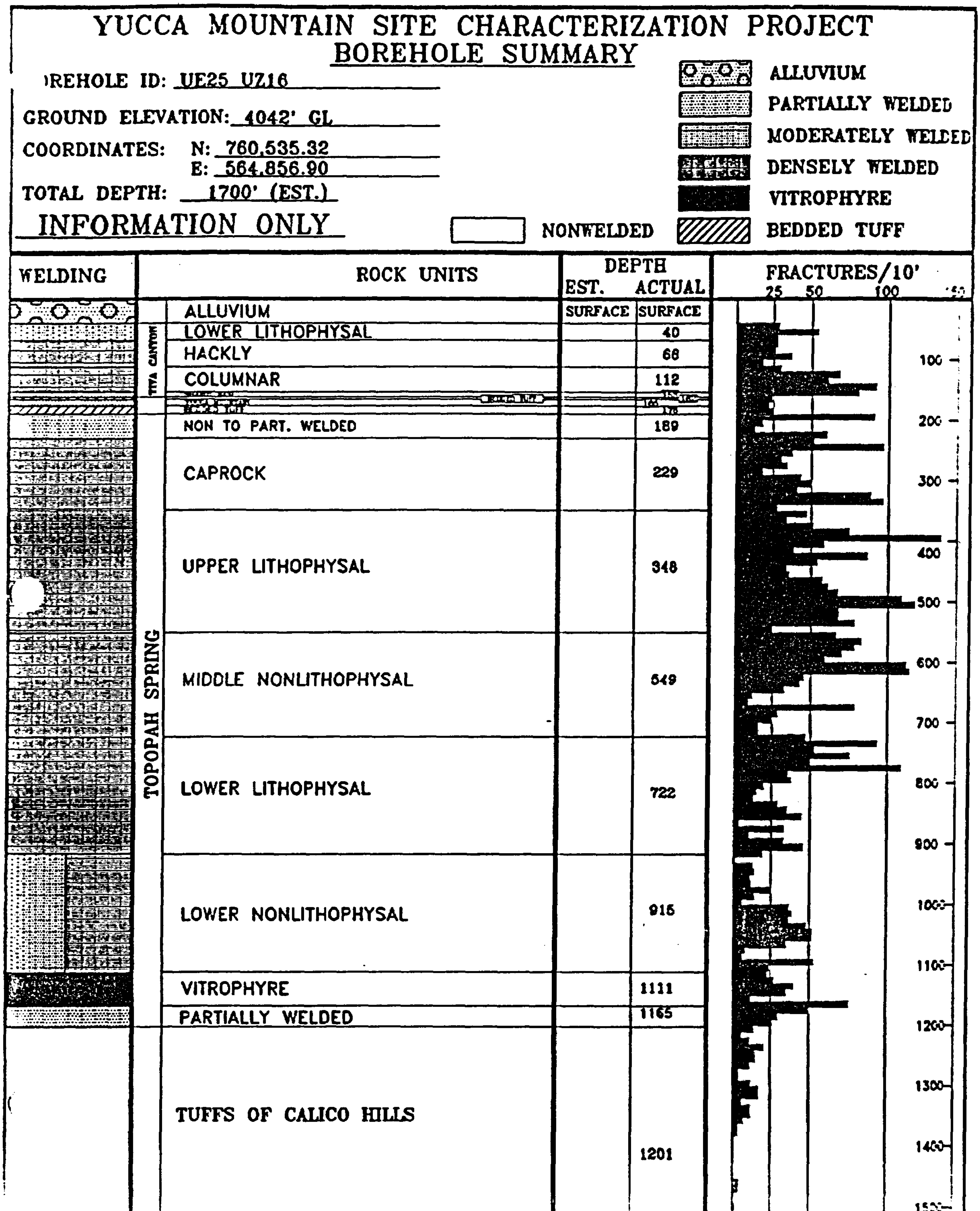


Figure 4 Map showing the existing and proposed boreholes within 2 km of UZ-16 (EG&G.



USW SD-4
UE-25 UZN#23
UE-25 UZN#22
USW SD-5
USW H-4
USW SD-8
UE-25 SD#9
USW UZ-N52
USW UZ-N51
USW UZ-N48
USW UZ-N49
USW WT-2
USW UZ-8
USW SD-10
USW SD-11
USW UZ-N55
USW UZ-N54
USW UZ-N53
USW SD-12
USW SD-7
USW UZ-N85
USW SRG-4
USW SRG-3
UE-25 SRG-2

Figure 6 UE-25 UZ#16 (VSP#2) Borehole Summary (Doyle, 1993).



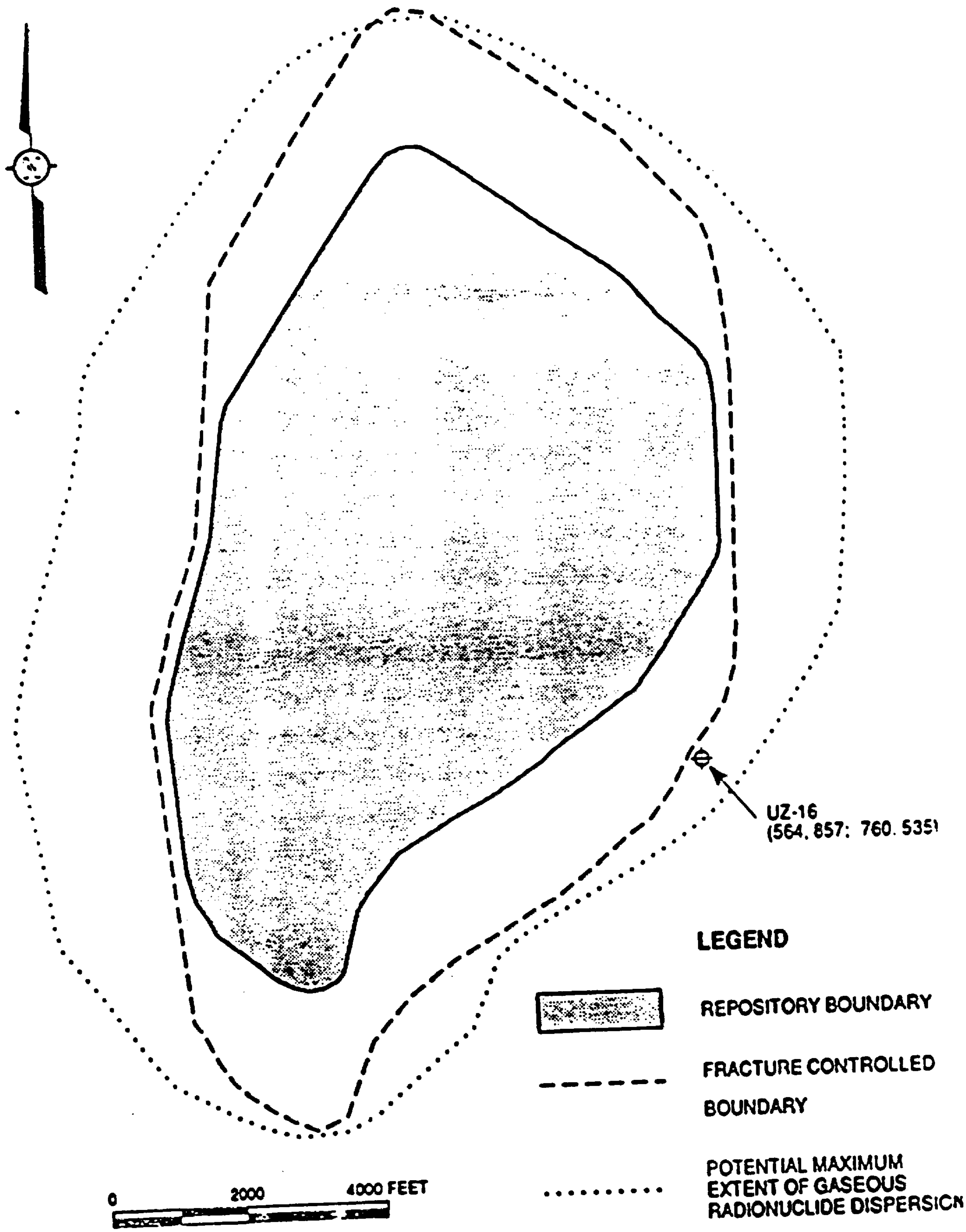


Figure 7 Repository boundary and extent of radionuclide dispersion using a simplified advection-dispersion calculation (Fernandez and Case, 1992).

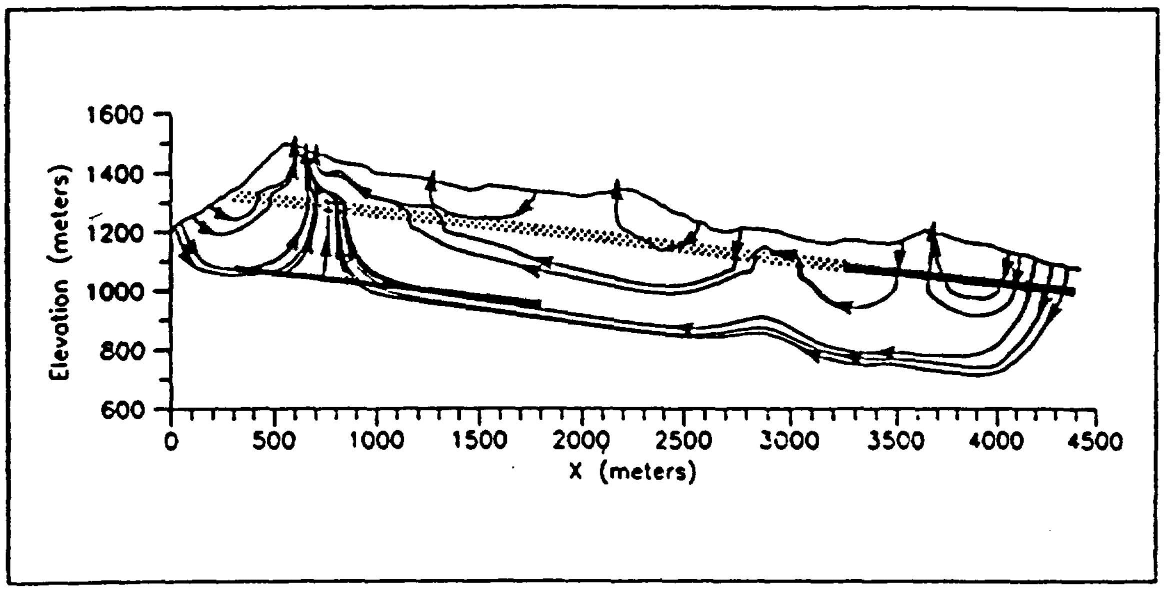


Figure 6-7. Path lines with ambient temperature, permeability contrast between welded and nonwelded tuffs 10x (3.3x in faulted area). (cross section N760000)

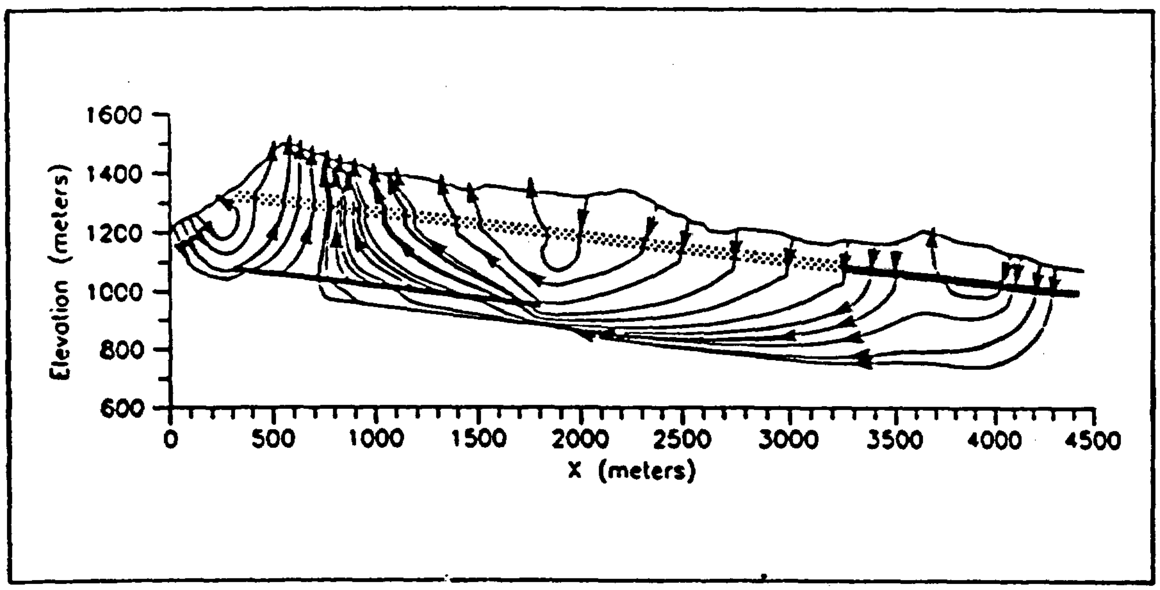


Figure 6-8. Path lines with the repository heated to 330 K, permeability contrast between welded and non welded tuffs 10x (3.3x in faulted area). (cross section N760000)

Figure 8 Path lines for ambient temperatures and 330 K in the vicinity of UE-25 UZ#16 (VSP#2) (Ross, et al., 1992).

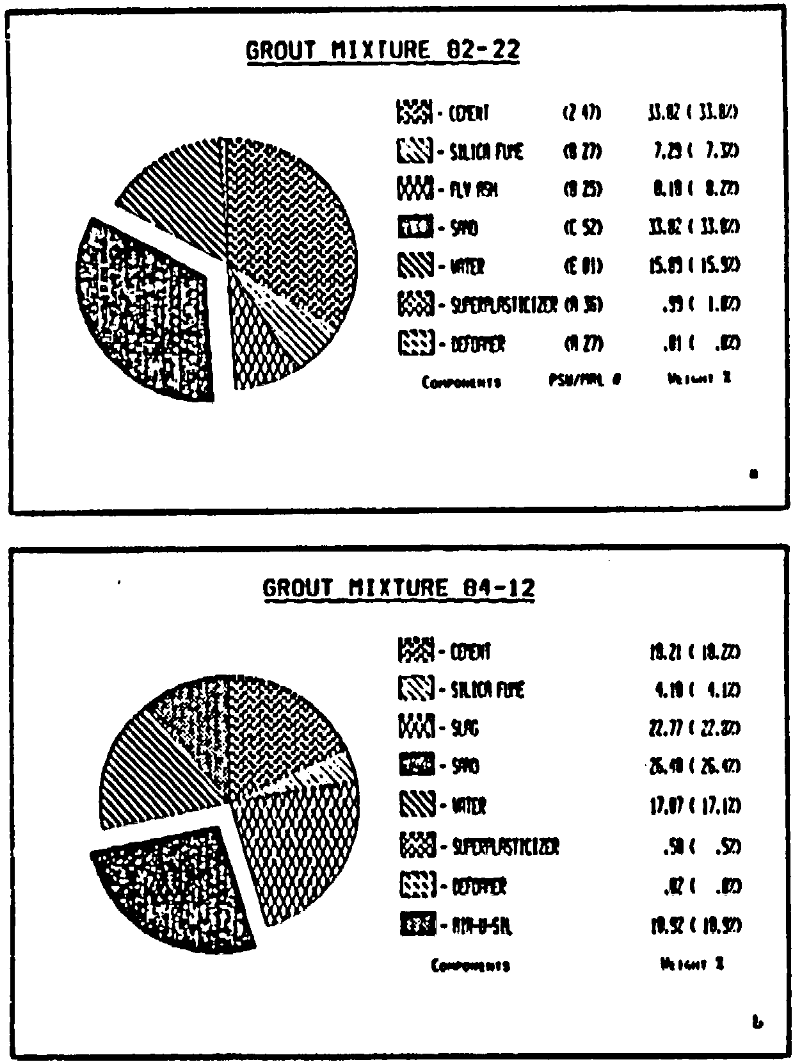


Fig. 1. Schematic representation of (a) 82 22 mortar and (b) 84-12 grout compositions.

TABLE I

BULK CHEMICAL COMPOSITION OF GROUTS

	Grout (wt %)	
Oxide	82 22	84 12
SiO_2	64.16	61.98
Al_2O_3	4.50	4.19
Fe_2O_3	2.74	1.10
CaO	25.88	27.52
MgO	1.83	4.65
MnO	0.12	0.17
Na_2O	0.10	0.10
K_2O	0.48	0.27
P_2O_5	0.11	0.02
Total	99.92	100.00

TABLE II

BULK CHEMICAL COMPOSITIONS OF GROUTS WITHOUT SAND AGGREGATE

	Grout (wt %)	
Oxide	82 22	84 12
SiO_2	38.60	48.45
Al_2O_3	7.74	5.44
Fe_2O_3	4.72	1.59
CaO	44.59	37.69
MgO	3.14	6.05
MnO	0.04	0.22
Na_2O	0.15	0.13
K_2O	0.83	0.40
P_2O_5	0.18	0.04
Total	99.99	100.01

Figure 9 Composition of SNL grouts 82-22 and 84-12 (Scheetz and Roy, 1986).

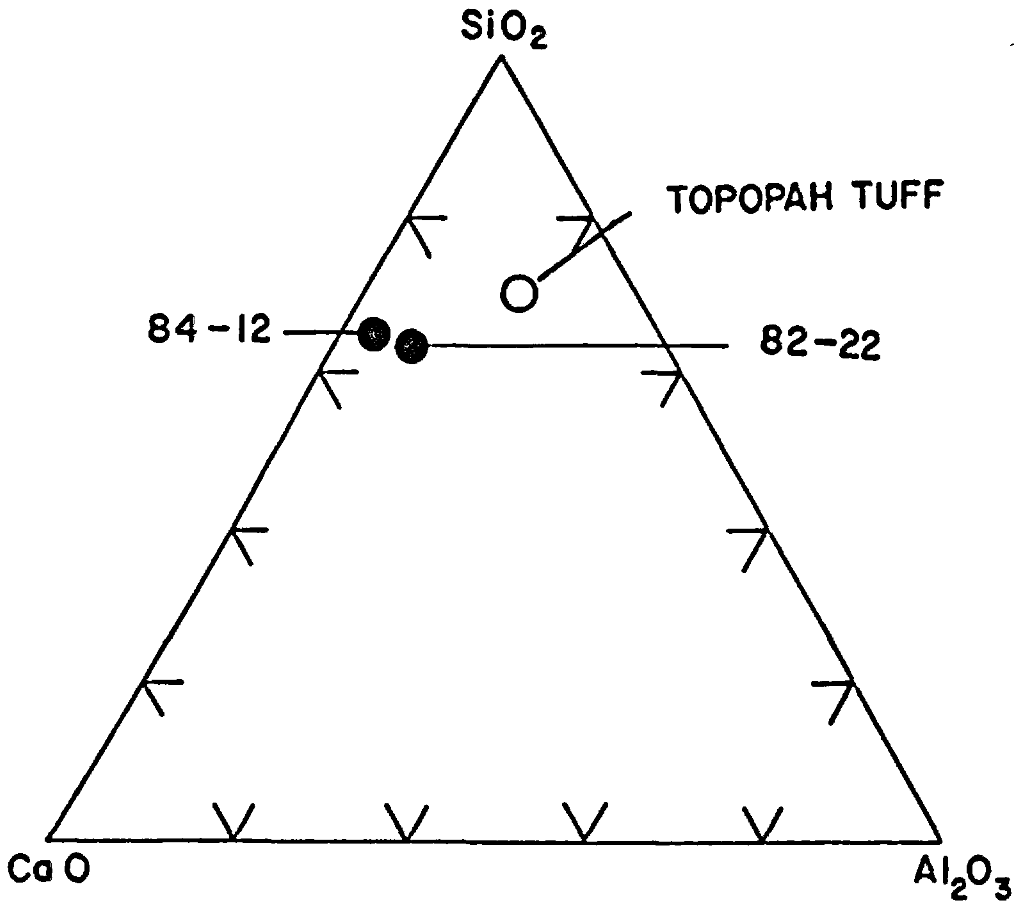


Fig. 3. Bulk chemical composition of tuff, 82-22, and 84-12 mortar normalized to SiO_2 ($+TiO_2+P_2O_5$) - CaO (+alkali and alkaline earth oxides) - Al_2O_3 ($+Fe_2O_3$); neglects SO_3. (See Table I for bulk oxide composition.)

Figure 10 Bulk chemical composition of tuff and SNL grouts 82-22 and 84-12 (Scheetz and Roy, 1986).

APPENDIX A

MODELS OF LONG-TERM LIQUID FLOW THROUGH UZ#16

A.1 Introduction

The presence of the borehole UE-25 UZ#16 (VSP#2) raises several issues relating to the movement of water. Relatively early in a 10,000-year post-closure period, one might expect the borehole backfill to degrade and to become more hydraulically conductive. Most of the analyses to follow assume, for conservatism, that the resulting conductivity is similar to that of sand. This assumption might suggest that the borehole becomes an avenue through which water can redistribute itself among various stratigraphic units. Thus, the fact that the borehole lies in the 500-year flood zone might play a role in the water balance of both unsaturated and saturated zones.

Nevertheless, a borehole has a relatively high surface-to-volume ratio that drives its backfill toward capillary equilibrium with the surrounding rock. For a fractured formation, a high fracture surface-to-volume ratio facilitates this equilibration, giving rise to the equivalent continuum model. For such a model, fracture saturations remain at insignificantly small levels until the matrix rock approaches saturation. The equivalent continuum model does not apply precisely to the degraded borehole backfill, particularly during a storm event. Nevertheless, it does suggest that the capillary pressure of the borehole backfill will seek capillary equilibration with the surrounding rock.

Just as it drives water from a high-permeability fracture into the low-permeability rock which surrounds it, even so the capillary equilibration process drives water from the borehole backfill into the matrix rock of the welded tuff units. Consequently, the equilibration process slows the downward advance of borehole recharge water in two ways. First, water removed from the borehole generally moves downward through a much lower permeability. Second, water remaining in the borehole moves downward through a sand-like material which, because of reduced saturation levels, has a low relative permeability.

This study considers three scenarios. The first assumes that the backfilled borehole has impermeable walls. Ignoring any effects deriving from equilibration with the rock surrounding the borehole, this scenario focuses on partially saturated flow within the borehole. It examines both the effect of storm recharge and the effect of long-term recharge into UZ#16. The second scenario is much like the first, except that it considers hydraulic coupling between borehole and surrounding rock. In addition to the effect of partially saturated borehole flow, this scenario characterizes the effect of the capillary equilibration process on borehole flow.

With the effects of both partially saturated borehole flow and capillary equilibration with the surrounding rock limiting borehole flow, the third scenario considers the additional effect of low-permeability seals within the borehole. In order to characterize the maximum benefit to be derived from sealing, Scenario 3 assumes that the seals have a permeability which is significantly lower than that of natural Yucca Mountain rock and which does not degrade appreciably with time.

A.2 Scenario 1: Borehole with Impermeable Walls

Conceptualization. For most of a 10,000-year post-operational period, the scenario conceptualization assumes that degraded grout fills the borehole. This material was characterized by hydraulic properties typical of a sand, with saturated conductivity K_s = 4.4E-6 m/s (0.45 darcy) and with parameters $\alpha = 1.28\ m^{-1}$ and $\beta = 4.23$ specifying the van Genuchten-Maulem relations (van Genuchten, 1978, and Maulem, 1976). In a degraded state, the partially saturated backfill serves two important functions. It provides a capillary-pressure barrier and a relatively small relative permeability, both of which substantially limit the amount of water which can be imbibed into the borehole during a storm event. This scenario examines only the latter function, reserving the former for consideration by Scenarios 2 and 3.

Description of Analysis. The analysis of Scenario 1 divides into two cases. For both, the TOSPAC code (Dudley *et al.*, 1988; Gauthier *et al.*, 1992) developed by Sandia National Laboratories was used. Though limited to one-dimension, TOSPAC is very user friendly when compared to other codes available within the Yucca Mountain Project.

Taking no credit for surface evaporation, the analysis of these cases considered recharge at the surface of a one-dimensional column and water-table conditions at the bottom. The latter consists of a liquid saturation $S = 1$ and a capillary pressure head $p_c = 0$. For a borehole discretized by 185 grid blocks, Table A-1 indicates that, starting from a value $\Delta z = 10$ cm at the surface, increment thicknesses grade upward to a value $\Delta z = 3$ m over most of the vertical dimension. In common with other analyses performed herein, the analysis of Scenario 1 assumed a water-table depth of 531 m. The chosen depth, though consistent with that used for test cases of the COVE2a code-comparison study (*e.g.*, see Birdsell and Travis, 1991a), is inconsistent with the water-table depth (491-2 m) at UZ#16. This variance, however, should not affect the conclusions drawn below.

Discussion of Results (Case 1). The first case considers a worst-case storm event. It assumed that the event, together with subsequent sheet flow, caused the surface of the backfilled borehole to be saturated for a period of 14 hours. This introduces a pulse of water into the borehole backfill. As an initial condition, the backfill was assumed to be at hydrostatic equilibrium. Given that UZ#16 is located within the 500-year flood plain, ponding is possible. However, since the ponding depth would be small compared to the depth of the water table below the surface, it may be safely ignored.

Figure A-1a displays computed results. It shows that the pulse disperses significantly as it moves downward within the column. For the hydraulic parameters assumed, the calculation indicated that 3.46E-2 m^3 would enter a borehole of radius 0.156 m (6.125 in) during the storm event.

Discussion of Results (Case 2). The second case considers a steady recharge rate of 0.178 m/yr (7 in/yr). (The Reference Information Base gives an average rainfall of 6.88 in/yr). Computed steady-state results showed a gravity-controlled flow with constant saturation (S = 0.175) and capillary pressure head (p_c = -1.40 m) extending throughout most of the unsaturated zone. Only within a few meters of each boundary did saturation and head values vary from these constants in order to satisy boundary conditions.

For a borehole radius of 0.156 m (6.125 in) and an assumed rainfall rate of 0.178 m/yr (7 in/yr), the steady analysis yielded a borehole discharge rate to the water table of 1.35E-2 m^3/yr, which of course equals the borehole recharge rate. Thus, the analysis of Scenario 1 (Case 1) predicted that storm recharge due to a 14-hour worst-case event (3.46E-2 m^3) exceeds that due to the annual average rainfall by a factor of approximately 2.5, a factor which is not unreasonable considering that such a 14-hour event arises from a 500-year flood.

A.3 Scenario 2: Borehole with Permeable Walls

Conceptualization. In contrast to Scenario 1, Scenario 2 considers hydraulic coupling between borehole backfill and surrounding rock. For the borehole backfill, hydraulic properties were assumed to be the same as in Scenario 1. For the surrounding rock, it would be most appropriate for the analysis to use the stratigraphy and hydraulic properties obtained at UZ#16. However, the latter are not available. Furthermore, the stratigraphy and hydraulic properties used for the COVE2a study (*e.g.*, see Birdsell and Travis, 1991a) are sufficiently representative to indicate the magnitude of the effects to be expected. Figure A-2 gives the stratigraphy used by Scenario 2, and Table A-2 gives the van Genuchten-Maulem parameters used to characterize each formation. As indicated, the analysis of Scenario 2 used the same stratigraphy and hydraulic properties as the COVE2a code-comparison study.

Description of Analysis. Like Scenario 1, the analysis of Scenario 2 divides into two cases. Unlike Scenario 1, the TRACR3D code (Birdsell and Travis, 1991b) developed by Los Alamos National Laboratory was used here in order to increase problem dimensionality. The TRACR3D code employs an iterative GMRES matrix solution. This algorithm makes it possible to solve two- and three-dimensional problems involving several thousand grid blocks using a personal computer. For the analyses presented in this report, a PC-486 computer with 64 megabytes of RAM memory was used.

The analysis of Scenario 2 employed a cylindrical grid. The vertical (z) dimension measures 530.5 m, a distance discretized by 235 increments. Thicknesses range from Δz = 10 cm to 3 m, with the smaller increments employed at boundaries and at formation interfaces. The horizontal (r) dimension measures 40 m and is discretized by 21 increments. One increment represents the radius of the borehole Δr = 15.6 cm (6.125 in). Outside the borehole, widths vary from Δr = 4.98 cm at the borehole periphery to a maximum value Δr = 9.69 m. Table A-3 lists increment widths in both horizontal and vertical directions for a grid containing 235 x 21 = 4.935 grid blocks.

Boundary conditions were specified along top and bottom surfaces of the grid. At the top, a net recharge rate of 0.1 mm/yr was applied to the surface overlying intact rock. This value discounts the precipitation rate for the effects of runoff and evapotranspiration. At the borehole surface, recharge conditions were applied as described below. At the bottom, a water-table condition ($S = 1$, $p_c = 0$) was used. Both the side boundary at $r = 0$ and the side boundary at $r = 40$ m were defaulted to no flow.

For both borehole and surrounding rock, initial saturations were specified by the steady-state results of one-dimensional vertical analyses subject to the same top and bottom boundary conditions. In the absence of hydraulic coupling between borehole and surrounding rock, these initial saturations would be maintained indefinitely.

Discussion of Results (Case 1). Case 1 considers a 14-hour storm event, assuming that a storm of this duration represents a worst case. Like Scenario 1, Scenario 2 sets the liquid saturation of the top boundary to its maximum value ($S = 1$) for a period of 14 hours and then applies a no-flow condition thereafter. For the hydraulic parameters assumed, the calculation predicted that 4.01E-2 m^3 of water would enter the borehole. A comparison with the value obtained in the analysis of Scenario 1 (3.46E-2 m^3) indicates that, even over the relatively short time span of 14 hours, hydraulic coupling has an effect. By diverting some flow from the borehole to intact rock, it permits approximately 16 percent more water to enter the borehole.

Over a somewhat longer time span (365 days), the hydraulic coupling between borehole backfill and surrounding rock has a very significant effect. Figure A-1a shows that, without coupling, the simulated moisture pulse due to a 14-hour storm advanced about 13 m into the borehole during a 365-day period. Figure A-1b shows that, with coupling, the simulated moisture front advanced 7 m into the borehole. However, at 365 days, saturations within the pulse barely exceeded residual levels. An examination of the computer output revealed that, in the horizontal direction, hydraulic coupling caused saturation increases out to a radius $r = 2.19$ m at the end of the 365-day period.

Discussion of Results (Case 2). Case 2 considers a steady borehole recharge of 0.178 m/yr (7 in/yr). To characterize the effect of hydraulic coupling between borehole backfill and the surrounding rock, Figures A-3 and A-4 compare predicted saturation profiles at 10,000 years with initial conditions. For the borehole (Figure A-3), the initial saturation level was arbitrarily set to the residual saturation level ($S_r = 0.039$). Except near the water table and near the surface, the 10,000-year borehole saturation levels did not deviate significantly from this initial value.

At the surface, the simulated recharge rate saturated the borehole ($S = 1$, approximately). However, within about 5 m of the surface, the predicted borehole saturation profile decayed to near residual levels. This suggests that, within five meters of its top surface, the welded tuff of the Tiva Canyon (TCw in Figure A-2) imbibes most of the water from the borehole in order to achieve a state of capillary equilibrium. Below five meters, and throughout most of the borehole, a state of capillary pressure equilibrium kept saturations at residual levels ($S_r = 0.039$). Given that the predicted borehole saturation level for Scenario 1 is $S = 0.175$, rather than the value ($S = 0.039$) obtained here, one may also conclude that the capillary pressure equilibration process can draw significant amounts of moisture from the borehole.

As borehole saturations approach their residual value, relative permeabilities k_r and effective permeabilities $k_s k_r$ approach zero, even though the value of the saturated permeability k_s may be comparatively large in relation to other saturated permeabilities within the system. The degraded borehole backfill itself is thus transformed into a barrier to borehole flow. Such a barrier may be identified as a "capillary pressure barrier".

Figure A-4a confirms that most of the borehole recharge is being diverted to the Tiva Canyon. At a radius $r = 0.18$, only slightly greater than the radius of the borehole $r_b = 0.156$ m, this recharge caused the top of the Tiva Canyon to saturate to a level $S = 1$, approximately. Mirroring the borehole itself, the predicted saturation profile decayed to initial conditions within about 5 m of the top surface. For depths greater than 5 m, predicted saturations showed no observable deviations from initial conditions, even at 2.4 cm (1 in) from the borehole wall.

At the top surface of the Tiva Canyon, the analysis predicted that elevated saturation levels would persist out to a radius of about 15 m. For larger radii, saturations at all depths showed no observable deviation from initial conditions, as evidenced by Figure A-4b for a radius $r = 35.2$ m.

A comparison of Cases 1 and 2 indicates that, as expected, a worst-case flood event moves water to a greater depth (7 m) than steady recharge (5 m). Such a comparison also indicates that steady recharge moves water horizontally to a greater radius (15 m) than a worst-case storm event (2.19 m). One may therefore conclude that the observable impact of surface recharge at UZ#16 will be confined to a 7 m x 15 m disk located in the top of the Tiva Canyon.

A.4 Scenario 3: Borehole with Permeable Walls and Two Seals

Scenario 2 suggests that a sand-like backfill provides a capillary-pressure barrier which diverts surface recharge into the top of the Tiva Canyon (TCw in Figure A-2) unit. Scenario 3 (Case 1) seeks to confirm this observation by considering two seals, one covering the Paintbrush Tuff (PTn in Figure A-2) unit and one covering the Calico Hills (CHnz) unit. If it is deemed desirable to seal off surface recharge, then Scenario 2 suggests that the Tiva Canyon unit would provide a desirable location for the seal. Scenario 3 (Case 2) seeks to confirm this observation by extending one of the two seals to the top of the Tiva Canyon unit.

Conceptualization. Except for the presence of two borehole seals, Scenario 3 is identical to Scenario 2. In Case 1, the top seal completely covers the Paintbrush Tuff unit. This seal extends

3.7 m into the bottom of the Tiva Canyon unit and 3.8 m into the top of the Topopah Spring (TSw_1) unit, measuring 45.7 m in total length. In Case 2, the top seal is lengthened to 68.8 m so that it will also cover the top of the Tiva Canyon unit. With a total length of 133.3 m in both cases, the bottom seal completely covers the Calico Hills (CHn) unit and extends 3 m into the bottom of the Topopah Spring (TSw_3) unit. The presence of a model boundary makes it unnecessary to extend the seal below the water table.

Licastro *et al.* (1990) consider 20 sealing materials, 18 of which have permeabilities less than a detection limit of 1.0E-8 Darcy (0.966E-13 m/s). Two orders of magnitude lower than the matrix permeability of the Topopah Spring units (Table A-2), the latter value was assumed to represent a desirable seal permeability. It was applied to both seals. Other hydraulic properties of the seals were taken to be identical to the matrix properties of the TSw units (Table A-2). Except for the seals, which were assumed to degrade insignificantly, other backfill properties were assumed to degrade to those characteristic of sand, just as in Scenarios 1 and 2.

<u>Description of Analysis.</u> Like Scenarios 1 and 2, the analysis of Scenario 3 divides into two cases. Both employed the same code (TRACR3D), the same grid (Table A-3), the same boundary conditions, the same intact-rock properties (Table A-2), and the same intact-rock initial conditions as used in the analysis of Scenario 2. Consistent with the initial conditions of Scenarios 1 and 2, initial saturations within the degraded backfill were taken to be only slightly greater than the residual saturation level ($S_r = 0.039$). Initial conditions of the seals were prescribed as $S_i = 0.87$, equal to the average steady-state saturation of the Topopah Spring units for a recharge rate i = 0.1 mm/yr.

<u>Discussion of Results (Case 1).</u> Case 1 considers a steady borehole recharge of 0.178 m/yr (7 in/yr). To characterize the effect of hydraulic coupling between borehole backfill and the surrounding rock, Figures A-5 and A-6 compare the predicted saturation profile at 10,000 years with initial conditions. Like Figure A-3 (unsealed borehole), Figure A-5 shows the effect of the capillary pressure equilibration process on the top 5 m of the borehole. Figure A-5 also indicates an adjustment of the calculated seal saturations caused by capillary equilibration with the Paintbrush and Calico Hills units. Elsewhere, the calculated saturations of the borehole backfill remained at residual levels ($S_r = 0.039$). As for Scenario 2, the results indicate that, except for the top 5 m of the Tiva Canyon unit, negligible quantities of moisture move vertically within the borehole.

Figures A-6a and A-6b present computed saturation profiles for the intact rock at 10,000 years, and these results are noteworthy in only one respect. They are virtually identical to the results obtained (Figures A-4a and A-4b) assuming no borehole sealing. *Via* the capillary equilibration process, the welded Tiva Canyon unit diverted most of the recharge water from the borehole, thus reducing the borehole to an insignificant channel for directly recharging deeper units in the stratigraphy. This effect reduces the borehole seals to the meaningless role of protecting the Paintbrush and Calico-Hills from an insignificant, perhaps nonexistent, source of surface recharge.

<u>Discussion of Results (Case 2).</u> With its top seal, in this case, protecting the entire Tiva Canyon

unit, Case 2 considers a 14-hour storm event, assuming that a storm of this duration represents a worst case. With the liquid saturation of the top boundary set at its maximum value (S = 1), the calculation predicted that 7.88E-7 m^3 would enter the borehole. A comparison with the results of Scenario 1 (3.46E-2) and Scenario 2 (4.01E-2 m^3) indicates that, by sealing the top few meters of the Tiva Canyon unit, the top seal significantly reduces storm recharge into the borehole. Although the analyses presented herein do not include effects of the alluvium, one may reasonably conclude that a seal over the Tiva Canyon would divert borehole storm recharge into the alluvium, where it may be dissipated by evapotranspiration.

A.5 Conclusions and Discussion

In order to characterize the hydraulic effects of the UZ#16 borehole, three scenarios were analyzed. Scenario 1 considers a borehole with impermeable walls, thus focusing on effects due to partially saturated flow within the borehole. Scenario 2 focuses on the effect of hydraulic coupling between borehole and surrounding rock assuming an unsealed borehole. Finally, Scenario 3 looks for the beneficial effects which might accrue from sealing the borehole.

Scenario 3 assumed that seal permeabilities do not degrade appreciably over a 10,000-year period. Otherwise, conservative assumptions were used throughout the study. Except for the seals, the borehole backfill was assumed to be highly conductive with sand-like hydraulic properties for liquid flow. Such properties, if realistic, could make the backfill highly conductive for gas flow, thus yielding substantial reductions in saturation levels *via* the evapotranspiration process. Nevertheless, all scenarios ignored the effects of evapotranspiration through the borehole. Finally, all analyses assumed non-dipping geologic units. If included, the resulting eastwardly directed flow would tend to mitigate any effects that the borehole might have upon the repository by moving them down dip.

The analyses of Scenarios 1 and 2 (Cases 1 and 2) indicate that hydraulic coupling between a sand-like borehole backfill and the intact rock, particularly the welded tuff units, creates a capillary pressure barrier within the borehole. Near the surface, recharge can penetrate this barrier to varying depths before being diverted into the surrounding rock. The vertical and lateral effects of recharge depend on the temporal profile of the recharge event. A 14-hour storm event gave a predicted vertical penetration into the borehole of 7 m, while a steady recharge rate gave a predicted horizontal penetration into the surrounding rock out to a radius of less than 15 m.

Assuming these distances to represent worst-case values means that the observable effects of surface recharge into the borehole are confined to the interior of a disk surrounding the borehole. Located at the top of the welded Tiva Canyon unit, this disk measures 15 m in radius by 7 m in depth. Below this disk, borehole saturations did not rise noticeably above the residual level (S_r = 0.039), thus ensuring a near-zero value of relative permeability for the borehole capillary pressure barrier. Outside this disk and within the intact rock, increases in saturation levels, though undoubtedly present, were too small to be observed.

Given that the borehole capillary pressure barrier effectively prevents borehole flow below the top 7 m of the Tiva Canyon unit, one does not expect any beneficial effects to arise from sealing the two most permeable units of the stratigraphy, *i.e.*, the nonwelded Paintbrush Tuff and Calico Hills units. Scenario 3 (Case 1) confirms that indeed there are none, insofar as surface recharge is concerned.

The analyses of Scenarios 2 and 3(1) appear to indicate that a borehole capillary pressure barrier provides adequate protection against surface recharge. By diverting flow from the borehole to the low-permeability Tiva Canyon unit, this barrier essentially removes any possibility that transient storm recharge through the borehole can facilitate nonequilibrium fracture flow. Nevertheless, should a seal be warranted by considerations other than liquid flow, the analyses of Scenarios 2 and 3(2) suggest that sealing the Tiva Canyon unit would have the maximum benefit for liquid flow. The analysis of Scenario 3(2) confirms this point. Sealing the entire Tiva Canyon unit reduces the recharge resulting from a 14-hour storm event by almost four orders of magnitude.

This report appears to dispel any concern that UZ#16 could become a significant channel for conveying surface recharge to lower units, even with no sealing. Should sealing be deemed necessary, the report notes that sealing the welded Tiva Canyon unit would provide the most protection against surface recharge and that sealing the nonwelded Paintbrush and Calico Hills units would provide no additional protection against surface recharge beyond that provided by a borehole capillary pressure barrier.

Nevertheless, there is an additional concern regarding the Calico Hills segment of the borehole that is not addressed sufficiently by this report. This concern relates to the possibility that, under appropriate conditions, the Calico Hills segment could become part of a preferred release pathway from repository to saturated zone. The conditions giving rise to this concern are: (1) the possibility that the proposed repository could be enlarged to include Expansion Area 6 and (2) the possibility that long-term climate changes could saturate the Calico Hills unit.

The inclusion of Expansion Area 6 in the repository would remove most of a natural barrier containing 430 meters of partially saturated rock. It would also introduce (possibly beneficial) thermal effects into the borehole backfill. If long-term climate changes saturate the Calico Hills unit, then the borehole capillary pressure barrier would vanish within that unit. In addition, the work of C.J. Fridrich of the USGS and others may substantially increase calculated travel times within the saturated zone, thus introducing the potential that the saturated zone itself offers a significant natural barrier to contaminant transport.

Before closing, it is appropriate to focus the conclusions of this study upon a plan recently presented by R. Long (see section 1.2). In response to issues relating to the instrumentation and permanent sealing of UZ#16, this plan calls for an alternating sequence of grout and coarse-grained material. Six-foot sections of grout would mechanically bond geophones to the walls of the borehole while ten-foot sections of the coarse-grained material would maximize the probability that removing the instrumentation would be successful, should it be necessary. Before implementation, some of the details may change. Nevertheless, such changes should not affect the validity of the comments below.

With regard to surface recharge, this study indicates that a segment of coarse-grained material placed near the top of the borehole with a length greater than about 7 m (23 ft) would provide a capillary barrier of sufficient magnitude that it could not be fully penetrated by transient storm events. Additional sections of coarse-grained material would provide redundance, forming a system of capillary pressure barriers. Several neutron-moisture probes might be useful for verifying the long-term effectiveness of these barriers. By themselves, the capillary pressure barriers should provide adequate long-term protection without the necessity of re-entering the borehole. However, if desired, a low-permeability, long-term seal could be placed in the welded Tiva Canyon unit, an action which would necessitate partial re-entry.

With regard to the possibility that the Calico Hill segment of the borehole could become part of a preferred release pathway, additional study is required. The present study suggests that, if Conditions (1) and (2) above are false, capillary pressure barriers would not permit flow within UZ#16. Nevertheless, relatively high saturation levels within the Calico Hills introduce uncertainty into this conclusion, making sensitivity analyses highly desirable. Other true-false combinations of Conditions (1) and (2) also need to be assessed. While permitting instrumentation to progress, the plan advanced by Long, delays a decision on the final sealing of UZ#16, thus permitting additional assessments to be performed. Thus, this plan has considerable merit.

A.6 References

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TABLE A-1. Scenario 1: Vertical Discretization of Borehole; Scenario 3: Vertical and Horizontal Discretization of Fracture

DIMENSION	NUMBER	INCREMENTS[a] (m)
Vertical (z)	185	2*0.1, 2*0.2, 2*0.4, 2*0.8, 2*1.5, 175*3.0
Horizontal (x)	20	20*2.5

[a] Notation such as 2*0.2 indicates four increments, each at a length of 0.2 m

TABLE A-2. Hydraulic Properties for the COVE2a Study

MATRIX PROPERTIES							
UNIT	POROSITY	HYDRAULIC CONDUCTIVITY (m/s)	BULK MATRIX CONDUCTIVITY (m/s)	RESIDUAL SATURATION	VAN GENUCHTEN PARAMETERS		
					α (m^{-1})	β	$\lambda = 1-\frac{1}{\beta}$
TCw	0.08	9.7e - 12	9.7e - 12	0.002	0.821e - 02	1.558	0.3582
PTn	0.40	3.9e - 07	3.9e - 07	0.100	1.50e - 02	6.872	0.8545
TSw1	0.11	1.9e - 11	1.9e - 11	0.08	0.567e - 02	1.798	0.4438
TSw2-3	0.11	1.9e - 11	1.9e - 11	0.08	0.567e - 02	1.798	0.4438
CHnz	0.28	2.0e - 11	2.0e - 11	0.11	0.308e - 02	1.602	0.3758

FRACTURE PROPERTIES							
UNIT	FRACTURE POROSITY	FRACTURE CONDUCTIVITY (m/s)	BULK FRACTURE CONDUCTIVITY (m/s)	RESIDUAL SATURATION	VAN GENUCHTEN PARAMETERS		
					α (m^{-1})	β	$\lambda = 1-\frac{1}{\beta}$
TCw	14.e - 5	3.8e - 5	5.3e - 9	0.0395	1.2851	4.23	0.764
PTn	2.7e - 5	61.e - 5	16.e - 9	0.0395	1.2851	4.23	0.764
TSw1	4.1e - 5	2.2e - 5	0.9e - 9	0.0395	1.2851	4.23	0.764
TSw2-3	18.e - 5	1.7e - 5	3.1e - 9	0.0395	1.2851	4.23	0.764
CHnz	4.6e - 5	20.e - 5	9.2e - 9	0.0395	1.2851	4.23	0.764

TABLE A-3. Scenario 2: Discretization of Borehole and Surrounding Rock

DIMENSION	UNIT	NUMBER	INCREMENTS[a] (m)
Vertical	TCw	30	0.1, 0.2, 3*0.4, 2*0.6, 2*0.8, 5*1.5, 2*1.65, 5*1.5, 2*0.8, 2*0.6, 3*0.4, 0.2, 0.1
	PTn	30	2*0.1, 2*0.2, 2*0.4, 2*0.8, 1.05, 2*1.5, 8*3.0, 2*1.5, 1.05, 2*0.8, 2*04, 2*0.2, 2*0.10
	TSw_1	52	2*.01, 2*0.2, 2*0.4, 2*0.8, 1.1, 2*1.5, 41*3.0
	$TSw_{2\text{-}3}$	72	66*3.0. 2.3, 1.5, 1.3, 1.0, 2*0.5
	CHnz	51	2*0.5. 1.0, 1.2, 1.5, 2.0, 39*3.0, 2.0, 1.5, 1.1, 1.0, 2*0.5
Horizontal		21	0.156, 0.050, 0.066, 0.087, 0.114, 0.151, .0200, 0.263, 0.347, 0.458, 0.605, 0.798, 1.05, 1.39, 1.83, 2.42, 3.20, 4.22, 5.57, 7.35, 9.69

[a] Notation such as 4*0.2 indicates four increments, each with a length of 0.2 m

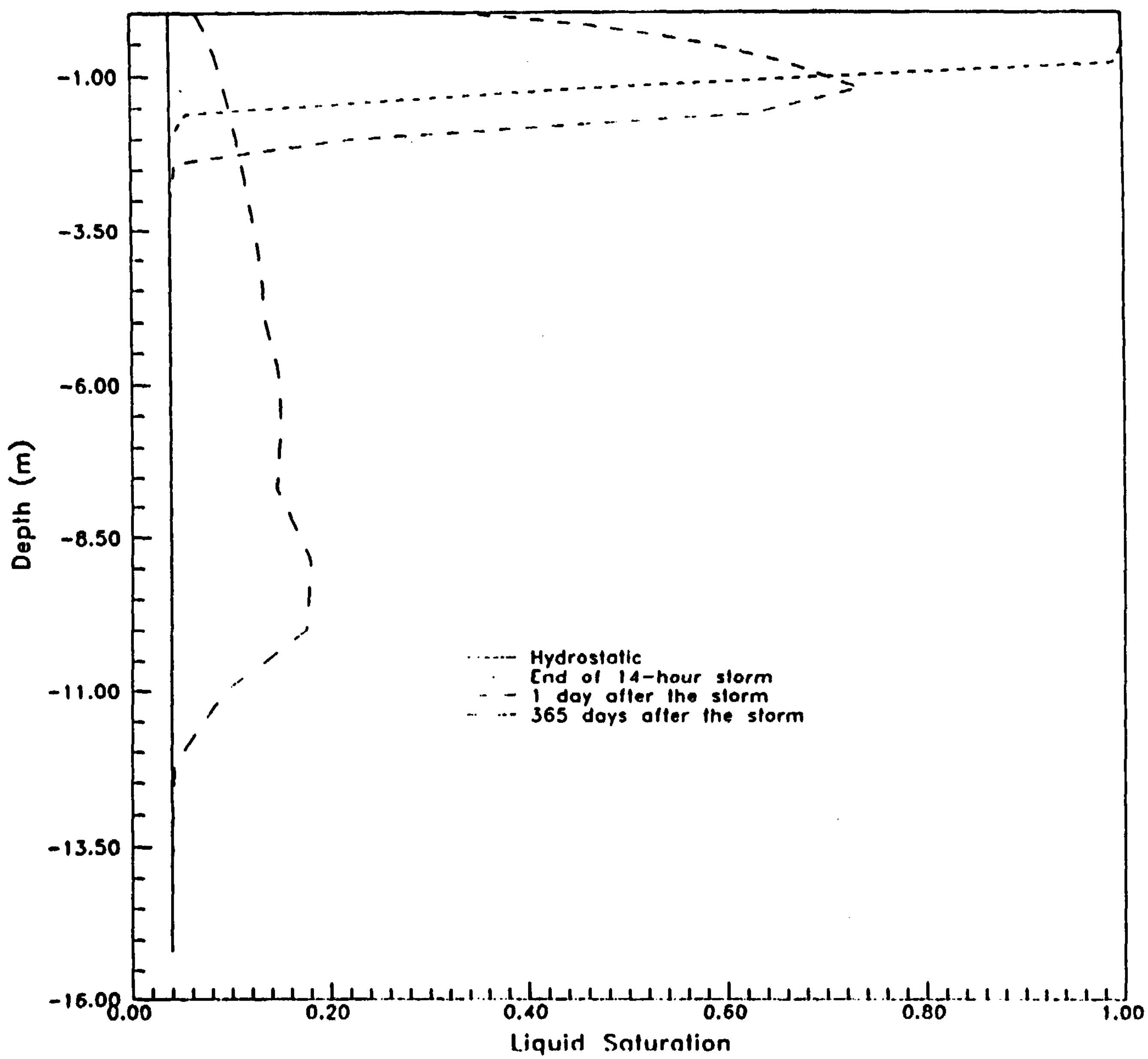

Figure A-1a. Scenario 1: Recharge Pulse Following a Storm Event.

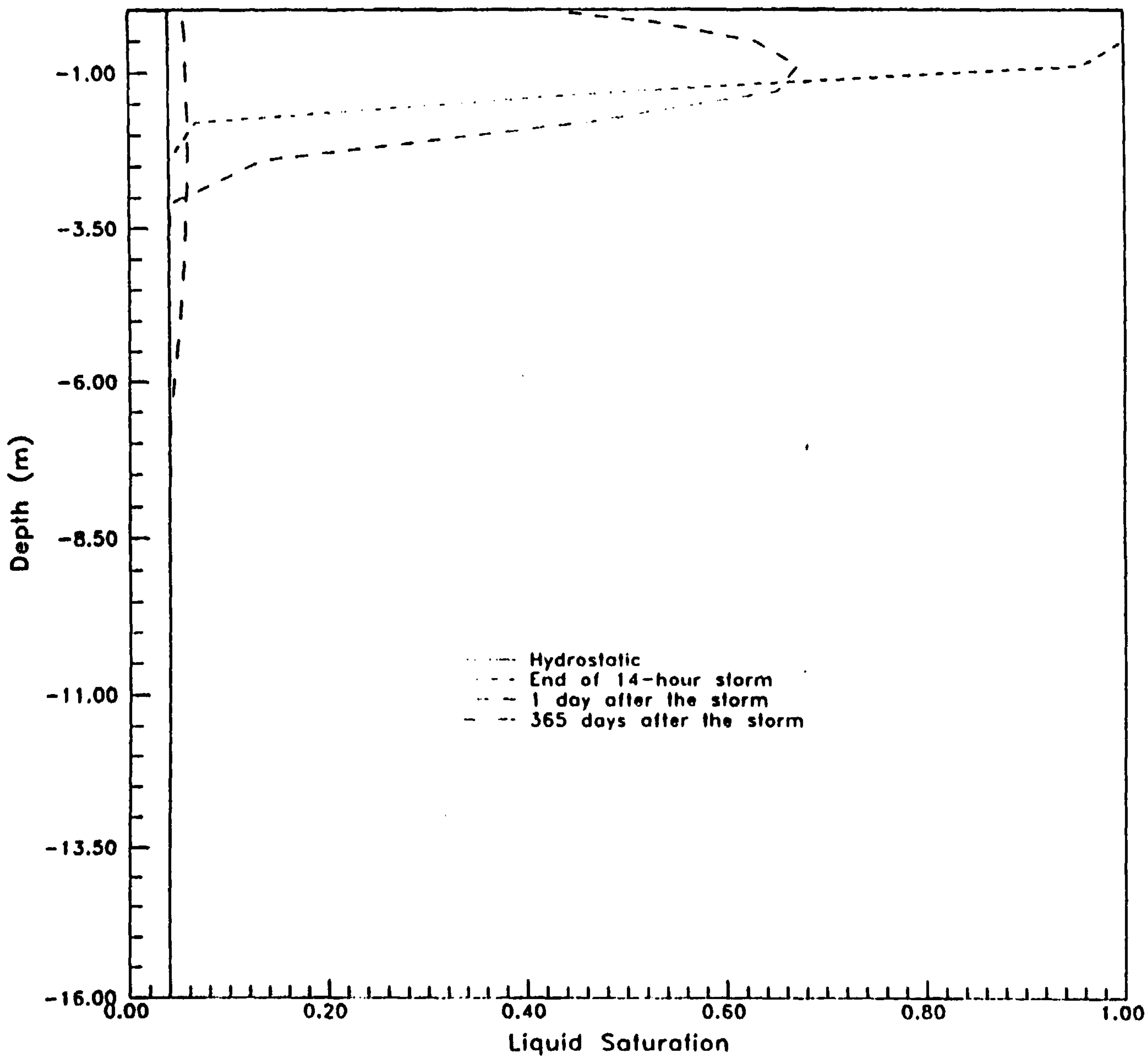

Figure A-1b. Scenario 2: Recharge Pulse Following a Storm Event.

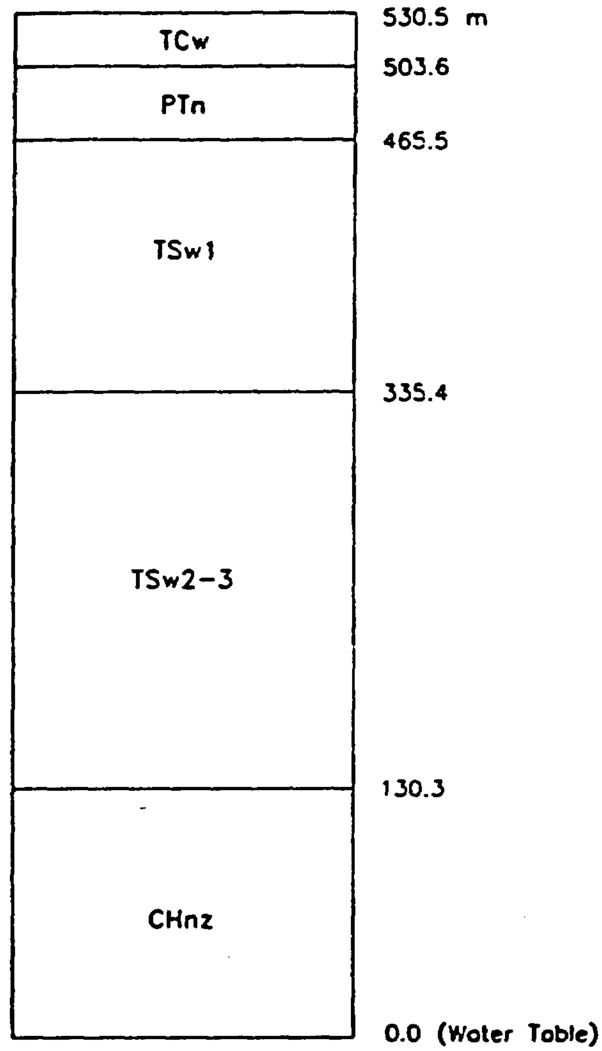

Figure A-2. Stratigraphy for the COVE2a Study.

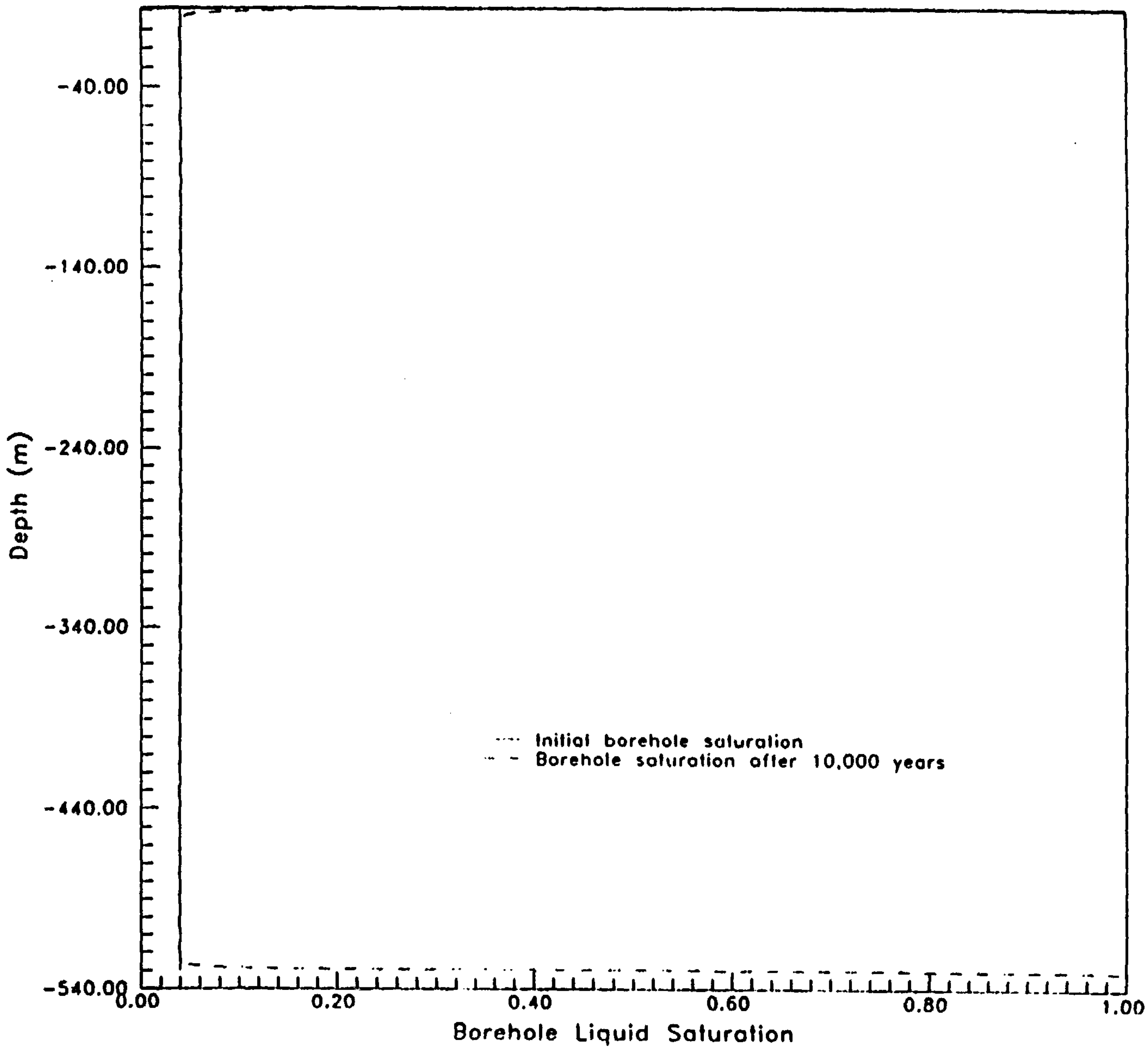

Figure A-3. Scenario 2: Saturation Changes Within the Borehole in Response to the Surrounding Rock.

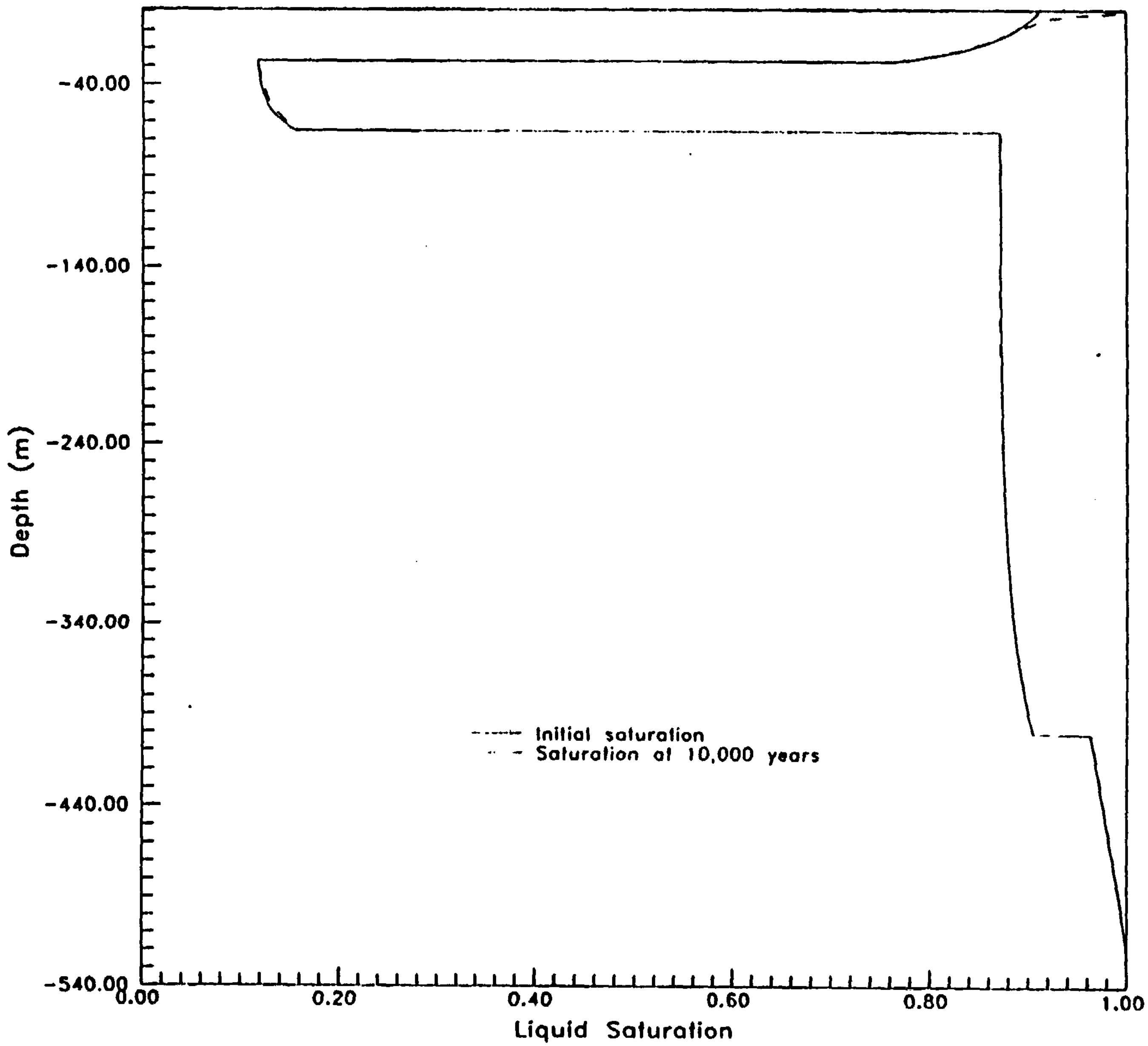

Figure A-4a. Scenario 2: Saturation Profiles at a Radius of 0.18 m.

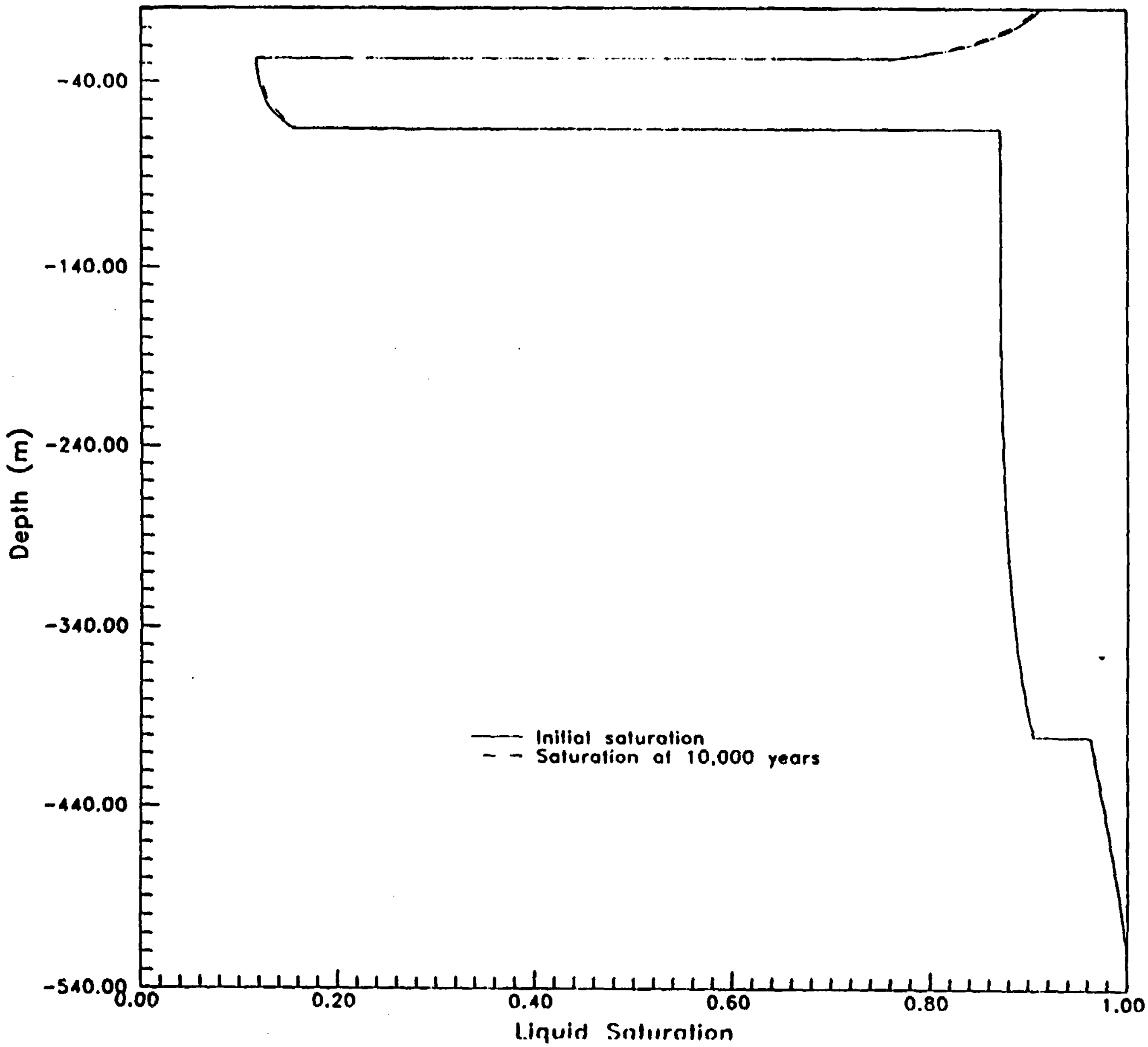

Figure A–4b. Scenario 2: Saturation Profiles at a Radius of 35.2 m.

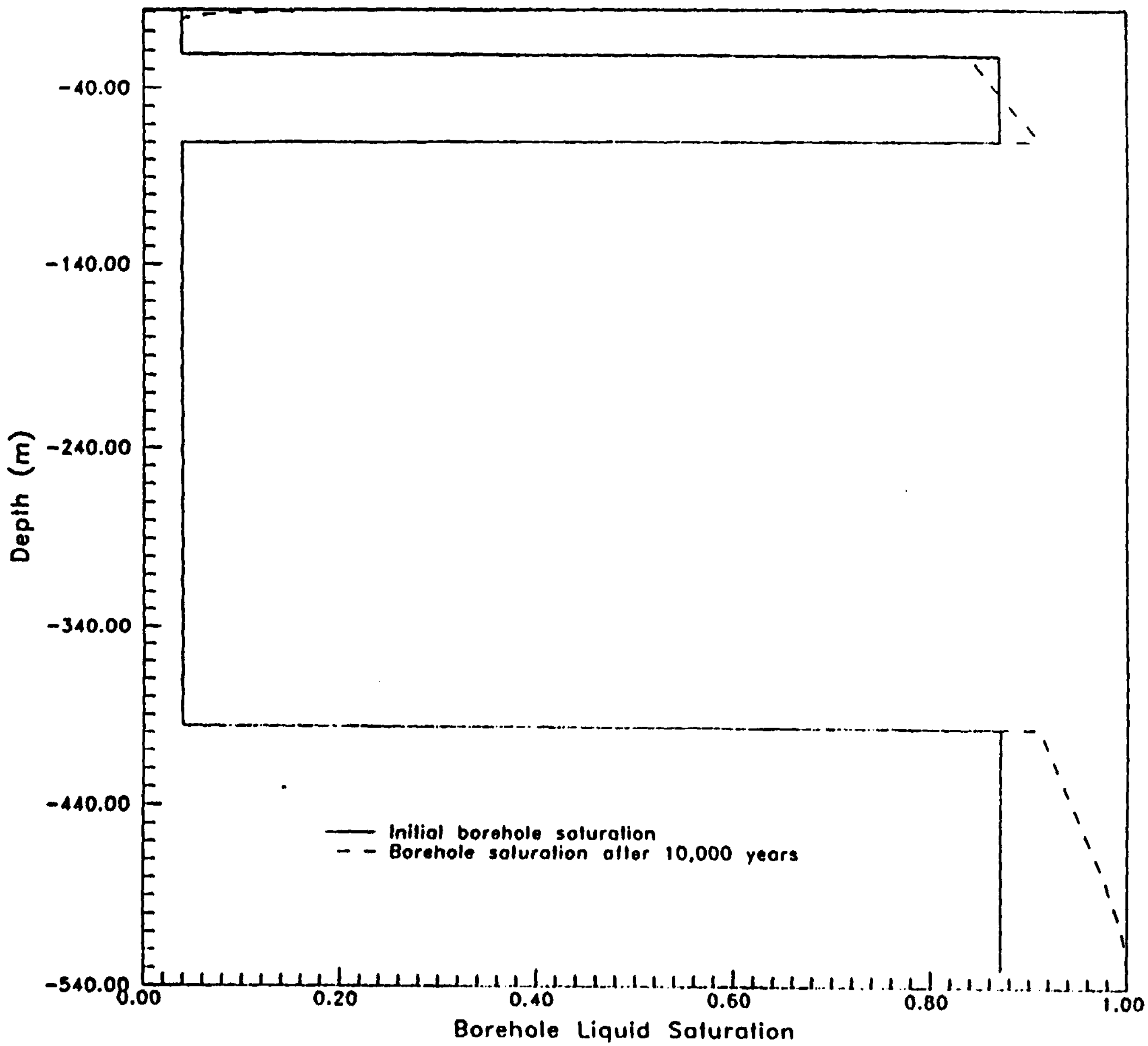

Figure A-5. Scenario 3: Saturation Changes Within the Borehole in Response to Sealing of the Two Most Permeable Units.

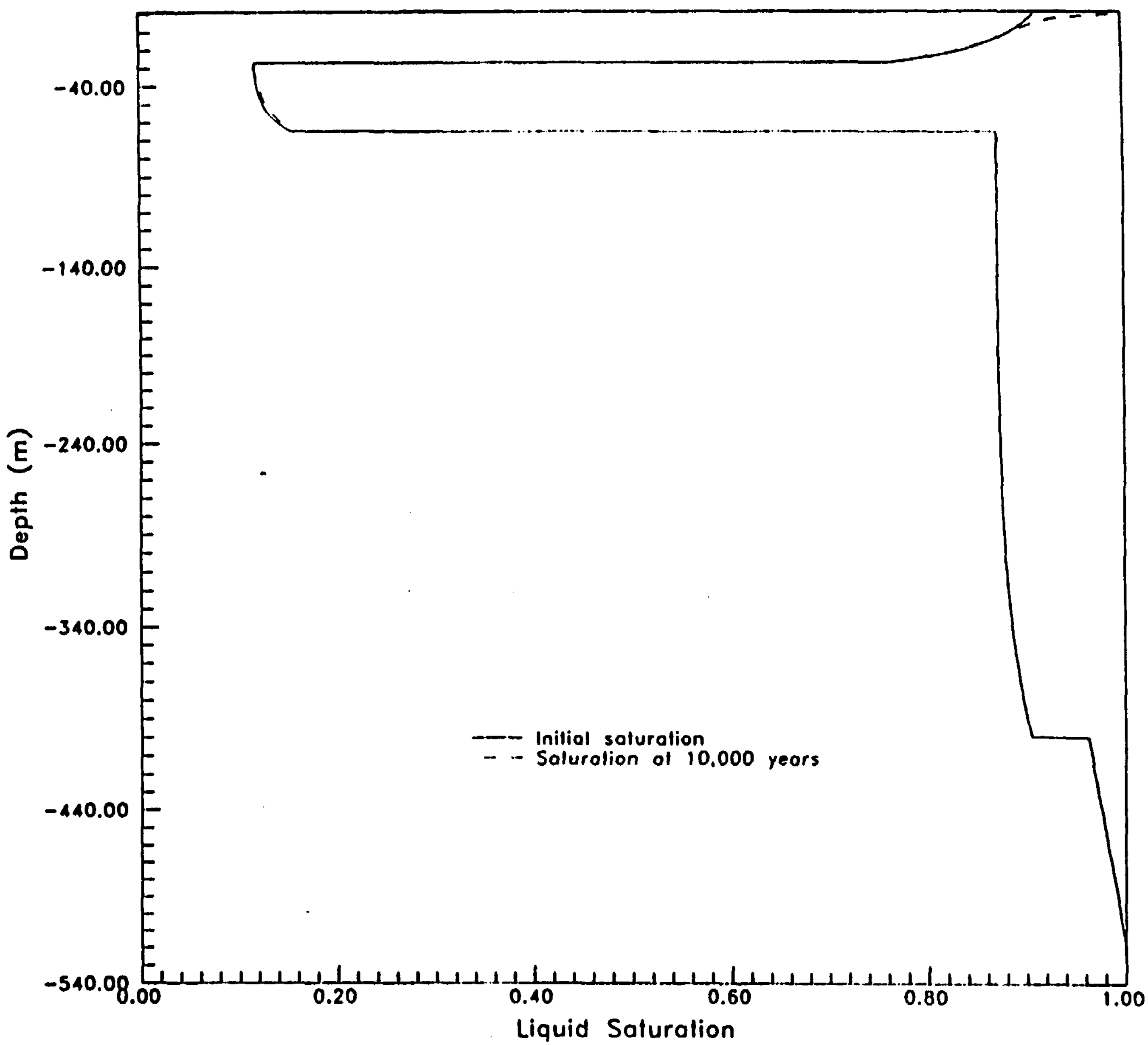

Figure A-6a. Scenario 3: Saturation Profiles at a Radius of 0.18 m in Response to Sealing of the Two Most Permeable Units.

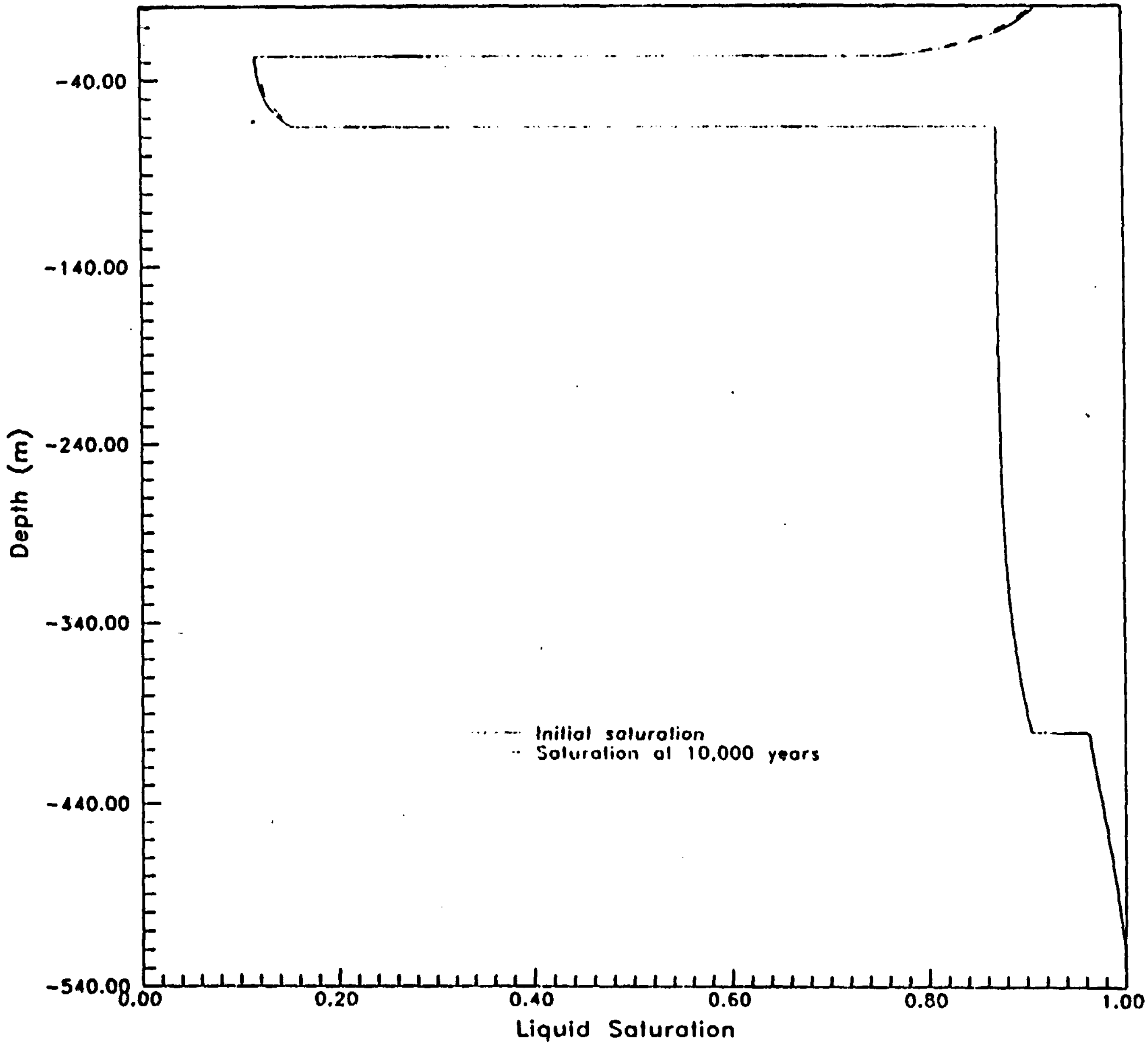

Figure A–6b. Scenario 3: Saturation Profiles at a Radius of 35.2 m in Response to Sealing of the Two Most Permeable Units.

APPENDIX B

BOUNDING CALCULATIONS OF WATER AND GAS FLOW THROUGH UZ#16

B.1 Basics

First, we calculate the volume of the borehole. We assume that UZ#16 is cylindrical, i.e. no sloughing. This is accurate to a depth of approximately 1100 ft (330 m), at which point the partially welded and nonwelded tuffs beneath the Topopah Spring vitrophyre exhibit little integrity. There has been significant sloughing in these stratigraphic units, but the majority of the hole is cylindrical. Furthermore, as is shown later, water from a probable maximum flood does not infiltrate to a depth of 1100 ft until after the floodwaters have subsided. The volume V of the borehole is

$$V=\pi r^2 d$$

where r, the radius of the hole, is 6.125 in (half of the reamed diameter of 12.25 in) and d, the total depth of the borehole, is 1690 ft (see Section 1.4). This yields a volume of 1383 ft^3. As the water table occurs at a depth of about h'=1611 ft, we may consider an effective volume V_{eff} with d' replacing d in the above equation. Then, V_{eff}=1318.5 ft^3.

B.2 Matrix Flow (Water)

We shall consider two scenarios for water flowing into the borehole: matrix flow and fracture flow. For the former, we shall assume that the borehole is filled with sand. This is an extremely conservative assumption, as the cement will not degrade to a state with a hydraulic conductivity comparable to that of sand. Furthermore, we shall assume that the sand is of uniform size. This assumption is also conservative, since sand of varied size has less pore space. Then, approximately 33.3% of the volume will be pores into which water can flow. Thus, the total amount of water that this sand-filled borehole can contain at any one time, V_w, is $V_w= 0.33V_{eff}$ = 439 ft^3. The irreducible water content, the part of the water which will adhere to the sand after draining, is approximately 10% of the pore space. Once the sand has been wetted, the maximum amount of infiltrating water which can be contained in the borehole, V_r, is $V_r = 0.9V_w = 395$ ft^3.

Fernandez and Case (1992) calculated that a probable maximum flood would produce a head of about 2 ft (including the debris level) over UZ#16. The duration of the flood is estimated to be approximately 14 hours, based on Bullard (1986). Thus, we consider the worst-case scenario of a 14 hour flood of depth two feet at UZ#16.

We shall calculate the flow of water into the borehole using Darcy's equation (see Amyx *et al.*, 1960). The assumptions necessary for the validity of Darcy's equation are incompressible, steady flow. As we shall see, the steady flow assumption leads to a slight underestimation of the amount of water infiltrating the borehole. Similarly, we assume 100% saturation of existing media (no fingering of the water). Darcy's equation is given by

$$Q=\frac{kA}{\mu}\left(\frac{h}{L}+1\right)\rho g$$

where h is the liquid head (2 ft), L is the length of the borehole to the water table (~1611 ft), μ is the viscosity of the water (1 cp), k is the permeability of the sand, A is the cross-sectional area of the borehole (0.82 ft^2), ρ is the water density (1 g/cm^3), and g is the gravitational constant (981 cm/s^2). Substituting the values for the different variables into Darcy's equation, we obtain Q=0.702 k, where k has units of darcy and Q has units of gallons per hour.

We now select a range of permeability for sand. From Dominico and Schwartz (1990), the hydraulic conductivity of fine sand is 2.0×10^{-7} to 2.0×10^{-4} m/s. For 20°C water, 1 m/s hydraulic conductivity corresponds to a permeability of 1.04×10^5 darcy. Thus, the permeability of fine sand is 0.0208 to 20.8 darcy.

The velocity of the water flowing through the borehole, v, can be calculated by

$$v=\frac{Q}{A}\frac{V_{eff}}{V_r}$$

where Q, A, V_{eff}, and V_r are the same as previously defined.

Substituting the values for permeability into Darcy's equation, we can obtain the volume flow rate and velocity of the water for a flood event:

k (darcy)	Q (gal/hr)	Q (ft^3/hr)	v (ft/hr)
0.0208	0.0146	0.00195	0.00795
20.8	14.6	1.95	7.95

Thus, for the most permeable sand, about 27.3 cubic feet of water enters the borehole during the fourteen hours of the probable maximum flood. The saturated portion of the borehole is only the top 111.3 ft (33.9 m) of the borehole, about 6.9% of the distance to the water table.

We have assumed steady state flow, but it is obvious from Darcy's equation that the fluid moves faster near the top initially. If we assume that the water is moving slowly, then the velocity is approximately constant over a small depth Δx. The time ΔT that it takes to travel this interval is

$$\Delta T=\frac{\Delta x}{v}=\frac{\Delta x}{(Q/A)\ (V_{eff}/V_{r})}=\frac{A\Delta x}{Q}\frac{V_{r}}{V_{eff}}$$

The total time it takes to travel to that interval is the sum of the ΔTs. If we take the limit of small intervals (Δx approaches 0), then the sum becomes an integral, and the total travel time T becomes

$$T=\int_{0}^{L}\frac{A}{Q}\frac{V_{r}}{V_{eff}}dx=\frac{V_{r}}{V_{eff}}\frac{\mu}{k\rho g}\int_{0}^{L}\frac{x}{x+h}dx$$

where Darcy's equation was used for Q. From the Handbook for Chemistry and Physics (CRC. 1971), we are able to complete the integral:

$$\int\frac{x}{a+bx}=\frac{x}{b}-\frac{a}{b^{2}}\ln(a+bx)$$

Thus, the total travel time to reach depth L with head h is

$$T=\frac{V_{r}}{V_{eff}}\frac{\mu}{k\rho g}[(L-h\ln(h+L))-(0-h\ln(h))]$$

Simplifying,

$$T=\frac{V_{r}}{V_{eff}}\frac{\mu}{k\rho g}[L-h\ln(1+\frac{L}{h})]$$

Hence, in a probable maximum flood lasting fourteen hours at the borehole filled with the most permeable sand (k=20.8 darcy), water would infiltrate L=119.4 ft (36.4 m), approximately 8.1 ft (2.5 m) farther than was estimated earlier in this section. This corresponds to 29.3 ft^3 of water.

The flow rates calculated in this section are greater than those calculated in Appendix A. This is primarily because we have assumed that the matrix was saturated, when it would have already drained from the previous event, and that the permeability of the sand was higher. If the sand has a permeability of 0.45 darcy (as assumed in Appendix A), then the water infiltrates 4.874 ft (1.49 m) in the fourteen hours of the flood. This is about the same distance that the saturation front travels (see Figures A-1a and A-1b). The difference is that the totally saturated (S=1) region in these figures extends only about 1 m into the borehole. The movement of the front of water through the unsaturated sand is slowed by capillary pressures, thus causing less water to infiltrate the borehole.

B.3 Fracture Flow (Water)

We now consider fracture flow in the borehole. For this section, we shall assume that fractures have uniform cross section and extend the entire length of the borehole (an extremely conservative assumption as self-healing and settling would usually take place).

Our first conceptual fracture is a slot of thickness 0.01 in extending the width of the borehole. The area of this fracture is A_f=8.51 x 10^{-4} ft^2. From Amyx *et al.* (1960), the permeability of a slot fracture is given by k=54.4 x 10^6 h^2, where h has units of inches and k has units of darcy. Thus, the permeability of this fracture is k=5440 darcy.

The volumetric flow rate in the fracture, Q_f, is given by

$$Q_f = Q_{matri} \frac{A_f}{A_{matri}}$$

From above, the volumetric matrix flow rate during a probable maximum flood is Q_{matri}=0.702k. Then, Q_f=0.000729k. For this fracture, Q_f=396 gal/hr=0.530 ft^3/hr. The fracture flow velocity, v_f, is given by $v_f = Q_f/A_f$. Thus, v_f=623 ft/hr. Fracture flow during a flood is clearly very rapid, but not much water travels through the fracture (approximately 7.4 ft^3) because of its relatively small size.

The second conceptual fracture is an annular fracture of 0.01" around a 0.89 in OD (outer diameter) cable. The cross-sectional area of this annular fracture is A_{an}=0.000196 ft^2. The radius of curvature, r=0.445 in, is much larger than the thickness of the fracture, t=0.01 in, so we may approximate the annulus as a slot fracture with a thickness of 0.01 in and a width of w=A_{an}/0.01 in=2.83 in.

As for above, k=54.4 x 10^6 h^2=5440 darcy, and

$$Q_{an} = Q_{matri} \frac{A_{an}}{A_{matri}}$$

We then have Q_{an}=0.000168k=0.913 gal/hr=0.122 ft^3/hr. During the flood, about 1.7 ft^3 of water enters the hole. As before, the velocity of the water through the annular fracture is v_{an}=623 ft/hr.

The third conceptual fracture is an annular fracture around the outside of the support tube. The fracture has a thickness of 0.01 in and an inner radius of 1.19 in. Then,

k=5440 darcy
A_{an}=0.00052 ft^2
Q_{an}=2.42 gal/hr=0.324 ft^3/hr
V_{inflow}=4.5 ft^3
v_{an}=623 ft/hr

The fourth conceptual fracture is an annular fracture around the inside of the support tube. The fracture has a thickness of 0.01 in and an outer radius of 1.06 in. Then,

$k=5440$ darcy
$A_{an}=0.00046\ ft^2$
$Q_{an}=2.14$ gal/hr$=0.286\ ft^3/hr$
$V_{inflow}=4.0\ ft^3$
$v_{an}=623$ ft/hr

The final conceptual fracture is an annular fracture between the grout and the rock matrix. The fracture has a radius of 6.125 in and thickness of 0.01 in. Then,

$k=5440$ darcy
$A_{an}=0.0027\ ft^2$
$Q_{an}=12.6$ gal/hr$=1.68\ ft^3/hr$
$V_{inflow}=23.5\ ft^3$
$v_{an}=623$ ft/hr

Clearly, the most significant fracture is the one at the interface between the grout and the host rock. However, none of the fracture flow is as great as the matrix flow.

B.4 Effect on the Saturated Zone

The effect of a pulse of infiltrating water on the saturated zone may be conservatively estimated by spreading the volume of the water that flows into the borehole uniformly over an area of radius 1400 ft (the distance to the repository). This is a conservative estimate as there would tend to be mounding of water near the borehole and water in the saturated zone near UZ#16 flows southward, away from the potential repository (DOE, 1988a).

As can be seen from sections B.2 and B.3, a conservative estimate of the total water which would flow down the borehole through cracks and the matrix is 66 ft^3, obtained by summing $V_{matrix} + 3V_{cable} + V_{supportout} + V_{supportin} + V_{interface}$. If this is spread evenly over an area of $6.2 \times 10^6\ ft^2$ (a circle of radius 1400 ft, the shortest distance to the conceptual repository), the rise in the water table at the conceptual perimeter drift boundary would be 1.1×10^{-5} ft (3.3 μm)--quite insignificant!

B.5 Fracture Flow (Gas)

Gas flow through Yucca Mountain is primarily through fractures (Barnard *et al.*, 1992, p. 5-5). We consider the propensity for gas to flow through the largest of the fractures. Fracture porosity is defined as

$$n_{frac} \equiv \frac{A_{frac}}{A_{total}}$$

Then, the fracture porosity for an annular fracture between the grout and the rock matrix which extends the entire length of the borehole is n_{frac}=0.0027 ft^2/0.818 ft^2=0.33%. Estimates of facture total porosities of the different layers range from 0.012% to 0.32% for the different tuffs in the equivalent-continuum model (Eslinger *et al.*, 1993). Thus, our worst-case scenario has a fracture porosity of the same order as thought reasonable for the tuff fracture porosity.

CHECKLIST OF
GENERAL CONCERNS REGARDING IMPACTS ON WASTE ISOLATION

CONCERNS	COMMENTS
I. Water	
A. Surface Sources	
1. Road watering for dust control	Not applicable
2. Drillpad dust control	Not applicable
3. Equipment washdown	Not applicable
4. Natural surface runoff	See sections 2.5.1 and 2.5.2
5. Accidental water spillage	Not applicable
6. Used in testing	Not applicable
B. Underground	
1. Water loss during drilling	
a) Normal	Not applicable
b) Fishing	Not applicable
c) Unexpected	Not applicable
2. Recovered or produced during drilling	
a) Perched water	Not applicable
b) Water table	Not applicable
3. Used in testing	Not applicable
II. Tracers, Fluids and Materials (other than water)	
A. Used in surface construction	
1. Building materials	Not applicable
2. Leachates from rock & muck piles	Not applicable
B. Used in borehole construction and/or sealing	
1. Grout for surface casings	Not applicable
2. Drilling fluids	Not applicable
3. Other materials left in boreholes	See sections 2.5.7 and 2.5.8
C. Used in testing	Not applicable
III. Other considerations	
A. Physical and chemical characteristics of seals	See sections 2.5.6 and 2.5.8
B. Seals may not achieve design objectives	See section 2.5
C. Cut-and-fill for roads, pads, trenches & pits	Not applicable
D. Blasting	See section 2.5.6