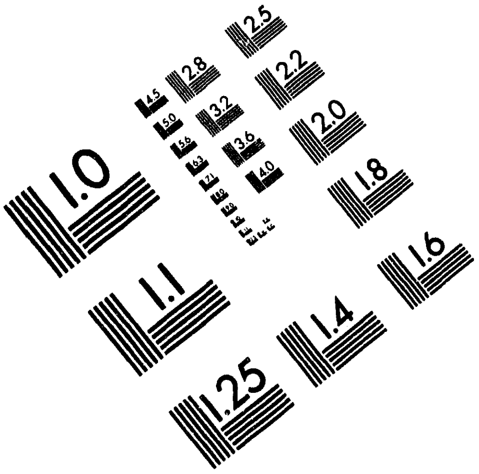
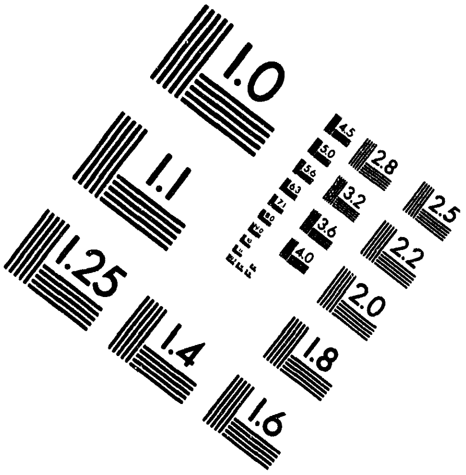


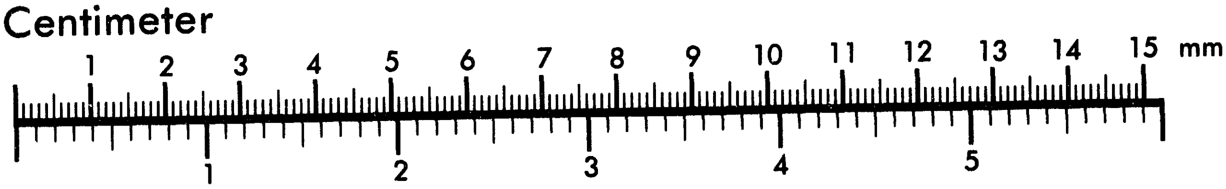
AIIM

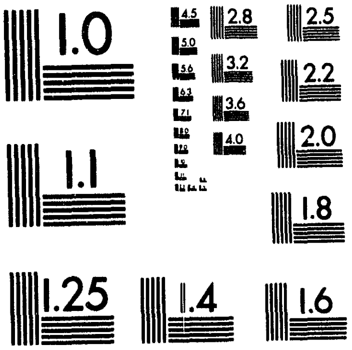
Association for Information and Image Management

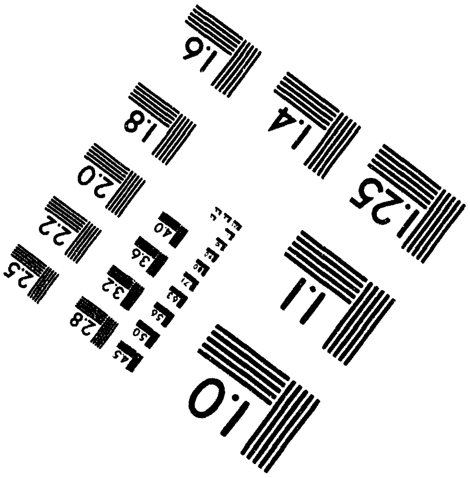
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

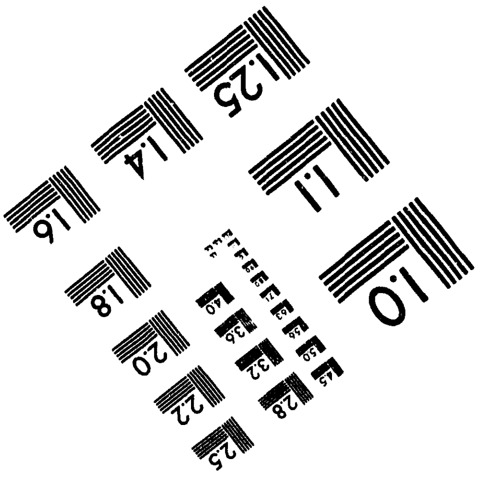
301/587-8202











MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 6

SAND 93-1184
Unlimited Distribution
Printed April 1994

Distribution
Category UC-814

A Strategy to Seal Exploratory Boreholes in Unsaturated Tuff

Joseph A. Fernandez
Environmental Restoration
Department 7583
Sandia National Laboratories
Albuquerque, NM 87185

John B. Case
Craig A. Givens
B. Clayton Carney
IT Corporation
5301 Central Avenue NE
Albuquerque, New Mexico 87108

Abstract

This report presents a strategy for sealing exploratory boreholes associated with the Yucca Mountain Site Characterization Project. Over 500 existing and proposed boreholes have been considered in the development of this strategy, ranging from shallow (penetrating into alluvium only) to deep (penetrating into the groundwater table). Among the comprehensive list of recommendations are the following: Those boreholes within the potential repository boundary and penetrating through the potential repository horizon are the most significant boreholes from a performance standpoint and should be sealed. Shallow boreholes are comparatively insignificant and require only nominal sealing. The primary areas in which to place seals are away from high-temperature zones at a distance from the potential repository horizon in the Paintbrush nonwelded tuff and the upper portion of the Topopah Spring Member and in the tuffaceous beds of the Calico Hills Unit. Seals should be placed prior to waste emplacement.

Performance goals for borehole seals both above and below the potential repository are proposed. Detailed construction information on the boreholes that could be used for future design specifications is provided along with a description of the environmental setting, i.e., the geology, hydrology, and the in situ and thermal stress states. A borehole classification scheme based on the condition of the borehole wall in different tuffaceous units is also proposed. In addition, calculations are presented to assess the significance of the boreholes acting as preferential pathways for the release of radionuclides.

Design calculations are presented to answer the concerns of when, where, and how to seal. As part of the strategy development, available technologies to seal exploratory boreholes (including casing removal, borehole wall reconditioning, and seal emplacement) are reviewed. It is recommended that the surface-based site characterization program maintain exploration boreholes with casing so that seals can be placed at selected sealing locations, that grout not be introduced at sealing locations, and that work plans for drilling additional boreholes be developed that address sealing issues. Borehole-specific sealing plans should also be developed.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Acknowledgments

The authors acknowledge the following individuals for providing technical contributions/advice to this report.

IT Corporation

Saeid Saeb	Airflow Analysis
Richie Spangler (formerly of IT)	Hydrologic Analysis
Karol Lorraine (formerly of IT)	Available Sealing Technologies
Malcolm Jarrell	Available Sealing Technologies
Paul Schweng (formerly of IT)	Available Sealing Technologies
Richard Abitz	Geochemistry
Margie Marley	Quality Assurance

Sandia National Laboratories

Dave Eley	Rock Property Models and Site Variability
Charles Gullick (Retired)	Materials Selection

EG&G Energy Measurements

David W. Brickey	Preparation of Figure 3-8

The authors also thank the following individuals for their peer review of this document: Larry Costin and Raymond Finley of Sandia National Laboratories, Peter Kelsall of IT Corporation, and Russ Dyer of the U.S. Department of Energy. Thanks are also extended to the IT Corporation support staff for their support in processing the document and to the technical editors, Debbie Russo and Susan Shipley.

This report was prepared under the Yucca Mountain Site Characterization Project WBS 1.2.4.6.1, QAGR 1.2.4.6.1. DIM 239 was the planning document that guided the work activity. The information and data documented in this report were initially developed at a Quality Assurance Level NQ (the work activity was not subject to quality assurance controls at that time). The information in this report is not qualified and is not to be used for licensing.

Table of Contents

Table of Contents *(Continued)*

List of Tables

List of Tables *(Continued)*

List of Figures

List of Figures *(Continued)*

List of Figures *(Continued)*

List of Figures *(Continued)*

List of Figures *(Continued)*

List of Figures (Continued)

List of Abbreviations/Acronyms

API	American Petroleum Institute
AOSC	Association of Oil Well Servicing Contractors
Ca	calcium
$CaCl_2$	calcium chloride
CFR	Code of Federal Regulations
COE	U.S. Army Corps of Engineers
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
K	potassium
LAPD	local area power density
MPBH	multiple position borehole extensometer
MPZ	modified permeability zone
NAC	Nevada Administrative Code
NACE	National Association of Corrosion Engineers
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
OD	outside diameter
OPC	ordinary portland cement
PMF	Probable Maximum Flood
PVC	polyvinyl chloride (pipe)
RMR	rock mass rating
RQD	rock quality designation
SCP	site characterization plan
Si	silicon
SNL/NM	Sandia National Laboratories/New Mexico
STC	southern tracer complex studies
TDAST	two-dimensional analytical solute transport
TGIF	Topographic Induced Flow
UCRL	University of California Research Laboratory
UIPC	Underground Injection Practices Council
WOC	waiting on cement
YMP	Yucca Mountain Project

Executive Summary

This report presents a strategy for sealing boreholes to satisfy seal performance requirements for the Yucca Mountain Site Characterization Project. Inherent in this strategy are answers to the following concerns: where to seal, relative to the potential repository and geologic setting; how to seal, relative to selection of seal materials, geometry, and placement methods; and when to seal during the stages of potential repository operation. The strategy for sealing boreholes addresses performance requirements given in 10 CFR 60 (1986) and presented in Issue 1.12 and the availability of technologies to place borehole seals as discussed in Issue 4.4 (DOE, 1988). This strategy also includes an evaluation of the performance of the sealing system. Because performance reliability is critical to the strategy, reducing the likelihood of degradation and selecting measures to avoid deleterious events are both addressed through performance and design calculations.

The strategy is intended to provide guidance for those acquiring site information from the surface-based program (Figure ES-1). This report is consistent with iterative performance assessment and ties sealing design concepts with site-specific features. The borehole sealing concepts are flexible in that they may be modified if the assumptions made about the rock properties change as a result of site characterization efforts, if additional scenarios for seal degradation are defined, or if changes in potential repository or waste package design occur. The strategy also provides recommendations to the surface-based testing program in maintaining access to boreholes, grouting in seal zones, preparing borehole sealing plans, and evaluating the risks of abandoning boreholes.

Borehole Performance Goals and Performance. In previous studies (Fernandez et al., 1987), the regulations for borehole-seal performance (10 CFR 60.134) require that "boreholes shall be designed so that following closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives." The position adopted was that the restriction of vertical flow through the boreholes to only 1 percent of the potential for vertical flow through the rock mass satisfies this requirement. For both boreholes and rock mass, the effective hydraulic gradient was assumed to be 1 for the condition of vertical infiltration under atmospheric pressure. Considering the area within the potential repository perimeter, the potential vertical flux through the rock mass was the effective hydraulic conductivity of the rock units between the potential repository and the water table times the floor area of the potential repository drifts, or more conservatively, the total area within the potential repository. The potential flow through boreholes was the sum of the cross-sectional areas of the boreholes within the potential repository area times the effective hydraulic conductivity of the seal material (including the effect of the seal host-rock interface). Considering a range of rock-mass hydraulic conductivities, selecting a low value of rock-mass conductivity results in a low required hydraulic conductivity for the seal material.

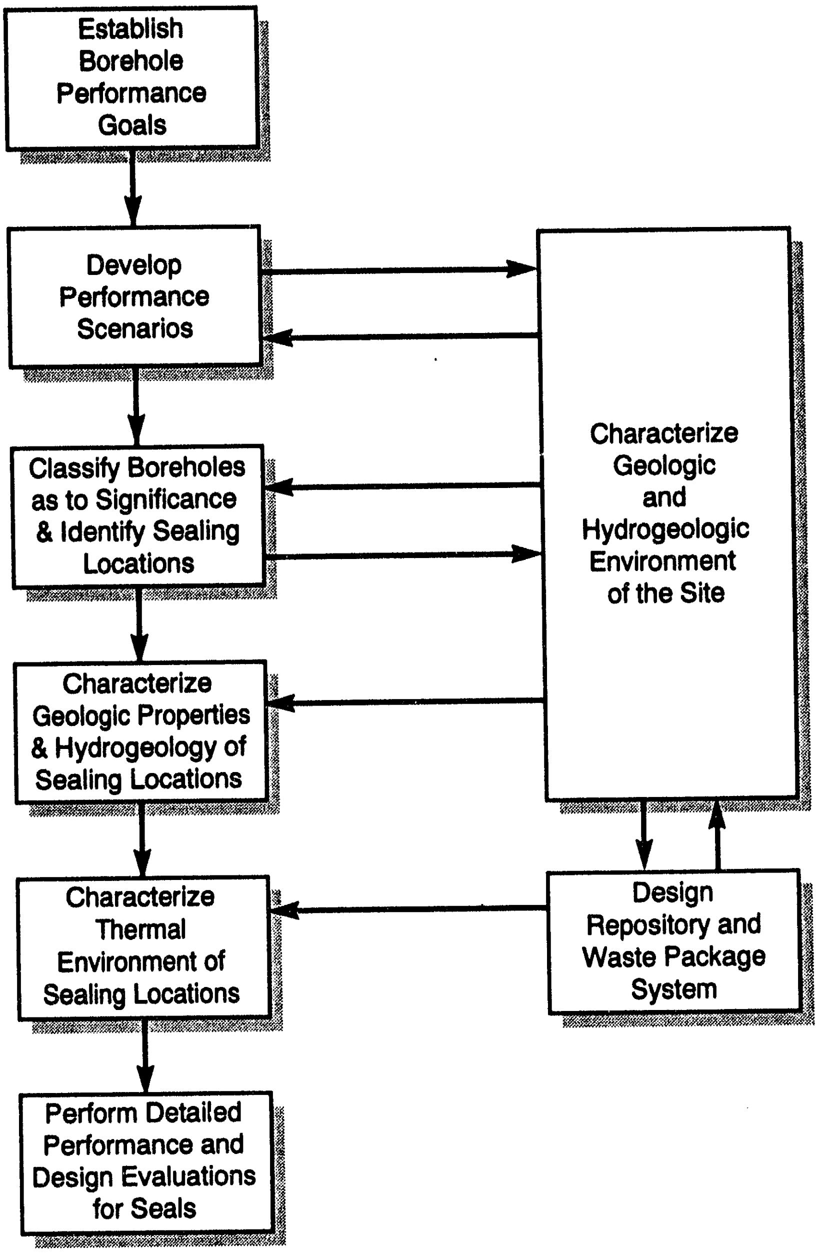


Figure ES-1
Development of Borehole Sealing Strategy

The current strategy recognizes that groundwater flow to the accessible environment below the potential repository is the main concern in sealing boreholes. Several scenarios exist for water flow towards or away from the potential repository that allows boreholes to become preferential pathways, potentially compromising the ability of the geologic disposal system to meet performance requirements. These water-flow scenarios could affect the significance of the boreholes within and near the boundary of the potential repository. These scenarios include:

- Inundation of a potential repository drift under unanticipated conditions, resulting in lateral spreading from the edge of the drift (Figure 2-2)
- Flooding events near alluvial recharge areas, resulting in a saturation front moving downward, potential perching of water, and potential enhancement of flooding at the Tiva Canyon contact (Figure 2-3).

For a drift inundated with water, a saturated flow plume would develop downward to the groundwater table. A deep borehole (e.g., UE-25a #7) intersecting such a plume represents a preferential pathway for the flow of water to the accessible environment. While several low-angled fracture sets exist, the fracture systems in the welded tuff are dominantly vertical, and there is only a small tendency for lateral flow from the potential repository horizon.

Surface flooding and the development of perched water could compromise the ability of the geologic potential repository to meet performance objectives following closure. The alluvium could become saturated and recharge the borehole, resulting in perched water. The potential for flooding at borehole locations depends on the size of the drainage basin, topographic features of the drainage basin, stream characteristics, and the presence of alluvium that could recharge the borehole. Existing and proposed boreholes within or near the potential repository periphery could be subject to flooding. With several exceptions, the proposed boreholes are to be located outside of flood-prone areas and are less subject to flooding.

Additional concerns have evolved regarding the potential for preferential flow of gaseous radionuclides, due to convective airflow out of the potential repository to the ground surface. Seals might degrade due to adverse loading and therefore not meet the basic hydrologic and airflow performance objectives. These concerns have evolved from a literature review of previous performance tests of potential repository seals, which is a basic objective of the current design investigations; from technical issues raised by the NRC; and from the need to provide additional seal-design requirements for backfill to augment the basic isolation characteristics of the unsaturated zone at Yucca Mountain. These concerns address sealing boreholes from the potential repository horizon to the ground surface, within the potential repository, or immediately outside the potential repository area. The performance goal adopted restricts airflow through the borehole seals to 1 percent of the total flow through the rock.

After radioactive waste is emplaced in the repository, convective air transport will develop through shafts, ramps, and boreholes accessing the potential repository. Convective airflow will also develop through the rock and other geologic features. As flow is drawn upwards from cooler regions surrounding the potential repository, lateral spreading can occur (Figure 2-5). Lateral spreading depends upon advection or airflow and dispersion that, in turn, depend on molecular diffusion and dispersivity. For boreholes near the edge of the potential repository, flow upward to the atmosphere could occur (depending upon the depth of the borehole) through rock and then through the borehole.

Airflow may also be affected by contrast in permeabilities, which could force air to migrate laterally. The Paintbrush nonwelded tuff formation possesses relatively fewer fractures and lower conductivity than the underlying Topopah Spring Formation. Flow could exit in Solitario Canyon, and boreholes to the west of the potential repository could be affected. To the east of the potential repository, the convective cell formation would be contained in the welded unit until a cooler region is reached and air is drawn back towards the potential repository.

The consideration of the regulatory criteria for preferred pathways and the air and water and flow scenarios suggest that boreholes could be categorized according to temperature (inside versus outside the potential repository), borehole depth, and the potential for flooding. The established criteria are as follows:

- Plan Location—Air Flow—The borehole is located within or immediately outside the potential repository periphery. Boreholes within the extended boundary of the potential repository[1] are subject to convective airflow.

- Depth—Air Flow and Water Flow—The depth of the borehole determines whether airflow above the potential repository occurs predominantly through rock and then through the borehole or through just the borehole and associated backfill and seals. For deep boreholes, a preferential pathway could exist for water flow from the potential repository horizon to the groundwater table.

- Plan Location—Water Flow—The location of the borehole with respect to flood-prone areas.

Chapter 2.0 presents a categorization of the exploratory boreholes based upon the above criteria for properties of boreholes. The following observations are made:

- The water-flow enhancement for deep boreholes under perched water conditions is a far more significant condition than for shallow boreholes, since flow is proportional to standing water columns within the borehole.[2]

---

[1] The extended boundary of the potential repository includes boreholes immediately outside of the potential repository that might be subject to advection/dispersion.

[2] The evaluation assumes a worst-case scenario that a standing water column develops within the borehole. The development of a standing water column depends on the amount of water recharged to the borehole and the amount dissipated to surrounding formations.

- The airflow through deep boreholes penetrating the potential repository is far more significant than for shallow boreholes, since airflow through a hole is resisted principally by flow through the web of rock below the borehole. Shallow boreholes not penetrating the Tiva Canyon Member are inconsequential and need not be sealed.

- Stratigraphic contacts may direct perched water to travel laterally primarily to the east of the potential repository. A seal placed at the stratigraphic contact reduces the potential for the borehole becoming a preferential pathway.

For deep boreholes outside the potential repository perimeter, sealing is not necessary in the upper zone, while sealing could be required in the lower zone extending to the east of the potential repository. Away from the potential repository, the upper seal zone is not necessary to prevent surface inundation, and reduce contaminated airflow. This is because the surface plume does not intersect the potential repository, and air would be drawn into the ground in cooler regions. Yet the lower seal may be required, if perched water occurs on contact zones that tend to move laterally to the east. This water could become a preferential pathway through deep boreholes.

The above evaluations establish the need for sealing above and below the potential repository. The following discusses borehole wall conditions for selecting sealing locations within a borehole.

In selecting sealing locations above and below the potential repository, it was found that the condition of the borehole wall depends on the degree of welding, the lithophysae content, the extent of clay and zeolitic mineral development, and the degree of fracturing in response to borehole drilling. A classification scheme was developed, and borehole video logs were reviewed as a direct means of assessing borehole wall condition. The categories included Category C1 for an excellent hole with no or few lithophysae; Category C2 for a good hole with a slight degree of hole enlargement and lithophysae present and frequent fractures; Category C3 with a rough surface, and hole enlargement; and Category C4 with nonsymmetrical hole enlargement, large lithophysae, and pronounced fractures.

- A high percentage of Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and Topopah Spring Units.

- Category C1 occurs in the Paintbrush nonwelded tuff.

- Categories C1 and C2 occur in the upper portion of Topopah Spring Unit.

- Categories C1 and C2 occur in the nonwelded vitric and zeolitic portions of the Calico Hills Unit.

This evaluation suggests placement of key seals in the Paintbrush nonwelded tuffs, in the upper portion of the Topopah Spring Unit, and in the nonwelded vitric and zeolitic portions of the Calico Hills Unit. While borehole classifications show more favorable conditions in the nonwelded tuffs that are relatively free of fractures, the assessed rock-mass strength for nonwelded tuff is somewhat lower, due to the contrast in unconfined compressive strength between the welded and nonwelded tuffs (150 versus 15 MPa). The rock-mass strength is important, because higher strength gives greater confidence in the mechanical stability of the boreholes. Nevertheless, the varying conditions suggest that sealing locations with higher rock-mass quality in welded and nonwelded units that are not intensely fractured can be selected.

Following development of the strategy, the performance scenarios are evaluated in detail in Chapter 4.0 for the following:

- Air dispersion of radionuclides through fractured rock above the potential repository and into a borehole
- Convective air transport of radionuclides through rock above the potential repository and into a borehole
- Water transport of radionuclides from a flooded perimeter drift at the potential repository horizon through fractured rock beneath the potential repository into a borehole above the groundwater table
- Transport of water from a flooded borehole, within a potentially flooded area, to the potential repository horizon.

The results reached from the detailed evaluation of these scenarios are summarized below:

- Significant lateral dispersion of air above the potential repository, assuming the more conservative case of isotropic rock conditions, is limited to approximately 600 m from the edge of the potential repository (see Figure 4-7).
- Significant lateral dispersion of air above the potential repository, assuming the orientation and strike of the fracture system, is probably more restricted on the east and west sides of the potential repository than on the north and south (see Figure 4-7).
- Considering convective air transport, Lu et al. (1991) showed that where the permeability of the nonwelded Paintbrush tuff was low relative to the welded tuff, lateral dispersion under the nonwelded unit was greater. It was also shown that radionuclides could also be released to the west of where the bedded tuffs outcrop on the west side of Yucca Mountain.

- If the perimeter drift were fully saturated, water transport from the perimeter drift to the groundwater table is estimated at a maximum vector of 30 degrees from vertical.

- From calculations estimating the flood heights for the PMF, about 30 shallow and deep boreholes may be subject to flooding. Most of these boreholes are collared in alluvium. Of the boreholes subject to flooding, about 14 deep boreholes penetrate to below the Tiva Canyon member. Three boreholes penetrate through the Tiva Canyon and the Paintbrush nonwelded tuff into the Topopah Spring Member. The remaining deeper holes (for example, USW WT-2, USW G-4, USW H-4, and USW G-1) penetrate through the potential repository horizon. If these holes are not sealed, the deep boreholes are far more significant in enhancing flow to the underground by 1 to 2 orders of magnitude.

Summary conclusions of "where," "when," and "how" to seal are presented below.

Where to Seal. The two most significant issues addressed are the characteristics of the host formation and the anticipated in situ and thermal stress environment at these prospective sealing locations as discussed above. The recommendations for where to seal are as follows:

- Place seals in competent zones to eliminate the effects of surficial erosion.

- Place seals in zones that are free of fractures or in zones having few fractures (i.e., above and below the potential repository horizon). The results of the current borehole wall classification show that the bedded, nonwelded tuffs above the potential repository horizon and the Calico Hills Unit below the potential repository horizon represent the best sealing locations. In welded tuff, the less densely welded upper portion of the Topopah Spring Unit presents an optimum sealing location. The stiffer units are more desirable from the standpoint of developing interface stress.

- For boreholes upgradient of the potential repository or within the elevated temperature zone outside the potential repository perimeter that penetrate to the potential repository horizon, place seals in the upper contact zones in the Paintbrush or alternatively in the Topopah Spring Formation to restrict airflow to 1 percent of the total that would occur through the rock. It is conservatively assumed that the potential exists for perched water conditions at these borehole locations and that the seals at these upper contact zones would prevent saturation of seals below the potential repository horizon.

- Temperature effects are far more significant near the potential repository horizon and suggest seal emplacement away from the potential repository horizon.

- Place seals in the upper portion of the Topopah Spring Unit to the west of the potential repository, as the potential exists for convective airflow to break out at the ground surface in Solitario Canyon. In other directions from the potential repository, the results of the air-dispersion calculations suggest boreholes within a distance of 600 m may represent preferential pathways for the release of gaseous radionuclides.

When to Seal. Prior to sealing, the borehole casing would be removed and an open borehole wall would be exposed at the sealing location. Elevated temperature in the potential repository could collapse the casing, resulting in no access to the seal location as a result of borehole decrepitation. The "when" to seal issue is addressed by a corrosion assessment and stress analysis of an open borehole, which will evaluate potential corrosion effects on borehole casing and the stability of open boreholes prior to sealing. This evaluation will consider the effects of elevated temperature on casing and area borehole wall stability if sealing occurred 60 years after waste emplacement. As of now, no site-specific data are available for the corrosion of carbon-steel casing at the Yucca Mountain site.

Considering casing configurations, deep casings, such as those used in the grouting of UE-25a #1, occurred over short distances, and the casings were freestanding over much of their length. Shallow casings grouted to a depth of 100 to 200 ft, such as those used in UE-25a #5, could be subject to long-cell action. In deeper zones, the state of in situ stress is higher, and rock mass strength is lower (e.g., the Calico Hills). In other areas, rock mass quality is lower in more highly fractured tuff. The possibility then exists for collapse of the borehole against the casing, exposing steel to the host formation. Here, the range of saturation is 46 to 84 percent for welded tuff and 46 to 76 percent for nonwelded tuff (DOE, 1992), suggesting long-cell action. The low conductivity of both welded and nonwelded tuff suggests that local-cell action would be insignificant. Corrosion might be higher in these areas, because of the synergistic effects of contact with the host rock and stresses within the casing; however, these zones are expected to be isolated, reducing the potential for long-cell action, and the actual corrosion rates will probably be the same as those for carbon steel exposed to air and (possibly) a humid environment.

The Kirsch solution (Goodman, 1980) was used to evaluate stress concentration effects for open boreholes and boreholes penetrating near the roof, sidewall, and floor of a drift at the potential repository excavation. The proximity of these locations, combined with stress-concentration effects, suggest that the development of shear stress of 10 to 20 MPa under some confinement may occur and that the potential exists for localized rock-mass failure. Also, elevated temperatures at the lower seal location would occur due to the proximity of the potential repository horizon to this location. The upper seal location would be affected much less significantly.

In conclusion, seals should be emplaced prior to waste emplacement within the potential repository boundary for the following reasons:

- To avoid the potential development of high boundary stresses during potential repository heating in an open borehole
- To prevent collapse of the casing, which would limit access to selected sealing locations
- To prevent accelerated corrosion of casing, due to collapse of the formation around the casing (which would result in higher corrosion rates than those for atmospheric corrosion) and due to potential synergistic effects between stress and corrosion.

A separation distance of at least 15 m (Fernandez et al., 1987) from the potential repository drifts should be maintained to eliminate stress concentration effects.

How to Seal. Two basic areas are considered: (1) recommended design requirements for borehole seals for air and water flow and (2) identification of sealing strategies that can be used to mitigate seal degradation. Both are discussed below.

Seals should be emplaced at key locations to reduce the potential for airflow out of the potential repository, to reduce the potential for water flow out of or into the potential repository, to resist loads, and to provide strength. The analyses done for this report suggest that the best and most effective seals should couple structural performance with hydrologic performance. For seals below the potential repository, it is recommended that cementitious seals be selected with conductivities of 10^{-3} cm/s, with an effective interface aperture of 100 microns; for seals above the potential repository, cementitious materials should be selected with conductivities of 10^{-1} cm/s, with an effective interface aperture of 500 microns.

To resist load and provide strength, these seals should be placed as follows:

- Seal locations, material properties, and placement methods should be selected that provide adequate strength and deformational serviceability for sealing components to resist various combinations of dead, seismic, and thermal loads. These include:
  - Dead loads from overlying seal materials
  - Thermal loads, due to the hydration of the cement and radioactive waste generation
  - Differential volumetric expansion, due to placement methods, cement hydration, and differences in selected material properties
  - Liquefaction and consolidation of backfill, due to seismic events.
- In Appendix I, the parametric studies using available data suggest that cementitious seals be placed under a slight pressure and with a low placement temperature.

Saturation of the backfill could load the seal and reduce effective stress. A cementitious seal with a tensile strength of 1 MPa and a compressive strength of 21 to 34 MPa (3,000 to 5,000 psi) is adequate for combined loads.

- A backfill that has a specified porosity and grain-size distribution should be placed between the rigid seals, which will provide a capillary barrier to unsaturated flow occurring downward or laterally at stratigraphic contacts.

Summary of Available Technologies to Seal Boreholes. One objective of this report was to review the technologies available for borehole seal emplacement. Chapter 6.0 includes a review of tasks needed to place seals. These tasks are as follows:

- Removal of freestanding casing and borehole materials, if present
- Reconditioning of the borehole wall
- Selection of seal materials
- Emplacement of seals.

As discussed in Chapter 6.0, technologies are available to accomplish casing removal, borehole reconditioning, and seal emplacement. However, some difficulty in removing materials from selected boreholes may occur. As a consequence of the available technologies for sealing boreholes, sealing concerns should be taken into account *before* new boreholes are drilled. The following conclusions are included as part of the borehole sealing strategy:

- Maintain detailed construction documentation

- Select drilling methods, if possible, that will reduce wall-cake build-up

- Select drilling methods, if possible, that will result in better wall condition

- Minimize risk of losing drilling tools and "junk" in the borehole, i.e., develop a protocol for tool inspection; make routine field inspections intermittent with downhole operations

- Utilize materials that are relatively easy to remove through fishing or milling

- Limit the number of exploratory boreholes.

Risk Involved in Abandoning a Single Borehole. Chapter 4.0 and Appendix H present calculations for the abandonment of a single borehole. For purposes of evaluation, the existing USW UZ-6 borehole has the largest diameter at the potential repository horizon. Also, it should be considered that the effective hydraulic conductivity of the abandoned borehole equals 10 cm/s (equivalent to an air conductivity of 0.4 meters per minute). The conductance can be compared to the cumulative conductance for the three models. The relative significance of a single abandoned borehole depends on the model employed. For the low-conductivity model, where the conductivity of the rock matrix is low (Model 1), a single abandoned borehole provides a greater conductance than 100 boreholes combined together (or 30 boreholes penetrating through the potential repository horizon). For Model 2, where the rock matrix conductivity is increased over Model 1, the conductance of a single abandoned borehole represents about 10 percent of the total flow. For the most conductive model (Model 3), where the rock matrix conductivity is high, the flow through a single abandoned borehole is not significant, in that the design requirement expressed as a hydraulic conductivity for seals is of the order of 100 cm/s.

The above analysis does not include fault zones that may have a higher conductivity. If fault zones are persistently higher in conductivity, they might tend to dominate convective airflow, and a single abandoned hole would have less significance. On the other hand, if the low-conductivity model is appropriate with a flow resistance dominantly occurring in low-conductivity formations, the abandoned borehole has added significance. Further, while no specific calculations are presented of the potential impacts on water flow, the abandonment of a single borehole would be expected to have a similar impact. The project should recognize that the current understanding of the hydrologic source is not complete at this time and will be updated as site characterization information becomes available.

Based upon the preliminary calculations presented in the report, the project proceeds at risk in abandoning boreholes where access to sealing location cannot be assured or where performance cannot be evaluated.

Recommendations for the Surface-Based Program. The evaluations and conclusions presented in this report provide guidance for the surfaced-based program. This guidance is provided for addressing sealing plans and answering questions regarding grouting, borehole access, borehole abandonment, and at which point these issues should be addressed. These issues are discussed in more detail below.

Maintain Casing. Borehole casing will be maintained for most of the planned boreholes, although several boreholes have been proposed that require grouting of fractures and other material in sealing zones where casing has been removed. Where casing has been removed, it will be very difficult to reenter boreholes for purposes of seal emplacement, and current confidence is low that such an operation would be successful. Because of the potential risks involved, it is recommended that casing be maintained in deep boreholes within the extended boundaries of the potential repository to provide continued access to borehole sealing locations.

Fracture Grouting. Fracture grouting at the upper and lower sealing locations may be necessary during site characterization to achieve borehole stability. These grouted fractures are then potentially susceptible to stress relief during drilling or alteration during potential repository heating. The high temperature regime may result in microcracking, a tendency for grout filled fractures to open up, resulting in degradation of overall seal performance. For these reasons, it is recommended that no grout should be introduced at the upper and lower sealing locations during site characterization, since it could affect performance at the time of potential repository decommissioning and well abandonment. It is therefore recommended that a general sealing plan, as outlined in detail by this report, be developed for all exploratory boreholes and that a detailed sealing plan be developed for each borehole.

The seal plans developed by the project would exist as controlled documents with design specifications and construction drawings and would consider general and specific problems encountered at the sealing locations after detailed borehole inspection and in situ testing. Each borehole would be surveyed for accurate well trajectories. The emphasis in the plan would be to use a combination of mechanical calipers and video-logging during inspection to search for obstructions. Injection pressures may be determined by controlled hydrofracturing in zones near seal locations.

Borehole Sealing Plans. The borehole sealing plans would be developed through consideration of general and specific problems encountered at the specific sealing locations after inspection. The borehole sealing plans would specify the quantities of seal materials, material specifications for cementitious seals and earthen materials, and QC methods to be followed during placement. In areas where pregrouting is necessary, grout design would be tailored to provide materials performance at specified grout-injection pressures, viscosity, and strength. An important issue to be addressed in the surface-based program is at what point sealing plans should be in place. Calculations presented in this report state that, near the potential repository, the potential exists for future deep boreholes to be affected by air dispersion or flooding. These boreholes should be evaluated prior to drilling to define specific seal design requirements. It is recommended that sealing plans be prepared for all proposed deep boreholes within the extended boundary of the potential repository prior to borehole drilling and that work plans address issues with respect to well abandonment and casing removal. Further, no grouting should be introduced into sealing zones as part of the current surface-based program without addressing the risks in not complying with federal regulations. In this manner, work-plan preparation will reflect an evaluation of the trade-offs in proceeding with the surface-based program relative to the risks of well abandonment prior to drilling and well completion.

1.0 Introduction

The Yucca Mountain Project (YMP), managed by the U.S. Department of Energy (DOE), is examining the suitability of the disposal of high-level radioactive waste in a mined geologic potential repository at Yucca Mountain. Yucca Mountain is situated both on and adjacent to the Nevada Test Site (NTS) in Nye County, Nevada. The potential repository would be located in an unsaturated tuff formation within Yucca Mountain.

In December 1988, DOE (1988) issued a comprehensive site characterization plan (SCP) for evaluating the suitability of Yucca Mountain as a potential site for a high-level nuclear waste repository. This plan defined a broad range of activities, such as exploratory borings, surface excavations, excavations of exploratory ramps, and limited subsurface lateral excavations needed to characterize the site. This report develops a strategy to seal existing boreholes and proposed exploratory boreholes associated with the site characterization effort. In developing this strategy, the report also considers the regulations pertinent to borehole sealing. The two primary requirements that address the performance of the borehole seals, defined in 10 CFR 60, are as follows:

- §60.112, "Overall system performance objective for the geologic potential repository after permanent closure":

  "The geologic setting shall be selected and the engineered barrier system and the shafts, boreholes, and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency [EPA] with respect to both anticipated processes and events and unanticipated processes and events."

- §60.134, "Design of seals for shafts and boreholes":

  (a) "General design criterion: Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives over the period following permanent closure."

  (b) "Selection of materials and placement methods: Materials and placement methods for seals shall be selected to reduce, to the extent practicable, (1) the potential for creating a preferential pathway for groundwater to contact the waste packages or (2) radionuclide migration through existing pathways."

The SCP presents a process for responding to all regulations, including those given above. This process includes defining issues and associated information needs that must be resolved in order to respond to these regulations. The specific issues and information needs pertinent to this area of borehole sealing are given below:

- Issue 1.12:

  "Have the characteristics and configurations of the shaft and borehole seals been adequately established to (a) show compliance with the postclosure design criteria of 10 CFR 60.134 and (b) provide information to support resolution of the performance issues?"

  Information Needs

  1.12.1 Not applicable
  1.12.2 Materials and characteristics of seals for shafts, drifts, and boreholes
  1.12.3 Placement method of seals for shafts, drifts, and boreholes
  1.12.4 Reference design of seals for shafts, drifts, and boreholes

- Issue 4.4:

  "Are the technologies of potential repository construction, operation, closure, and decommissioning adequately established to support resolution of the performance issues?"

  Information Needs

  4.4.10 Determination that the seals for shafts, drifts, and boreholes can be emplaced with reasonably available technology.

The primary areas of interest in the issues and information needs that must be considered are the performance and design of the borehole seals and the technologies available to seal exploratory boreholes.

This report presents a sealing strategy and provides information to address the design of exploratory boreholes, materials and characteristics of the design, and available technologies for seal emplacement. This report is organized to present a sealing strategy in Chapter 2.0 based upon fundamental considerations, such as location, with respect to the potential repository boundary and flooded areas and depth. Subsequent chapters provide more detailed evaluation to answer specific questions regarding the sealing strategy.

The issues and uncertainties addressed in this report are presented in Table 1-1. This table presents the type of information, the issue or uncertainty addressed, seal performance goals, and the parameters of concern. The information type identifies what information is needed. The property, issue, or uncertainty identifies why the information is needed. In answering these questions, the parameter(s) of concern identify information developed. The table identifies the current and needed confidence level and identifies which section of the report and supporting appendices address each issue. Each supporting section states how the information is subsequently used in performing analysis or formulating strategies.

Table 1-1

Issues and Uncertainties in Sealing Exploratory Boreholes Addressed in this Report

Information Type	Property, Issue or Uncertainty	Performance Goal	Parameter(s) of Concern	Needed Confidence	Current Confidence	Report Section	Supporting Appendix
Borehole Sealing Strategy	What is the water-flow performance requirement for the potential repository?	Restrict water flow to less than 1 percent of flow through the potential repository.	Required seal performance expressed as an effective permeability	High	Low	2.1	--
	What is the airflow performance requirement for the potential repository?	Restrict airflow to less than 1 percent of flow through the potential repository.	Required seal performance expressed as an effective permeability	High	Low	2.1	--
	What is the proximity of boreholes to the potential repository and flooded areas?	NA	Categorize boreholes as to significance	High	Medium	2.2, 2.3	--
	What seal locations within critical boreholes are available for sealing?	NA	Borehole classification for wall condition	High	High	2.4, 3.4	D
	What is the in situ stress at seal locations?	NA	Stress state	Medium	Medium	2.4, 3.3	--
	What is the temperature and induced thermal stress at seal locations?	NA	Temperature and thermal stress	Medium	Medium	2.4, 3.3	--
	What is the rock mass strength at seal locations?	NA	Rock mass strength	Medium	Medium	2.4, 3.3	--

Refer to footnotes at end of table.

Table 1-1 *(Continued)*

Issues and Uncertainties in Sealing Exploratory Boreholes Addressed in this Report

Information Type	Property, Issue or Uncertainty	Performance Goal	Parameter(s) of Concern	Needed Confidence	Current Confidence	Report Section	Supporting Appendix
Borehole Sealing Strategy (Continued)	What is the basic design configuration for shallow boreholes?	NA	None	NA	NA	2.5	--
	What seal materials are available for selection?	Stable seals with high longevity	Seal hydrological and mechanical properties	High	Medium to High	2.5	--
	What is the basic design configuration for deep boreholes?	Air- and water-flow effective permeabilities	Seal locations and lengths	High	Medium	2.5	--
General Site Information and Surface-Based Borehole System	What is the basic description of the exploratory borehole system?	NA	Location, size, depth, and casing configuration of exploratory boreholes	Medium	High	3.1	A & B
	Geology and hydrology of Yucca Mountain	NA	Stratigraphy Rock hydrologic Properties Sources of water	Medium High High	High Medium Low	3.2 3.2 3.2	C
Where to Seal	Where are deep boreholes affected by inundation at the potential repository horizon?	NA	Lateral distance from the potential repository boundary	High	Low	4.1	E
	Where are boreholes inundated by surface water flow?	NA	Depth of flooding at borehole locations	High	Medium	4.1	F

Refer to footnotes at end of table.

Table 1-1 *(Continued)*

Issues and Uncertainties in Sealing Exploratory Boreholes Addressed in this Report

Information Type	Property, Issue or Uncertainty	Performance Goal	Parameter(s) of Concern	Needed Confidence	Current Confidence	Report Section	Supporting Appendix
Where to Seal (Continued)	For a potential perched water scenario, which boreholes are significant?	NA	The relative significance of water flow between shallow and deep boreholes	High	Medium	4.1	H
	Where does air lateral dispersion occur from the potential repository?	NA	Distance from the potential repository affected by air dispersion.	Medium	Low	4.2	G
	How is lateral air dispersion influenced by contrasts in air conductivity?	NA	Distance air migrates into Solitario Canyon	Medium	Low	4.2	--
	Where are the boreholes significant to airflow located?	Seal conductivity	Product of the effective permeability and cross-sectional area	High	Medium	4.2	H
How to seal for air- and water-flow performance	What is the hydrologic design requirement to restrict flow?	Water-flow effective permeabilities	Seal matrix and interface-zone conductivity	High	Medium	5.1	--
	What is the airflow design requirement to restrict flow?	Airflow effective permeabilities	Seal matrix and interface-zone conductivity	High	Medium	5.1	--
When to Seal	How stable are open and cased boreholes for heated and unheated conditions?	Stable boreholes prior to sealing	Stress to strength comparisons Corrosion allowance	High Low	Low to Medium Low	5.3 5.3	--

Refer to footnotes at end of table.

Table 1-1 *(Continued)*

Issues and Uncertainties in Sealing Exploratory Boreholes Addressed in this Report

Information Type	Property, Issue or Uncertainty	Performance Goal	Parameter(s) of Concern	Needed Confidence	Current Confidence	Report Section	Supporting Appendix
How to seal for structural performance	Can seals be designed to resist seal, backfill, thermal, and seismic loading?	Stable borehole sealed after potential repository decommissioning	Triaxial compressive strength to resist combined loadings	Medium	Medium to High	5.4	I, J
How to seal using available emplacement technologies	Can instrumentation and other material be removed from cased boreholes using available methods?	NA	NA	High	High	6.2	--
	Can instrumentation and other material be removed from uncased boreholes using available methods?	NA	NA	High	Low	6.2	--
	Can casing be removed at seal locations?	NA	NA	High	High	6.2	--
	Are methods available for seal emplacement?	NA	NA	High	High	6.2	K
	Are quality control methods available for seal emplacement?	NA	NA	Medium	Medium	6.2	--
	Are seal testing methods to verify performance available?	NA	NA	High	Low	6.2	--

Refer to footnotes at end of table.

Table 1-1 *(Continued)*

Issues and Uncertainties in Sealing Exploratory Boreholes Addressed in this Report

Information Type	Property, Issue or Uncertainty	Performance Goal	Parameter(s) of Concern	Needed Confidence	Current Confidence	Report Section	Supporting Appendix
Programmatic Constraints for the Surface-Based Program	Can access be gained to seal locations after completion of the program?	NA	NA	High	Low[a]	7.3-7.4	--
	Should grouting be allowed in sealing zones?	NA	NA	High	Low[b]	7.3-7.4	--
	Could individual boreholes be abandoned without risking degradation in potential repository performance after completion of the program?	NA	NA	High	Low	7.4	--
	Should sealing and abandonment issues be addressed during work plan preparation?	NA	NA	High	Low[c]	7.5	--

[a] The confidence is high for cased boreholes and low for uncased boreholes. Since some boreholes are uncased with grouted instrumentation, the overall confidence is low.

[b] The surface-based program currently identifies no restriction on grouting.

[c] There is currently no project requirement for addressing sealing and abandonment during the preparation of work plans.

NA = Not applicable.

2.0 Exploratory Borehole Seal Strategy

This chapter presents a strategy for sealing boreholes to satisfy seal performance requirements. Inherent in this strategy are answers to the following concerns: where to seal, relative to the potential repository and geologic setting; how to seal, relative to selection of seal materials, geometry, and placement methods; and when to seal during the stages of potential repository operation. As discussed in Chapter 1.0, the strategy for sealing boreholes addresses performance requirements given in 10 CFR 60 and presented in Issue 1.12 and the availability of technologies to place borehole seals as discussed in Issue 4.4. Therefore, this strategy includes an evaluation of the performance of the sealing system. Because performance reliability is critical to the strategy, reducing the likelihood of degradation and selecting measures to avoid deleterious events are both addressed through performance evaluations and design calculations presented in Chapters 4.0 and 5.0.

The strategy is intended to provide guidance for those acquiring site information from the surface-based program. This report is consistent with iterative performance assessment and ties sealing design concepts with site-specific features. The borehole sealing concepts are flexible in that they may be modified if the assumptions made about the rock properties change as a result of site characterization efforts or as requirements for borehole seal performance and additional scenarios for seal degradation are defined. In the sections that follow, results from performance and design evaluations are presented. Collectively, the conclusions reached from these results form the borehole sealing strategy.

2.1 Borehole Performance Goals

In previous studies (Fernandez et al., 1987), the regulations for borehole-seal performance (10 CFR 60.134) require that "boreholes shall be designed so that following closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives." The position adopted was that the restriction of vertical flow through the boreholes to only 1 percent of the potential for vertical flow through the rock mass satisfies this requirement. For both boreholes and rock mass, the effective hydraulic gradient was assumed to be 1 for the condition of vertical infiltration under atmospheric pressure. Considering the area within the potential repository perimeter, the potential vertical flux through the rock mass was the effective hydraulic conductivity of rock units between the potential repository and the water table times the floor area of the potential repository drifts, or more conservatively, the total area within the potential repository. The potential flow through boreholes was the sum of the cross-sectional areas of the boreholes within the potential repository area times the effective hydraulic conductivity of the seal material (including the effect of the seal/host rock interface). Considering a range of rock mass hydraulic conductivities, selecting a low value of rock mass conductivity results in a low required hydraulic conductivity for the seal material.

The current strategy recognizes that groundwater flow to the accessible environment below the potential repository is the main concern in sealing boreholes. But, additional concerns have evolved regarding the potential for preferential flow of gaseous radionuclides due to convective airflow out of the potential repository to the ground surface. The performance of seals might degrade due to adverse loading and therefore not meet the basic hydrologic and airflow performance objectives. These concerns have evolved from a literature review of previous performance testing of potential repository seals, which is a basic objective of the current design investigations; from technical issues raised by the U.S. Nuclear Regulatory Commission (NRC); and from the need to provide additional seal design requirements for backfill to augment the basic isolation characteristics of the unsaturated zone at Yucca Mountain. These concerns require sealing from the potential repository horizon to the ground surface, within the potential repository, or immediately outside the potential repository area. The performance goal adopted restricts airflow through the borehole seals to 1 percent of the total flow through the rock.

2.2 Performance Scenarios

In this section, performance scenarios for borehole seals are developed for conditions where the performance of the potential repository could be affected. This list is considered comprehensive. The performance scenarios consider flow mechanisms for air and water and how such flow would be affected by (1) geologic and stratigraphic considerations and (2) the surface-based exploratory borehole system.

Volcanic rocks are the predominant rock type at Yucca Mountain. They are typically ash flow in origin, but ash fall, bedded, and reworked tuffs are also present. Most tuffs are high-silica rhyolites, but the large-volume ash-flow cooling units are compositionally zoned, grading upward from rhyolite to quartz latite in the upper part of the sequence (Broxton et al., 1987). Also, the units are quite variable in degree of welding, alteration, and zeolitization. Tuff units above the water table are commonly devitrified or are still vitric, with the exception of the Pah Canyon Member as observed in borehole USW G-2 (Bish et al., 1982).

The sequence of tuff units at Yucca Mountain include the Paintbrush tuff, the tuffaceous beds of the Calico Hills, and other sequences of ash-flow tuffs and intercalated lavas (Figure 2-1). These tuffs are quite variable in the degree of welding and their alteration. The fractured welded tuffs exhibit higher permeability than the less fractured nonwelded tuffs. Permeability contrasts (high permeability in welded tuffs to low permeability in nonwelded tuffs) exist at contact zones. The tuffs of primary interest from a sealing perspective are the Paintbrush tuff and the tuffaceous beds of the Calico Hills. The Paintbrush tuff is comprised of the Tiva Canyon Member, the Paintbrush nonwelded tuff (i.e., the Yucca Mountain and Pah Canyon Members), and the Topopah Spring Member. Most of the bedrock outcropping at the surface consists of welded ash-flow tuffs of the Tiva Canyon Member. Along the western slope of Yucca Crest, the nonwelded and bedded tuffs of the Paintbrush tuff and the portions of the Topopah Spring Member are exposed in Solitario Canyon.

A wide variety of boreholes have been developed and drilled as part of the surface-based program. The exploratory borehole system, in terms of spatial location, borehole configuration,

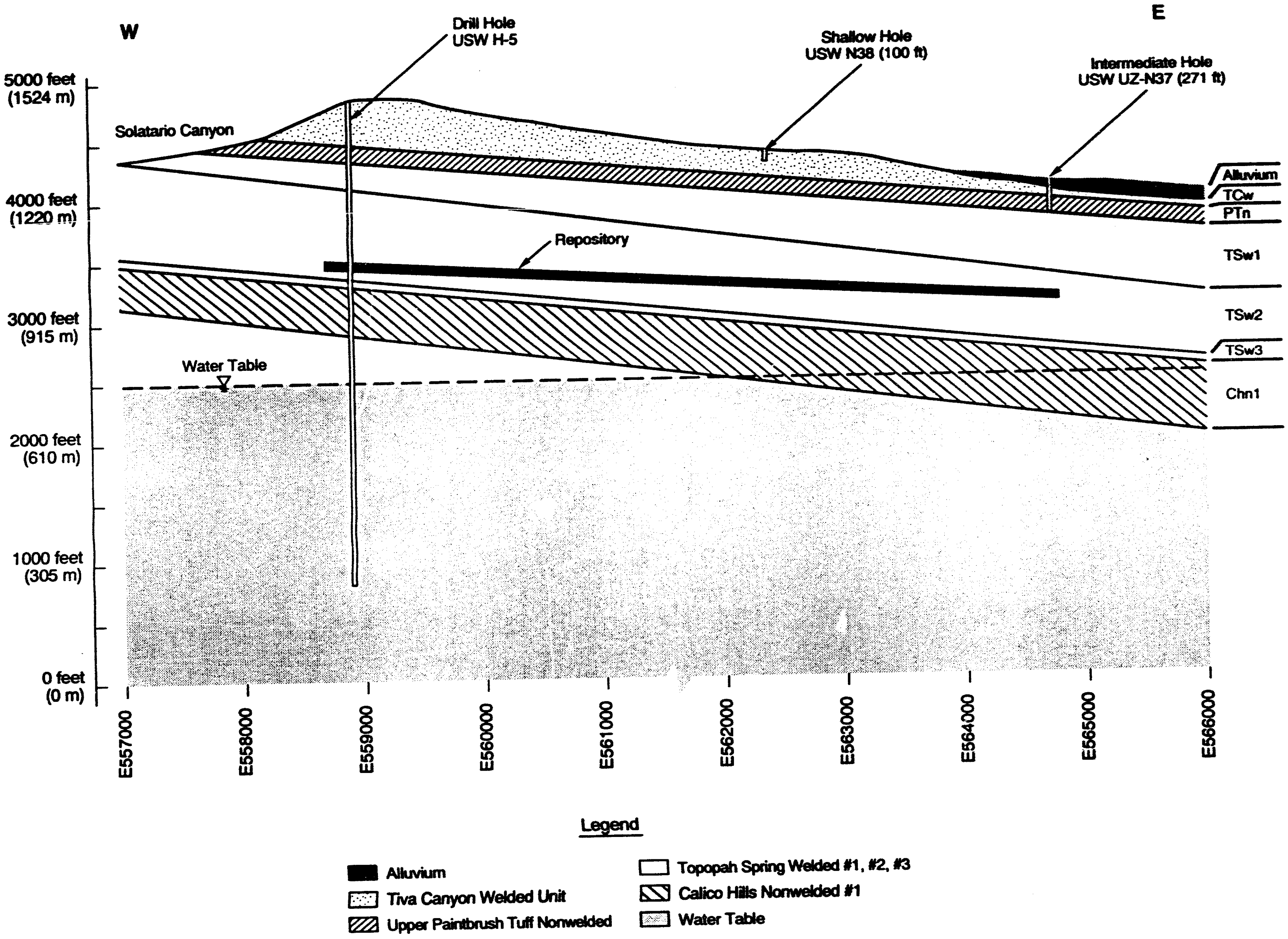


Figure 2-1
Typical Boreholes at Yucca Mountain

and purpose, is described in detail in Chapter 3.0. Also Chapter 3.0 describes the in situ state of stress, borehole conditions, and drilling methods. The important aspects for developing a seal strategy include the location within or away from the potential repository perimeter and the depth to which boreholes penetrate, as illustrated in Figure 2-1. There are approximately 191 existing and 322 proposed boreholes within the restricted area[1] varying in depth from 5 to 6,000 ft.

2.2.1 Water Flow

Two scenarios exist for water flow to occur towards or away from the potential repository. These water-flow scenarios could affect the significance of boreholes within and near the potential repository boundary and include the following:

- Inundation of a potential repository drift under unanticipated conditions, resulting in lateral spreading from the edge of the potential repository (Figure 2-2)
- Flooding events near alluvial recharge areas resulting in a saturation front moving downward, potential perching of water, and potential enhancement of flooding at the Tiva Canyon contact (Figure 2-3).

Figure 2-4 shows several existing and proposed boreholes within and near the edge of the potential repository that could be affected by water flow.

For a drift inundated with water, a saturated flow plume would develop downward to the groundwater table. A deep borehole (i.e., UE-25a #7) intersected by such a plume represents a preferential pathway for the flow of water to the accessible environment. While several low-angled fracture sets exist, the fracture systems in the welded tuff are dominantly vertical, and only a small tendency (MacDougall et al., 1987) for lateral flow from the potential repository horizon exists.

Surface flooding and the development of perched water could compromise the ability of the geologic potential repository to meet performance objectives following closure. The alluvium could become saturated and recharge the borehole, resulting in perched water. The potential for flooding at borehole locations depends on the size of the drainage basin, topographic features of the draining basin, stream characteristics, and the presence of alluvium that could recharge the borehole. Existing and proposed boreholes within or near the potential repository periphery could be subject to flooding. With several exceptions, the proposed boreholes are to be located outside of flood-prone areas and are less subject to flooding.

---

[1] 10 CFR 60.2 defines the restricted area as "any areas access to which is controlled by the licensee for the purpose of protection of groundwater."

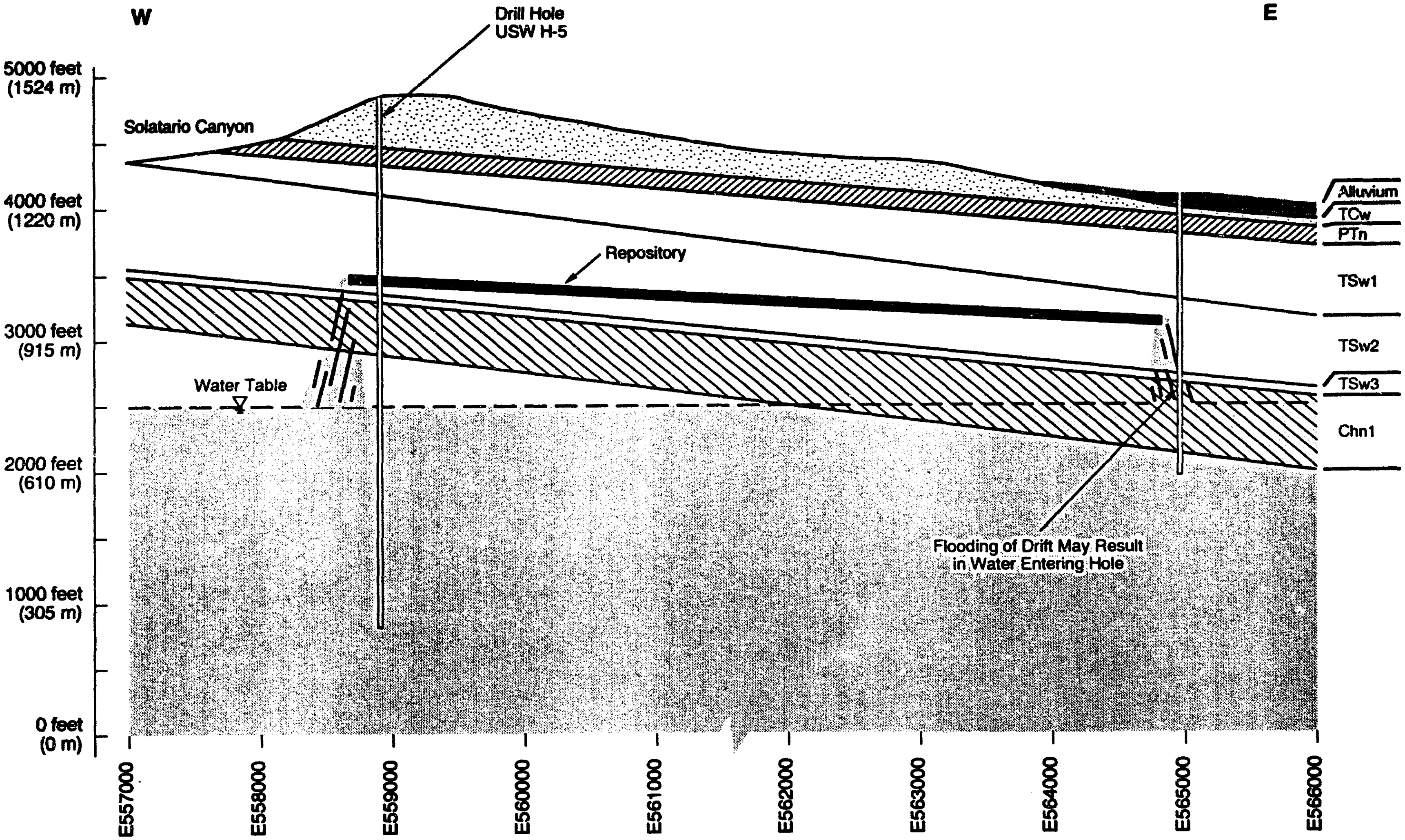


Figure 2-2
Hypothetical Water Flow from the Perimeter Drift

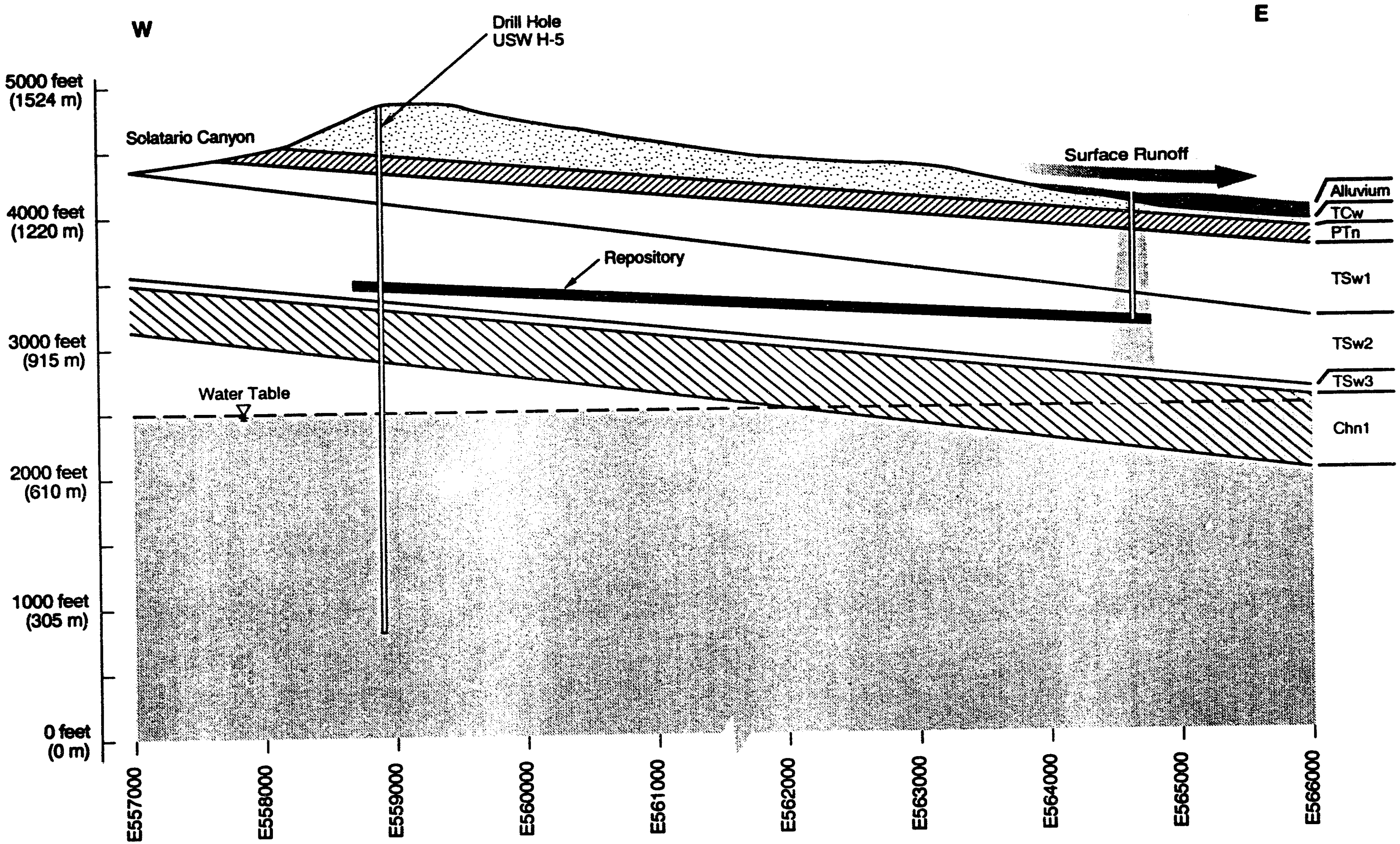


Figure 2-3
Surface-Water Infiltration Through a Borehole

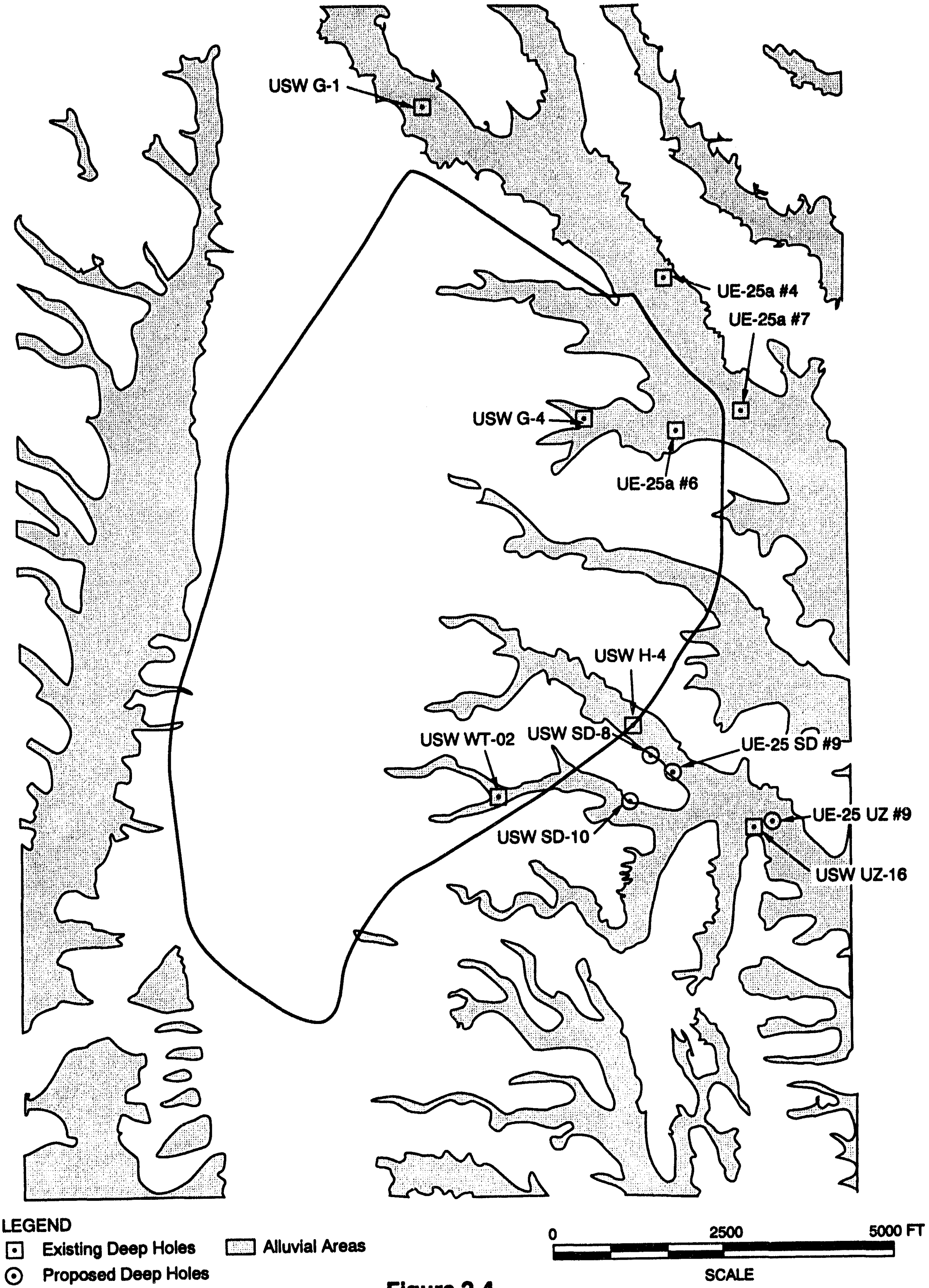


Figure 2-4
Existing and Proposed Deep Holes in Flood-Prone Areas

2.2.2 Airflow

After radioactive waste is emplaced in the potential repository, convective air transport develops through shafts, ramps, and boreholes accessing the potential repository. Convective airflow also develops through the rock and other geologic features. As flow is drawn upwards from cooler regions surrounding the potential repository, lateral spreading can occur (Figure 2-5). The lateral spreading depends upon advection or airflow and dispersion that in turn depends on molecular diffusion and dispersivity. For boreholes near the edge of the potential repository, flow upward to the atmosphere could occur (depending upon the depth of the borehole) through rock and then through backfill.

Airflow may also be affected by contrast in permeabilities that could force air to migrate laterally. The Paintbrush nonwelded tuff formation possesses fewer fractures and lower conductivity than welded, fractured tuff below. Air could flow laterally along this contact and exit in Solitario Canyon. Boreholes to the west of the potential repository could be affected by this lateral migration. To the east of the potential repository, the convective cell formation would be contained in the welded unit until a cooler region is reached and air is drawn back towards the potential repository.

2.3 Spatial Classification of Boreholes

The consideration of regulatory criteria for preferred pathways and the water and flow scenarios suggest that boreholes could be categorized according to the potential for convective airflow (inside versus outside the potential repository), potential for flooding, and borehole depth. These established criteria are as follows:

- Plan Location—Airflow—The borehole is located within or immediately outside the potential repository periphery. Boreholes within the extended boundary of the potential repository[2] are subject to convective airflow. A value of 1 is assigned for boreholes outside the extended boundary of the potential repository, while a value of 2 is assigned for holes within the extended boundary of the potential repository.
- Plan Location—Water Flow—The location of the borehole with respect to alluvial areas (Figure 2-4). A value of 1 is assigned for boreholes subject to flooding, while a value of 0 is assigned for unflooded holes.
- Depth[3]—Airflow and Water Flow—The depth of the borehole determines whether airflow occurs predominantly through rock and then through the borehole or through just the borehole and associated backfill and seals. For deep boreholes, such as

---

[2] The extended boundary of the potential repository includes boreholes just outside the potential repository that might be subject to advection/dispersion.

[3] Depth affects temperature for sealing locations near the potential repository horizon. The temperature factor presented above considers temperature relative to the potential repository in plan while the depth factor considers temperature in elevation.

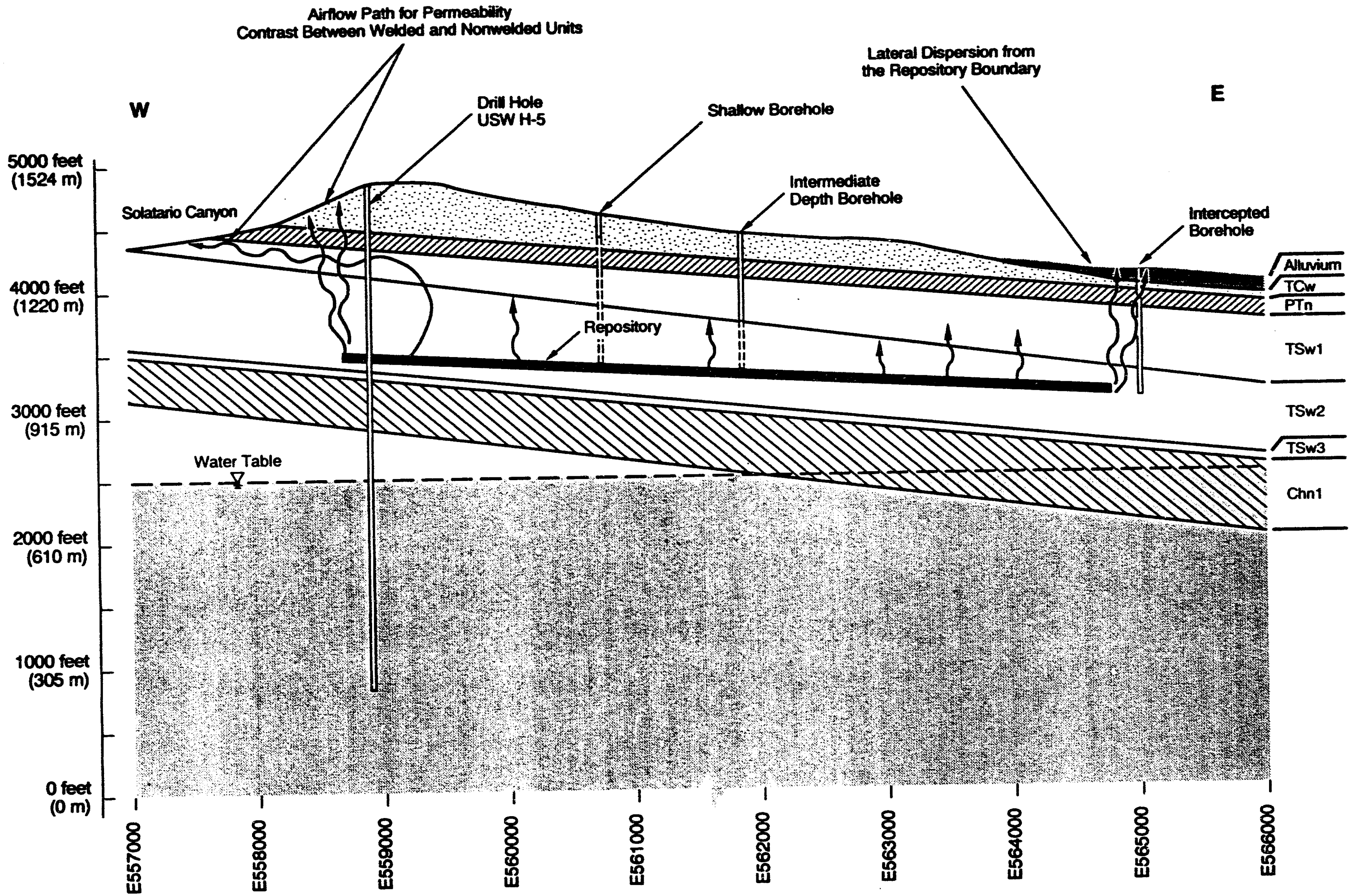


Figure 2-5
Lateral Dispersion from the Potential Repository

USW H-5, a preferential pathway could exist from the potential repository horizon to the groundwater table. A value of 1 is assigned for shallow boreholes terminating in the Tiva Canyon member. A value of 2 is assigned for boreholes terminating in the Paintbrush nonwelded tuff. A value of 3 is assigned for holes terminating above the potential repository. For holes penetrating the potential repository, a value of 4 is assigned.

Tables 2-1 and 2-2 present a categorization based upon the above criteria for properties of boreholes. A lower rank (2) suggests little significance regarding the criteria, while a higher ranking (4 through 7) suggests potentially greater significance. Figure 2-6 presents a schematic of borehole categories. In determining sealing requirements, the following observations are made:

- The water-flow enhancement for deep boreholes under perched water conditions is a far more significant condition than for shallow boreholes, since flow is proportional to the standing water columns[4] within the borehole.
- The airflow through deep boreholes penetrating the potential repository is far more significant than for shallow boreholes, since airflow through a hole is resisted principally by flow through the web of rock below the borehole. Shallow boreholes not penetrating the Tiva Canyon Member are inconsequential and need not be sealed.
- Stratigraphic contacts may direct perched water to travel laterally primarily to the east of the potential repository. A seal placed at the stratigraphic contact reduces the potential for the borehole becoming a preferential pathway.

For deep boreholes outside the potential repository perimeter, sealing is not necessary in the upper zone, while sealing could be required in the lower zone extending to the east of the potential repository. Away from the potential repository, the upper seal zone is not necessary to prevent surface inundation and reduce contaminated airflow. This is because the water plume from perched water does not intersect the potential repository, and air would be drawn into the ground in cooler regions. Yet the lower seal may be required if perched water occurs on contact zones and moves laterally to the east. This water could become a preferential pathway through deep boreholes.

The above evaluations establish the need for sealing above and below the potential repository. The upper and lower seal locations discussed require further detailed characterization (borehole wall condition, in situ state of stress, and temperature). The following section discusses borehole

---

[4] The evaluation assumes a worst-case scenario that a standing water column develops within the borehole. The development of a standing water column depends on the amount of water recharged to the borehole and the amount dissipated to surrounding formations.

Table 2-1
Categorization of Existing Boreholes Within the Extended Boundary

Borehole ID	Borehole Length (m)	Plan Location—Airflow[a]	Plan Location—Water Flow[b]	Depth[c]	Borehole Classification (Summation)	Notes
USW UZ-N33	22.9	1		1	2	Shallow boreholes outside potential repository boundary
UE-25 UZN #97	18.3	1		1	2	
US-25 SEISMIC #1	16.2	1		1	2	
USW UZ-N34	25.6	1		1	2	
USW UZ-N65	15.2	1		1	2	
USW UZ-N70	10.7	1		1	2	
UE-25 UZN #30	10.7	1		1	2	
UE-25 UZN #28	7.9	1		1	2	
UE-25 UZN #29	10.7	1		1	2	
USW UZ-N94	9.1	2		1	3	Shallow boreholes within potential repository
USW UZ-N93	12.2	2		1	3	
USW UZ-N96	10.7	2		1	3	
USW UZ-N72	9.1	2		1	3	
USW UZ-N52	7.6	2		1	3	
USW UZ-N50	6.1	2		1	3	
USW UZ-N73	9.1	2		1	3	
USW UZ-N49	11.0	2		1	3	
USW UZ-N74	11.3	2		1	3	
USW UZ-N75	11.3	2		1	3	
USW UZ-N71	15.8	2		1	3	
USW UZ-N40	10.7	2		1	3	
USW UZ-08	17.4	2		1	3	
USW UZ-N24	22.9	2		1	3	
USW UZ-N76	12.2	2		1	3	
USW UZ-N95	6.1	2		1	3	
USW UZ-N38	28.7	2		1	3	
UE-25 UZN #20	12.5	2		1	3	
UE-25 UZN #23	10.7	2		1	3	
USW UZ-N54	74.6	1		2	3	Intermediate depth boreholes outside potential repository boundary
USW UZ-N55	77.8	1		2	3	
USW UZ-N66	15.2	1		2	3	
UE-25 UZN #18	18.6	1	1	1	3	
USW UZ-N53	71.5	1		2	3	
USW UZ-N45	13.7	2	1	1	4	Shallow boreholes within potential repository subject to flooding
UE-25 UZN #21	12.8	2	1	1	4	
USW UZ-N64	18.3	2	1	1	4	
USW UZ-N98	22.9	2	1	1	4	
UE-25 UZN #22	29.0	2	1	1	4	
USW UZ-07	63.1	2	1	1	4	
USW UZ-6s	158.2	2		2	4	
USW UZ-N25	18.0	2	1	1	4	
USW UZ-N43	13.7	2	1	1	4	
USW UZ-N26	10.7	2	1	1	4	
USW UZ-N48	10.7	2	1	1	4	
USW UZ-N51	6.1	2	1	1	4	
USW UZ-N44	11.0	2	1	1	4	
UE-25 UZN #19	12.2	2	1	1	4	
USW UZ-N42	12.2	2	1	1	4	
USW UZ-N41	11.3	2	1	1	4	

Refer to footnotes at end of table.

Table 2-1 *(Continued)*
Categorization of Existing Boreholes Within the Extended Boundary

Borehole ID	Borehole Length (m)	Plan Location—Airflow[a]	Plan Location—Water Flow[b]	Depth[c]	Borehole Classification (Summation)	Notes
UE-25a #4	152.4	1	1	3	5	Deep boreholes within or outside potential repository that may or may not be subject to flooding; deep boreholes outside potential repository and subject to flooding
UE-25a #5	148.4	1	1	3	5	
USW H-3	1219.1	1		4	5	
USW H-1	1828.7	1		4	5	
USW UZ-N37	82.7	2		3	5	
UE-25a #6	152.4	2		3	5	
UE-25a #7	305.4	1	1	3	5	
USW G-1	1828.7	1	1	4	6	Deep horizon boreholes that may or may not be subject to flooding
USW UZ-16	506.9	1	1	4	6	
USW H-5	1219.1	2		4	6	
USW UZ-6	575.1	2		4	6	
USW H-4	1219.1	2	1	4	7	Deep horizon borehole within potential repository and subject to flooding
USW G-4	915.3	2	1	4	7	
USW WT-2	627.9	2	1	4	7	

[a] 1—Borehole outside of potential repository boundary but within extended boundary; 2—Borehole inside of potential repository boundary.

[b] 1—Borehole potentially located in probable maximum flood (PMF) zone.

[c] 1—Borehole terminates in Tiva Canyon Member; 2—Borehole terminates in the Paintbrush nonwelded tuff; 3—Borehole terminates in Topopah Spring Member above the potential repository; 4—Borehole penetrates the potential repository horizon.

wall conditions. Characterization of these properties at the potential repository horizon illustrates the potential difficulties that might be encountered in the high-temperature environment and how sealing away from this zone reduces undesirable temperature effects.

2.4 Borehole Wall Conditions and Preferred Sealing Locations

Because of the variations in structural geology (see Section 3.2.2 and Appendix C), it was anticipated that the condition of the borehole wall would vary, depending on the degree of welding, the lithophysae content, the extent of clay and zeolitic mineral development, and the degree of fracturing in response to borehole drilling. This section summarizes the condition of the borehole wall to answer the following question: Are there unique features that would indicate preferred sealing locations above and below the potential repository?

Selected borehole video logs were reviewed as a direct means of assessing the wall condition. Boreholes were selected based on their location and the availability of video-logging. Nine locations (see Figure 2-7) were selected over a broad area to capture a range of subsurface geologic conditions. Following a preliminary review of all video logs, a classification scheme was developed based on smoothness of the borehole wall, the presence of lithophysae, the degree

Table 2-2

Categorization of Proposed Boreholes Within the Extended Boundary

Borehole ID	Borehole Length (m)	Plan Location—Airflow[a]	Plan Location—Water Flow[b]	Depth[c]	Borehole Classification (Summation)	Notes
SPRS-09	1.5	1		1	2	Shallow boreholes outside potential repository boundary
SPRS-22	1.5	1		1	2	
SPRS-23	1.5	1		1	2	
SPRS-10	1.5	1		1	2	
SPRS-11	1.5	1		1	2	
SPRS-05	1.5	1		1	2	
LPRS 11	10.7	1		1	2	
LPRS 3	10.7	1		1	2	
LPRS 6	10.7	1		1	2	
LPRS 13	10.7	1		1	2	
LPRS 12	10.7	1		1	2	
SRG-5	45.7	2		1	3	Intermediate depth boreholes outside potential repository or shallower boreholes within potential repository
USW UZ-N35	30.5	2		1	3	
SPRS-19	1.5	1		2	3	
SPRS-04	1.5	2		1	3	
SPRS-03	1.5	2		1	3	
SPRS-02	1.5	2		1	3	
SPRS-08	1.5	2		1	3	
SPRS-12	1.5	2		1	3	
SPRS-13	1.5	2		1	3	
SPRS-07	1.5	2		1	3	
SPRS-16	1.5	1	1	1	3	
LPRS 2	10.7	2		1	3	
LPRS 10	10.7	1		2	3	
LPRS 4	10.7	2		1	3	
LPRS 5	10.7	2		1	3	
LPRS 9	10.7	1		2	3	
LPRS 8	10.7	1	1	1	3	
NRG-5	304.8	1		3	4	Shallow boreholes within potential repository subject to flooding or intermediate in depth
USW UZ-N31	54.9	2		2	4	
USW UZ-N32	54.9	2		2	4	
SPRS-14	1.5	2	1	1	4	
USW SD-11	609.6	1		4	5	Deeper boreholes within or outside potential repository not subject to flooding
USW SD-12	600.4	1		4	5	
USW SD-7	710.1	1		4	5	
USW SD-1	640.0	1		4	5	
UE-25 SD#9	606.5	1	1	4	6	Deep boreholes outside potential repository boundary and subject to flooding
UE-25 UZ#9A	585.2	1	1	4	6	
USW SD-10	624.8	1	1	4	6	
USW SD-8	609.6	1	1	4	6	
UE-25 UZ#9B	582.1	1	1	4	6	
UE-25 UZ#9	585.2	1	1	4	6	

Refer to footnotes at end of table.

Table 2-2 *(Continued)*

Categorization of Proposed Boreholes Within the Extended Boundary

Borehole ID	Borehole Length (m)	Plan Location—Airflow[a]	Plan Location—Water Flow[b]	Depth	Borehole Classification (Summation)	Notes
USW UZ-7A	480.0	2	4	1	7	Deep boreholes within potential repository boundary and subject to flooding

[a] 1—Borehole outside of potential repository boundary but within extended boundary; 2—Borehole inside of potential repository boundary.

[b] 1—Borehole potentially located in the probable maximum flood (PMF) zone.

[c] 1—Borehole terminates in Tiva Canyon Member; 2—Borehole terminates in the Paintbrush nonwelded tuff; 3—Borehole terminates in Topopah Spring Member above the potential repository; 4—Borehole penetrates the potential repository horizon.

of fracturing, and hole enlargement. The qualitative criteria for the classification scheme are presented in Table 2-3.

Table 2-3

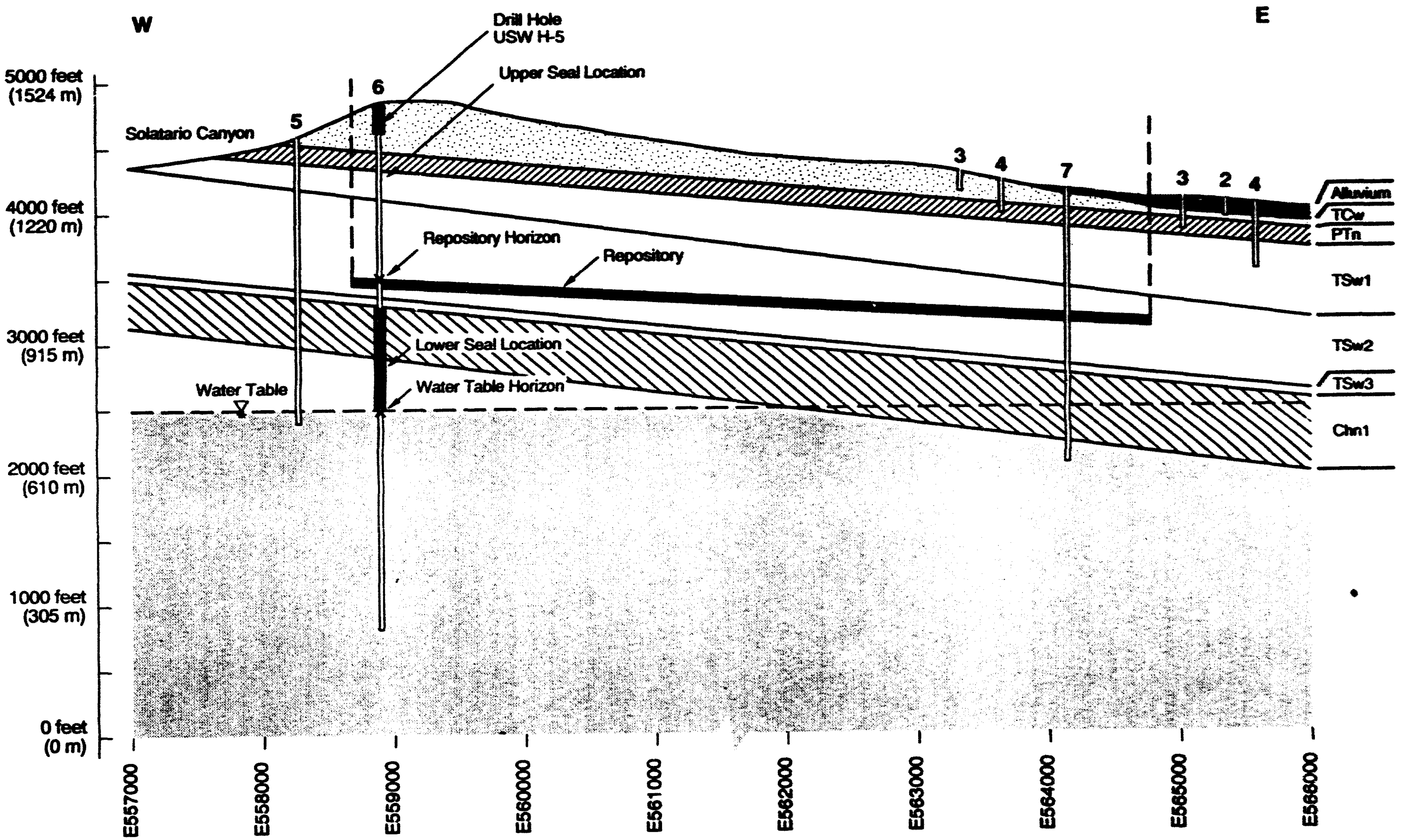
Criteria for Categorizing Borehole Wall Condition[a]

Category	Criteria
C1	Excellent, typically symmetrical hole with a smooth surface; no hole enlargement; no to few lithophysae; no pronounced fractures; minor "pluckouts."
C2	Good, typically symmetrical hole with a smooth surface; hole enlargement small or intermediate[b] but infrequent; no to few fractures; uniform lithophysae can be present.
C3	Poor—typically a rough surface; hole enlargement is intermediate and frequent, but it is possible for hole to be symmetrical; lithophysae can be prevalent, large, and nonuniformly distributed; fractures are frequent.
C4	Extremely poor, typically a nonsymmetrical hole having an extremely irregular surface; hole enlargement is large; large lithophysae can be present; fractures are frequent and pronounced.

[a] It is not necessary for the borehole wall to have all the features listed. For example, it is possible for numerous lithophysae to be present with no evident fractures.

[b] Intermediate hole enlargement is equivalent to up to one-half of the hole diameter. Large hole enlargement is equivalent to one-half or greater than the hole diameter. This logic also applies to the size of the lithophysae.

Following this initial step, each of the borehole video logs were reviewed in detail, and sections of the borehole were placed in the C1, C2, C3, or C4 categories. Additionally, these categories were correlated with a simplified stratigraphic log. More detailed information on the results of



Borehole Classification

2	Shallow Holes Outside Repository
3	Intermediate Depth Holes Outside Repository, or Shallow Holes Subject to Flooding, or Shallow Hole Inside Respository
4	Shallow Holes Subject to Flooding or Intermediate Holes within Repository
5	Deep Boreholes outside Repository
6	Deep Borehole within Repository, or Deep Borehole Outside Repository Subject to Flooding
7	Deep Boreholes within Repository Subject to Flooding

Legend

■	Seal Locations
x	Thermal Analysis Study Locations

Figure 2-6
Borehole Categories Schematic

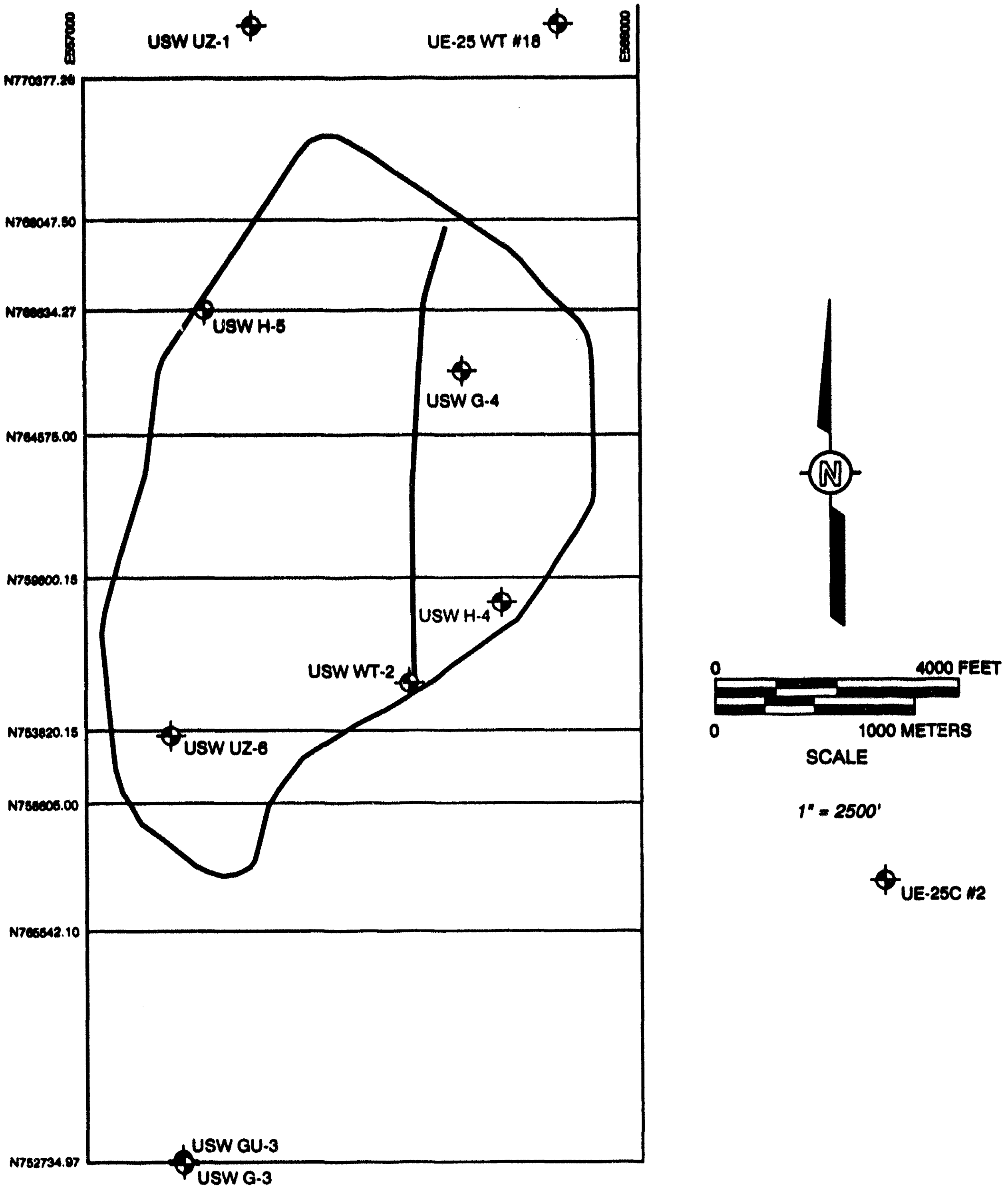


Figure 2-7
Review of Selected Boreholes for Borehole Wall Condition

video-logging is presented in Chapter 3.0 and in the correlations in Figures D-1 through D-10 in Appendix D. Additionally, Tables D-1 through D-10 in Appendix D contain a summary of the percentage of each category for each stratigraphic unit for which video was available. Based upon these categories, the generalized hole conditions were found to be as follows:

- A high percentage of Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and Topopah Spring Units.
- Category C1 occurs in the Paintbrush nonwelded tuff.
- Categories C1 and C2 occur in the upper portion of Topopah Spring Unit.
- Categories C1 and C2 occur in the nonwelded vitric and zeolitic portions of the Calico Hills Unit.

This evaluation suggests placement of key seals in the Paintbrush nonwelded tuffs, in the upper portion of the Topopah Spring Unit, and in the nonwelded vitric and zeolitic portions of the Calico Hills Unit. While borehole classifications show more favorable conditions in the nonwelded tuffs that are relatively free of fractures, the assessed rock-mass strength for nonwelded tuff is somewhat lower, due to the contrast in unconfined compressive strength between the welded and nonwelded tuffs (150 versus 15 MPa). The rock-mass strength is important, because higher strength gives greater confidence to the mechanical stability of the boreholes. Nevertheless, the varying conditions suggest that sealing locations with higher rock-mass quality in welded and nonwelded units that are not intensely fractured can be selected.

Chapter 3.0 presents anticipated in situ and thermal stress conditions at depth. The in situ stresses range from 1 to 2 MPa at the upper seal location above the potential repository to 10 to 11 MPa at the lower sealing location below the potential repository. At the potential repository horizon, the results show horizontal compression due to radioactive heat generation of approximately 4 to 16 MPa and slight vertical decompression after about 100 years. Radioactive waste heat generation sustains the horizontal compression for several hundred years. After this time, temperatures decline over time (500 to 10,000 years). At the upper seal zone, the rock mass experiences a horizontal decompression of approximately 1 to 2 MPa and slight vertical compression. At this zone, the results show a reversal in thermally induced stress from tension to compression from 300 to 1,000 years. After this time, temperatures decline gradually over time (2,000 to 10,000 years). Borehole seals should be placed in regions with limited thermal stress changes.

Other deep boreholes within the potential repository or near to the potential repository boundary show similar trends in the development of far-field thermal stress. The thermal stress analysis predicts a smaller rise in temperature and thermally induced stresses at the potential repository boundary or just outside the potential repository boundary. At the potential repository horizon, the thermally induced stresses for USW H-5 shows a slightly lower horizontal compression after about 100 years than that shown for USW SD-4, as this borehole locates at the western edge of the potential repository. A slight vertical decompression occurs during this period. At the upper contact zone, the analysis shows similar trends as shown for USW SD-4. For boreholes at some distance (UE-25 WT-15, USW G-2, and USW WT-1), the analysis predicts almost no thermally induced effects.

These seal-placement considerations for boreholes within or near the potential repository boundary, in Solitario Canyon, and east of the potential repository are reflected in Figure 2-8. This figure is a typical borehole and casing configuration. These borehole cementitious seal locations reflect the conclusion that high-quality seals should be located away from the high-temperature environments and in zones with a favorable borehole classification. In zones where placement occurs in fractures, a grout bulb could be provided as a redundant design feature.

A current borehole sealing strategy places a porous backfill below denser cementitious seals in which the contrast in matrix potential is at least equivalent or greater than the contrast in matrix potential between the welded and nonwelded host rocks. Further the porous backfill would be engineered to provide a capillary barrier with the host formation to restrict potential flow into the borehole. While no specific analyses are presented, it is likely that a porous backfill with specified porosity, grain-size distribution, and hydrologic properties can be selected to satisfy these dual objectives.

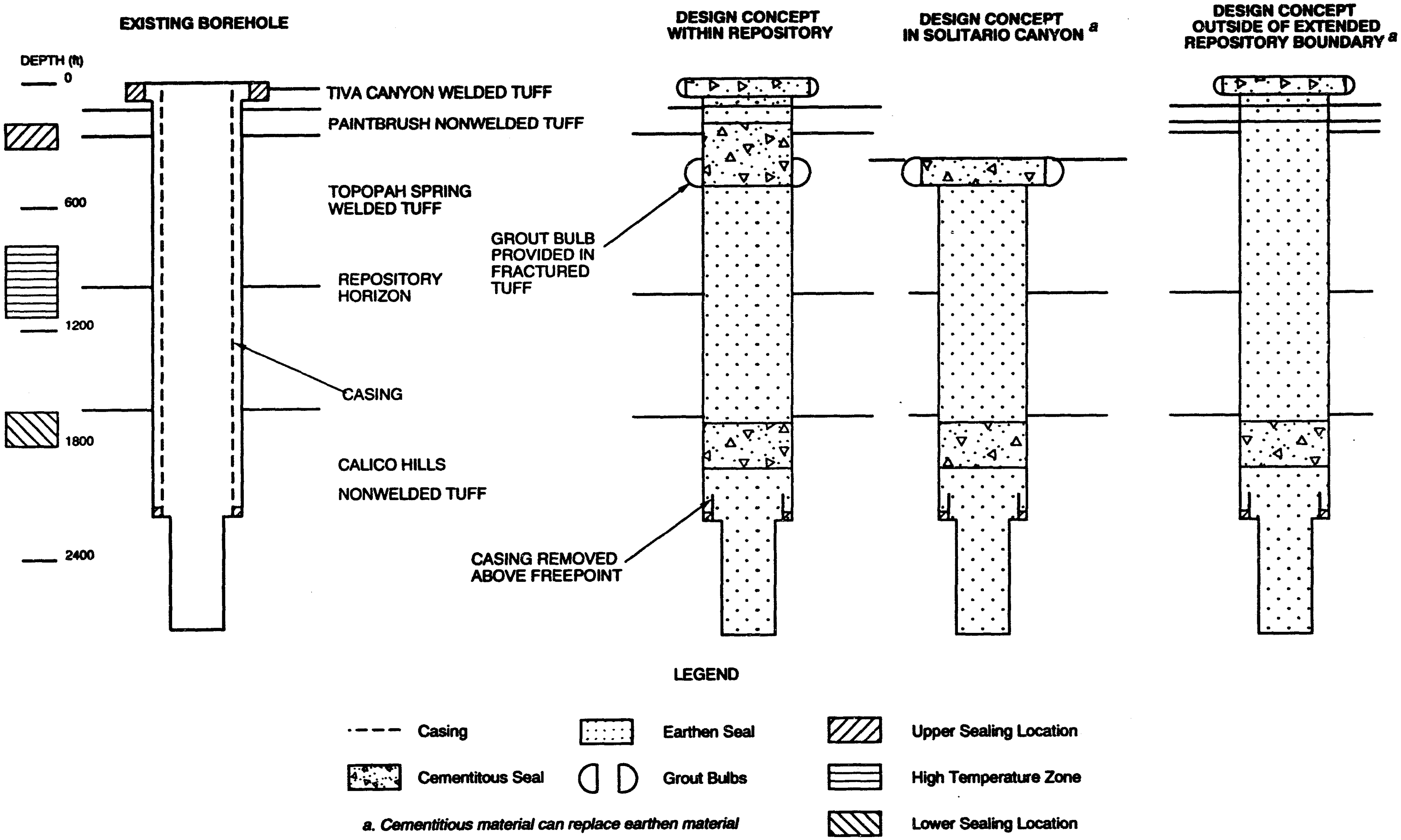
2.5 How to Seal

Four areas to be considered in addressing the question of how to seal are: interface and structural considerations, seal material selection, grout bulb effectiveness, and available technologies to seal exploratory boreholes. These are discussed individually below.

2.5.1 Interface and Structural Considerations

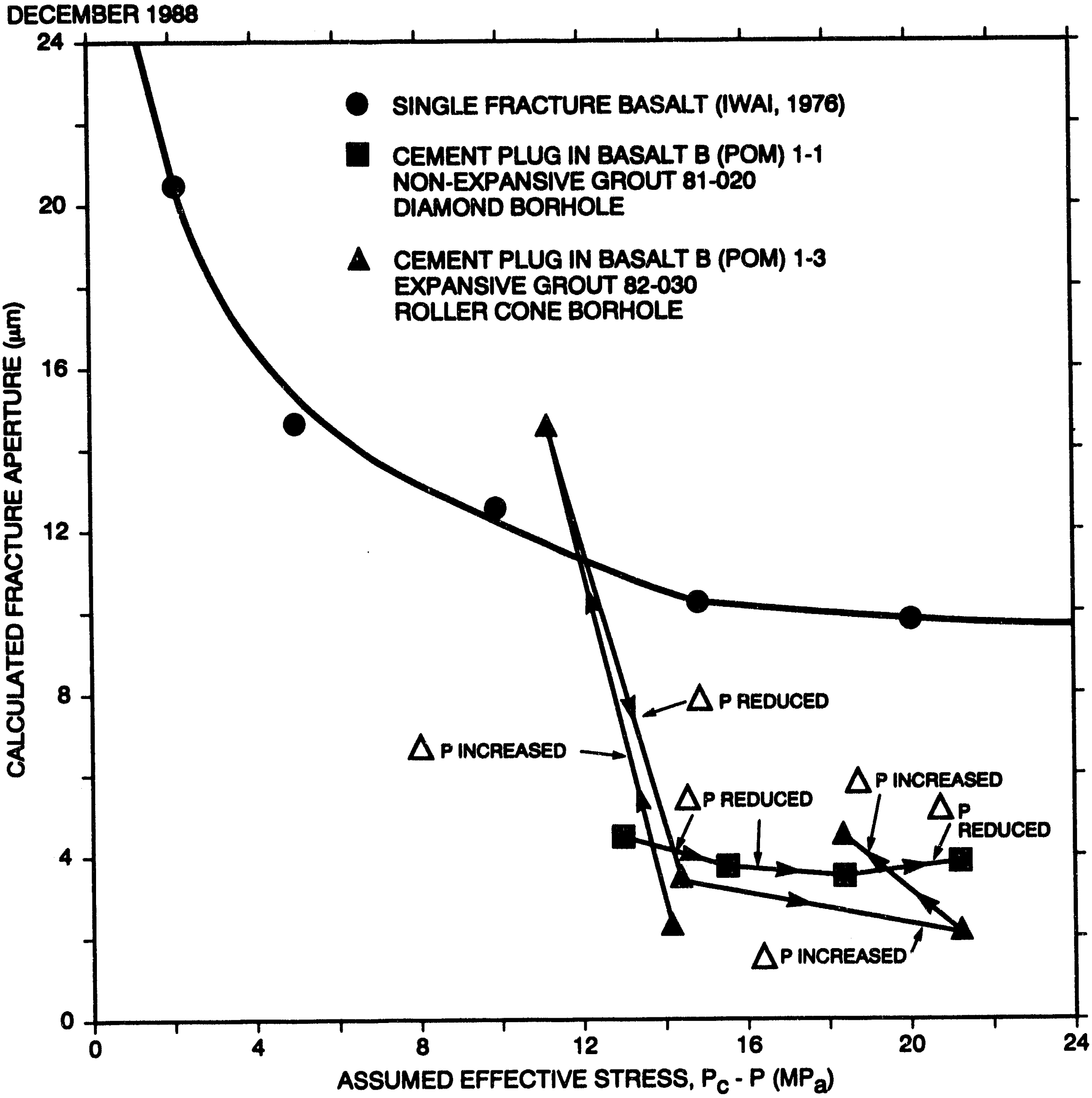
Bench-scale tests done by Terra Tek showed the importance of interface-zone permeability (DOE, 1988). For sealed boreholes, flow occurs either through the seal matrix or through the interface zone. These tests showed that the "effective plug permeability" for flow through the interface zone to be 1 to 2 orders of magnitude greater than the permeability of the plug material. This result supports the theory that the interface zone behaves like a fracture, in that at low effective stress levels, the interface opens and exhibits high conductivity. At higher stress levels, the interface closes and exhibits a much lower conductivity that is independent of effective stress level (Figure 2-9).

Daemen et al. (1983) reported on an experiment on a borehole seal in welded tuff. A rock specimen 31 cm long by 15 cm in diameter was installed in a permeameter and loaded axially and laterally with confining stresses ranging from 7 to 20 MPa and with axial stresses ranging from 8 to 23 MPa. A coaxial hole (2.5 cm in diameter) was then drilled from each end of the specimen, leaving a rock bridge in the center. A differential pressure was applied, and flow measurements were performed. Following these initial flow measurements, the rock bridge was



Note: Nonwelded Tuffs tend to be low in permeability and rock mass strength

Figure 2-8
Design Concepts for Sealing Exploratory Boreholes



Δ P BOREHOLE PRESSURE

P_C CONFINING PRESSURE

Figure 2-9

Comparison of Borehole Plug Test with Experimental Data for Fractured Basalt. Data for Plug Test from DOE (1988)

drilled out and replaced with a cement plug. The plug was tested under a similar set of total stress and pore pressure conditions. Daemen et al. expressed the conductivity of the plug as an equivalent conductivity for flow through the plug and interface zone. The reported values ranged from 10^{-13} to 10^{-10} cm/s. Assuming flow occurs through a smoothwall crack at the plug perimeter, an equivalent smoothwall fracture of 0.5 to 5 μm is calculated, which is similar to the calculated value from the Terra-Tek test in basalt.

While scale effects may exist in the application of these results to the emplacement of larger-scale seals in tuff, they prove the significance of the interface zone in airflow and hydrologic performance. As discussed subsequently in Chapter 5.0, the airflow and hydrologic design requirements can be expressed in terms of an equivalent smooth-wall aperture and the seal-matrix conductivity.

The interpretations made of the Terra-Tek test suggest a coupling between structural interface performance and flow performance. There exists a need to reduce or eliminate seal degradation that might occur due to rock/seal structural interaction effects. In selecting seal materials, consideration is given in Chapter 5.0 to structural loading occurring prior to sealing, during sealing, and after decommissioning of the potential repository.

The scenarios considered for the seal design concerns are as follows:

- Open borehole at ambient temperature prior to sealing
- Sealed borehole with backfill
- Initial static, thermal, and dynamic (dry backfill) loading
- Postclosure static, thermal, and dynamic loading.

Seal locations, material properties, and placement methods should be selected that provide adequate strength and deformation serviceability for sealing components to resist various combinations of loads, including:

- Dead loads from overlying seal materials

- Thermal loads, due the hydration of the cement and radioactive waste generation

- Differential volumetric expansion, due to placement methods, cement hydration, temperature changes, and differences in selected material properties

- Liquefaction and consolidation of backfill, due to seismic events.

- A backfill that has a specified porosity and grain-size distribution, which will provide a capillary barrier to unsaturated flow occurring downward or laterally at stratigraphic contacts.

In Chapter 5.0, Appendices I and J, a series of structural design calculations are presented for various combinations of leads. These calculations suggest that seals should be comprised of a low hydration cement placed under a slight pressure at a low placement temperature and that they should be at least 10 m long to resist backfill loads.

2.5.2 Seal Material Evaluations

The YMP potential repository sealing program at SNL concentrates on selected cementitious and earthen-based materials for sealing applications (Fernandez et al., 1987; Hinkebein and Fernandez, 1989). Cementitious materials are the primary materials that have been considered for fracture grouting and borehole seal emplacement. The use of smectite clays (bentonite) is also being considered, because it is a ubiquitous alteration product at Yucca Mountain, although it occurs in small quantities (Bish, 1988). There are two zones of abundant smectite: one is at the top of the vitric, nonwelded base of the Tiva Canyon and contains 7 to 35 percent smectite, and the other is at the top of the basal vitrophyre of the Topopah Spring Member and contains 5 to 45 percent smectite (Bish and Vaniman, 1985). The discussion below summarizes the logic that was used to select specific, cementitious-based grouts. Geochemical, thermomechanical, and fracture aperture considerations are also discussed.

Unlike the smectite clay, the cementitious material, including the grouts, are not indigenous to the volcanic tuffs. The SNL YMP potential repository sealing program developed cementitious material that are similar in bulk chemistry to the tuffs and contain enough reactive silica present in the mixture to react with the calcium hydroxide to form a more stable calcium-silica-hydrate (C-S-H) (Licastro et al., 1990). Laboratory analyses conducted under the SNL YMP potential repository sealing program show the instability of ettringite, an expansive agent, above approximately 100°C, but that tobermorite, a C-S-H, is present up to as high as 300°C (Scheetz and Roy, 1989). Based on these results, the strategy is to minimize the presence of ettringite and reduce the presence of calcium hydroxide by including enough silica to form a C-S-H such as tobermorite.

To gain a greater understanding of the chemical alteration of cementitious material, the computer code EQ3NR/EQ6 (Wolery, 1983) was used to simulate the geochemical alterations of three cementitious materials in the presence of water and tuff (Hinkebein and Gardiner, 1991) at temperatures ranging from 25 to 76°C. Two of these materials were variations of an ordinary portland cement (OPC)-based concrete, and one was a variation of an ettringite-rich concrete. Chemically the three concretes were described as an OPC-B concrete with a balance of silica and calcium, an OPC-C concrete that is calcium-rich, and an expansive portland cement (EPC)-S concrete that contains silica and ettringite. Hinkebein and Gardiner (1991) concluded that ettringite or excess portlandite decomposes to open the concrete structure and that excess silica reacts with hydrogarnet to tighten the concrete structure. Also, the analysis shows that OPC-B containing a balance of calcium and silica produces the least volume change. The analysis suggests the least modification to the overall structure and the resulting permeability for the OPC-B grout.

In these calculations, the C-S-H gel was modeled as 14-A tobermorite, considered a reasonable substitute for the C-S-H gel, because the thermodynamic differences between the behavior of C-S-H gel and tobermorite may be less than 1 percent (Atkinson et al., 1987). It was further assumed by Hinkebein and Gardiner (1991) in their model that thermodyanamic equilibrium between the cement and pore water was maintained. With this assumption, the degree of dissolution or precipitation predicted by the model is dependent upon the volume of water equilibrated with a given volume of cement, and is independent of reaction rates or surface areas. The equilibrium assumption is conservative in the sense that it will maximize the amount of dissolution predicted to occur in cements that contain ettringite or excess portlandite for water that contacts the cement. The information from Hinkebein and Gardiner (1991) can be applied as follows:

- The development of a C-S-H gel was preferred to development of a more thermodynamically stable (i.e., less reactive) cementitious material.
- Tobermorite could be used to approximate the behavior of a C-S-H gel.
- Geochemical analyses showed that balancing of the calcium and the silica composition of a cementitious sample results in a material undergoing the least volumetric change.
- Material containing excess ettringite and calcium resulted in the most volumetric change.
- Tobermorite was observed at temperatures as high as 300°C.

Geochemical criteria for the formation of cementitious material were developed for use in the sealing program. These criteria are presented below:

- Minimize the development of ettringite by selecting a cement that has a low sulfate content. (Ettringite is a sulfate-bearing cement phase in concrete.)
- Achieve a Ca/Si molar ratio of 0.83 or a CaO/SiO_2 mass ratio of 0.77, consistent with the composition of tobermorite, $Ca_5Si_6O_{17} \bullet 10.5H_2O$, by adding reactive silica.

The second consideration was based on a degradation model, developed by Hinkebein (1991). In his evaluation he considered thermal-mechanical, mechanical, and shrinkage concerns. The objective of the model development was to assess factors that would have a tending to "open up" the seal structure, i.e., increase the porosity, thereby increasing the permeability. General conclusions reached from his study were that high-quality cementitious sealing materials may be achievable by controlling the sealing material composition. Further, it was concluded that the amounts of gypsum, portlandite, and unreacted cement phases must be also controlled. If ductility is required in a seal, higher water-to-cement ratios and lower aggregate fractions are preferred. In this case, strength would also be reduced.

In the following sections, preliminary grout/concrete formulations are proposed. Because scoping laboratory analyses have not been performed to verify required flow characteristics, the reader is cautioned on using these formulations as final mixtures.

2.5.2.1 Borehole Seal Formulation and Placement Considerations

In this section, two cementitious formulations are presented: (1) a standard grout formulation for sealing fractures with apertures greater than 1 cm and borehole seals and (2) a standard concrete formulation for placement in the larger cross-sections of the boreholes. Formulation 84-12 (Licastro et al., 1990) was used as a starting point for the cementitious formulations. Changes were then made to the formulations to achieve the geochemical goals defined in the previous section.

Class H cement has a lower sulfate content than Type K cement and therefore will reduce the amount of ettringite formed during hydration. Class H cement is a coarser grind and thus reduces water demand for the same flow characteristics. This allows a lower cement content to achieve the same strength. The coarse grind also results in a slower rate of hydration during the first few days and therefore a lower rate of heat generation. This is particularly important in large mass pours.

Reactive silica products (silica fume, silica flour, and slag) are included to maximize the amount of C-S-H produced and reduce the free $Ca(OH)_2$ in the hardened state. The reactive silica and lower water demand of the cement results in the reduced porosity of the grout and concrete. The higher silica content is also likely to be more compatible with the high silica content of the Yucca Mountain tuffs. The compositions of recommended grout and concrete (84-12R2 and 84-12CR1) are listed in Table 2-4.

Changes in the Ca/Si ratio were made by increasing the silica flour and reducing the slag (while holding the cement and silica fume constant between 84-12 and 84-12R2). Silica fume was kept constant because of its extreme fineness. In the concrete with a lower cement content, the relative amounts of cement and reactive silica were kept constant to maintain the Ca/Si ratio at 0.77. For the Ca/Si ratio calculations, the following chemical compositions for the cement and reactive silica were used:

Material	CaO (%)	SiO_2 (%)
Class H cement	64.1	22.27
Silica fume	0.1	96.0
Silica flour		100.0
Slag	44.64	32.68

Table 2-4
Composition of Grout and Concrete Formulations

Component	84-12R2	84-12CR1
Weight percentage of total mixture		
Class H cement	18.1	12.3
Water	17.9	10.9
Silica fume	4.1	2.8
Silica flour	12.6	8.5
Slag	21.0	14.2
Silica sand (20-40 mesh)	26.0	
Concrete sand		16.4
Aggregate (3/4" MSA)		34.5
Dispersant D-65	0.3	0.4
Defoamer	0.1	0.02
	100.1	100.02
Weight in lb/ft^3		
Class H cement	23.5	17.6
Water	23.2	15.5
Silica fume	5.3	4.0
Silica flour	16.3	12.1
Slag	27.2	20.3
Silica sand	33.7	
Concrete sand		23.4
Aggregate (3/4" MSA)		49.2
Dispersant D-65	0.4	0.6
Defoamer	0.1	0.02
Total	129.7	142.72
Water/cement	0.99	0.88
Water/reactive solids	0.32	0.29
Ca/Si	0.764	0.77

In future use of these formulations, the same Ca/Si ratio can be achieved (when the actual chemical compositions of cement and reactive silica products are determined) using this technique.

The dispersant (D19, D65, or CFR-2) is in the mixture to enhance the "wetting" ability of the water in lubricating the surfaces of the soil particles. Dispersants are modified naphthalene sulphonate formaldehyde condensate, solubilized in a special carrier and containing no calcium chloride. The defoamer is in the mixture to reduce foaming of the coarse cement during the mixing process. It is a blend of proprietary ingredients and is used in very small amounts.

The grout 84-12R2 should have a flow through the standard U.S. Corps of Engineers (COE) flow cone of 12 to 15 seconds. This would enable it to be pumped into place through the standard moyno or centrifugal pumps. Minor adjustment of the water and/or dispersant in the mixture can be made to reach the required flow characteristics. The rheology of concrete is measured by the slump cone. Concrete should have a slump of 4 to 5 in. for pumping and be placed in seals where consolidation can be achieved by concrete vibrators. For inaccessible parts of a seal, the slump should be increased to about 9 to 11 in. of "flowing concrete," which can also be achieved by the addition of water and/or dispersant.

Working time for both grouts and concretes in most field applications should be about 3 hours from the start of mixing. The temperature of the mixture affects the rate of stiffening. For most applications, a mixture temperature of 65 to 75°F will reduce the problem. The addition of Plastiment at a rate of 3 oz per sack of cement will also reduce early stiffening, because of its retarding effect on hydration of cement particles during the first few hours. The grout 84-12R2 is a suitable sanded grout for filling all boreholes, both vertical and horizontal, because it can be pumped into place.

The physical properties of grout 84-12R2 should be within 10 percent of those listed in Table 26 of SAND 86-0558 (Licastro et al., 1990). For the concrete 84-12CR1, the unconfined compressive strength should be about the same (110 to 140 MPa). Static Young's Modulus for 84-12CR1 should be about 10 to 20 percent higher than the grout—about 10 to 11 GPa. The bulk density for the concrete should be about 2.18 g/cc, and the porosity should be about 6 to 8 percent.

Standard concrete mixers are suitable for mixing the 84-12CR1 concrete. The inside of the mixer should be clean, and the mixing vanes or blades should not be worn down. Because of the relatively large amount of cementitious fines in the formulation, the cement, reactive solids, and dispersant should be weighed and then blended together before introduction into the mixer. The mixer is then loaded with water, the blended cementitious material is blown into the mixer while the mixer is being rotated at maximum speed, and the sand and aggregate are loaded in the normal matter.

Mixers for the grout 84-12R2 should have a high shearing action. The size of the plug will dictate the size of the mixer. Sizes range from the small 6-ft^3 grout mixer to the large capacity MX and "Lightning" mixers. For large volume batches, the cementitious material, dispersant, and silica sand are weighed and blended together and transported to the mixing site as described above. For small-volume plugs, each material can be weighed separately and then loaded into the grout mixer.

Surfaces should be moistened just prior to the beginning of a placement. The first load dumped or pumped into a plug should be several cubic yards of a grout slurry mixture of cementitious material, dispersant, and water. This will help coat the rock surface and improve the bonding. For borehole plugs, the hole should be washed to remove any drilling mud. The grout can then be placed as described.

2.5.2.2 Pressure Grout Formulations and Placement Considerations

An additional consideration in selecting grouting material is the aperture of fractures that need to be sealed. Cementitious grouts contain cement particles that could clog the fractures, resulting in limited or no penetration into the fracture.

Sealing of fissures in rock involves the use of grouts that can be pumped into injection holes under pressures high enough to move the grout but not so high as to cause additional cracks in the rock. Recent development of microfine cements has provided a material that has 50 percent of its particles less than 4 µm, with the largest approximately 13 µm for MC-500. Microfine cement grouts have been used in sealing fine fractures at NTS, in commercial field applications, in research studies at McNary Dam, and in research studies at the COE Waterways Experiment Station. The Ca/Si mass ratio is 1.53 for MC-500 microfine cement. Studies at the Waterways Experiment Station have shown that addition of high silica fines (which would lower the ratio) cuts the strength significantly. Adjusting the Ca/Si ratio for the microfine cement pressure grouts is not recommended. Table 2-5 lists the formulations for two pressure grout formulations using the microfine cement MC-500 PG-1 and PG-2. The major difference between PG-1 and PG-2 is the water/cement ratio (higher for PG-1 to increase the fluidity). PG-1 should be used for fine fissures having apertures of about 10 to 100 µm. PG-2 should be used for fissures having apertures of 100 µm to about 1 mm.

Table 2-5

Microfine Cement Grouts

	PG-1	PG-2
Microfine Cement MC-500, kg	80	80
NS 200 (Dispersant), liters	0.7	0.7
Water, liters	160	80
Yield, liters	187	107

For fissure apertures greater than about 1 mm, the use of Class A portland cement grout is recommended for pressure-grouting. Pressure grout formulation PG-3 is a neat Class A cement grout for use in pressure-grouting fissure apertures of 1 mm to 1 cm. Pressure grout formulation PG-4 includes the addition of silica sand and is suitable for pressure-grouting fissure apertures greater than 1 cm. Aqua gel (a fine bentonite clay) is included in the formulations to reduce settling of the cement grains and sand particles (bleeding) (see Table 2-6).

Table 2-6

Portland Cement Grouts

	PG-3	PG-4
Cement, Class A, lb.	46.9	40.0
Gel, lb.	0.9	2.0
Sand (20–40 mesh), lb.	—	22.9
Dispersant, D-65, lb.	0.14	0.2
Plastiment, fl. oz.	1.5	1.6
Water, lb.	46.9	40.0
Density	94.4 lb/ft^3	105.1 lb/ft^3
Water/cement	1.00	1.00
Ca/Si	3.0	3.0

If desired, the Ca/Si ratio can be adjusted by adding silica fume and silica flour to the formulations. Pressure grout formulation PG-5 is comparable to PG-3 for field use, and formulation PG-6 is comparable to PG-4 (see Table 2-7).

Table 2-7
Adjusted Portland Cement Grout

	PG-5	PG-6
Cement, Class A, lb.	30.7	25.3
Silica Fume, lb.	6.1	5.1
Silica Flour, lb.	12.8	10.5
Gel, lb.	0.6	1.6
Sand (20–40 mesh), lb.	—	27.9
Dispersant, D-65, lb.	0.1	0.1
Plastiment, fl. oz.	1.3	1.6
Water, lb.	44.7	36.4
	95.0 lb/ft^3	107.3 lb/ft^3
Water/Cement	1.46	1.45
Water/reactive solids	0.90	0.90
Ca/Si	0.776	0.776

2.5.3 Grout-Bulb Effectiveness

Consideration is being given to placement of a grout bulb around a primary seal, with an objective of reducing the likelihood that water could dissolve the seal. The following discussion provides a qualitative discussion of factors potentially affecting the durability of grout bulbs.

Several grout formulations have been specified for sealing boreholes that extend into the proposed potential repository horizon at Yucca Mountain. The longevity of the planned grout-bulb seals will depend on many site-specific factors, including the following:

- Condition of groundwater saturation (i.e., unsaturated or saturated) at the horizon of seal emplacement
- Chemical composition of groundwater that may contact the grout-bulb seals
- Permeability of the grout-bulb seals
- Kinetic rates for dissolution of grout minerals, precipitation of secondary phases, and exchange reactions
- Temperature of the groundwater/grout/gas system
- Fugacity (partial pressure) of carbon dioxide in gas contacting the seals.

Although data are available on groundwater composition and expected seal temperature, a quantitative analysis of seal longevity requires data on groundwater infiltration rates, permeability of grout bulbs, kinetic rates for dissolution, precipitation, exchange reactions, and fugacity of carbon dioxide after the potential repository is sealed. These data are currently unavailable. Therefore, a qualitative discussion of seal longevity is presented here to provide contrast for a variety of conditions that may develop at the proposed repository. This qualitative assessment establishes a number of seal-degradation scenarios and identifies the type of data needed for a quantitative assessment of the scenarios.

The principal factor affecting grout-seal longevity will be the absence or presence of groundwater. If current unsaturated conditions prevail into the distant future, there will be little impetus for chemical degradation of the grout seal in the absence of water. However, unsaturated conditions do not rule out intermittent periods of saturation that may occur if infrequent surface flooding sends an infiltrating groundwater pulse to the seal and potential repository horizon.

If future site characterization predicts that saturated conditions can prevail at the seal and potential repository horizon for an extended period of time, assessment of the chemical degradation requires data on groundwater composition, kinetic rates for dissolution, precipitation, exchange reactions, permeability of the grout, temperature of the groundwater/grout/gas system, and fugacity of carbon dioxide. (As noted above, kinetic rates, permeability, and fugacity data are unavailable.)

Assuming instantaneous kinetic rates for dissolution, precipitation, and exchange reactions, thermodynamic data and computer models can calculate the dissolved grout minerals and precipitated secondary phases. These calculations can be applied to a range of temperatures and fugacities to bracket the expected grout-degradation conditions. Using these calculations and varying the permeability of the grout, it can be shown that the surface area of grout exposed to groundwater determines the longevity of the seals. If groundwater contacts only the leading edge of the grout (i.e., the grout is impermeable), the seal longevity will be greater than that of one composed of permeable grout. Because the grout is designed to provide an effective seal against fluid migration, it is less permeable than surrounding rock and can be considered impermeable for assessment purposes. Therefore, grout-degradation conditions are most realistic for groundwater contacting the leading edge of the grout, and temperature and fugacity variation is assessed for this condition.

Temperature in the vicinity of the seals has been estimated as high as 87°C. All other factors being equal, an increase in the temperature of the groundwater/seal/gas system will probably degrade the grout more rapidly by increasing the kinetic rates of dissolution, precipitation, and exchange reactions along the leading edge of the grout. In general, these temperature-enhanced reactions degrade the grout by increasing the porosity and permeability along the leading edge, resulting in greater grout-surface area exposed to groundwater. Conversely, increasing temperature in the absence of groundwater will enhance kinetic rates for formation of calciumaluminum-silicate phases in the grout, resulting in shorter curing time and better short-term durability.

The fugacity of carbon dioxide is an important factor in saturated and unsaturated scenarios. For unsaturated conditions where gas containing carbon dioxide contacts the grout, the following reaction between portlandite and carbon dioxide is thermodynamically favored:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O.$$

Although this reaction results in a solid volume increase of about 4 cubic centimeters per mole (i.e., grout porosity is decreased), water is an undesirable product that can act as a leachant for future degradation reactions. This reaction can be controlled by minimizing portlandite formation in grout through the addition of silica fume, silica flour, or slag. These silica additives react with portlandite to form more stable calcium-silicate phases (e.g., tobermorite), and all are included in proposed seal grouts to minimize the formation of free portlandite. Therefore, minimizing portlandite formation will be effective in controlling grout degradation when unsaturated conditions prevail.

If saturated conditions exist at the seal horizon, the following reaction between carbon dioxide and groundwater is important:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+.$$

This reaction produces bicarbonate and hydrogen ion, which results in a lower pH for groundwater and increased chemical degradation of grout in contact with the groundwater. The hydrogen ion reacts readily with hydroxide-bearing grout phases to form water and free metal ions. Therefore, decreasing the pH of the groundwater enhances its capability to serve as a leachant for grouted seals. If saturated conditions are a probable scenario for the seal horizon, the fugacity of carbon dioxide should be minimized by eliminating sources in the waste. There is no significant source for carbon dioxide in the volcanic rock that surrounds the proposed repository site.

This brief qualitative analysis suggests that grout seals placed in an unsaturated zone will perform well when silica additives are combined with the grout to minimize the formation of free portlandite. If saturated conditions are shown to have a reasonable probability of occurring, the grout seals will perform well when the grout permeability is lower than the surrounding rock, temperatures in the vicinity of the grout seals are minimized, and waste sources for carbon dioxide are eliminated or minimized.

2.5.4 Available Technologies to Seal Boreholes

One of the objectives of this report is to review the technologies available to place seals in boreholes. Chapter 6.0 includes a review of tasks needed to place seals. These tasks are as follows:

- Removal of freestanding casing and borehole materials, if present
- Reconditioning of the borehole wall
- Selection of seal materials
- Emplacement of seals.

As discussed in Chapter 6.0, technologies are available to accomplish all of the tasks identified above. However, some difficulty may occur in removing materials in selected boreholes. In this regard, sealing concerns should be taken into account before drilling proposed boreholes. The following conclusions are included as part of the borehole sealing strategy:

- Maintain detailed construction documentation

- Select drilling methods, if possible, that will reduce wall-cake build-up

- Select drilling methods, if possible, that will result in better well condition

- Minimize risk of losing drilling tools and "junk" in the borehole, e.g., develop a protocol for tool inspection; make routine field inspections intermittent with downhole operations

- Utilize materials that are relatively easy to remove through fishing or milling

- Limit number of exploratory boreholes.

Other conclusions, which are an outcome of this review, involve the testing and quality control of cementitious plugs. These recommendations include performing the following:

- Adherence to API-published specifications
- Laboratory testing of "bonding" to host rock
- Sample testing program during field application
- Verification of seal placement and curing
- Performance testing in a selected test hole.

The current state of the art in seals testing, as discussed in Chapter 6.0, assumes a structurally stable seal capable of supporting weight satisfactorily tests a seal. While there exists a relationship between structural and hydrologic/airflow performance, this aspect of available technology testing for seal quality is considered inadequate. Therefore, performance confirmation testing of borehole seals would be necessary.

Preliminary concepts have been presented by Fernandez et al. (1993) for remote borehole seal testing. As discussed by them, the testing would be performed using transient or steady-state methods to satisfy a test performance objective, such as the following:

$$\frac{Q}{\Delta H} \leq C_r$$

where

Q = Total flow rate through a seal system parallel to the seal axis (MPZ, interface zone, and seal) during the test

ΔH = Change in potential or head loss through the seal system during the tests

C_r = Required conductance as determined from potential repository or seal design studies. The required conductance is proportional to the product of the hydraulic conductivity and seal area and inversely proportional to seal length.

2.6 When to Seal

At the time of seal emplacement, access needs to be maintained at preferred sealing locations to prevent the following:

- Collapse of the casing
- Accelerated corrosion of casing, due to collapse of the formation around the casing (which would result in higher corrosion rates than those for atmospheric corrosion) and due to potential synergistic effects between stress and corrosion
- Collapse of the open borehole at sealing locations after casing removal.

The high-temperature environment at the potential repository horizon could result in casing failure prior to sealing or failure of the open borehole during sealing that would limit access to the lower sealing locations. Even for cased boreholes, the higher-temperature environment might increase formation stress and result in formation collapse against the casing and accelerate corrosion. These considerations suggest casing removal and seal placement prior to waste emplacement to assure the placement of high-quality seals.

2.7 Summary

In the preceding discussion, borehole performance goals were stated and scenarios were developed for evaluation. Conceptual designs were developed based upon the sealing considerations—where boreholes should be sealed, where preferred sealing locations exist, when seals should be emplaced, and how seals should be emplaced. These issues and conclusions are summarized in Table 2-8.

Table 2-8
Summary of Conclusions

Significance	Significant boreholes are within and close to the edge of the potential repository. Deep boreholes are potentially more important than shallow boreholes.
When to Seal	Seal deep and significant boreholes within the potential repository boundary before waste emplacement.
Where to Seal	Place seals away from high-temperature zones near the potential repository. Place primary seals (cementitious seals) where hole conditions are good or excellent: • Paintbrush tuff nonwelded to partially welded zones • Upper part of Topopah Spring Member • Calico Hills vitric and zeolitic zones. Place earthen materials in selected fracture areas, in partially saturated zones not in primary seal area (to dissipate porewater pressure), and in high-temperature areas
How to Seal	Use low-pressure squeezing to develop compressive stress at the interface zone. Increase length of plug up to 10 m to resist static, dynamic, and thermal loads (see Appendix J). Lower the temperature of grout by reducing the heat of hydration and prechilling materials (see Appendix I). Remove all freestanding casing.
Seal Materials Selection	Use a rigid cementitious seal where structural performance is desired. Avoid placement of cementitious seals in high-temperature environments. Enhance stability of cementitious seals: • Minimize leachable phases, portlandite $Ca(OH)_2$ and reactive alkalis, NaOH, and KOH by adding excess reactive silica (silica flour and slag) • Reduce ettringite formation by selecting a cement with a low sulfate content. Use earthen materials (clay and crushed rock) as a seal in highly fractured areas. Avoid placing cementitious and clay seals together, if possible. Where both are necessary, use a calcic form of clay and/or use a grout formulation that will not release calcium.

3.0 Description of the Exploratory Borehole System

This chapter contains a more complete description of the exploratory boreholes, emplacement locations, and environmental conditions at Yucca Mountain. There are approximately 191 existing and 322 proposed boreholes, varying in depth from very shallow (5 ft) to very deep (6,000 ft). The borehole diameters vary from 3 to 48 in. This chapter and Appendices A, B, and C contain the following information:

- A description and location of the exploratory boreholes (Section 3.1)
- A construction summary of the existing boreholes (Appendices A and B)
- General and specific problems (debris in borehole) encountered in boreholes (Section 3.1 and Appendix A)
- Geology and hydrology (Section 3.2 and Appendix C)
- The environmental conditions encountered within and in the vicinity of the boreholes, including in situ stress (Section 3.3.1), temperature states (Section 3.3.2), and properties of the rock mass (Section 3.3.3)
- Borehole wall conditions (Section 3.4)
- Air conductivity models and variability of welded and nonwelded units (Section 3.5).

This information provides the basis for performance and design calculations and the validation of the borehole sealing strategy.

3.1 Description of the Exploratory Borehole System

Existing and proposed exploratory borehole locations are shown on Figures 3-1 through 3-7. Their locations are displayed according to their depths. For existing boreholes, the different categories for depth are less than 100, 100 to 499, 500 to 999, and 1,000 ft and greater. For proposed boreholes, the depth categories are less than 100, 100 to 499, and 500 ft and greater. All figures display the potential repository boundary and the outline for the restricted zone, which is defined in 10 CFR 60.2 as "any areas access to which is controlled by the licensee for the purpose of protection of individuals from exposure to radiation and radioactive materials."

The restricted area is placed on figures for reference only to show the location of the borehole relative to the restricted area. Table 3-1 lists the number of proposed and existing boreholes by type and location, within and outside the potential repository boundary. A summary description of the existing exploratory boreholes is given below.

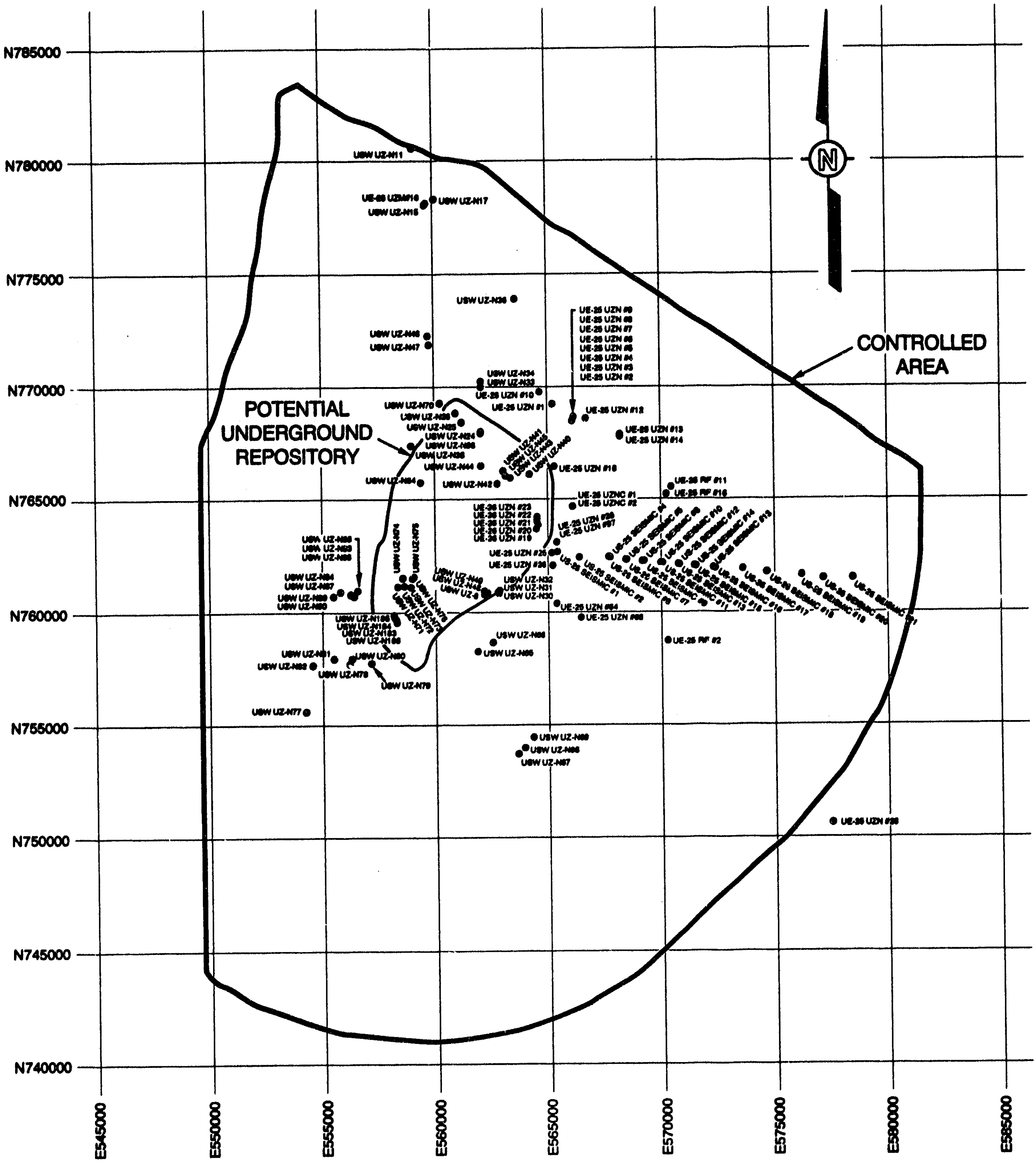


Figure 3-1

Existing Boreholes Less Than 100 Feet Deep (SAN0092)

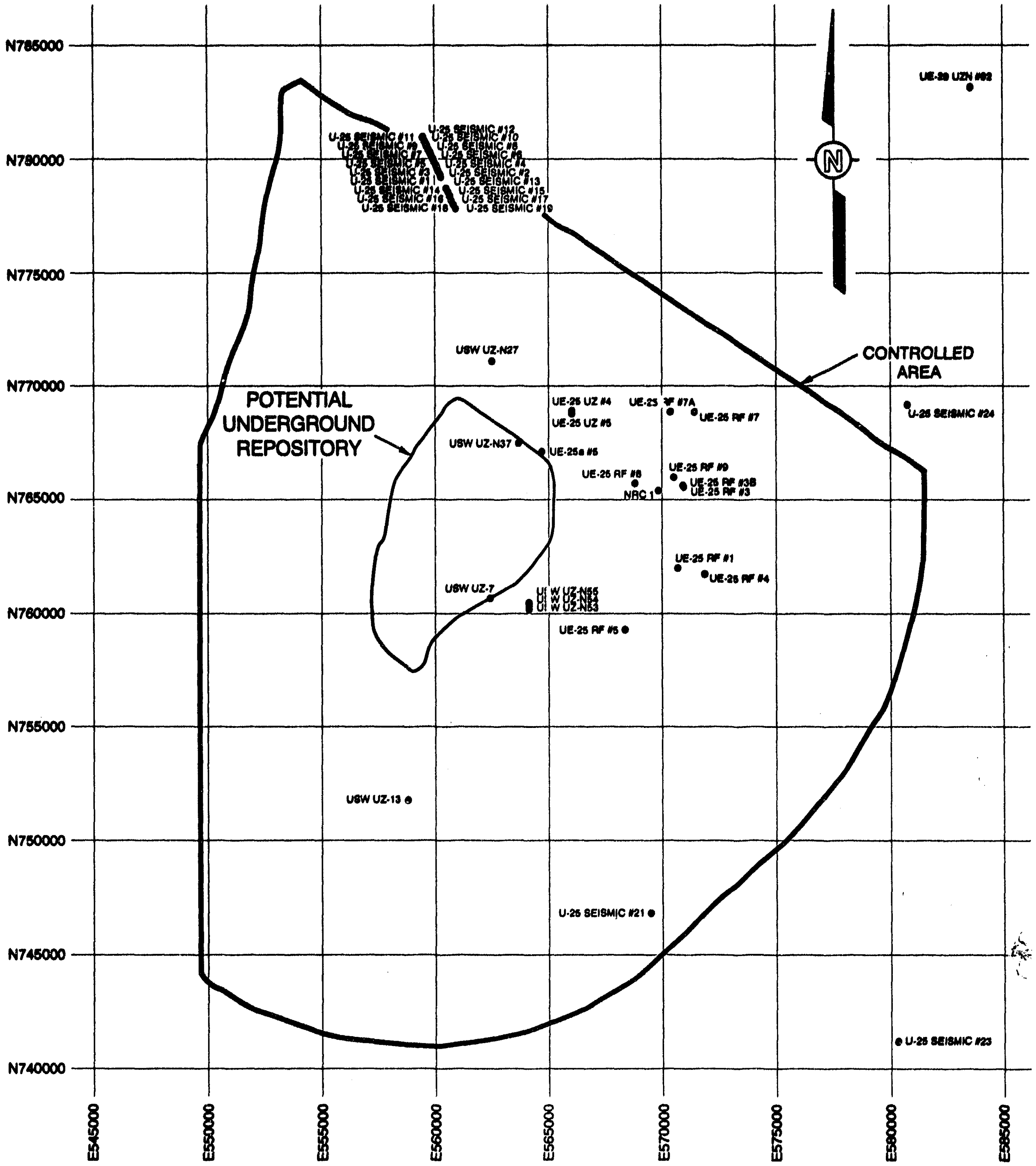


Figure 3-2
Existing Boreholes 100 to 499 Feet Deep (SAN0093)

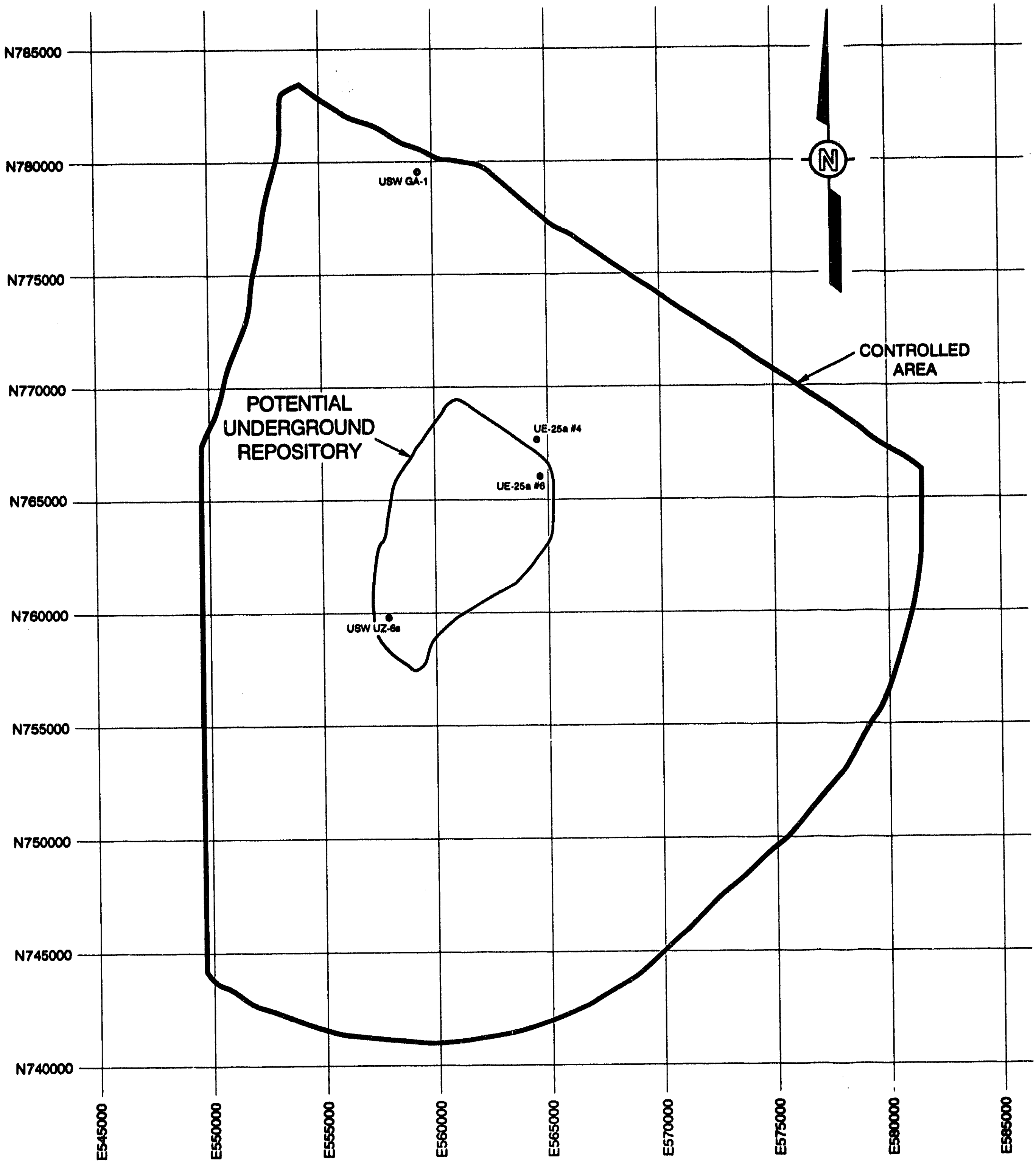


Figure 3-3
Existing Boreholes 500 to 999 Feet Deep (SAN0099)

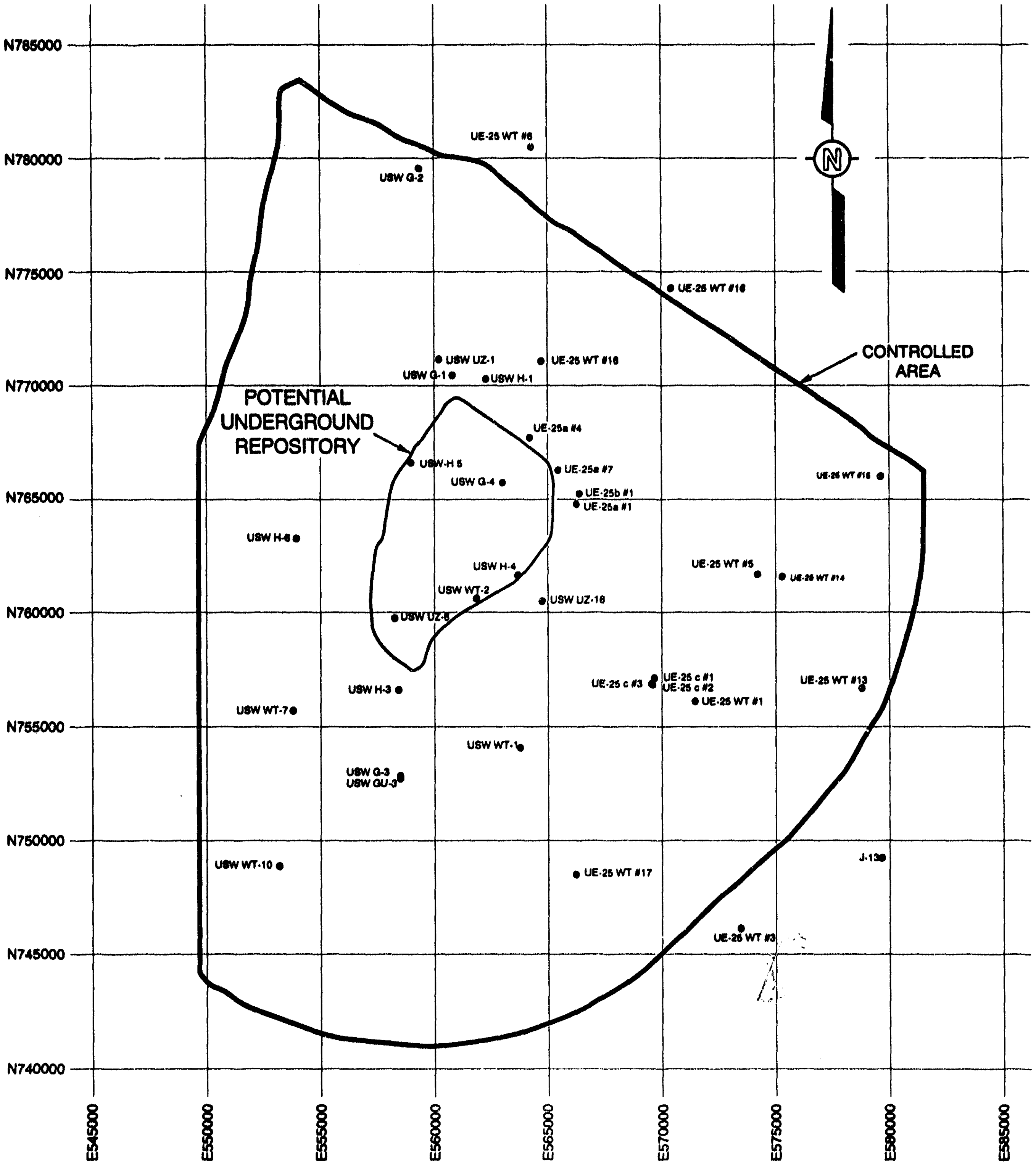


Figure 3-4
Existing Boreholes Greater Than 1,000 Feet Deep (SAN0098)

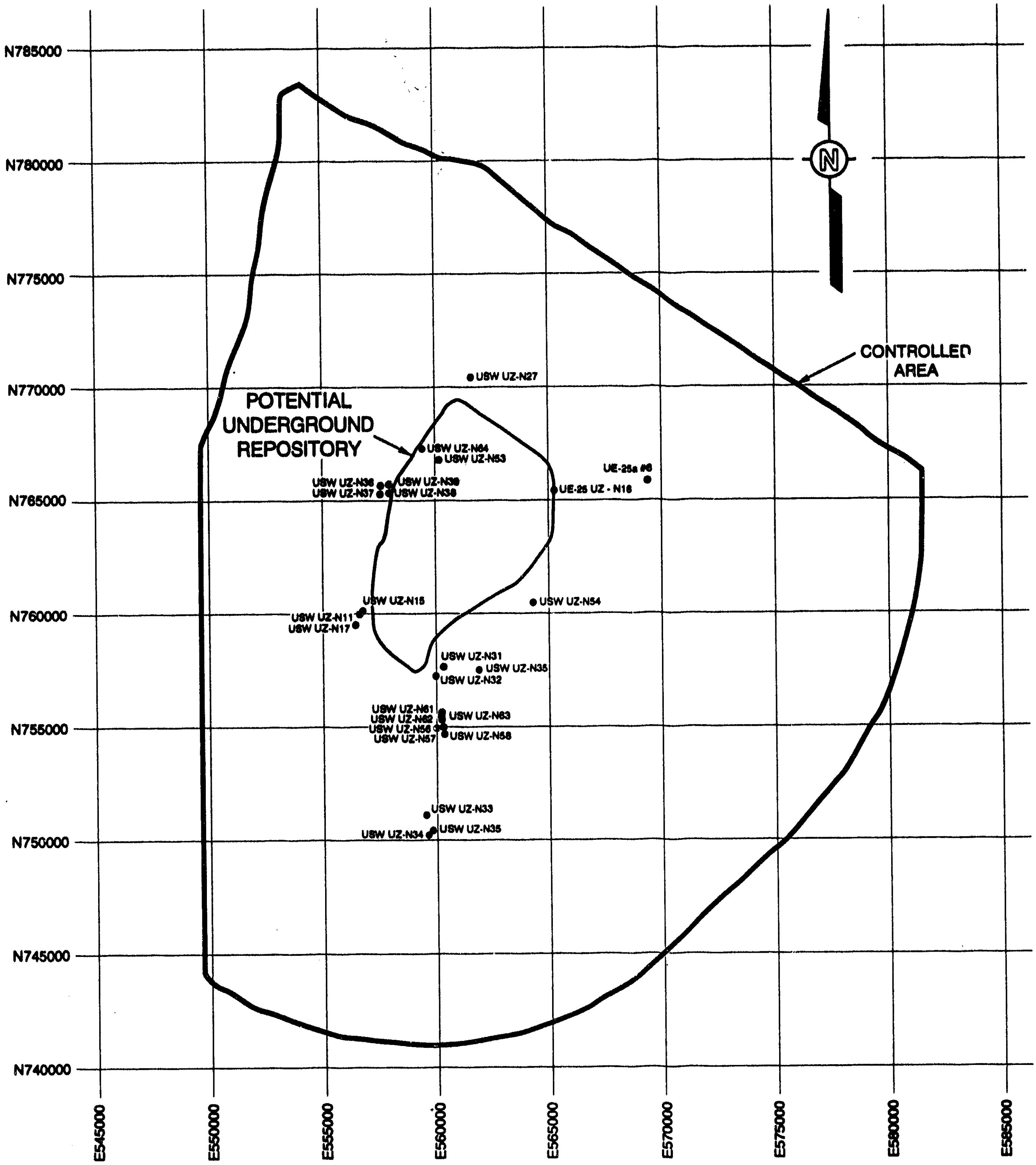


Figure 3-5
Proposed Boreholes Less Than 100 Feet Deep (SAN0094)

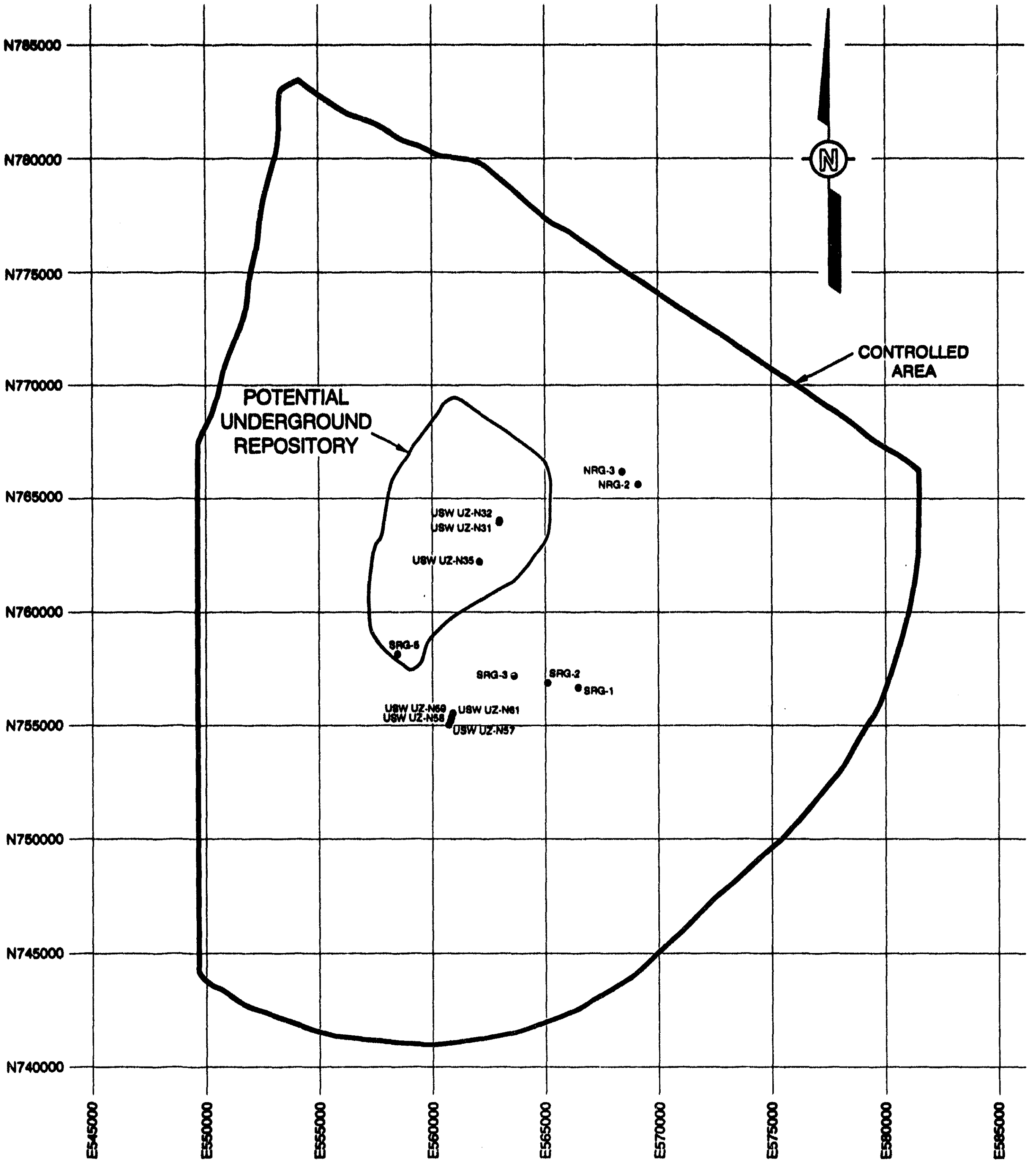


Figure 3-6
Proposed Boreholes 100 to 499 Feet Deep (SAN0095)

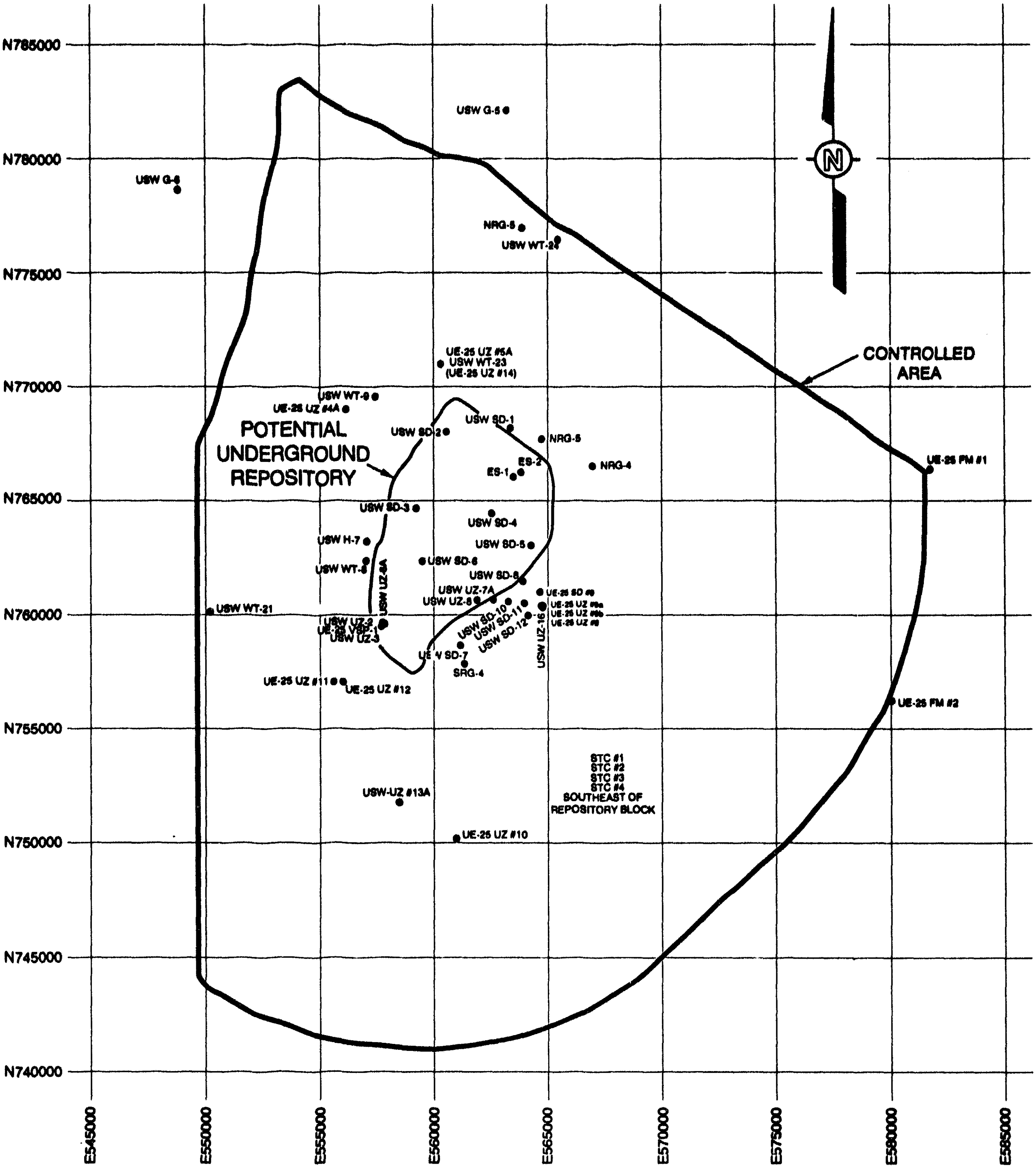


Figure 3-7
Proposed Boreholes Greater Than 500 Feet Deep (SAN0096)

Table 3-1

Number of Existing and Proposed Boreholes by Category and Location

Category of Borehole	Existing			Proposed			Total by Category
	Within Potential Repository Boundary	Outside Potential Repository, Inside Restricted Area	Outside Restricted Area	Within Potential Repository Boundary	Outside Potential Repository, Inside Restricted Area	Outside Restricted Area	
UZ	4	5	–	6	10	–	25
UZN	33	52	2	3	6	1	97
UZNC	–	2	–	–	–	–	2
WT	1	10	5	–	5	3	24
A	1	4	–	–	–	–	5
C	–	3	–	–	–	–	3
H	2	3	–	–	1	–	6
G	1	5	–	–	–	4	10
P	–	1	–	–	–	–	1
B	–	1	–	–	–	–	1
RF	–	12	–	–	–	–	12
SEISMIC	–	38	5	–	–	–	43
SD[a]	–	–	–	5	7	–	12
FMN[b]	–	–	–	–	2	11	13
LPRS[c]	–	–	–	30	110	–	140
SPRS[d]	–	–	–	32	60	–	92
NRG[e]	–	1	–	–	5	–	6
STC[f]	–	–	–	–	4	–	4

Refer to footnotes at end of table.

Table 3-1 *(Continued)*

Number of Existing and Proposed Boreholes by Category and Location

Category of Borehole	Existing			Proposed			Total by Category
	Within Potential Repository Boundary	Outside Potential Repository, Inside Restricted Area	Outside Restricted Area	Within Potential Repository Boundary	Outside Potential Repository, Inside Restricted Area	Outside Restricted Area	
SRG[e]	–	–	–	1	4	–	5
V[g]	–	–	–	–	–	5	5
PH[h]	–	–	–	–	6	–	6
ISS[i]	–	–	–	–	–	1	1
Total by Location	42	137	12	77	220	25	513

[a] SD = Systematic drilling program boreholes.
[b] FMN = Forty-mile Wash recharge boreholes.
[c] LPRS = Large-plot rainfall simulation boreholes.
[d] SPRS = Small-plot rainfall simulation boreholes.
[e] NRG/SRG = Surface facility drill holes.
[f] STC = Southern tracer complex studies.
[g] V = Volcanic drill holes.
[h] PH = Calcite-silica studies boreholes.
[i] ISS = In situ stress drill hole.
Other borehole identifiers are referred to in the text.

Unsaturated Zone Holes (UZ). The UZ objective is to obtain information on the hydrologic properties, moisture content, and moisture potential in the unsaturated zone. Nine existing holes fall in this category. They range in depth from shallow (57 ft) to deep (1,887 ft), with diameters ranging from 30 to 48 in. at the surface to 3.94 in. at depth. The deeper holes have casings that are fully grouted down to about 40 ft, and in only one case, a separate casing is spot-grouted at 324 ft. For the deeper holes, the casing is generally spot-grouted at the base of the casing. Typical drilling techniques include reverse air vacuum, ODEX 115, or ODEX 165 systems. The circulating medium is air.

Unsaturated Zone Neutron Holes (UZN). The UZN objective is to characterize the present infiltration processes and rates within the surficial materials of Yucca Mountain. The UZN category includes 87 existing boreholes, ranging in depth from 20 to 150 ft, typically with a hole diameter of 6 in. Typical casing is not grouted in place. Typical drilling techniques include the ODEX 115 system. The circulating medium is air.

Water Table Holes (WT). The WT objectives are to determine the potentiometric surface at Yucca Mountain and to characterize the chemistry of the groundwater. The WT category includes 16 existing boreholes, ranging from 1,100 to 2,100 ft deep, that, as the name implies, penetrate to the groundwater table. The casing is grouted near the surface, usually less than 220 ft from the surface; however, one existing hole has a casing grouted up to 250 ft from the surface. In all cases except one, 2.875-in.-OD tubing with a 12-in. screen is landed on fill at the bottom of the hole. Usually the hole varies in diameter from 15 in. at the surface to 8.75 in. at depth. Typically the holes are drilled using conventional rotary techniques with air foam.

Hydrologic Holes (H). The H objective is to characterize the hydrologic properties of rock, including fracture and matrix properties. Five existing boreholes fall into the H category, which are either 4,000 or 6,000 ft in depth. The holes are typically 48 or 36 in. in diameter at the surface and are 8.75 in. at the bottom. The fully grouted casing usually extends over a distance of less than 330 ft. Typically, the deepest casing will be set with grout at the bottom of the casing, which can occur as shallow as 1,840 ft and up to 2,585 ft. The holes are drilled using conventional rotary techniques and air foam.

Exploratory Geologic Holes (G). The G objective is to determine the vertical and lateral variability and emplacement history of stratigraphic units within the Yucca Mountain area. Six existing holes fall in the G category, the majority of which range in depth from 2,644 to 6,006 ft; however, one hole is only 551 ft in depth. Casing extends to depths of about 2,600 ft. The surface casing is generally grouted to a depth of less than 40 ft, with two deeper holes with casing grouted to 280 ft. The deeper casing is not grouted over the entire depth; it is spot-grouted at the bottom of the casing. Hole sizes range from 23 in. in diameter at the surface to 2.98 in. at depth. Typical drilling techniques include conventional rotary using bentonite mud, polymer mud, and air foam.

Potential Repository Facility Holes (RF). The RF objective is to obtain basic engineering properties of the soil and rock in the vicinity of the surface facilities. There are 12 existing potential repository facility holes, typically shallow in depth, ranging from 60 to 306 ft. The diameter of the holes is typically 9.875 in. at the surface to about 3.94 in. at the bottom of the hole. The casing extends over most of the hole depth; however, in three holes, PVC pipe was grouted in place. Typical drilling techniques were conventional rotary and ODEX using air foam, polymer mud, gel, and polymer and water.

Seismic Holes. The objective of the seismic holes is to characterize the geologic structure of the Yucca Mountain areas. There are 43 holes in the seismic category. Twenty-one boreholes have diameters of 8.75 in. over the entire depth with 6-in. flexible plastic tubing placed over the entire length. The other holes are typically 200 ft in depth, 6.25 in. in diameter over the entire depth, and cased with PVC pipe over the entire depth. No grout was used in either category, and all, because of the nature of the hole, were backfilled and shot. Typical drilling techniques include conventional rotary using air foam.

A Holes (A). The objectives of A holes are to examine the subsurface stratigraphy and lithologic variations, determine the distribution and nature of structural discontinuities, and obtain limited hydrologic information. There are five existing boreholes in this category, ranging from 500 to 2,500 ft in depth. Hole size depends on the depth of the hole and ranges from 17.5 in. at the surface to 2.98 in. at depth. Maximum depth at which the casing is grouted is 138 ft. Hydril™ tubing, 2.375 in. outside diameter (OD), and NQ rods extend to depth in some of the holes. Many holes are 10 to 12 years old. Typical drilling techniques include conventional rotary using bentonite mud, revert mud, and/or air foam as the circulating media.

B Hole (B). The objective of the B hole is to determine the geologic and hydrologic characteristics of the tuff sequence penetrated. There is only one B-hole, which is 4,002 ft in depth. The hole diameter is 36 in. at the surface and reduces to 8.5 in. at the bottom of the hole. The casing extends to 1,705 ft and is fully grouted 35 ft from the surface. The two casing segments extending below 35 ft are spot-grouted at the base. This hole was drilled using conventional rotary and air foam.

C Hole (C). The objective of the C holes is to determine the hydrologic characteristics of the tuff unit penetrated. Only three holes of this type exist, and they extend to 3,000 ft. Casing extends to approximately 1,365 ft; however, surface casing is fully grouted to less than 368 ft. The second casing, which extends below the grouted casing at the surface, is only spot-grouted at the bottom. The holes are large at the surface, 36 or 48 in., and reduce in size to 9.875 in. These holes were drilled using conventional rotary techniques and air foam.

P Hole (P). The primary objective of the one P hole is to obtain information about rocks of Paleozoic age assumed to underlie the volcanic, tertiary rocks. The secondary objective is to obtain geohydrologic information on these. There is only one paleozoic hole, which is 5,923 ft in depth. The hole diameter is 30 in. at the surface and reduces to 6.125 in. at the bottom. The casing extends to 4,256 ft, and the surface casing is fully grouted down to 341 ft. The second casing is spot-grouted at 1,564 ft, and the final segment of casing extends from 1,487 to 4,256 ft and is grouted in multiple places. The hole was drilled using conventional rotary techniques with air foam, water, and polymer mud.

The proposed boreholes include additional UZ, UZN, WT, H, and G holes. New, major categories included as proposed boreholes are:

- ***Systematic Drilling Program Holes (SD).*** The SD objective is to develop a three-dimensional characterization of the rock in the unsaturated zone.
- ***Forty Mile Wash Recharge Holes (FMN).*** The FMN objective is to monitor aquifer recharge in Forty Mile Wash during precipitation events.
- ***Surface Facilities Holes (NRG and SRG).*** The NRG and SRG objective is to determine soil and rock properties along the alignment of the north and south ramps.
- ***Large- and Small-Plot Rainfall Simulation Holes (LPRS and SPRS).*** The objective in drilling these holes is to monitor infiltration under artificial precipitation rates.
- ***Tracer Complex Studies (STC).*** The STC objective is to perform tracer pump tests to characterize geohydrologic units and groundwater flow.
- ***Volcanic Drill Holes (V).*** The objective in drilling these holes is to investigate the origin of four aeromagnetic anomalies in Crater Flat and Amargosa Valley.
- ***Calcite-Silica Studies (pH).*** The objective of these holes is to determine the ages, distribution, origin, and paleohydrologic significance of calcite, and opaline deposits along faults and fractures.
- ***In Situ Stress Studies (ISS).*** The ISS objective is to perform in situ stress hydrofracture studies at several locations.

Historically, exploratory boreholes were developed using conventional rotary, ODEX, and reverse-air vacuum drilling techniques. Depending on the type of hole, drilling fluids, such as air foam, bentonite mud, and polymer mud, were used. Typically, air is the circulating medium when the ODEX and reverse-air vacuum techniques are used. The primary functions of the drilling fluids are to remove cuttings, stabilize the borehole, cool and lubricate the drill bit, control fluid loss, drop cuttings into a settling pit, acquire information about the boring, and suspend cuttings in the borehole when drilling fluid is not being circulated. Because the drilling fluid in the conventional rotary technique runs down the outside of the drill pipe, the drilling fluids contact the rock along the entire length of the borehole. Therefore, residual drilling fluids typically can build up on the wall of the borehole when drilling muds are used.

When using the ODEX system, the hole is drilled, and the casing is emplaced simultaneously. The ODEX system is an eccentric (off-centered) bit attached to a down-the-hole hammer. Because the circulating medium is air, no drilling fluids are introduced into the borehole. In using reverse-air vacuum, air is introduced into the outside of the drill pipe and returns up through the drill pipe. This is accomplished by creating a vacuum internal to the drill pipe. Again, no drilling fluids are introduced into the hole.

Drilling of proposed boreholes will be accomplished through the use of the ODEX system, conventional rotary, and a technique currently under development by the DOE. This technique, termed the dual wall drilling/coring system, is similar to the dual-wall reverse circulation rotary method. The circulating medium is air, with the cuttings being lifted up through the center of the dual-wall pipe. The primary objective of this technology is to acquire samples that are representative of the in situ conditions, while minimizing contamination and maximizing the quality of the borehole.

3.2 Geology and Hydrology

Because exploratory boreholes will be emplaced over a wide variety of stratigraphic units, a description of the geology and hydrology that is relevant at Yucca Mountain is presented in this section. The section is divided into three subsections: general geology, subsurface geology, and rock hydraulic and physical properties.

3.2.1 General Geology

In Chapter 2.0, important features relative to sealing were described. This section describes these features and their evaluation in detail. Yucca Mountain is broken into elongated blocks by five west-dipping, north-striking normal faults. Within these blocks, however, the rock is highly fractured and cut by minor faults. The potential repository is within a block between the Solitario Canyon fault to the west and Bow Ridge to the east (Fox et al., 1990). The thickness of the unsaturated zone is about 500 to 700 m (Montazer and Wilson, 1984). The fault block within the potential repository area has a eastward dip of 5 to 10 degrees. A predominant northwest-trending strike-slip system also exists. Unconsolidated alluvium found at the surface exists within the washes that dissect Yucca Mountain. Surface runoff is infrequent and of short duration, occurring only as a direct result of intense precipitation or rapid snow melt. Further, the thickness, lithology sorting, and permeability of the alluvium are quite variable. Figure 3-8 illustrates the features mentioned above. Discrimination is made between alluvium and bedrock. Tectonic features, including mapped, inferred, and concealed faults and tectonic breccia are also indicated. All of these features are shown relative to the perimeter drift boundary (Wittwer et al., 1992). The surface is divided for modeling purposes into three infiltration zones—alluvium

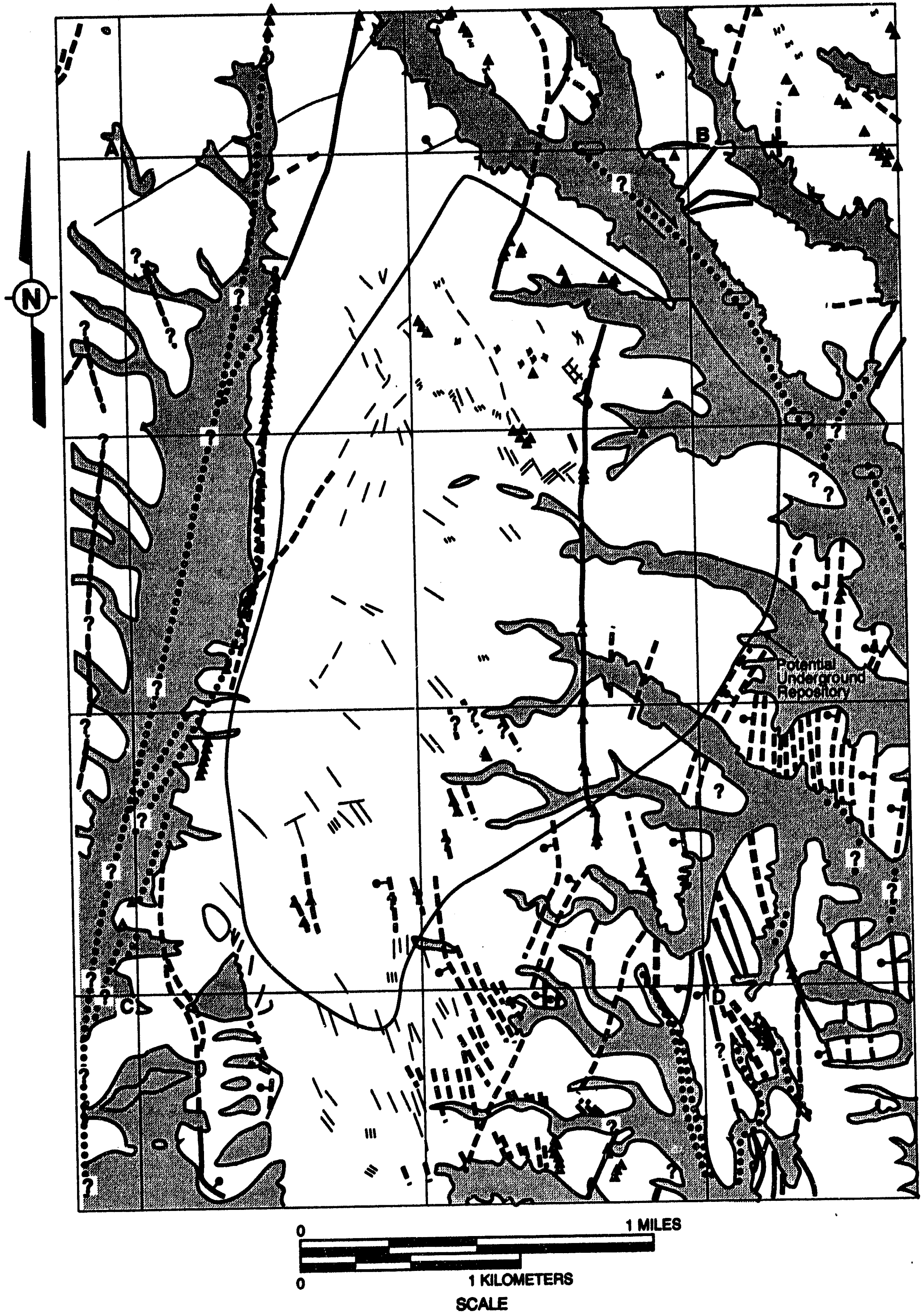


Figure 3-8
Surficial Geologic Features in the Vicinity of the Potential Repository

▨	ALLUVIUM
□	BEDROCK
─	BEDROCK-ALLUVIUM CONTACT
⬠	PERIMETER DRIFT BOUNDARY
━	FAULT
╍╍╍	INFERRED FAULT
•••••••••••	CONCEALED FAULT
••••(•••)••••	CONCEALED FAULT, INDICATED BY ELECTROMAGNETIC SURVEY
— ∕	FRACTURES
⫯	BAR AND BALL ON DOWNTHROWN SIDE OF FAULT
⇆	ARROWS SHOW RELATIVE STRIKE-SLIP DISPLACEMENT
T	DIRECTION OF FAULT DIP
?	QUERIED WHERE DOUBTFUL
▲	TECTONIC BRECCIA
‴	STRIKE OF DOMINANT NEAR VERTICAL FRACTURE SET
⊞	GRID BASED ON NEVADA STATE PLANE COORDINATE SYSTEM, CENTRAL ZONE. GRID INTERVAL IS 4000 FEET. POINTS A, B, C, AND D REPRESENT THE FOLLOWING LOCATIONS.

A = E556,000 N770,000
C = E556,000 N758,000
B = E564,000 N770,000
D = E564,000 N758,000

GRID NORTH IS AT THE TOP OF THE MAP

SCALE = 1:24,000

Figure 3-8 (Continued)
Surficial Geologic Features in the Vicinity of the Potential Repository

(24 percent), sideslopes (62 percent), and ridgetops (14 percent). The greatest potential infiltration can occur in the alluvium and lowest along the ridgetops.

3.2.2 Subsurface Geology

The origin of the rocks at Yucca Mountain is predominantly ash flow, although there are also ash-fall, reworked, and bedded tuffs. The various origins of the volcanic tuff result in the rock having distinctive physical properties, the differences between which form the basis for the thermal/mechanical stratigraphy (Figure 3-9). Figure 3-9 also shows a subdivision of the formal stratigraphic unit. Detailed geologic cross sections are provided in Appendix C.

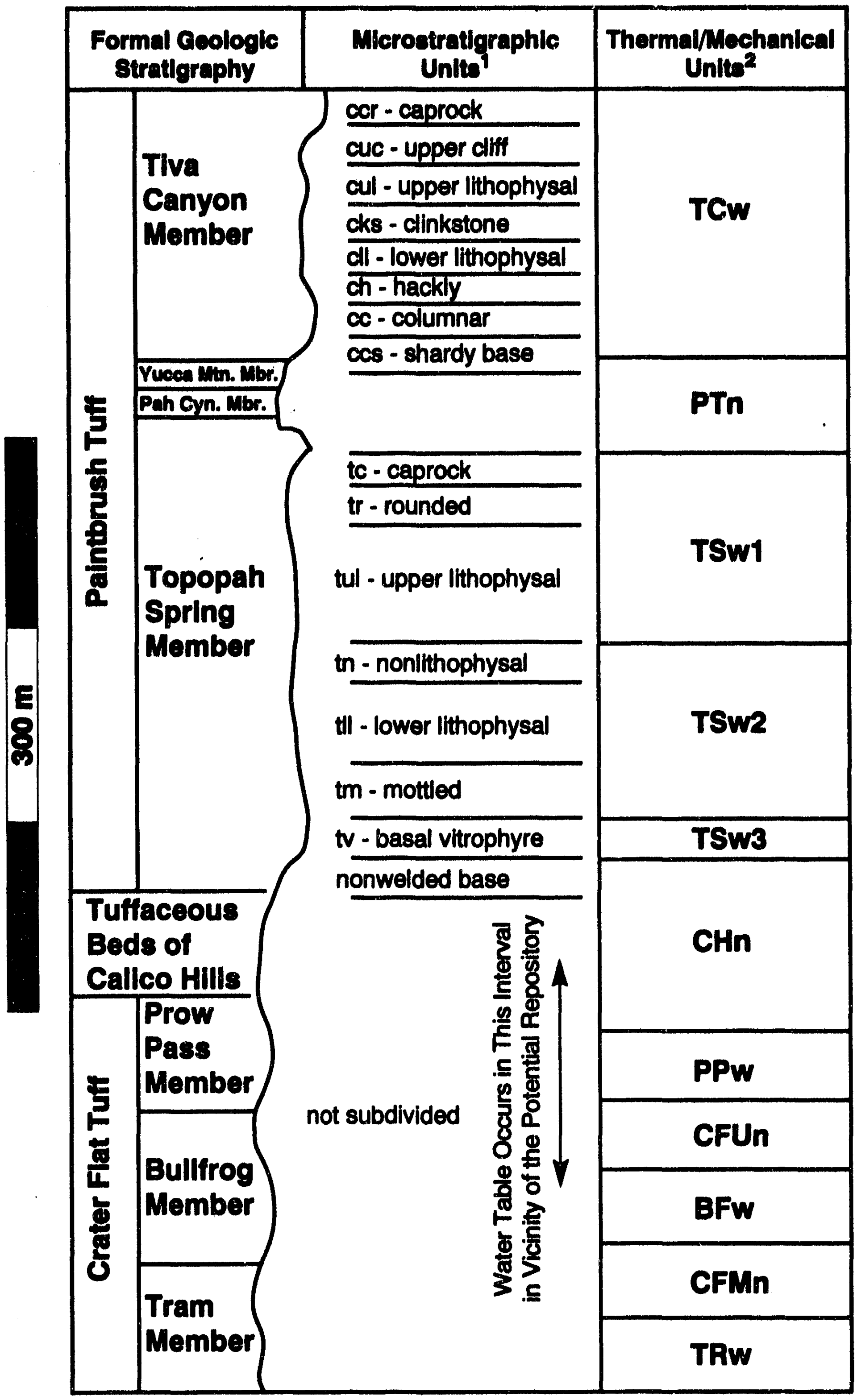
The brief discussion below has been condensed from Scott et al. (1983). Above the potential repository, the two major ash-flow units of the Paintbrush tuff are the Tiva Canyon and the Topopah Spring Members. Both are comprised of multiple ash flows. Because of the thickness of the ash flows, the degree of welding and physical properties vary within the unit. Both consist predominantly of moderately to densely welded tuff, and they are compositionally zoned from high-silica rhyolites at their basal and central portions to quartz latites at the top of the unit to densely welded caprocks. Following the subsequent cooling of the ash flow, other effects are superimposed on the units. These include devitrification, vertical extension of the joints during cooling, alteration to secondary phases by the reactions with pore waters to form zeolites and clays that are concentrated in the less welded portions of the cooling units, and faults and joints related to tectonic events. The Pah Canyon and Yucca Mountain Members are present at the north end of Yucca Mountain as distal edges of nonwelded to moderately welded sheets that pinch out to the south and the east. Where these two members are too thin, they are lumped together with unnamed bedded tuffs. These units and the modifications to the geology, together with the Calico Hills nonwelded unit below the potential repository, are described in more detail in Appendix C.

3.2.3 Rock Hydrologic and Physical Properties

Due to cooling processes and different response to tectonic events, the brittle welded and porous nonwelded tuffs have different physical and hydrologic properties. Important properties include the degree of fracturing, porosity, and density of the tuff units. The abundance of fractures is a function of both tectonic stresses and cooling stresses. There is positive correlation between the degree of welding, which influences the mechanical response of the rock to stress, and the number of fractures. The more elastic (lower Young's modulus or stiffness), zeolitized nonwelded and partially welded tuffs have as few as 1 to 3 fractures per cubic meter, whereas the more brittle densely welded tuffs have 8 to 40 fractures per cubic meter (Scott et al., 1983; Montazer and Wilson, 1984).

Porosity varies over a broad range—1 to 53 percent. Porosity declines as the degree of welding increases (Nelson and Anderson, 1992). In general, the following categorization can be made:

- Devitrified tuff: low porosity, high-grain density



Notes: 1 *Modified after Scott and Bonk (1984) for the immediate repository vicinity.*

2 *From Ortiz and Others, 1985.*

Thicknesses and "Weathering Profile" are highly schematic, character varies with location.

Figure 3-9

Comparative Stratigraphic Terminology in Common Usage at Yucca Mountain

(Rautman and Flint, 1992)

- Vitric, welded tuff: low porosity, low-grain density
- Vitric, nonwelded tuff: high porosity, low-grain density
- Zeolitized tuff: high porosity, low-grain density (higher than the vitric) (Ortiz et al., 1985).

Welded tuffs, such as the Tiva Canyon and Topopah Spring Members, are characterized by relatively low porosities (10 to 15 percent). Nonwelded and bedded tuffs, such as the Paintbrush nonwelded unit, have higher matrix porosities (25 to 50 percent). Zeolitic alteration in the lower part of the Topopah Spring Member and in portions of the Calico Hills Unit results in a decrease in porosity. In the vitric zone, the porosity (25 to 40 percent) is slightly higher than that of the zeolitic (15 to 35 percent). The porosity of two samples from the vitrophyre unit at the base of the Topopah Spring Member is only 2.2 percent. A prominent feature is the marked increase in porosity in the upper portions of both the Tiva Canyon (cul and cuc) and the Topopah Spring Members (tul). The caprock units near the tops of the Tiva Canyon and Topopah Spring Members have extremely low porosities (Rautman and Flint, 1992).

Densities in general increase as welding increases. Also, variations do occur within units having similar degrees of welding; for example, there is a trend of increasing particle density in the upper part of both the Tiva Canyon and the Topopah Spring Members (Rautman and Flint, 1992).

The most significant rock property for this report is the hydraulic conductivity[1] of the rock unit that is a function of the degree and nature of fracturing and the porosity of the rock. In general, the hydraulic conductivity increases as the porosity increases, but the porosity is a poor predictor of the hydraulic conductivity for a given sample, since the pore space may or may not be interconnected (Nelson and Anderson, 1992). Because the porosity of the welded tuff is lower than the porosity for the nonwelded tuff, the hydraulic conductivity is also lower. Typical matrix and rock mass conductivity values for different rock types are given in Table 3-2.

As summarized by Nelson and Anderson (1992), where zeolites are present, the permeability is greatly reduced from the permeability of unaltered samples at comparable porosities. This reduction could be as great as 2 orders of magnitude, as illustrated above.

---

[1] The property of hydraulic conductivity is specific for water and corresponds to an intrinsic permeability. For airflow, the "conductivity" used subsequently for analyses is calculated from the air-fluid properties (density and viscosity) and the intrinsic permeability.

Table 3-2
Saturated, Matrix Hydraulic Conductivity of Selected Tuffs

Rock Type	Matrix (cm/s)	Rock Mass (cm/s)
Densely welded Tiva Canyon	2.5×10^{-9} [a]	1.2×10^{-3} [a]
Paintbrush nonwelded, vitric	1×10^{-5} [b]	1×10^{-3} [c]
Densely welded Topopah Spring	3.5×10^{-9} [b]	1.2×10^{-3} [a] 3×10^{-2} to 10^{-5} [c]
Zeolitic, nonweld and bedded tuffs underlying the Topopah Spring Member	4×10^{-9} to 1.5×10^{-6} [a]	
Calico Hills, vitric	4.6×10^{-6} [b]	2.4×10^{-4} [a] 1×10^{-3} [c]
Calico Hills, zeolitic	9.3×10^{-9} [b]	2.4×10^{-4} [a]
Vitric nonwelded tuff	1×10^{-4} [d]	
Densely welded tuff	$2\text{-}3 \times 10^{-9}$ [b,d]	
Nonwelded bedded tuff	1×10^{-5} [b]	

[a] Sinnock et al., 1984.
[b] Montazer and Wilson, 1984.
[c] Scott et al., 1983.
[d] Winograd and Thordarson, 1975.

The presence of fractures can also influence the saturated hydraulic conductivity of the rock. Highly fractured, densely welded tuffs have an effective hydraulic conductivity about 5 to 6 orders of magnitude higher than their matrix conductivity (Scott et al., 1983), or between 10^{-4} to 10^{-2} cm/s (Montazer and Wilson, 1984). Thordarson (1983) measured the saturated bulk rock hydraulic conductivity over a 120-m section of the Topopah Spring welded unit to be 1.3 by 10^{-3} cm/s. Weeks (Montazer and Wilson, 1984) measured a range of hydraulic conductivities of the upper 30 m of the Topopah Spring welded unit in borehole UE-25a #4 of 1.2×10^{-2} to 7.0 by 10^{-4} cm/s. The influence of fractures in the nonwelded tuffs can be considerably less. For example, the nonwelded vitric tuffs have an effective hydraulic conductivity of only about 1 order of magnitude higher than their matrix (Scott et al., 1983).

3.3 Environmental Conditions at Key Sealing Locations

This section presents specific information on environmental conditions at the key sealing locations identified in Chapter 2.0, including the in situ state of stress, temperature, and rock-mass strength. Environmental conditions are also identified at the potential repository horizon.

3.3.1 In Situ Stresses

This section presents an evaluation of the state of in situ stress at the upper and lower seal location and at the potential repository horizon as described in the previous chapter. As discussed in Chapter 5.0 of this report, the state of in situ stress at various seal locations forms the far-field stress boundary condition used to evaluate stress in the rock for open boreholes and, subsequently, for cased boreholes. The state of stress in rock adjacent to boreholes is subsequently combined with other stresses induced in the rock, such as stresses from seal emplacement and backfilling and increased thermal stress.

Bauer and Holland (1987) developed a method for evaluating in situ stress at Yucca Mountain for a nonhomogeneous media. The method utilized finite-element analysis that takes cross sections of the mountain parallel to the measured direction of minimum horizontal stress. The analysis included three types of models: (1) an isotropic and linear elastic model using average values for a homogeneous media; (2) a linear elastic model using a specified set of matrix properties for each mechanical unit; and (3) a compliant-joint model using a specified set of matrix and joint properties for each unit.

The models calculate vertical stress by allowing the model to deform and equilibrate to a solution under gravity. The models include the effects of topography and thermal/mechanical stratigraphy. In general, the vertical stress at a point at depth is determined by the product of the average bulk density times the depth of overburden. The minimum horizontal stress depends on the vertical stress, the material constitutive model, and the loading and boundary conditions. With great depth, and away from free surfaces and topographic effects, the minimum horizontal stress equals $\nu/(1-\nu)$, where ν equals Poisson's ratio of the rock. Below the groundwater table, pore-water pressures develop and influence effective stress. Yet, all sealing locations considered in this analysis are above the groundwater table, and pore pressures do not affect lithostatic stress at these locations. Further, the maximum horizontal stress equals twice the minimum horizontal stress (DOE, 1992).

The results of the linear elastic calculations are presented in Figures 3-10 and 3-11 for two cross sections. The results show that topographic effects result in spatial variations in the horizontal stress field at the elevations of the proposed repository. Near the ground surface, the analysis predicts regions of low stresses.

The calculated stresses compare well with in situ stress measurements and interpretations of regional tectonics made at this site. The modeling technique provides a means to help understand the potential variability in minimum horizontal stress that may be encountered in different sealing locations.

Bauer and Holland (1987) report that calculations of the minimum horizontal stress using a compliant joint model do not differ significantly from those using a linear elastic model for a nonhomogeneous media. It appears that material anisotropy introduced by the presence of

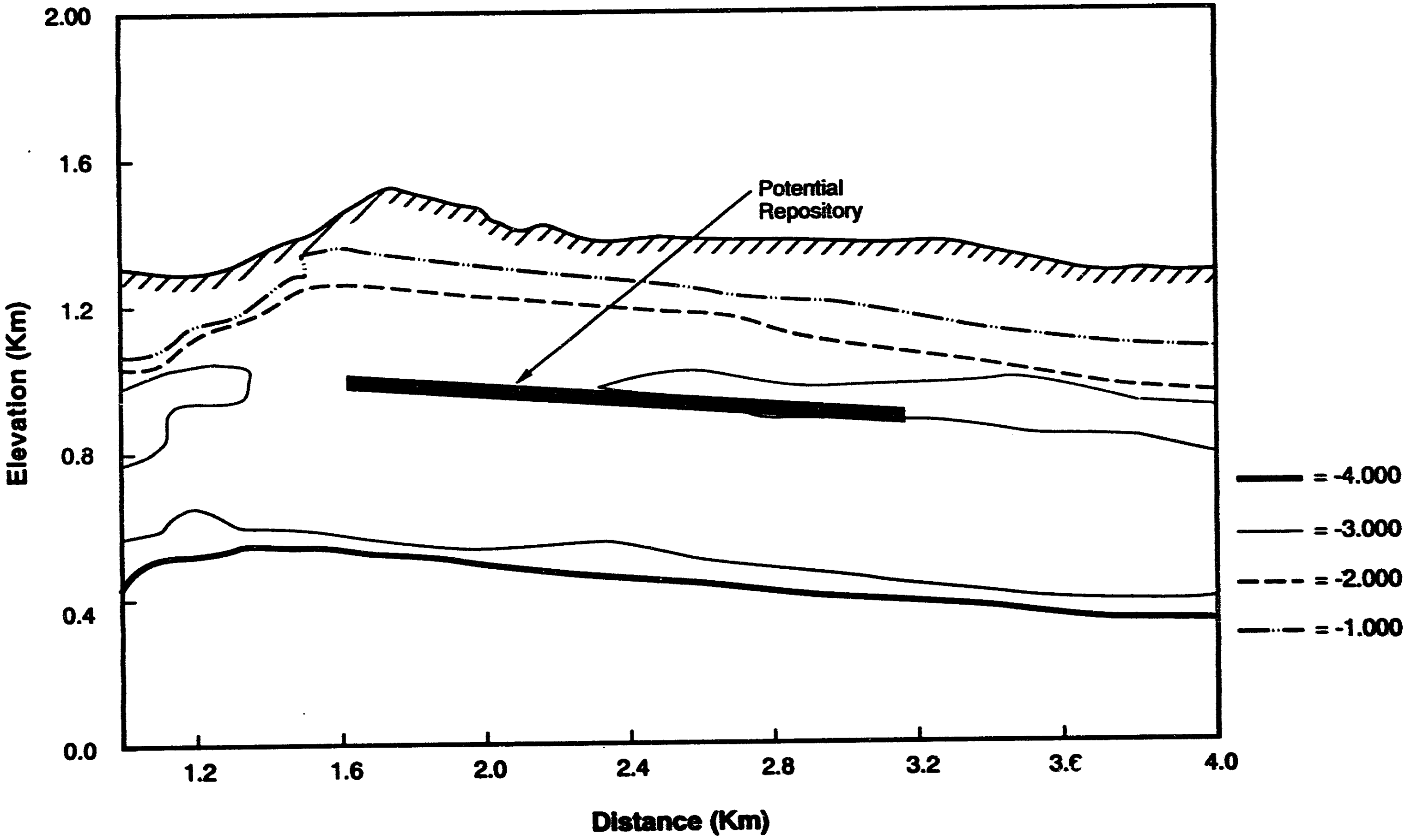


Figure 3-10
Stress Contours for a Northern Cross Section

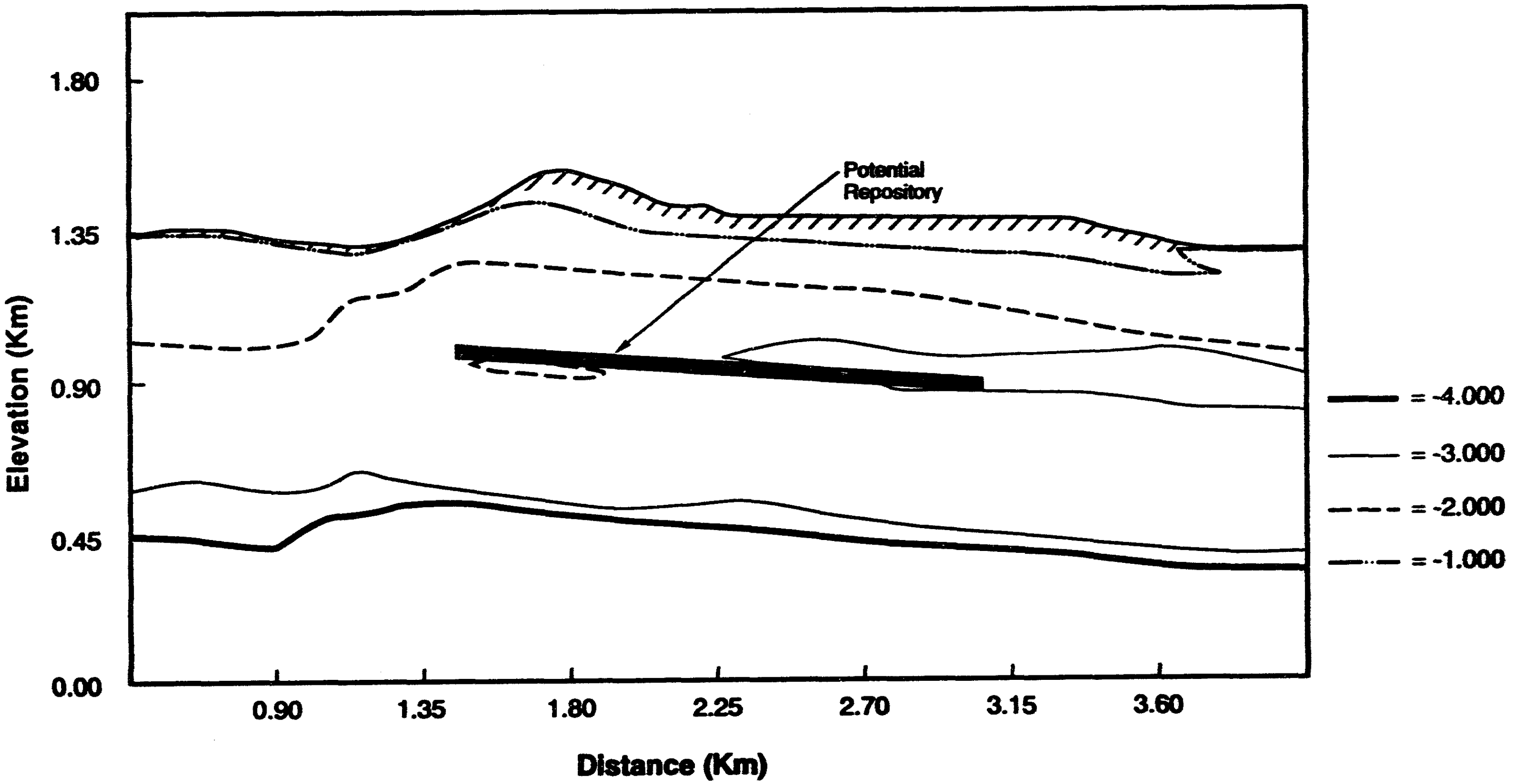


Figure 3-11
Stress Contours for a Southern Cross Section

vertical fractures is not significant, except in the most fractured areas. As explained subsequently, these areas are not likely to be sealing areas. As concluded by Bauer and Holland (1987), both linear and nonlinear models can be used to approximate measured data for in situ stress.

The minimum horizontal, maximum horizontal, and vertical stresses for (each sealing location for several boreholes) (illustrated in Figure 3-12) are presented in Tables 3-3 through 3-5, based upon the stress profile at the exploratory shaft used in previous design studies. The results show that the most significant variation is with depth and that the current stress profiles for these stresses at this location may be used to evaluate stress at individual seal locations.

In summary, the results show that at the sealing location near the Paintbrush/Topopah Spring contact, the stresses range from 0.6 to 3.4 MPa. The results show that, for the Topopah Spring Unit at the potential repository horizon, the stresses range from 2.4 to 9.2 MPa and that at the Calico Hills/Topopah Spring location, the stresses range from 2.9 to 10.4 MPa.

3.3.2 Temperature

This section presents evaluations of the state of thermal stress at various sealing locations. As discussed in Chapter 5.0 of this report, the state of thermal stress forms the far-field stress boundary condition used to evaluate casing stability and increased rock or seal thermal stress in subsequent design calculations. After waste emplacement, temperatures within the rock mass rise due to heating from the radioactive waste and subsequent thermal conduction to the surrounding rock mass. The magnitude of the temperature rise depends on the spatial location (both in the vertical and horizontal directions) of the seals near the waste emplacement rooms. Also, it depends on other factors, such as the type of waste (spent fuel versus high-level waste), the age and power of the waste at the time of emplacement, and the schedule for waste emplacement. The preliminary calculations (Hardy et al., 1992) presented below were performed for a selected series of boreholes (illustrated in Figure 3-13). These boreholes include those within the potential repository boundary (USW SD-4, USW SD-6, USW H-5, USW MPBH-2, and USW UZ-6), and near, but outside, the potential repository boundary (USW H-3, UE-25a #1, and USW H-1). For each borehole, the calculations were performed at the upper and lower seal locations, the potential repository horizon and at the water table.[2] These include the upper contact zone between the Topopah Spring Unit and the Paintbrush Unit, the potential repository horizon, and the contact zone between the Topopah Spring Unit and the Calico Hills Unit and the groundwater table.

The STRES3D computer code calculates temperatures using multiple planar sources and the principle of superposition, in that it calculates the rise in temperature at specific locations from each source and then adds these contributions together. The code calculates thermally induced

---

[2] The locations are approximate in that the model uses a semi-infinite half space and does not account for local variations in the elevation of the contact zone for specific boreholes.

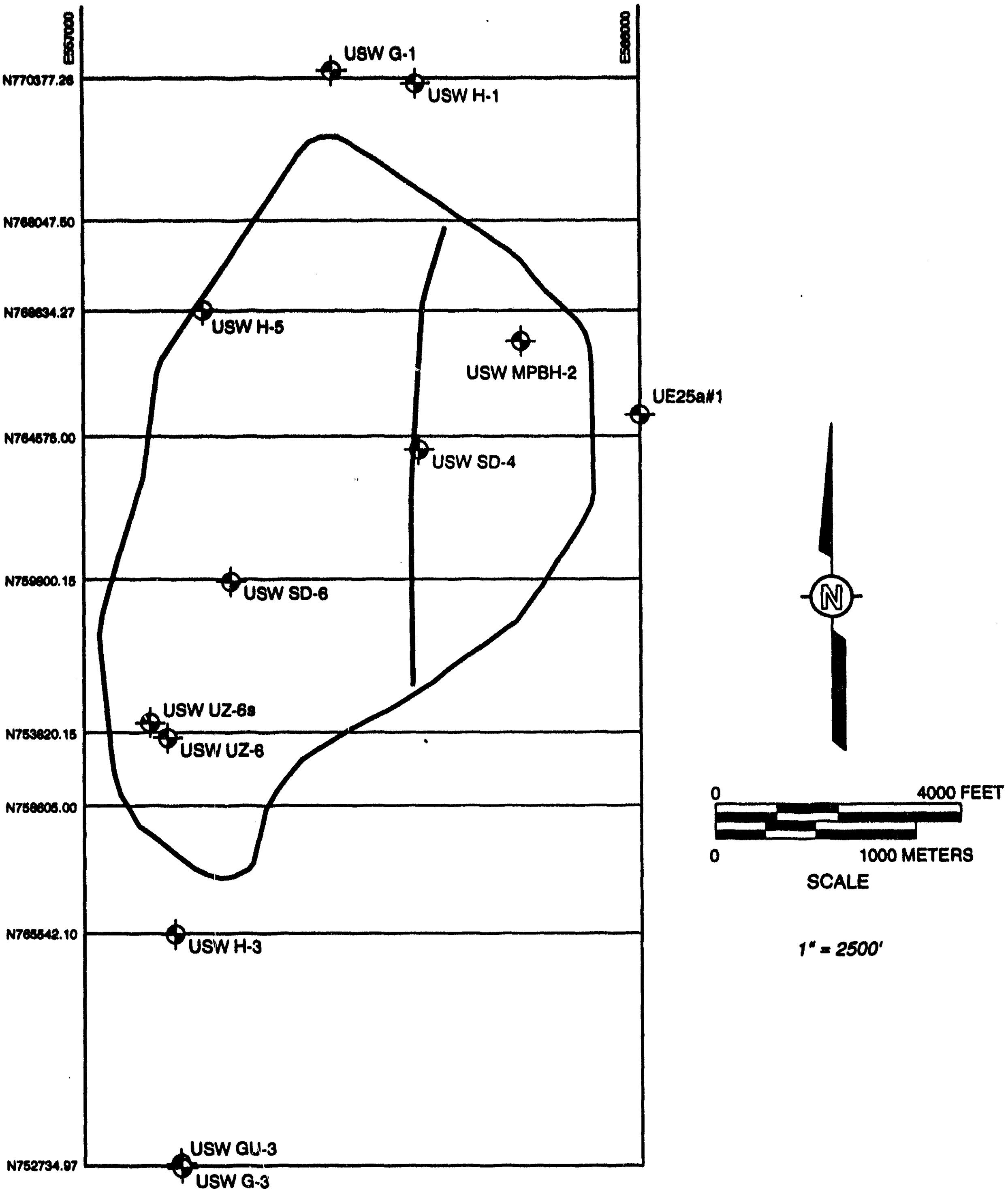


Figure 3-12
Borehole Locations for In Situ Stress Determinations

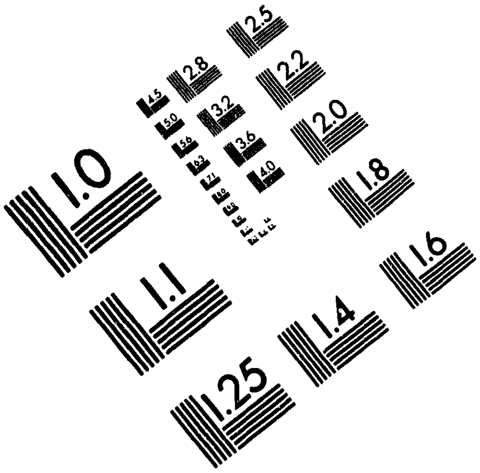
Table 3-3
Summary of Stresses at the Paintbrush/Topopah Spring Contact

Borehole ID	Depth to Contact (ft)	Minimum Horizontal Stress (MPa)	Maximum Horizontal Stress (MPa)	Vertical Stress (MPa)
USW H-1	332.4	0.72	1.44	2.09
USW H-3	450.7	0.70	1.41	2.66
UE-25a #1	422.1	0.64	1.29	2.53
USW H-5	569.6	0.91	1.82	3.29
USW UZ-6	585.1	0.92	1.84	3.39
USW MPBH-2	252.6	1.12	2.23	1.58
USW SD-4	246.8	1.15	2.29	1.55
USW SD-6	498.4	0.81	1.62	2.88
Maximum Value		1.15	2.29	3.39
Minimum Value		0.64	1.29	1.55

stresses using elastic closed-form analytical solutions for a semi-infinite homogeneous, isotropic half space. The analyses use the thermal and thermomechanical properties for the Topopah Spring Unit from the Reference Information Base (DOE, 1992). The calculations considered times of 10; 35; 50; 100; 300; 500; 1000; 2,000; 5,000; and 10,000 years for each of the borehole locations.

In addition, the following modeling assumptions are made:

- Heat transfer occurs by heat conduction.
- The potential repository is situated in a homogeneous, isotropic, and time-independent medium.
- The analysis assumes a constant surface temperature of 19°C.
- The analysis models the ground surface as a horizontal plane. The ground-surface elevation for all boreholes was assumed at 4,500 ft.

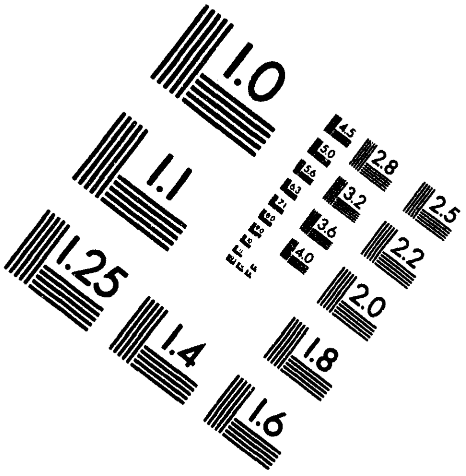


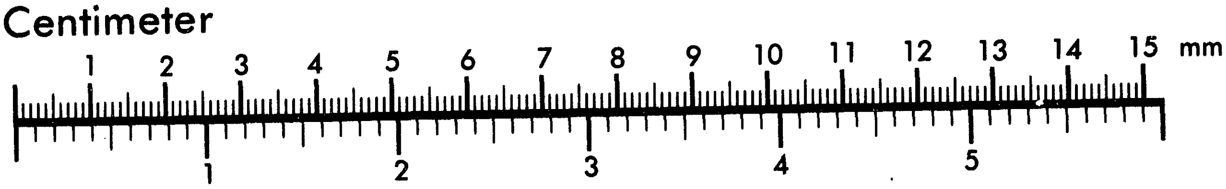
AIIM

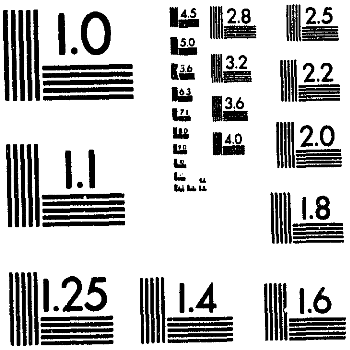
Association for Information and Image Management

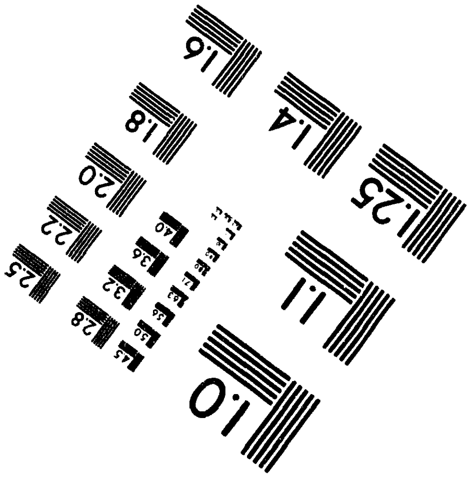
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

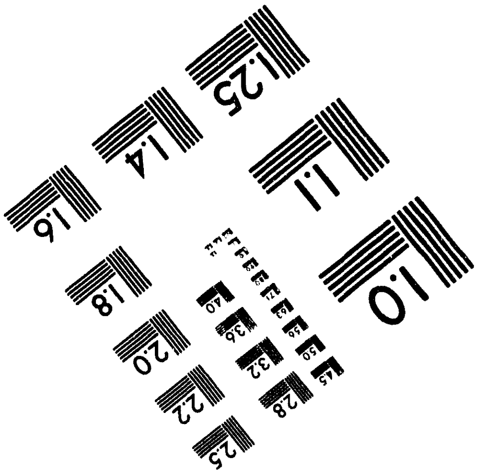
301/587-8202











MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 6

Table 3-4
Summary of Stresses at the Potential Repository Horizon

Borehole ID	Depth to Contact (ft)	Minimum Horizontal Stress (MPa)	Maximum Horizontal Stress (MPa)	Vertical Stress (MPa)
USW H-1	—	—	—	—
USW H-3	—	—	—	—
UE-25a #1	—	—	—	—
USW H-5	1473.2	3.10	6.20	9.21
USW UZ-6	1271.2	2.89	5.78	7.85
USW MPBH-2	1025.1	2.44	4.88	6.23
USW SD-4	1030.4	2.47	4.94	6.26
USW SD-6	1242.6	2.86	5.71	7.66
Maximum Value		3.10	6.20	9.21
Minimum Value		2.44	4.88	6.23

- The analysis evaluated five cases with different local area power densities (LAPD) and correspondingly scaled LAPDs as presented in Table 3-6.

- The waste configuration assumes the waste canisters are placed in vertical boreholes in the floor of the emplacement drift. The center of the waste canister is assumed to be 30 ft below the emplacement drift.

- For the higher heat loadings (87 and 100 kW/acre), the waste is emplaced in the northern end of the potential repository.

Tables 3-7 through 3-9 summarize the temperature calculations for several boreholes 60 years after waste emplacement and at the time of peak temperature. For a heat loading of 57 kW/acre, the highest peak temperature (80 to 90°C) occurs at the potential repository after 100 to 300 years. Slightly lower peak temperatures occur at the lower contact zone over a 500- to 1,000-year period. The upper contact zone experiences lower peak temperature (46°C) after about 1,000 to 5,000 years.

Table 3-5
Summary of Stresses at the Topopah Spring/Calico Hills Contact

Borehole ID	Depth to Contact (ft)	Minimum Horizontal Stress (MPa)	Maximum Horizontal Stress (MPa)	Vertical Stress (MPa)
USW H-1	1411.9	3.05	6.10	8.78
USW H-3	1252.9	2.87	5.74	7.73
UE-25a #1	1461.1	3.09	6.18	9.13
USW H-5	1656.4	2.87	5.74	10.42
USW UZ-6	1458.3	3.09	6.18	9.11
USW MPBH-2	1372.0	3.00	6.01	8.52
USW SD-4	1302.5	2.93	5.85	8.06
USW SD-6	1467.5	3.10	6.20	9.17
Maximum Value		3.10	6.20	10.42
Minimum Value		2.87	5.74	7.73

Figures 3-14 through 3-19 present far-field thermally induced stresses for various heat loadings for USW SD-4 and USW H-5 at the upper contact zone and at the potential repository horizon. These boreholes were selected because USW SD-4 represented the most severe loading within the potential repository boundary. USW H-5 was selected to evaluate the thermal effects near the edge of the potential repository. At the potential repository horizon, the results show horizontal compression of approximately 4 to 16 MPa and slight vertical decompression after about 100 years. Radioactive waste heat generation sustains the horizontal compression for several hundred years. After this time, temperatures decline (from 500 to 10,000 years). At the upper contact zone, the rock mass experiences a horizontal decompression of approximately 1 to 2 MPa and slight vertical compression. At this zone, the results show a reversal in thermally induced stress from tension to compression from 300 to 1,000 years. After this time, temperatures decline gradually (from 2,000 to 10,000 years).

Other boreholes within the potential repository or near the potential repository boundary show similar trends in the development of far-field thermal stress. The analysis predicts a smaller rise in temperature and thermally induced stresses at the potential repository boundary or just outside of the potential repository boundary. At the potential repository horizon, the thermally induced

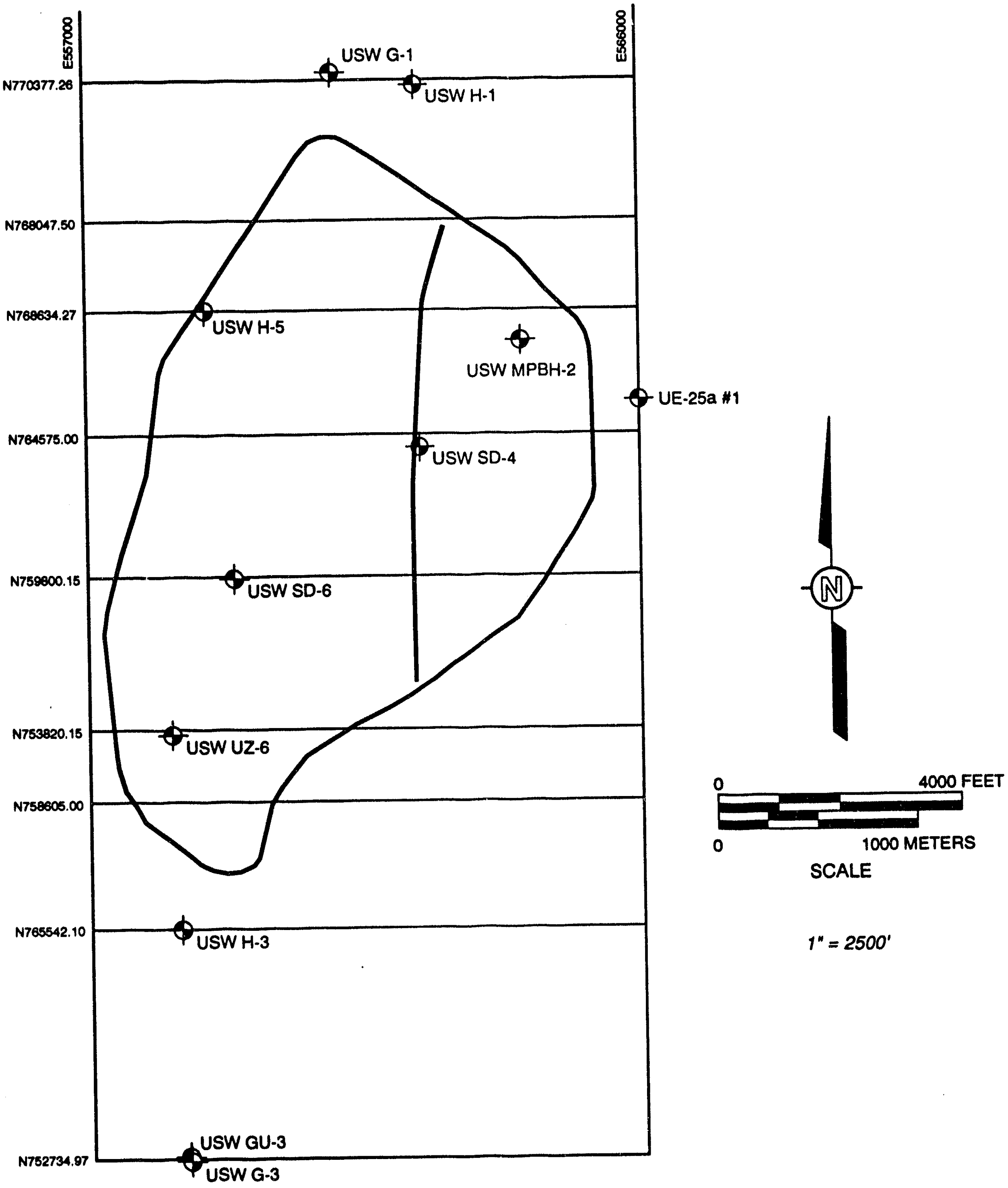


Figure 3-13
Borehole Locations for Thermal Stress Determinations

Table 3-6
Summary of LAPD Cases Evaluated for Selected Seals

Case	Nominal LAPD (kW/acre)	Adjusted LAPD (kW/acre)	Waste Age (years)	Power Output (kW/canister)	Canister (ft)	Spacing (m)
1	20	20	30	1.52	39.7	12.1
2	20	20	60	0.96	25.2	7.68
3	57	51.6	30	1.52	15.39	4.69
4	80	72.5	30	1.52	10.96	3.34
5	100	90.6	30	1.52	8.77	2.67

Table 3-7
Summary of Temperatures at the Paintbrush/Topopah Spring Contact

Borehole ID	Maximum Temperature		
	Temperature at 60 years (°C)	Temperature (°C)	Time (Years)
USW H-5	19.91	28.48	1000
USW UZ-6	19.58	20.06	5000
UE-25a #1	24.05	26.53	5000
USW H-1	21.73	23.89	5000
USW H-3	19.18	19.18	5000
USW MPBH-2	22.27	29.09	2000
USW SD-4	21.81	46.22	1000
USW SD-6	20.31	39.22	1000

stresses for USW H-5 (as illustrated in Figure 3-18) show a slightly lower horizontal compression after about 100 years than shown for USW SD-4, as this borehole is located at the western edge of the potential repository. A slight vertical decompression occurs during this period. At the upper contact zone, the analysis shows similar trends as those for USW SD-4. For boreholes at some distance (UE-25a #1, USW WT-15, USW G-2, and USW WT-1), the analysis predicts almost no thermally induced effects.

Table 3-8
Summary of Temperatures at the Potential Repository Horizon

Borehole ID	Maximum Temperature		
	Temperature at 60 years (°C)	Temperature (°C)	Time (Years)
USW H-5	77.07	79.78	100
USW UZ-6	23.05	25.15	5000
UE-25a #1	—	—	—
USW H-1	—	—	—
USW H-3	—	—	—
USW MPBH-2	25.44	35.64	5000
USW SD-4	85.19	89.06	100
USW SD-6	84.21	99.78	300

3.3.3 Properties of the Rock Mass

Rock mass strength when combined with loading (ambient and thermal stresses) can be used as an indication of borehole stability. The stability of the borehole is itself important as an indication of where to place seals. Hoek and Brown (1980) proposed a criterion for the strength of discontinuous rock masses. Laboratory and in situ strength data were compiled and interpreted according to the following empirical relation:

$$\frac{\sigma_1}{\sigma_u} = \frac{\sigma_3}{\sigma_u} + \sqrt{m \frac{\sigma_3}{\sigma_u} + s}$$

where

σ_u = Unconfined compressive strength of intact rock
m, s = Constants depending on rock quality
σ_1, σ_3 = Major and minor principal stress at failure (ambient and/or thermal)

or alternatively,

$$\tau_n = A(\sigma_n - \sigma_{tn})^B$$

Table 3-9

Summary of Temperatures at the Topopah Spring/Calico Hills Contact

Borehole ID	Maximum Temperature		
	Temperature at 60 years (°C)	Temperature (°C)	Time (Years)
USW H-5	30.71	58.78	1000
USW UZ-6	24.29	26.79	5000
UE-25a #1	29.66	32.68	5000
USW H-1	27.56	31.72	5000
USW H-3	23.51	23.56	5000
USW MPBH-2	28.31	39.06	5000
USW SD-4	28.06	62.83	2000
USW SD-6	28.47	71.11	1000

where

σ_n = Normalized normal stress (ambient and/or thermal)
σ_{tn} = Tensile strength normalized to uniaxial compressive strength
A, B = Constants depending on rock quality
σ_1, σ_3 = Shear and normal stress on the failure plane normalized to uniaxial compressive strength
τ_n = Normalized shear stress.

$$\tau_n = \left(\frac{\tau}{\sigma_u} \right)$$

$$\sigma_n = \left(\frac{\tau}{\sigma_u} \right)$$

σ_u = Unconfined compressive strength.

Hoek and Brown (1980) provide a detailed discussion of the factors that influence rock mass-strength and propose a method for estimating rock-mass strength from laboratory testing and field investigations of rock-mass quality. The laboratory testing involves triaxial compression testing of intact rock over the range of confining pressures expected in the field. The test data are then

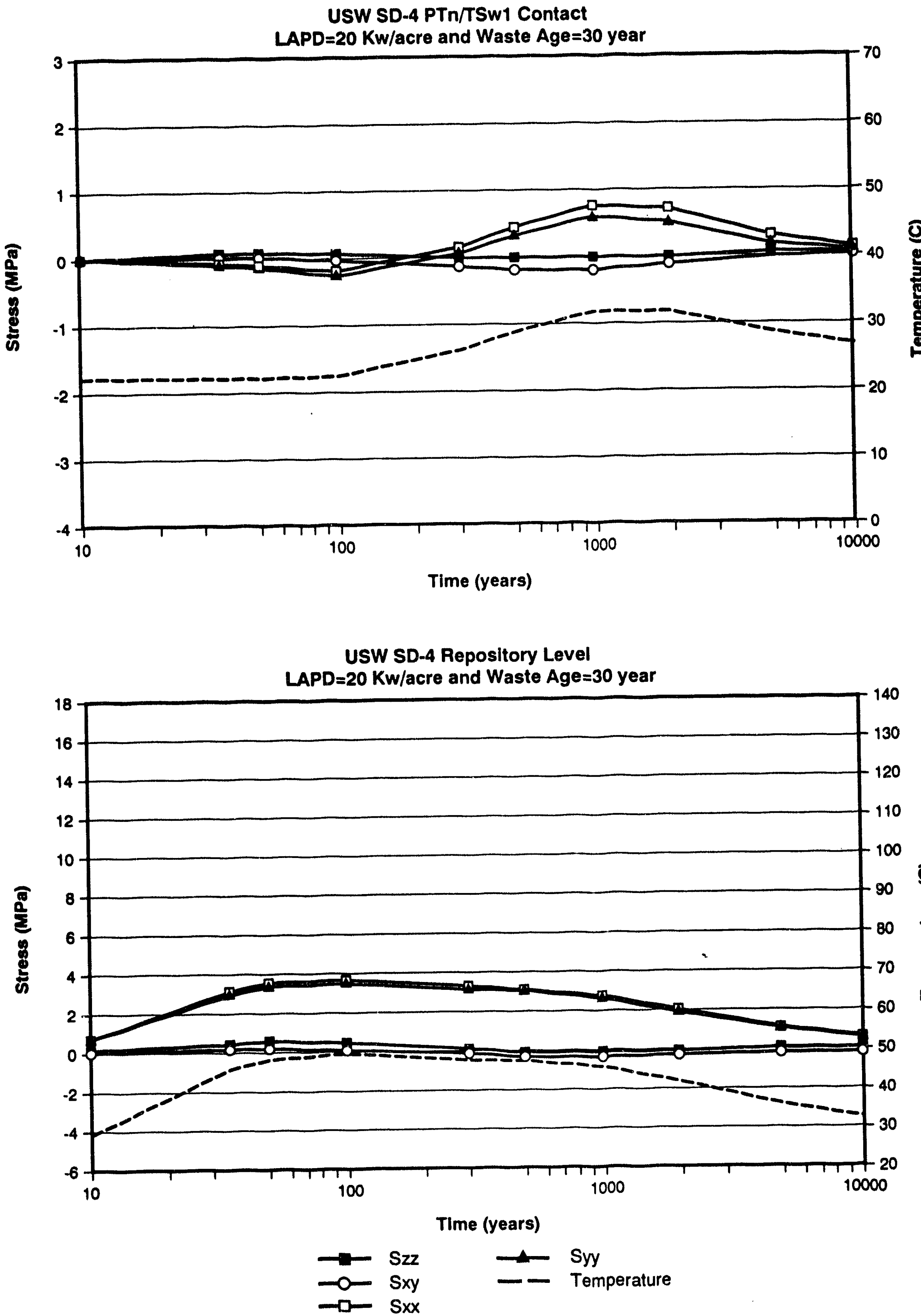


Figure 3-14
Development of Temperature and Thermal Stress for USW SD-4
(Local Areal Power Density of 2C kW per Acre) for Seal Locations 1 and 2

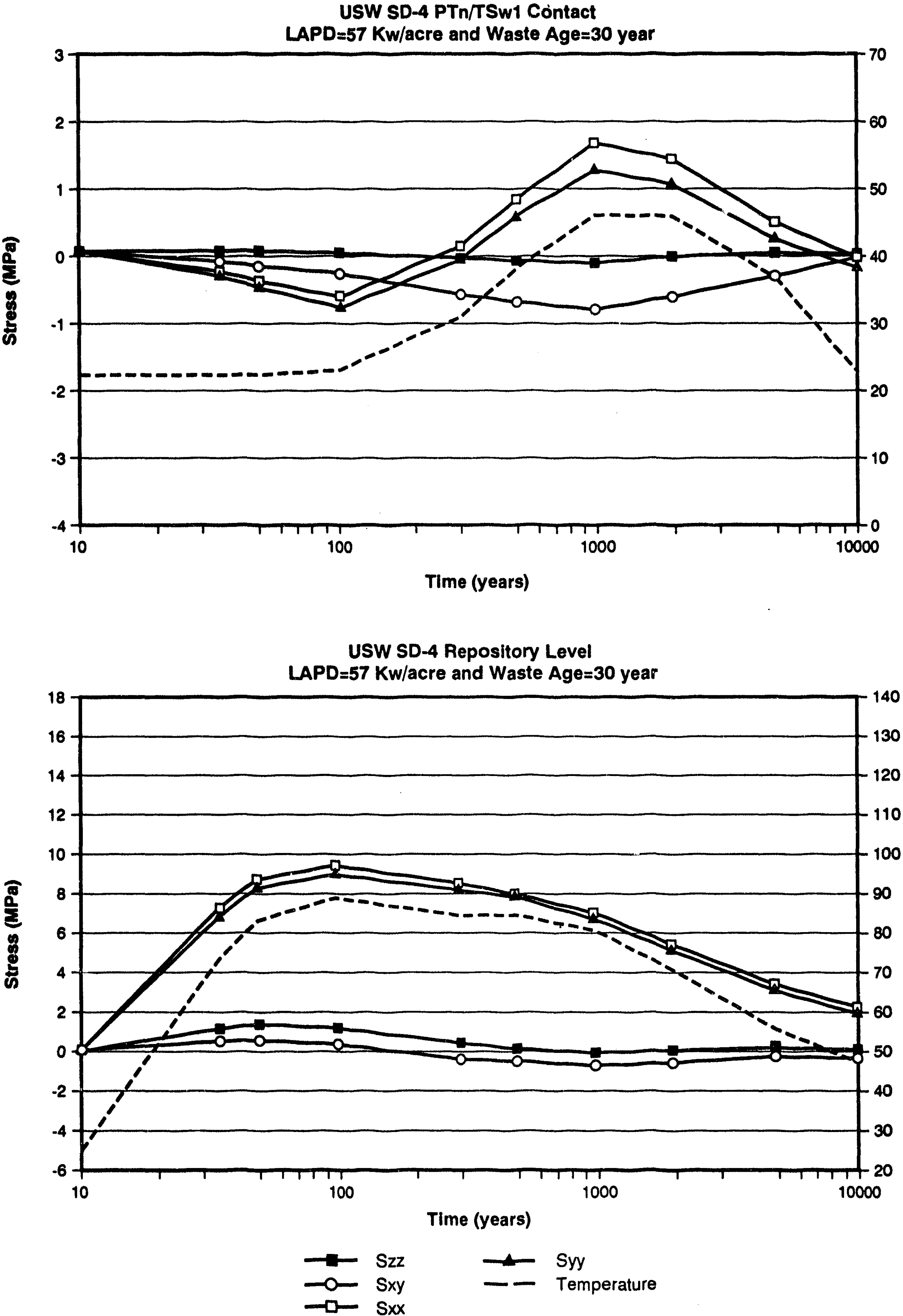


Figure 3-15
Development of Temperature and Thermal Stress for USW SD-4 *(Local Areal Power Density of 57 kW per Acre)* for Seal Locations 1 and 2

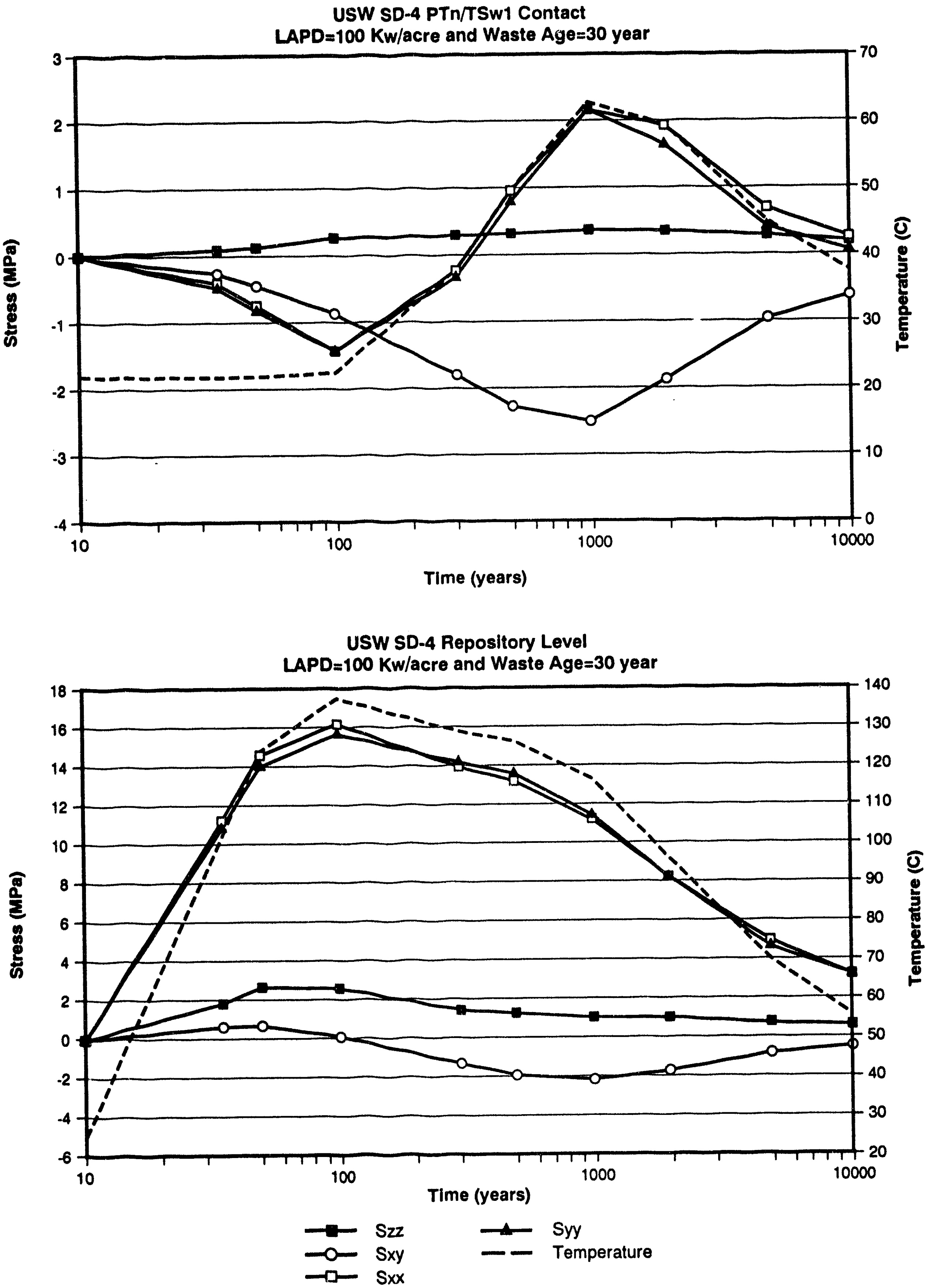


Figure 3-16
Development of Temperature and Thermal Stress for USW SD-4
***(Local Areal Power Density of 100 kW per Acre)* for Seal Locations 1 and 2**

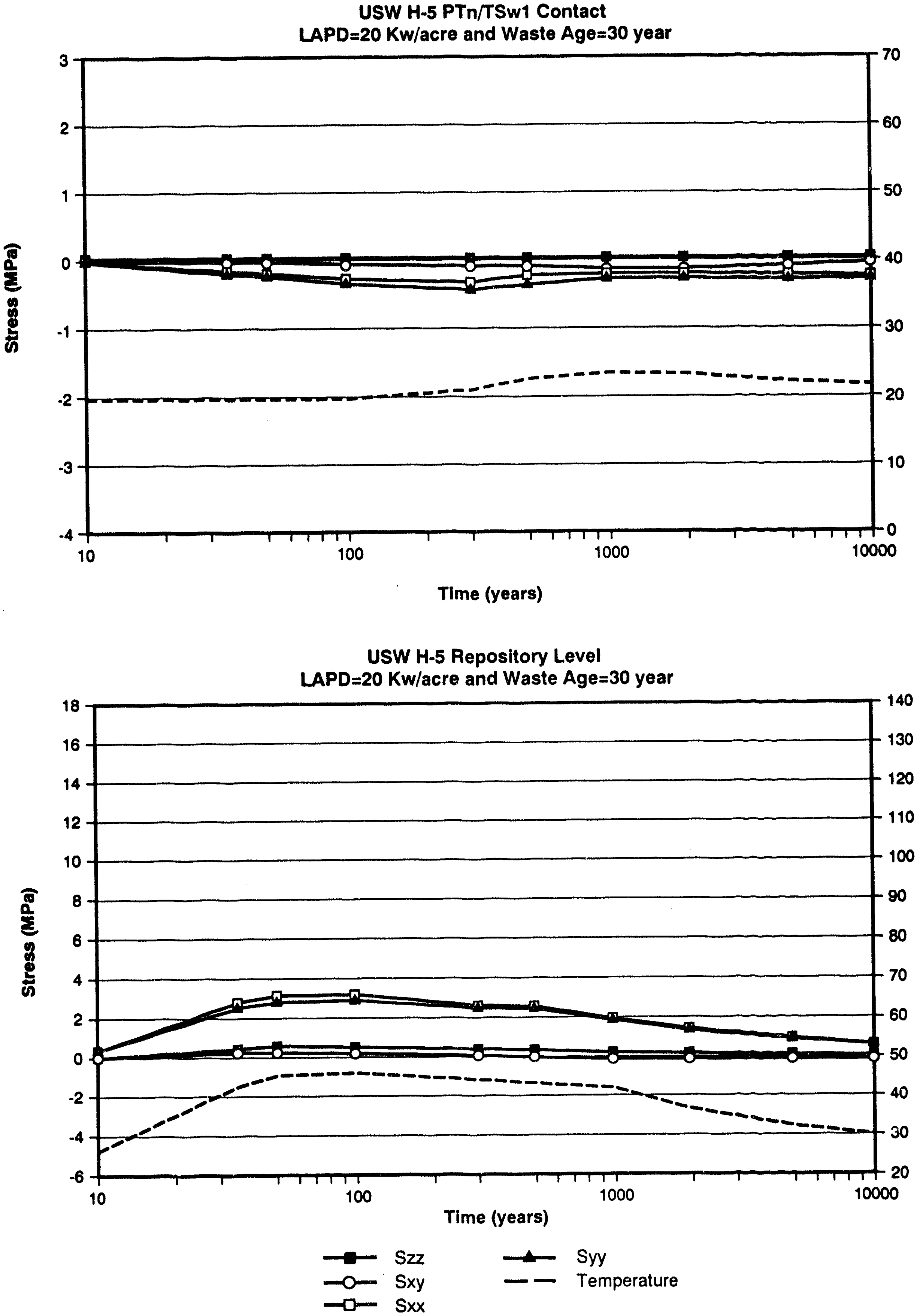


Figure 3-17

Development of Temperature and Thermal Stress for USW H-5 ***(Local Areal Power Density of 20 kW per Acre)*** **for Seal Locations 1 and 2**

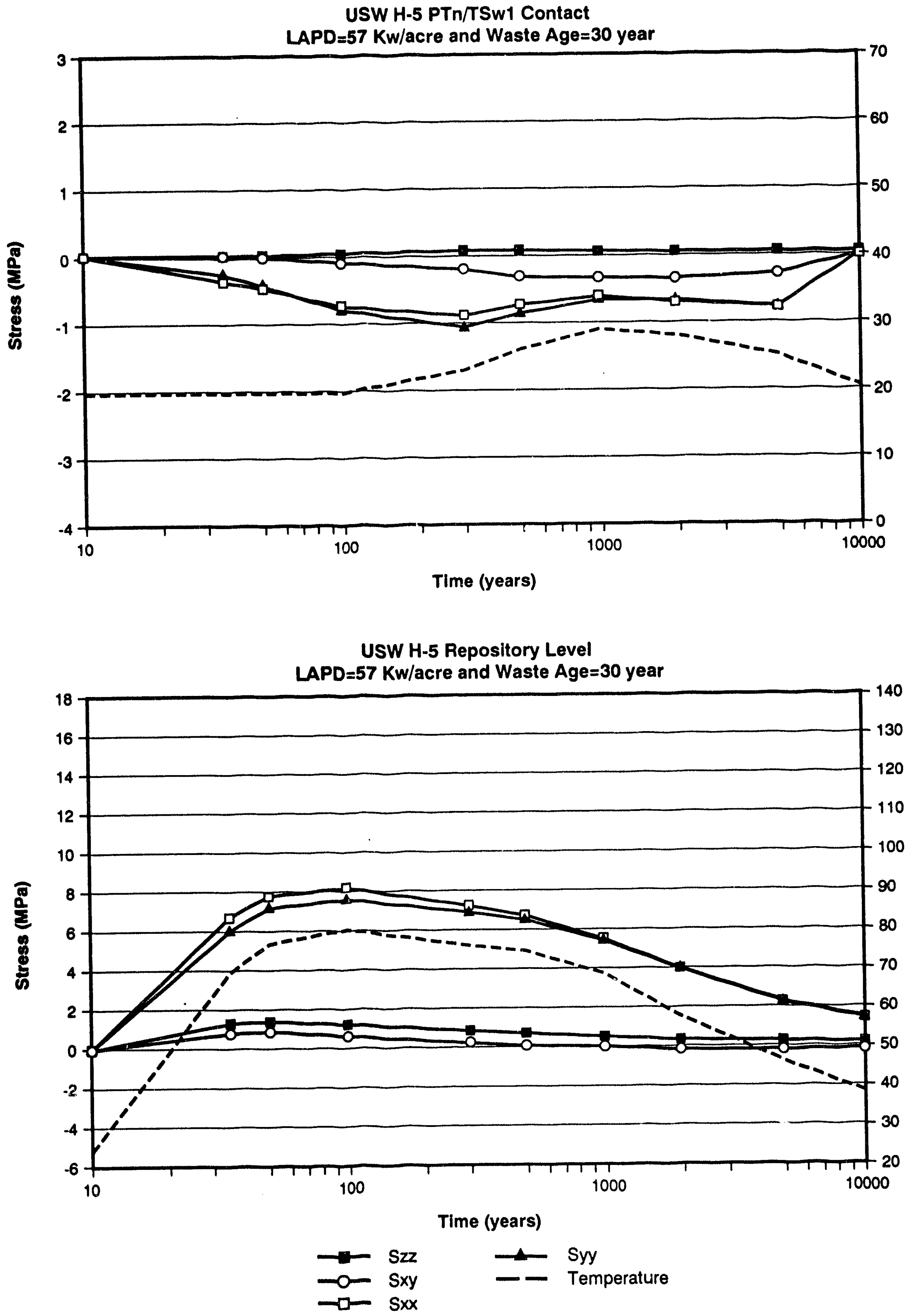
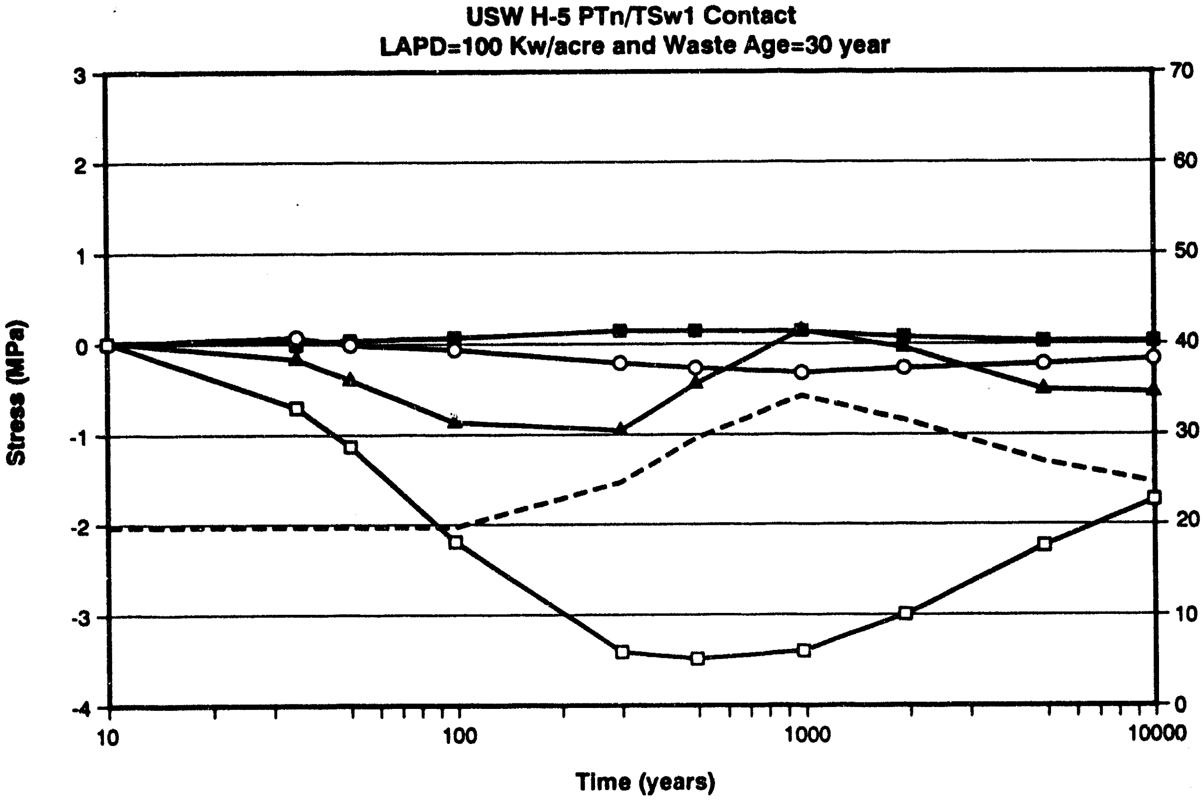


Figure 3-18

Development of Temperature and Thermal Stress for USW H-5 *(Local Areal Power Density of 57 kW per Acre)* for Seal Locations 1 and 2



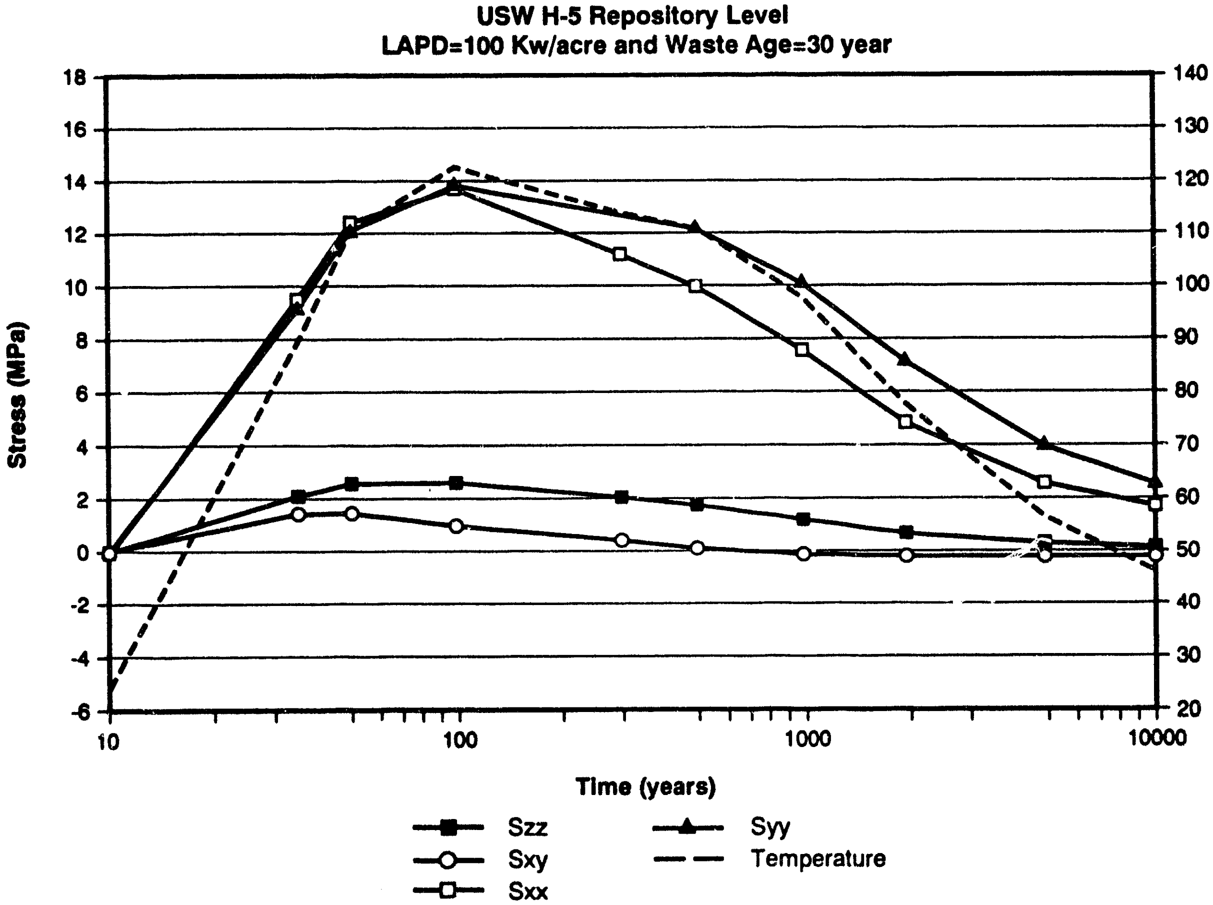


Figure 3-19

Development of Temperature and Thermal Stress for USW H-5 *(Local Areal Power Density of 100 kW per Acre)* for Seal Locations 1 and 2 analyzed statistically to obtain the *m* constant for intact rock. The field investigations involve rock mass classification, either by the Geomechanics Classification System Rock Mass Rating (RMR) (Bieniawski, 1984) or the Q System (Barton et al., 1974). The results obtained are input to empirical relationships to obtain *m* and *s* constants for the rock mass.

The method proposed by Hoek and Brown has been applied to the Topopah Spring lithophysal and nonlithophysal welded units and the Calico Hills Unit, for which laboratory and field data are available. The analysis presented below provides median, upper, and lower bound estimates to the expected rock mass strength for welded and nonwelded tuff.

Case and Kelsall (1987) present methods for determining the *m* and *s* parameters in the empirical strength criterion. This approach was adopted with updated unconfined (uniaxial) compressive strength, as presented in the Yucca Mountain Reference Information Base (DOE, 1992).

The rock mass quality for the welded, nonlithophysal Topopah Spring Unit and the nonwelded Calico Hills Unit was assessed by using the values for RMR and Q Systems provided by Langkopf and Gnirk (1986). The following is a brief summary of the rock mass quality obtained by means of the RMR method:

- Topopah Spring Unit
    - Unconfined Compressive Strength—The unconfined compressive strength ranged from 96 to 215 MPa; this results in an RMR strength ranging from 7 to 15.
    - Rock Quality Designation (RQD)—The average RQD obtained from data for several exploratory boreholes ranged from 35 to 80; this results in an RMR/RQD that ranges from 8 to 17.
    - Joint Frequency—The joint frequency values after accounting for bias from sampling near vertical fractures in vertical holes ranged from 2 to 16 fractures per meter; this results in a joint-spacing RMR that ranges from 10 to 20.
    - Joint Condition—A description of the rock mass condition upon which the lower bound estimate is based, including slightly rough surfaces, separation(s) of less than 1 mm, and hard-joint wall rock. The upper bound estimate rating of 12 is based on very rough surfaces, noncontinuous, nonseparated, hard-joint wall rock.
    - Groundwater Condition—The excavation is above the groundwater table, is considered dry, and is assigned the highest groundwater RMR of 10.

- Calico Hills Unit
  - Unconfined Compressive Strength—The unconfined compressive strength ranged from 10 to 34 MPa; this results in an RMR strength that ranges from 2 to 4.
  - RQD—The average RQD obtained from data for several exploratory boreholes ranged from 85 to 99; this results in an RMR/RQD that ranges from 17 to 20.
  - Joint Frequency—The joint frequency, after accounting for bias from sampling in vertical boreholes, ranged from 0.5 to 1.2 fractures per meter; this results in a joint-spacing RMR that ranges from 20 to 25.
  - Joint Condition—A description of the condition upon which the estimate is based includes slightly rough surfaces, separation of less than 1 mm, and soft-joint wall rock. This condition results in a joint-condition RMR of 12.
  - Groundwater Condition—The excavation is above the groundwater table, is considered dry, and is assigned the highest groundwater RMR of 10.

In the analysis presented by Langkopf and Gnirk (1986), the RMR adjustment for joint orientation ranged from zero, for a favorable orientation, to minus 12 for a very unfavorable orientation. These limits were also adopted herein for boreholes excavated through welded and nonwelded units; a favorable orientation was adopted for an upper-bound estimate, and unfavorable orientation was adopted for a lower-bound estimate.

The RMR for the Topopah Spring welded unit ranged from 35 to 74, with a corresponding rock mass assessment of very good to fair rock conditions. The RMR for the Calico Hills nonwelded unit ranged from 49 to 71, with a corresponding description of from good to fair rock conditions. The Topopah Spring unit exhibits a greater degree of variability reflecting, principally, variations in the RQD and joint spacing indices.

Priest and Brown (1983) present empirical relations that scale the intact properties for estimating the range of rock-mass strength from the RMR presented above. The upper bound corresponds to the unconfined compressive strength plus one standard deviation. The lower bound corresponds to the unconfined compressive strength minus one standard deviation. After identification of the triaxial failure criterion, the Mohr failure envelope is determined using the procedure outlined by Hoek and Brown (1980).

Figures 3-20 through 3-23 present the results of the analysis and indicate a broad range of conditions that could potentially be encountered. The lower bound for rock mass strength is considered conservative. Hoek and Brown (1980) state that the envelopes be used for preliminary analyses of underground excavation to establish the sensitivity of the design to changes in rock-mass behavior, and these results will be used in Chapter 4.0 for borehole scoping analyses.

Although the approach adopted by Hoek and Brown (1980) provides a promising method for assessing rock-mass strength of fractured rock, several assumptions and limitations should be noted. The scaling relationship presented by Priest and Brown (1983) is based upon a comprehensive set of strength data for Paguna andesite. Tests were performed on samples of intact rock, on undisturbed core samples, and on samples with various degrees of weathering. These samples were classified according to the RMR system, and except for the samples of intact rock, the RMR values ranged from 8 to 46. The range of RMR values (40 to 90) for welded and nonwelded tuff reflects unweathered joints encountered at depth and is somewhat higher than the range for Paguna andesite, except for the samples of intact rock and undisturbed core (RMR = 46). Thus, the scaling relationships developed by Priest and Brown (1983) in this analysis may reflect a different range of conditions than those that will be encountered for boreholes excavated in tuff.

The empirical strength criterion presented by Hoek and Brown (1980) is for the brittle failure of rock. The authors established a limitation that rock specimens should be tested and strength data evaluated under the test condition that the major principal stress, σ_1, should be at least twice as great as the confining stress σ_3. In conducting their own analysis, Hoek and Brown (1980) evaluated test conditions in which the major principal stress was at least 3.4 times greater than the confining stress; this value corresponds to the transition from the brittle to ductile behavior. The condition of $\sigma_1 = 2\sigma_3$ is easily satisfied for the higher-strength Topopah Spring tuff. In the case of the lower-strength nonwelded Calico Hills tuff, the condition is again satisfied, but test conditions were closer to the conditions in which ductile behavior would be in evidence.

The empirical strength criterion for fractured rock assumes that strength is isotropic or that no single discontinuity orientation affects strength. As stated by Hoek and Brown, this condition is satisfied for random jointing or where the discontinuities are grouped in four or more sets. Langkopf and Gnirk (1986) have considered fracture orientation sets as mapped from surface outcrops by Scott et al. (1983) at Yucca Mountain and as determined from oriented core and mapped surface fractures in drifts in Grouse Canyon welded tuff within the G-Tunnel complex. Analysis of these data indicated that the Topopah Spring Unit would have either two sets plus random joints or three sets plus random joints. In contrast, the joint spacing in the nonwelded tuff of the Calico Hills is such that the rock is characterized as massive with no or few joints. Thus, the effects of shearing on isolated discontinuities may result in strength anisotropy in the Calico Hills nonwelded tuff.

3.4 Borehole Wall Condition

Because of the modification that could occur to the geology (see Appendix C), it was anticipated that the condition of the borehole wall would vary depending on the degree of welding, the lithophysae content, the degree of fracturing, and the extent of clay and zeolitic mineral

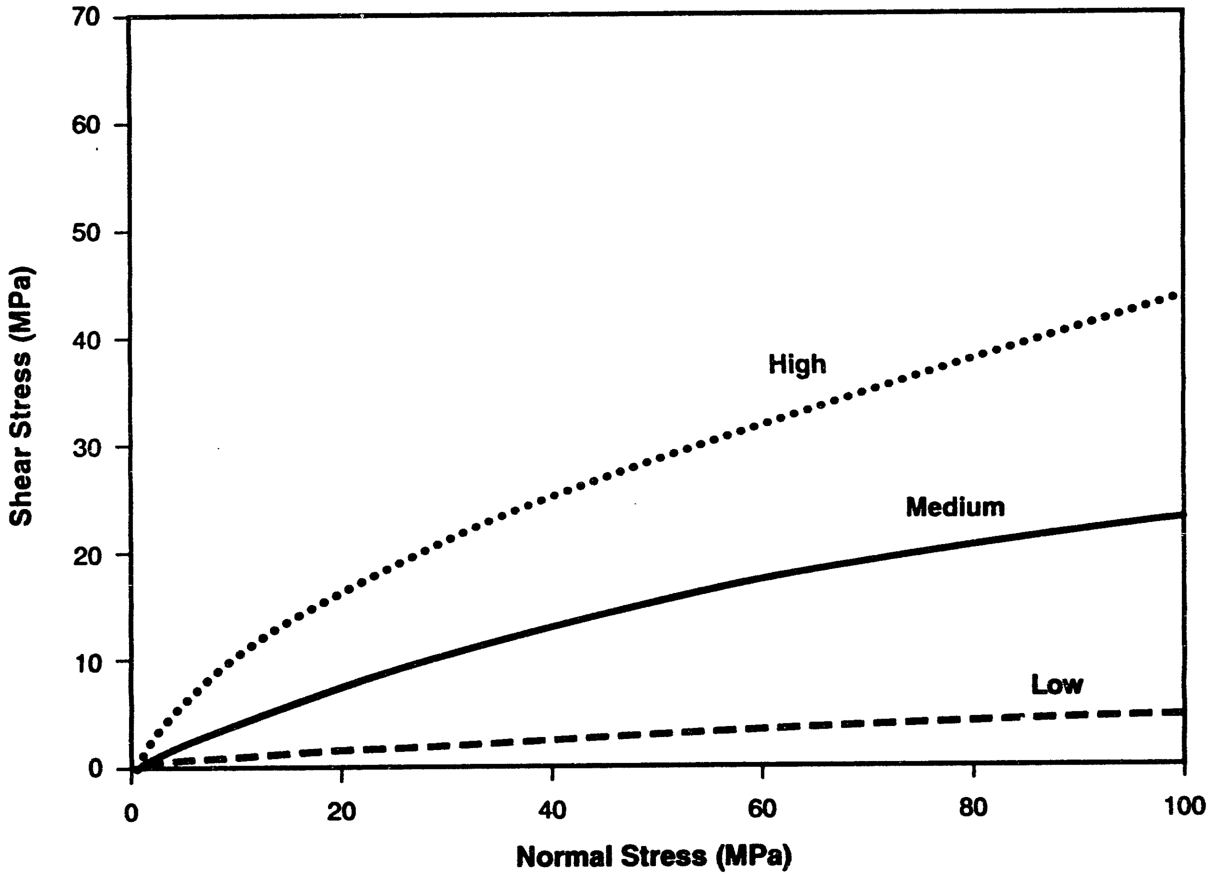


Figure 3-20
Mohr Failure Envelope (TSw1 Unit Lithophysae-Rich)

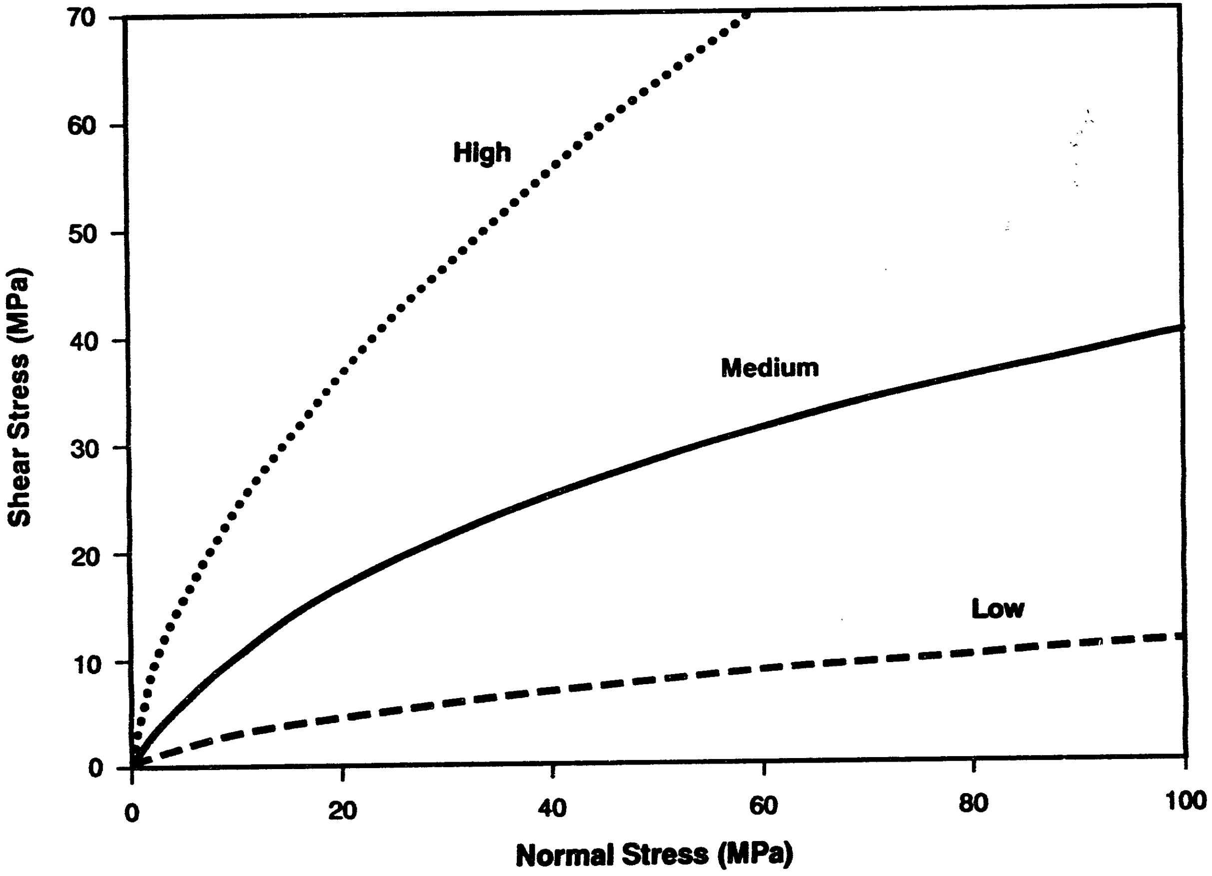


Figure 3-21
Mohr Failure Envelope (TSw1 Unit Lithophysae-Poor)

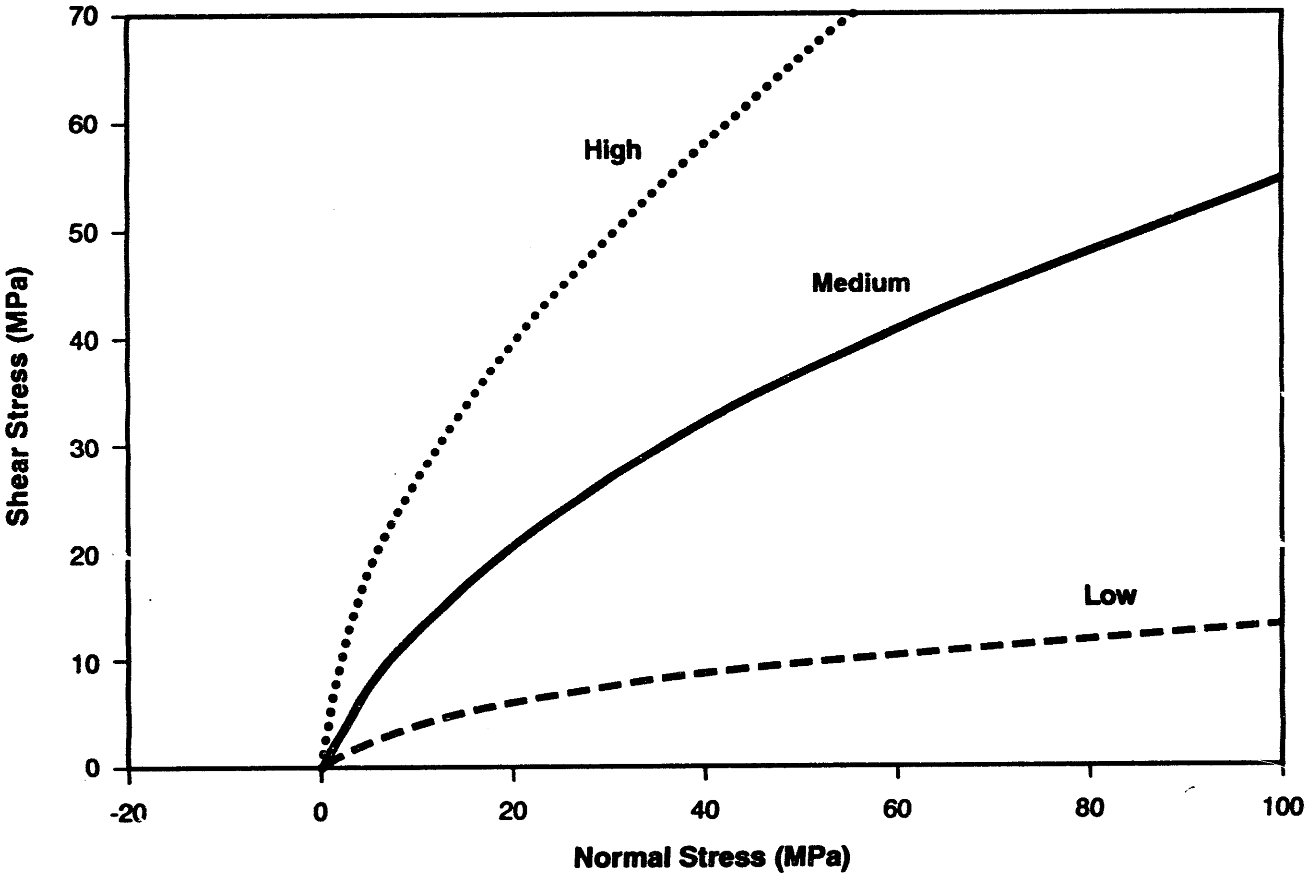


Figure 3-22
Mohr Failure Envelope (TSw2 Unit)

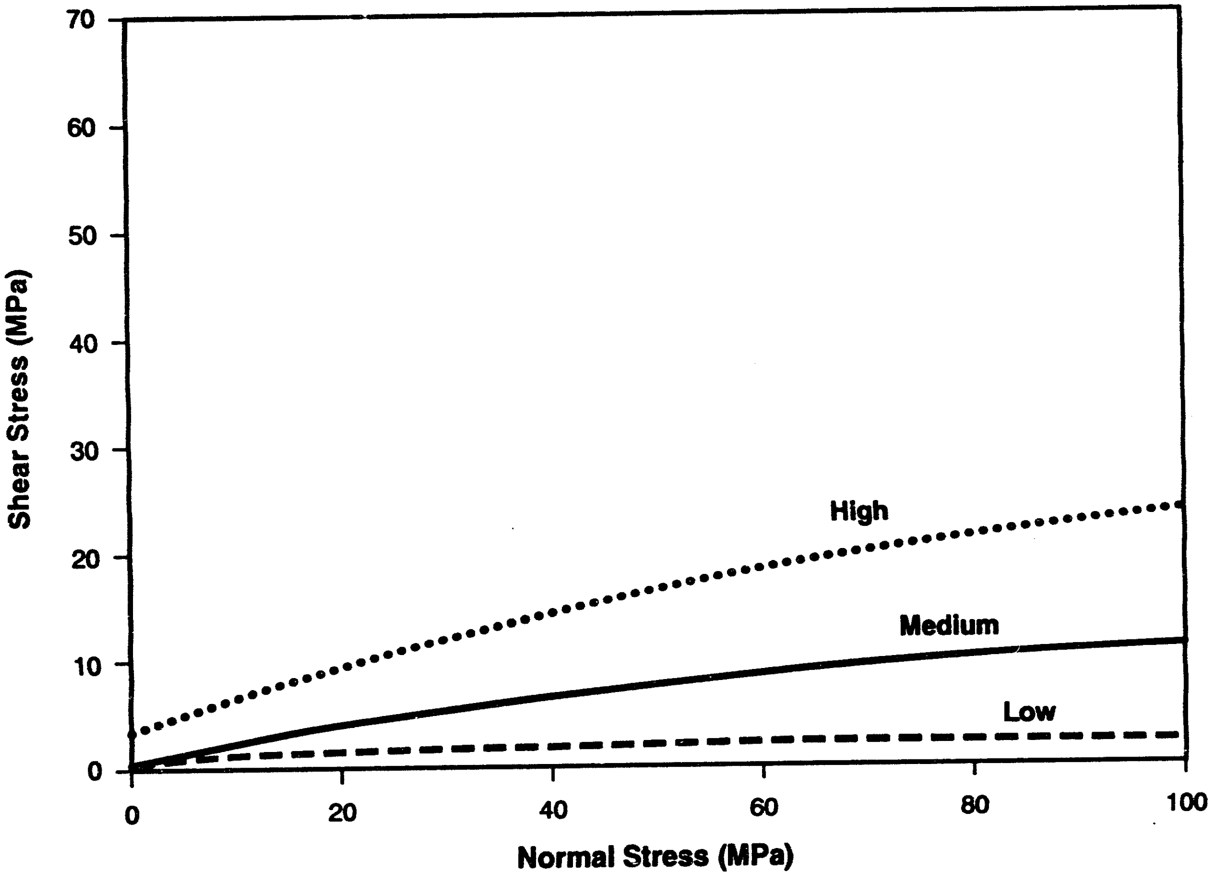


Figure 3-23
Mohr Failure Envelope (CHn1 Unit)

development in response to borehole drilling. This section assesses materials present in boreholes and the condition of the borehole wall to answer the following question: Are there unique features that would complicate the sealing of the borehole?

In the previous chapter selected boreholes were identified for logging, and a classification system was developed. In this chapter, a more detailed description with photographs is presented, as well as a more detailed description of borehole classification within individual units. In summary, the following generalization of the borehole wall condition can be made:

- A high percentage of Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and the Topopah Spring Members.
- The Paintbrush nonwelded tuff typically falls in Category C1.
- The upper portion of the Topopah Spring Member typically falls into Categories C1 and C2.
- The tuffaceous beds of Calico Hills nonwelded vitric and zeolitic tuff typically fall into Categories C1 and C2.
- Hole enlargement can occur within the softer nonwelded zones, such as the Calico Hills and the Pah Canyon, where alteration to smectites have occurred.

No special problems are likely to arise from placing seals in borehole locations categorized as C1 or C2. However, special considerations may be necessary for those areas that fall into Category C3 and may be most likely for Category C4 locations, due to their high degree of fracturing, irregularity, and hole enlargement. Problems could include loosing seal materials to the formation and difficulty in actual placement of the seal.

In all drilling operations, other materials have the potential for entering into the holes. These include the following:

- ***Defoamer Organosilicon Fluid Emulsion.*** This emulsion is added to an air foam mixture and subsequently introduced into the hole in limited quantities. After the hole is "blown out," trace amounts are anticipated to be left in the hole.
- ***Lithium Grease and Other Lubricants.*** These lubricants are used in assembling the drill stem and bit assembly. Only trace amounts are anticipated to be located in exploratory holes.
- ***Rock Drill Oil.*** This oil is used to lubricate the air stream. Only trace amounts are anticipated to be left in the hole.

As indicated above, trace amounts to no amounts of the materials mentioned above are anticipated to remain in the hole. As a result, their use should not impact the strategy to seal boreholes. However, other materials introduced into holes and conditions encountered in the holes need to be considered in developing a strategy to seal boreholes. These are summarized in Table 3-10. Tables A-8 and A-9 in Appendix A specify potential problems that could be encountered in the boreholes.

A brief discussion is presented below on the categorization within each major stratigraphic unit. The categories for borehole wall classification were presented previously in Section 2.4. Examples of borehole wall conditions are illustrated in Figures 3-24 to 3-35.

Tiva Canyon Member. The Tiva Canyon Member from its base can include a basal, air-fall, nonwelded, and unaltered tuff; a densely welded, vitric tuff; a densely to moderately welded, devitrified tuff; and a caprock. Because of the nature of tuff, variations in the degree of welding can be anticipated. As mentioned by Rautman and Flint (1992), the caprock unit of the Tiva Canyon appears to be absent from much of the potential repository site.

Typically the thickness of the densely to moderately welded, devitrified tuff for all the wells surveyed is large in comparison to the remainder of the member. With the exception of USW UZ-1, the thicknesses vary from approximately 100 ft in USW G-4 to 380 ft in USW UZ-6. Most often the borehole wall condition categorizes as C2 and C3. The worst wall conditions are encountered in boreholes USW UZ-6, USW UZ-6s, and USW G-4, all of which are mostly C3 and C4.

Underlying this subunit is the occasional presence of a laterally extensive vitrophyre that occurs within the columnar microstratigraphic unit (cc) (Rautman and Flint, 1992). This feature is observed in boreholes USW GU-3, USW UZ-6 and USW UZ-6s, and USW WT-2, having thicknesses of approximately 4, 24, and 21 ft, respectively. The conditions of the wall in this zone are always either C1 or C2.

Beneath this vitrophyre, or the densely welded tuff, is a moderately to nonwelded vitric tuff. This section of the Tiva Canyon usually categorizes a C1, if nonwelded, to C3, if moderately welded. However, the majority of this zone is either C1 or C2. Only in boreholes USW G-4 and USW H-5 is a C3 designation given. Thicknesses can be as high as 125 ft.

The bedded/reworked tuff at the base of the Tiva Canyon is as much as 50 ft thick for the boreholes evaluated. In almost all cases, a C1 categorization is given. Clearly, from the discussion, the physical condition of the wall correlates to the degree of welding.

Table 3-10
Problems Encountered/Anticipated In Exploratory Boreholes

Removal of 2.875-in-OD tubing (or other size) with 12-in screen; freestanding.
Steel casing grouted in at surface.
Eroded zones and sloughing holes.
Lost circulation.
Uncemented steel casing in deeper holes.
Uncemented steel casing in shallow neutron holes, 20 to 120 ft in depth.
Cement on wall, typically neat cement plus 2% $CaCl_2$. Cement was placed and then drilled out.
Residual drilling fluids on borehole wall.
PVC pipe grouted at the surface.
Perforated casing cemented.
Perforated casing uncemented.
Steel casing spot-grouted at the bottom or along selected areas over the length of the casing.
Water inflows.
Removal of "grouted-in" seismometers.
Instruments in the UZ holes.
Deviations in the surface and at-depth coordinates.

In several of the drillers' logs, hole enlargement and washout were noted. In USW UZ-6, for example, hole enlargement was noted between 324 and 372 ft. Categories C3 or C4 were assigned to this interval, where a number of high-angle fractures were observed.

In USW GU-3, washout occurred between 358 and 425 ft. Within this zone, pumice fragments are common, and alteration of the groundmass to smectite varied from sparse to common. The reason for the washout could be attributed not only to the poorly consolidated nature of the basal tuff but also to the presence of the smectite. Both poor consolidation and the presence of clay would make the tuff more susceptible to erosion. Even though some washout occurred at this location, the wall was smooth and symmetrical and categorized as a C1 or C2.

Figure 3-24
USW G-4; Tiva Canyon Member; Densely Welded, Devitrified; 60 ft. (C4);
Borehole Diameter—12.25 in.

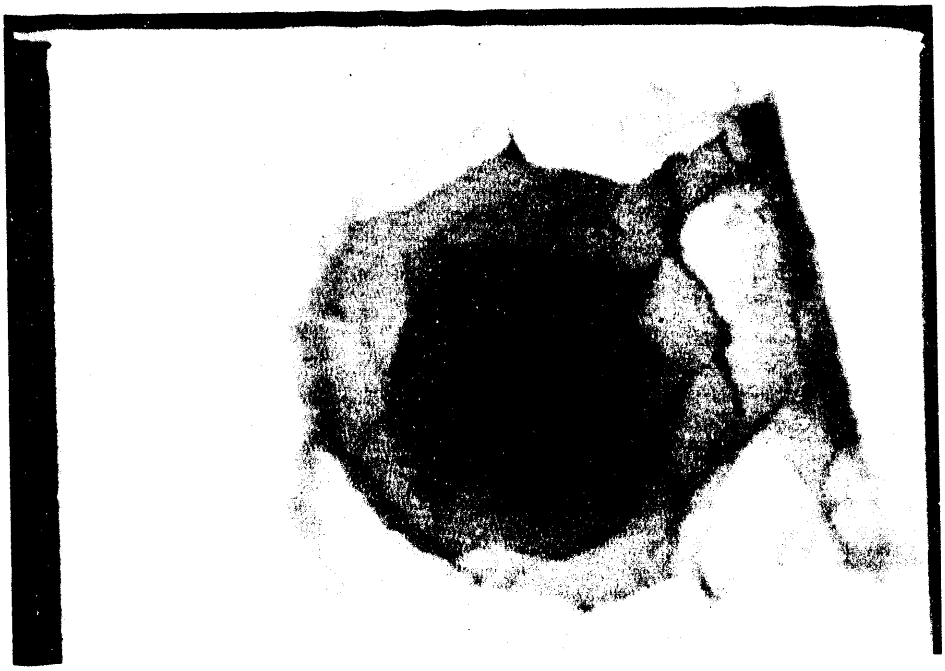


Figure 3-25
USW UZ-6s; Tiva Canyon Member; Densely Welded, Devitrified; 150 ft. (C3);
Borehole Diameter—8.34 in.

Figure 3-26
USW UZ-1; Yucca Mountain Member; Partly Welded to Nonwelded, Vitric; 80 ft. (C1); Borehole Diameter—36 in.

Figure 3-27
USW UZ-1; Bedded Tuff (Vitric) Below the Yucca Mountain Member; 95 ft. (C1); Borehole Diameter—36 in.

Figure 3-28
USW UZ-6; Topopah Spring Member Caprock; Densely Welded, Devitrified; 520 ft. (C4); Borehole Diameter—17.5 in.

Figure 3-29
USW UZ-6; Topopah Spring Member; Densely Welded, Devitrified; 850 ft. (C4); Borehole Diameter—17.5 in.

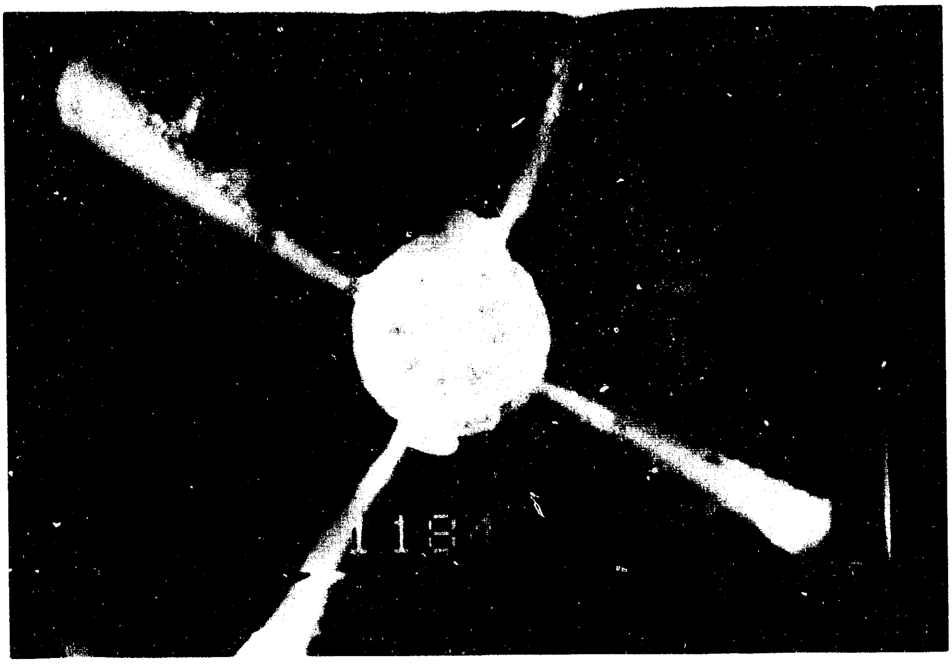


Figure 3-30
USW WT-2; Topopah Spring Member; Densely Welded, Glassy Vitrophyre; 1,184 ft. (C2); Borehole Diameter—8.75 in.

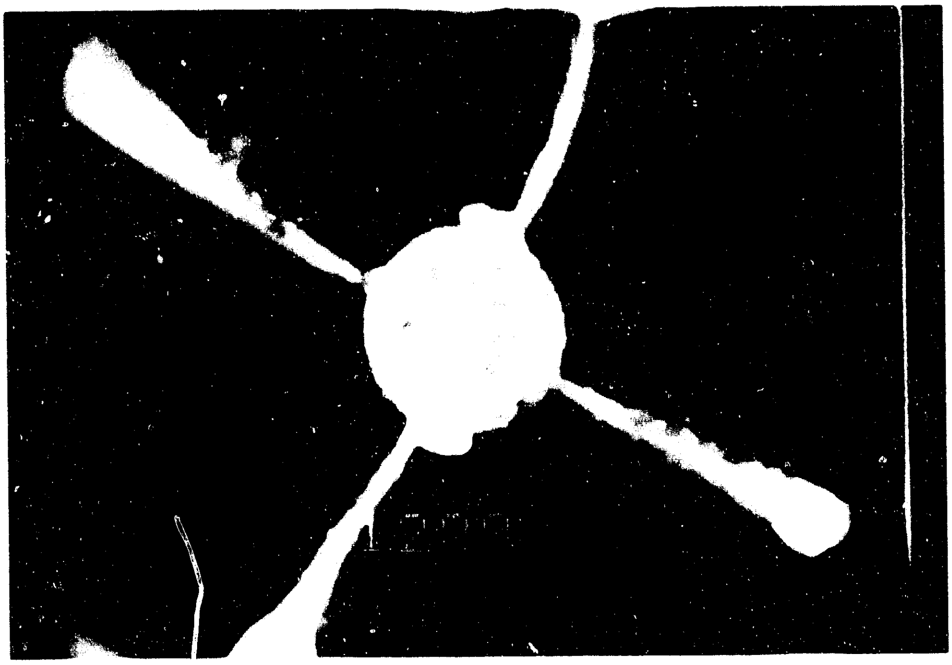


Figure 3-31
USW WT-2; Bedded/Reworked Tuff (Vitric) at Base of Topopah Spring Member; 1,299 ft. (C1); Borehole Diameter—8.75 in.

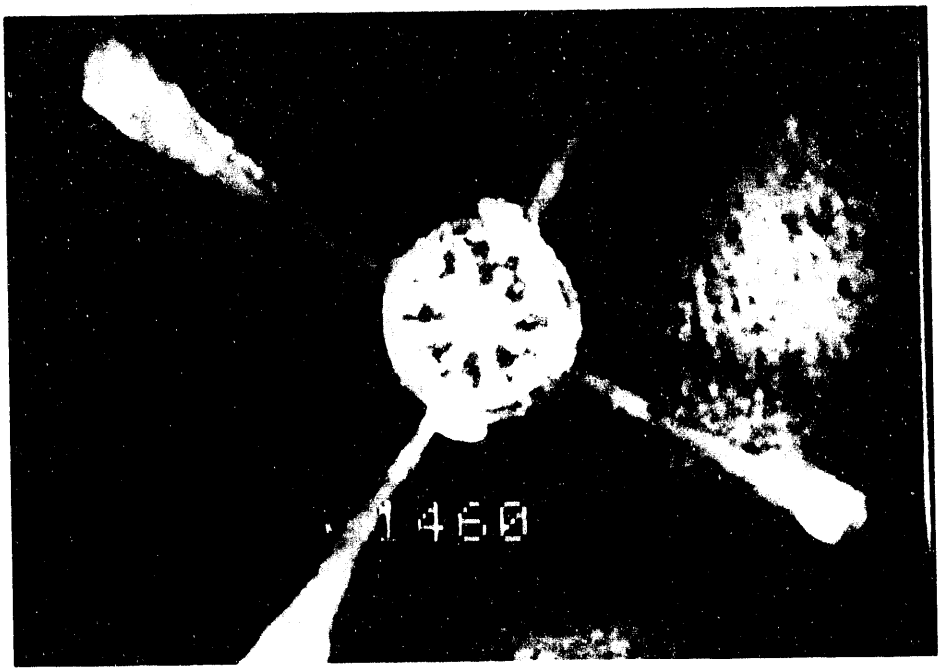


Figure 3-32
USW WT-2; Calico Hills Member; Nonwelded, Vitric;
1,460 ft. (C1); Borehole Diameter—8.75 in.

Figure 3-33
USW G-4; Calico Hills Member; Nonwelded to Partly Welded, Zeolitic;
1,416 ft. (C3); Borehole Diameter—12.25 in.

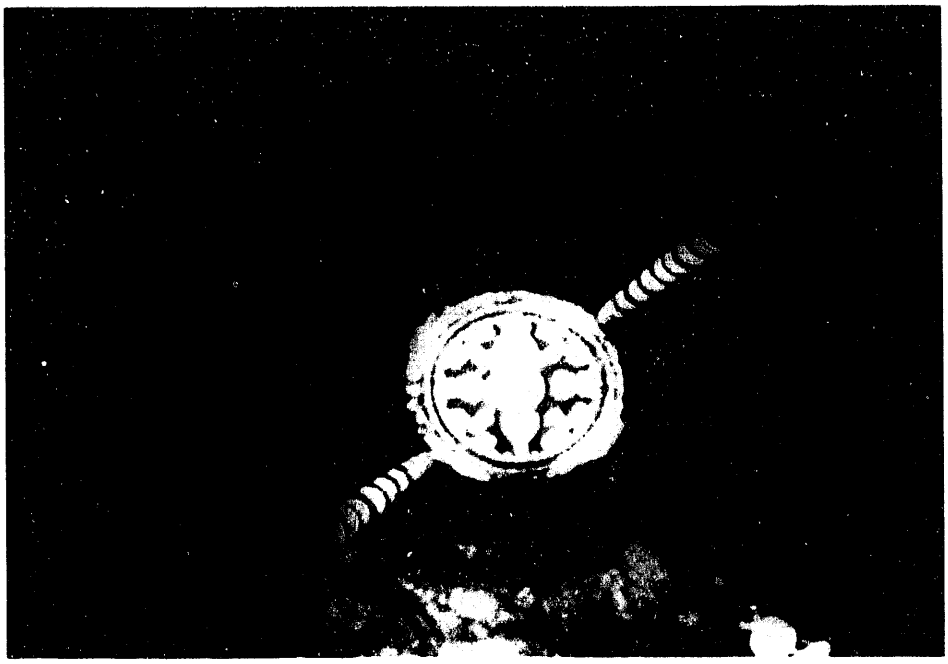


Figure 3-34
UE-25 WT#18; Topopah Spring Member; Densely Welded, Devitrified; 1,241 ft. (C2); Borehole Diameter—12.25 in.

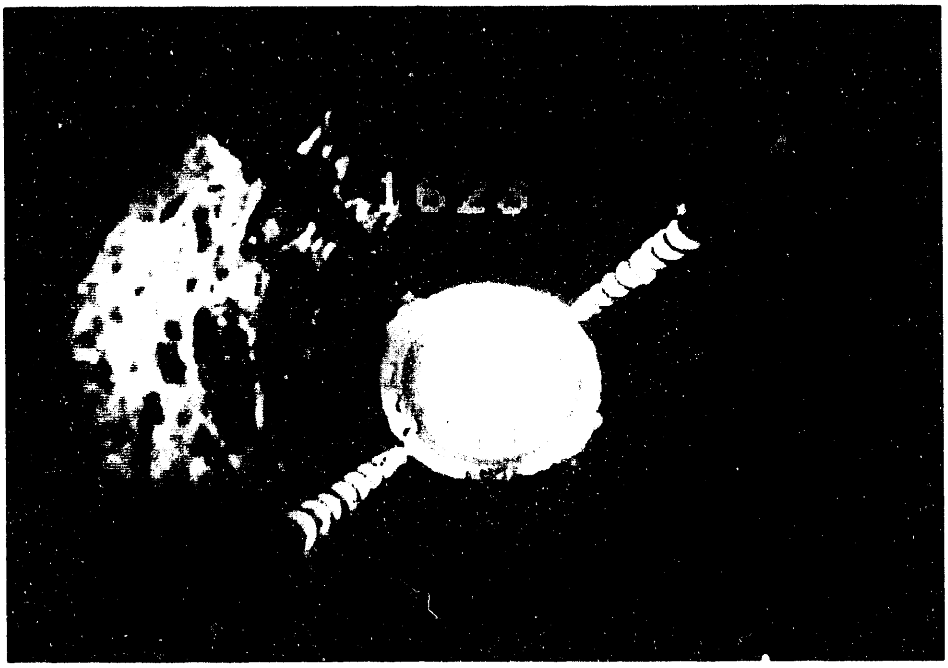


Figure 3-35
UE-25 WT#18; Calico Hills Member; Lava, Devitrified, Partly Zeolitic; 1,623 ft. (C1); Borehole Diameter—12.25 in.

Yucca Mountain and Pah Canyon Members. Typically, the Paintbrush nonwelded tuff thins from the northwest to the southeast. This can be seen in the cross sections given in Appendix B, where the PTn thickens to the northern end of the potential repository. Further, the Yucca Mountain and Pah Canyon Members are only discriminated in boreholes of interest that are located at the northern end of the potential repository, i.e., USW G-4, USW H-5, USW UZ-1, and UE-25 WT#18. In these boreholes, both members are comprised of moderately to nonwelded tuff, both vitric and devitrified. The bedded/reworked vitric tuff underlying both members is usually poorly consolidated. With only one exception (USW G-4 with a 1-ft interval), the Yucca Mountain Member categorizes as C1 or C2. In the Pah Canyon Member, portions of the nonwelded vitric layers in boreholes UE-25 WT#18 and USW G-4 were categorized as C4. The remainder was categorized as C1 or C2. Of the boreholes evaluated, the maximum thicknesses of the Yucca Mountain and the Pah Canyon Members are 119 and 217 ft, respectively.

In USW G-4, hole enlargement was noted in the driller's log between 180 and 199 ft in the Pah Canyon nonwelded vitric to the underlying poorly consolidated basal tuff. A very large hole was noticed between 180 and 187 ft that did not appear to be caused from fractures. A possible explanation is that because the vitric zones of this member are pervasively altered to smectites, their presence would make these zones more susceptible to erosion during borehole development. Also, in USW H-5, washout occurred between 420 and 570 ft, with maximum washout between 486 and 545 ft. This corresponds to the Pah Canyon Member. In this instance, because the hole maintained its smoothness and symmetry, it categorizes as a C1. Additionally, no major fractures or cavities were observed. In UE-25 WT#18, eroded and lost circulation zones occur from 465 to 564 ft. This range corresponds to the lower portion of the Yucca Mountain Member and the bedded vitric tuff through the nonwelded vitric zone of the Pah Canyon Member. It is in the Pah Canyon Member that the hole is categorized alternately between C1 and C4. Numerous areas have large, irregular voids and intense fracturing. Finally, lost circulation in USW UZ-1 occurs at the interface between the alluvium and the Yucca Mountain Member.

Topopah Spring Member. The Topopah Spring Member contains a very thin upper vitrophyre and a thicker vitrophyre closer to its base. Above the lower vitrophyre are moderately to densely welded, devitrified tuffs. Below this are moderately to partially welded vitric tuffs and nonwelded vitric tuffs. Above the upper vitrophyre are moderately welded to nonwelded tuffs. In this upper portion where the tuffs are nonwelded to moderately welded and vitric, they can be categorized as C1 or C2. Within the caprock portion, the wall conditions were categorized evenly between C1 and C4 in USW UZ-6. In UE-25c #2, the categories were C1 and C2. The thickness above the upper vitrophyre, if present, is less than 50 ft for the boreholes evaluated. The upper vitrophyre for the selected boreholes was on the order of several feet, while the lower vitrophyre ranges from about 30 to 80 ft. In all cases, the borehole walls within these zones were smooth and symmetrical and categorized as either C1 or C2. Above the lower vitrophyre, the densely welded, devitrified tuff was often categorized as C2 or C3, with some occurrences of C4. The vitric and bedded tuffs at the base of the unit were almost always categorized as C1 or C2. The combined thicknesses of these tuffs ranged from about 50 to 150 ft for the boreholes evaluated.

As shown in Appendix D, Categories C3 and C4 occur frequently due to the presence of large lithophysae, numerous fractures, and combinations of both. In USW GU-3, at about 500 to 575 ft (which is within the moderately to densely welded, devitrified portion), numerous hole enlargements occur due to a combination of fractures and lithophysae. In UE-25 WT#18, between 900 and 1,000 ft, a high percentage of lithophysae occurs throughout the entire zone. In USW WT#2, between 641 and 657 ft, the borehole wall appears to be notched, giving the appearance of a slab of rock being removed from the borehole. This feature is most likely fracture-controlled. In the same borehole, between 750 and 100 ft, in the densely welded, devitrified lower lithophysal zone, considerable hole enlargement occurs, due predominantly to the presence of large lithophysae.

The Tuffaceous Beds of Calico Hills and the Prow Pass Member. The Tuffaceous Beds of the Calico Hills and the Prow Pass Member generally contain a combination of nonwelded zeolitic and vitric tuffs and bedded and reworked tuffs. While there were limited borehole videos for these units, it is clear that the majority of the borehole walls within these units can be categorized as C1 or C2. In viewing the videos, fractures were detected in only a limited number of cases. In USW H-4, at approximately 1,400 and 1,420 ft, several fractures and voids were encountered. In USW UZ-6, the borehole was eroded over an interval from the partially to nonwelded, vitric base of the Topopah Spring Member through the poorly consolidated vitric portion of the Calico Hills into the nonwelded vitric portion of the Prow Pass Member. While this zone was eroded, it was smooth and symmetrical and categorized as C1.

3.5 Air Conductivity Models and Variability of Welded and Nonwelded Units

After emplacing waste containers, heat gradually transfers by conduction from the waste containers to the surrounding rock, achieving a maximum temperature in the rock adjacent to the potential repository after several thousand years. Vertical temperature gradients will develop from the potential repository horizon and potentially affect air and water-vapor density. If sufficient energy, in the form of heat, is imparted to the air or water vapor, convective transport is established. Also, barometric effects may induce flow from the potential repository to the ground surface.

The resistance to airflow for incompressible fluid flow depends on the length and cross section of the flow paths and air conductivities[3] of the flow-path materials. In previous analyses (Fernandez et al., 1989), three combinations of bulk rock hydraulic conductivity were evaluated. These combinations cover a range of conductivities for welded and nonwelded tuff and examine

---

[3] Air conductivity may be derived by calculating an intrinsic permeability from the hydraulic conductivity relationship presented by Freeze and Cherry (1979) and then calculating the air conductivity using the fluid properties of air.

the influence of a thinner less permeable layer of nonwelded tuff on total airflow rates if the conductivities of the welded tuff were high (10^{-2} cm/s). Table 3-11 shows these combinations.

Table 3-11
Air Conductivity of Welded and Nonwelded Tuff

	Nonwelded Air Conductivity (m/min)	Welded Air Conductivity (m/min)
Model 1 (Low)	4.1×10^{-7}	4.1×10^{-7}
Model 2 (Intermediate)	4.1×10^{-7}	4.1×10^{-4}
Model 3 (High)	4.1×10^{-5}	4.1×10^{-4}

The variations in thickness of the various welded and nonwelded units are shown in Figures 3-36, 3-37, and 3-38 for the Tiva Canyon, the Paintbrush, and the Topopah Spring Units above the potential repository, respectively. The variation in total thickness through the rock above the potential repository is illustrated in Figure 3-39, which shows that the thickness ranges from 300 m in the southeastern portion and 220 m on the western edge of the potential repository to 440 along Yucca Crest, in the northwestern portion of the potential repository. These figures illustrate less variability in unit thicknesses than in the range of conductivities presented above.

To understand the variations in resistance to airflow offered by the rock overlying the potential repository, conductance models were prepared for three combinations (models) of rock conductivities (given in Table 3-11). The conductance (C) is defined as:

$$C = \frac{1}{\sum_{i=1}^{3} \frac{L_i}{K_i}}$$

where

K_i = Air conductance of the *i*th unit
L_i = Thickness of the *i*th unit.

The conductance as used here is inversely proportional to resistance, directly proportional to air conductivity, and inversely proportional to the flow-path length. The conductance is calculated considering the thicknesses over the entire area shown in Figures 3-36, 3-37, 3-38, and 3-39. The spacing between discrete points is 76 m. The conductance is contoured in Figures 3-40, 3-41, and 3-42 for Models 1, 2, and 3, respectively, as a percentage of the maximum value calculated within the study area. For Model 2, the contour values vary over a broad range, and the

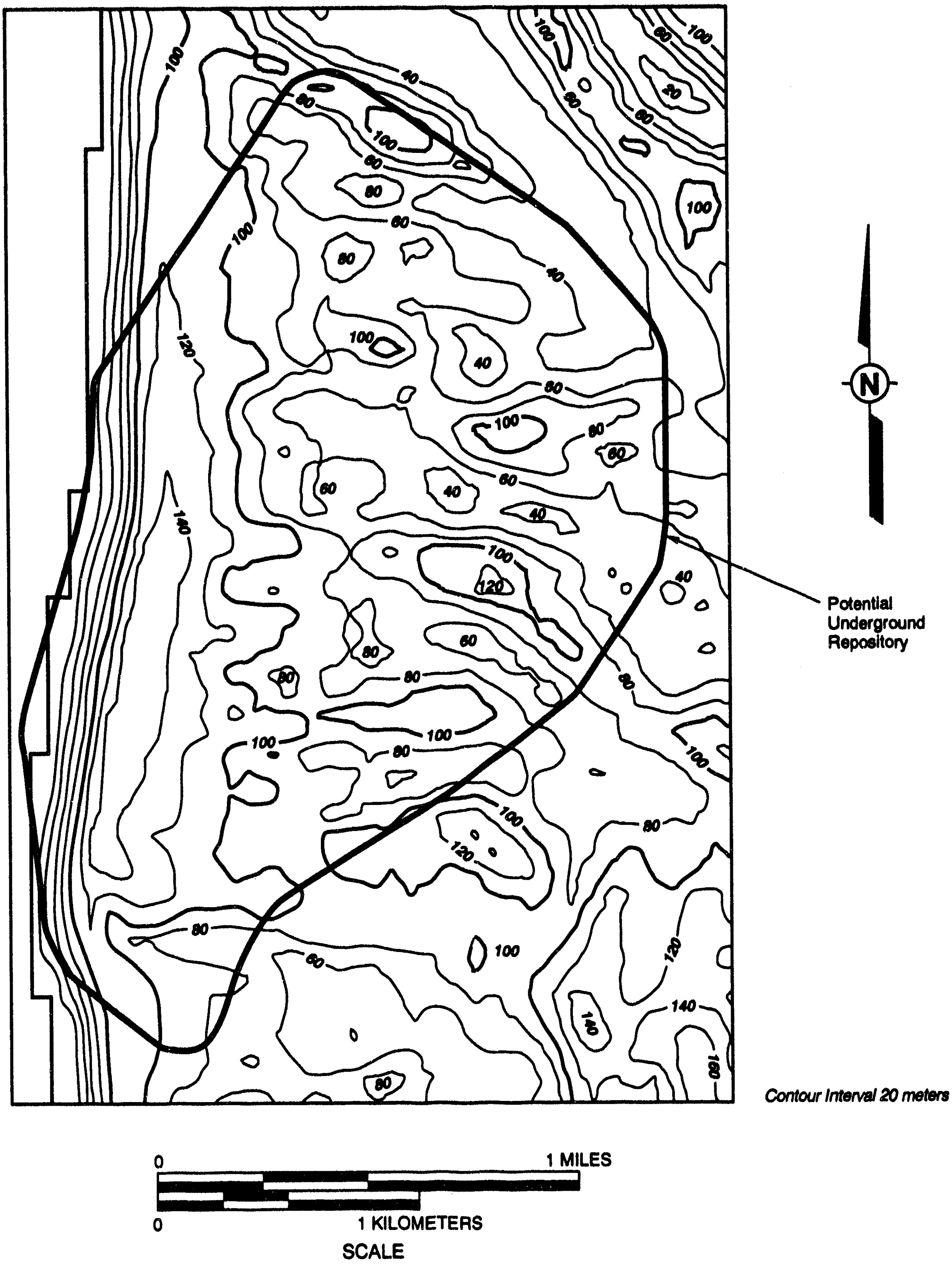


Figure 3-36
Thickness of the Tiva Canyon (TCw) Unit (REF0287)

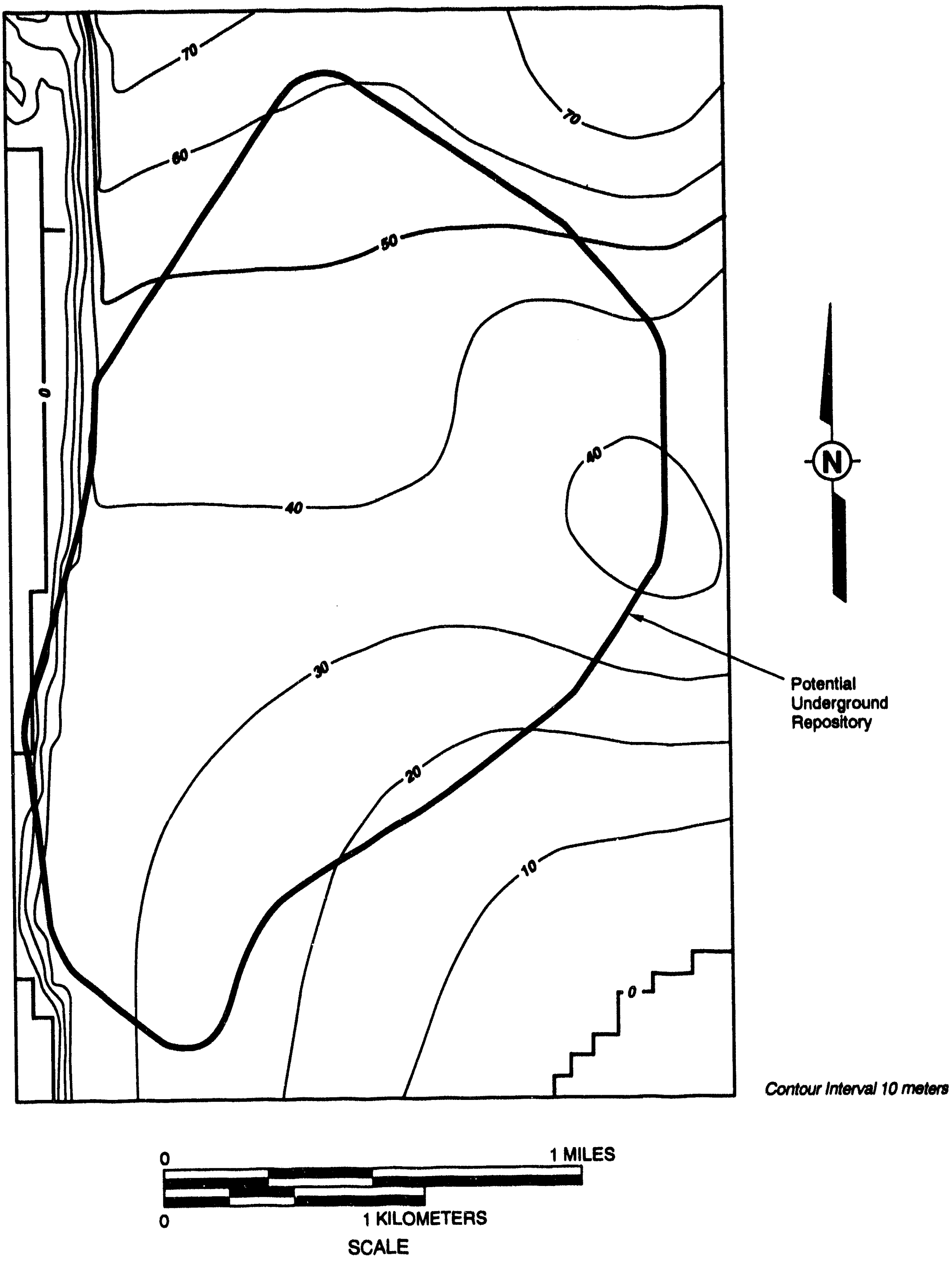


Figure 3-37
Thickness of the Paintbrush Nonwelded (PTn) Unit (REF0283)

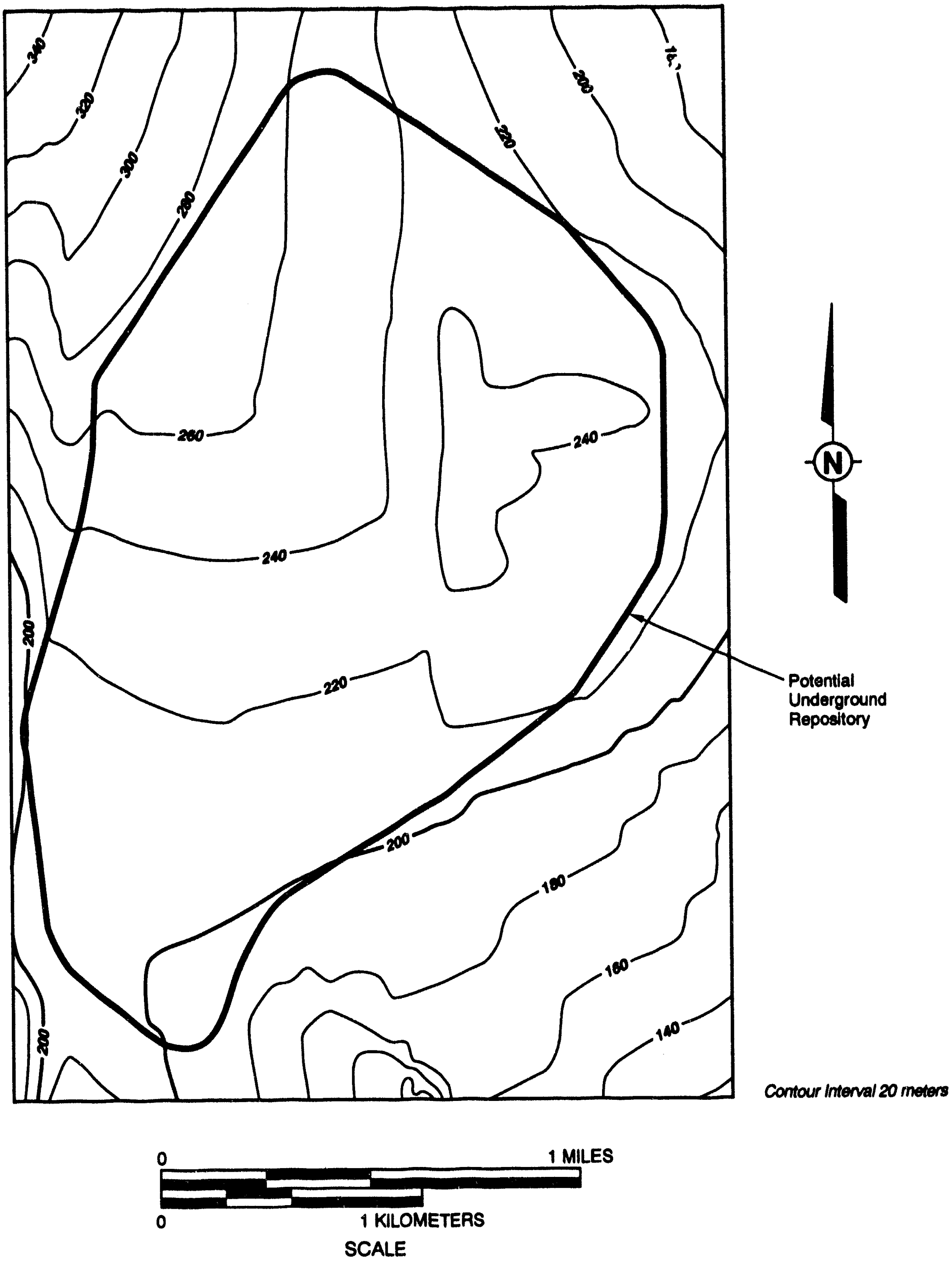


Figure 3-38
Thickness of the Topopah Spring Member Above the Repository Floor (REF0284)

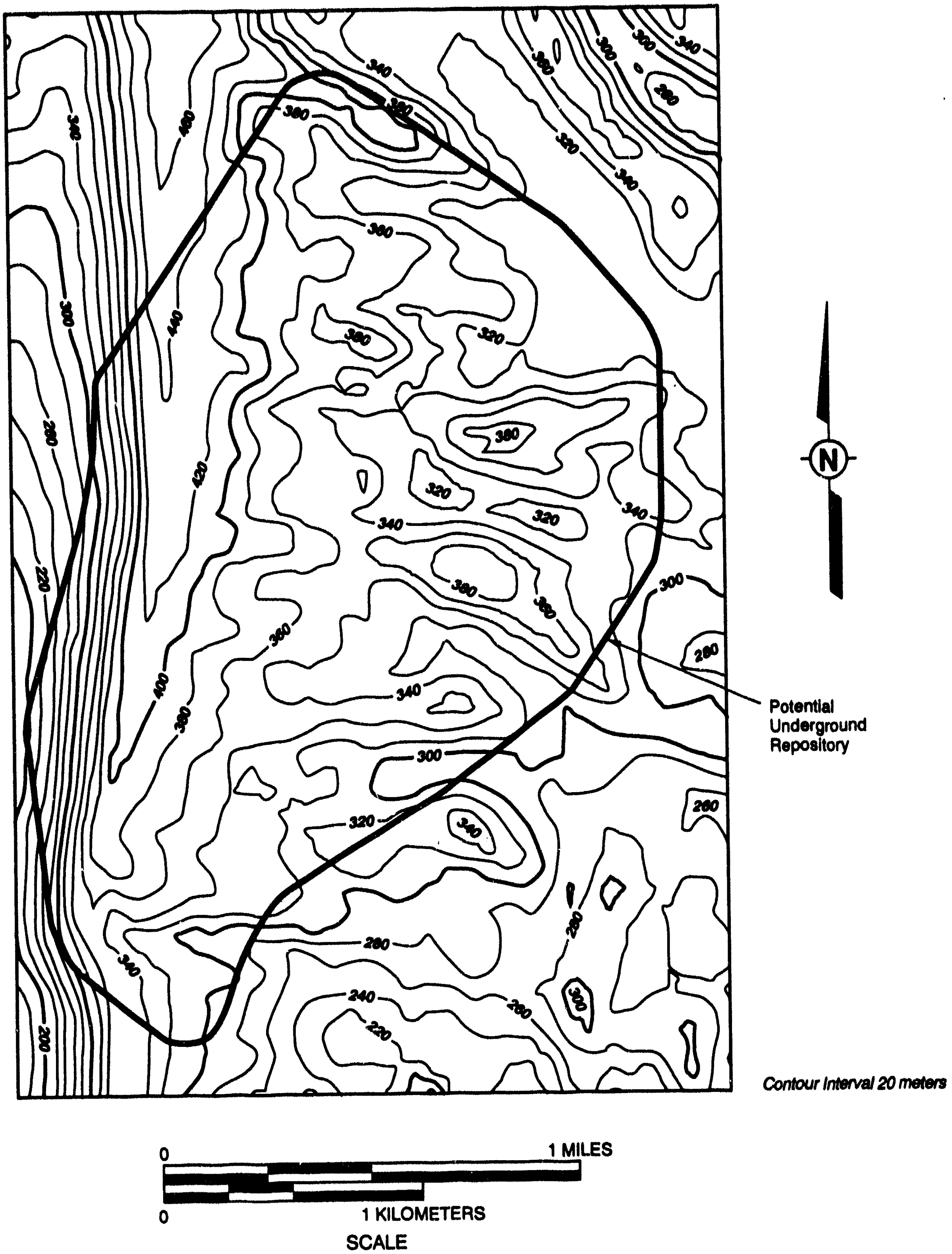


Figure 3-39
Total Thickness of the Rock Above the Repository Floor
(REF0283, REF0284, REF0287)

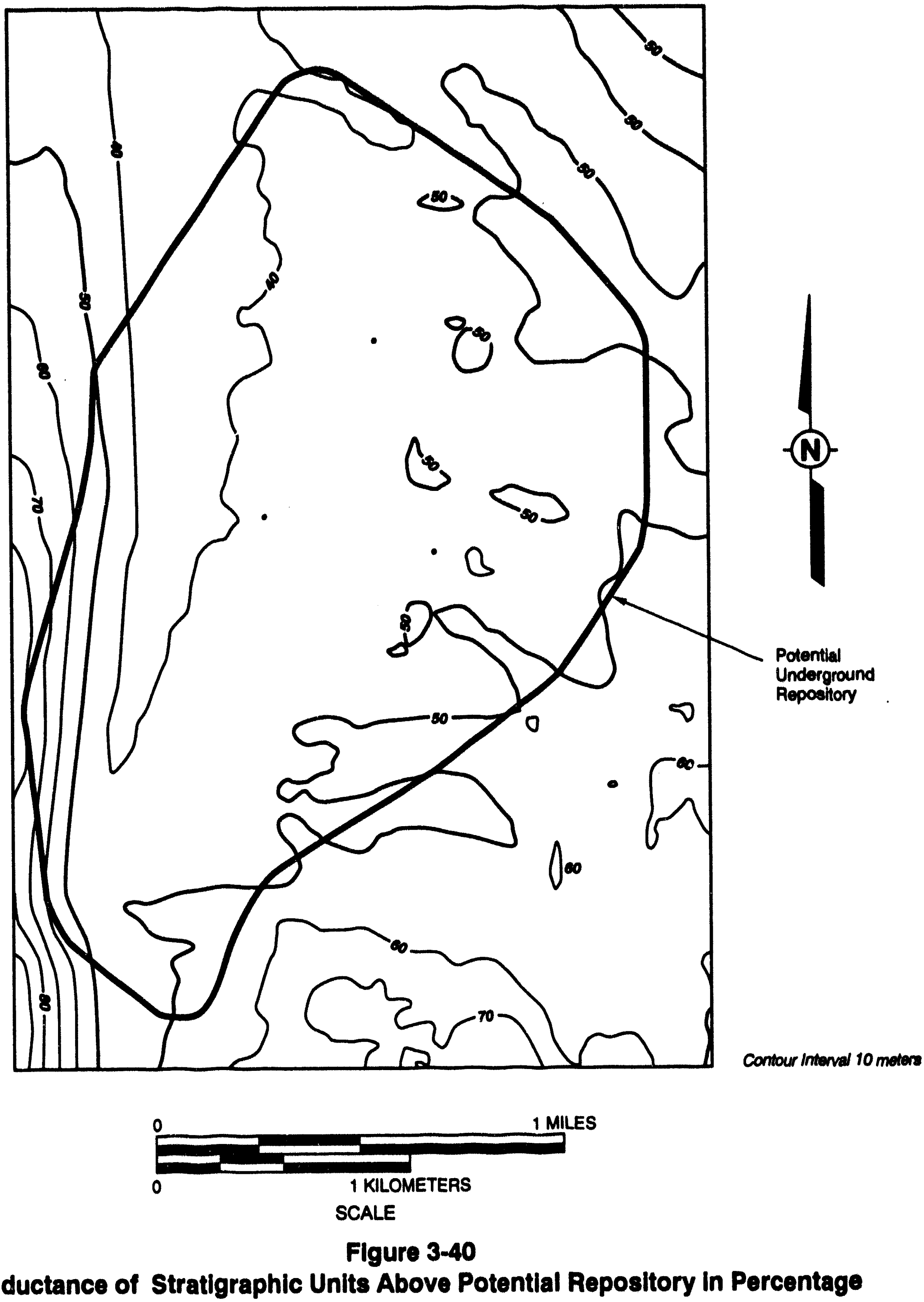


Figure 3-40
Conductance of Stratigraphic Units Above Potential Repository in Percentage of Maximum Conductance Encountered Over Entire Area, Model 1

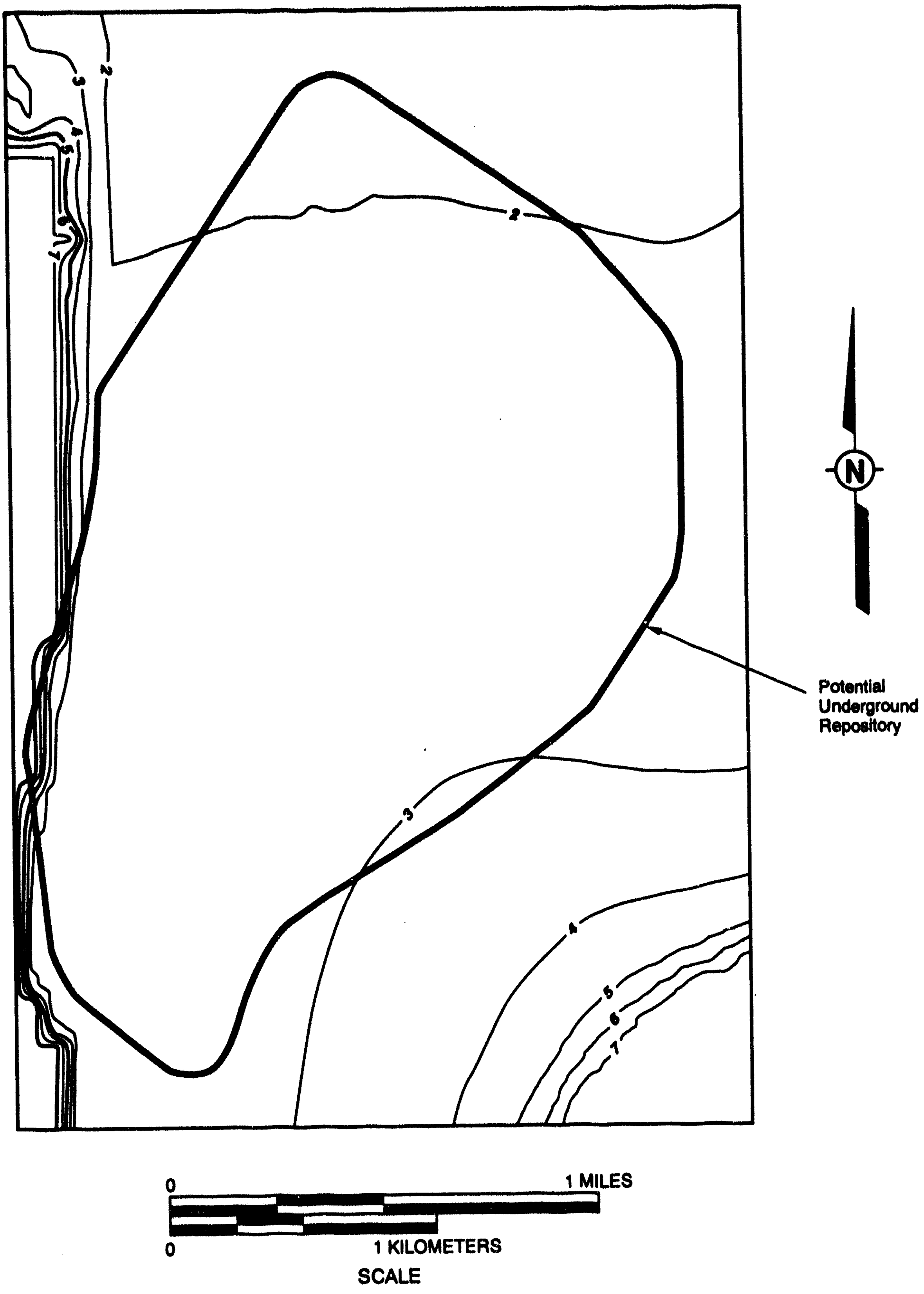


Figure 3-41
Conductance of Stratigraphic Units Above Potential Repository
***(Ln-value x 10^{9}/min)*, Model 2**

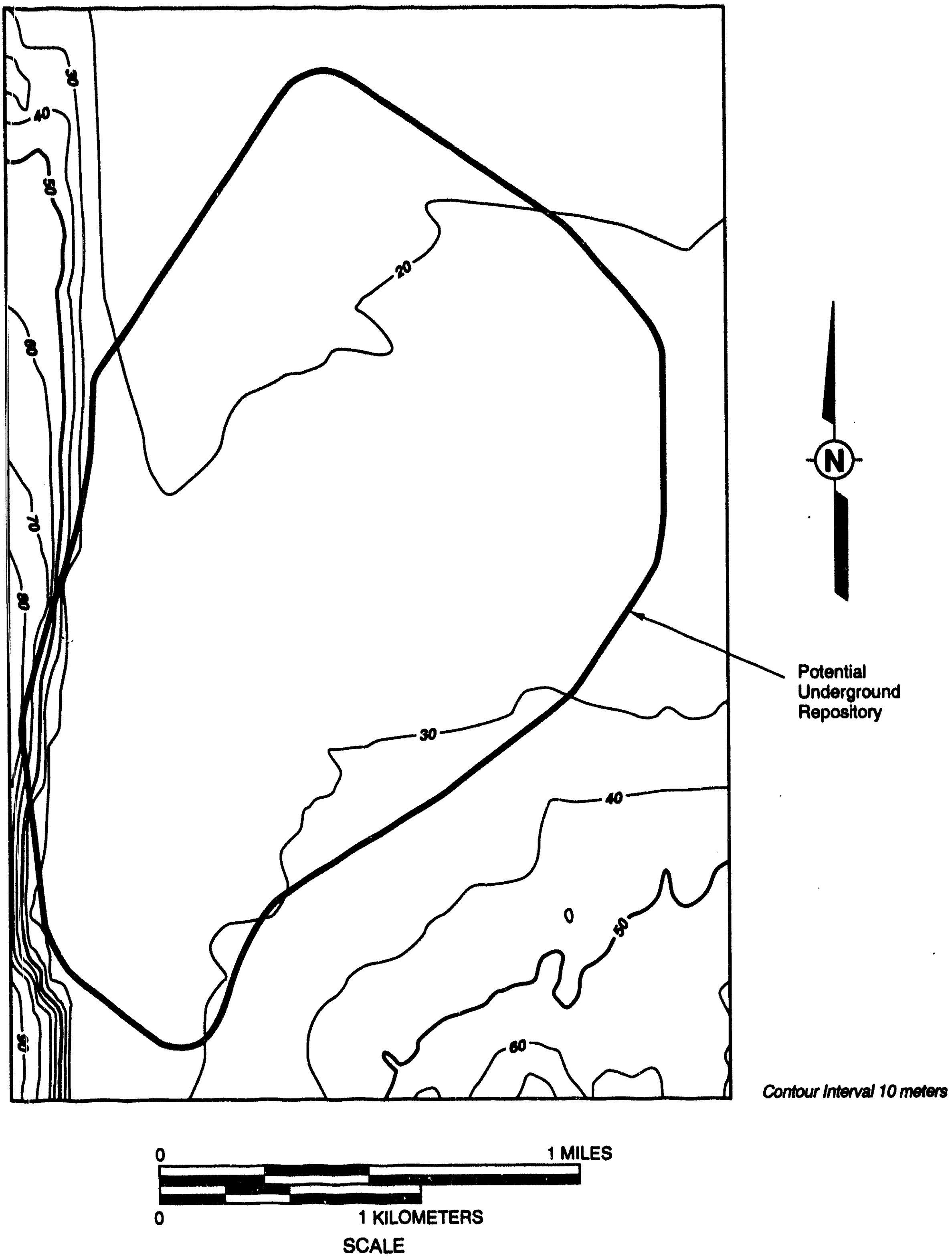


Figure 3-42
Conductance of Stratigraphic Units Above Potential Repository in Percentage of Maximum Conductance Encountered Over Entire Area, Model 3

4.0 Detailed Performance Evaluation of Seals

This chapter presents detailed seal evaluations to help address the issue of where to seal. Information developed in the previous chapter is used to perform confirmatory analysis for water flow and airflow. This information is then used to perform various calculations of the extent of lateral flooding from the potential repository, surface flooding at the ground surface, and air diversion. These calculations identify the most significant boreholes to be sealed.

4.1 Water Flow

Two issues arise because of several surface and subsurface flooding events and the potential interaction of boreholes with potential repository drifts at the potential repository horizon. These issues result from potential flooding scenarios for boreholes and the need to provide a hydrologic barrier zone around the boreholes within the potential repository perimeter. These issues are as follows:

- Extent of lateral flooding at the potential repository horizon (flow from a potential repository drift)
- Potential for surface inundation of boreholes at the ground surface (potential flooding of surface boreholes).

In addition to these calculations, the hydrologic significance of boreholes within the potential repository is also evaluated.

4.1.1 Flow From a Potential Repository Drift

For drifts subject to flooding under unanticipated conditions, the potential exists for inundation of drifts in low areas and lateral spreading of water below the potential repository horizon. In this evaluation, it is assumed that the fracture system becomes saturated, resulting in fracture flow being the dominant flow mechanism downward toward boreholes penetrating below the potential repository. Since the fracture patterns are dominantly vertical, the flow may be directed downward. The orientation, spacing, and condition of the fractures govern lateral spreading below the potential repository in an anisotropic media. For anisotropic flow, the direction of flow is not orthogonal with horizontal potential lines. The analysis uses the following approach to obtain a flow net to evaluate lateral spreading from a flooded drift:

- Select the principal permeabilities for the fracture set at orientation θ.
- Transform the principal permeabilities to the xy coordinate system.
- Sum the conductivities for each fracture orientation.
- Calculate the principal conductivities.

- Use the transformed section method (Freeze and Cherry, 1979) to draw the flow net and find the extent of lateral migration.

Appendix E presents these calculations for a drift, assuming the strike direction of the fracture is oriented parallel to the axis of the drift.[1] It is further assumed that the fractures are uniformly spaced with a uniform smooth-wall aperture. The permeability tensor (K′) for the orientation along the fracture system is expressed as follows:

$$[K'] = \begin{bmatrix} \frac{\rho g}{\mu} \frac{Nb^3}{12} & 0 \\ 0 & k_m \end{bmatrix}$$

where

b = Fracture aperture
g = Gravity acceleration constant
ρ = Mass density
μ = Absolute viscosity
N = Fracture frequency
k_m = Matrix conductivity.

The principal permeabilities orient at a direction of angle θ to the xy coordinate system. To express the permeabilities in the xy coordinate system, the similarity transformation uses the following:

$$[K] = [A]\,[K']\,[A]^t$$

where

$[K]$ = Permeability tensor in the xy coordinate system
$[K']$ = Permeability tensor along the fracture system
$[A]$ = Matrix of direction cosines
$[A]^t$ = Matrix of direction cosines—transposed.

This expression is equivalent to the second-order tensor transformation for permeability by Bear (1976).

The calculations presented in Appendix E find the anisotropy in the permeability tensor following the technical approach outlined above by directly summing the contributions from each fracture set of variable orientation using the principle of superposition. The summation then determines

---

[1] For purposes of lateral spreading, it is conservatively assumed that the strike direction orients along the drift axis.

the anisotropy in the permeability tensor for the rock mass that can be subsequently used to construct a flow net.

The results of the calculations for the worst-case scenarios are presented in Figure 4-1. This figure illustrates the flow net in the untransformed and transformed sections. Lateral spreading may be affected by contrasts in permeability at contacts. A contrast from a more permeable to a less permeable fractured zone might result in additional lateral spreading.

The flow, as determined from the lateral spreading near a drift under worst-case assumptions, shows lateral spreading at an angle of about 30 degrees that corresponds with the direction of the principal permeability from the calculations in Appendix E. Because of the indicated anisotropy, the direction of flow is not orthogonal with the horizontal potential lines in the unsaturated zone. The lateral dispersion from the potential repository boundary is illustrated in Figure 4-2. This figure also shows the depth to the groundwater table. The extent of lateral spreading (200 m) is greater to the western side of the potential repository and less to the eastern side of the potential repository.

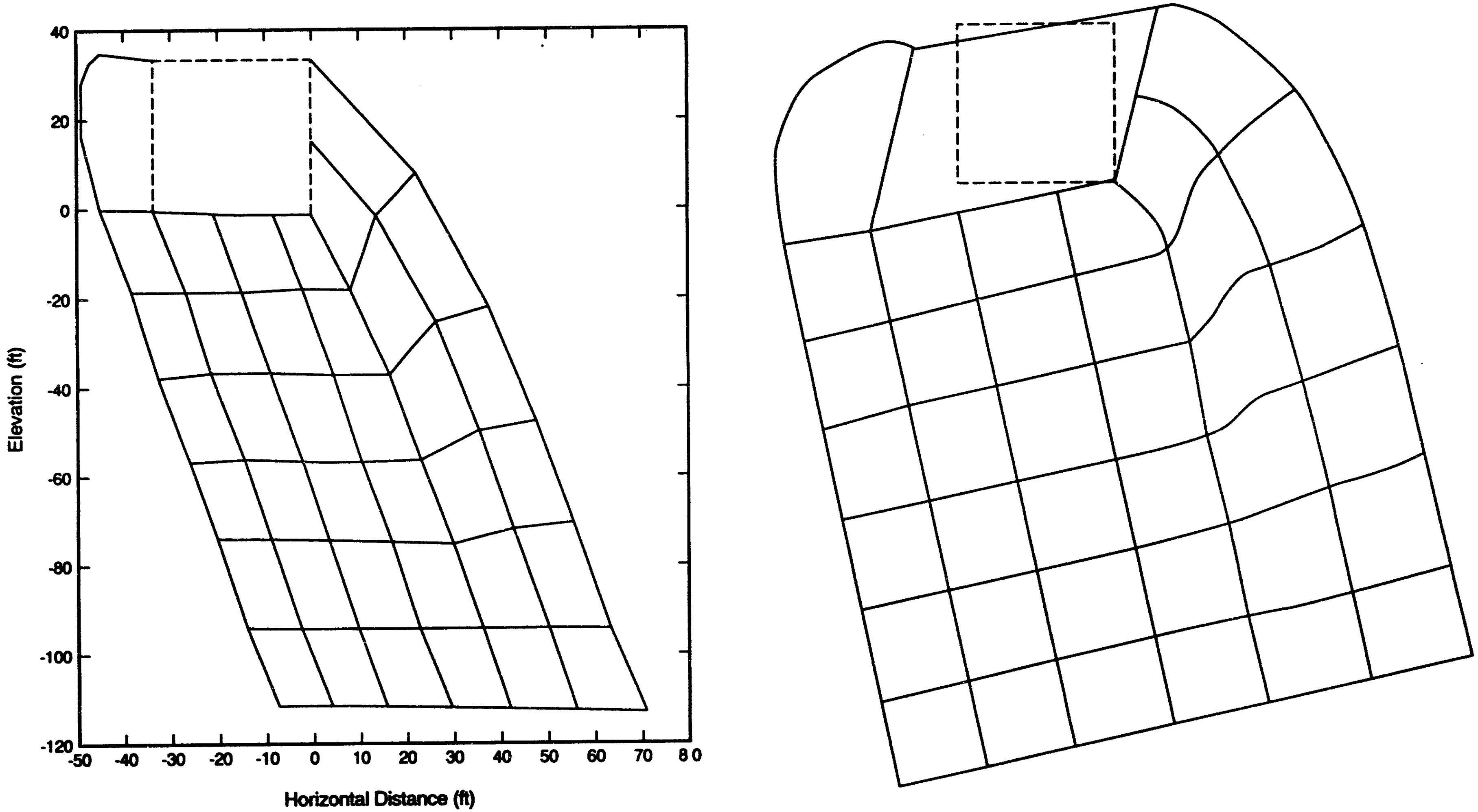
4.1.2 Potential Flooding of Surface Boreholes

Surface boreholes may be subject to flooding. Currently the allowable amount of water that could enter the potential repository is unknown. Further, the manner in which water in the unsaturated zone in a high-temperature environment could enter the potential repository is unknown. Deep boreholes outside the potential repository may not influence water flow and may not be significant. Nevertheless, surface boreholes within or immediately adjacent to the potential repository could potentially contribute flow. The following analyses consider (1) the potential for boreholes to be flooded, given their location relative to naturally occurring channels; (2) the potential for saturation of the alluvium surrounding the borehole that could result in flow from the alluvium to the borehole; and (3) the potential for perched water within the borehole that could contribute flow to the potential repository horizon.

4.1.2.1 Potential Inundation of Surface Boreholes

Exploratory boreholes represent potential pathways that could compromise the ability of the geologic potential repository to meet the performance objectives following permanent closure. Existing and proposed boreholes within the extended boundary of the potential repository may be subject to flooding in certain low areas. Figure 2-4 presents a map of existing and proposed deep boreholes within the potential repository showing the many existing and several proposed boreholes in alluvial areas subject to flooding. With several exceptions, the proposed boreholes are to be located outside low areas and are less subject to flooding.

The potential for flooding of existing and proposed boreholes depends on the extent and depth of flooding near each borehole. In turn, the extent and depth of flooding depend on the size of



a) Real Plane

b) Transformed Section

Figure 4-1
Flow Net for Lateral Dispersion from the Potential Repository

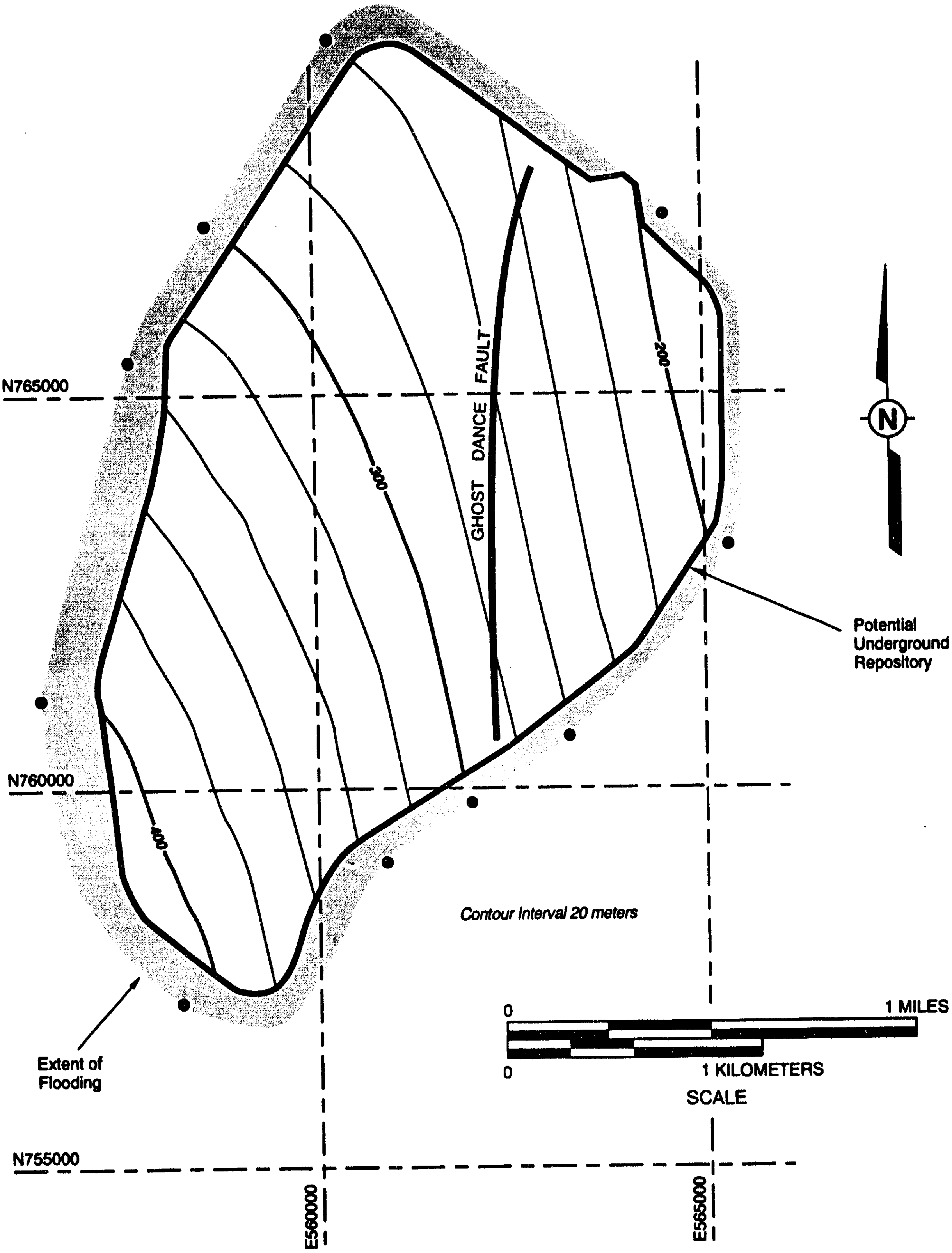


Figure 4-2
Extent of Lateral Flooding at the Groundwater Table

the drainage basin, topographic features[2] of the drainage basin, and stream characteristics near each borehole. This report uses the Probable Maximum Flood (PMF) because it represents a "hypothetical" flood that attempts to define the maximum flood potential at a specific site. The PMF is defined as "the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region" (National Research Council, 1985). This evaluation identifies the drainage area tributary to the borehole for stream flow. Empirical relationships relating the size of the area to peak discharge (Crippen and Bue, 1977) provide an estimate of the peak discharges at borehole locations. The extent and depth of flooding is determined using methods developed for natural channel flow (Fernandez et al., 1989).

The analysis then considers the natural channel cross section, as illustrated in Figures 4-3a and 4-3b, and uses the Manning equation (Trefethen, 1959) for open-channel flow in a natural channel to estimate the height of flow in the channel near the borehole:

$$V = \frac{1.49}{n} R^{\frac{2}{3}} \sqrt{s}$$

where

V = Velocity for uniform flow (m/s)
n = Roughness coefficient
s = Slope of the hydraulic grade equivalent to the slope of the channel
R = Hydraulic radius equal to the cross-sectional area (A) of flow divided by the wetted perimeter (P).

By considering the continuity equation, the flow rate (Q) can be expressed as a function of the wetted perimeter (P) and cross-sectional area (A):

$$Q= \frac{1.49}{n} \frac{A^{\frac{5}{3}}}{P^{\frac{2}{3}}} \sqrt{s} \ .$$

In applying the Manning equation, the assumptions used were similar to those used by Squires and Young (1984). Specifically, the values for slope of the energy-grade line used in Manning's equation were assumed to be equivalent to the slope of the water surface and the channel bottom. The value for the roughness coefficient, n, in Manning's equation was assumed to be 0.06. Squires and Young used roughness coefficients ranging from 0.03 to 0.055. To conservatively

---

[2] The cross section used in developing the extent of the PMF channel assumed the current topography.

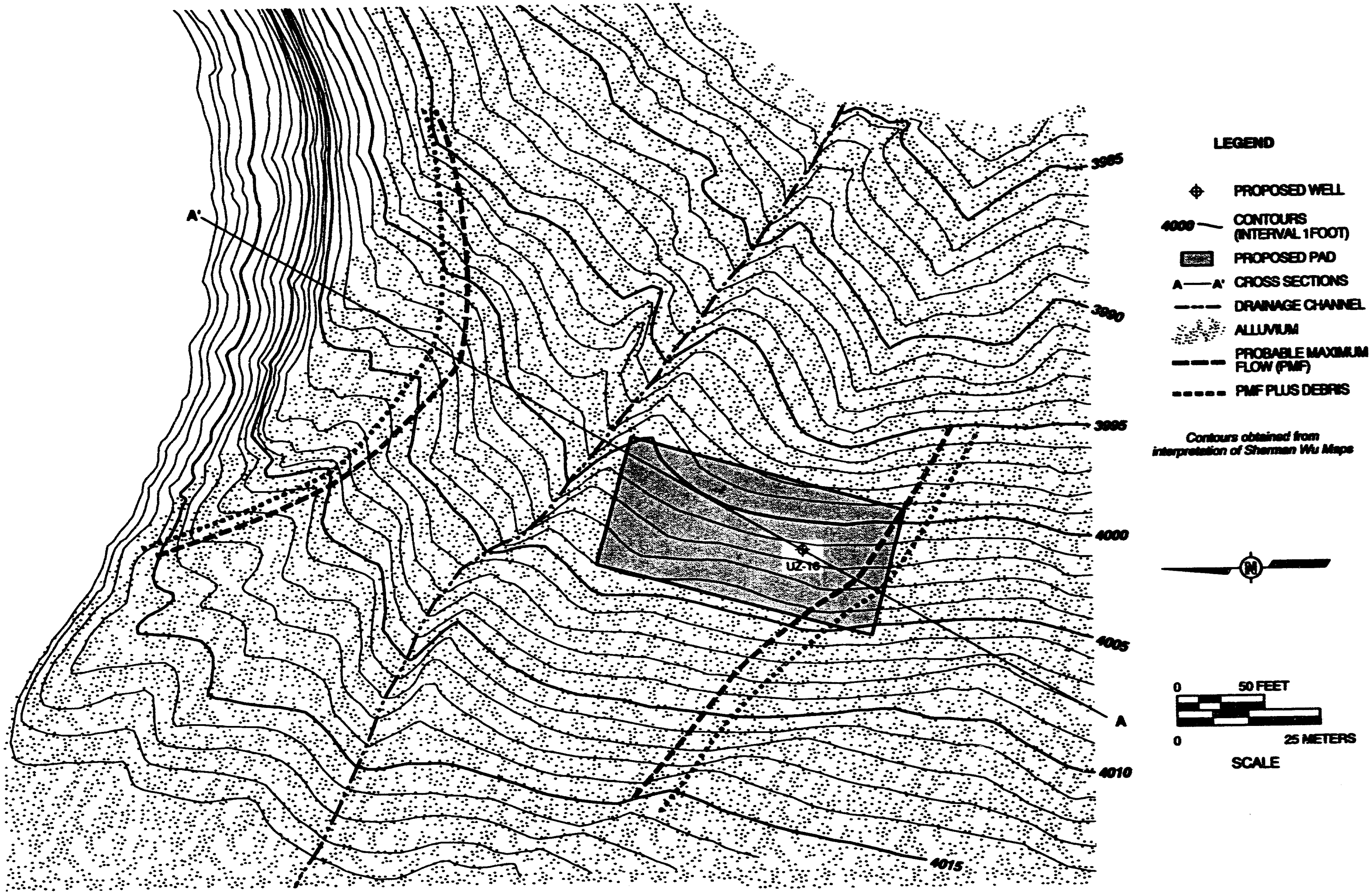


Figure 4-3a
Extent of Flooding Near USW UZ-16
(a) Plan View and (b) Topographic Cross Section with Probable Maximum Flood Levels

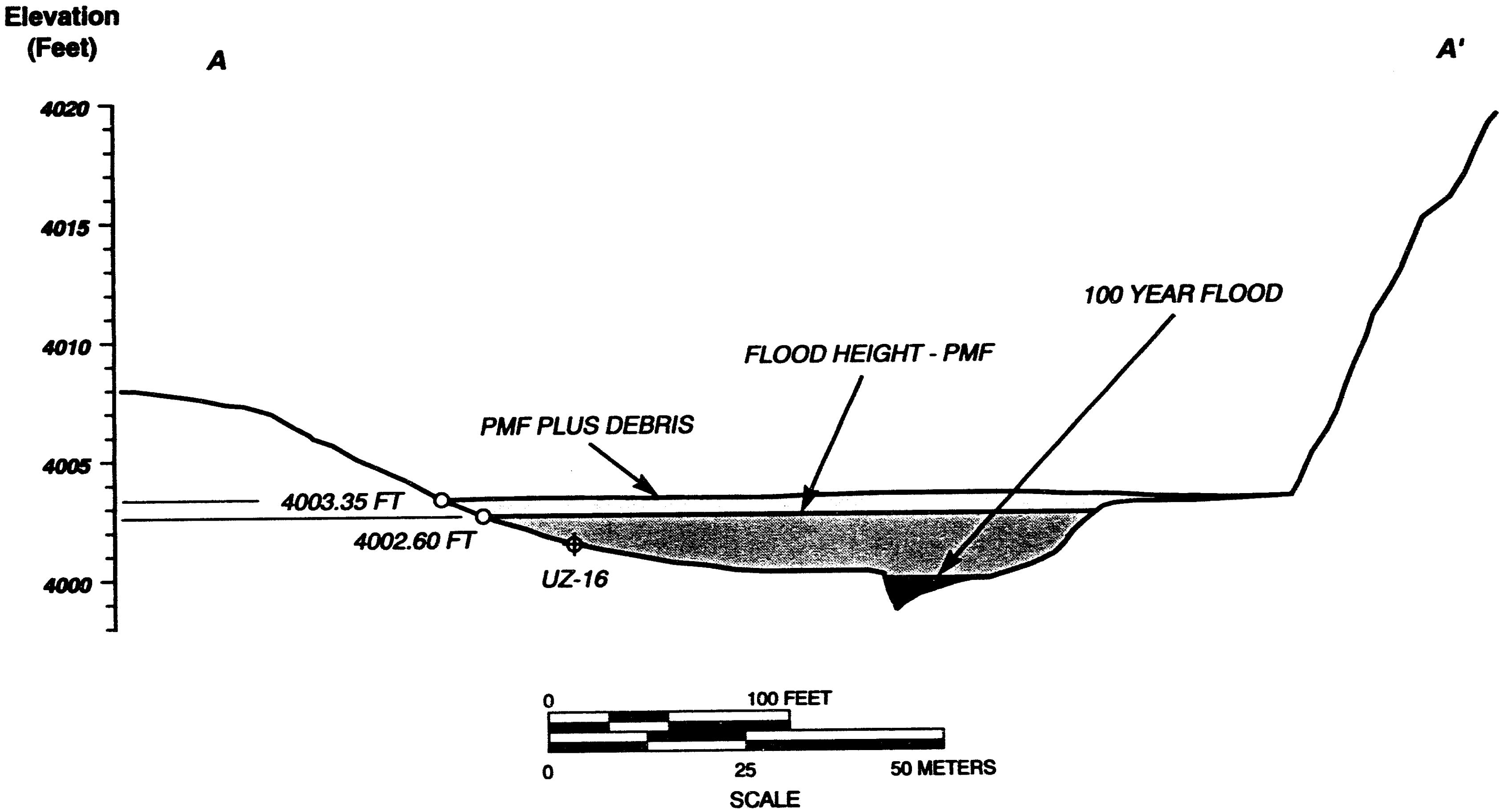


Figure 4-3b
Extent of Flooding Near USW UZ-16
(a) Plan View and (b) Topographic Cross Section
with Probable Maximum Flood Levels

estimate the highest water elevation (or cross-sectional area of water flow in the channel) during a PMF at selected locations, it is necessary to reduce the velocity of channel flow as presented in the Manning equation. This reduction of velocity can be achieved by selecting a greater "n" value (as used in this analysis), which conservatively predicts a higher water-level rise.

To develop realistic flow conditions, cross sections were selected near groups of exploratory boreholes. The cross-sectional area and wetted perimeter for a trapezoidal cross section were evaluated at selected locations. The conveyance curve, or flow rate (Q), versus height (h) relationship at each cross section is solved iteratively for a known flow rate. The debris flow is assumed equal to 150 percent of the clear-water flow (Fernandez et al., 1989).

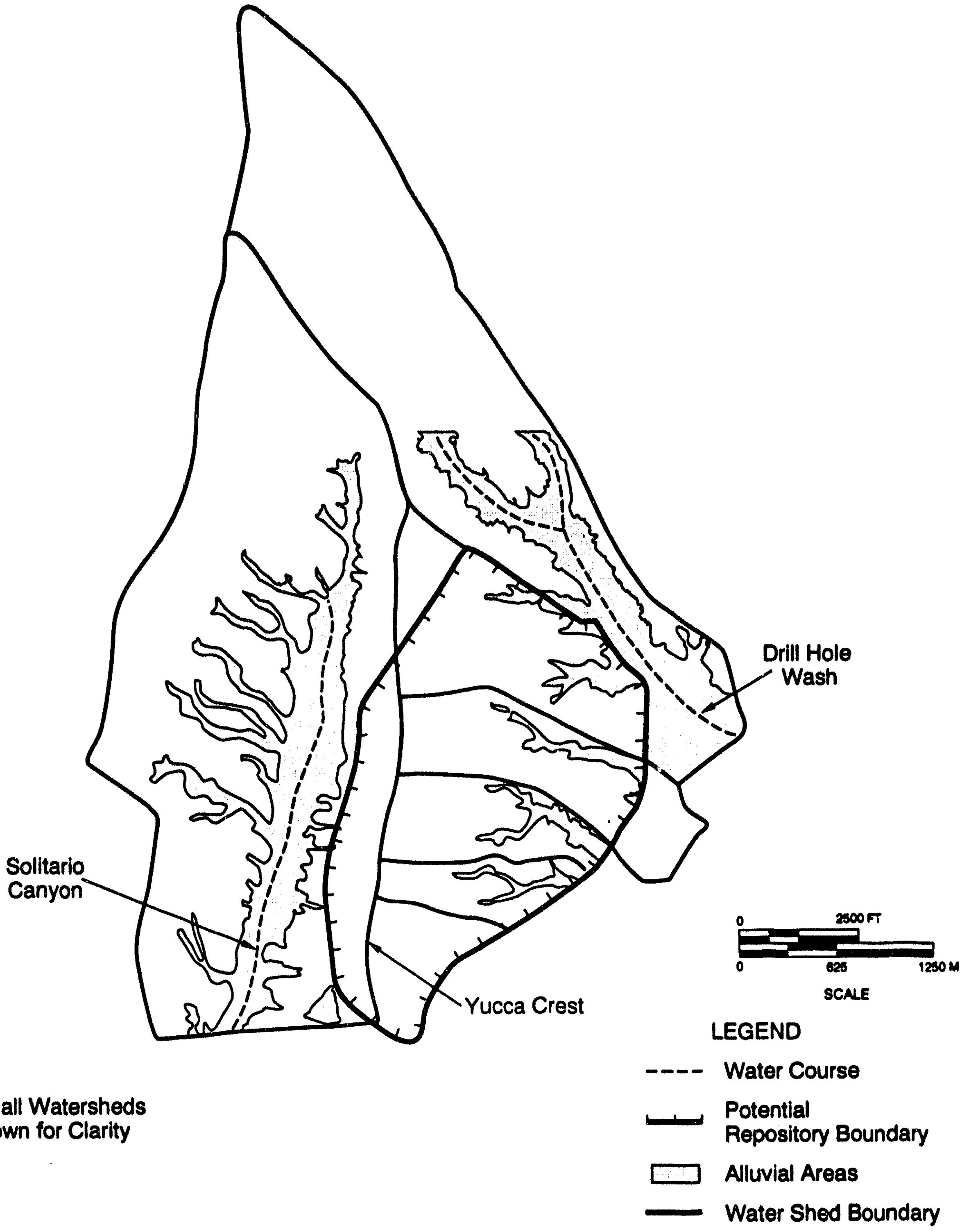
The known flow rate Q is evaluated for the drainage basin that is tributary to the cross section. Figure 4-4 shows several typical drainage basins used in these calculations. Table 4-1 presents the calculations for the existing and proposed boreholes. Cumulative flow is evaluated for the general storm lasting 14.7 hours (Fernandez et al., 1989). The extent and depth of flooding were determined based on the existing channel topography (Wu, 1985). In many cases, the channels are incised in a broad, terraced plane that is several hundred feet in width (shown in Figure 4-4). Under worst-case assumptions, the boreholes might be located in the channel invert and subject to flooding for the duration of a hydrologic event. In other cases, the channels incise bedrock in steeper terrain and meander over less lateral distance. Based upon these considerations, engineering judgment was used to establish three borehole categories:

- Category A: Boreholes within the broad terrace containing an incised channel in alluvial areas that locate near the channel invert of the incised channel.
- Category B: Boreholes within steeper areas of terrain, where it is much less likely that flooding will occur.
- Category C: Boreholes outside flood zones not subject to flooding. Most proposed boreholes are not subject to flooding.

A more detailed evaluation and mapping of these boreholes near alluvial areas might result in a different categorization of existing boreholes; however, the present evaluation defines the probable number of boreholes subject to flooding, which is sufficient for planning and scoping purposes.

4.1.2.2 Potential Saturation of the Alluvium

In flood-prone areas, water flows across the top of the borehole at depths on the order of several meters. Where standing water develops at the ground surface, saturation occurs, and an infiltration front moves vertically downward. As the water penetrates deeper and the wetted part of the profile lengthens, the average suction gradient decreases. This trend continues until eventually the suction gradient in the upper part of the profile becomes negligible. This leaves



Note: Not all Watersheds
Shown for Clarity

Figure 4-4
Watershed Areas in the Vicinity of the Potential Repository

Table 4-1
Potential Flooding of Boreholes

Category[1]	Boreholes	Basin Area (m²)	Peak Discharge		Distance of Borehole from Stream (m)	Flood Depth		Plotted Height Above Water		Flood Duration (Hrs)
			Peak (m³/s)	+Debris (m³/s)		Peak (m)	+Debris (m)	Peak (m)	+Debris (m)	
Category A	USW UZ-N24	561439	65	97.5	0	2.13	2.48	-2.13	-2.48	14.70
	USW UZ-N98	561439	65	97.5	0	2.13	2.48	-2.13	-2.48	14.70
	USW UZ-N25	288394	35	52.5	0	1.67	1.95	-1.67	-1.95	14.70
	USW UZ-N26	257247	30	45	0	1.62	1.88	-1.62	-1.88	14.70
	USW UZ-N37	965418	110	165	0	1.44	1.68	-1.44	-1.68	14.70
	USW UZ-N44	232560	30	45	0	1.29	1.50	-1.29	-1.50	14.70
	UE-25 UZ#09a *	1111864	135	202.5	90	1.25	1.48	-1.25	-1.48	14.70
	UE-25 UZ#09b *	1111864	135	202.5	80	1.25	1.48	-1.25	-1.48	14.70
	LPRS-08 *	102472	25	37.5	0	1.14	1.32	-1.14	-1.32	14.70
	SPRS-16 *	102472	25	37.5	0	1.14	1.32	-1.14	-1.32	14.70
	UE-25 UZN #18	7262649	800	1200	5	1.10	1.40	-1.10	-1.40	14.70
	UE-25a #07	7262649	800	1200	40	1.10	1.40	-1.10	-1.40	14.70
	UE-25a #05	6373981	700	1050	10	1.02	1.30	-1.02	-1.30	14.70
	UE-25a #04	5185403	565	847.5	0	0.89	1.14	-0.89	-1.14	14.70
	USW SD-10 *	646773	75	112.5	0	0.70	0.89	-0.70	-0.89	14.70
	USW UZ-07	569127	65	97.5	0	0.64	0.81	-0.64	-0.81	14.70
	USW UZ-7a *	569127	65	97.5	0	0.64	0.81	-0.64	-0.81	14.70
	USW UZ-N51	569127	65	97.5	0	0.64	0.81	-0.64	-0.81	14.70
	USW UZ-N48	515838	60	90	0	0.61	0.78	-0.61	-0.78	14.70
	USW G-1	1656816	185	277.5	40	0.61	0.77	-0.61	-0.77	14.70
	UE-25 SD#9 *	65550	25	37.5	0	0.60	0.76	-0.60	-0.76	14.70

Refer to footnotes at end of table.

Table 4-1 *(Continued)*
Potential Flooding of Boreholes

Category[1]	Boreholes	Basin Area (m²)	Peak Discharge Peak (m^3/s)	Peak Discharge +Debris (m^3/s)	Distance of Borehole from Stream (m)	Flood Depth Peak (m)	Flood Depth +Debris (m)	Plotted Height Above Water Peak (m)	Plotted Height Above Water +Debris (m)	Flood Duration (Hrs)
	USW UZ-N41	568230	65	97.5	0	0.55	0.70	-0.55	-0.70	14.70
	USW UZ-N45	568230	65	97.5	0	0.55	0.70	-0.55	-0.70	14.70
	USW WT-02	437084	50	75	30	0.55	0.70	-0.55	-0.70	14.70
	USW H-4	631281	70	105	20	0.51	0.65	-0.51	-0.65	14.70
	USW SD-08 *	631281	70	105	0	0.51	0.65	-0.51	-0.65	14.70
	USW UZ-N43	498130	55	82.5	0	0.50	0.63	-0.50	-0.63	14.70
	UE-25 UZN #19	976557	110	165	30	0.48	0.61	-0.48	-0.61	14.70
	UE-25 UZN #21	976557	110	165	0	0.48	0.61	-0.48	-0.61	14.70
	UE-25 UZN #22	976557	110	165	25	0.48	0.61	-0.48	-0.61	14.70
	USW UZ-16	1111864	135	202.5	110	1.25	1.48	-0.34	-0.56	14.70
	SPRS-14 *	265570	30	45	0	0.32	0.41	-0.32	-0.41	14.70
	USW G-4	265570	30	45	0	0.32	0.41	-0.32	-0.41	14.70
	USW UZ-N42	265570	30	45	0	0.32	0.41	-0.32	-0.41	14.70
	UE-25 UZ#09 *	1111864	135	202.5	100	1.25	1.48	-0.25	-0.48	14.70
Category B	LPRS-11 *	1248367	140	210	90	0.59	0.74	0.41	0.26	0.00
	SPRS-22 *	1248367	140	210	90	0.59	0.74	0.41	0.26	0.00
	UE-25 UZN #28	1248367	140	210	90	0.59	0.74	0.41	0.26	0.00
	UE-25 UZN #97	1248367	140	210	90	0.59	0.74	0.41	0.26	0.00
	UE-25 UZN #20	976557	110	165	10	0.48	0.61	0.52	0.39	0.00
	USW UZ-N33	1885061	210	315	20	0.48	0.61	0.52	0.39	0.00

Refer to footnotes at end of table.

Table 4-1 *(Continued)*
Potential Flooding of Boreholes

Category[1]	Boreholes	Basin Area (m²)	Peak Discharge Peak (m³/s)	Peak Discharge +Debris (m³/s)	Distance of Borehole from Stream (m)	Flood Depth Peak (m)	Flood Depth +Debris (m)	Plotted Height Above Water Peak (m)	Plotted Height Above Water +Debris (m)	Flood Duration (Hrs)
	USW UZ-N54	727341	80	120	30	0.48	0.60	0.52	0.40	0.00
	UE-25a #06	790952	90	135	50	0.30	0.38	0.70	0.62	0.00
	USW H-1	102472	25	37.5	20	1.14	1.32	0.86	0.68	0.00
	USW UZ-N50	569127	65	97.5	30	0.64	0.81	1.36	1.19	0.00
	USW UZ-N52	569127	65	97.5	10	0.64	0.81	1.36	1.19	0.90
	LPRS-05 *	515838	60	90	30	0.61	0.78	1.39	1.22	0.00
	SPRS-08 *	515838	60	90	30	0.61	0.78	1.39	1.22	0.00
	USW UZ-08	515838	60	90	30	0.61	0.78	1.39	1.22	0.00
	USW UZ-08 *	515838	60	90	30	0.61	0.78	1.39	1.22	0.00
	USW UZ-N49	515838	60	90	30	0.61	0.78	1.39	1.22	0.00
	US-25 Seismic #01	1248367	140	210	140	0.59	0.74	1.41	1.26	0.00
	USW UZ-N38	692845	80	120	20	0.50	0.63	1.50	1.37	0.00
	SPRS-12 *	976557	110	165	45	0.48	0.61	1.52	1.39	0.00
	UE-25 UZN #23	976557	110	165	45	0.48	0.61	1.52	1.39	0.00
	USW UZ-N53	727341	80	120	25	0.48	0.60	2.52	2.40	0.00
	USW UZ-N40	643046	75	112.5	20	0.33	0.43	2.67	2.57	0.00
	NRG-5 *	5185403	565	847.5	30	0.89	1.14	3.11	2.86	0.00
	USW SD-12 *	727341	80	120	40	0.58	0.74	3.42	3.26	0.00
	USW UZ-N35 *	360216	40	60	10	0.36	0.46	3.64	3.54	0.00
	USW UZ-N34	1885061	210	315	40	0.48	0.61	5.52	5.39	0.00
	USW UZ-N55	727341	80	120	95	0.48	0.60	7.52	7.40	0.00

Refer to footnotes at end of table.

Table 4-1 *(Continued)*
Potential Flooding of Boreholes

Category[1]	Boreholes	Basin Area	Peak Discharge		Distance of Borehole from Stream	Flood Depth		Plotted Height Above Water		Flood Duration
		(m^2)	Peak (m^3/s)	+Debris (m^3/s)	(m)	Peak (m)	+Debris (m)	Peak (m)	+Debris (m)	(Hrs)
	LPRS-04 *	179743	25	37.5	30	1.18	1.38	7.82	7.62	0.00
	SPRS-07 *	179743	25	37.5	30	1.18	1.38	7.82	7.62	0.00
	USW UZ-N32 *	760517	85	127.5	30	0.56	0.71	10.44	10.29	0.00
	SPRS-11 *	727341	80	120	110	0.48	0.60	10.52	10.40	0.00

[1] Category C boreholes have no flooding potential; therefore, they do not appear on this table.

* Proposed borehole.

the constant gravitational gradient as the only remaining force moving water downward in the transmissive zone.

Appendix F presents detailed calculations based upon the Green and Ampt solution. The results show that, depending upon the initial moisture content (20 to 70 percent), the time required for penetration to 10 m is 5 to 10 hours for sand and 100 to 300 hours for clay loam. During a flooding event, it would be expected that saturation of sand would take place, while saturation of fine-grained soils would be much less likely. The results show that the sand might act as a reservoir for recharging a borehole collared in alluvium, which in turn, could result in perched water.

4.1.3 Perched Water Scenarios

The objectives of this analysis are to compare the relative significance of "shallow" versus "deep" boreholes in contributing water to the potential repository. Analysis assumes that under worst-case assumptions water enters the borehole in the unsaturated zone and pressure head develops within the borehole, resulting in flow to the surrounding rock. The analysis further assumes that under the worst case this water enters the potential repository. Under these assumptions, the relative significance of shallow versus deep boreholes can be compared.

The degree of flow occurring to the subsurface depends on the area of the borehole, the depth of perched water in the borehole, and the time duration that water is available for saturating alluvial areas. The time duration depends on lateral flow through the alluvium and likely is not affected by flow down the boreholes. The following analysis assumes this time duration equals the average duration of the event (14.7 hours) for evaluating the relative significance of borehole flow. It is further assumed that a standing column of water develops within the borehole and that flow occurs to the surrounding tuff formation, which has a conductivity of 10^{-5} cm/s. Fernandez et al. (1987) present several solutions for infiltration from an open borehole, as discussed by Stephens and Neuman (1982). The Glover solution is as follows:

$$Q=K\ C_u\ r\ H$$

where

Q = Flow rate
H = Height of standing water in borehole
r = Radius of borehole
K = Saturated conductivity of fractured tuff (10^{-5} cm/s).

$$C_u = 6.283 \frac{\left(\frac{H}{r}\right)}{[\sinh^{-1}\left(\frac{H}{r}\right)-1]}$$

A second solution developed by Nasberg-Terlestkata is:

$$Q = \frac{K\ H^2}{0.423\ \log(\frac{2\ H}{r})}$$

Table 4-2 presents borehole diameter, seal length, flow rate, and cumulative flow enhancement and allows comparison of flow for shallow and deep boreholes. The cumulative flow enhancement is based upon the 14.7-hr time duration, using the Glover and Nasberg-Terlestkata (Stephens and Newman, 1982) solutions for the 33 shallow and deep boreholes subject to flooding that fall within the extended boundary of the potential repository. Figures 4-5 and 4-6 present the Glover and Nasberg-Terlestkata relationships, with individual points representing each borehole. The potential flow from deep boreholes to the potential repository is greater by 2 orders of magnitude than that of shallow boreholes. Fifteen boreholes are surficial within the Tiva Canyon Unit and contribute flow of the order of 10 m^3. Three boreholes penetrate through the Tiva Canyon Member and the Paintbrush nonwelded tuff into the Topopah Spring Unit. The remaining deep holes (for example, USW WT-2, USW G-4, USW H-4, and USW G-1) penetrate through the potential repository horizon and under worst-case assumptions could contribute a flow of as much as 500 m^3.

4.1.4 Conclusions from the Hydrologic Calculations

The current sealing strategy considers basic performance objectives for the exploratory borehole sealing system, including previous hydrological objectives for restricting water flow below the potential repository and the requirement for restricting airflow above the potential repository. Each of these is discussed below with reference to the boreholes subject to potential flooding.

4.1.4.1 Restricting Water Flow Below the Potential Repository

In previous studies (Fernandez et al., 1987), the regulations for borehole-seal hydrologic performance (10 CFR 60.134) require that "boreholes shall be designed so that following closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives." The position adopted was that the restriction of vertical flow through the boreholes to only 1 percent of the potential for vertical flow through the rock mass

Table 4-2

Relative Hydrologic Significance of Boreholes Subject to Flooding

Flooded Boreholes	Borehole Coordinates East	North	Borehole Diameter (in.)	Borehole Diameter (m)	Effective Seal Length (m)	Flood Duration (Hrs)	Flow Rate[a] (m^3/s)	Cumulative Flow[a]	Flow Rate[b] (m^3/s)	Cumulative Flow[b]
SPRS-14*	562859.0	765729.0	6.0	0.15	1.5	14.70	5.43e-07	0.03	3.427e-07	0.02
SPRS-16*	562300.0	770450.0	6.0	0.15	1.5	14.70	5.43e-07	0.03	3.427e-07	0.02
USW UZ-N51	562909.4	760860.8	6.0	0.15	6.1	14.70	5.73e-06	0.30	3.986e-06	0.21
LPRS-08*	562300.0	770450.0	6.0	0.15	10.7	14.70	1.54e-05	0.82	1.099e-05	0.58
USW UZ-N26	561022.9	768757.2	6.0	0.15	10.7	14.70	1.54e-05	0.82	1.099e-05	0.58
USW UZ-N48	562413.6	760834.9	6.0	0.15	10.7	14.70	1.54e-05	0.82	1.099e-05	0.58
USW UZ-N44	563139.6	766192.5	6.0	0.15	11.0	14.70	1.62e-05	0.86	1.157e-05	0.61
USW UZ-N41	563520.9	765867.2	6.0	0.15	11.3	14.70	1.70e-05	0.90	1.217e-05	0.64
UE-25 UZN #19	564570.6	763688.9	6.0	0.15	12.2	14.70	1.96e-05	1.04	1.403e-05	0.74
USW UZ-N42	562858.5	765728.6	6.0	0.15	12.2	14.70	1.96e-05	1.04	1.403e-05	0.74
UE-25 UZN #21	564591.0	763806.1	6.0	0.15	12.8	14.70	2.14e-05	1.13	1.534e-05	0.81
USW UZ-N43	563263.6	765997.0	6.0	0.15	13.7	14.70	2.42e-05	1.28	1.740e-05	0.92
USW UZ-N45	563429.2	765976.7	6.0	0.15	13.7	14.70	2.42e-05	1.28	1.740e-05	0.92
USW UZ-N25	561218.9	768430.4	6.0	0.15	18.0	14.70	3.94e-05	2.09	2.859e-05	1.51
UE-25 UZN #18	565246.5	766472.4	6.0	0.15	18.6	14.70	4.18e-05	2.21	3.040e-05	1.61
USW UZ-N24	562054.2	768005.4	6.0	0.15	22.9	14.70	6.08e-05	3.22	4.447e-05	2.35
USW UZ-N98	562083.5	767996.2	6.0	0.15	22.9	14.70	6.08e-05	3.22	4.447e-05	2.35
UE-25 UZN #22	564604.5	763880.3	6.0	0.15	29.0	14.70	9.35e-05	4.95	6.881e-05	3.64
USW UZ-07	562911.3	760836.1	6.0	0.15	63.1	14.70	3.90E-04	20.64	2.923e-04	15.47
USW UZ-N37	563713.5	767499.1	6.0	0.15	82.7	14.70	6.43e-04	34.02	4.845e-04	25.64
UE-25a #05	564755.1	766956.4	6.13	0.16	148.4	14.70	1.91e-03	101.11	1.454e-03	76.97
UE-25a #04	564471.6	767971.9	6.13	0.16	152.4	14.70	2.01e-03	106.19	1.528e-03	80.88

Refer to footnotes at end of table.

Table 4-2 *(Continued)*

Relative Hydrologic Significance of Boreholes Subject to Flooding

Flooded Boreholes	Borehole Coordinates East	Borehole Coordinates North	Borehole Diameter (in.)	Borehole Diameter (m)	Effective Seal Length (m)	Flood Duration (Hrs)	Flow Rate[a] (m^3/s)	Cumulative Flow[a]	Flow Rate[b] (m^3/s)	Cumulative Flow[b]
UE-25a #07	565468.5	766249.9	5.5	0.14	305.4	14.70	7.26e-03	384.02	5.594e-03	296.04
USW UZ-07a	562911.3	760836.1	12.25	0.31	290.5	14.70	7.34E-03	388.36	5.585e-03	295.55
USW UZ-16	564856.9	760535.0	12.25	0.31	383.6	14.70	1.23e-02	652.11	9.420e-03	498.52
UE-25 UZ#09b*	564850.0	760600.0	12.25	0.31	271.2	14.70	6.46e-03	341.81	4.910e-03	259.83
UE-25 UZ#09*	564750.0	760600.0	12.25	0.31	272.3	14.70	6.51e-03	344.33	4.946e-03	261.75
UE-25 UZ#09a*	564800.0	760600.0	12.25	0.31	271.8	14.70	6.48e-03	343.08	4.928e-03	260.80
UE-25 SD#9*	564625.0	761160.0	12.25	0.31	290.1	14.70	7.32e-03	387.29	5.569e-03	294.73
USW SD-08*	564010.0	761415.0	12.25	0.31	298.5	14.70	7.72e-03	408.51	5.877e-03	311.03
USW SD-10*	563610.0	760681.0	12.25	0.31	292.3	14.70	7.43e-03	392.95	5.651e-03	299.08
USW WT-02	561923.6	760660.5	8.75	0.22	290.7	14.70	7.02e-03	371.53	5.372e-03	284.29
USW G-4	563081.6	765807.1	12.25	0.31	313.2	14.70	8.44e-03	446.86	6.431e-03	340.35
USW H-4	563911.1	761643.6	14.75	0.37	303.0	14.70	8.15E-03	431.06	6.184e-03	327.24
USW G-1	561000.5	770500.2	6.25	0.16	339.0	14.70	8.97e-03	474.47	6.910e-03	365.65

* Proposed borehole.

[a] Glover Saturated Hydraulic Conductivity Solution for an open borehole above the water table.

[b] Nasberg-Terlestkata Saturated Hydraulic Conductivity Solution for an open borehole above the water table.

Shading denotes boreholes that penetrate through the repository horizon.

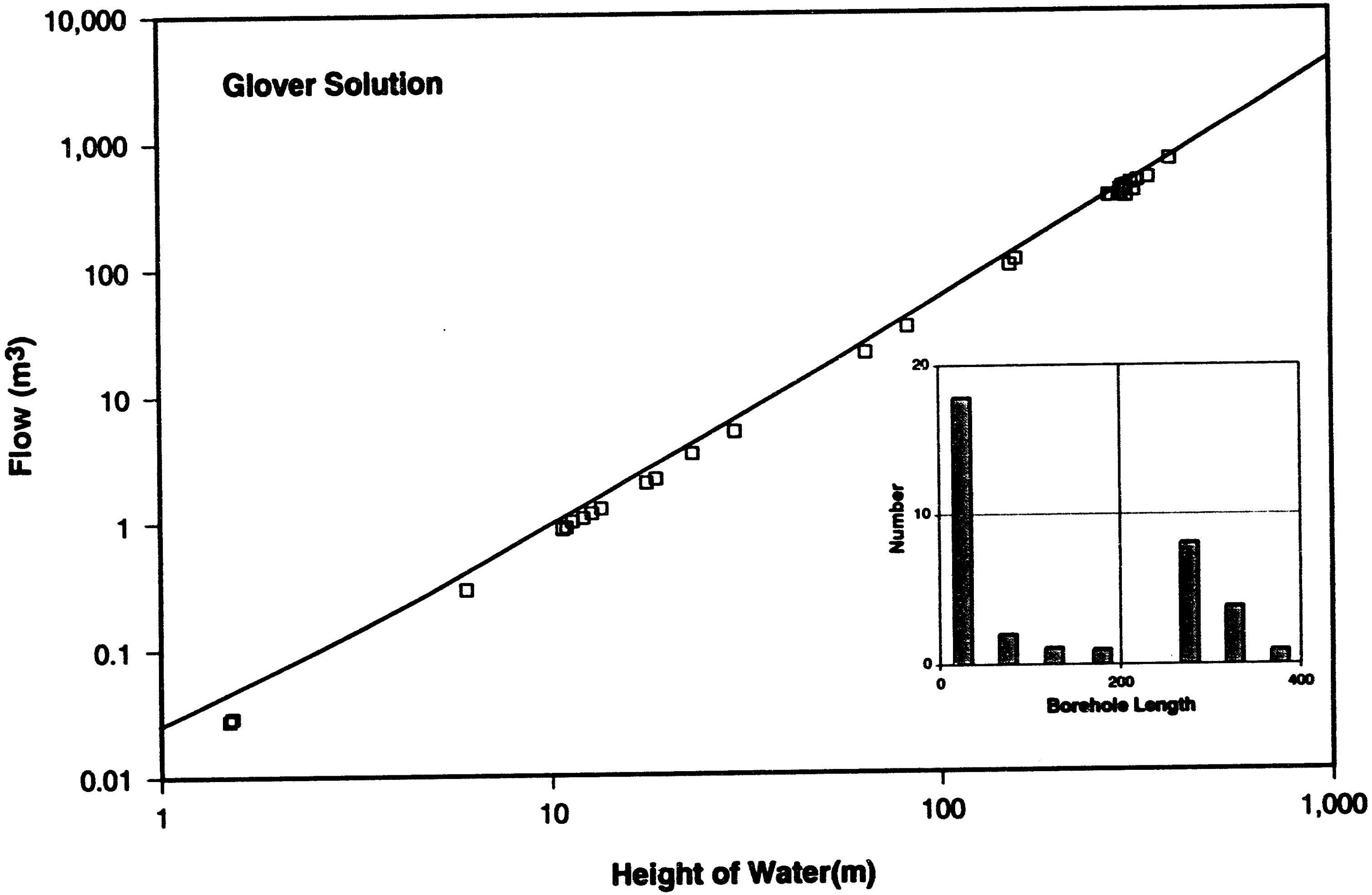


Figure 4-5

Hydrologic Significance of Borehole Seals
Glover Solution

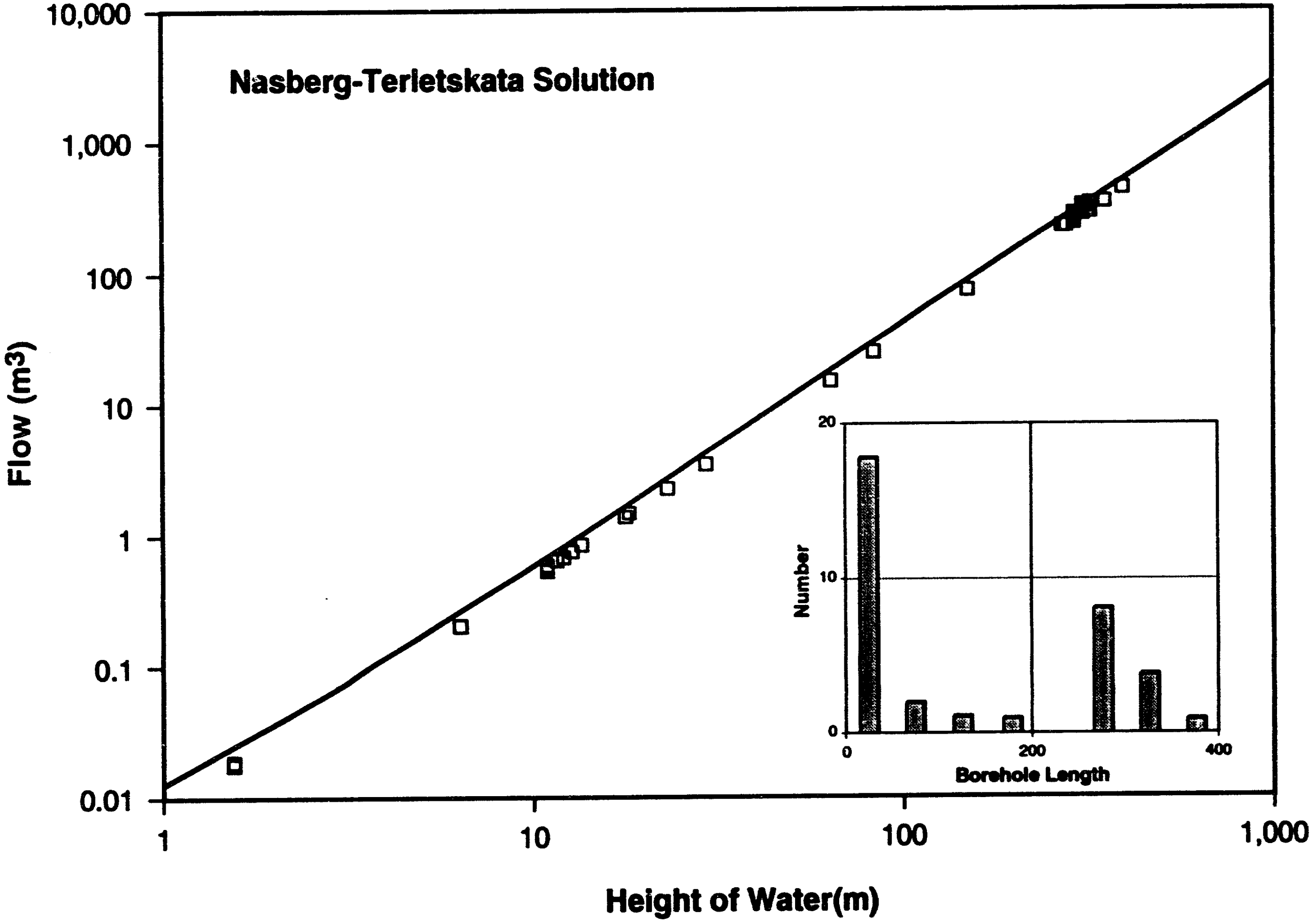


Figure 4-6
Hydrologic Significance of Borehole Seals
Nasberg-Terletskata Solution

satisfies this requirement. The previous approach adopted involved placing a moderately low-permeability material in the Calico Hills section for holes that penetrate through the underground facility and into the groundwater table. These holes represent potential flow paths to the accessible environment.

In the current study, 14 deep boreholes are identified. These 14 boreholes should be sealed to restrict flow through them to 1 percent of the flow through the rock. Design requirements are discussed in Chapter 5.0.

4.1.4.2 Restricting Water Flow Above the Potential Repository

Because of the depth of several of the deeper boreholes and the potential for flooding that might occur, the possibility exists for water to enter several boreholes during flooding, resulting in an increase in the saturation state of the rock around the potential repository. In the current sealing strategy, the placement of a high-quality seal above and below the nonwelded Paintbrush tuff/Topopah Spring contact zone reduces vertical flow, assuming the occurrence of perched water conditions at this contact or below this seal. Below the seal, a coarse backfill is placed to provide a capillary barrier to vertical flow to augment the formation of a capillary barrier in the rock (Montazer and Wilson, 1984). In setting the performance goals for seals, specified earthen or cementitious materials achieve conductivities that are several orders of magnitude lower than the anticipated design requirement (discussed in Chapter 5.0).

4.2 Airflow

The objective of the following analyses is to determine the extent of lateral dispersion from the edge of the potential repository, which would then determine the extended boundary of the potential repository boundary. A subsequent analysis evaluates the influence of a less-fractured, less-permeable tuff that forces flow into Solitario Canyon. The final analysis calculates seal conductivities satisfying the 1 percent performance requirement and evaluates borehole significance.

4.2.1 Upward Dispersion

As air flows upward from the potential repository by either barometric or convective mechanisms, lateral spreading of radionuclides through the processes of molecular diffusion and hydrodynamic dispersion is likely to occur. Recent research (Burkhard et al., 1989; Peterson et al., 1987) associated with barometric or atmospheric pumping suggests that this is a reasonable scenario to consider and that the fractures may play a role in contaminant transport. Some pertinent conclusions follow:

- Contaminant transport in the vertical direction through a nonhomogeneous porous medium is enhanced by atmospheric pumping (Peterson et al., 1987).
- It appears that fractures control the pneumatic diffusivity and contaminant transport of the volcanic rocks (Burkhard et al., 1989).

- Fluid travels much faster along the fractures than through the blocks, and the speed differs along fractures having different apertures (Endo et al., 1984).

Therefore, analyses were performed to determine the nature and extent of such lateral spreading due to the fractured nature of the tuff as discussed previously in Chapter 2.0.

The advection-dispersion analysis was performed with a two-dimensional plane dispersion model (Javandel et al., 1984). Using a cartesian coordinate system with the x axis oriented along the direction of the flow, the two-dimensional advection-dispersion equation can be written as follows:

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v \frac{\partial C}{\partial x} - \lambda R C = R \frac{\partial C}{\partial t}$$

where

C = Concentration
D_L = Dispersion coefficient along the flow direction
D_T = Dispersion coefficient perpendicular to the flow direction
v = Average linear flow velocity
R = Retardation factor
t = Time
λ = Decay constant.

In Appendix G, an advection-dispersion analysis is presented that treats the single-line source perpendicular to the flow direction and has an approximate width of 1,100 m.

Javandel et al. (1984) used TDAST to evaluate equations for different locations at various times. TDAST was adapted here, with minor changes to model the transport of radionuclides by airflow from the potential repository. A subroutine was added to perform the integration because the numerical libraries that the original program used are inaccessible. The simple two-dimensional potential repository model assumes the following:

- Steady-state flow is in two dimensions, and air disperses from a single-line source approximately the width of the potential repository.

- A homogeneous and isotropic flow medium and a single average linear velocity, as determined from the previous analysis in which the direction of flow is normal to a line source, characterizes the flow.

- Both longitudinal and lateral dispersion can occur in the two-dimensional plane. Dispersion depends on both the longitudinal and lateral dispersion coefficients for the media.

- The gaseous radionuclides are nonreactive, and the retardation factor is 1 ($R = 1$).

- Radioactive decay is zero, due to the short transit time from the potential repository to the ground surface ($\lambda = 0$).

- Radionuclides are released from the waste packages at a constant rate ($\alpha = 0$) at concentration (Co). (The resulting analyses are scaled to this concentration.)

Airflow relationships were developed to construct the contour plots of average linear velocity. The three combinations of bulk-rock conductivity presented previously were evaluated. These combinations were selected to produce a range of conductivities for welded and nonwelded tuff and to examine the influence of a thinner, less permeable layer of nonwelded tuff on overall airflow rates, if the conductivities of the welded tuff were high (10^{-2} cm/s).

A sensitivity study was conducted using three different velocity values: 7×10^{-7}, 7×10^{-6}, and 4×10^{-4} m/min. In each case, $\alpha_L = 100$ m, and $\alpha_T = 1, 20$, and 100 m. The coefficient of molecular diffusion, D^*, was assumed to be zero, due to its low value compared to other terms. The distance to the ground surface was 300 m. An additional analysis was performed for lateral spreading to the Paintbrush contact at a distance of 60 m. The results of the analyses for the assumed properties are presented in Appendix G.

For the isotropic case, the lateral spreading would be limited to several hundred meters from the edge of the potential repository. This is a conservative estimate, because the dominance of the vertical fracture system would force flow to be more narrowly confined around the perimeter of the potential repository, and in the case of convective airflow analysis, there would be a tendency for air to be drawn into the potential repository from cooler regions. For the anisotropic case, lateral spreading would be limited to several meters using more realistic dispersivity values.

Figure 4-7 presents the potential maximum degree of lateral spreading, considering the 600 m boundary and a boundary controlled by the north-south trending fractures. Two cases were considered. In the first case, lateral spreading occurs 600 m from the potential repository boundary.[3] In the second case, the degree of spreading reduces on the western and eastern boundaries of the potential repository.

---

[3] The model assumes the width from the repository centerline to the edge of the repository is 1,100 m. Clearly, distances at the southern portion of the repository would be less, and the 600 m would scale accordingly.

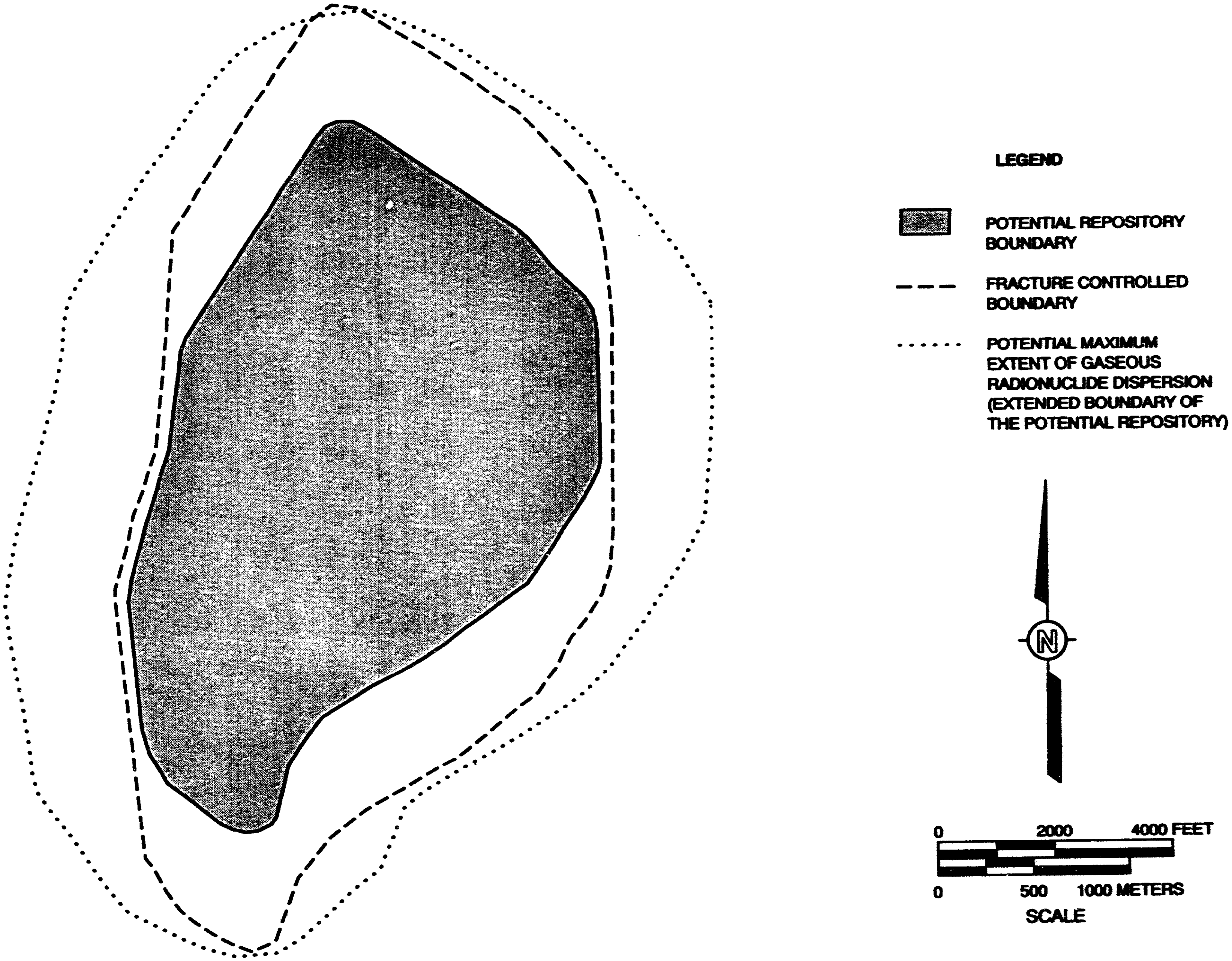


Figure 4-7
Extent of Lateral Spreading from the Potential Repository

4.2.2 Barometric and Convective Airflow

Recent work by Lu et al. (1991) evaluated two-dimensional flow and the effects of a low-permeability layer on potential gas flow at Yucca Mountain. They used a model developed by Amter and Ross (1990), named the Topographic Induced Flow (TGIF), to simulate gas flow under Yucca Mountain. The TGIF model assumes that the air, water vapor, and water are in thermodynamic equilibrium and flow occurs by advection. Also, the model assumes that the air behaves as an ideal gas under steady-state flow in a single porosity medium. With these and other assumptions, the model solves the fundamental equations for volume balance, the constitutive relation for gases and Darcy's Law. From the mass airflow rates, the model uses a post-processor to trace particle path lines.

The physical properties of the system include Yucca Crest, with three distinct hydrostratigraphic units, as illustrated in Figure 4-8. The model includes the thin, nonwelded, sparsely fractured tuff layer that entails all or part of several stratigraphic subdivisions of the Paintbrush Tuff. As in previous analyses performed by Fernandez et al. (1989), the analysis evaluated conductivity contrasts between the nonwelded and welded units. The hydraulic conductivity of the Tiva Canyon and the Topopah Spring Units was 10^{-2} cm/s, while the nonwelded hydraulic conductivity ranged from 10^{-5} to 10^{-1} cm/s. Thus, Lu et al. (1991) selected conductivities somewhat higher for the welded units. Yet, as they note, it is the conductivity contrast between the two kinds of tuff and not the absolute magnitude of the conductivity that determines flow-path trajectories.

Also, Lu et al. (1991) evaluated various temperatures of the potential repository and surrounding rock. Figures 4-9 and 4-10 present the results of these analyses. These cross sections through Yucca Crest developed by Lu et al. (1991) with the given potential repository layout correspond closely with the cross section near USW UZ-6. These analyses evaluate the condition of no permeability contrast and for permeability contrasts of 1,000 between the welded and nonwelded tuffs. The results at ambient temperature show that with no permeability contrast flow concentrates at Yucca Crest. For the case of a permeability contrast by the factor of 1,000, confinement by the nonwelded tuff is complete, and separate convection cells develop above and below this layer. On the western side of the potential repository, flow exits in Solitario Canyon in the upper portion of the Topopah Spring Unit. The results at elevated temperature with no permeability contrast show that the large temperature gradients dominate the flow regime with a much less significant tendency for flow to concentrate near Yucca Crest. For the case of a permeability contrast at elevated temperature, two separate flow systems again develop, and the results suggest that even for airflow that develops at the center of the potential repository, flow exits in Solitario Canyon in the upper portion of the Topopah Spring Unit.

In considering the significance of individual boreholes, Figure 4-11 presents the distances of existing and proposed boreholes from Yucca Crest. Boreholes within the range of about 100 m of the crest might undergo enhanced flow under ambient temperature conditions due to the concentration of flow near Yucca Crest. The existing boreholes include USW UZ-6s, USW H-3, USW H-5, and USW UZ-6. The proposed boreholes include only USW SD-3. After potential

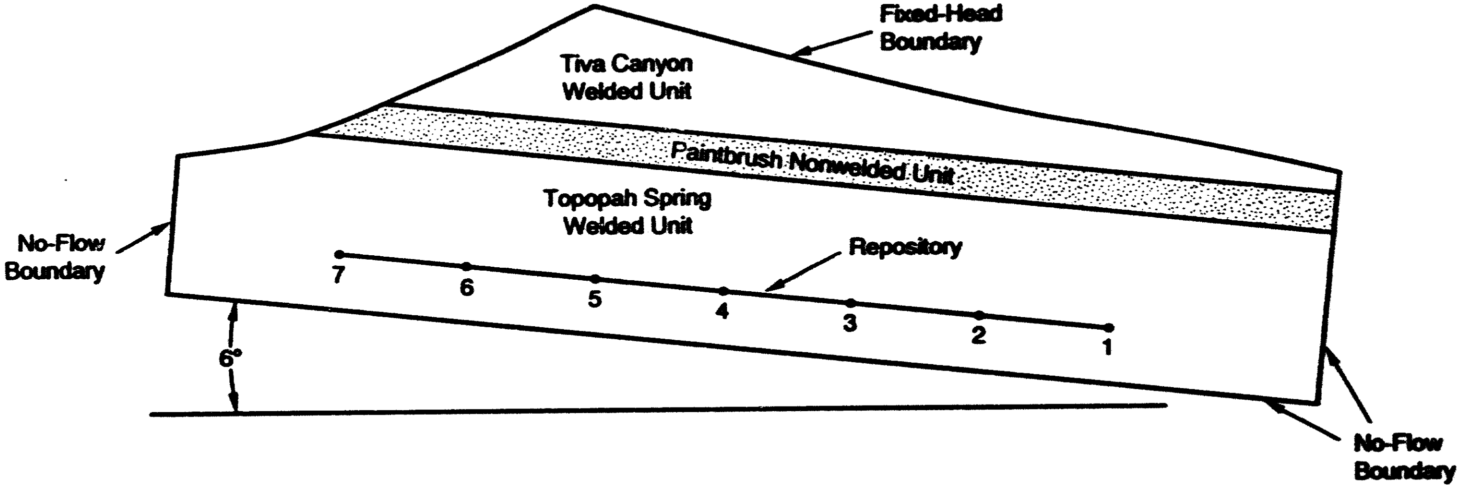


Figure 4-8
Geometry of Cross Section Used in the Gas Flow Simulation
After Lu et al., 1991

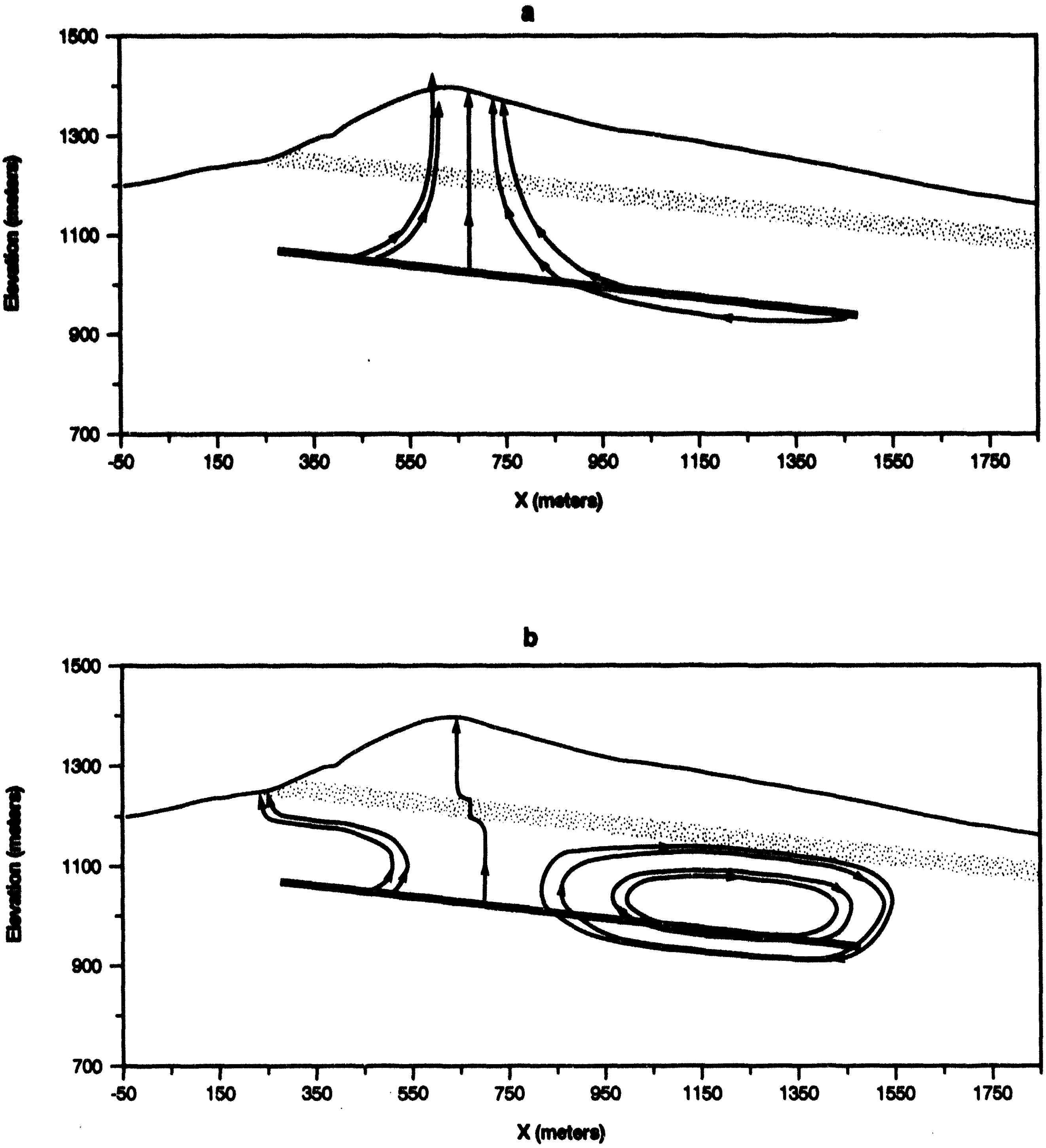


Figure 4-9
Airflow Path at Ambient Temperature
(a) No Permeability Contrast and (b) Permeability Contrast of 1,000.
After Lu et al., 1991

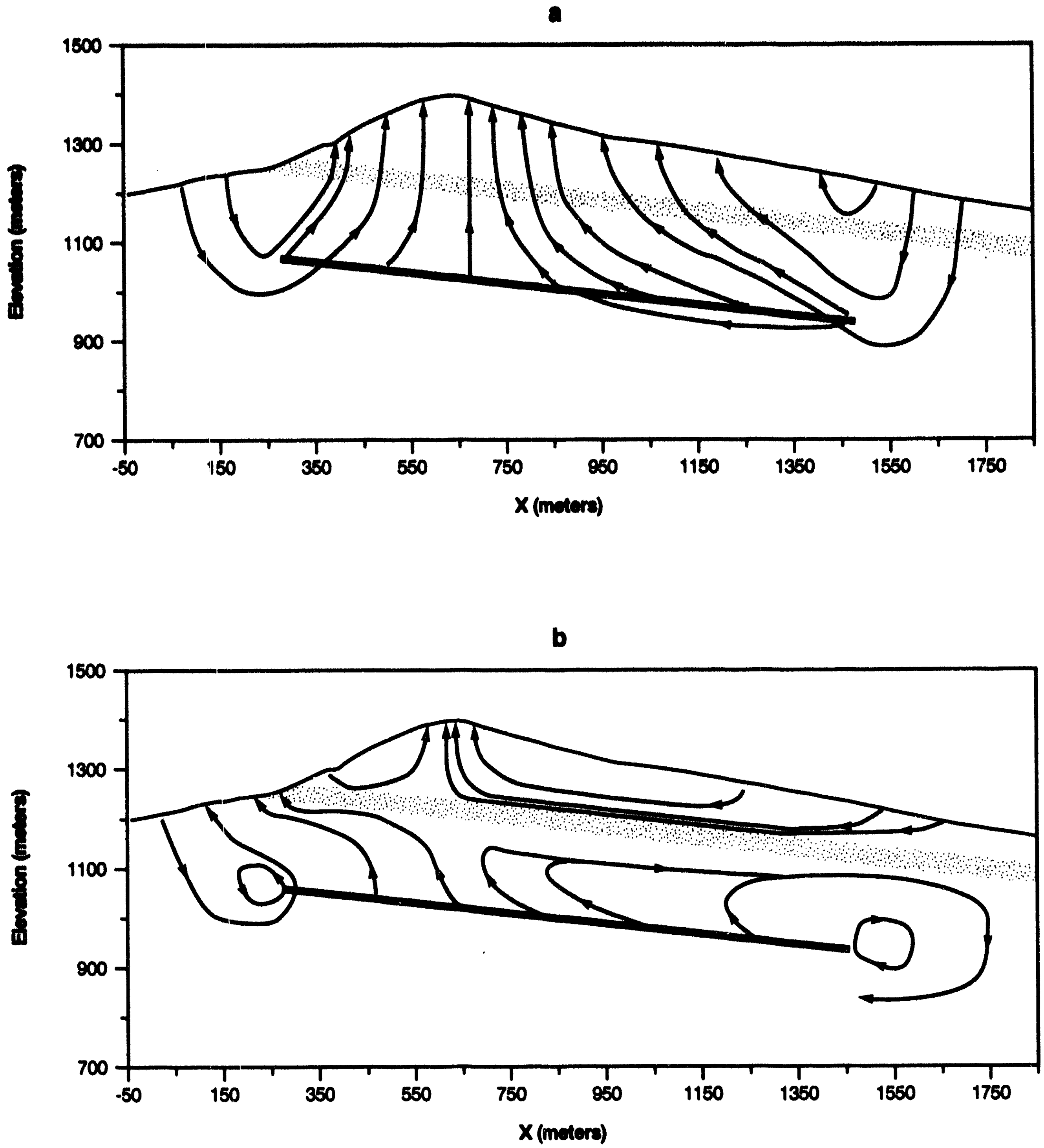


Figure 4-10
Airflow Path at Elevated Temperature
(a) No Permeability Contrast and (b) Permeability Contrast of 1,000.
After Lu et al., 1991

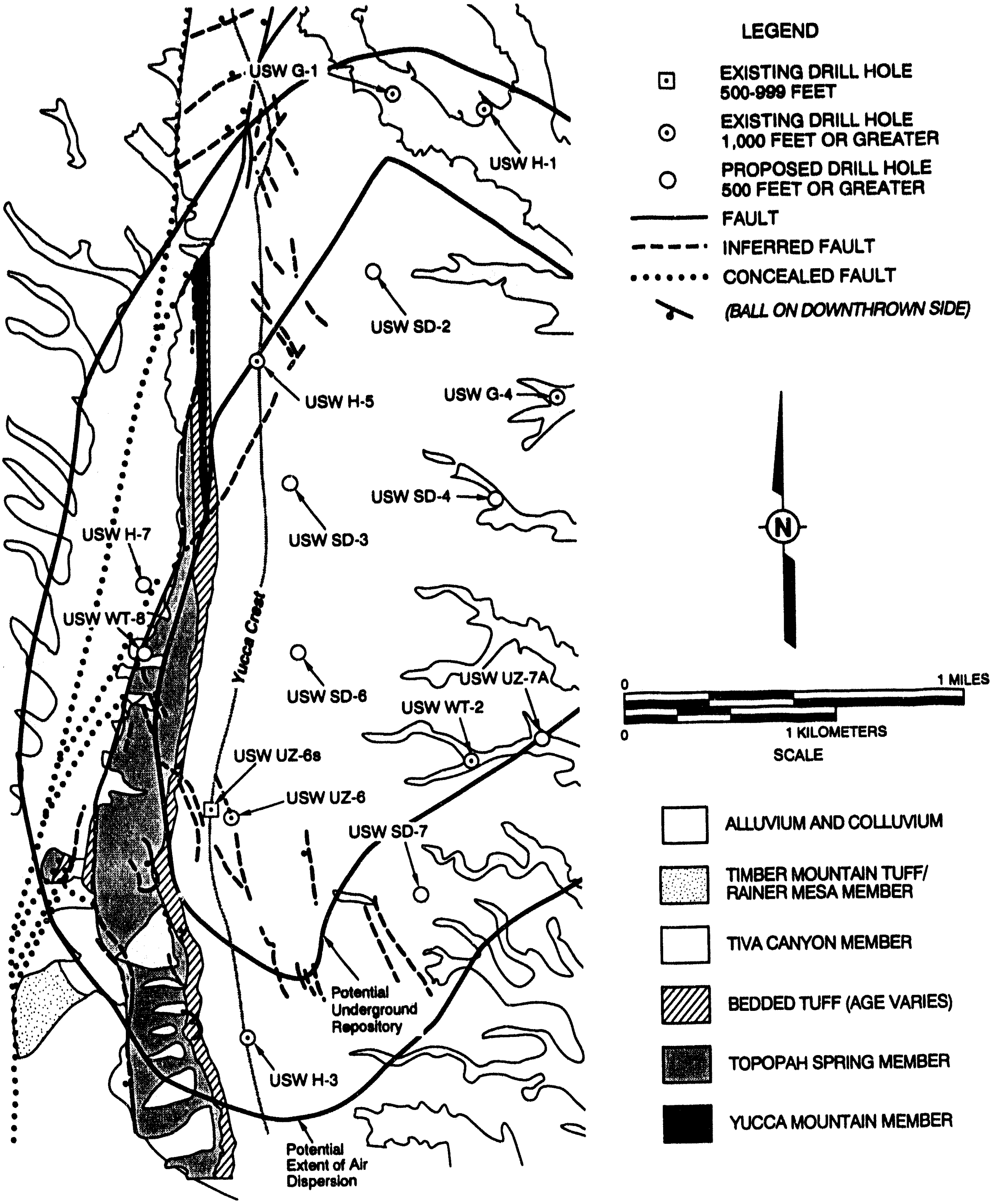


Figure 4-11
Geologic Map of Yucca Crest

repository heating occurs, the results show that boreholes within the potential repository, or more specifically, the heated areas of the potential repository, would be significant and that the boreholes near Yucca Crest have little added significance with respect to convective transport.

Where a significant contrast in conductivity occurs, the results suggest separate flow regimes above and below the nonwelded tuff and the need to place a high-quality seal in the Paintbrush nonwelded tuff unit to reduce the potential for flow to occur across this zone above the potential repository. Preferential flow of contaminated air could occur up through boreholes collared in the Topopah Spring Unit to the west of the potential repository (USW H-7 or USW WT-8), as illustrated in Figure 4-11. High-quality seals need to be placed from the top of the Topopah Spring Unit in these areas.

4.2.3 Performance Requirements for Airflow

This section presents the results of an airflow or advection calculation, considering existing and proposed boreholes within the potential repository and the extended boundary of the potential repository as presented in Section 4.2.1. Flow occurs completely through the seals from the potential repository to the ground surface or in series through the rock web below the borehole and then through the backfilled borehole (Figure 2-5). The calculations use the three rock-mass models presented previously to find the performance requirements for borehole seals. This section addresses the relative significance of drilling boreholes to varying depths and the performance requirements that satisfy the performance goals established for airflow.

Flow will be established through the rock web near the heat source and through the backfilled hole (for shallow holes) or through the entire backfilled hole (for holes penetrating through the potential repository horizon). The performance requirement limits airflow caused by either convective or barometric transport to 1 percent of the flow through the rock mass for all affected boreholes. This is expressed mathematically as follows:

$$.01(d*c_x)A*i = \sum_{i=1}^{n}(K_b*A_b)i$$

where

d = Mean depth of potential repository to the ground surface
c_x = Mean conductance of the rock model
K_b = Equivalent vertical conductivity of the backfill
A_b = Cross-sectional area of boreholes near the surface depth
i = Airflow gradient
A = Cross-sectional area of the potential repository.

Appendix H presents harmonic mean computations for individual boreholes. In these computations, the seal conductivity is selected for each rock model, and the harmonic mean is calculated for each borehole and summed over all boreholes that satisfies the above relationship. The harmonic mean computation depends on the depth of borehole and the units penetrated. As discussed in the appendix, for deep holes penetrating the potential repository, the equivalent vertical conductivity equals the effective seal conductivity. For shallow boreholes, the vertical conductivity is nearly equivalent to that of the rock.

The air-dispersion calculations established the extended boundary of the potential repository. Approximately 116 existing and proposed boreholes could be subjected to convective and barometric airflow. Of these holes, approximately 30 deep boreholes penetrate to the potential repository horizon.

Using the criterion established for airflow above, the calculated conductivities satisfying the 1 percent criterion are presented in Table 4-3:

Table 4-3
Required Seal Performance (m/min) [Allowable Seal Conductivity Calculation]

Area	Model 1	Model 2	Model 3
Extended Repository[a]	9.0×10^{-3}	1.4×10^{-1}	4.9×10^{0}
Repository	1.7×10^{-2}	2.6×10^{-1}	8.8×10^{0}

[a] This analysis conservatively assumes that flow through the rock is over the area of the repository. If flow through the rock of the extended repository is included, the seal performance requirement would be somewhat higher.

The lower values for the seal conductivity (K_s) for the extended boundary of the potential repository reflect air flowing through additional boreholes, requiring a more conservative value to satisfy the 1 percent flow requirement.

Tectonic features may affect the convective or barometric air transport out of the potential repository. Scott and Bonk (1984) present several categories of tectonic features for the potential repository. Assuming that fault zones are 15 m wide and fractures are 5 m wide, the area of these zones represents approximately 4 percent of the total potential repository area. The effect of tectonic features such as faults would result in a higher and less restrictive performance requirement for air conductivity for seals, if such zones exhibit higher conductivity than the surrounding rock mass, since these zones would become dominant zones for airflow. When encountering high-conductivity fault zones, sealing boreholes becomes less imperative because flow may dominantly occur through such zones. Alternatively, tectonic features lower in conductivity are unlikely to affect the seal performance requirements because their cross-sectional areas are small compared to that of the potential repository.

4.2.4 Conclusions from the Air Release Calculations

The product of the equivalent seal conductivity (K_b) multiplied by the cross-sectional area (A_b), represents the seal-system conductance for a single borehole. Appendix H illustrates the relative significance for the boreholes as the cumulative flow rate and for the 116 boreholes cumulative thin rate plotted as a function of borehole length. The selected performance requirement depends on the rock conductivity model employed. Model 1 is the least conductive rock combination, while Model 3 is the most conductive combination. The results for all three models show less significance by 5 to 6 orders of magnitude for surficial boreholes than for intermediate-depth boreholes penetrating the potential repository.

The following analysis is presented to provide guidance to the surface-based testing program as to the consequence and risk involved in abandoning a borehole without sealing. The objective of the following analysis compares airflow through a single abandoned borehole to the flow through sealed deep boreholes.

The calculation presented above and in Appendix H shows cumulative flow through all boreholes within the extended boundary of the potential repository. The most significant boreholes are deep boreholes that are cased. Thus, the casing provides access to sealing locations at depth. Yet, several boreholes may be uncased, and in these few instances, an evaluation of the performance of a single abandoned borehole for each of three models is of interest, since the placement of high-quality seals may not be possible.

For purposes of evaluation, this report considers the existing USW UZ-6 borehole that has a large diameter at the potential repository horizon. It also considers that the effective hydraulic conductivity of the abandoned borehole equals 10 cm/s (equivalent to an air conductivity of 0.4 meters per minute). The conductance can be compared to the cumulative conductance for the three models in Appendix H. The relative significance of a single abandoned borehole depends on the model employed. For the low-conductivity model (Model 1), a single abandoned borehole provides a greater conductance than 100 boreholes combined together (or 30 boreholes penetrating through the potential repository horizon). For Model 2, the conductance of a single abandoned borehole represents about 10 percent of the total flow. For the most conductive model (Model 3), the flow through a single abandoned borehole is not significant, in that the design requirement expressed as an air conductivity for seals is of the order of 4 m per minute (equivalent to a hydraulic conductivity of 100 cm/s).

The above analysis does not include fault zones that may have a higher conductivity. If fault zones are persistently higher in conductivity, they might tend to dominate convective airflow, and a single abandoned hole would have less significance. On the other hand, if the low-conductivity model is appropriate with a flow resistance dominantly occurring in low-conductivity formations, the abandoned borehole has added significance.

The 30 boreholes penetrating through the potential repository dominate airflow and require sealing to the performance requirement. The surficial boreholes do not require sealing to the performance requirements and can be backfilled or left untreated.

5.0 Design Evaluation of Borehole Seals

This chapter presents hydrologic, airflow, and structural design evaluations that address the selection of design requirements to satisfy the water-flow and airflow performance requirements presented in the previous chapter. This chapter also addresses other how and when to seal issues. Structural seal designs are evaluated for combinations of seal, backfill, thermal, and seismic loading. This design information is then used to identify important design issues and to select seal materials and placement methods that will optimize seal design.

5.1 Air and Water Design Requirements

In relatively unfractured rock, flow can occur through the seal matrix and through the seal interface (Figure 5-1). In Chapter 2.0, flow through a borehole test seal supported the theory that the interface zone behaves like a fracture in that, at low effective stress levels, the interface opens and exhibits high conductivity. At higher stress levels, the interface closes and exhibits a much lower conductivity. The following analysis develops a model for the interface zone to identify properties of the seal matrix and interface that satisfy the performance requirement.[1]

Flow can occur in parallel through the interface zone and the seal matrix (Figure 5-1) as follows:

$$K_s * A_s = K_m * A_m + K_i * A_i$$

where

K_s = Effective seal conductivity for the seal as calculated previously
A_s = Seal cross-sectional area
K_m = Seal matrix conductivity
A_m = Seal matrix area
K_i = Interface zone conductivity
A_i = Interface zone area.

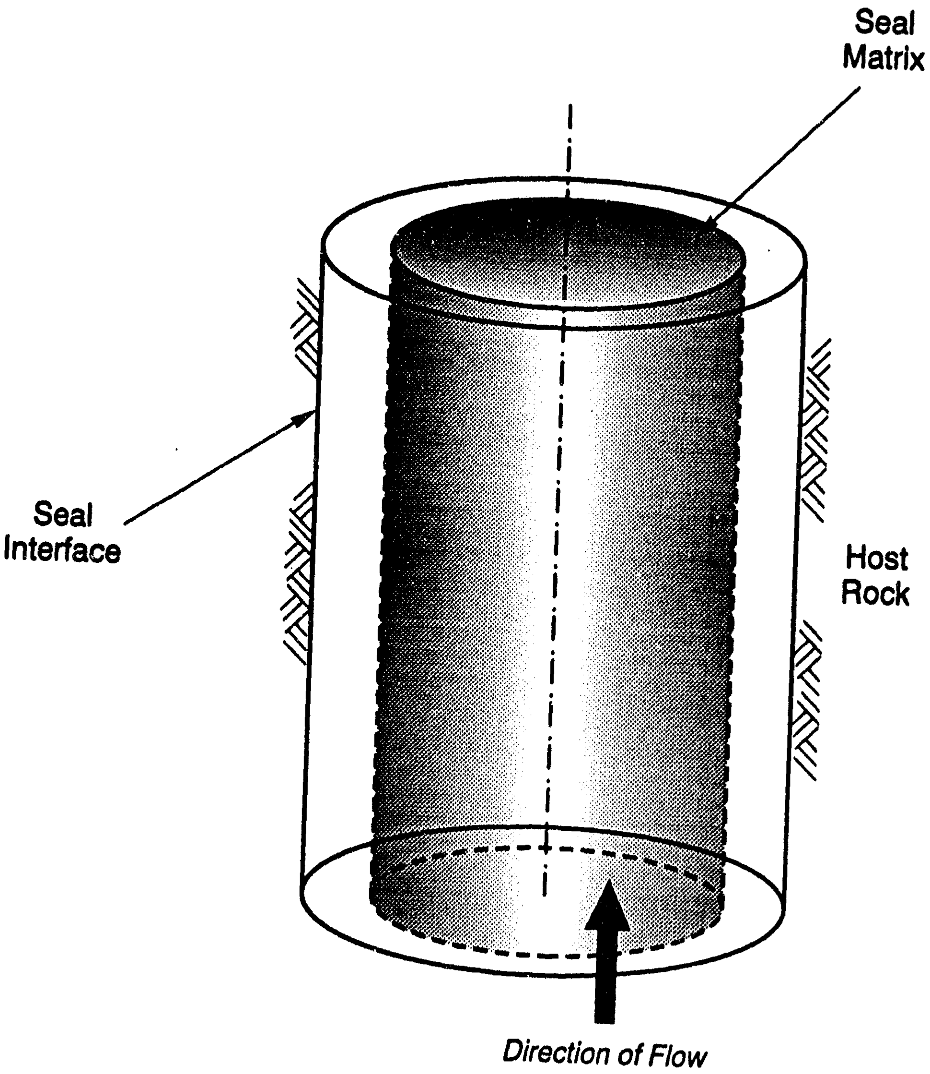
Noting that the area of the seal and the matrix are nearly identical, the following is obtained:

$$A_s \approx A_m = \pi * r^2$$

where r = Radius of the borehole.

---

[1] In this theoretical discussion, it may be difficult in practice to identify and measure separate flow regions through the seal matrix and interface zone. Consequently, performance testing needs to look at composite effects. The acceptance criteria might state that the flow rate divided by the head difference be less than a certain conductance value. Yet, it is of interest to discuss theoretical properties, in that discussion can highlight important design issues to be considered in selecting materials and placement conditions.



Note that the interface is modeled as a smoothwall fracture aperture and horizontal scale is exaggerated

Figure 5-1
Model for Flow Through the Seal and Interface Zone

The area of the interface is approximately equal to the interface aperture times the circumference:

$$A_i = 2\pi\ rb.$$

From Case and Kelsall (1987), the hydraulic conductivity of a single fracture may be related to the equivalent smooth-wall fracture aperture by the following relationship:

$$K = \frac{g\rho b^2}{12\mu} = \frac{gb^2}{12\upsilon}$$

where

b = Smooth-wall aperture
K = Fracture conductivity
ρ = Mass density
g = Acceleration due to gravity
μ = Dynamic viscosity (or absolute viscosity).

By definition, $\mu = \upsilon * \rho$, where υ = kinematic viscosity.

Substituting the above relationships in the relationship for parallel flow:

$$K_s * \pi * r^2 = K_m * \pi * r^2 + \frac{g\rho b^2}{12\mu}\ 2 * \pi * r * b.$$

The relation states that flow through the seal matrix equals the product of the cross-sectional area and the matrix conductivity. The flow through the interface is given by the cubic law for smooth-wall fracture apertures, which states that there exist combinations of seal matrix conductivity and interface aperture that satisfy the performance requirements. Another relationship, which assumes a fracture runs down the center of the seal with interface aperture properties equivalent to the properties of the interface zone, states:

$$K_s * \pi * r^2 = K_m * \pi * r^2 + \frac{g\rho b^2}{12\mu} 2 * \pi * r * b + \frac{g\rho b^2}{12\mu} 2rb.$$

5.1.1 Airflow

The calculations presented in this section evaluate several combinations of airflow to obtain seal design requirements, including flow through the interface, represented by a peripheral crack or a peripheral crack in combination with a longitudinal crack through the seal matrix. For boreholes penetrating the potential repository, the seal design satisfies the 1 percent performance requirement by selecting a seal-matrix conductivity and interface-zone conductivity that results in an effective seal conductivity. The effective seal conductivities were obtained in Section 4.2.3 for rock Models 1 through 3 and for the potential repository (Models 1, 2, and 3) and extended boundary of the potential repository (Models 1E, 2E, and 3E) boundaries. Figure 5-2 illustrates the combinations of seal-matrix and interface-zone conductivities, as expressed by an effective smooth-wall aperture and matrix conductivity that satisfies this requirement. The three rock models are presented for both the potential repository and the extended boundary of the potential repository as presented in the previous chapter. Combinations below the frontier provide acceptable performance for each of the six cases analyzed. The results suggest materials that exhibit matrix conductivities below 10^{-1} cm/s and an effective smooth-wall aperture of less than 500 μm satisfy the performance requirement. As stated previously, the results suggest selecting more conservative requirements when considering the potential repository boundary. They also suggest a close relationship between requirements and the host-rock conductivity, with a lower performance requirement for Model 1 than for Model 3. Figure 5-2 presents the influence of a longitudinal crack with assumed properties equivalent to the peripheral interface zone. These nearly identical results suggest that there is no significance to the development of longitudinal cracks if they are tight or (as suggested by previous studies) are under confining pressure, which tends to result in a tight interface.

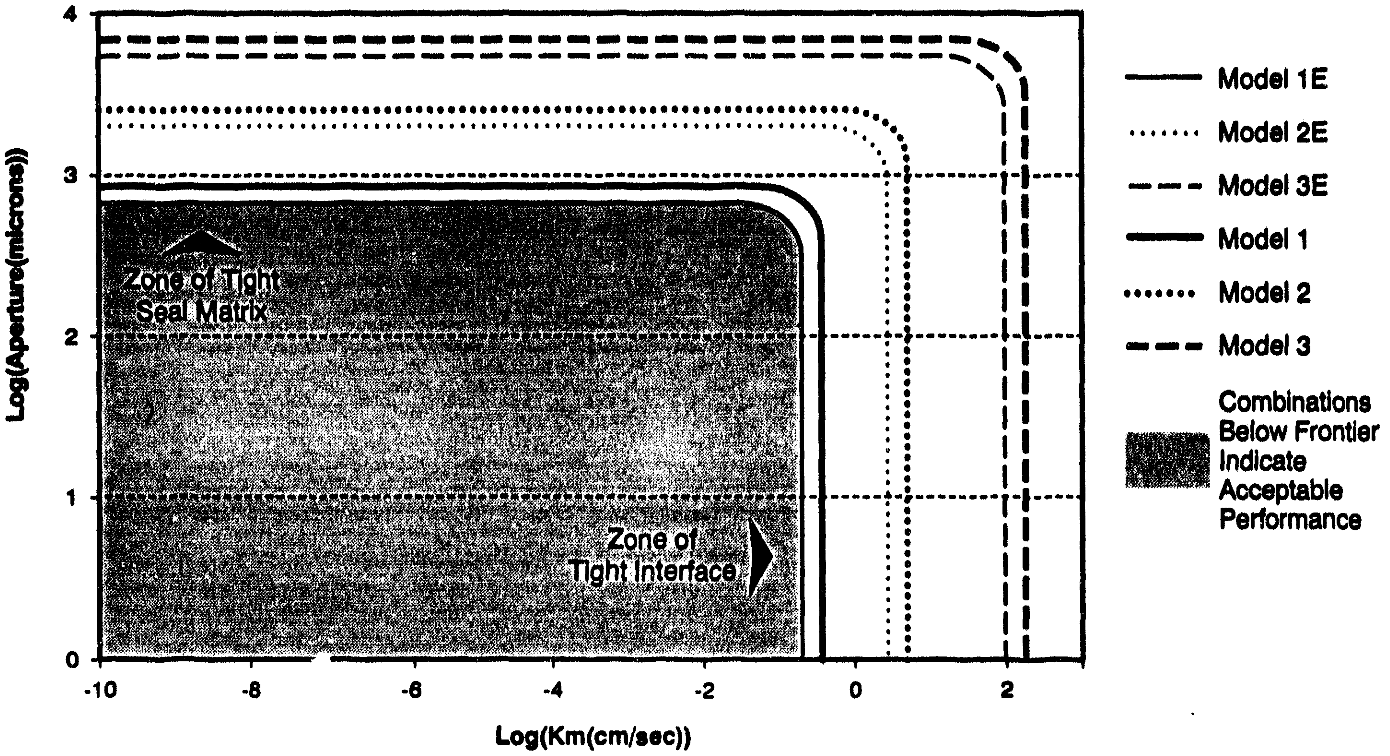
5.1.2 Water Flow

The calculations presented in Figure 5-3 evaluate hydrologic flow to obtain a seal-design requirement, using the same approach presented above for airflow. The seal design for hydrologic flow below the potential repository satisfies the 1 percent performance requirement for water flow by selecting a seal matrix conductivity and interface-zone conductivity that results in an acceptable effective seal conductivity. The results suggest that materials exhibiting matrix conductivities below 10^{-1} cm/s and an effective smooth-wall aperture of less than 100 μm satisfy the current performance requirement.

5.1.3 Conclusions for Air and Water Design Requirements

In selecting design requirements, more stringent requirements are applicable below the potential repository for water flow than are applicable to airflow above the potential repository. This suggests that the selection of a low seal matrix conductivity alone is not sufficient, if the

Seal with no Longitudinal Crack



Seal with Longitudinal Crack

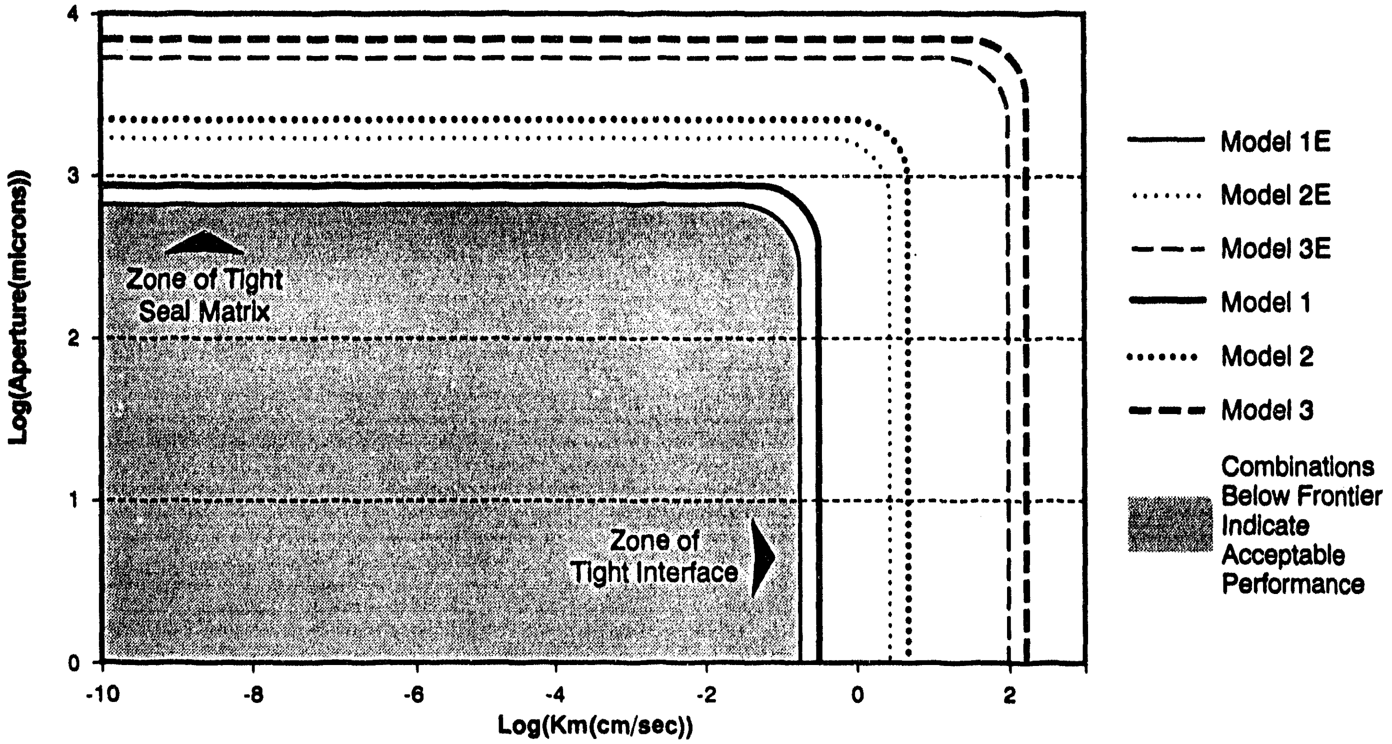


Figure 5-2
Airflow Performance Requirements for Seals
(a) No Longitudinal Crack and (b) with Longitudinal Crack

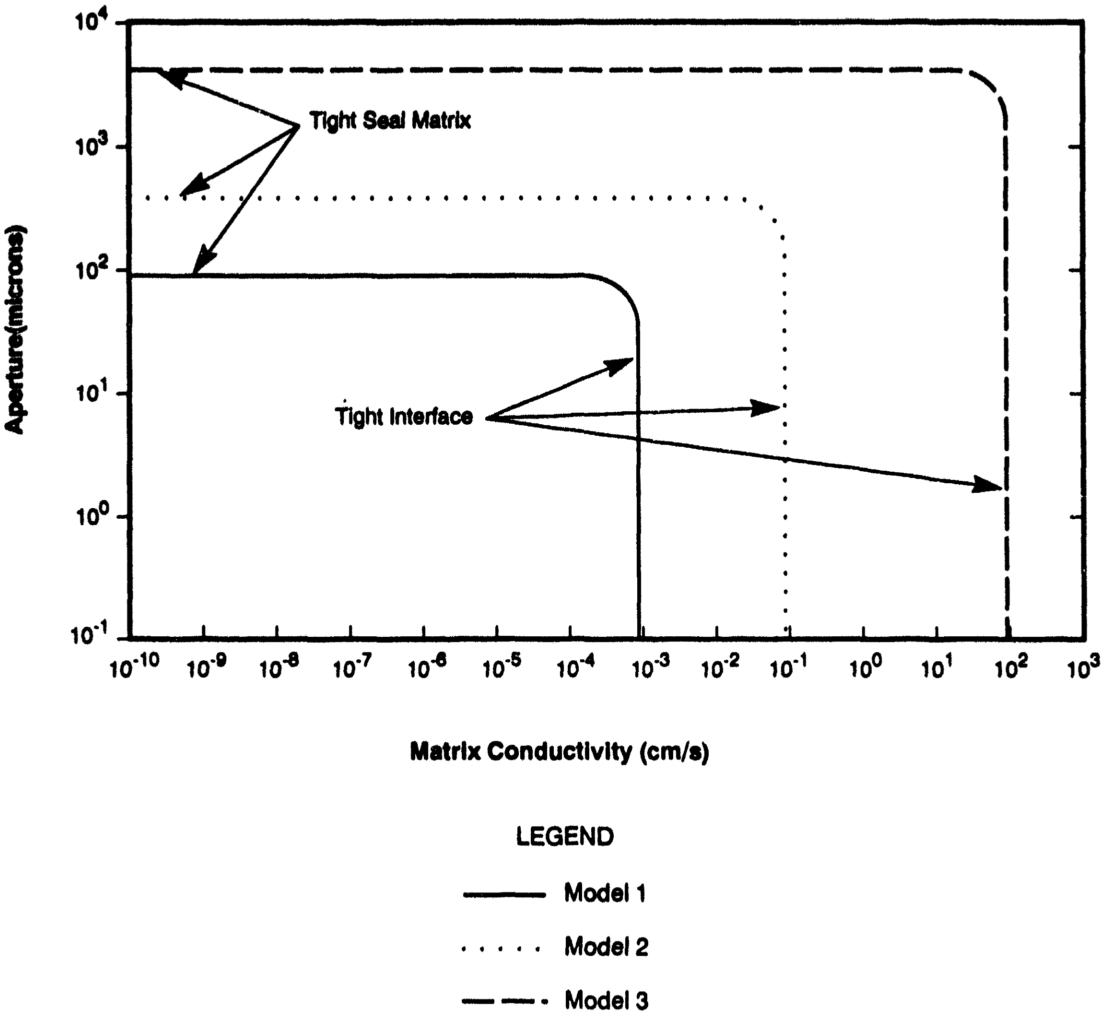


Figure 5-3
Hydrologic Design Requirements of Seals

5.2 Considerations When Emplacing Seals

This section presents information on how and when to seal exploratory boreholes. Section 5.2.1 discusses the various stages in plug development and loadings of seals and includes a discussion of open boreholes, open boreholes near the potential repository horizon, sealed boreholes, and the postclosure environment. Section 5.2.2 discusses methods of analysis, modeling assumptions, and input properties for performing analysis for open boreholes, sealed boreholes, and evaluations of sealed boreholes during the postclosure period.

5.2.1 Stages In Plug Development and Sealing

Seals should be emplaced at key locations using selected material placement methods and geometry to provide load resistance to various combinations of dead, seismic, and thermal loads and to provide strength serviceability. The list of potential degradation mechanisms (Table 5-1) shows those physical mechanisms that might affect hydrologic performance, including channeling around the seal, mechanical degradation and deformation of the seal, modification of borehole fill properties, and chemical degradation. Associated with each failure mechanism are strategies to mitigate seal degradation. All of these general strategies are recommended to be part of the overall sealing strategy.

In the following discussion, the various stages in casing removal, seal development, and postclosure seal performance are presented. At each stage, the sealing design and emplacement strategies can be adopted to mitigate seal degradation.

5.2.1.1 Casing Removal and Exposure of an Open Borehole

The results of previous studies (summarized in Chapter 2.0) established the importance of an interface zone between seal and rock (DOE, 1988). Prior to sealing, the casing may or may not be in contact with the surrounding formation. If the formation has collapsed around the casing, the potential exists for casing corrosion and instability. For an open borehole, the radial stress relieves and the tangential boundary stress increases, resulting in potential failure of the surrounding rock. If waste is emplaced in the potential repository before seal emplacement, the tangential boundary stress increases in response to the higher-temperature environment. Further, if boreholes penetrate to the potential repository horizon, stress-interaction effects with the underground openings could result in stress-concentration effects near boreholes.

5.2.1.2 Plug Emplacement and Backfilling

During seal emplacement (Figure 5-4), the heat of hydration from the selected seal materials produces an increase in temperature and thermal gradients that results in short-term thermal stress. The plug expands thermally during curing and subsequently contracts during cooling. Residual compressive or tensile stresses can develop within the plug and could result in potential separation at the interface zone. The permanent effect, shown subsequently by modeling, depends on (1) heat evolution due to hydration, (2) thermal diffusion to the surrounding welded and nonwelded tuff, (3) thermal expansion of the plug, and (4) evolution of the thermomechanical properties of the plug during the curing process.

Table 5-1

Sealing Strategies to Mitigate Seal Degradation

		Sealing Strategy to Mitigate Failure	
Degradation Mechanism	Initiating Process or Event	Design	Placement
Channeling around seal: Interface bond separates in shear	Increase in load resulting from flooding Lower than anticipated resistance due to bond imperfections	Increase length of the plug (1) Emplace seals periodically or continuously (2) Reduce hydraulic gradient across the plug by increasing drainage into formation (casing removal), by increasing the length of the seepage path (plug length), by decreasing fill porosity (densifying fill), and by injection of grout into formation (3)	Decrease potential load by placing plug near surface (4) Provide higher interface zone bond strength by using low pressure squeezing or by including expansive properties (5) Place seals in areas where the plug emplacement is not as sensitive to emplacement procedures (6) Implement quality control procedures during placement (7) Recondition wall to remove mudcake or other material buildups on borehole wall (8)
Interface bond fails in tension	Seismic load in excess of interface strength	Place seals away from the ground or zones of large anticipated displacements or accelerations (10) Engineer deformational properties of the seal to be similar to the surrounding formation (11) Provide stiffness and expansivity to increase the interface effective stress and frictional resistance (12)	(5) (7)

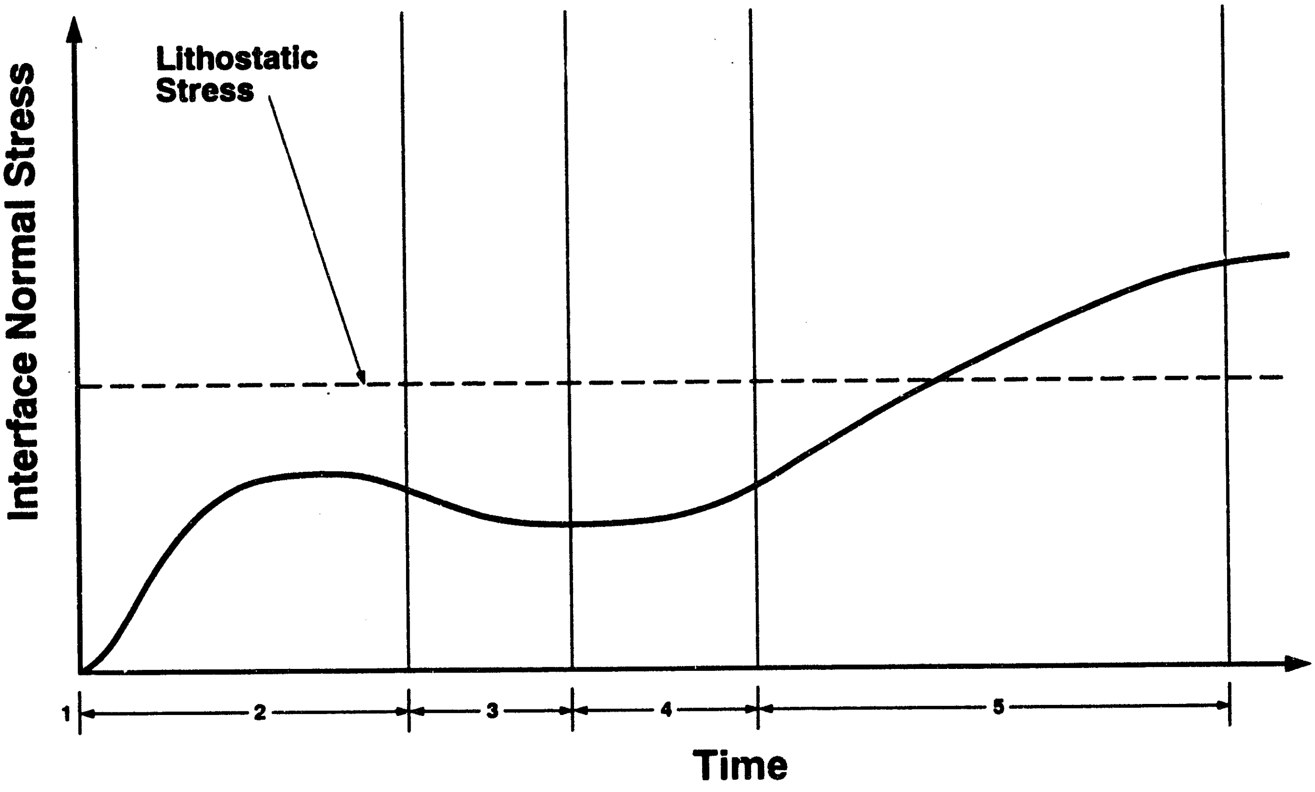
Table 5-1 *(Continued)*

Sealing Strategies to Mitigate Seal Degradation

Degradation Mechanism	Initiating Process or Event	Sealing Strategy to Mitigate Failure	
		Design	Placement
Zone around seal separates due to improper placement	Overpressurization/expansion results in high stress and subsequent failure at the interface Differential thermal expansion between seal and host rock Insufficient seal-injection pressure and/or volume	(1) (2) (3)	(7) (5) Place seals away from high temperature zone Place cementitious seal at a temperature lower than the surrounding formation (15)
Mechanical degradation and deformation: Axial and radial deformation Massive deterioration of seal	Erosion of surficial materials at surface leads to mechanical instability at the surface Shrinkage of material due to thermal loading from waste Cracking due to saturation and desaturation of seals Cracking of plug material resulting from a superimposed stress field comprised of in situ, thermal, seismic, and static stresses	(1) (2) (3) (10) (11) & (12) Control thermal strains during cement hydration and subsequent cooling to prevent micro-cracking of the plug	(5) (6) (7) (8) (15) Place a seal material that has the least susceptibility to saturation/ desaturation cycling

Table 5-1 *(Continued)*
Sealing Strategies to Mitigate Seal Degradation

Degradation Mechanism	Initiating Process or Event	Sealing Strategy to Mitigate Failure	
		Design	Placement
Modification of fill properties: Settlement	Static loading of fill from overlying fill (unsaturated and saturated)	Reduce potential load by periodic installation of weight-bearing plugs Restrict water from entering borehole (13) by • Emplacing a capillary barrier in the unsaturated zone • Emplacing an impermeable fill in saturated zones through selection of suitable materials, compaction control, and use of additives	Reduce permeability by emplacing backfill at high density and low porosity (14)
Liquefaction	Dynamic consolidation caused by seismic loads	(13) Provide suitable gradation to reduce dilation of particles in granular fill	(14)
Chemical degradation: Dissolution of seal	Heated/unheated water moving past the seal will dissolve the seal material	Balance geochemistry of seal with that of the rock Reduce the surface area of the grout exposed to the groundwater by having a low-permeability grout	Place primary seals away from heated environment which will decrease the kinetic rates of dissolution Place grout bulb around primary borehole seal to decrease the potential of groundwater contacting the primary seal



1. Initial mixing and placement
2. Volumetric and thermal expansion (cement hydration)
3. Thermal contraction during cooling
4. Backfill emplacement and subsequent deformational response of plug
5. Postclosure period

Figure 5-4
Stages in Plug Development

separation at the interface zone. The permanent effect, shown subsequently by modeling, depends on (1) heat evolution due to hydration, (2) thermal diffusion to the surrounding welded and nonwelded tuff, (3) thermal expansion of the plug, and (4) evolution of the thermomechanical properties of the plug during the curing process.

5.2.1.3 Increased Temperature Environment

After seal emplacement and potential repository decommissioning, the temperatures increase at key sealing locations over a period of 50 to 5,000 years, resulting in an increase in thermal stress for the seals. As discussed previously, the thermal environment at specific sealing locations depends on the elevation above or below the potential repository and on the proximity of the borehole to the waste-emplacement areas. The farther away from the potential repository that the borehole is located, the smaller the thermal effects during the postclosure period.

5.2.1.4 Saturation of the Backfill

After plug emplacement, backfill emplaced above the plug results in an increase in confining pressure and instability of the interface zone. If settlement occurs below the plug, this could result in the loss of support, an increase in shearing stress, and potential failure across this zone.. Further, if the backfill becomes saturated, resulting in perched water in the borehole, pore pressures could increase, and effective stresses could be reduced across the interface zone.

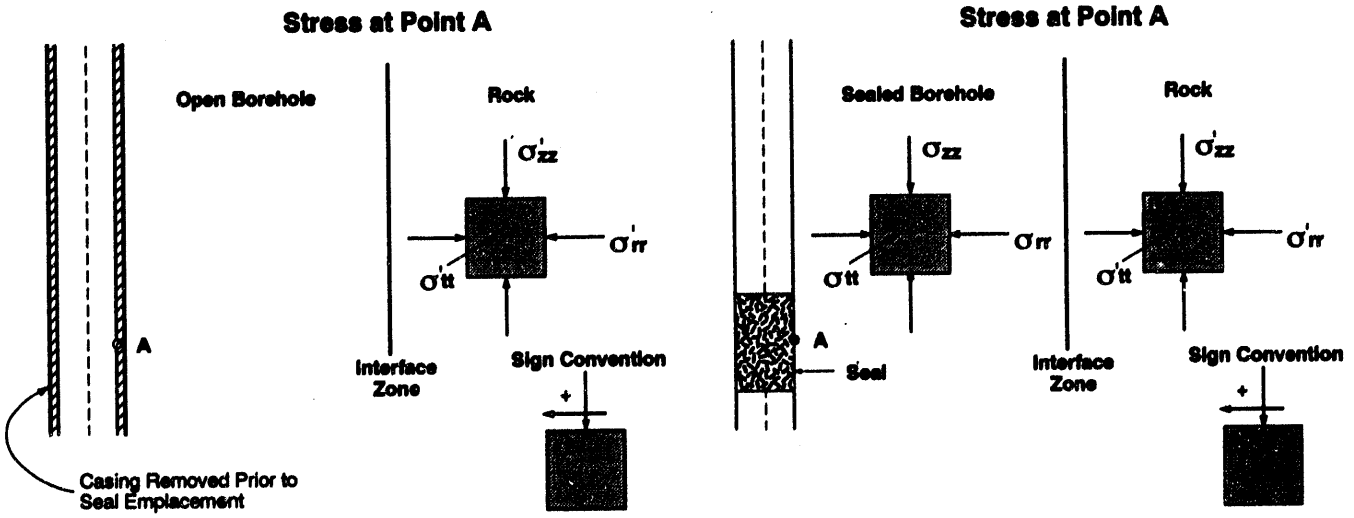
5.2.2 Technical Approach to Corrosion Allowance and Stress Calculations

The preliminary calculations evaluate the various combinations of loadings occurring during the various stages. In superimposing loads, the analysis uses simple calculations. Some of these calculations use conservative loading assumptions. Figure 5-5 shows the state of stress in (1) casing and an open borehole, (2) a sealed borehole, (3) a backfilled borehole subject to thermal loading, and (4) a backfilled borehole subject to saturation over some depth.

In Section 5.3, the "when" to seal issues are evaluated. A general discussion of casing corrosion is presented followed by a corrosion-allowance calculation. In the corrosion-allowance concept, the allowable reduction in casing wall thickness under the conditions of uniform corrosion is calculated using standard buckling formulas for casing. This allowance is compared to the expected corrosion rate to show how long the casing is structurally sound after the emplacement of waste. This calculation will determine "when" to seal.

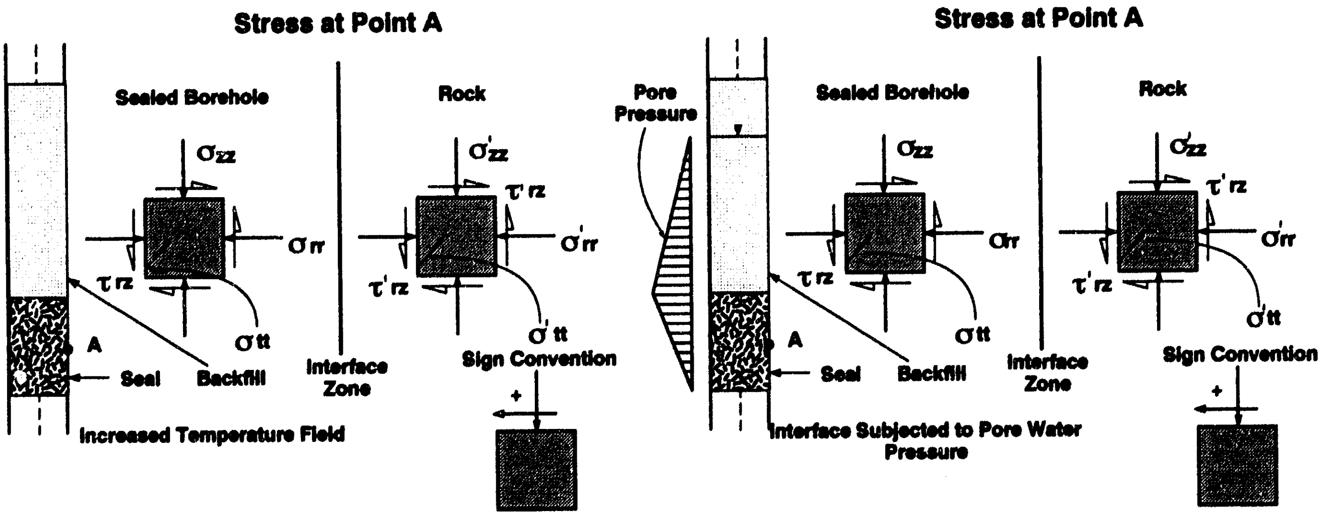
Open borehole evaluations using the Kirsch (Goodman, 1980) solution are presented at the upper sealing location, the potential repository horizon, and the lower sealing location. These evaluations consider in situ and elevated temperature. Further evaluations of the interaction of open boreholes with the surrounding excavation are made at the potential repository horizon. Conclusions are drawn as to "when" to seal.

In Section 5.4, structural analysis of cementitious seals are made that consider the properties of the cementitious materials and surrounding rock and emplacement environment. These



Initial State of Stress in an Open Borehole after Casing Removal

Placement of a Cementitious Seal



State of Stress After Backfilling and Waste Emplacement

State of Stress After Saturation of the Backfill

Figure 5-5

States of Stress Around Open and Sealed Boreholes

evaluations use the SHAFT.SEAL code (Case, 1985). A combination of analytical methods are then used to evaluate backfill, thermal, and seismic loads after seal emplacement.

5.3 Corrosion of Casing and Open Borehole Issues

Prior to seal emplacement, access to the upper and lower seal location must be assured. The following discussion considers cased and open boreholes after removal of casing at sealing locations.

5.3.1 Corrosion of Casing

Several factors affect corrosion of the steel casing. The fundamental consideration is whether the host rock contacts the steel. That in turn determines the nature of the electrolyte. Other considerations include the composition and humidity of the air for a freestanding casing and the host-rock resistivity, groundwater chemistry, and drainage for earthen materials contacting the steel casing. Appendix A presents the physical system at Yucca Mountain for cased boreholes, which includes borehole configurations, casing configurations, and locations where casing is grouted. Tables A-10 through A-12 present the casing information at key sealing locations. In general, the casing does not contact the host-rock formation; however, in isolated zones where rock-mass strength may be exceeded, the casing may contact the host formation. The remainder of the section discusses these considerations as they apply to corrosion of API Grades H and J carbon-steel casing at the Yucca Mountain site.

5.3.1.1 Atmospheric Corrosion

Atmospheric corrosion is generally an electrochemical process (Mattsson, 1982). When the casing surface is exposed to air, corrosion develops because of point-to-point differences in potential. These include local differences in composition, as from a precipitated phase or the presence of an impurity or inclusion, and differences in structure induced by cold work or surface preparation, the presence of welds, and the lack of homogeneity. These influence the formation of corrosion cells.

For casing exposed to air, oxidation occurs when the relative humidity is greater than 70 percent. Oxidation requires surface moisture and the presence of an electrolyte. For hydroscopic salt deposited on the casing surface, the critical humidity equals the vapor pressure of its saturated solution.

5.3.1.2 Soil-Rock Corrosion

Earthen materials can be considered aqueous electrolytes; the corrosion of steel in contact with earthen materials is a special case of aqueous corrosion. The availability of dissolved oxygen and the conductivity of the electrolyte determine the corrosion rate of carbon steel in neutral aqueous solutions. The conductivity of the electrolyte in turn depends on the percentage of moisture saturation. Steel in contact with earthen materials corrodes by local-cell action, long-cell action, or a combination of both. Both local-cell and long-cell action are possible for casing in contact with tuff. In earthen materials that have variations in composition with respect to permeability and saturation, long-cell action resulting in nonuniform corrosion is an issue.

In local-cell action, oxygen is reduced at microscopic cathodic sites, oxidizing iron at adjacent anodic sites. This results in uniform corrosion and is not often severe in unsaturated earthen materials. The corrosion rate of a dry host rock should be small, due to the high resistivity of the electrolyte. Because of extremely high corrosion rates in earthen materials, the idea of an earthen material as a homogeneous static electrolyte is not always applicable.

As electrical conductivity of the host rock increases (increasing moisture content), long-cell action becomes possible. In long-cell action, a macroscopic distance separates the cathodic and anodic sites, or zones. The driving force for the long-cell action derives solely from the difference in availability of oxygen between the two zones, independent of the means of achieving this difference. The host-rock conductivity of the electrolyte determines how far apart the zones can be for long-cell action to occur. In high-conductivity situations, the distance can be greater than 100 ft.

The dependence of long-cell action on differential availability of oxygen evolves from a variety of corrosion phenomena. An anodic zone occurs (1) where salt content is higher or there is a lower solubility of oxygen than at a nearby zone; (2) where the water velocity is lower than at an adjacent region, even when the bulk oxygen concentrations for both regions are the same; and (3) in a material of low permeability to water.

In unsaturated rock, a thin film of water is left on the surface of steel exposed to soil. In contrast to aqueous solutions, where the diffusion film separates steel from water that contains a few parts per million of dissolved oxygen, air separates the casing from the host rock.

Schashl and Marsh (1963) reported a set of corrosion experiments in drained soils. They conducted experiments by inserting a steel electrical-resistance corrosion meter probe, a zinc anode, and a steel cathode into soil maintained at various water saturations. A recording zero-resistance ammeter between the zinc and steel electrodes measured cathodic activity that would be available to drive long-cell action. The isolated probe provided the corrosion rate as a measure of local-cell action. At saturation, both local- and long-cell actions were negligible. With draining of the soil, local-cell action and long-cell cathodic activity sharply increased, with a decrease in water saturation. Oxygen entered the pores and contacted the steel across the thin film of water. When the water saturation had decreased to about 70 percent, cathodic activity was at a maximum. Further decreases in water content introduced additional resistance to long-cell action to the point that long-cell action became negligible. Figure 5-6 summarizes these findings. They include the following (Schashl and Marsh, 1963):

- Long-cell action can occur at water saturations between 50 and 95 percent. Local-cell action occurs between saturations of 5 and 95 percent.

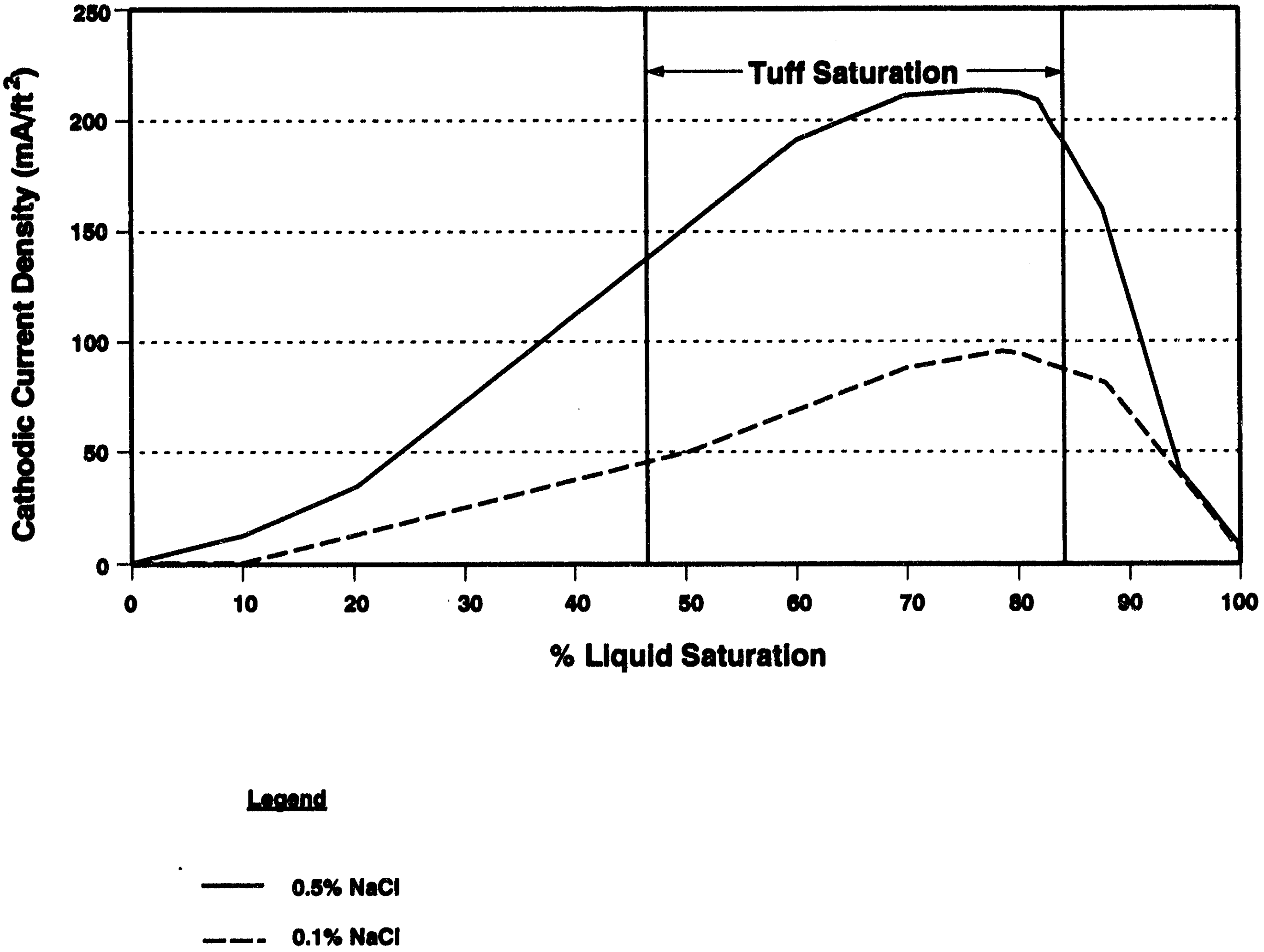


Figure 5-6

Long–Cell Action in Soil/Rock Corrosion (After Schashl and Marsh, 1963)

- Soil electrical resistivity determines the intensity of local-cell action at any given water saturation.
- A soil that does not drain at all, but remains 95 to 100 percent water-saturated, is noncorrosive, despite its resistivity.
- A soil that drains slowly and therefore remains 50 to 95 percent water-saturated for long periods will be corrosive, especially if its resistivity is low.
- Where carbon-steel casing penetrates a homogeneous soil and the soil's water content ranges between 50 and 95 percent water saturation in the upper zone of contact and between 95 to 100 percent water saturation in the lower zone of contact, long-cell action will occur. Cathodic activity may be so high that no corrosion will occur in the upper drained zone. The observer, noticing intense pitting at the deaerated lower depth, might conclude the soil is very corrosive in the region, whereas the corrosion depends on the presence of the upper aerated zone.

The suction potential also affects the development of long-cell action by influencing the degree of saturation. Sands exhibit a flat curve of water saturation versus suction potential. Steel contacts the sand at the critical water saturation at essentially one line. Cathodic activity would be intense here, but the area of metal exposed as a cathode would be small. Clays retain moisture at nearly 100 percent, and air cannot enter, resulting in small cathodic activity. For practical purposes, steel exposed entirely to this soil will not corrode. If the steel contacts a drained, impermeable clay soil, it will corrode at the anodic area because of long-cell action.

For other soils, a range of saturation over some distance of the casing occurs, and cathodic activity over this distance is expected. There may be many feet of vertical distance above the water table in which the water saturation is between 50 and 95 percent. Intense cathodic activity would be expected throughout the vertical distance for steel in contact with this host rock.

Another factor affecting the corrosion rate is the rate that soil conducts electrolyte or host-rock permeability. Schashl and Marsh (1963) reported experiments in sand that show the relationship of the local-cell corrosion rate with permeability and indicate that, as permeability reduces, the corrosion rate reduces. Corrosion caused by local-cell action should decrease with depth of soil as the material becomes less dense and less porous. Corrosion caused by local-cell action decreases with depth for steel pilings driven into undisturbed soil, but corrosion commonly increases with depth, suggesting long-cell action.

5.3.2 Computation of the Corrosion Allowance

The following analysis evaluates the structural stability of the casing at key depths for selected boreholes and supports the sealing strategy development for casing removal. The analysis uses the corrosion-allowance concept, which calculates the reduction in casing wall thickness under the condition of uniform corrosion that can be sustained before casing collapse develops. This allowance is compared to the expected corrosion rate to show how long the casing may be structurally sound. The preliminary analysis considers the geometric and material properties of the casing, the depth to the casing (in situ state of stress) at approximate sealing locations, and the proximity of these locations to the potential repository heat sources (Figure 5-7). To perform preliminary analysis, a number of assumptions were required:

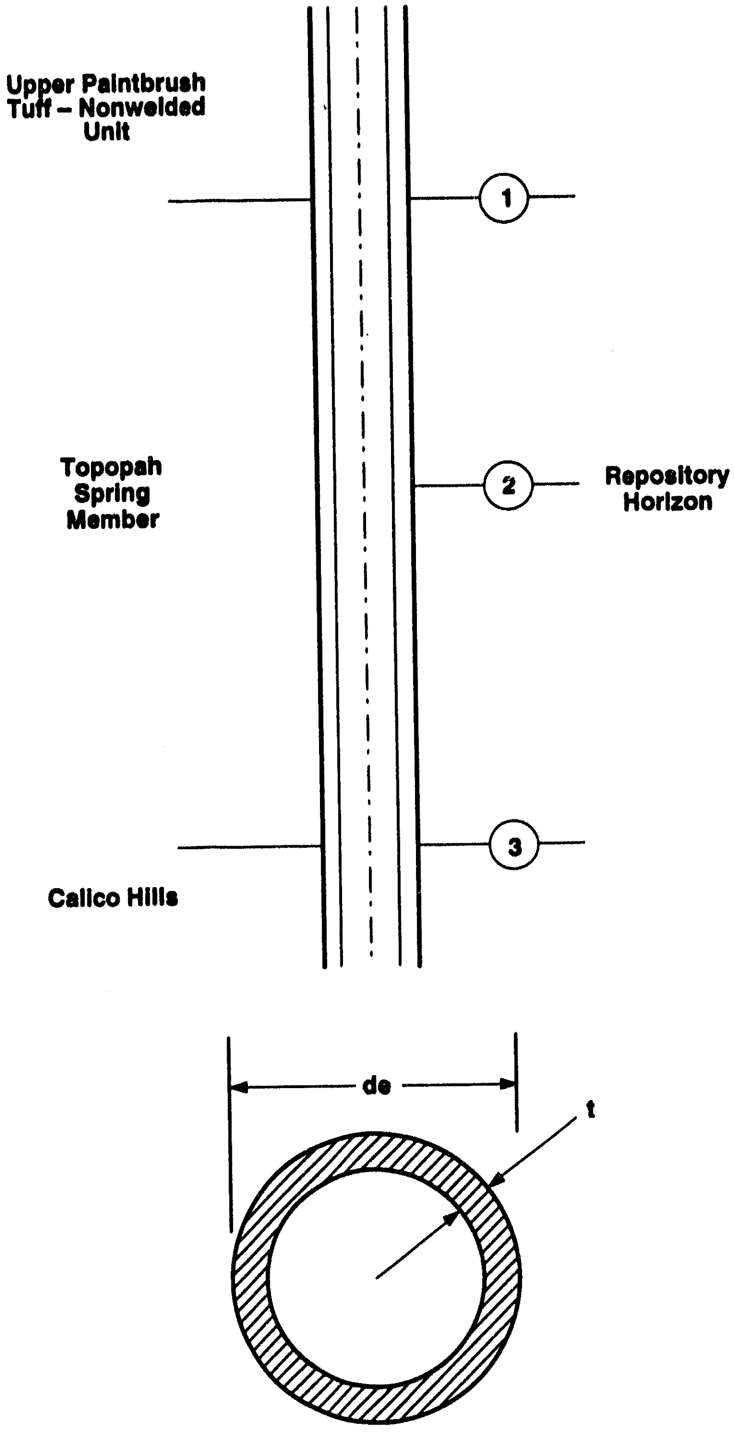
- The formation contacts the casing at each seal location and subjects the casing to a uniform isotropic external pressure due to the interaction of the steel casing with the formation at each sealing location for the unheated case. The analysis uses the SHAFT (Agapito and Associates, 1990) code to calculate the external pressure acting on the casing.

- The temperature increase caused by potential repository heating results in a thermal stress field that depends on the sealing location. For boreholes penetrating the potential repository or near the potential repository boundary, the thermal stress field is compressive, while the stress field is slightly tensile farther away from the potential repository. The thermal stress components are calculated for an isotropic homogeneous medium using the STRESS3D analysis presented previously. The analysis averages the thermal stress components in the horizontal plane and calculates the increase or decrease in external casing pressure for the heated case using the SHAFT computer code.

- The casing is comprised of either H40 or J55 carbon steel (Craft et al., 1962), which have yielded stresses of 50,000 or 65,000 psi, respectively. The mode of failure is either elastic or plastic buckling, depending on the critical buckling stress for the casing, that in turn depends on the casing slenderness ratio (the ratio of the external diameter to wall thickness).

The analysis is conservative in that if the critical buckling load were reached under thermal loading, the loads would likely redistribute and result in only localized buckling. The casing would be deformed but would not pose a serious operational hazard. On the other hand, the casing may be suspended from above and subjected to tension or supported from below and subjected to compression. Either tension or compression would result in potential biaxial loading in which the casing could buckle under a combined state of stress. On balance, the adopted approach is reasonable for performing preliminary calculations and addressing issues of casing removal prior to sealing.

Tables A-10 through A-12 present the casing geometries at three potential sealing locations, including the PTn/TSw1 contact, the potential repository horizon (TSw2), and the TSw3/CHn1 contact. The slenderness ratios range from 18 to 36 above the potential repository and from 18 to 30 at or below the potential repository. The critical elastic buckling stress (Craft et al., 1962) is as follows:



Plan View

Figure 5-7
Sealing Locations for Casing Stability Analysis

$$P_c = \frac{46.95\ x\ 10^6}{(d_e/t)[(d_e/t)\ -\ 1]^2}$$

where

P_c = External collapse pressure (psi)
d_e/t = External diameter (d_e) to thickness ratio (t).

The critical plastic buckling stress (Craft et al., 1962) is as follows:

$$P_c = Y_a\left(\frac{1.877}{d_e/t} - 0.0345\right)$$

where Y_a equals the yield strength of the casing (psi).

In these calculations, a uniform isotropic stress field is assumed for purposes of utilizing the buckling formulas. The critical slenderness ratio is calculated, and the allowable change in wall thickness is computed. A nonuniform state of stress may result in nonuniform buckling, which may differ significantly from what is presented above. Further, the analysis does not fully consider the differential thermal expansion occurring between the steel and surrounding formation, although it does consider differences in stiffness between the casing and the surrounding formation. Nevertheless, the analysis approximates conditions that might result in buckling and is useful to compare the relative differences in casing conditions that may be encountered at depth.

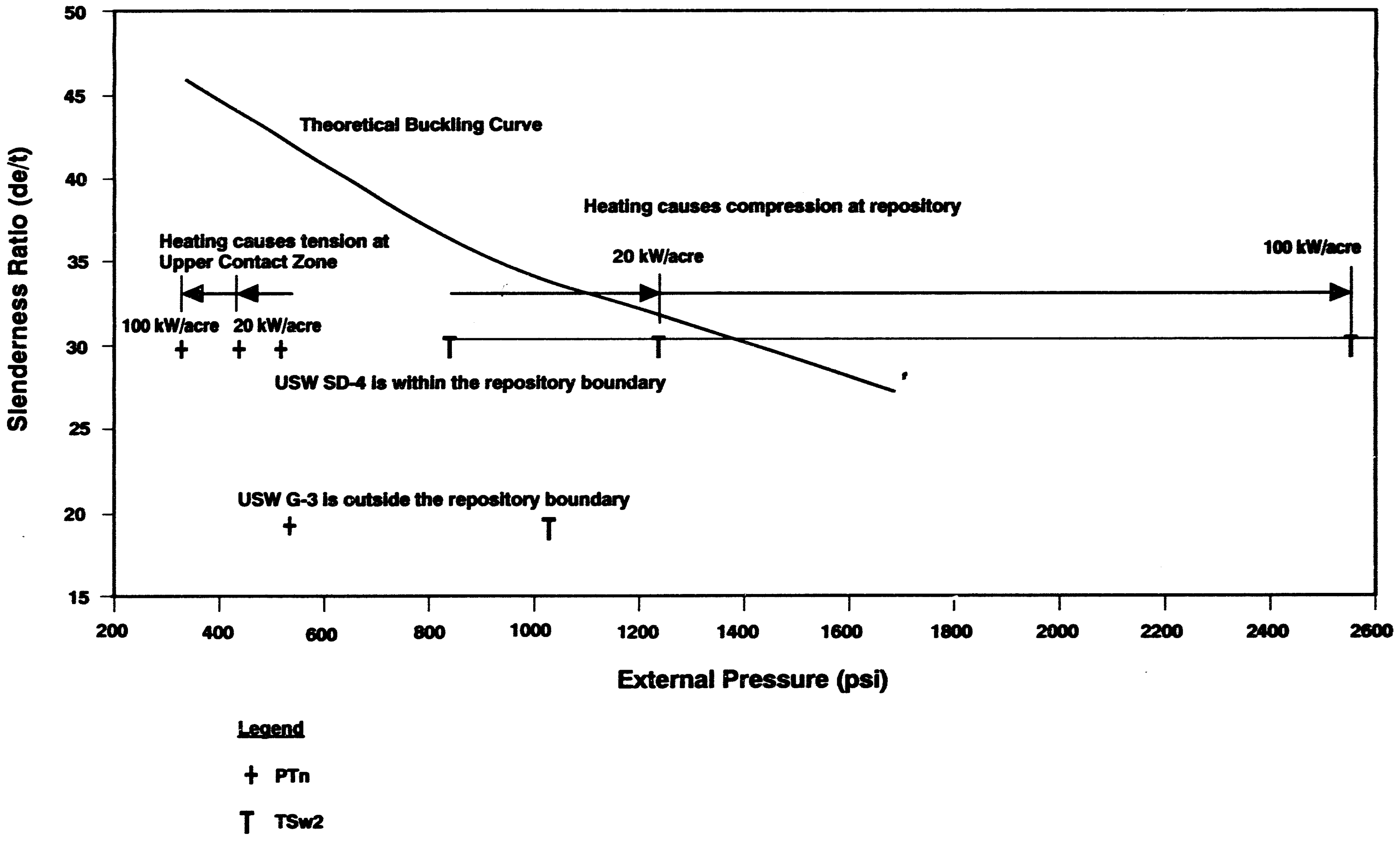
Table 5-2 presents the results and several interesting trends. These results show that differences in the grades of carbon steel are not significant in calculating the corrosion allowance. The corrosion allowance principally reflects the design margin in selecting different casing configurations at the time of exploratory drilling. The design margins vary widely and decrease with depth. Figure 5-8 presents results for USW SD-4 and USW G-3 that compare the slenderness ratios to the casing buckling curve for the heated and unheated cases at three sealing locations and show the design margin for casing collapse. A comparison between the unheated and heated cases shows either no effect or a tensile effect at the upper Paintbrush contact zone, large temperature effects at the potential repository horizon for holes penetrating the potential repository (USW SD-4 and USW G-3), and intermediate temperature effects at the lower contact zone. For USW SD-4, the casing is not at incipient buckling at the lower contact zone for the unheated case subject to external formation pressure. For USW SD-4, potential repository heating after 60 years results in increased thermal stress and in incipient buckling of the casing, suggesting removal of the casing and placement of a seal prior to potential repository

Table 5-2

Borehole Casing Corrosion Allowance

					In Situ Stress			In Situ Plus Thermal Stress[a]		
Seal Location	Thermal/ Mechanical Unit	Borehole	Casing Diameter (in.)	Initial Casing Thickness	External Pressure (MPa)	H-40 Corrosion Allowance (in.)	J-55 Corrosion Allowance (in.)	External Pressure (MPa)	H-40 Corrosion Allowance (in.)	J-55 Corrosion Allowance (in.)
1	PTn	H-5	10.75	0.35	3.529	.094.	.0107	2.773	0.106	0.117
		H-1	16	0.438	3.465	.058	0.078	3.563	0.056	0.076
		H-3	10.75	0.4	3.573	.143	0.157	3.651	0.142	0.156
		SD-4	16	0.495	3.511	.114	0.134	2.744	0.133	0.149
		SD-6	16	0.495	3.511	.114	0.134	2.431	0.141	0.155
1	TSw1	H-5	10.75	0.35	2.824	.105	0.116	2.219	0.116	0.124
		H-1	16	0.438	2.664	.078	0.093	2.740	0.076	0.092
		H-3	10.75	0.4	2.941	.154	0.165	3.005	0.152	0.164
		SD-4	16	0.495	2.778	.132	0.148	2.171	0.147	0.160
		SD-6	16	0.495	2.778	.132	0.148	1.923	0.153	0.164
2	TSw2	H-5	10.75	0.35	5.897	.054	0.072	11.998	-.047	-.001
		SD-4	10.75	0.35	5.897	.054	0.072	12.931	-0.62	-0.013
		SD-6	10.75	0.35	5.897	.054	0.072	13.348	-0.069	-0.018
3	TSw3	H-5	10.75	0.35	10.156	-0.016	0.018	10.561	-0.022	0.015
		H-1	9.62	0.352	10.521	0.019	0.052	10.521	0.018	0.051
		H-3	10.75	0.4	10.577	0.027	0.064	10.624	0.026	0.064
		SD-4	10.75	0.35	10.156	-.016	0.018	9.844	-0.011	0.022
		SD-6	10.75	0.35	10.156	-.016	0.018	10.029	-0.014	0.020

[a] The corrosion allowance is calculated for a thermal load of 57 kW/acre for fuel aged 30 years.



Note: Arrows show influence of heating at several locations

Figure 5-8
Casing Stability and the Influence of Heating

decommissioning. The results also suggest that heat-loading density affects potential buckling of casing for USW SD-4 at the potential repository horizon, with the casing external pressures near incipient failure for the lower heat loading and well above incipient failure for the higher heat loading of 100 kW/acre. This is in contrast to the thermal response of USW G-3, which is outside the high thermal compression zone after 60 years and experiences no rise in external pressure.

5.3.3 Structural Analysis of Open Boreholes

5.3.3.1 Kirsch Solution for Open Boreholes

The state of stress around an open borehole can be represented by the Kirsch solution (Goodman, 1980). In an isotropic stress field, the Kirsch solution gives the radial and tangential stress distributions as follows:

$$\sigma_r = \sigma_h[1 - \frac{a^2}{r^2}]$$

$$\sigma_\theta = \sigma_h[1 + \frac{a^2}{r^2}]$$

where

σ_h = Far-field horizontal stress
σ_r = Radial stress
σ_θ = Tangential or boundary stress
a = Borehole radius
r = Radius.

At the borehole wall (r = a), the Kirsch solution predicts for an isotropic stress field that the radial stress is zero and that the tangential or boundary stress is twice the far-field stress.

5.3.3.2 Stress Analysis at Various Seal Locations

For the upper sealing location, the potential repository horizon, and the lower sealing location, the far-field states of stress are 2.4, 7.3, and 8.7 MPa, respectively. Considering that the maximum time of emplacement is 60 years after potential repository development (heat loading equals 57 kW/acre), the combined in situ and thermal far-field stresses are 1.7, 15.2, and 10.7 MPa, respectively. A slight reduction in compression occurs in the far-field horizontal stress at the upper seal location No. 1 consistent with an increase in compression near the potential repository after potential repository heating. Table 5-3 presents these calculations. In comparing these stress levels with the strength criteria in Chapter 2.0, it is found that, for the upper sealing location, there is likely to be adequate rock-mass strength. For the lower sealing location, rock-mass strength is less, and it is possible that open boreholes could fail under high temperatures.

Table 5-3
Simple Stress Calculations for Open Boreholes

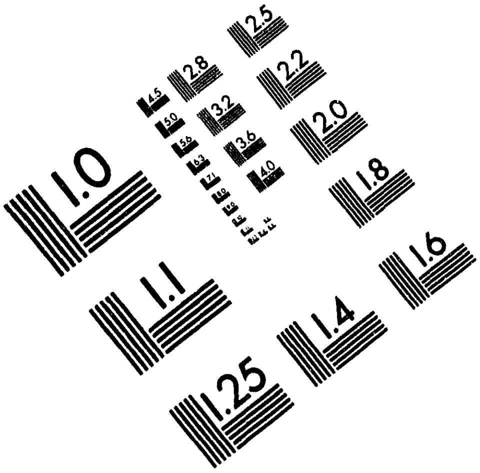
Seal Location	Loading	Temperature (°C)	Radial Stress (MPa)	Tangential Stress (MPa)	Vertical Stress (MPa)
1	In situ	22.7	0	4.80	3.39
1	Thermal	26.7	0	3.42	3.49
2	In situ	29.2	0	14.56	9.21
2	Thermal	60.8	0	30.30	5.42
2 (Center of Panel)	Thermal	87.2	0	36.68	9.90
3	In situ	29.8	0	17.48	10.42
3	Thermal	42.3	0	21.38	11.56

5.3.3.3 Structural Analysis of an Open Borehole Near Underground Openings

A zone of influence defines a domain of significant disturbance of the pre-mining stress field by an excavation at the potential repository horizon (Brady and Brown, 1985). The excavation of a drift in a rock mass disturbs the state of stress around the opening and generates a stress concentration that may then cause failure in the surrounding rock mass. A proposed borehole (Figure 5-9) in the zone of influence of an opening should not pass through the failure zone around the opening. Neither should the state of stress around the proposed borehole, due to the stress concentration around the opening, cause failure around the borehole.

Because a drift is much larger than a borehole, it is outside the influence zone of the borehole, but the influence zone of the drift may include the borehole. An engineering estimate of the boundary stresses (far-field stresses) for a borehole can be obtained by calculating the state of stress at the center of the borehole prior to excavation (Brady and Brown, 1985).

St. John (1987) studied the state of stress around YMP drifts using finite- and boundary-element methods for ventilated and unventilated cases. For purposes of analysis, these stresses are assumed to be far-field stresses for evaluating thermal effects around open boreholes near the potential repository openings. The far-field stress results include projected stresses for selected

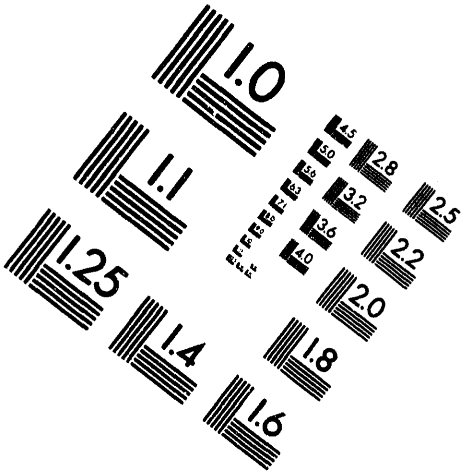


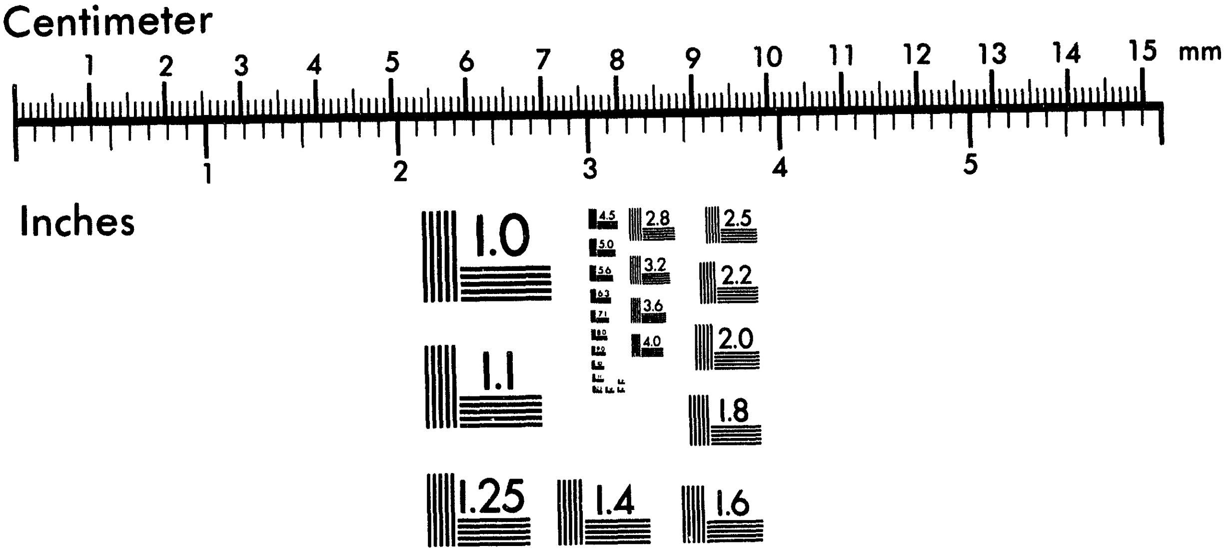
AIIM

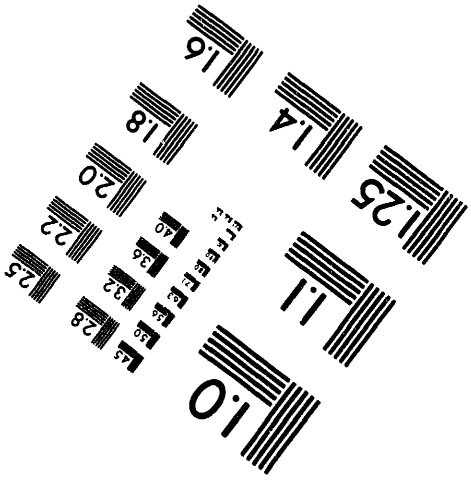
Association for Information and Image Management

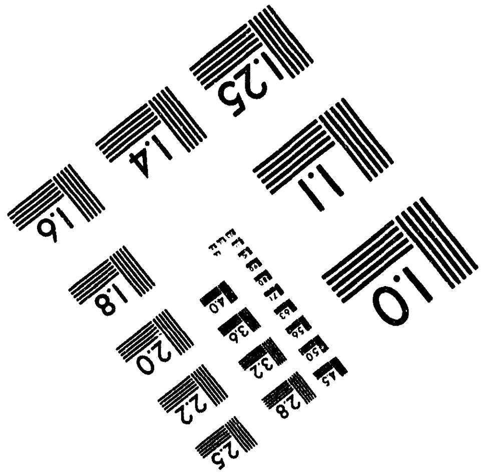
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202



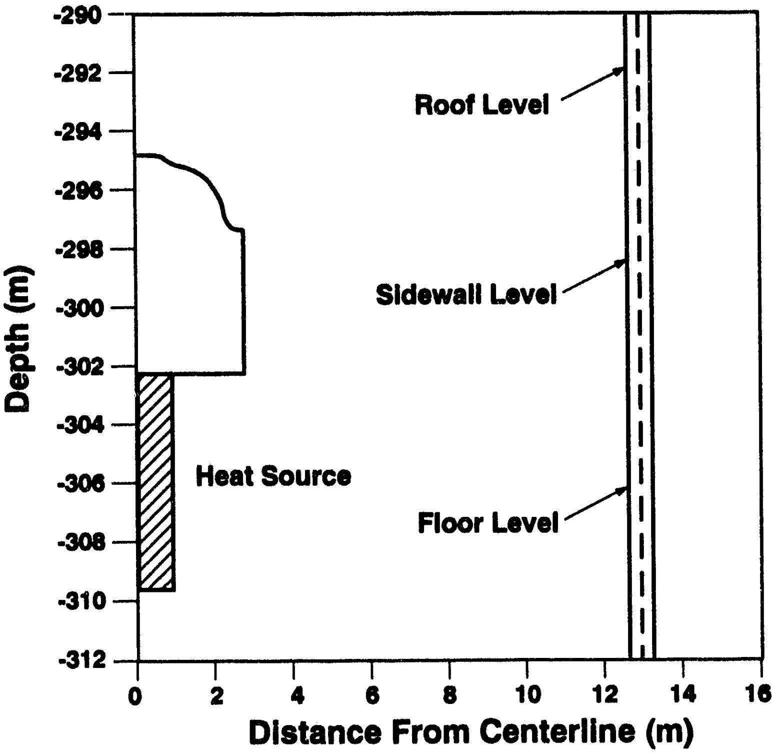




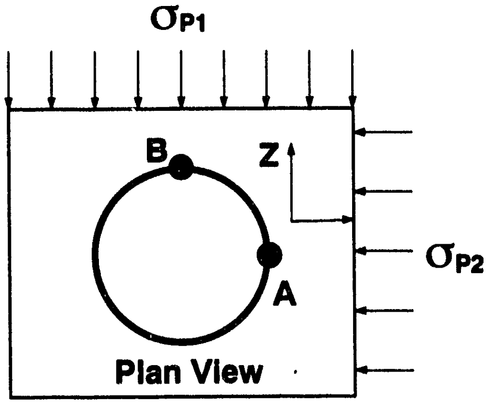


MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

3 of 6



Kirsch Solution



Tangential or Boundary Stress at A

$3\sigma_{P1} - \sigma_{P2}$

Tangential or Boundary Stress at B

$3\sigma_{P2} - \sigma_{P1}$

Figure 5-9
State of Stress Around an Open Borehole at the Potential Repository Horizon

points around the drift for the period of excavation and for points in time 0, 10, and 100 years after waste emplacement.

The axes of the proposed boreholes are perpendicular to the axes of the drift (Figure 5-9). Such boreholes would therefore be under a generalized plane strain condition, which includes in-plane and out-of-plane shear stresses. The computer program SHAFT (Agapito and Associates, 1990) was used to obtain the state of the stress around the perimeter and the boreholes. The SHAFT code models generalized plane strain conditions. The state of the stress for each sampling point was used as the far-field stress for each borehole modeled with the SHAFT code.

For points at a distance from the drift, the major principal stresses are nearly horizontal and vertical. For these cases, the Kirsch solution was used to calculate the stresses around the borehole. For example, the states of stress for a point 10 m from the drift near the floor, sidewall, and roof of the drift are shown in the Mohr diagrams in Figure 5-10.

This figure illustrates the low-, medium-, and high-strength criteria for the Topopah Spring Weld unit for the surrounding rock mass (described in Section 3.3.3). The uncertainty in the strength parameters required a range to be defined for rock-mass strength criteria. This range is between low- and high-strength criteria, with the medium-strength criteria represented by an estimate of the expected values, as discussed previously. The figures show that a hollow borehole might be barely stable from the time of excavation until 10 years after emplacing the nuclear waste, but medium-strength criteria are violated 100 years after emplacing nuclear waste. The analysis suggests that boreholes should be sealed to prevent future failure due to stresses that arise from the temperature increase in the potential repository. Further investigation could show that the expected failure criteria is closer to the high-strength criteria shown in Figure 5-10 and that failure is less likely.

5.3.4 Conclusion of When to Seal

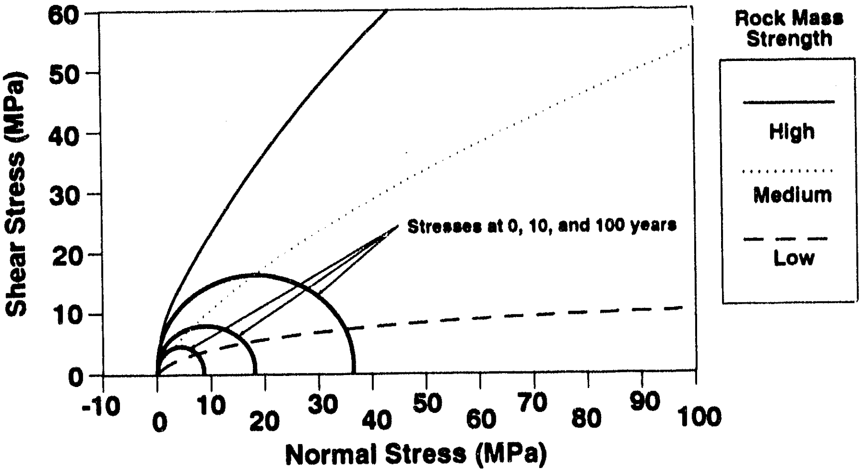
No site-specific data are available for the corrosion of carbon-steel casing at the Yucca Mountain site; however, the following information is available on general corrosion rates for carbon steel in air and soil:

- The penetration rate for carbon steel in air ranges from less than 1 to approximately 7 mil per year (Mattsson, 1982). The National Association of Corrosion Engineers (NACE) reports higher corrosion rates in acidic atmospheres (not considered a factor at Yucca Mountain).

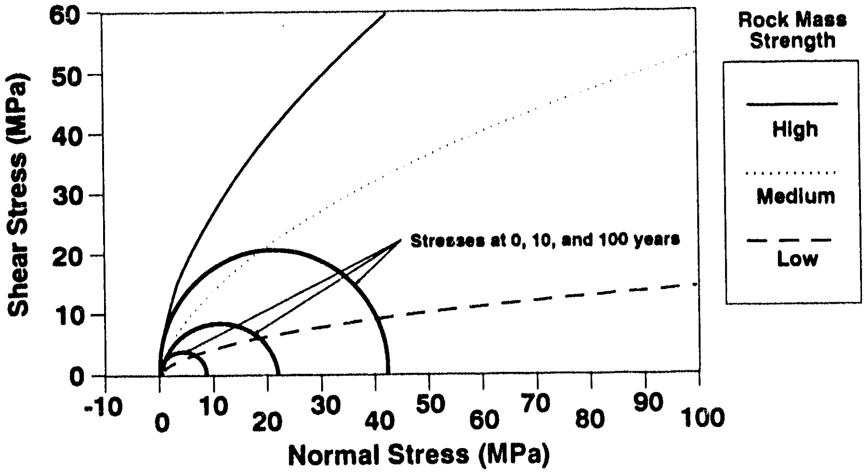
- The penetration rate for carbon steel in soils varies from 5 to 100 mil per year depending on resistivity, that in turn depends on moisture content.

Considering casing configurations, for deep casings such as those used in UE-25a #1, grouting occurred over short distances, and the casings are freestanding over much of their length. For shallow casings, such as those used in UE-25a #5, grouting to a depth of 100 to 200 ft could be

TSw2 Unit Roof at a Distance of 10 m



TSw2 Unit Sidewall at a Distance of 10 m



TSw2 Unit Floor at a Distance of 10 m

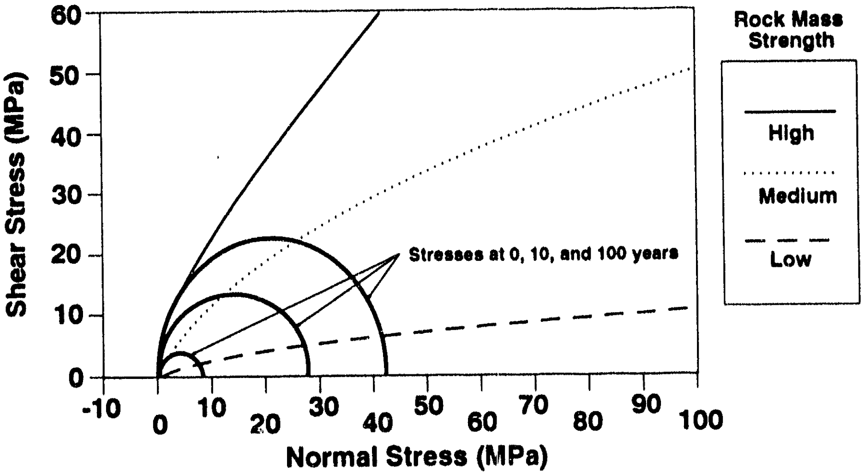


Figure 5-10
Mohr Failure Envelopes for an Open Borehole Near an Excavation

subject to long-cell action. In deeper zones, the state of in situ stress is higher, and rock-mass strength is lower (i.e., the Calico Hills). In other areas, rock-mass quality is lower in more highly fractured tuff. The possibility exists for collapse of the borehole against the casing, exposing steel to the host formation. Here, the range of saturation is 46 to 84 percent for welded tuff and 46 to 76 percent for nonwelded tuff (DOE, 1992), suggesting long-cell action. The low conductivity of both welded and nonwelded tuff suggests that local-cell action would be insignificant. Corrosion might be higher in these areas because of the synergistic effects of contact with the host rock and stresses within the casing; however, these zones are expected to be isolated, reducing the potential for long-cell action, and the actual corrosion rates probably will be the same as those for carbon steel exposed to air and possibly a humid environment.

This discussion highlights several important issues concerning corrosion for casing emplaced in or near unsaturated earthen materials. Generally, low corrosion rates caused by exposure to air are anticipated in the range of less than 0.1 to 4.0 mil per year. In isolated zones where the host rock contacts the steel casing, the corrosion rates probably will be higher. In general, it is found that casing under heated conditions after 60 years is near failure, with little corrosion allowance.

The analysis also shows potential failure of an open borehole under heated conditions could occur at the lower sealing location. For the open borehole analysis, no consideration was given to support pressure as might be exerted by drilling muds. The analysis of open boreholes at the potential repository horizon shows potentially high stresses due to a high temperature and stress interaction effects. For these reasons, it is concluded that sealing should take place prior to waste emplacement to maintain access to deep boreholes. It is further concluded that an adequate separation of 15 m should be maintained between the underground excavation and any exploratory borehole to assure access through the potential repository horizon to the lower sealing location.

5.4 Structural Analysis of Cementitious Seals

The supporting calculations presented in this section evaluate seal properties and conditions favorable to developing a tight interface zone. Also, these calculations predict temperature and interface stress. The models presented below are preliminary and will undergo refinement as additional information on seal properties and in situ seal performance becomes available.

5.4.1 Model Descriptions

Several models are used to evaluate combinations of loads. These models include the SHAFT.SEAL code (Case, 1985) for thermal and thermomechanical effects due to seal hydration and closed-form methods for evaluation of backfill loadings that consider the plug loaded in uniform shear and ignore elastic interaction effects that would result in compressive stress. The thermal calculations use the SHAFT code (Agapito and Associates, 1990) to evaluate seal/rock interactions during potential repository heating. Finally, combinations of loads are evaluated.

5.4.2 Selection of Conditions for Seal Emplacement

The structural analysis of the seal is performed using the SHAFT.SEAL. At each time, SHAFT.SEAL solves for temperatures and stresses as a function of radial position either in the plug or the surrounding host rock. The model analyzes the temperature rise and subsequent fall following completion of the hydration by the implicit finite difference method (Carnahan et al., 1969). Assuming heat transfer is conductive, the model performs thermal and volumetric stress analysis using closed-form solutions that account for thermal or initial volumetric strains. The structural model uses the theory of linear elasticity for calculating thermal or volumetric stresses.

Appendix I presents the input properties for the seal, rock, and environment. The parametric studies evaluated two cement types (Type K and Type II), two placement temperatures, and two injection pressures. These analyses used the Type K and Type II cements because of availability of properties.

5.4.3 Evaluation of Cement Hydration

Figures 5-11, 5-12, and 5-13 present rock tangential stress and shear stress as functions of interface normal stress at the upper seal location, the potential repository horizon, and lower sealing location. The analyses suggest two major groupings in the development of interface stress that depend on the type of cement used. Type II cement grout develops interface stress from minus 1 to 3 MPa for various conditions of placement temperature and injection pressure, while the more expansive Type K grout develops interface stress from 4 to 8 MPa.

The results show an inverse relationship between radial plug interface stress and the tangential boundary stress within the rock. Further, the results suggest that the minimum rock-shear stress occurs when the radial interface stress equals the far-field stress. The results reflect higher tangential and shear stress at depth associated with higher states of in situ stress and show the importance of tailoring the design (lower placement temperature, more expansive cement, and injection pressure tied to the in situ state of stress).

The ultimate achievable volumetric expansion represents an unknown. No data are available on the effects of temperature or restraint on the expansive properties of grout, although data available for cements suggest a reduction of effective expansion due to increasing restraint and temperature. Other unknown factors include the effects of primary and secondary rock porosity in bleeding off cement to the surrounding rock mass and volumetric size effects.

Further, the use of ettringite in Type K cements may result in longevity issues due to the preferential dissolutioning. For these reasons, the conditions for seal emplacement for subsequent analysis include using a Type II cement, lowering the placement temperature to 4°C, emplacing the seal at ambient rock temperature, and using an injection pressure equal to 50 percent of the minimum horizonal stress.

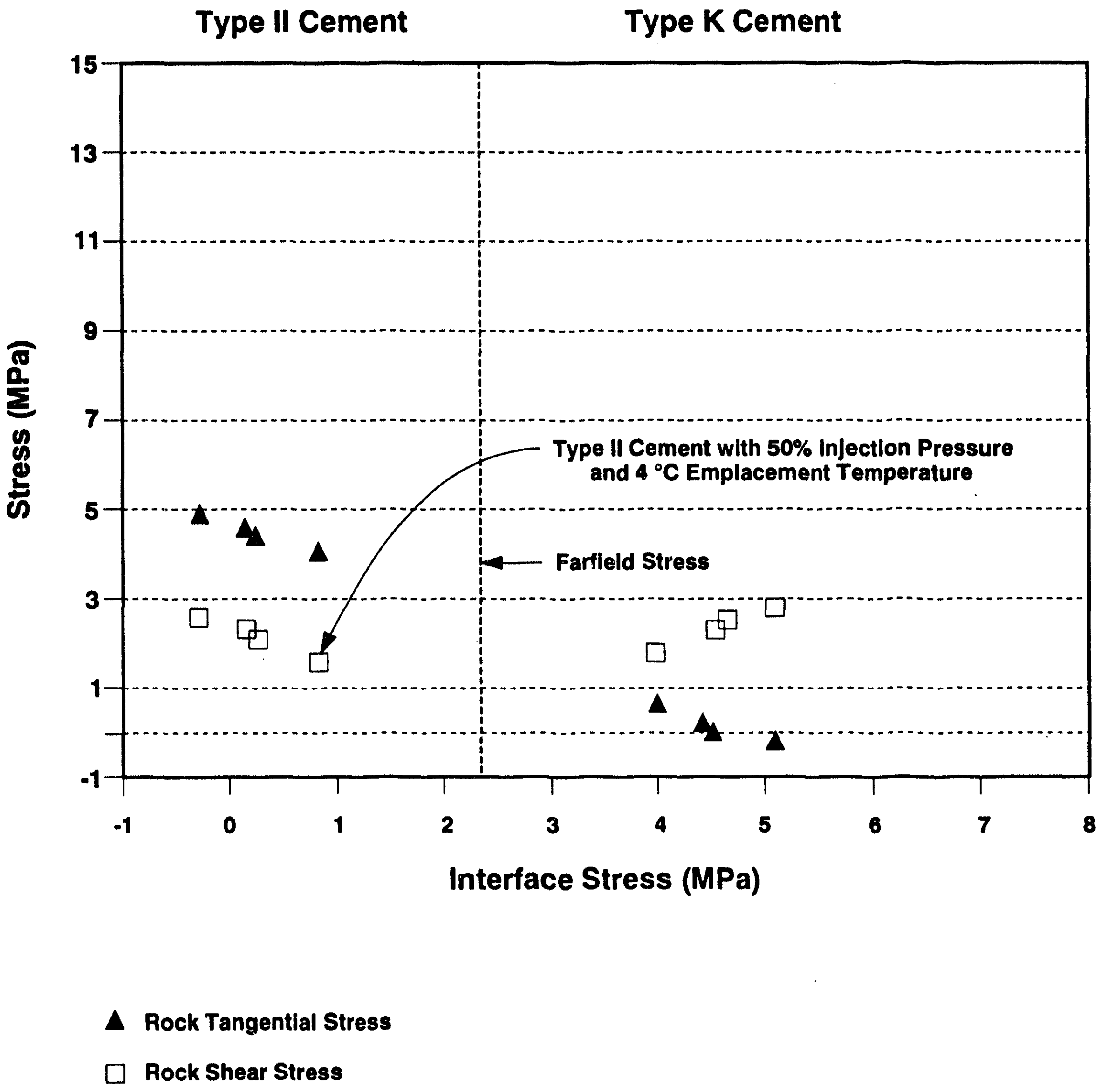


Figure 5-11

Stress Development at Ambient Temperature in the Plug and Rock at the Upper Sealing Location

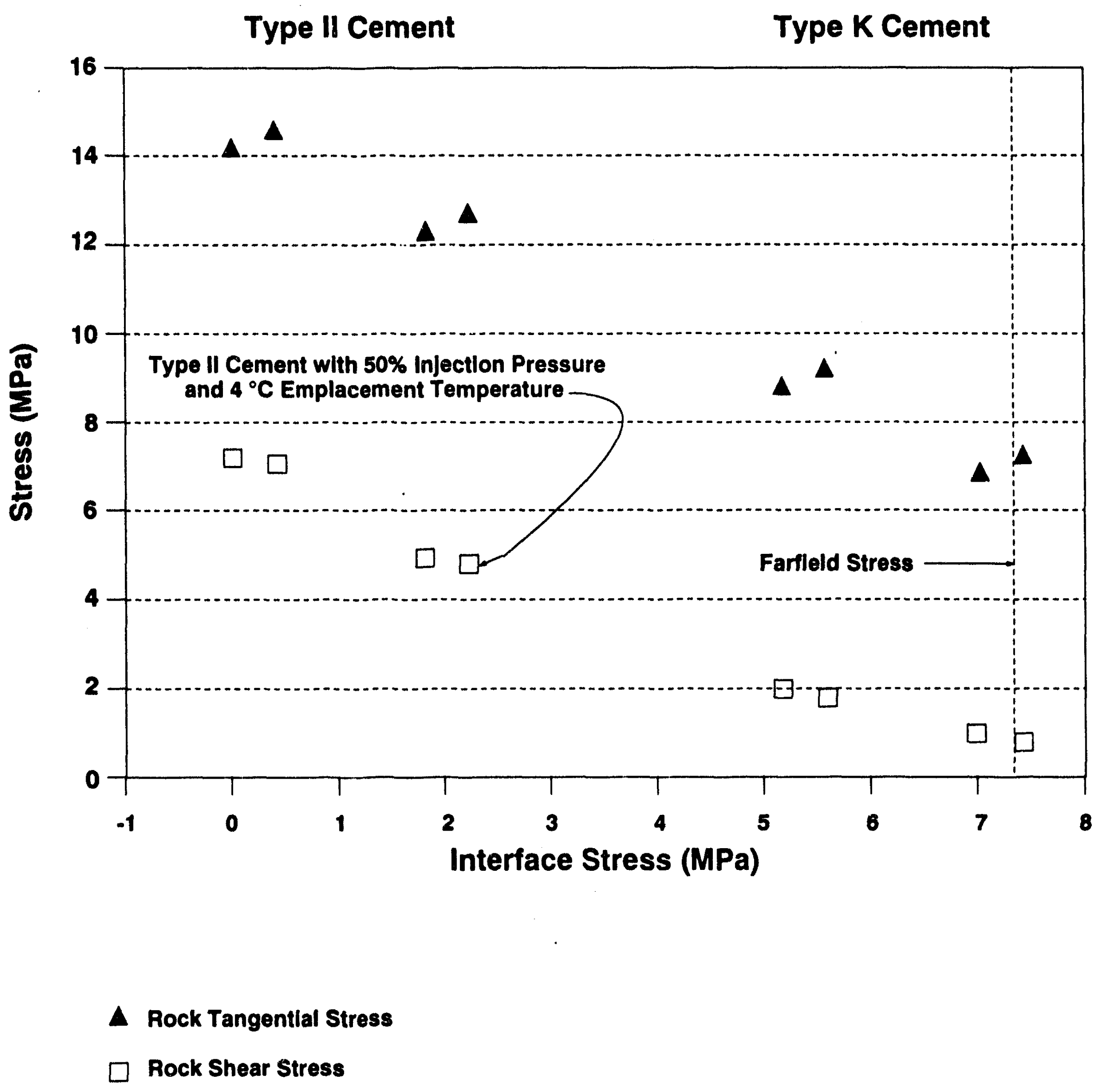


Figure 5-12

Stress Development at Ambient Temperature in the Plug and Rock at the Potential Repository Horizon

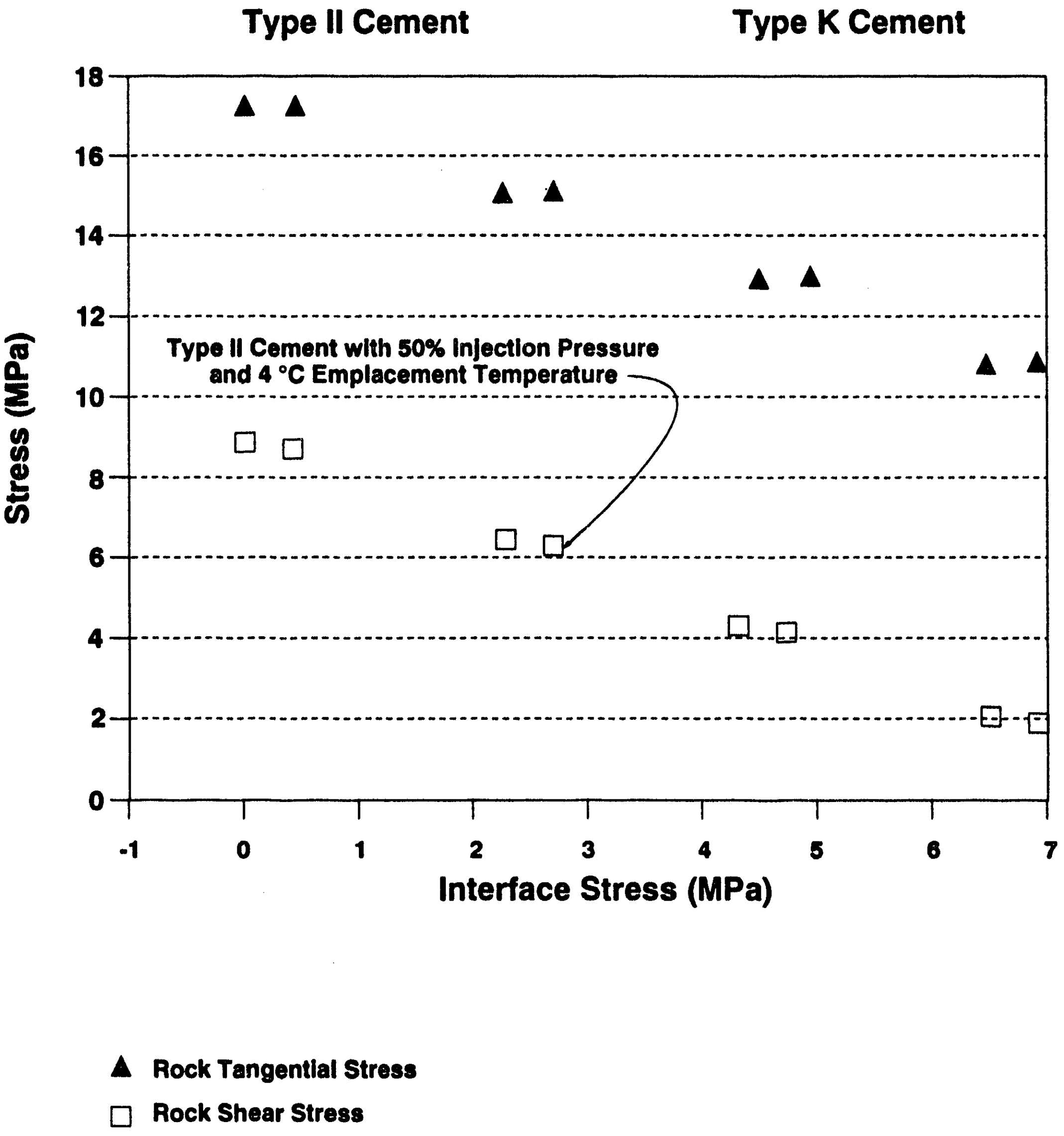


Figure 5-13

Stress Development at Ambient Temperature in the Plug and Rock of the Lower Sealing Location

5.4.4 Structural Analysis of Backfill Loading

The addition of backfill above the plug results in additional loading on the plug. The analysis presented in Appendix J disregards the compressive stresses that would develop because of elastic interaction between the plug and the surrounding rock. These conservative calculations do not account for the effects of confinement. In addition, the analysis assumes the backfill settles below and does not support the plug. The analysis are presented at the upper and lower seal locations and at the potential repository horizon. The conditions evaluated considered both saturated and unsaturated conditions with static and dynamic loadings. The vertical seismic loads result in shear stress that is approximately one-third of the total loading that would be expected for an acceleration of 0.3 g. Also, the results show little reduction in shear stress for seal lengths greater than 10 m.

5.4.5 Structural Analysis of Postclosure Thermal Loadings

The resulting far-field thermal stress induces thermal stress in the seals at the three sealing locations. The SHAFT code can be used to evaluate induced thermal stresses within the seal. These stresses can then be combined with other loadings in the scenario evaluations. The postclosure thermal loadings depend on the proximity of the seals to the sources of heat. Section 3.3.2 presented the far-field thermal stresses. It was determined that boreholes USW SD-4 represented the expected condition for thermal loadings within the reporting boundary. Table 5-4 presents the maximum thermal stresses for USW SD-4.

5.4.6 Evaluation of Scenarios

The scenarios for stress in the seal and rock are presented in Figures 5-14 through 5-16. The scenarios considered are as follows:

- Open borehole at ambient temperature
- Sealed borehole with backfill
- Initial static, thermal, and dynamic (dry backfill)
- Postclosure static, thermal, and dynamic (saturated backfill).

The results show combinations of the above loadings as Mohr circles of stress within the seal and rock. The deep borehole USW SD-4 within the potential repository is evaluated. The conclusions are presented below.

5.4.7 Conclusions of How to Seal Using Cementitious Materials

The results show that the interface stress reduces the tangential boundary stress in the rock at the time of seal emplacement and backfilling. Because of the "skin" friction, the backfill does not significantly load the seal and the hydration of the cementitious seal predominantly governs the state of stress in the seal. As potential repository heating takes place, the maximum shear stress increases in the plug and is reduced in the surrounding rock. The shearing stresses are higher near the potential repository horizon.

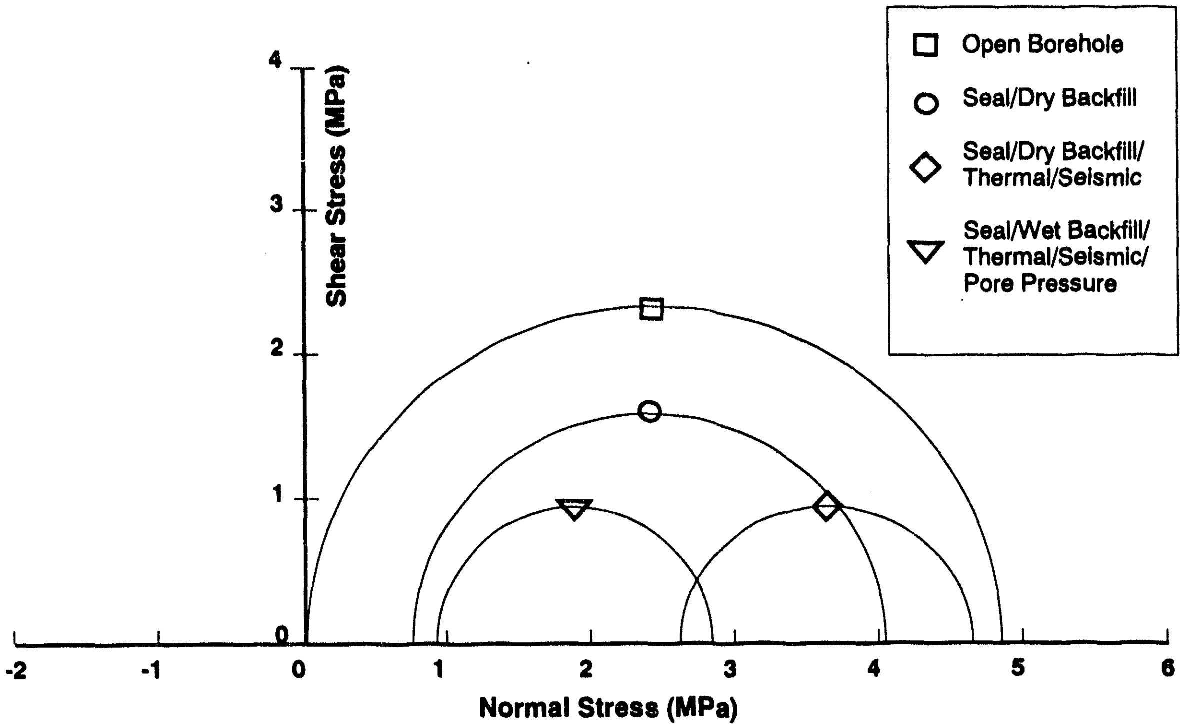
Table 5-4

Summary of Induced Thermal Stresses in Seals at the Interface Zone

Seal Location	Seal				Rock			
	Radial Stress (MPa)	Tangential Stress (MPa)	Vertical Stress (MPa)	Shear Stress (MPa)	Radial Stress (MPa)	Tangential Stress (MPa)	Vertical Stress (MPa)	Shear Stress (MPa)
1	2.25	0.70	0.59	-0.67	2.25	0.58	0.45	-0.67
2	6.00	5.49	2.30	0.056	6.02	11.88	4.65	0.056
3	4.39	3.29	1.54	0.12	4.39	3.38	1.32	0.122

(a)

Rock Stress: USW SD-4, Seal Location 1, LAPD = 57 kW/acre, Waste Age = 30 years



(b)

Seal Stress: USW SD-4, Seal Location 1, LAPD = 57 kW/acre, Waste Age = 30 years

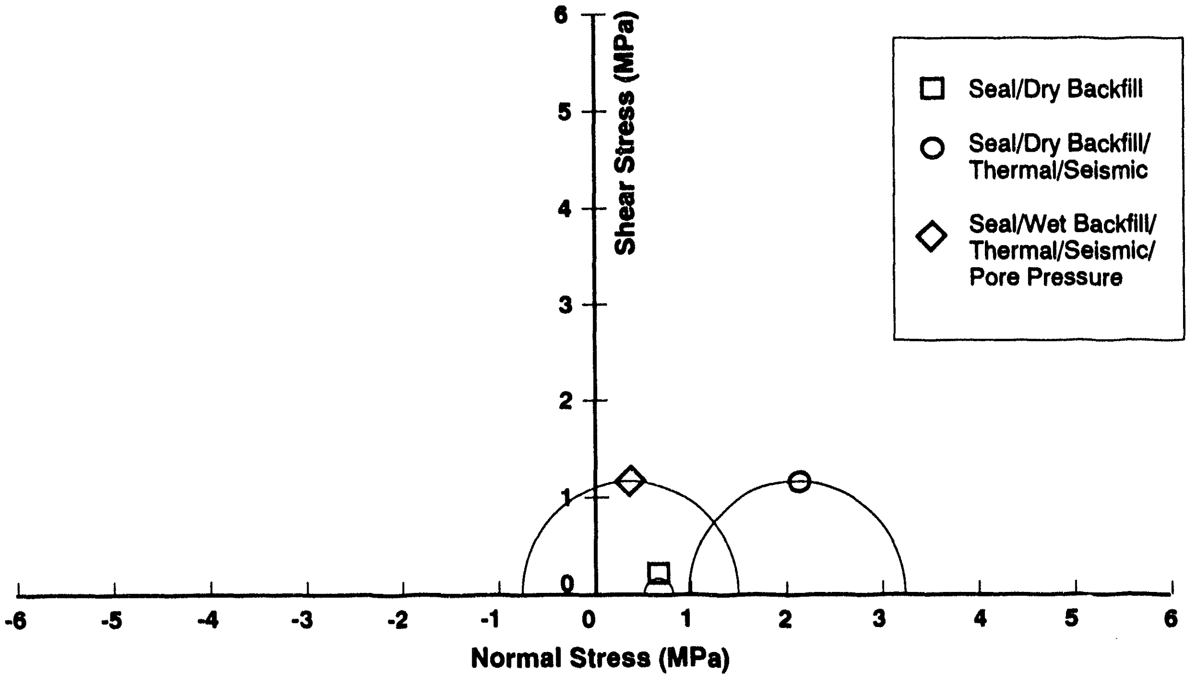
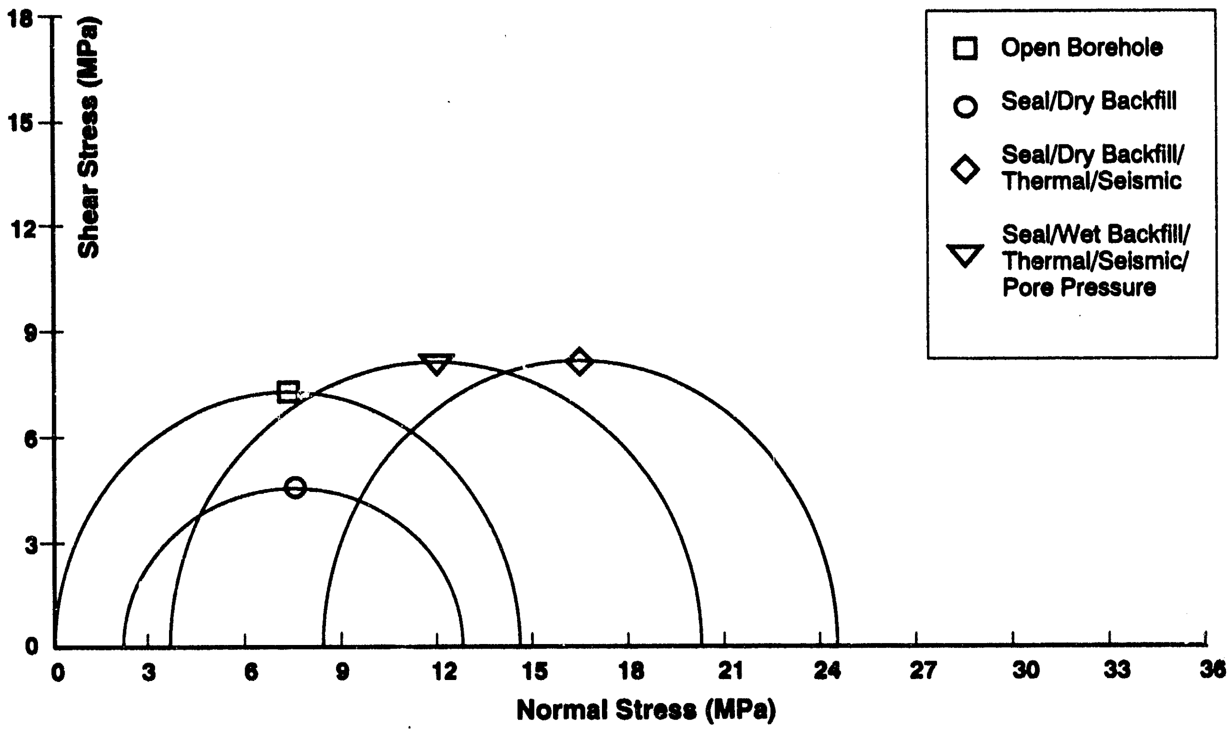


Figure 5-14
Evaluation of Scenarios in the (a) Rock and (b) Seal at the Upper Sealing Location

(a)

Rock Stress: USW SD-4, Seal Location 2, LAPD = 57 kW/acre, Waste Age = 30 years



(b)

Seal Stress: USW SD-4, Seal Location 2, LAPD = 57 kW/acre, Waste Age = 30 years

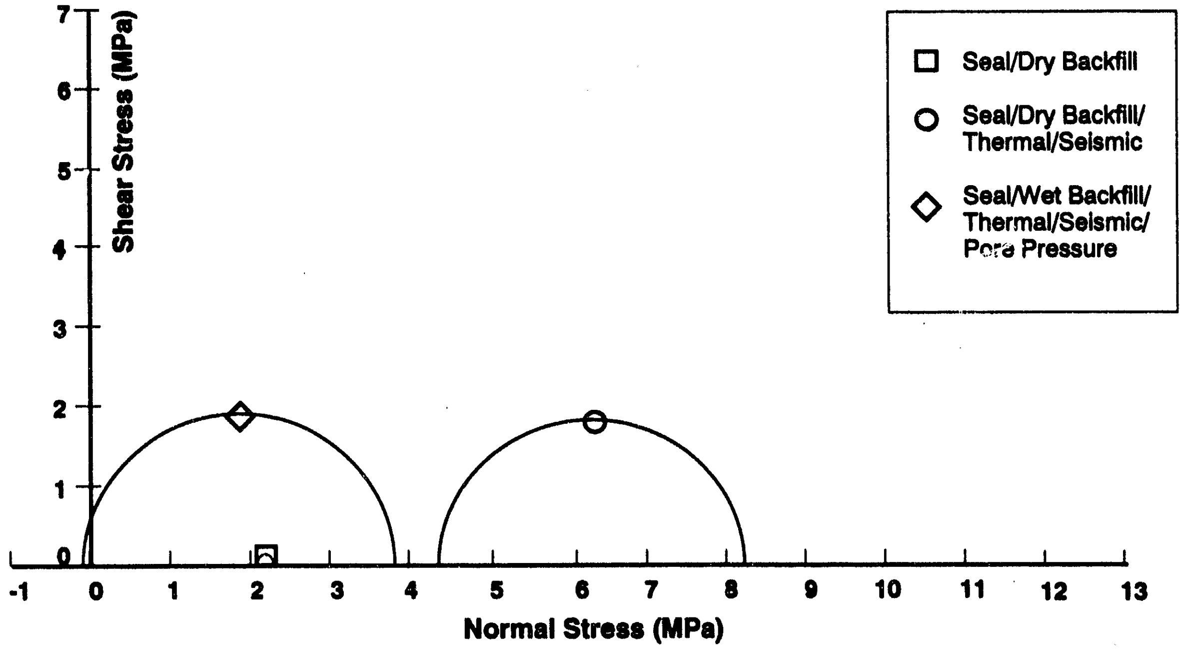
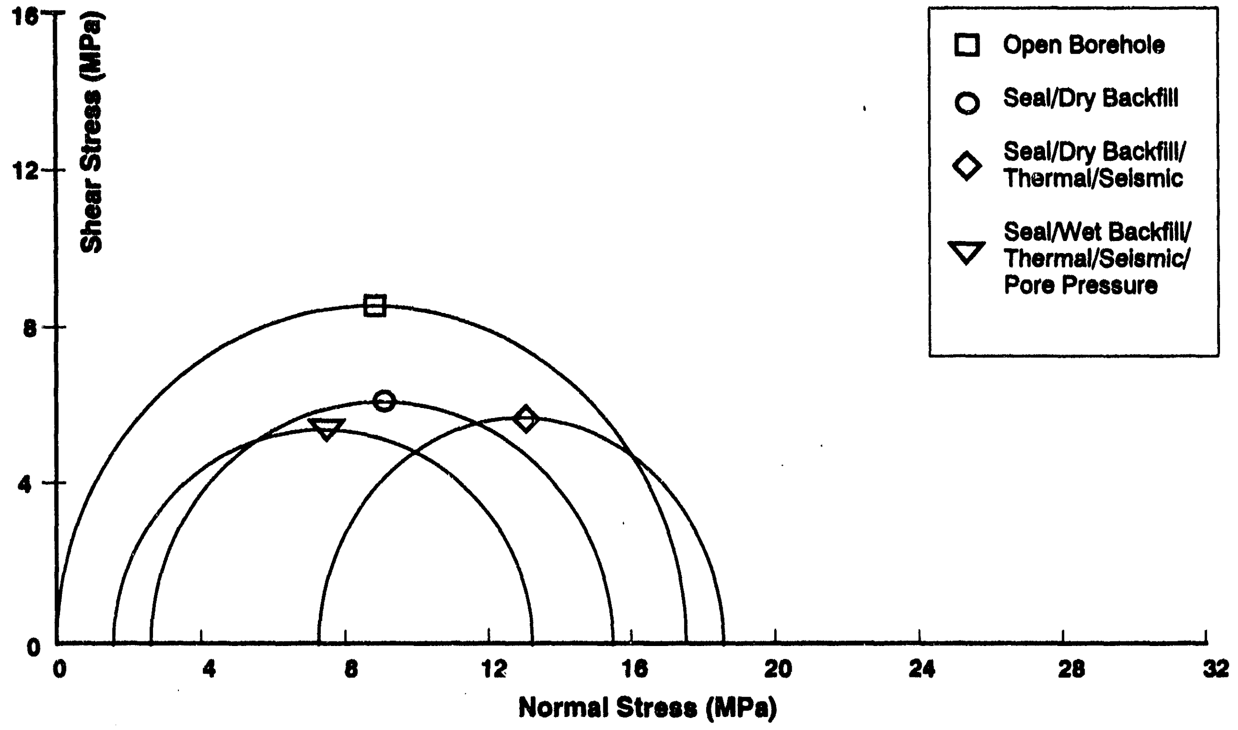


Figure 5-15

Evaluation of Scenarios in the (a) Rock and (b) Seal at the Potential Repository Horizon

(a)

Rock Stress: USW SD-4, Seal Location 3, LAPD = 57 kW/acre, Waste Age = 30 years



(b)

Seal Stress: USW SD-4, Seal Location 3, LAPD = 57 kW/acre, Waste Age = 30 years

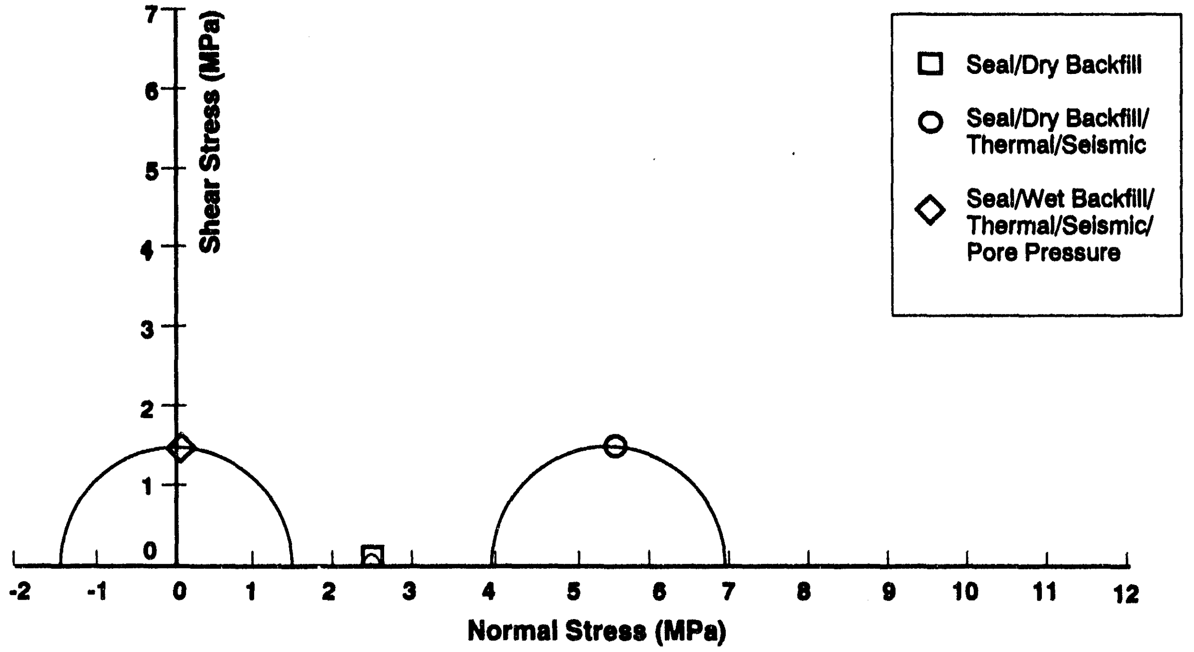


Figure 5-16

Evaluation of Scenarios in the (a) Rock and (b) Seal at the Lower Sealing Location

If saturation and perched water occurs, the effective stress near the interface zone reduces by the magnitude of the pore pressure. Under the conservative assumption that the plug resists load in uniform shear and that compression does not occur due to elastic interaction effects, the analysis predicts the development of a slight degree of tension (1 to 2 MPa). A more refined analysis for a 10-m-long plug would predict that the loading would be resisted in shear and bearing compression and that the interface zone would not be subject to tension, although it would be subject to reduced compression. However, the preliminary results can be used to select conservative design requirements that should prove to be satisfactory with more advanced analysis.

The calculations presented in this section suggest the adoption of the following approach for emplacing seals:

- The seal material should be selected with a reduced heat of hydration.
- Type II cement is preferred to a Type K cement to avoid issues with respect to the preferential dissolutioning of ettringite.
- The seal should be emplaced at a lowered temperature (4°C) to eliminate undesirable thermal effects. The analysis suggests the importance of emplacing the seal under a slight injection pressure. The actual emplacement should be tailored to conditions existing at depth.
- Under dry or unsaturated conditions, an increase in temperature will increase confinement, either increase or reduce shear stress in the surrounding rock, and increase shear stress in the seal. The temperature effects depend on the proximity of the seal to the potential repository horizon and suggest seal emplacement away from the potential repository horizon.
- A 10-m plug length is adequate to reduce shear stress (see Appendices I and J).
- Saturation of the backfill significantly reduces effective stress. For a long plug, loads would be resisted by a combination of shear and compression. A cementitious grout with a tensile strength of 1 MPa and a compressive strength of 21 to 34 MPa (3,000 to 5,000 psi) is adequate for combined loads.

The analysis suggests the avoidance of perched water at key sealing locations. Future analyses should evaluate the inflow rate into exploratory boreholes, outflow rates, and storage potential for perched water. If lower-conductivity backfill is specified or if sealing occurs at potential infiltration locations, the potential for perched water should be substantially reduced.

6.0 Feasibility of Emplacing Borehole Seals

This chapter reviews materials and techniques available in the oil and gas industry and industrial nonradioactive waste injection well industry to assess feasible options for permanently plugging and abandoning wellbores. This chapter also presents possible techniques for sealing boreholes, including conceptual schematics for removal of casing, reconditioning of the borehole wall, and emplacement of the plug, based on available materials and techniques.

Current available technologies initially evolved from the petroleum engineering and oil industry. Recent significant environmental legislation has placed new importance on applying the best current technology to the plugging of abandoned oil and gas wells and to the closure of injection wells used in the disposal of hazardous materials.

6.1 Design Process for Emplacing Seals

During the 1930s, states began passing laws and establishing oil and gas agencies to regulate the abandonment and plugging of oil and gas wells. Today, most states require specific plugging plans, and many require notification of intention to abandon a well in order to have a representative present during plugging operations.

The established injection well industry began in the 1950s and 1960s. During the 1970s, most states passed regulations detailing abandonment procedures for wastewater injection wells. Oil and gas agencies permitted and controlled abandonment of deep wells in most states (Warner and Lehr, 1977). States such as Michigan, Ohio, Oklahoma, and Texas followed regulations that included plugging requirements specifically for injection wells. Now abandonment of injection wells is regulated under the EPA by direct implementation or by state regulation. States may apply for and receive primacy to promulgate and enforce rules and regulations that are equally or more protective than the federal regulations.

The following discussion applies to borehole sealing technology for cased and uncased vertical borehole penetrations with diameters limited to approximately 40 in. and typically 3 3/4 to 18 5/8 in. and depths ranging from 1,000 to 15,000 ft.

6.1.1 Existing Strategies Used in Sealing Boreholes

The development of a borehole sealing strategy, the location and type of sealing material, and the emplacement technique depend on several factors, including formation characteristics, borehole construction, hydrologic regime, fluid environment, regulatory requirements, and associated economics.

Under EPA, Section U, 40 CFR 146.3, "Definitions," a confining bed is "a body of impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers." Under this section, the EPA defines a confining zone as "a geological formation, group of formations, or part of a formation that is capable of limiting fluid movement above an injection zone." The Nevada UIC regulations, Section U, 445.42235, use this definition, replacing "fluid movement above an injection zone" with "the movement of fluids from a zone of injection." Under Section U, 445.42695, "Location and Construction of Well," the State of Nevada characterized a confining zone as one "that is free of known open faults or fractures within the area of review." The regulations consider geophysical logging and/or core tests of the confining zones as methods for characterizing fracture zones. The regulations specify no quantitative criteria for the selection of a confining zone. The operation evaluates each well on its own characteristics and its influence upon the area of review.

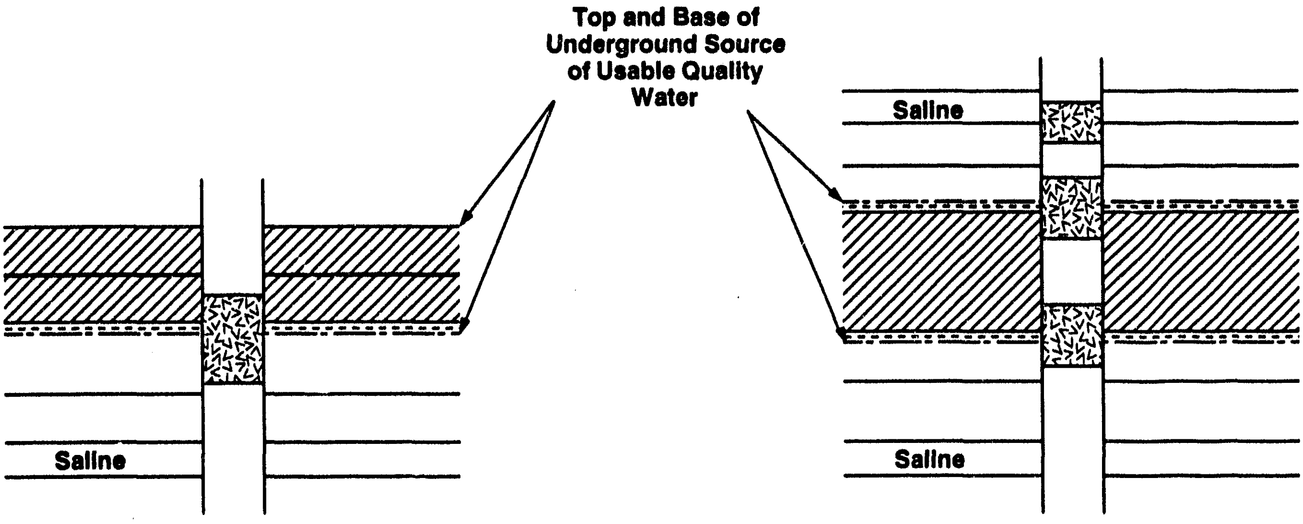
Concerns regarding conservation of natural resources and public health resulted in regulations addressing the construction and closure of wellbores, which were aimed at isolating underground resources, such as underground sources of drinking water, from commercial oil and gas resources. Regulations require the confinement of oil and gas and underground waste to the allowed or permitted production or disposal zone. These regulations emphasize restoring the controlling geological conditions that existed prior to drilling.

Underground aquifers that are sources of drinking water typically exist above saline water. Generally accepted practices for isolating these aquifers from formations bearing saline water require setting a seal at a point below the aquifer and extending it up at least to the base of the aquifer formation (Figure 6-1). If the drinking water source exists in a formation below saline water, seals would be placed across the top and bottom of the underground drinking water source and possibly across the base of the formation containing the saline water (Figure 6-1).

Regulations require the closure of Class I injection wells to permanently confine waste within the disposal zone (UIPC/EPA, undated). Seals can be placed either at the upper and lower boundary of the confining zones or across the entire zone. The placement of a seal across the entire confining zone prevents fluid from migrating down the borehole and coming into contact with other formations (Figure 6-1). The likelihood of emplacing a high-performance seal improves with an increased-length-of-seal material.

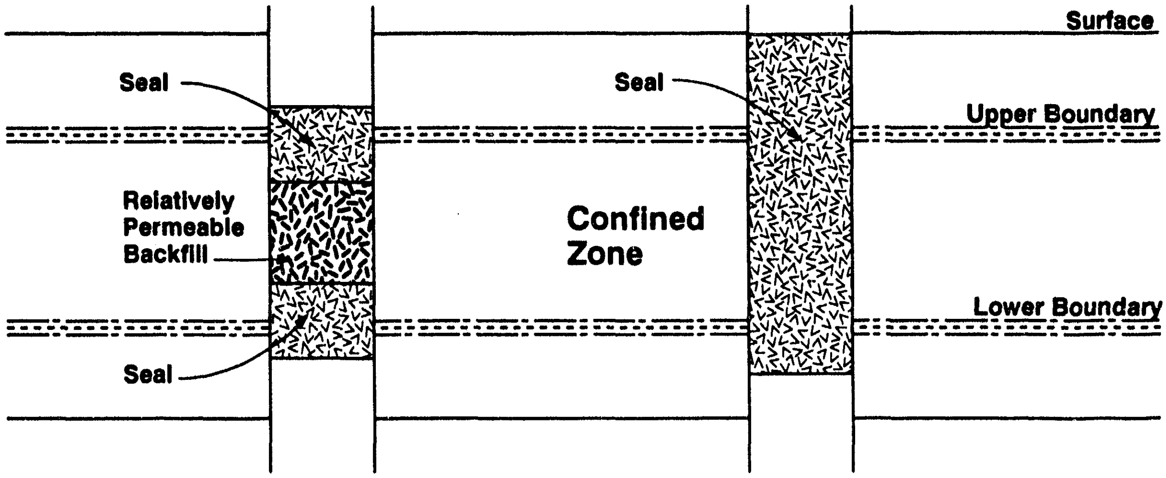
Seal materials used for oil and gas and injection wells are designed to bond to the formation to accomplish hydraulic and shear isolation. For cased wells, the bonding must occur between the casing, the seal material, and the formation. If poor bonding is detected, the casing should be either removed altogether or in part, so that the seal may be emplaced against the formation. Special seal material(s) may be required, if there are potential incompatibilities between injected waste waters or native brines and conventional portland cement.

The method of well construction determines whether well casing will be removed. Casing removal is generally not required by regulatory agencies for deep injection wells that are fully cemented from top to bottom. Yet, they require surface casing (steel casing extending through



Partial Sealing of the Lower Contact Zone

Partial Sealing of the Upper and Lower Contact Zones



Complete Sealing of the Confined Zone

Figure 6-1
Strategies in Sealing Boreholes

freshwater horizons) in injection wells to be completely cemented when installed. If casing strings are not completely cemented during installation, it is generally recommended that they be pulled, perforated, slotted, or ripped, so that cement can be placed in the annular space between the casing and borehole wall, particularly between permeable intervals.

The point at which the casing should be cut for removal can be determined by several methods or combinations of methods: (1) the casing could be cut at some point above the calculated top of the annular cement; (2) it could be cut above the top of the cement, as shown on an acoustical cement bond log; (3) it could be cut below the known base of a specific lithologic interval; (4) or the casing could be cut at a free point based on the results of an electric line-conveyed free-point tool determination. For cemented casing that cannot be pulled from across a critical seal interval, an alternate method must be considered to install a plug or seal to the borehole wall. Here, the casing must be milled out in sections or removed by "washing" over the casing with a rotary shoe and washover pipe. Typically, washover operations limit the depth of the washover attempt to 500 ft. The casing recovery occurs between washover attempts by using a cutter to sever the free pipe.

The placement of a good seal requires reconditioning of the borehole wall and fluid within the borehole to maximize the sealing performance of the plug. When using abandonment mud in a well penetrating below the water table, plugging regulations may require that the density of the mud system be balanced throughout the well and that the well be in a static state prior to beginning emplacement operations.

6.1.2 Design Process for Emplacing Seals

In designing a sealing program for boreholes, an objective is to maintain compliance with applicable regulatory requirements. Due to the type of boreholes and their association with the Yucca Mountain Mined Geologic Disposal System, the sealing requirements of 40 CFR 146, Subpart G ("Closure of Class I Hazardous Waste Injection Wells"); Nevada Administrative Code (NAC) 445.4277 ("Plugging and Abandonment of Injection Wells"); and NAC 534.420 ("Plugging of Water Wells") will be addressed.

For injection wells, both NAC 445.4277.04 and 40 CFR 146.71(d)(4) specify that cement shall be used "in a manner which/that will not allow the movement of fluids into or between underground sources of drinking water." These regulations imply that the type of cement and location of well plug be engineered to confine the waste to permitted injection zones and prevent any contamination of underground drinking water sources. Other sealing materials may be used between successive cement plugs. Figure 6-2 illustrates the general process for the design and emplacement of seals for oil and gas or deep-well injection applications. Figure 6-3 illustrates decisions associated with the design and emplacement of seals.

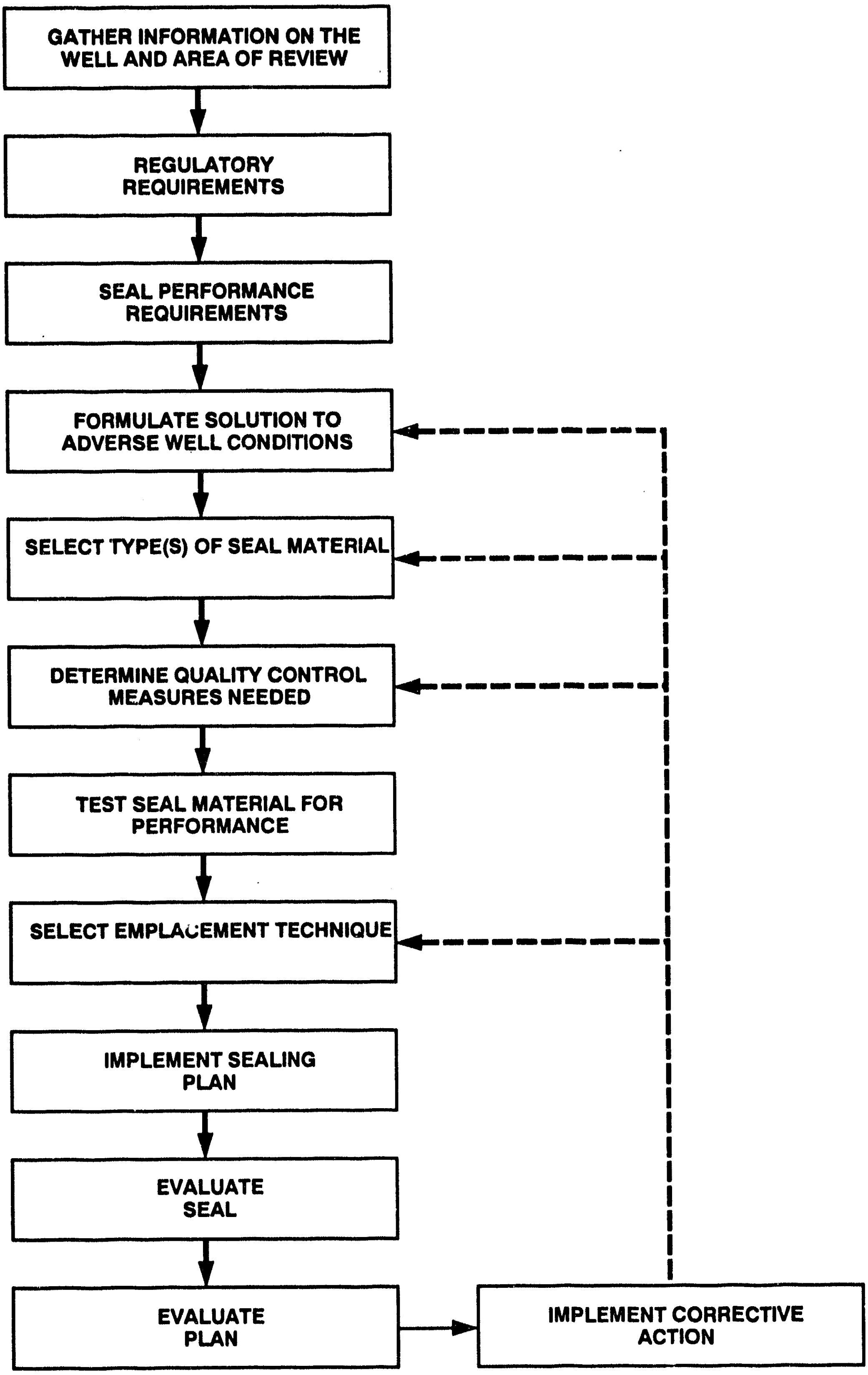


Figure 6-2

General Process for Design and Placement of Seals

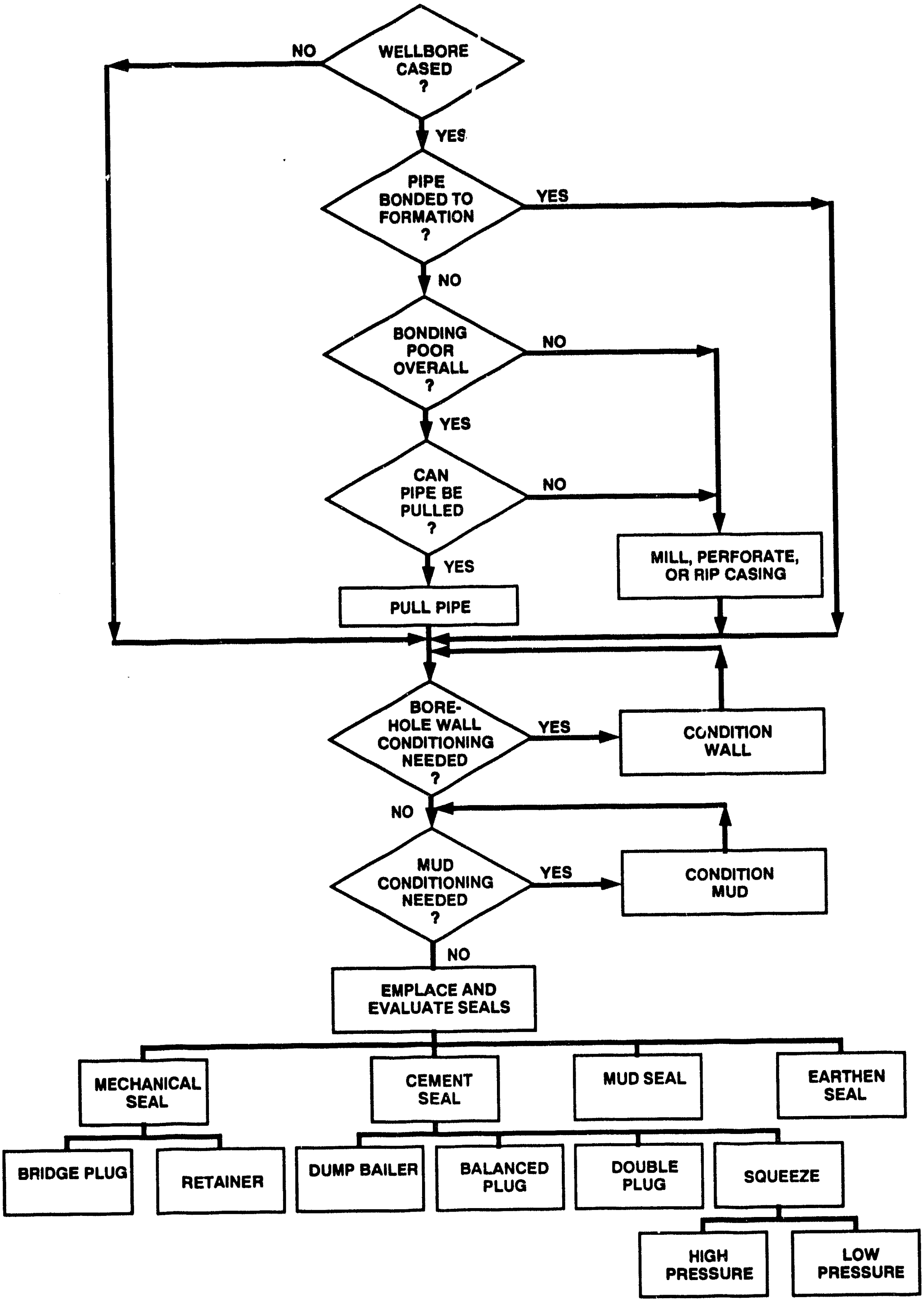


Figure 6-3

Decisions Associated with Design and Emplacement of Seals

The sealing materials referenced in NAC 534.420 and NAC 534.421 (regulations for water wells and wells for purposes other than water wells) are bentonite, abandonment mud, drill cuttings, inorganic fill material, cement grout, concrete grout, and neat cement. If the well is to be sealed with cementitious material, it must be circulated from the total depth of the well to the surface. Additional regulations apply to wells completed in saturated environments when using bentonite-laden slurries or "mud" in abandonment operations. 40 CFR 146.71(d)(7) requires the well to "be in a state of static equilibrium with the mud weight equalized" from "top to bottom." This may be done through circulation of a mud of equal density and sufficiently to prevent well caving during any cement emplacement. This requirement addresses cement slurry contamination issues known to occur during emplacement that adversely affect the curing of the cement.

Seal emplacement techniques of 40 CFR 146.71(d)(5)(i) to (d)(5)(iv) represent the most common techniques used in plug-back cementing and address the need for an individualized closure design. Evaluation of the "seal and stability" of "each plug" falls within 40 CFR 146.71(d)(6). Plugs must be "appropriately tagged and tested for seal and stability before closure is completed." The most practical technique of testing plugs is running drill pipe into the borehole and locating the plug by applying weight. This will give a positive indication of whether there is some degree of plugging at the desired location. Most wells have cement emplaced inside the casing that is intact to the ground level. This allows for pressure-testing of the hydraulic seal. New tools may have to be developed for the Yucca Mountain Mined Geologic Disposal System to test the sealing capabilities of a plug in an open hole.

Information, such as depth, downhole temperature and pressure, hole conditions, and drilling problems, must be considered when designing optimum cementing composition and emplacement methods. The API provides testing standards for well cements that have become an integral part of cement design (API, 1979). Table 6-1 presents the property for each test, a summary of the API slurry tests, and required field testing.

Thickening time of cement is a measure of the cement's pumpability under simulated downhole conditions without any shutdown periods. The estimated time to mix, emplace, and reverse out any excess cement typically determines the thickening-time specifications for a particular job. The time allowed for the slurry to become static may reduce the desired total thickening time.

The hydration of cement involves gel-strength development during the transition phase followed by compressive strength development during the setting phase. Excessive water or lower-than-expected temperatures contribute to slow the hydration process. Compressive strength development determines the waiting on cement (WOC) time.

Sealing experience shows that downhole temperature has the greatest impact on thickening and WOC time. An accurate measurement of static bottom-hole temperature helps to ensure meaningful thickening and WOC times. Accelerators or retarders are used to compensate for

Table 6-1

Summary of Tests Used in Cement-Slurry Design[a]

Slurry Property	Laboratory Test	General Field Requirements	Test Reference
Slurry preparation for laboratory mixing and testing	Balances and high-shear mixer.	Mixing water variable with composition and API cement class. Mixing time 35 sec on high-speed mixer.	API Document 10, Sec. 5, and Appendix A
Slurry viscosity	Atmospheric thickening-time tester.	10 to 15 Bc, which is a unit of consistency used in cement testing (thin slurry).	API Document 10, Sec. 9
Pumping time	Determined on pressure, temperature, thickening-time tester.	Variable with type of job. Normal casing design is 2-1/2- to 4-hr fluid time.	API Document 10, Sec. 8, and Appendix E
Free water	Settling of slurry in 250-mL graduate after setting.	Maximum 1.5% free water after setting 2 hr.	API Document 10, Sec. 6, and Appendices B and M
Fluid loss of cement slurry	High-pressure fluid-loss cell at 1,000 psi on 325-mesh screen or core for 30 min.	Variable with job requirements. General rule: squeezing, 50 to 125 mL; production casing or liner, 50 to 200 mL.	API Document 10, Appendix F
Slurry density	Standard mud balance or pressure/ density balance.	Variable with mud densities and hole conditions. Generally 12- to 16-lb/gal.	API Document 10, Appendix C
Rheological properties	Rotational viscometer at various shear rates.	Depends on slurry water, density, and desired flow rates. Plug, laminar, or turbulence.	API Document 10, Appendix H
Permeability testing	Special water-permeability apparatus for set cement.	Less than 0.1 md.	API Document 10, Appendix G

[a]From Smith, 1990.

downhole temperatures and pressures to ensure adequate time to emplace the slurry and minimize WOC times.

Other testing may be warranted due to special conditions, such as an acidic environment, abnormal temperature fluctuation, or environmentally sensitive areas. Compatibility testing between the cement slurry, borehole, and spacer fluids could be of great importance when anticipating difficulty in proper placement of the cement. Also, for gas migration, testing of the cement permeability to air should be performed.

6.2 Technologies Available for Casing Removal and Sealing

A combination of materials and techniques may be used to tailor a plugging operation to specific situations and environments. Tasks involving the technology of sealing wellbores include the following:

- Removal of casing
- Reconditioning the borehole
- Selection of seals
- Emplacement of seals.

Several techniques can be used for removing casing from wells, such as those associated with the Yucca Mountain Site Characterization Project, including the following:

1. "Washing" over the cemented casing with a rotary shoe and washover pipe

2. Free-pointing the casing and cutting it above the top of the annular cement with internal cutters, then pulling the free casing only

3. Milling a window over a specific region of cemented casing with a section milling tool to remove casing and underreaming the cement to the original hole diameter.

Complete removal of the casing may not be necessary in wells that are not cemented across a critical seal area. If the casing is free down to the bottom of that interval, an internal cut can be made below the interval using a workstring- or wireline-conveyed cutting tool. After making the cut, the casing above the cut can be moved, and the borehole can be prepared for plug or seal emplacement.

The process of reconditioning borehole walls uses the following tasks:

1. Evaluate condition of borehole wall.

2. Optimize mud properties (in mud-rotary-drilled holes when using abandonment mud).

3. Remove wall cake from the seal area (in mud-rotary or foam-drilled holes).

Smith (1990) recommends the conditioning of borehole walls to optimize the plugging and sealing of wells, yet due to the expense involved, conditioning is not often done. Mud properties affect the removal of cuttings and debris from the wellbore; yet, good mud properties may be totally negated by the presence of mud-wall cake between the seal material and the formation.

The method used for seal emplacement depends on the materials used for sealing, which include earthen materials, cement, mechanical, and mud plugs. Since mechanical plugs are not normally used for primary sealing and since compacted earthen materials lack strength for sealing deep wellbores, this discussion will concentrate on emplacement techniques for cementitious materials. Also, these emplacement techniques include the use of mud.

6.2.1 Removal of Casing, Monitoring, and Test Equipment

There are many types of casing used for wellbore construction. The type of casing used and the condition of the casing after well construction will determine the types of tools and equipment needed to remove the casing. The tools and equipment discussed here are most commonly used by the oil and industrial injection well industries. The functions of these tools are as follows:

- Show free, unstuck casing
- Washover the casing
- Cut the casing
- Remove the casing
- Evaluate casing removal.

Table 6-2 presents the types of tools typically used for these functions.

6.2.1.1 Geophysical Exploration

Cement-bond logging tools use controlled acoustic signals to decide whether cement exists behind the casing; evaluate qualitative bonding of the cement to the casing or the formation, or both; and evaluate overall cement integrity. This is done by acoustic transmitters and receivers strategically located on the logging tool. This logging tool will not function in air-or foam-filled wellbores. Cement-bond logging tools allow qualitative rather than quantitative evaluation regarding the cement and bonding characteristics. The pipe recovery logs provide a quantitative determination for pulling the casing.

The pipe recovery logs use pipe-stretch calculations. Pipe recovery logs can find the point at which lodged casing is no longer stuck. The electronic signal generated from torsional, tensile, and/or compressional casing distortion determines the percentage of free pipe within the wellbore. Free-point indicator logs must be in contact with the internal diameter of the casing to measure this distortion. As an integral part of these tools, the bow springs contact the casing either electromagnetically or frictionally.

Table 6-2
Tools Typically Used in Removal of Casing

Indicate free/unstuck casing:

- Cement evaluation logs
- Pipe recovery logs
- Pipe stretch calculations

Washover the casing:

- Rotary shoes
- Washover pipe

Cut the casing:

• Workstring	- Inside cutter - Hydraulic	- Mechanical
	- Outside cutter	- Mechanical
• Wireline	- Chemical - Jet	

Remove the casing:

• Retrieve	- Outside mechanical cutter - Casing spear
• Mill out	- Section mill

Evaluate casing removal:

• Retrieval	- Length recovered - Geophysical logs (depth control)
• Mill out	- Hydraulics - Wear markings - Pipe measurements

For quality control, the service company performs calibration of logging tools either at the service company shop or at the well site. Geophysical logs form an integral part of cement evaluations. These include the gamma-ray and/or neutron instruments and a casing collar locator. A collar locator and gamma-ray logs are normally run with pipe recovery logs. These logs provide depth control and may be used to correlate to the workstring and casing measurements.

Pipe-stretch calculation results may be compared to pipe recovery logs for the evaluation of the free-point accuracy; yet pipe recovery logs usually prove to be the most accurate method of locating the free point. Most of these logging tools are available in a 1-11/16-in. diameter for use in smaller pipe sizes.

6.2.1.2 Mechanical and Hydraulic Cutters

The mechanical and hydraulic cutters include the use of rotary shoes placed at the bottom of a washover pipe, mechanical cutters, and hydraulic cutters. Each of these is discussed below.

The rotary shoe can be attached to the washover pipe. The washover pipe telescopes over various types of casing to be recovered and is designed for limited clearance. Specially designed rotary shoes can cut cement or earthen material away from the casing in the casing wellbore annulus and/or the annular space between casings (Figure 6-4). Orientation of the cutting surfaces and the material that will be cut or milled are the two concerns when selecting a rotary shoe. To maintain the integrity of the casing, there should be no cutting action on the casing unless removing an outward flare at the top of the casing. When cutting cement or formation, an aggressive cutting structure is preferred. These two criteria typically lead to the selection of a rotary shoe with a tooth-type bottom and no cutting surface on the inside.

Once the casing is washed-over, it is ready to be cut and retrieved from the well. The two basic types of tools used in the oil and gas industry to cut casing are workstring- and wireline-conveyed tools.

Workstring-conveyed cutters work from outside the casing to the inside (Figure 6-5) or from inside the casing to the outside (Figure 6-6). The cutter knives are comprised of hardened and ground-tool steel. Both styles use anchoring devices that, once engaged, allow the cutter knives to rotate separately from the workstring rotation.

Cutting the casing from the inside can be done by hydraulically and mechanically actuated tools (Figures 6-6 and 6-7). For hydraulically actuated tools, the differential pressure across the orifice achieves the hydraulic actuation. It attaches to a piston in the tool for circulation of fluid down the workstring. The application of compression or tension to the tool achieves the mechanical

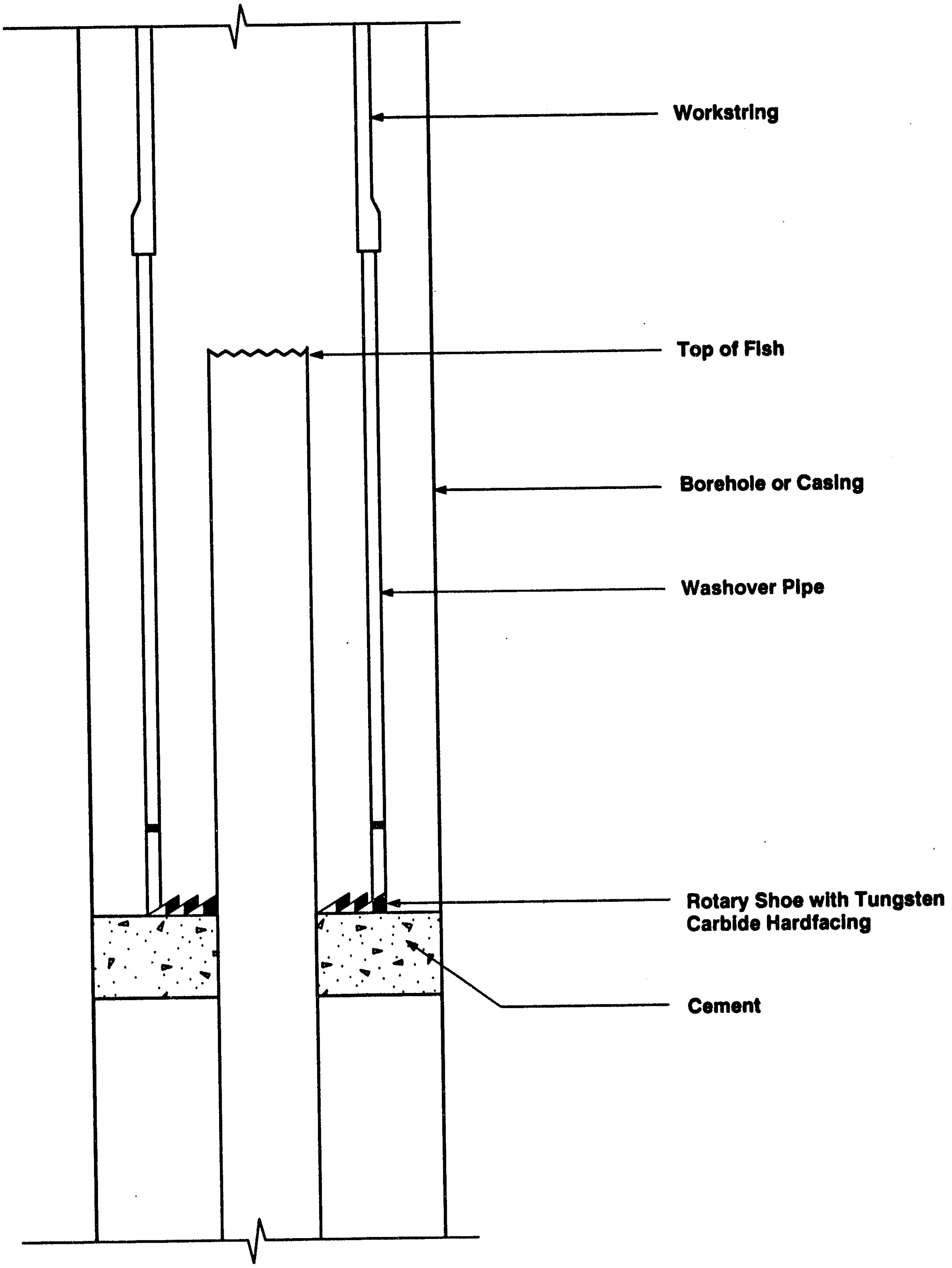


Figure 6-4
Washing Over the Casing

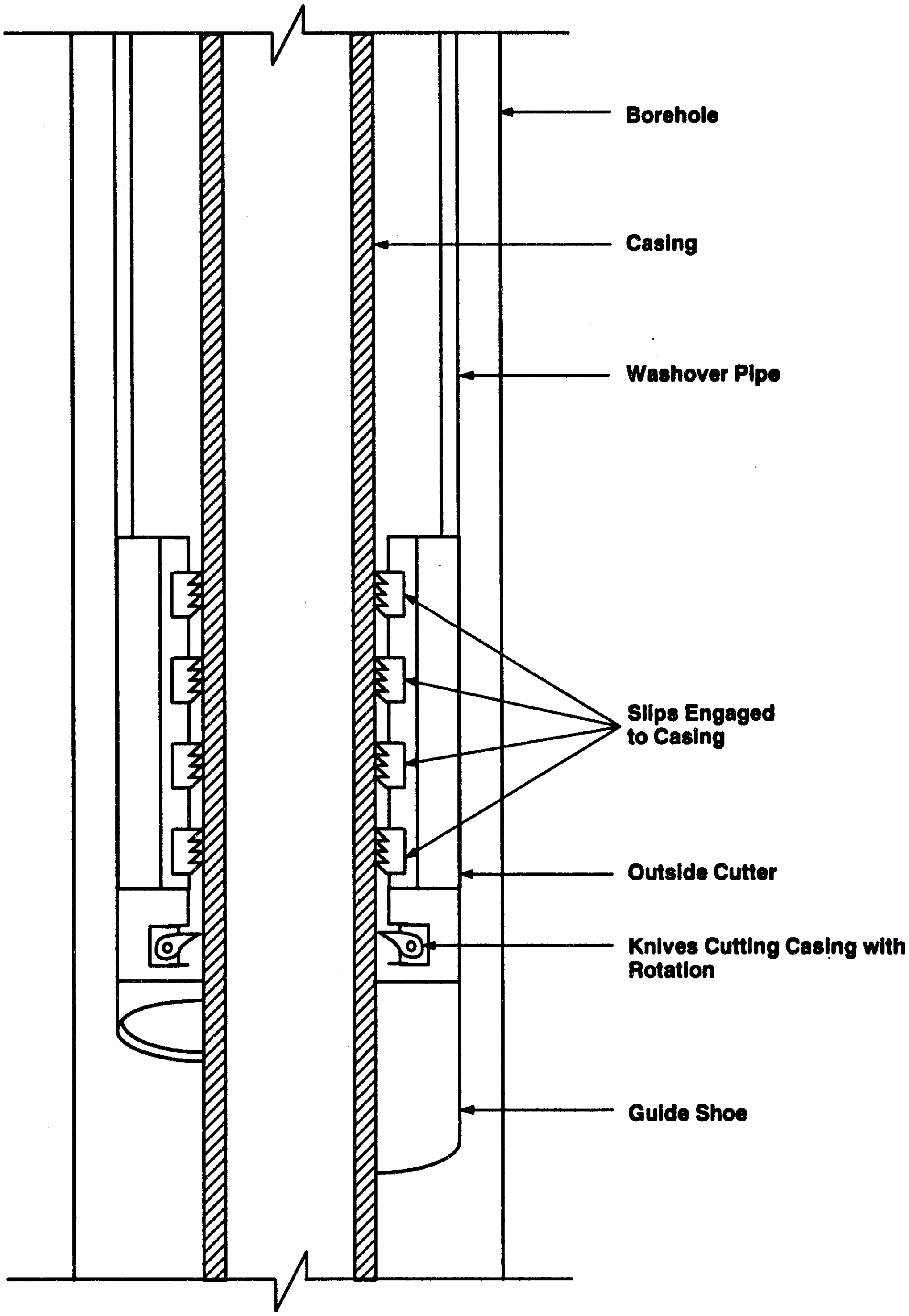


Figure 6-5
Outside Mechanical Cutter

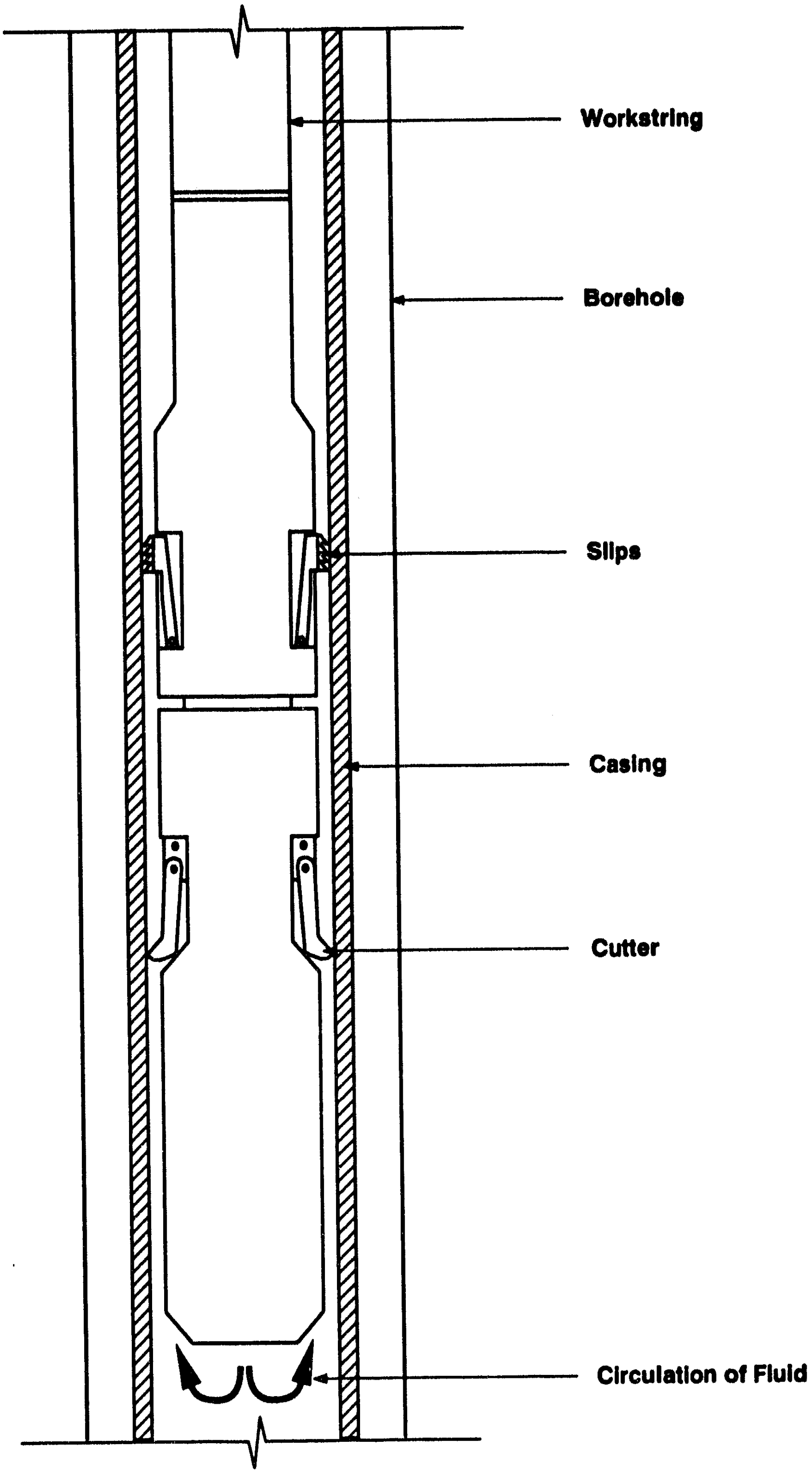


Figure 6-6
Inside Hydraulic Casing Cutter

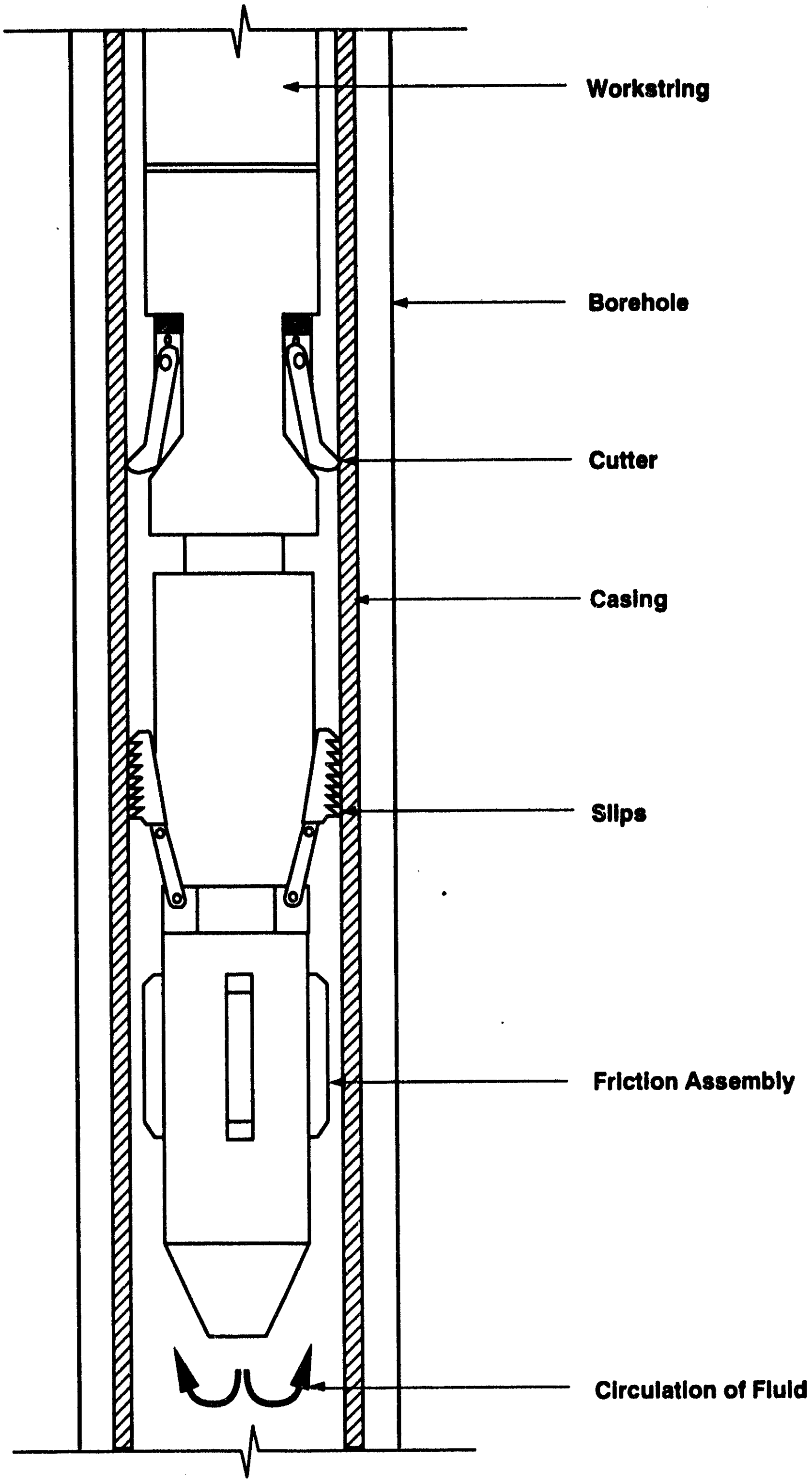


Figure 6-7
Inside Mechanical Casing Cutter

actuation and depends upon the type of tool chosen. The outside mechanical cutter will retrieve the casing above the finished cut. Most inside cutters require a separate retrieval tool.

6.2.1.3 Chemical and Jet Cutters

Wireline-conveyed cutters generally consist of chemical and jet cutters. Both tools can cut from inside the casing when activated by an electrical current controlled from the surface. The chemical typically used in chemical cutters (Figure 6-8) comes from the halogen fluoride family. This cutter provides a burr-free cut without pipe distortion, yet it will not perform in dry pipe, and it is recommended that there be at least 100 ft of fluid in the casing above the tool when making a cut. At this time, 5½-in. casing is the largest casing that may be cut with a chemical cutter.

Jet cutters sever pipe by use of a circular, conical-shaped explosive (Figure 6-9). Unlike the chemical cutter, the jet cutter typically causes a flare on the severed pipe. This flaring effect may require corrective action if the remaining casing is to be washed-over and/or retrieved.

6.2.1.4 Casing Removal

After freeing the casing, it can be removed by using a casing spear to pull the casing out of the borehole in one or more sections (Figure 6-10), by recovering the cut piece with an outside mechanical cutter or by milling out one or more sections. The mechanical actuation of the casing spears, when run inside the casing, can be used to transmit the pulling force to the cut section of casing (Figure 6-11). Reciprocation or rotation, or both, with tension at the tool, engage the spear to the casing. A casing stop ring, which has a larger diameter than the casing, can be run just above the spear to show that the spear is in the casing. Oil or bumper jars are usually run with casing spears to aid in removing the casing from the borehole and releasing the spear.

If retrieval of the casing from the borehole is not possible, an alternate method of removal is to mill out the casing in one or more sections. Section milling tools, shown in Figure 6-12, generally incorporate three or six cutting blades. Each blade is equipped with cutting material on the leading edge and outer face of the blade. For some section mills, a hydraulic indicator provides a loss of pressure when the blades fully open into the milling position. This helps to ensure complete casing removal from across the section. The differential circulating pressure hydraulically drives the cutting action. Casing can be milled at the rate of 1 to 3 ft/hr (Petroleum Extension Service, 1971) with this method.

Evaluation of casing removal is a function of the method employed, retrieval, or mill out. Measurements on casing retrieved from the borehole provide a comparison to the installation record, workstring, and wireline depths. During a section mill run, if the tool has a hydraulic indicator, the recorded circulation pressures should provide a good indication as to whether or not section milling to the full diameter of the casing occurred. Wear markings on the blades of the section mill also should show a pattern similar in shape and size to the casing.

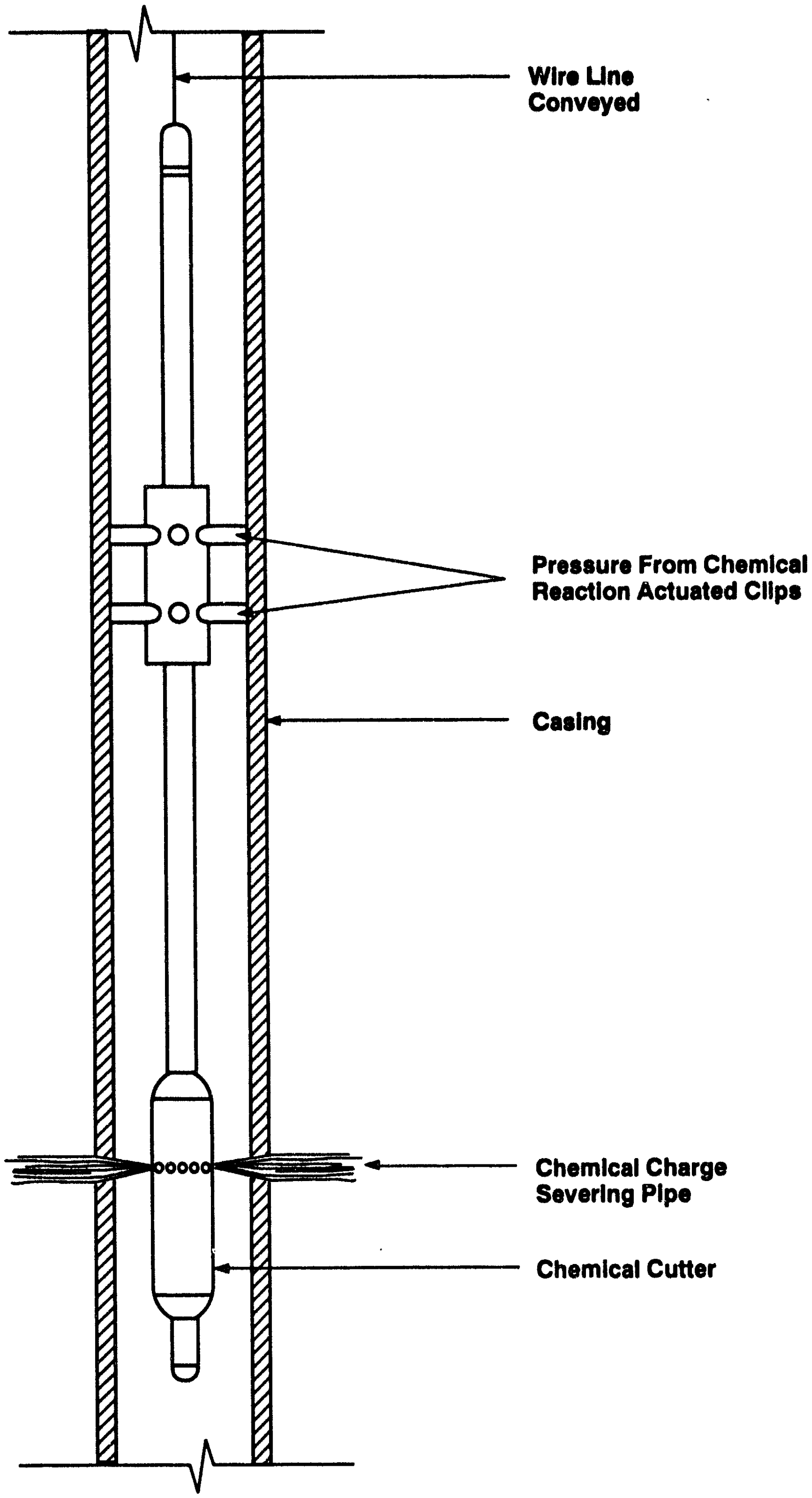


Figure 6-8
Chemical Cutter

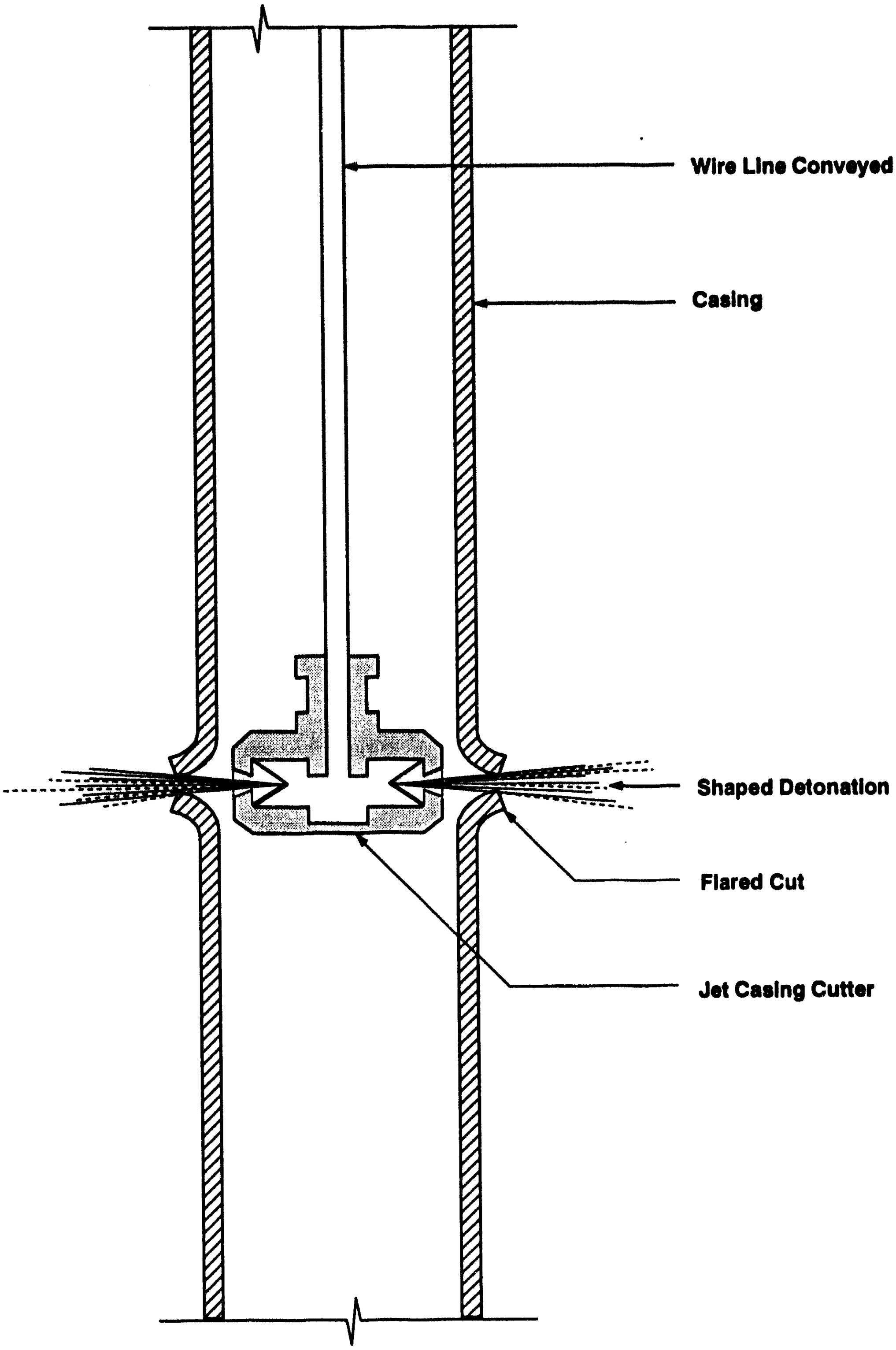


Figure 6-9
Jet Casing Cutter

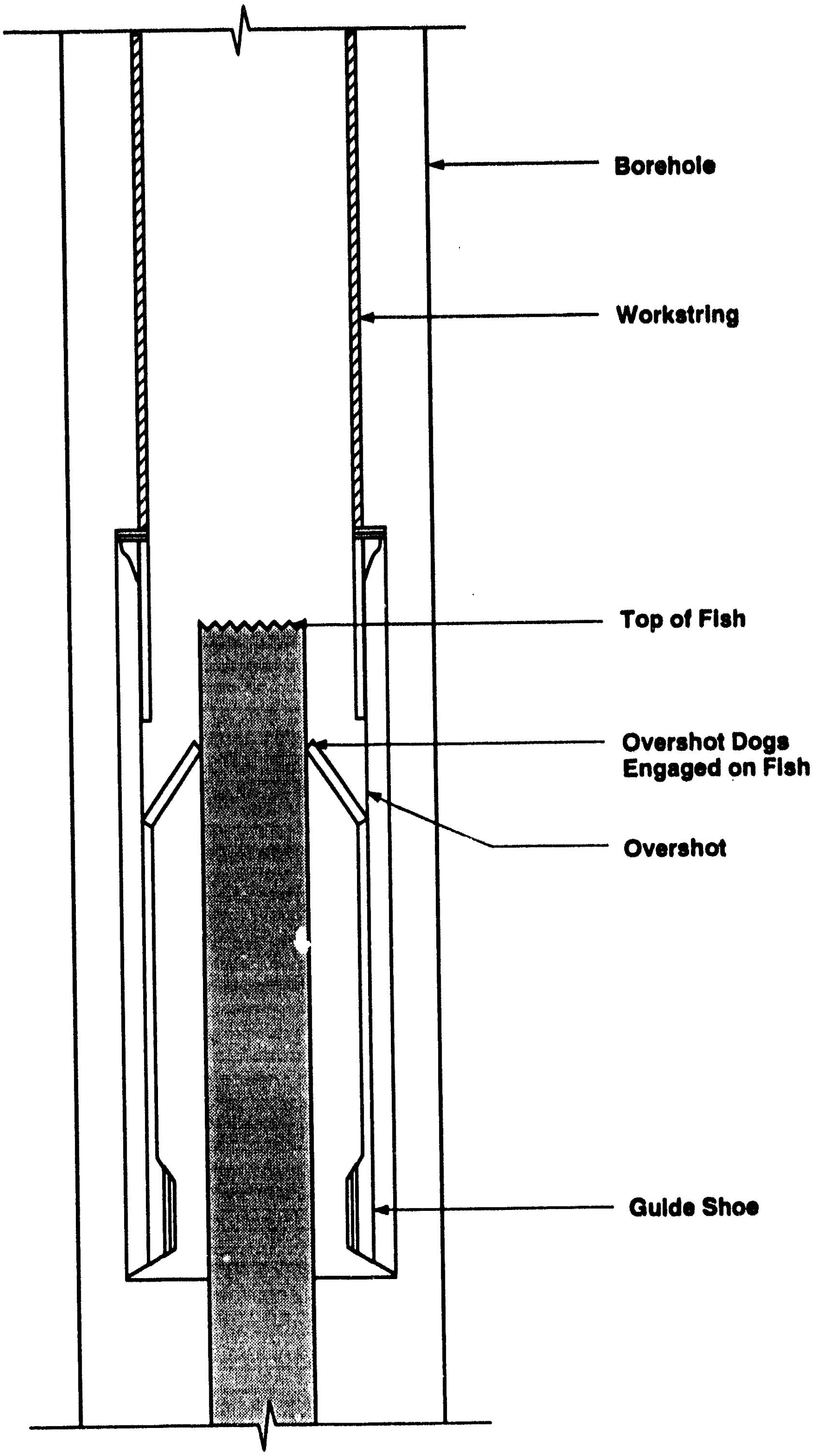


Figure 6-10
Removing Section of Casing

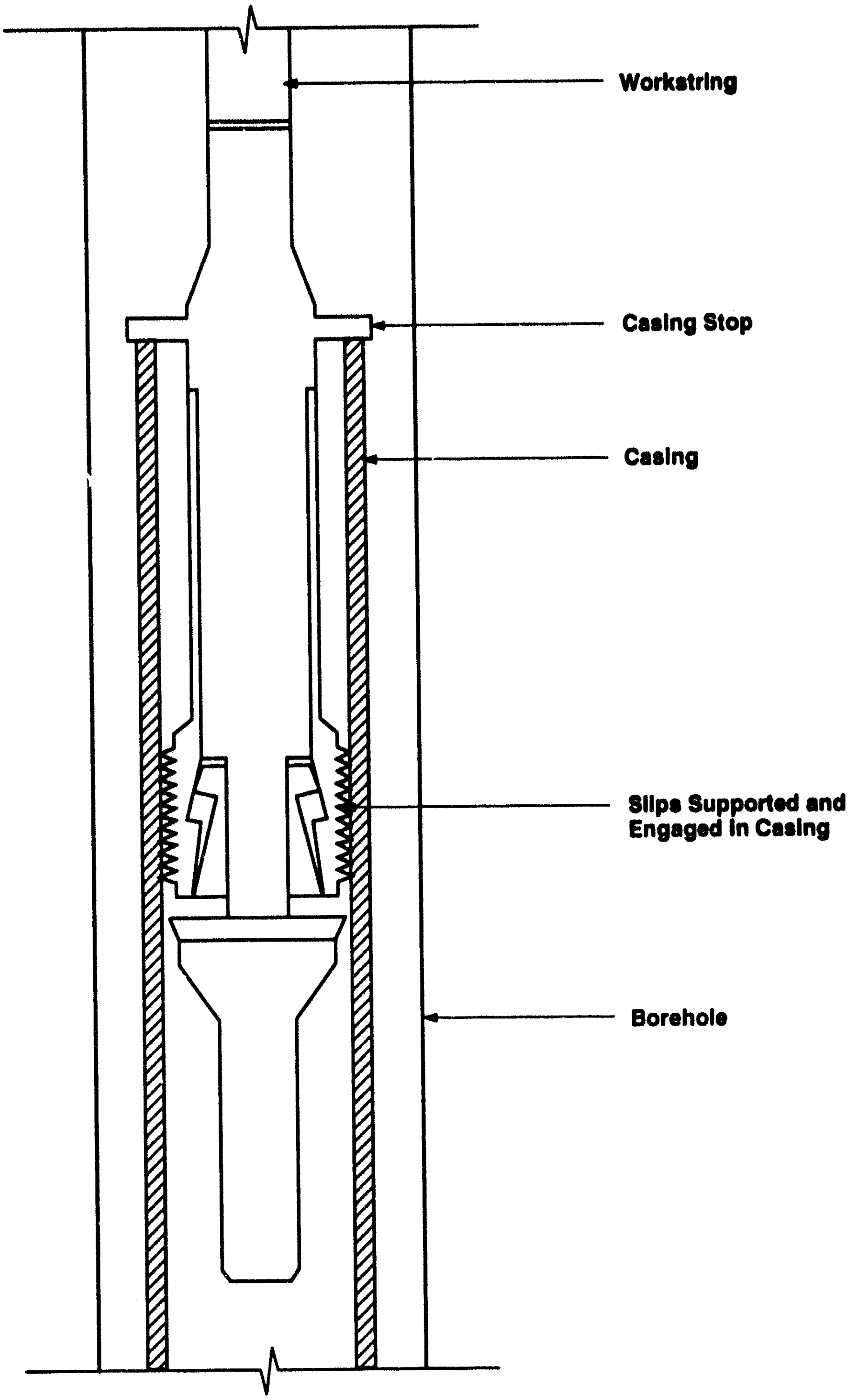


Figure 6-11
Casing Spear

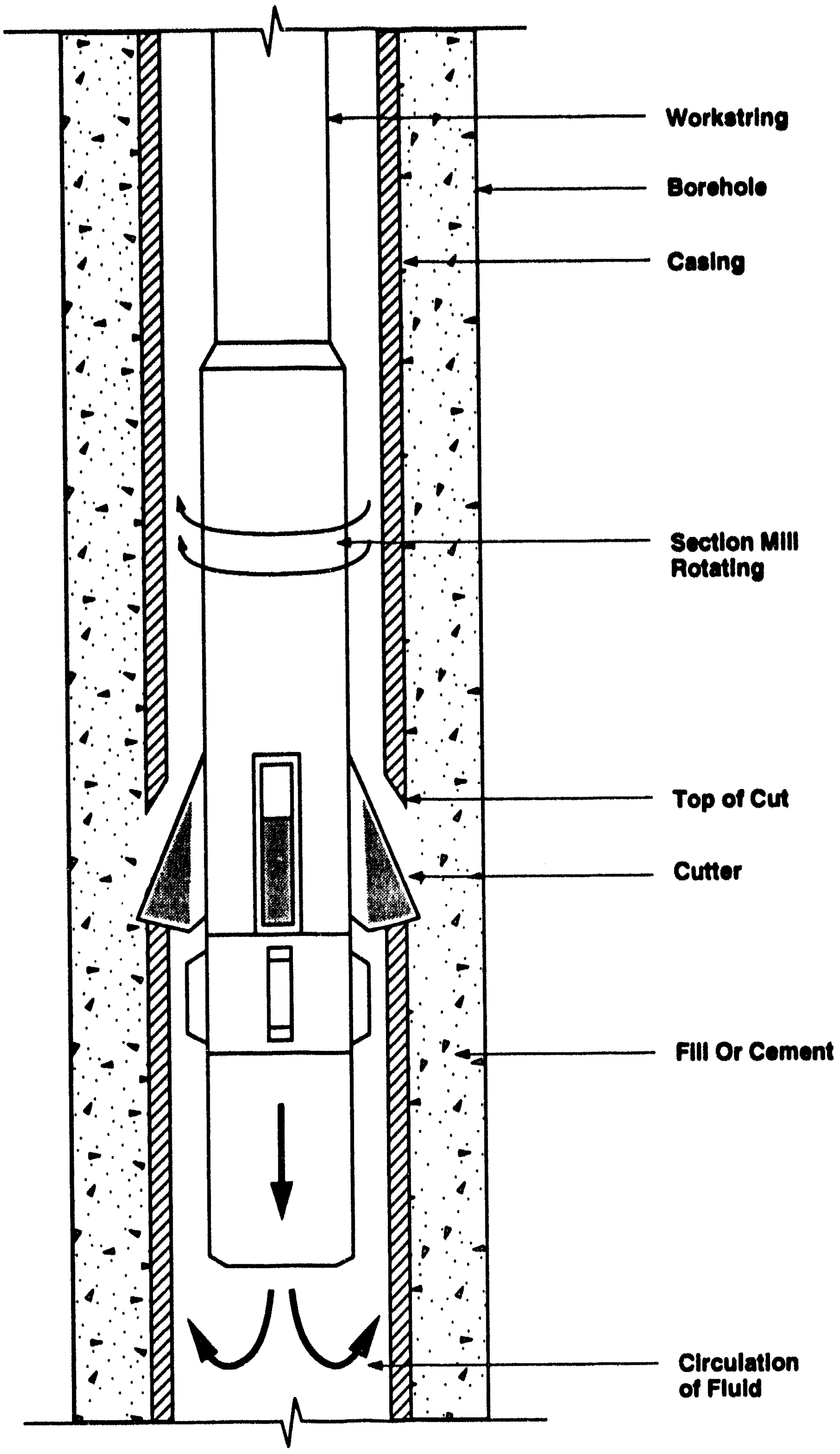


Figure 6-12
Section Milling

Geophysical logging may be employed to aid in the evaluation of casing removal but is not typically used in this function at this time, except in performing depth control. Some of these logging tools may include the use of cameras (for visual inspection), electromagnetic thickness, and mechanical caliper logs.

6.2.1.5 Removal of Existing Material from the Borehole

"Junk" or "fish" refers to material that cannot be readily removed from the borehole. Junk removal can be accomplished by using special tools. Alternately, milling the junk out may be the only available option as documented in the next section. Usually any junk removal occurs prior to removing casing. This minimizes exposure of the formations to any detrimental effects, such as those associated with fluid circulation and pipe rotation. There are many different types and sizes of equipment used in the drilling, completion, monitoring, testing, and remediation of wells in the oil and gas and industrial waste industries. The equipment to remove these tools if they are stuck or lost in a well is very similar to that used to remove casing (Table 6-3).

The previous discussion addressed methods common to casing removal; the following discussion addresses only those tools that are not common—the string-shot, overshots, box, and taper taps.

Ideally, a string-shot back-off is a pipe recovery method for unscrewing the fish at a particular connection, if it has any. Generally, it has an explosive initiator or fuse and a predetermined size and length of detonating cord. It operates by wireline, with a collar locator log for depth control, locating the connections, and locating the top of the fish. To make a string-shot back-off, the operator places the workstring in neutral weight (neither tension or compression), applies counter-clockwise torque to the fish via the workstring, and lowers the string-shot into the fish. The operation locates it at or just slightly above the desired connection and then detonates it. The explosion produces an effect similar to an intense hammer blow and enables the fish to be unscrewed at the connection. In foam- and air-filled wells, the operation uses a size of the string-shot equal to twice that used in liquid-filled ones.

The following factors must be known to aid in proper design of the string-shot back-off:

- Desired back-off depth
- Mud or fluid weight
- Well temperature.

The string-shot or workstring may be run through an internal diameter as small as 3/4 in.; it may also be run in the annulus to back-off the fish from the outside.

To impart torque to the fish, the workstring must be attached into or onto the fish. If a threaded male (pin) or female (box) end comprises the uppermost part of the fish and has threads that are

Table 6-3

Tools Typically Used in Removal of Fish

Indicate free/unstuck fish:			
	• Pipe recovery logs		
	• Pipe stretch calculations		
Washover the fish:			
	• Rotary shoes		
	• Washover pipe		
Free the fish:			
	• Workstring	- Inside cutter	- Mechanical - Hydraulic
		- Outside cutter	- Mechanical
	• Wireline	- Chemical[a] - Jet	
	• Back-off (unscrew)	- String-shot[a]	
Remove the fish:			
	• Retrieve	- Outside mechanical cutter - Overshots with grapples[a] - Box and taper taps[a]	
	• Mill out	- Junk mills	
Evaluate fish removal:			
	• Retrieval	- Length recovered - Geophysical logs (depth control)	
	• Mill out	- Pipe measurements - Wear markings	

[a] Not normally used in casing removal.

in good condition in the center of the borehole, then an opposite-end box or pin may be screwed onto the fish. This allows transmission of torque to the fish.

If the top threads of the fish do not allow proper screw-in of the workstring, a box tap may be used to swallow and screw onto the outside of the fish (Figure 6-13). A taper tap may be used to screw into the inside of the fish, but they usually have less coupling strength than a box tap and cannot guide themselves onto an uncentered fish. Box and taper taps are designed to pull on a stuck fish.

An overshot and grapple is a frictionally anchored assembly that may be used to swallow over and apply torque and/or pulling force to the fish (Figure 6-14). The small inner threads of the grapple are what anchor onto the fish. After the release of upward pull, usually with clockwise rotation, the tool releases from the fish. The bore of the overshot should be large enough to allow passage of a free point and string-shot instruments. This allows a partial recovery of the fish with a string-shot back-off attempt. The grapple must transmit counter-clockwise torque when set by upward strain (Petroleum Extension Service, 1971).

6.2.1.6 Material Milling

Material milling can occur in both cased and open holes. There are many mill types and sizes that may be required during the milling of junk. A concern regarding the milling of junk in an open hole is the possibility of sidetracking the borehole. Internal and external cutters and rotary shoes dressed with tungsten-carbide grade cutters comprise the cutting surfaces of most milling tools. The placement of the carbides on the milling tool promotes the most efficient metal, cement, or formation removal. In general, tungsten, titanium, tantalum, or some combination of carbides of tungsten in a matrix binder (usually cobalt) comprise these wear-resistant cutting materials.

The following criteria are critical to proper selection of a milling and/or casing recovery program:

1. Proper tool selection: Various size milling tools can meet almost any condition encountered. The type of tool, style of tool, application, dressed inside and outside diameters, connection size, and type should be specified. Data handbooks published by mill manufacturers, such as Servo or Drilco, provide guidance in the selection and specification of milling tools.

2. Proper drilling fluid selection: The operation requires a properly designed drilling fluid to provide for circulation of cuttings out of the hole and for control of mill temperature. A low-solid, clay-water-base mud is desirable. Rheological conditions, such as yield point and viscosity, should be specified to optimize cutting removal. When using foam, close attention should be given to the foam quality and cutting removal efficiency.

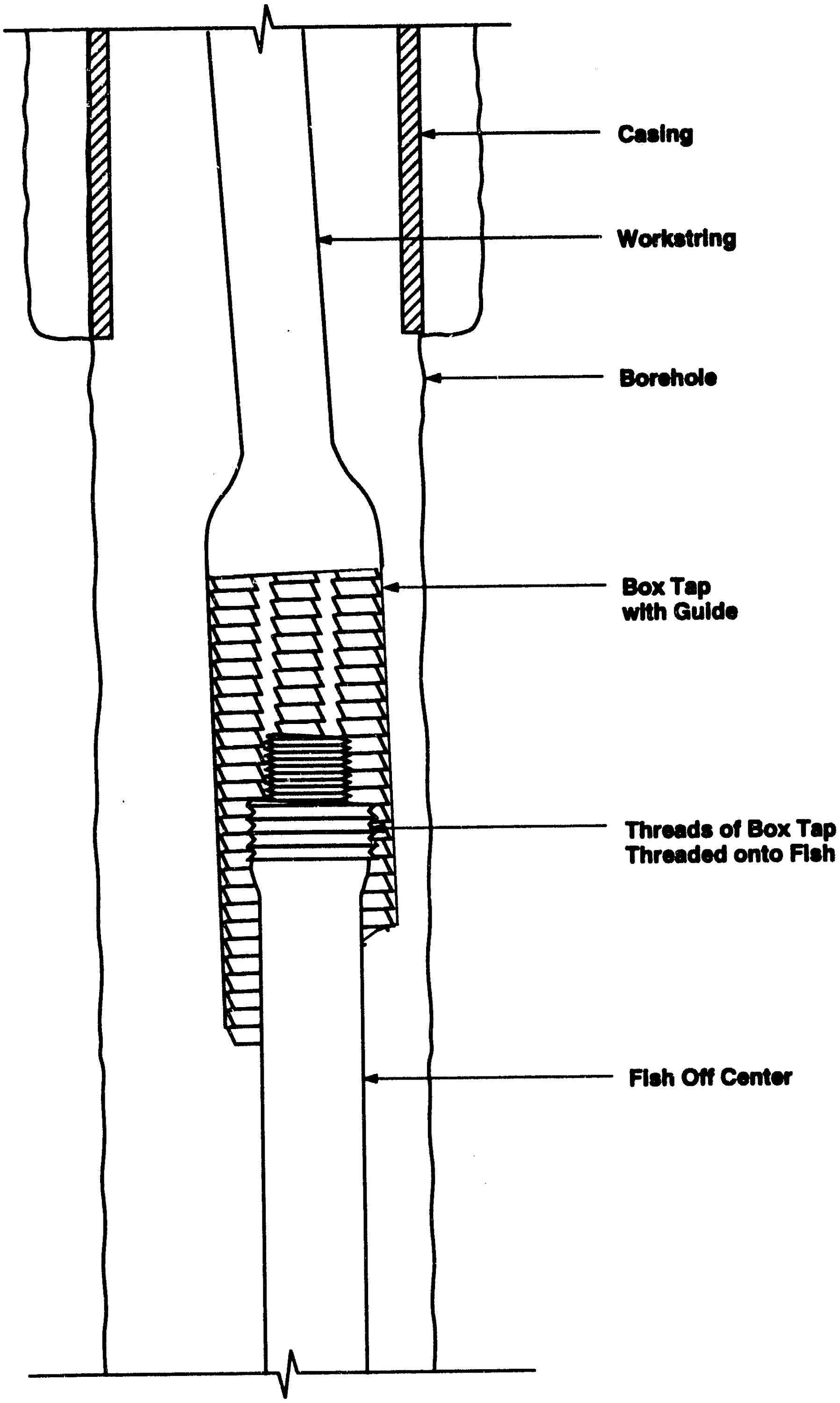


Figure 6-13
Box Tap Threaded Onto Fish

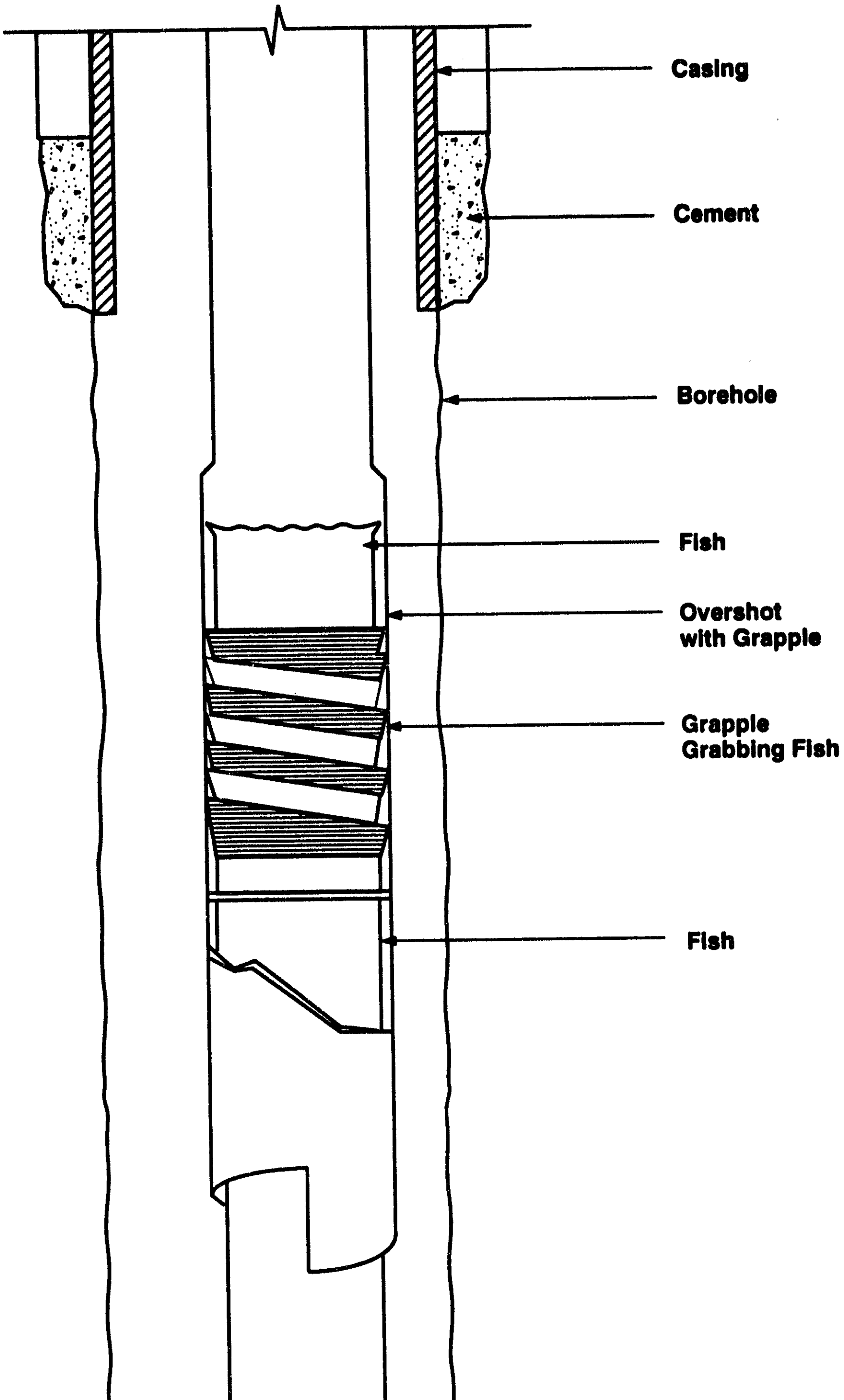


Figure 6-14
Overshot and Grapple on Fish

3. Hydraulics: A pump or pumps should provide circulation of the mud to maintain a minimum annular velocity of 110 ft/min. If washouts are a problem or this velocity is unattainable, the rheology of the fluid should be adjusted to compensate for reduced particle-lift capability at a reduced velocity.

4. Experienced supervision: General guidelines can be specified for getting the mill started and controlling cutting removal. Yet no substitute exists for competent operators and field supervision to maintain ideal cutting conditions and avoid problems as they are encountered in the field. Field control includes the following:

   - Maintenance of adequate fluid properties and circulation rate
   - Proper mill break-in operation (initial rotational speed and weight on mill)
   - Proper cuttings removal
   - Proper mill wear
   - Proper cutting size and length
   - Avoidance of downhole tools, such as jars or bumper subs, that would make the milling operation difficult to control
   - Proper stabilization of the drill string, if necessary, to avoid excessive mill wobble and wear
   - Optimization of rotational speed and weight on the mill to maximize milling rate.

5. Properly sized drill rig: A drill rig should be selected with sufficient pumps to achieve maximum required hydraulics and sufficient drawworks and hook load capacity to match the casing to be pulled.

6. Bottomhole and workstring assembly: A detailed casing removal plan will specify the special connection pieces necessary to link the cutting tools to properly designed workstring or washover string. Operations may require heavy-duty rotary-shouldered tool joints to withstand the torsional loading of milling operations. AOSC (1981) is one source of published data on workstring and washover pipe recommendations for drilling through various commonly sized casing strings.

6.2.2 Reconditioning of the Borehole Wall and Selection of the Area to Place the Seal

It is important to establish the condition of the borehole wall after removing the casing to determine if reconditioning of the borehole wall may be required in critical seal areas. Smith

(1990) recommends taking precautions for proper emplacement of cement during sealing of oil and gas wells, including the following:

- Placing cementitious seals in a gauged section of the hole for proper cement displacement
- Consulting caliper logs in selecting seal location and determining cement volumes
- Rotating the workstring using tail pipe with centralizers and borehole scratchers, while placing the cement
- Placing cementitious seals in a clean, hard formation
- Determining static borehole-fluid conditions prior to beginning plugging operations in fluid-filled boreholes.

6.2.2.1 Geophysical Logging

In the injection well and the oil and gas industries, acoustical or mechanical coupled geophysical logging can establish the condition of the borehole wall. Caliper logging tools and downhole cameras are versatile in functioning in different environments. Mechanical calipers are selected to match the size of the hole. Acoustical logging may also be used, although acoustical techniques require fluids and will not function in air or foam environments. Also, the size of the mechanical calipers limit the size of borehole that can be calipered. This limitation does not exist with downhole cameras that are used to evaluate the condition of the borehole and its wall.

For acoustical logging, the preferred mud-fluid system for openhole plug-back operations has a Marsh funnel viscosity of 45 to 80 seconds (s), a plastic viscosity of 12 to 20 centipoise (cp), a yield point of less than 5 lb/100 ft^2, and a water loss of less than 15 cm^3 (Smith, 1990). The mud density should be as uniform as possible within the mud system, such that the fluids within the well are static.

If either air or foam are used during plug-back cementing, there is no need to balance the fluid system. Still, the cement requires a base, either earthen or mechanical, to settle on and to provide support. The base prevents gravitational settling between the cement slurry and other well fluids. If the design uses a mechanical plug in the plugging process, a check should be made before running the plug, to insure that the hole will accept the maximum diameter of the tool. The operation normally uses wiper plugs to clean any residual cement from within the workstring, especially if the operation used foam or air during cementing. The wiper plug, just above the cement, may be displaced with mud, foam, or a compressed gas such as air.

6.2.2.2 Wall Reconditioning

The rotation of scratchers across the borehole wall, where the seal is to be emplaced, serves as a mechanical method for removing mud-wall cake (Figure 6-15). Removal of this wall cake permits exposure of the formation to the cement for improved hydraulic bonding at the interface. Scratchers are likely to dislodge formation and wall cake from the borehole walls. The debris

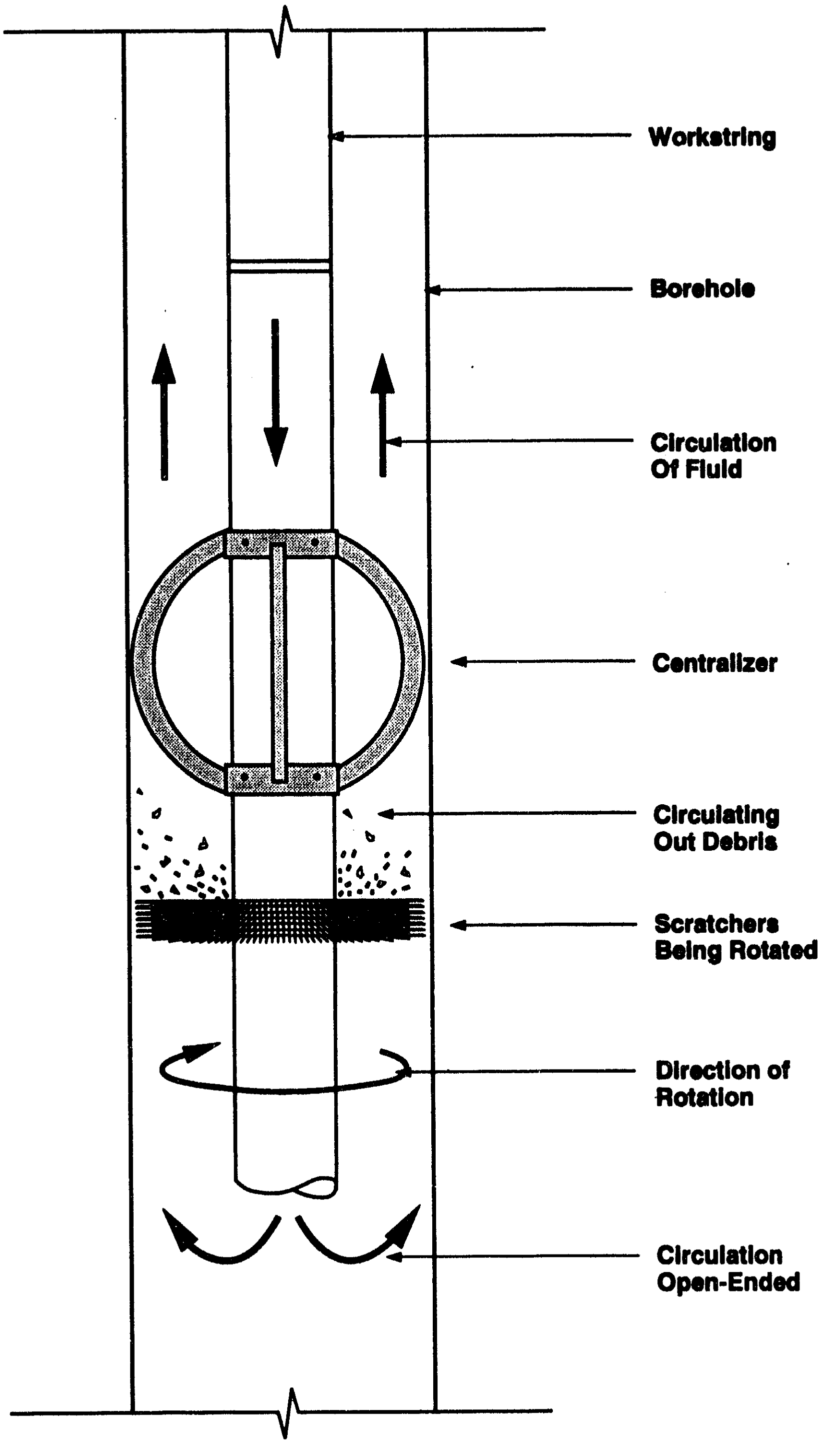


Figure 6-15
Removing Wall Cake With Scratchers

usually circulates above the cement-plug placement area with a viscous mud system during cementing operations. Removing this dislodged material prior to initiating sealing appears warranted when using air or foam in boreholes during cementing. Otherwise, when using air or foam in the well during cementing, debris may fall back down the wellbore when circulation has ceased. Intermixing of formation and/or wall cake with cement or seal material is likely to cause detrimental effects to the quality of the seal.

Removal of cement used during construction may be required to condition the borehole wall where cement designs were used to stabilize washout and/or caving of the boreholes. Underreamers can achieve cement removal from borehole walls (Figure 6-16). However, there are limitations on the maximum opening diameter to which a specific size and type of underreamer can physically be built.

Due to the unconsolidated and fractured nature of some formations at Yucca Mountain, caving and washouts were evident during drilling of the boreholes. By use of a highly viscous medium for cuttings removal, the circulating velocities may be reduced to minimize fluid turbulence, which contributes to washouts. This viscous medium would also aid, if not remedy, lost circulation problems experienced during drilling of these wells.

6.2.2.3 Location of Seals

As discussed previously, identification of an area across which to emplace cementitious material in abandonment operations is typically a function of zonal isolation requirements and formation characteristics. Where the design requires zonal isolation, Smith (1990) suggests a hard formation for maximum bonding. This plug should extend through an impermeable zone (confining zone) to isolate well fluids.

Reconditioning of boreholes that penetrate or that are close to the Yucca Mountain Mined Geologic Disposal System appears to be more feasible prior to potential repository construction. Reconditioning those boreholes that penetrate the Topopah Spring Member, where it is to be mined, would be logistically difficult after excavation, due to the need to move in and set up a rig and to circulate the borehole for conditioning. If there is no borehole survey data for accurate determination of the existing well trajectories, it would be beneficial to reenter and survey the wells. This would enable excavation of the shafts and potential repository with accurate knowledge of the borehole locations. If any fish or casing is currently located at the potential repository or shaft horizons, these hazards should be avoided during repository excavation by maintaining an adequate separation distance between the excavation and the fish.

6.2.2.4 Sealing Materials

Plugging and sealing of oil and gas and industrial waste wells usually have one or a combination of the following mechanical, cement, and drilling mud seals. The sealing materials referenced

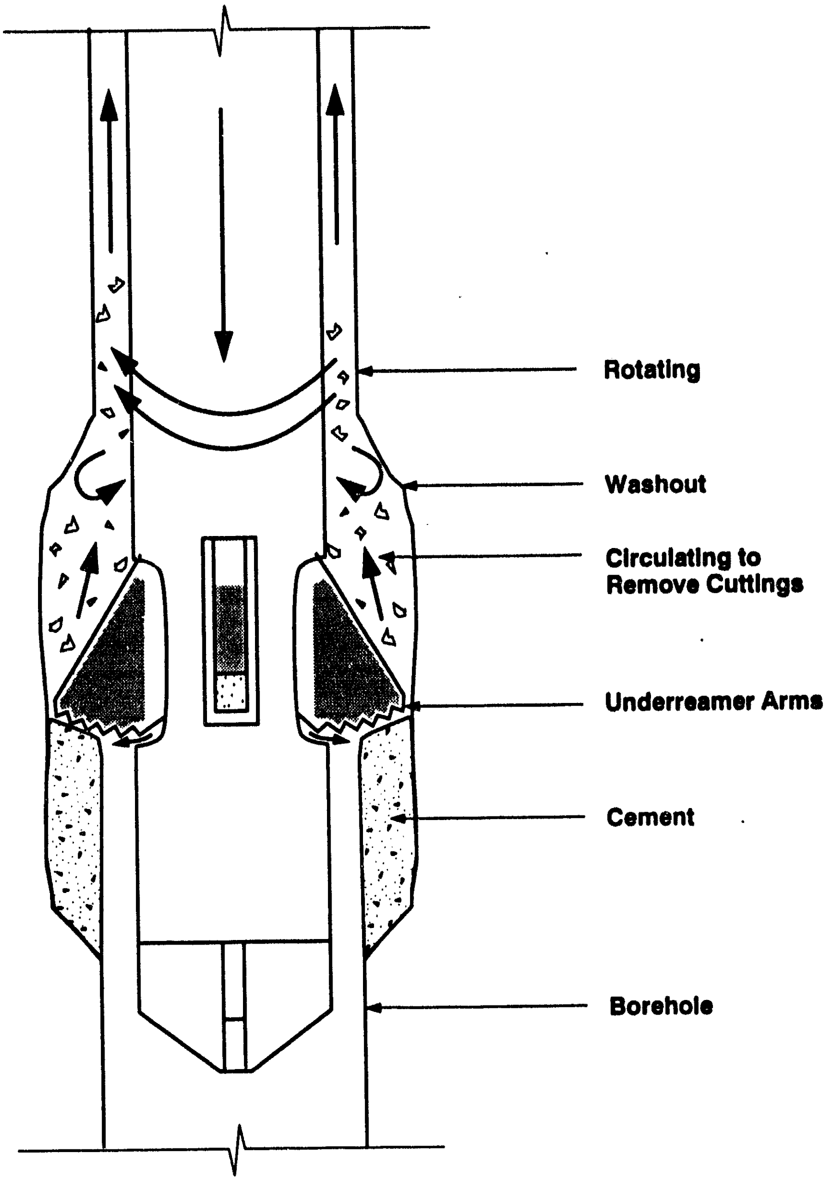


Figure 6-16
Underreaming a Borehole

in the applicable sealing regulations for water wells are bentonite, abandonment mud, drill cuttings, inorganic fill material, cement grout, concrete grout, and neat cement.

6.2.2.5 Earthen Materials

For relatively shallow groundwater geotechnical or environmental wells, designs use dry sodium bentonite for plugging. In these wells, powdered granular or pelletized bentonite is poured, blown, or pumped into the well or borehole from the surface. A technique for emplacement of compacted bentonite in deep vertical boreholes (as described in the literature of Roland Pusch [1983]) may have future application in sealing both saturated and unsaturated boreholes using a perforated tubing conveyance system. However, this chapter will address those materials and techniques in current industrial practice rather than those still in the developmental phase.

6.2.2.6 Mechanical Plugs

Mechanical plugs are normally set in cased holes, while open-hole plugs are generally made with cement. There are a few mechanical plugs that can be set in an open hole. These plugs can be used as a temporary support for a cement or other material plug or seal that would become self-supporting after a curing period. Mechanical plugs can be run and set hydraulically next to the wellbore tubing or drill pipe. Besides the type, wellbore dimensional considerations, and downhole temperature, the corrosive nature of the service environment may affect the elastomer and metallurgical requirements of mechanical plugs.

6.2.2.7 Sealing Materials Used in the Oil and Gas Industry

The oil and gas industry often uses cement plugs in the abandonment of oil and gas wells and industrial injection wells to prevent migration of formation fluids (natural and man-placed) that might infiltrate underground freshwater sources. The typical practice is to either completely fill the cased or uncased borehole with cements or to place discrete cement plugs across selected depth intervals with drilling mud left between the cement plugs. Appendix K presents a discussion of cementitious materials used in the oil and gas industry.

6.2.3 Placement of Seals

The five cementing emplacement methods available for plug-back cementing are the balanced plug, dump bailer, two-plug, and high- and low-pressure squeeze packer methods. Table 6-4 lists the advantages and disadvantages of each method. The following discusses the process and application of each method.

The balanced plug method, as depicted in Figure 6-17, involves pumping a desired quantity of cement slurry through pipe until the level of cement outside the pipe is equal to the level inside. This is the most common method for placing plugs in oil and gas wells filled with drilling mud (Suman and Ellis, 1977). The pipe is then pulled slowly from the slurry, leaving a plug in place. The physical and chemical properties of any fluid in the hole through which the slurry is

Table 6-4

Advantages and Disadvantages of Cement Emplacement Methods

Placement Method	Advantages	Disadvantages
Balanced Plug	Open or cased hole Permits establishing the top of the plug	Static well condition required Allows fluid/slurry intermixing Requires excess cement to compensate for contamination Need base for plug
Dump Bailer	Typically less expensive Open or cased hole Position of cement located easily	Small volume per bail Not readily adaptable to setting deep plugs May have to wait for cement set prior to subsequent bails May need to retard the cement Not applicable in severely traversed boreholes Static well conditions required Need base for plug
Two-Plug	Open or cased hole Separated fluid within work string Minimizes backflow Pressure indication of desired displacement Permits establishing the top of the plug	Static well condition required Need base for plug
High-Pressure Squeeze	May cement secondary zone(s) of permeability Solids-laden fluids ahead of cement do not have to be displaced	Uses more cement May breach confining zone May stick pipe during open-hole squeezing May require two blends of cement to achieve desired pressure More fluid lost to formation May not get full coverage in the borehole
Low-Pressure Squeeze	May cement secondary zone(s) of permeability May cement permeable formations Uses less cement than high-pressure squeeze Less likely to stick pipe during open-hole squeezing	Must use clean lead fluid Cement must allow for hesitation May not get full coverage in the borehole May stick pipe during open-hole squeezing

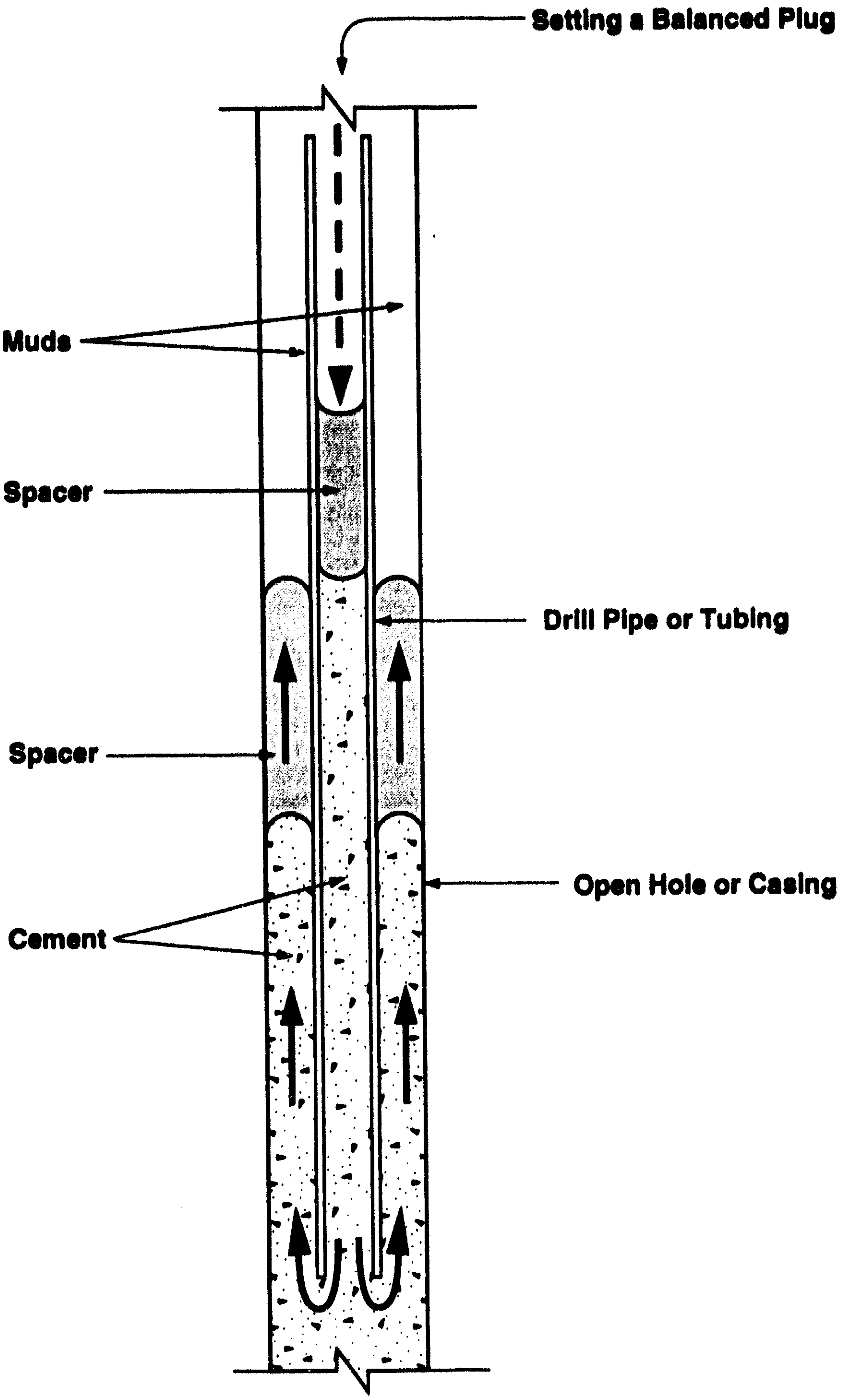


Figure 6-17
Balanced Plug Emplacement

emplaced and the displacement fluid are important in achieving a balanced set in which the cement does not move or "U-tube" before curing.

A dump bailer, as depicted in Figure 6-18, is a mechanical tool that contains a measured quantity of cement for lowering into a cased or uncased borehole on a wireline. A mechanical tool, such as a cased-hole or open-hole bridge plug, is placed below the desired plugging location. The bailer is raised after tagging the mechanical plug and then opened by detonating a charge that shatters a glass disk supporting the cement in the bailer. There is a limit to the volume (usually approximately 1 ft^3) that can be emplaced per each wireline run; however, it is not necessary for the initial cement to set before another batch may be dumped.

In the two-plug method, top and bottom plugs are run to isolate the cement slurry from any well or displacement fluids. A mechanical plug is usually set at the base of the cement plugging depth. A special baffle tool is run on the bottom of the tubing string and placed at the depth desired for the bottom of the cement plug. This tool permits the bottom plug to pass through and out of the tubing. Cement is then pumped out of the tubing string, at the plugging depth, and begins to fill the annulus between the tubing string and the borehole. The top tubing plug, following the cement, is caught by the plug-catcher tool, causing a sharp rise in the surface pressure, which indicates that the plug has landed. The latching device holds the top plug to help prevent the cement from backing up the string but permits reverse circulation. The string is then pulled, leaving the cement plug in place.

The two-plug method helps to reduce the possibility of over-displacing the cement or contaminated it with adjacent fluids. It is the preferred method with regard to the quality of the emplaced cement.

High-pressure squeeze cementing, as depicted in Figure 6-20, is a job in which the fluid pressure in the wellbore exceeds formation fracture pressure prior to or when the cement is in contact with the formation. Boreholes and formations may both be sealed with this technique, but it is not normally recommended for plugging operations at horizons deeper than 2,000 ft. If the goal is to isolate or stop flow behind pipe and/or cement, there may be no choice but to perform a high-pressure squeeze. However, with high-pressure squeezes, it is not possible to control either the location or orientation of the generated fracture. The fracture will be oriented perpendicular to the least principal stress and will not be created horizontally, if the fracture pressure is less than the overburden pressure (Hubbert and Willis, 1972). Fractures induced in formations deeper than 3,000 ft are usually vertical. Thus, vertical communication between the zones may be established in the fracture, and horizontal fractures containing cement "pancakes" may be generated by high-pressure squeeze cementing in some shallow wells.

After fracture creation, it must be sealed off with cement, although sealing off a fracture can be difficult. Fluid displaced into a fracture preceding cement is ideally a high-fluid-loss cement.

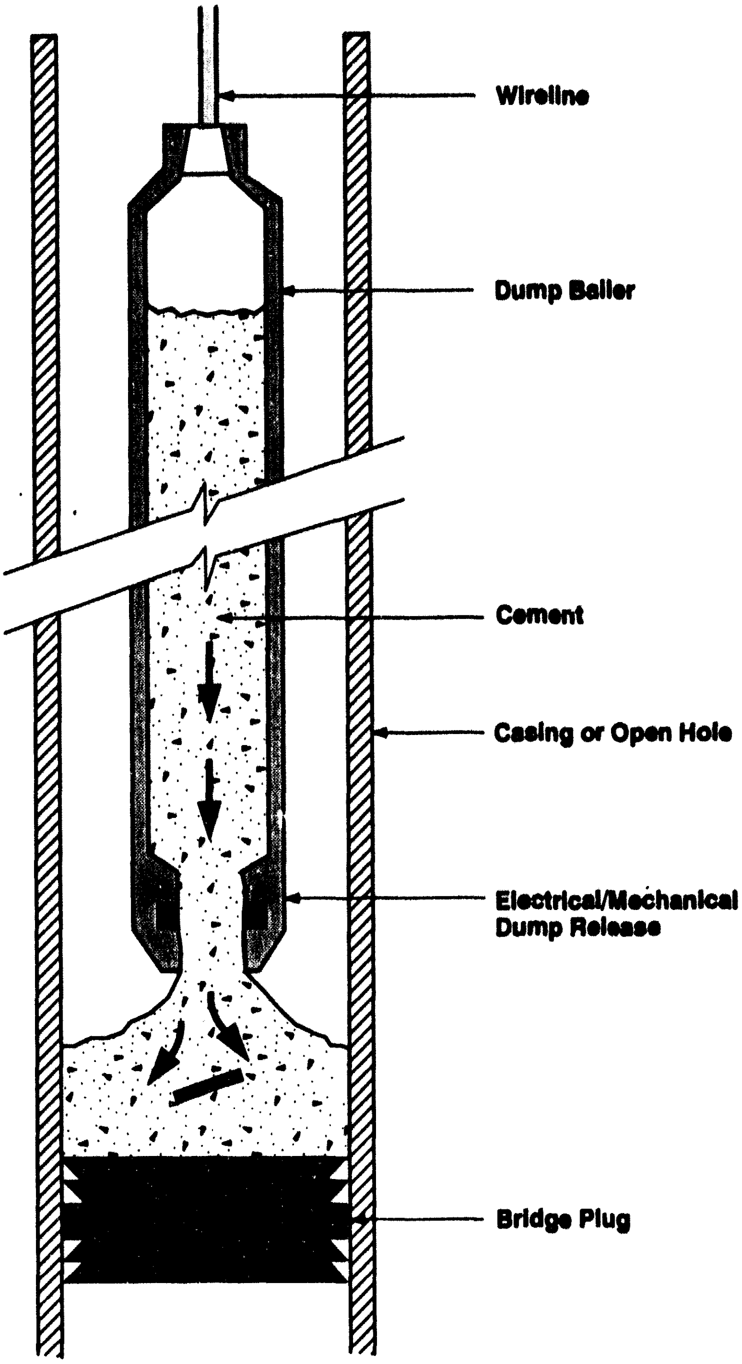


Figure 6-18
Dump Bailer Method of Plug Emplacement

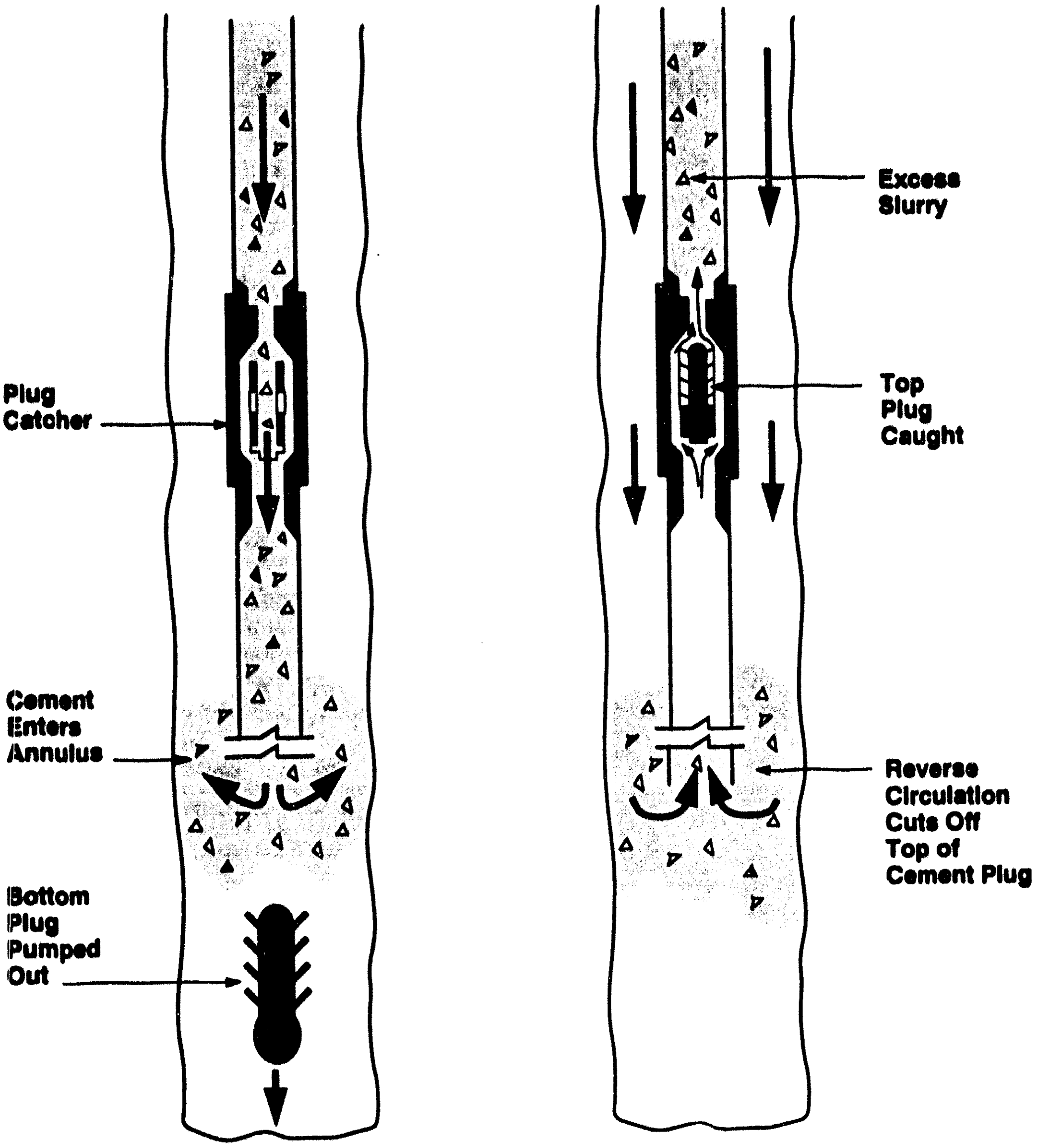
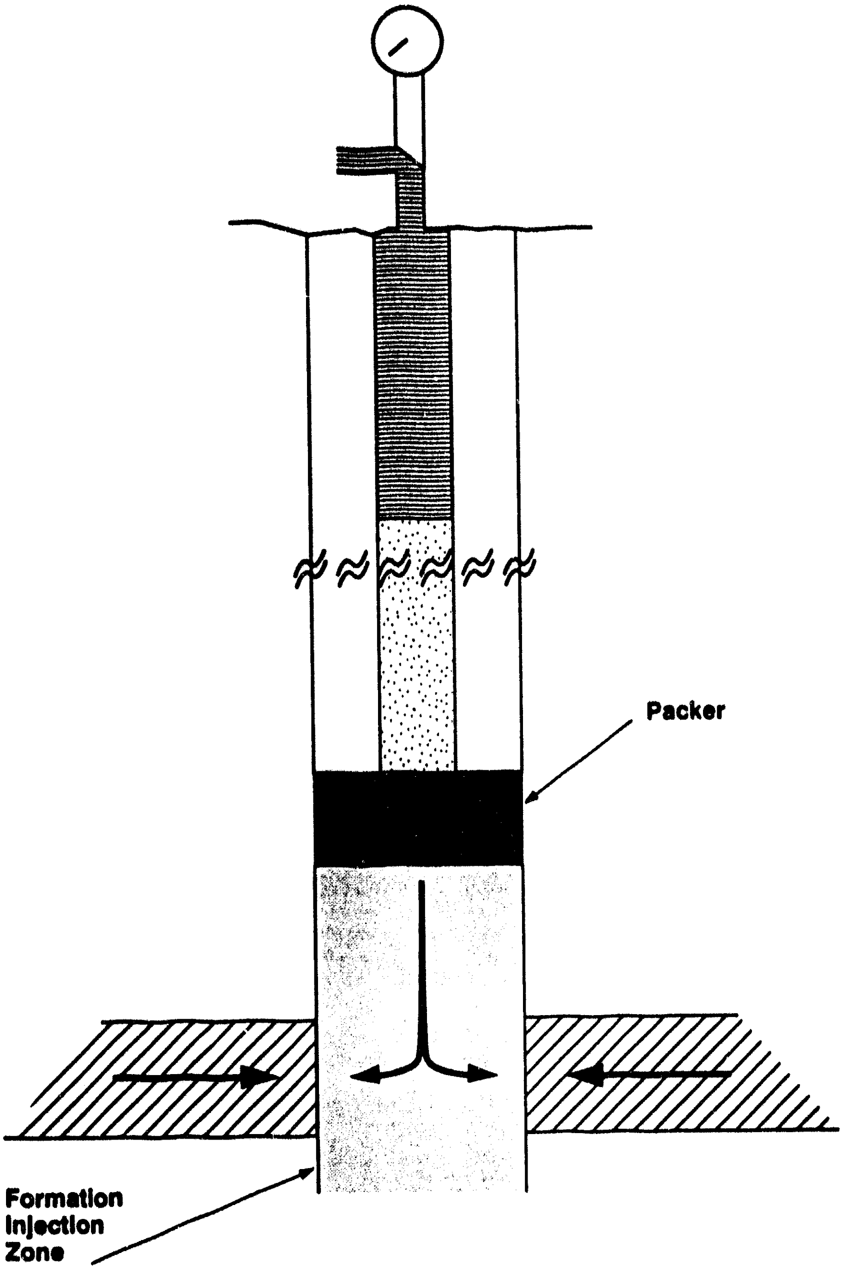


Figure 6-19
Two-Plug Method of Cement Plug Emplacement



Note: 1) Injection pressure is established from the surface pressure, the fluid column height and the formation fracture pressure

2) In a low-pressure squeeze, the fracture pressure is maintained below the formation pressure

Figure 6-20

Low- or High-Pressure Squeeze Conceptual Diagram

This material will reduce the potential for fracture extension during cement emplacement. The use of a high-fluid-loss, accelerated, or thixotropic cement helps reduce the amount of whole cement (not filtrate) lost to fractures by bridging at some point in or along the fracture.

Low-pressure squeeze cementing, as depicted in Figure 6-20, is a job in which the fluid pressure in the wellbore is maintained below the fracture pressure of exposed formations prior to and during the time the slurry is in contact with the formations. Low-pressure squeeze cementing uses a small volume of low-fluid-loss slurry placed against exposed permeable formations with a moderate squeeze pressure. It involves forcing the filtrate from the slurry into the formation permeability, which allows buildup of cement filter cake. Low fluid loss reduces the dehydration rate of the cement and discourages bridging as the slurry is forced along openings or channels. Low-pressure squeezing is more applicable in weak zones where no competent zone may be found. The low-pressure squeeze may be a solution to the problem of sealing the region of secondary permeability surrounding the discrete wellbore in artificial penetrations at the Yucca Mountain Mined Geologic Disposal Site. The zone known as the "disturbed area" occurred in all penetrations. Use of resin or plastic cement with low-pressure squeeze techniques may result in the squeezing of the resin phase into the secondary permeability surrounding the wellbore, which will form a seal within the formation. Low-pressure squeezing by itself or in combination with an expanding cement could be considered for application in areas where temperature elevation is small relative to the temperature elevation at the potential repository horizon.

In uncased holes, the low-pressure squeeze would be conducted between two mechanical plugs or between an upper mechanical plug and a lower material plug, such as cured cement. In either case, the mechanical plugs are likely to be left in the hole. The general procedure for setting a low-pressure squeeze plug in an open hole would be as follows:

1. Set lower mechanical plug or cement-type plug.

2. Set upper mechanical packer or squeeze tool, and initiate injection into zone to be squeezed. Find the downhole injection pressure.

3. Unset upper tool, and circulate cement slurry to desired location.

4. Set upper tool, and apply moderate squeeze pressure. Consider increased hydrostatic effect of cement column.

5. Restore squeeze pressure by engaging the pump as bleed-off occurs.

6. Gradually increase downhole pressure to predetermined squeeze pressure, usually a few hundred pounds above the pressure required to initiate flow (from Step 2).

7. Disengage from upper packer tool, and remove workstring from borehole.

The following precautions should be used in the planning and field placement of cement plugs (Herndon and Smith, 1978):

1. Conduct a caliper log of the borehole to determine accurately the cement volume and displacement requirements. This serves to identify the size mechanical plug required and where to set it.
2. Carefully calculate cement, water, and displacement volumes.
3. Use an excess volume of cement to accommodate for losses.
4. Application of weight is the usual manner of testing the quality of cement plugs to satisfy regulatory requirements in the oil and gas industry.
5. Select clean, hard formation for zone isolation intervals.
6. Conduct pilot test with the actual on-site cement blend, and mix water under simulated well conditions to determine actual thickening time.
7. Allow ample time for the plug to set before moving to next downhole operation.

When placing cement plugs across a selected interval of a borehole, a gauge section of the hole may be identified by using any of several types of caliper logs or even down-hole cameras in air-filled boreholes. Yet, mechanical caliper logs are the only caliper instruments known to function in air- or foam-filled boreholes.

Quality control measures that help to ensure the performance requirements of the emplaced seal may include the following:

- On-site laboratory testing facilities
- On-site calibration of mixing equipment
- Redundant testing of seal materials and additives
- Redundant measuring of blended materials
- Continuous sampling of blended materials throughout the emplacement operation.

On-site laboratory testing facilities allow better control of the quality of blending materials and methods of blending to meet the blend specifications. On-site testing could be available in time to take corrective action (Granberry et al., 1989). Table 6-5 illustrates the effect of mixing water on the performance of Class H cement. Table 6-6 presents the API acceptance requirements of Classes G and H cements.

Table 6-5

Effect of Mixing Water on the Performance of API Class H Cement[a]

Type of test: 6,000-ft API Casing Cementing Test
Curing time: 24 hr
Curing temperature: 95°F
Curing pressure: 5,000 psi

Type of Water	Thickening Time (hr:min)	Compressive Strength (psi)
Tap water	2:34	2,150
Tap water plus 2,200 ppm carbonates	1:18	2,300
Seawater	1:52	2,610

[a]From Smith, 1990.

Table 6-6

API Acceptance Requirements[a]

Cement Class	Maximum Consistency 15 to 30 Min Stirring Period (Cp)	Minimum Thickening Time 100 Cp (min)	Maximum Thickening Time 100 Cp (min)
G	30	90	120
H	30	90	120

[a]From Smith, 1990.

A service company normally performs calibration of the mixing equipment at their service shop; however, on-site calibration would ensure better performance of the blending operations. These operations employ redundant measuring devices during blending, such as flowmeters, volume calibrated tanks, densimeters, and pressurized mud-weight balances.

In-line sampling of the bulk and blended materials, both dry and liquid, are preferred over a thief-type sampler. Automatic or continuous sampling throughout the job will give a better representation of the sealing material quality (Smith, 1990).

The various types of cement mixers include jet, recirculating, and batch mixers. Normally, both the jet and recirculating mixers are a part of the pump unit, which usually has two positive-displacement pumps. These are either duplex double-acting piston pumps or single-acting triplex plunger pumps. A batch mixer is a separate piece of equipment from the pump unit. It is used when requiring a specified volume of cement but may be expanded with multiple mixing tanks. It enables precise slurry consistency and volume.

A jet mixer uses a funnel-shaped hopper and fluid stream to move the blended cement into a tank for pump suction. The volume of water forced through the jet determines the mixing speed and the amount of cement that may be fed through the hopper during mixing. A normal slurry mix rate is 50 ft^3/min for a jet mixer. A recirculating mixer has a jet mixer, tub, recirculating pump, and agitation paddles or jets to improve the uniformity of the cement slurry. Slurry densities of 22 lb/gal may be pumped as slow as 0.5 barrels/minute (bbl/min). Table 6-7 compares the slurry densities and mixing rates of jet and recirculating mixers.

Table 6-7
Range of Slurry Densities and Mixing Rates[a]

	Jet Mixer		Recirculating Mixer	
	Mix Rate (bbl/min)	Slurry Density (lb/gal)	Mix Rate (bbl/min)	Slurry Density (lb/gal)
Densified and weighted slurries	2–5	16–20	0–8	16–22
Neat slurries	2–8	15–17	0–10	14–18
High-water-ratio slurries	2–14	11–15	0–14	11–15

[a] From Smith, 1990.

7.0 Borehole Sealing Strategy Conclusions and Recommendations

This chapter presents the conclusions from this study and a strategy for sealing boreholes in terms of seal performance requirements. Inherent in this strategy are answers to the following concerns: where to seal, relative to the potential repository and geologic setting; how to seal, relative to selection of seal materials, geometry, and placement methods; and when to seal during the stages of potential repository operation. As discussed in Chapter 1.0, the strategy for sealing boreholes addresses performance requirements given in 10 CFR 60 and presented in Issue 1.12 and the availability of technologies to place borehole seals as discussed in Issue 4.4. Therefore, this strategy includes an evaluation of the performance of the sealing system. Because performance reliability is critical to the strategy, reducing the likelihood of failure and selecting measures to avoid deleterious events are important to the sealing strategy. Recommendations are made to the surface-based program to address issues identified in this report.

The strategy provides guidance for those acquiring site information from the surface-based program. This report is consistent with iterative performance assessment and ties design concepts with site-specific features. The concepts are flexible in that they may be modified if the assumptions made on the rock properties change as a result of site characterization efforts or as additional scenarios for seal failure are defined. In the sections that follow, results from performance and design evaluations are presented. Collectively, the conclusions reached from these results validate the borehole sealing strategy presented in Chapter 2.0.

7.1 Significance of Borehole Performance

The purpose in evaluating borehole significance is to determine those boreholes that could act as preferential pathways for radionuclide releases (both airborne and water pathways) and that could introduce water in the potential underground potential repository. The following scenarios were evaluated in Chapter 4.0:

- Air dispersion of radionuclides through fractured rock above the potential repository and into a borehole
- Convective air transport of radionuclides through rock above the potential repository and into a borehole
- Water transport of radionuclides from a flooded perimeter drift at the potential repository horizon through fractured rock beneath the potential repository into a borehole above the groundwater table
- Transport of water from a flooded borehole, within a potentially flooded area, to the potential repository horizon.

Results reached from the detailed evaluation of these scenarios are summarized below:

- Significant lateral dispersion of air above the potential repository, assuming the more conservative case of isotropic rock conditions, is limited to approximately 600 m from the edge of the potential repository (see Figure 4-7).

- Significant lateral dispersion of air above the potential repository, assuming the orientation and strike of the fracture system, is probably more restricted on the east and west sides of the potential repository than the north and south sides of the potential repository (see Figure 4-7).

- Considering convective air transport, Lu et al. (1991) showed that where the permeability of the nonwelded Paintbrush tuff was low relative to the welded tuff, lateral dispersion under the nonwelded unit was greater. It was also shown that radionuclides could also be released immediately to the west of where the bedded tuffs outcrop on the west side of Yucca Mountain.

- If the perimeter drift were fully saturated, water transport from the perimeter drift to the groundwater table is estimated at a maximum vector of 30 degrees from vertical.

- From calculations estimating the flood heights for the PMF, about 30 shallow and deep boreholes within or near the potential repository may be subject to flooding. Most of these boreholes are collared in alluvium. Of the boreholes subject to flooding, about 14 deep boreholes penetrate to below the Tiva Canyon Member. Three boreholes penetrate through the Tiva Canyon and the Paintbrush nonwelded tuff into the Topopah Spring Member. The remaining deeper holes (for example USW WT-2, USW G-4, USW H-4, and USW G-1) penetrate through the potential repository horizon. If these holes are not sealed, the deep boreholes are more significant in enhancing flow to the underground by 5 to 6 orders of magnitude.

These results confirm the following conclusions presented on the borehole sealing strategy in Chapter 2.0:

- Those boreholes within the potential repository and within an extended boundary are significant from an airborne release perspective. This extended boundary is defined as being 600 m from the edge of the potential repository.

- To restrict airborne flow above the potential repository, it is concluded that a high-quality seal should be placed in the Paintbrush nonwelded tuff into the upper portion of the Topopah Spring Member. For those boreholes that are immediately west of the outcropping of the bedded tuff on the western slope of Yucca Mountain, such as USW H-7 and USW WT-8, a high-quality seal should be placed in the upper portion of the Topopah Spring Member.

- Because the distance from the potential repository to the groundwater table ranges from about 200 m in the northeast to about 400 m in the southwest and because the water-flow direction, under fully saturated conditions, would be no greater than about 30 degrees from vertical, the maximum lateral dispersion of water under the potential repository is computed to be about 210 m.[1] Because this water-flow calculation considers a uniformly distributed fractured system and does not consider effects of stratigraphic contacts dipping to the east, it is concluded that any borehole 300 m from the edge of the potential repository and penetrating beneath potential repository horizon could be considered a preferential pathway for radionuclide release and should have a high-quality seal in the Calico Hills Unit above the groundwater table.

- Boreholes subjected to flooding, especially deep boreholes, should be backfilled or sealed to significantly reduce water infiltration into the underground potential repository.

7.2 Summary Conclusions of Where, When and How to Seal

This section presents summary conclusion regarding "where," "when," and "how" to seal. The analyses presented in Chapter 3.0 through 5.0 are discussed with regard to the strategy presented in Chapter 2.0.

7.2.1 Where to Seal

In selecting alternate depths above and below the potential repository and in analyzing current information characterizing boreholes, geologic setting, and anticipated conditions to be encountered following decommissioning of a potential repository, the two most significant issues addressed are the characteristics of the host formation and the anticipated in situ and thermal[2] stress environment at these prospective sealing locations.

In Chapter 2.0, sealing locations were determined by developing a borehole wall classification system and by considering the geologic setting for sealing. The classification identified four qualitative categories, from excellent (Category C1) to extremely poor (Category C4). Category C1 represented smooth boreholes, few lithophysae, and no fractures; Category C2 represented smooth surfaces, with small and consistent spacing of lithophysae and a few fractures; Category C3 represented poor rough surfaces, intermediate lithophysae, frequent fractures, and enlarged but usually symmetrical boreholes; and Category C4 represented the worst category, with rough and very irregular surfaces, large lithophysae, many fractures, and enlarged nonsymmetrical boreholes. Based upon these categories, the generalized hole conditions were found to be as follows:

---

[1] It is acknowledged that lateral spreading on contact zones could occur to the east due to contrasts in permeability between welded and nonwelded units. The degree of spreading depends on the infiltration rate recharging the perched water, the size of the perched water zone, and infiltration rate through the less permeable unit.

[2] If thermal loadings within the potential repository boundary change, the thermal stress environment at sealing locations may change with updated repository designs.

- A high percentage of Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and Topopah Spring Units.
- Category C1 occurs in the Paintbrush nonwelded tuff.
- Categories C1 and C2 occur in the upper portion of Topopah Spring Unit.
- Categories C1 and C2 occur in the nonwelded vitric and zeolitic portions of the Calico Hills Unit.

Key seals should be placed in the Paintbrush nonwelded tuffs, in the upper portion of the Topopah Spring Unit, and in the nonwelded vitric and zeolitic portions of the Calico Hills Unit. While borehole classifications show more favorable conditions in the nonwelded tuffs that are relatively free of fractures, the assessed rock-mass strength for nonwelded tuff is somewhat lower, due to the contrast in unconfined compressive strength between the welded and nonwelded tuffs (150 versus 15 MPa). Nevertheless, the varying conditions suggest that sealing locations with higher rock-mass quality in welded and nonwelded units can be selected that are not intensely fractured.

Other information presented on the in situ state stress, the development of thermal stress, and rock mass strength was presented in Chapters 2.0 and 3.0. Consideration of all information leads to the following conclusions:

- For deep boreholes, place seals in competent zones to eliminate the effects of surficial erosion. Shallow boreholes need not be sealed.
- Place seals in zones at the lower sealing location that are free of fractures or in zones having few fractures below the potential repository horizon. The results of the current borehole classification show that the bedded, nonwelded tuffs of the Calico Hills Unit below the potential repository horizon represent the best sealing locations. The stiffer units are more desirable from the standpoint of developing interface stress.
- For boreholes within the potential repository or just outside the potential repository perimeter that penetrate to the potential repository horizon, place seals at the upper contact zones in the Paintbrush, or alternatively, in the Topopah Spring Formation to restrict airflow to 1 percent of the total that would occur through the rock. It is conservatively assumed that the potential exists for perched water conditions at these borehole locations and that these seals at the upper contact zones would prevent saturation of seals below the potential repository horizon.
- Temperature effects are far more significant near the potential repository horizon and suggest seal emplacement away from the potential repository horizon.

- Place seals in the upper portion of the Topopah Spring Unit to the west of the potential repository, as the potential exists for convective airflow to break out at the ground surface in Solitario Canyon. In other directions from the potential repository, the results of the air-dispersion calculations suggest boreholes within a distance of 600 m may represent preferential pathways for the release of gaseous radionuclides.

7.2.2 When to Seal

In Chapter 5.0, a corrosion assessment for casing and a stress analyses of open boreholes were presented to address issues as to when seals should be emplaced. The casing-corrosion calculation provides information on how long the casing may be stable under heated conditions. A corrosion assessment was made to evaluate potential corrosion effects on borehole casing. No site-specific data are available for the corrosion of carbon-steel casing at the Yucca Mountain site; however, the following is known about general corrosion rates for carbon steel in air and soil.

- The penetration rate for carbon steel in air ranges from less than 1 to approximately 7 mil/yr (Mattsson, 1982). Higher corrosion rates occur in acidic atmospheres (not considered a factor at Yucca Mountain).

- The penetration rate for carbon steel in soils varies from 5 to 100 mil/yr, depending on resistivity that, in turn, depends on moisture content.

Considering casing configurations, deep casings, such as those used in UE-25a #1 grouting, occurred over short distances, and the casings were freestanding over much of their length. Shallow casings grouted to a depth of 100 to 200 ft, such as those used in UE-25a #5, could be subject to long-cell action. In deeper zones, the state of in situ stress is higher, and rock-mass strength is lower (i.e., the Calico Hills). In other areas, rock-mass quality is lower in more highly fractured tuff. The possibility exists for collapse of the borehole against the casing, exposing steel to the host formation. Here, the range of saturation is 46 to 84 percent for welded tuff and 46 to 76 percent for nonwelded tuff (DOE, 1992), suggesting long-cell action. The low conductivity of both welded and nonwelded tuff suggests that local-cell action would be insignificant. Corrosion might be higher in these areas because of the synergistic effects of contact with the host rock and stresses within the casing; however, these zones are expected to be isolated, reducing the potential for long-cell action, and the actual corrosion rates will probably be the same as those for carbon steel exposed to air and (possibly) a humid environment.

Reconditioning of the boreholes that penetrate or that are close to the Yucca Mountain Mined Geologic Disposal Site appear to be more feasible prior to potential repository construction. Reconditioning those boreholes that penetrate the Topopah Spring Member, where it is to be mined, would be logistically difficult after excavation, due to the need to move in and set up a rig and to recondition the borehole for conditioning. If there is no borehole survey data for determination of the well trajectories, it would be beneficial to reenter and survey the wells. This would enable excavation of the shafts and potential repository with accurate knowledge of the borehole locations. If any fish or casing currently locate at the potential repository or shaft horizons, these hazards should be avoided by maintaining an adequate separated distance of 15 m.

The Kirsch solution was used to evaluate stress concentration effects for open boreholes and boreholes penetrating near the roof, sidewall, and floor of a drift at the potential repository excavation. The proximity of these locations, combined with stress-concentration effects, suggest that the development of shear stress of 10 to 20 MPa under some confinement may occur and that the potential exists for localized rock-mass failure. Also, elevated temperatures at the lower seal location would occur due to the proximity of the potential repository horizon to this location. The upper seal location would be affected much less significantly.

In conclusion, seals should be emplaced prior to waste emplacement within the potential repository boundary for the following reasons:

- To prevent collapse of the casing, which would limit access to selected sealing locations
- To prevent accelerated corrosion of casing, due to collapse of the formation around the casing (which would result in higher corrosion rates than those for atmospheric corrosion) and due to potential synergistic effects between stress and corrosion.
- To avoid the potential development of high boundary stresses during potential repository heating in an open borehole after casing removal.

A separation distance of at least 15 m from the potential repository drifts should be maintained to eliminate stress-concentration effects.

7.2.3 How to Seal

In addressing the issue of "how to seal," two basic areas are considered: (1) recommended design requirements for borehole seals for air and water flow and (2) identification of sealing strategies that can be used to mitigate seal failure. Both are discussed below.

The regulations for borehole-seal performance (10 CFR 60.134) require that "boreholes shall be designed so that following closure they do not become pathways that compromise the geologic potential repository's ability to meet the performance objectives." The position adopted in a previous report on sealing (Fernandez et al., 1987) and in this report is that if vertical flow through all the boreholes is restricted to 1 percent of the total flow through the rock mass, this regulation is satisfied. The total area considered was the area within the extended boundary of the potential repository boundary (shown on Figure 4-7), which was determined through air dispersion calculations. Following the review of the air-dispersion calculations, about 116 existing and proposed boreholes were identified that would be subject to the airflow requirement. Of these holes, about 30 penetrate to the potential repository horizon. Two major results were derived from applying the 1 percent criterion for airflow:

- Borehole seals having a matrix conductivities of 10^{-1} cm/s or less, with an effective interface aperture of 500 microns or less, can satisfy the 1 percent criterion.
- The results for the three conductivity models presented in Chapter 3.0 show less significance by 5 to 6 orders of magnitude for surficial boreholes than for intermediate-depth boreholes penetrating the potential repository.

Therefore, it is concluded that the 30 boreholes penetrating through the potential repository horizon dominate airflow and require sealing to the air-flow performance requirements. The surficial boreholes do not require sealing to the performance requirements and can be simply backfilled.

A similar application was used to develop recommended performance requirements for borehole seals in the Calico Hills Unit. The results showed that a borehole seal having matrix conductivities below 10^{-3} cm/s and with an effective smooth-wall aperture of less than 100 microns satisfies the 1 percent criterion. It is recommended that this performance requirement apply to all boreholes within a boundary 300 m from the edge of the potential repository.

The second area that was considered was identification of sealing strategies that can be used to mitigate seal failure. Seals need to be emplaced at key locations using selected material placement methods and geometry to resist load and to provide strength serviceability. Seals need to resist various combinations of dead, seismic, and thermal loads. The list of potential degradation mechanisms (Table 5-1) includes those physical mechanisms that might affect hydrologic performance. The list includes channeling around the seal, mechanical degradation and deformation of the seal, modification of borehole fill properties, and chemical degradation. Associated with each failure mechanism are strategies to mitigate seal failure. All of these general strategies are recommended to be part of the overall sealing strategy.

In conclusion, seals need to be emplaced at key locations to reduce the potential for airflow occurring out of the potential repository or for water flow occurring either towards or away from the potential repository as follows:

- Cementitious materials should be selected with seal conductivities of 10^{-3} cm/s or less, with an effective interface aperture of 100 microns or less for seals below the potential repository.

- Cementitious materials should be selected with seal conductivities to 10^{-1} cm/s or less, with an effective interface aperture of 500 microns or less for seals above the potential repository.

Seals need to be emplaced at key locations to resist load and to provide strength, as the analyses in this report suggest a coupling of structural performance to hydrologic performance. These seals should be composed of cementitious materials and placed as follows:

- Seal locations, material properties, and placement methods should be selected that provide adequate strength and deformational serviceability for sealing components to resist various combinations of dead, seismic, and thermal loads. These include:
  - Dead loads from overlying seal materials
  - Thermal loads, due the hydration of the cement and radioactive waste generation
  - Differential volumetric expansion, due to placement methods, cement hydration, and differences in selected material properties
  - Liquefaction and consolidation of backfill, due to seismic events.
- Parametric studies using available data suggest in Appendix I that cementitious seals be placed under a slight pressure and with a low placement temperature. Saturation of the backfill could load the seal, and reduce effective stress. A cementitious seal with a tensile strength of 1 MPa and a compressive strength of 21 to 34 MPa (3,000 to 5,000 psi) is adequate for combined loads.
- A backfill should be placed between the rigid seals that has a specified porosity and grain-size distribution, which will provide a capillary barrier to unsaturated flow occurring downward or laterally at stratigraphic contacts.

7.3 Summary Conclusions Available Technologies to Seal Boreholes

One of the objectives of this report was to review the technologies available to place seals in boreholes. Chapter 6.0 included a review of tasks needed to place seals. These tasks are as follows:

- Removal of freestanding casing and borehole materials, if present
- Reconditioning of the borehole wall
- Selection of seal materials
- Emplacement of seals.

As discussed in Chapter 6.0, technologies are available to accomplish all of the tasks identified above. However, some difficulty may occur in removing materials in selected boreholes. In this regard, sealing concerns should be taken into account before drilling proposed boreholes. The following conclusions are included as part of the borehole sealing strategy:

- Maintain detailed construction documentation
- Select drilling methods, if possible, that will reduce wall-cake build-up
- Select drilling methods, if possible, that will result in better well condition
- Minimize risk of losing drilling tools and junk in the borehole, e.g., develop a protocol for tool inspection; make routine field inspections intermittent with downhole operations
- Utilize materials that are relatively easy to remove through fishing or milling
- Limit number of exploratory boreholes.

7.4 Risk Involved In Abandoning a Single Borehole

As part of the surface-based testing program, the DOE requires guidance as to the consequence and risk involved in abandoning boreholes without sealing. The following discusses the consequences of borehole abandonment on air and water flow. The calculations presented in Appendix H allow evaluation of a single borehole that is abandoned or left untreated. For purposes of evaluation, the existing USW UZ-6 borehole has the largest diameter at the potential repository horizon. Also, it should be considered that the effective hydraulic conductivity of the abandoned borehole equals 10 cm/s (equivalent to an air conductivity of 0.4 meters per minute). The conductance can be compared to the cumulative conductance for the three models. The relative significance of a single abandoned borehole depends on the model employed. For the low-conductivity model (Model 1), a single abandoned borehole provides a greater conductance than 100 combined together (or 30 boreholes penetrating through the potential repository horizon). For Model 2, the conductance of a single abandoned borehole represents about 10 percent of the total flow. For the most conductive model (Model 3), the flow through a single abandoned borehole is not significant, in that the design requirement expressed as a hydraulic conductivity for seals is of the order of 100 cm/s.

The above analysis does not include fault zones that may have a higher conductivity. If fault zones are persistently higher in conductivity, they may dominate convective airflow, and a single abandoned hole would have less significance. On the other hand, if the low-conductivity model is appropriate with a flow resistance dominantly occurring in low-conductivity formations, the abandoned borehole has added significance.

As noted previously in Section 4.1.2, the allowable amount of water that could contact the waste is unknown, and the manner in which water in the unsaturated zone under perched water conditions in a high temperature environment would enter the potential repository is not known. While no specific calculations are presented of the potential impacts on water flow, the abandonment of a single borehole might be expected under worst-case assumptions to have a similar impact. The project should recognize that the current understanding of the hydrologic source is not complete at this time and will be updated as site characterization information becomes available.

Based upon the preliminary calculations presented in the report, the project proceeds at risk in abandoning boreholes where access to sealing location cannot be assured.

7.5 Recommendations for the Surface Based Program

The evaluations and conclusions presented in this report provide guidance for the surface-based program. This guidance is provided in addressing sealing plans and answering questions regarding grouting, borehole access, borehole abandonment, and when these issues should be addressed. These issues are discussed in more detail below.

7.5.1 Maintain Casing

Borehole casing will be maintained for the majority of planned boreholes, although several boreholes have been proposed that require grouting of fractures and other material in sealing zones where casing has been removed. In these zones, it will be very difficult to reenter boreholes for purposes of seal emplacement, and current confidence is low that such an operation will be successful. Because of potential risks, it is recommended that casing be maintained in deep boreholes within the extended boundaries of the potential repository to provide continued access to borehole sealing locations. In all cases, sealing concerns should be taken into account *before* drilling proposed boreholes.

7.5.2 Fracture Grouting

Fracture grouting at the upper and lower sealing locations may be necessary to intercept fractures that might be subject to stress relief during drilling or alteration during potential repository heating. In such cases, no grout should be introduced at the upper and lower sealing locations during site characterization, since such grout may affect performance at the time of potential repository decommissioning and well abandonment.

7.5.3 Borehole Sealing Plans

Well abandonment procedures and plans exist and are used in water well, oil/gas well, and deep well injection to eliminate physical hazards, prevent groundwater contamination, conserve aquifer yield and hydrostatic head, and prevent intermixing of subsurface water. Many states regulate well abandonment. For example, NAC 445.4277 contains the State of Nevada's injection well plugging requirement, while NAC 534.420 contains the requirements for plugging water wells. The standards for closure of injection wells (40 CFR 146.71 [d] [1-7]) are performance-based, without clear methods or procedures to enact closure. For those wells that do not penetrate to the groundwater table, the State of Nevada (NAC 534.421.01(a)) allows backfilling of the well with soil cuttings drilled from the well or inorganic fill matter; yet, the top 50 ft must be filled with cement grout, concrete grout, or neat cement.

It is therefore recommended that a general sealing plan as outlined in detail by this report be developed for all exploratory boreholes as well as a detailed borehole-specific sealing plan.

The seal plans developed by the project should exist as controlled documents with design specifications and construction drawings and should consider general and specific problems encountered at specific sealing locations after detailed borehole inspection and in situ testing. Each borehole would be surveyed for accurate well trajectories. The emphasis in the plan would be to use a combination of mechanical calipers and video-logging during inspection to search for obstructions. Injection pressures may be determined by controlled hydrofracturing in zones near seal locations. In areas where pregrouting is necessary, grout design will be tailored to provide materials performance at specified grout-injection pressures, viscosity, and strength.

The project should establish administrative procedures for sealing exploratory boreholes. The surface-based site characterization manager, or his authorized designee, will complete a Well Borehole Sealing Request form to initiate activities. Before operations begin, he, or his designee, will complete an Exploratory Borehole Sealing Plan, documenting the specific construction information and special concerns, the types and amounts of fluids disposed during sealing, the appropriate seal design and construction methods, an estimate of the number and types of samples to be collected for quality assurance/quality control during seal emplacement, the required testing of the samples, in situ testing of seals to verify performance, and the proposed disposition of materials (casing, PVC, etc.) after emplacement.

The surface-based site characterization manager, or authorized designee, and the on-site geologist will complete as-built sealing diagrams during sealing. Before sealing operations begin, the surface-based site characterization manager, or authorized designee, and the on-site geologist will complete sealing and abandonment diagrams, locating the well, identifying the drilling subcontractor, and documenting as-built seals. Any changes from the sealing plan must be documented by a Field Change Request form transmitted to the design engineer, who will evaluate the field change request and authorize any changes by issuing a Design Change Notice that modifies the seal-design specifications and drawings. In this manner, all issues regarding field changes are resolved by both the design engineers and field operations personnel. The on-site geologist will complete a well plugging and abandonment progress report that includes descriptions of the daily activities performed during plugging and abandonment operations.

An important issue in the surface-based program is at what point should sealing plans be in place. The calculations presented in this report state that near the potential repository the potential exists for future deep boreholes to be affected by air dispersion or flooding. These boreholes should be evaluated prior to drilling to define specific seal design requirements. It is recommended that sealing plans be prepared for all proposed deep boreholes within the extended boundary of the potential repository prior to borehole drilling, and that work plans address issues with respect to well abandonment and borehole access, where confidence is low that access can be maintained. Further, no grouting should be introduced into sealing zones as part of the current surface-based program without addressing the risks associated with not complying with federal regulations. In this manner, work plan preparation will reflect an evaluation of the trade-offs in proceeding with the surface-based program relative to the risks of well abandonment prior to drilling and well completion.

8.0 References

NOTE: References listed here include references cited in Appendices A through K of this document.

Agapito, J. F. T., and Associates, 1990, "Documentation and Verification of the SHAFT Code," *SAND88-7065*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.911118.0082)

Amter, S., and B. Ross, 1990, "Simulation of Gas Flow Beneath Yucca Mountain, Nevada, with a Model Based on Fresh Water Head," *Proceedings of the Symposium on Waste Management*, Tucson, Arizona. (NNA.900918.0024)

American Petroleum Institute (API), 1979, *Specification for Oil-Well Cements and Cement Additives*, Specification 10A, 20th ed., Dallas, Texas. (NNA.940303.0047)

AOSC, see Association of Oil Well Servicing Contractors.

API, see American Petroleum Institute.

Association of Oil Well Servicing Contractors, 1981, *Manual of Basic Data for Oilwell Servicing Operations*, Dallas, Texas. (NNA.940203.0049)

Atkinson, A., J. A. Hearne, and C. F. Knights, 1987, "Aqueous Chemistry and Thermodynamic Modelling of $CaO-SiO_2-H_2O$ Gels," *AERE-R12548*, Harwell Laboratory, Oxfordshire, United Kingdom. (NNA.910123.0014)

Barton, N., R. Lien, and J. Lunde, 1974, "Engineering Classification of Rock Masses for the Design of Tunnel Support," *Rock Mechanics*, Vol. 6/4. (NNA.870406.0237)

Bauer, S. J., and J. F. Holland, 1987, "Analysis of In Situ Stress at Yucca Mountain," *Rock Mechanics: Proceedings of the 28th U. S. Symposium*, A. A. Balkema, Rotterdam, Netherlands. (NNA.891222.0029)

Bear, J., 1976, *Dynamics of Fluids in Porous Media*, American Elsevier, Inc., New York, New York. (NNA.911127.0046)

Bieniawski, Z. T., 1984, *Rock Mechanics Design in Mining and Tunneling*, A. A. Balkema, Rotterdam, Netherlands. (NNA.900614.0537)

Bentley, C. B., J. H. Robison, and R. W. Spengler, 1983, "Geohydraulic Data for Test Well USW H-5, Yucca Mountain Area, Nye County, Nevada," *USGS-OFR-83-853*, U.S. Geological Survey, Denver, Colorado. (NNA.870519.0098)

Bish, D. L., 1988, "Smectite Dehydration and Stability Applications to Radioactive Waste Isolation at Yucca Mountain, Nevada," *LA-11023-MS*, Los Alamos National Laboratory, Los Alamos, New Mexico. (NNA.920131.0214)

Bish, D. L., and D. T. Vaniman, 1985, "Mineralogic Summary of Yucca Mountain, Nevada" *LA-10543-MS*, Los Alamos National Laboratory, Los Alamos, New Mexico. (NNA.870407.0330)

Bish, D. L., D. T. Vaniman, F. M. Byers, Jr., and D. E. Broxton, 1982, "Summary of the Mineralogy-Petrology of Tuffs of Yucca Mountain and the Secondary-Phase Thermal Stability in Tuffs," *LA-9321-MS*, Los Alamos National Laboratory, Los Alamos, New Mexico. (NNA.870519.0040)

Brady, B. H. G., and E. T. Brown, 1985, *Rock Mechanics for Underground Mining*, George Allen & Unwin, London, England. (NNA.910327.0013)

Broxton, D. E., D. L. Bish, and R. G. Warren, 1987, "Distribution and Chemistry of Digenetic Mineral," *Clays and Clay Minerals*, Vol. 35, No. 2. (NNA.920319.0011)

Burkhard, N. R., J. R. Hearst, E. W. Peterson, R. H. Wilson, and K. H. Lie, 1989, "Containment of Cavity Gas in Fractured or Rubblized Emplacement Media," *UCRL-100953*, Lawrence Livermore National Laboratory, Livermore, California. (NNA.940303.0043)

Carnahan, B., H. A. Luther, and J. O. Wilkes, 1990, *Applied Numerical Methods*, John Wiley & Sons, New York, New York, Second Edition. (NNA.901005.0043)

Carr, M. D., S. J. Waddell, G. S. Vick, J. M. Stock, S. A. Monsen, A. G. Harris, B. W. Cork, and F. M. Byers, Jr., 1986, "Geology of Drill Hole UE-25p #1: A Test Hole into Pre-Tertiary Rocks Near Yucca Mountain, Southern Nevada," *USGS-OFR-86-175*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.2633)

Carsel, R. F., and R. S. Parrish, 1988, "Developing Joint Probability Distributions of Soil Water Retention Characteristics," *Water Resources Research*, Vol. 24, No. 5. (NNA.910128.0146)

Carter, L. G., Waggoner, H. F., George, C., 1966, "Expanding Cements for Primary Cementing," *Journal of Petroleum Technology*, Vol. 18. (NNA.940203.0050)

Case, J. B., 1985, *Program SHAFT.SEAL - A Program for Analysis of Stress and Temperature Changes in a Concrete Plug During Cement Hydration*, IT Corporation, Albuquerque, New Mexico. (NNA.940203.0051)

Case, J. B., and P. C. Kelsall, 1987, "Modification of Rock Mass Permeability in the Zone Surrounding a Shaft in Fractured, Welded Tuff," *SAND86-7001*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.891020.0181)

Craft, B. C., W. R. Holden, and E. D. Graves, 1962, *Well Design: Drilling and Production*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey. (NNA.940203.0052)

Craig, R. W., R. L. Reed, and R. W. Spengler, 1984, "Geohydrologic Data for Test Well USW H-6 Yucca Mountain Area, Nye County, Nevada," *USGS-OFR-84-856*, U.S. Geological Survey, Denver, Colorado. (NNA.870406.0058)

Crippen, J. R., and C. D. Bue, 1977, "Maximum Floodflows in the Conterminous United States," *Water-Supply Paper 1887*, U.S. Geological Survey, Washington, D.C. (HQS.880517.1748)

Daemen, J. J. K., J. C. Stormont, N. I. Colburn, D. L. South, S. A. Dischler, K. Fuenkajorn, W. B. Greer, G. S. Adisoma, D. E. Miles, B. Kousari, and J. Bertucca, 1983, "Rock Mass Sealing Experimental Assessment of Borehole Plug Performance," *NUREG/CR3483*, University of Arizona, Tucson, Arizona. (HQS.880517.3057)

Dane, J. H., and P. J. Wierenga, 1975, "Effect of Hysteresis on the Prediction of Infiltration, Redistribution, and Drainage of Water in a Layered Soil," *Journal of Hydrology*, Vol. 25. (NNA.910506.0134)

Darley, H. C. H., 1981, *Hole Stability*, seminar presented in Anchorage, Alaska. (NNA.940203.0053)

DOE, see U.S. Department of Energy.

Dowell, Inc., 1972, "Regulated Fill-Up Cement Controls Slurry Loss for More Predictable Fill-Up," *DWL-1443-5M-1272*, Dowell Division of Dow Chemical USA, Tulsa, Oklahoma. (NNA.940203.0054)

Dowell, Inc., 1973, "Expanding Cement for Superior Bonding of Pipe and Mud-Coated Formations in Oil Well Cement Systems," *DWL-1444-10M-373*, Dowell Division of Dow Chemical USA, Tulsa, Oklahoma. (NNA.940203.0055)

Driscoll, F. G., 1989, "Groundwater and Wells," Johnson Filtration Systems Inc., St. Paul, Minnesota. (NNA.900124.0032)

Endo, H. K., J. C. S. Long, C. R. Wilson, and P. A. Witherspoon, 1984, "A Model for Investigating Mechanical Transport in Fracture Networks," *Water Res. Research*, Vol. 20, No. 10. (NNA.940203.0007)

Evans, G. W., and Carter, L. G., 1962, "Bonding Studies of Cementing Compositions to Pipe and Formations," *API Drilling and Production Practice*, p. 72. (NNA.940303.0048)

Fenix & Scisson, 1987a, "NNWSI Drilling and Mining Summary," *DOE/NV/10322-24*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (NNA.890922.0283)

Fenix & Scisson, 1987b, "NNWSI Hole Histories Unsaturated Zone - Neutron Holes 76 Holes Drilled Between May 1984 and February 1986," *DOE/NV/10322-21*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (NNA.900208.0106)

Fenix & Scisson, 1987c, "NNWSI 51 Seismic Hole Histories," *DOE/NV/10322-25*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQX.890612.0055)

Fenix & Scisson, 1987d, "NNWSI Hole Histories, USW H-1, USW H-3, USW H-4, USW H-5, USW H-6," *DOE/NV/10322-18*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (NNA.871006.0069)

Fenix & Scisson, 1987e, "NNWSI Hole Histories, USW G-1, USW G-2, USW G-3, USW G-4, USW GA-1, USW GU-3," *DOE/NV/10322-19*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQS.880517.1194)

Fenix & Scisson, 1987f, "NNWSI Hole Histories, USW UZ-1, UE-25 UZ #4, UE-25 UZ #5, USW UZ-6, USW UZ-6s, USW UZ-7, USW UZ-8, USW UZ-13," *DOE/NV/10322-20*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (NNA.871006.0068)

Fenix & Scisson, 1986a, "NNWSI Hole Histories, UE-25 WT #3, UE-25 WT #4, UE-25 WT #5, UE-25 WT #6, UE-25 WT #12, UE-25 WT #13, UE-25 WT #14, UE-25 WT #15, UE-25 WT #16, UE-25 WT #17, UE-25 WT #18, USW WT-1, USW WT-2, USW WT-7, USW WT-10, USW WT-11," *DOE/NV/10322-10*, Fenix & Scisson, Inc., Tulsa Oklahoma. (NNA.870317.0155)

Fenix & Scisson, 1986b, "NNWSI Hole Histories, UE-25c #1, UE-25c #2, UE-25c #3," *DOE/NV/10322-14*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQS.880517.1201)

Fenix & Scisson, 1986c, "NNWSI Hole Histories, UE-25a #1, UE-25a #3, UE-25a #4, UE-25a #5, UE-25a #6, UE-25a #7," *DOE/NV/10322-9*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQS.880517.1199)

Fenix & Scisson, 1986d, "NNWSI Hole Histories, UE-25b #1," *DOE/NV/10322-13*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQS.880517.1200)

Fenix & Scisson, 1986e, "NNWSI Hole Histories, UE-29a #1, UE-29a #2," *DOE/NV/10322-12*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (HQS.880517.1198)

Fenix & Scisson, 1986f, "NNWSI Hole Histories, UE-25p #1," *DOE/NV/10322-16*, Fenix & Scisson, Inc., Tulsa, Oklahoma. (NNA.900326.0029)

Fernandez, J. A., J. B. Case, and J. R. Tyburski, 1993, "Initial Field Testing Definition of Subsurface Sealing and Backfilling Tests in Unsaturated Tuff," *SAND92-0960*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.930512.0001)

Fernandez, J. A., T. E. Hinkebein, and J. B. Case, 1989, "Selected Analyses to Evaluate the Effect of the Exploratory Shafts on Repository Performance at Yucca Mountain," *SAND85-0598*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.881202.0213)

Fernandez, J. A., P. C. Kelsall, J. B. Case, and D. Meyer, 1987, "Technical Basis for Performance Goals, Design Requirements, and Material Recommendations for the NNWSI Repository Sealing Program," *SAND84-1895*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.870717.0048)

Fox, K. F., Jr., R. W. Spengler, and W. B. Myers, 1990, "Geologic Framework and Cenozoic Evolution of Yucca Mountain Area, Nevada," *International Symposium on Unique Underground Structures*, Vol. 2, Colorado School of Mines, Golden, Colorado. (NNA.910301.0011)

Freeze, R. A., and J. A. Cherry, 1979, *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey. (NNA.870406.0444)

GAO—See U.S. Government Accounting Office.

Geraghty and Miller, Inc., 1982, *Injection Well Construction Practices and Technology*, Consultants' report prepared for U.S. Environmental Protection Agency, Office of Drinking Water, under Contract No. 68-01-5971. (NNA.940203.0056)

Ghislain de Marsily, 1986, *Quantitative Hydrogeology–Groundwater Hydrology for Engineers*, Academic Press, Inc., Orlando, Florida. (NNA.910207.0116)

Goodman, R. E., 1980, *Introduction to Rock Mechanics*, John Wiley and Sons, New York, New York. (NNA.910315.0132)

Granberry, V. L., W. H. Grant, and J. W. Clarke, 1989, "Mobile Laboratory Improves Oilfield Cementing Success," *Journal of Petroleum Technology.* (NNA.940301.0020)

Hardy, M., M. Bai, and R. R. Goodrich, 1992, *Temperature and Stress Environment at the Repository and Borehole Seal Locations*, J. F. T. Agapito and Associates, Grand Junction, Colorado. (NNA.940203.0057)

Herndon, J., and Smith D. K., 1978, "Setting Downhole Plugs: A State-of-the-Art," *Petroleum Engineer*, April 1978. (NNA.940203.0058)

Hillel, D., 1971, *Soil and Water: Physical Principles and Processes*, Academic Press, Inc., New York, New York. (NNA.900514.0069)

Hillel, D., 1982, *Introduction to Soil Physics*, Academic Press, New York, New York. (NNA.891108.0001)

Hinkebein, T. E., 1991, "Geochemical Considerations in Sealing," *U.S. Nuclear Waste Technical Review Board: Meeting of the Panel on Structural Geology and Geoengineering—Repository Sealing Program*, Federal Reporting Service, Inc., Aurora, Colorado. (NNA.940323.0012)

Hinkebein, T. E., and M. A. Gardiner, 1991, "Estimating Geochemical Behavior of Concretes to be Placed at Yucca Mountain," *SAND90-2150C*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.910724.0061)

Hinkebein, T. E., and J. A. Fernandez, 1989, "Initial Evaluation of Sealing Materials for the Yucca Mountain Project," presented at the 30th Annual Meeting of the Institute of Nuclear Materials Management, Northbrook, Illinois. (NNA.920819.0012)

Hoek, E., and E. T. Brown, 1980, *Underground Excavations in Rock*, Institution of Mining and Metallurgy, London, England. (NNA.891208.0052)

Hubbert, M. K., and D. G. Willis, 1972, "Mechanics of Hydraulic Fracturing," *Underground Waste Management and Environmental Applications*, American Association of Petroleum Geologists, Tulsa, Oklahoma. (NNA.870723.0004)

Javandel, I., C. Doughty, and C. F. Tsang, 1984, "Groundwater Transport: Handbook of Mathematical Models," *American Geophysical Union*, Washington, D.C. (NNA.940414.0122)

Langkopf, B. S., and P. R. Gnirk, 1986, "Rock-Mass Classification of Candidate Repository Units at Yucca Mountain, Nye County, Nevada," *SAND82-2034*, Sandia National Laboratories, Albuquerque, New Mexico. (HQS.880517.1662)

Licastro, P. H., J. A. Fernandez, and D. M. Roy, 1990, "Preliminary Laboratory Testing of Cementitious Material for the Yucca Mountain Project Repository Sealing Program," *SAND86-0558*, Sandia National Laboratory, Albuquerque, New Mexico. (NNA.900413.0037)

Lipman, S.C., 1987, "Geothermal Injection Wells," *International Symposium on Class V Injection Well Technology*, Underground Injection Practices Council, Inc., Washington, D.C. (NNA.940203.0059)

Lobmeyer, D. H., M. S. Whitfield, Jr., R. G. Lahoud, and L. Bruckheimer, 1983, "Geohydrologic Data for Test Well UE-25b #1, Nevada Test Site Nye County, Nevada," *USGS-OFR-83-855*, U.S. Geological Survey, Denver, Colorado. (NNA.890922.0285)

Lu, N., S. Amter, and B. Ross, 1991, "Effect of a Low-Permeability Layer on Calculated Gas Flow at Yucca Mountain," *Proceedings of the Second Annual International Conference on High Level Radioactive Waste Management*, Vol. 1, American Nuclear Society, La Grange Park, Illinois. (NNA.910819.0010)

MacDougall, H. R., L. W. Scully, and J. R. Tillerson, 1987, "Site Characterization Plan—Conceptual Design Report," *SAND84-2641*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.880902.0014–.0019)

Magcobar Company, 1977, *Drilling Fluid Engineering Manual*, Magcobar Division Oilfield Products Group, Dresser Industries, Houston, Texas. (NNA.940203.0060)

Maldonado, F. and S. L. Koether, 1983, "Stratigraphy, Structure, and Some Petrographic Features of Tertiary Volcanic Rocks at the USW G-2 Drill Hole, Yucca Mountain, Nye County, Nevada," *USGS-OFR-83-732*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.1329)

Mattsson, E., 1982, "The Atmospheric Corrosion Properties of Some Common Structural Metals—A Comparative Study," *Corrosion Source Book*, American Society for Metals, Metals Park, Ohio. (NNA.890919.0289)

Montazer, P., and W. E. Wilson, 1984, "Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada," *Water-Resources Investigations Report 84-4345*, U.S. Geological Survey, Denver, Colorado. (NNA.890327.0051)

Montgomery, P. C., and D. K. Smith, 1961, "Oil Well Cementing Practices and Materials," *The Petroleum Engineer*, May and June. (NNA.940203.0061)

National Research Council, 1985, *Safety of Dams, Flood and Earthquake Criteria*, National Academy Press, Washington, D.C. (NNA.910327.0001)

Nelson, P. H., and L A. Anderson, 1992, "Physical Properties of Ash Flow Tuff from Yucca Mountain, Nevada," in *Journal of Geophysical Research*, Vol. 97, No. B5. (NNA.920707.0061)

Ortiz, T. S., R. L. Williams, F. B. Nimick, B. C. Whittet, and D. L. South, 1985, "A Three-Dimensional Model of Reference Thermal/Mechanical and Hydrological Stratigraphy at Yucca Mountain, Southern Nevada," *SAND84-1076*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.890315.0013)

Ostroot, G. W., and J. Ramos, 1972, "Deep-Well Acid Disposal - Planning and Completion," *Underground Waste Management and Environmental Applications*, American Association of Petroleum Geologists, Tulsa, Oklahoma. (NNA.940303.0049)

Peterson, E. W., K. Lie, and R. H. Nilson, 1987, "Dispersion of Contaminant During Oscillatory Gas-Motions Driven by Atmospheric Pressure Variations," *Proceedings of the Fourth Symposium of Underground Nuclear Explosions*, U.S. Air Force Academy, Colorado Springs, Colorado. (NNA.940303.0050)

Petroleum Extension Service, 1971, "Lessons in Well Servicing and Workover," *Well Cleanout and Repair Methods*, University of Texas, Austin, Texas. (NNA.940203.0062)

Priest, S. D., and E. T. Brown, 1983, "Probabilistic Stability Analysis of Variable Rock Slopes," *Trans. Instn. Min. Metall. (Sect. A: Min. Industry)*, Vol. 92. (NNA.940303.0051)

Pusch, R., 1983, "Borehole Sealing for Underground Waste Storage," *Journal of Geotechnical Engineering*, Vol. 109, No. 1. (NNA.940323.0005)

Rautman, C. A., and A. L. Flint, 1992, "Deterministic Geologic Processes and Stochastic Modeling," *The Third International Conference on High-Level Radioactive Waste Management*, American Nuclear Society, La Grange Park, Illinois. (NNA.920505.0069)

Rogers, R. F., 1963, *Composition and Properties of Oil Well Drilling Fluids*, Gulf Publishing Company, Houston, Texas. (NNA.940301.0033)

Rush, F. E., W. Thordarson, and L. Bruckheimer, 1983, "Geohydrologic and Drill Hole Data for Test Well USW H-1, Adjacent to the Nevada Test Site, Nye County, Nevada," *USGS-OFR 83-141*, U.S. Geological Survey, Denver, Colorado. (NNA.870519.0103)

Schashl, E., and G. A. Marsh, 1963, "Some New Views on Soil Corrosion," *Corrosion Source Book*, American Society for Metals, Metals Park, Ohio. (NNA.940414.0124)

Scheetz, B. E., and D. M. Roy, 1989, "Preliminary Survey of Stability of Silica-Rich Cementitious Mortars 82-22 and 84-12 with Tuff," *LA11222-MS*, Los Alamos National Laboratory, Los Alamos, New Mexico. (NNA.891023.0022)

Scott, R. B., and J. Bonk, 1984, "Preliminary Geologic Map of Yucca Mountain, Nye County, Nevada with Geologic Sections," *USGS-OFR-84-494*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.1443)

Scott, R. B., and M. Costellanos, 1984, "Stratigraphic and Structural Relations of Volcanic Rocks in Drill Holes USW GU-3 and USW G-3, Yucca Mountain, Nye County, Nevada," *USGS-OFR-84-491*, U.S. Geological Survey, Denver, Colorado. (NNA.890804.0017)

Scott, R. B., R. W. Spengler, S. Diehl, A. R. Lappin, and M. P. Chornack, 1983, "Geologic Character of Tuffs in the Unsaturated Zone at Yucca Mountain, Southern Nevada," *Role of the Unsaturated Zone in Radioactive and Hazardous Waste Disposal*, Ann Arbor Science, Ann Arbor, Michigan. (NNA.870406.0034)

Shryock, S. H., and D. K. Smith, 1980, "Geothermal Cementing - The State-of-the-Art," *Technical Data Sheet C-1274*, Halliburton Services, Duncan, Oklahoma. (NNA.940303.0046)

Sinnock, S., Y. T. Lin, and J. P. Brannen, 1984, Preliminary Bounds on the Expected Post Closure Performance of the Yucca Mountain Repository Site, Southern Nevada, *SAND84-1492*, Sandia National Laboratories, Albuquerque, New Mexico. (NNA.870519.0076)

Smith, D. K., 1990, *Cementing*, Society of Petroleum Engineers of AIME, Dallas, Texas. (NNA.940203.0063)

Spengler, R. W., and J. G. Rosenbaum, 1980, "Preliminary Interpretations of Geologic Results Obtained From Boreholes UE-25a #4, #5, #6, and #7, Yucca Mountain, Nevada Test Site," *USGS-OFR-80-929*, U.S. Geological Survey, Denver, Colorado. (NNA.890823.0106)

Spengler, R. W., F. M. Byers, Jr., and J. B. Warner, 1981, "Stratigraphy and Structure of Volcanic Rocks in Drill Hole USW G-1, Yucca Mountain, Nye County, Nevada," *USGS-OFR-81-1349*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.1492)

Spengler, R. W., M. P. Chornack, D. C. Muller, and J. E. Kibler, 1984, "Stratigraphic and Structural Characteristics of Volcanic Rocks in Core Hole USW G-4, Yucca Mountain, Nye County, Nevada," *USGS-OFR-84-789*, U.S. Geological Survey, Denver, Colorado. (NNA.870519.0105)

Spengler, R. W., D. C. Muller, and R. B. Livermore, 1979, "Preliminary Report of the Geology and Geophysics of Drill Hole UW-25a #1, Yucca Mountain, Nevada Test Site," *USGS-OFR-79-1244*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.1491)

Squires and Young, 1984, "Flood Potential of Fortymile Wash and Its Principal Southwestern Tributaries, Nevada Test Site, Southern Nevada," *Water-Resources Investigations Report 83-4001*, U.S. Geological Survey, Carson City, Nevada. (NNA.890511.0110)

St. John, C. M., 1987, "Reference Thermal and Thermal/Mechanical Analyses of Drifts for Vertical and Horizontal Emplacement of Nuclear Waste in a Repository in Tuff," *SAND86-7005*, J.F.T. Agapito and Associates, Inc., Grand Junction, Colorado. (NNA.870622.0033)

Stephens, D. B., and S. P. Neuman, 1982, "Vadose Zone Permeability Tests: Summary," *Journal of the Hydraulics Division*, Vol 108, No. HY5, American Society of Civil Engineers, New York, New York. (HQS.880517.2348)

Suman, G. O., and R. C. Ellis, 1977, "Cementing Oil and Gas Wells," *World Oil*, Vol. 184. (NNA.940203.0070–.0071)

Thordarson, W., 1983, "Geohydrologic Data and Test Results from Well J-13, Nevada Test Site, Nye County, Nevada," *USGS Water-Resources Investigations Report 83-4171*, U.S. Geological Survey, Washington, D.C. (HQS.880517.1849)

Thordarson, W., F. E. Rush, R. W. Spengler, and S. J. Waddell, 1984, "Geohydrologic and Drill-Hole Data for Test Well USW H-3, Yucca Mountain, Nye County, Nevada," *USGS-OFR-84-149*, U.S. Geological Survey, Denver, Colorado. (NNA.870406.0056)

Trefethen, J. M., 1949, *Geology for Engineers*, D. Van Nostrand Company, Inc., Princeton, New Jersey. (NNA.910403.0046)

U.S. Department of Energy (DOE), 1988, "Site Characterization Plan: Yucca Mountain Site, Nevada Research and Development Area, Nevada," *DOE/RW-0199*, Office of Scientific and Technical Information, Oak Ridge, Tennessee. (HQO.881201.0002)

U.S. Department of Energy (DOE), 1991, "The Yucca Mountain Project Reference Information Base," *YMP/CC0002*, Version 4.0. (NNA.920131.0196)

U.S. Government Accounting Office (GAO), 1993, "Yucca Mountain Project Behind Schedule and Facing Major Scientific Uncertainties," *GAO/RCED-93-124*, U.S. General Accounting Office, Washington, D.C. (NNA.940203.0064)

Warner, D. L., and J. H. Lehr, 1977, "An Introduction to the Technology of Subsurface Wastewater Injection," *EPA-600/2-77-240*, U.S. Environmental Protection Agency, Ada, Oklahoma. (NNA.940414.0109)

Western Company, undated, *Cementing - Products, Applications, Procedures*, Western Company Cementing Research, Houston, Texas. (NNA.940203.0065)

Whitfield, M. S., Jr., W. Thordarson, and E. P. Eshom, 1984, "Geohydrologic and Drill-Hole Data for Test Well USW H-4, Yucca Mountain, Nye County, Nevada," *USGS-OFR-84-449*, U.S. Geological Survey, Denver, Colorado. (NNA.870407.0317)

Winograd, I. J., and W. Thordarson, 1975, Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, With Special Reference to the Nevada Test Site," *USGS Professional Paper 712-C*, U.S. Geological Survey, Washington, D.C. (NNA.870406.0201)

Wittwer, C. S., G. S. Bodvarsson, M. P. Chornack, A. L. Flint, L. E. Flint, B. D. Lewis, R. W. Spengler, and C. A. Rautman, 1992, "Design of a Three-Dimensional Site-Scale Model for the Unsaturated Zone," *The Third International Conference on High-Level Radioactive Waste Disposal*, American Nuclear Society, La Grange Park, Illinois. (NNA.930125.0071)

Wolery, T. J., 1983, "EQ3NR - A Computer Program for Geochemical Aqueous Speciation-Solubility Calculations: User's Manual and Documentation," *UCRL-53414*, Lawrence Livermore National Laboratory, Livermore, California. (HQS.880517.2912)

Wu, S. C., 1985, "Topographic Maps of Yucca Mountain, Nye County, Nevada," *USGS-OFR-85-620*, U.S. Geological Survey, Denver, Colorado. (HQS.880517.1929)

APPENDIX A

DETAILED INFORMATION ON BOREHOLE CONSTRUCTION AND LOCATIONS

Table A-1

Borehole Construction Information
Existing Boreholes within Potential Repository Boundary

	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
Borehole ID	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft³)	
UE-25 UZN #19	564571	763689	(6"@40')	40.0	(5.50"@40')	40.0	-	O-115 / Air
UE-25 UZN #20	564579	763760	(6"@41')	41.0	(5.50"@41')	41.0	-	O-115 / Air
UE-25 UZN #21	564591	763806	(6"@40')(3.94"@42')	42.0	(5.50"@40')	40.0	-	O-115 / Air
UE-25 UZN #22	564605	763880	(6"@94')(3.94"@95')	95.0	(5.50"@89')	89.0	-	O-115 / Air
UE-25 UZN #23	564545	763973	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
UE-25A #6	564502	765900	See Appendix B	500.0	See Appendix B	57.0	126	C / Bentonite Mud
USW G-4	563082	765807	See Appendix B	3,003.0	See Appendix B	2,017.0	63	C / Air Foam
USW H-4	563911	761644	See Appendix B	4,000.0	See Appendix B	1,839.0	1,061	C / Air Foam
USW H-5	558909	766634	See Appendix B	4,000.0	See Appendix B	2,585.0	1,368	C / Air Foam
USW UZ-6	558325	759731	See Appendix B	1,887.0	See Appendix B	324.0	189	RAV / Air
USW UZ-6S	558050	759909	See Appendix B	519.0	See Appendix B	3.0	-	O-165 / Air
USW UZ-7	562911	760836	See Appendix B	207.0	See Appendix B	20.0	-	O-115 / Air
USW UZ-8	562294	760762	(6"@55')(4.25"@57')	57.0	(5.50"@55')	55.0	-	O-115 / Air
USW UZ-N24	562054	768005	(6"@75')	75.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N25	561219	768430	(6"@59')	59.0	(5.50"@59')	59.0	-	O-115 / Air
USW UZ-N26	561023	768757	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N37	563714	766499		271.3			-	O-115 / Air
USW UZ-N38	563343	767466		94.3			-	O-115 / Air
USW UZ-N40	564221	766176	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N41	563521	765867	(6"@35')(4.25"@37')	37.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N42	562859	765729	(6"@35')(4.25"@40')	40.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N43	563264	765997	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW UZ-N44	563140	766193	(6"@35')(4.25"@36')	36.0	(5.50"@35')	35.0	-	O-115 / Air

Refer to footnote at end of table.

Table A-1 *(Continued)*

Borehole Construction Information Existing Boreholes within Potential Repository Boundary

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft³)	
USW UZ-N45	563429	765977	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW UZ-N48	562414	760835	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N49	562322	760860	(6"@35')(4.25"@36')	36.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N50	562912	760776	(6"@20')	20.0	(5.50"@20')	20.0	-	O-115 / Air
USW UZ-N51	562909	760861	(6"@20')	20.0	(5.50"@20')	20.0	-	O-115 / Air
USW UZ-N52	562909	760894	(6"@25')	25.0	(5.50"@25')	25.0	-	O-115 / Air
USW UZ-N64	559436	765729		60.0			-	O-115 / Air
USW UZ-N71	558406	761026	(6"@52')	52.0	(5.50"@52')	52.0	-	O-115 / Air
USW UZ-N72	558626	761068	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N73	558926	761049	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N74	558560	761362	(6"@35')(4.25"@37')	37.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N75	559076	761462	(6"@35')(4.25"@37')	37.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N76	559048	761353	(6"@40')	40.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N93	558321	759584	(6"@40')	40.0	(5.50"@40')	40.0	-	O-115 / Air
USW UZ-N94	558236	759724	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N95	558172	759899	(6"@20')	20.0	(5.50"@20')	20.0	-	O-115 / Air
USW UZ-N96	558403	759446	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N98	562084	767996	(6"@75')	75.0	(5.50"@31')	31.0	-	O-115 / Air
USW WT-2	561924	760661	See Appendix B	2,060.0	See Appendix B	58.0	101	C / Air Foam
Total Number 42			Total Footage	17,881				

[a] Drilling techniques include conventional rotary (C), ODEX 115 (O-115), ODEX 165 (O-165), and reverse air vacuum (RAV).

Refer to footnote at end of table.

Table A-2

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates East	Borehole Coordinates North	Borehole Size Diameter-Location (in.-ft.)	Total Depth (ft)	Casing Size Diameter-Location (in.-ft.)	Casing Depth (ft)	Grout Volume (ft^3)	Drilling Technique/ Circulating Media[a]
NRG-1	569890	765410		150.0				O-115 / Air
UE-25 RF #1	570890	762190	(9.88"@98') (8.75"@145')	145.0	(7.63"@99')	99.0	-	C / Air & Soap, Air Foam, and Air & Water
UE-25 RF #2	570335	758800	(8.75"@52')	52.0	(7.63"@29')	29.0	-	C / Air & Soap
UE-25 RF #3	571100	765575	(8.75"@141') (3.99"@151') (3.94"@301')	301.0	(8.25"@138')	138.0	-	C / Gel, Polymer & Water
UE-25 RF #3B	571066	765695	(6"@106') (3.94"@111')	111.0	(5.25"@106')	106.0	-	O-115 / Air
UE-25 RF #4	572063	762091	(9.88"@36') (6.75"@280') (3.90"@306')	306.0	Casing was Pulled	0.0	-	C / Gel, Polymer & Water
UE-25 RF #5	568098	759199	(9.88"@112') (3.94"@122')	122.0	(8.25"@112')	112.0	-	C / Gel, Polymer & Water
UE-25 RF #7	571171	768804	(9.88"@140') (3.94"@150')	150.0	(8.25"@100')	100.0	-	C / Gel, Polymer & Water
UE-25 RF #7A	570269	768768	(9.88"@150') (3.94"@153')	153.0	(8.25"@18')	18.0	-	C / Gel, Polymer & Water
UE-25 RF #8	568790	765631	(9.88"@90') (3.94"@128')	128.0	(8.25"@90')	90.0	-	C / Gel, Polymer & Water
UE-25 RF #9	570643	765945	(9.88"@106')	106.0	(6"@106') PVC Pipe Grouted	106.0	48	C / Gel, Polymer & Water

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
Borehole ID	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
UE-25 RF #10	570230	765308	(9.88"@60')	60.0	(6"@60') PVC Pipe Grouted	60.0	75	C / Mud
UE-25 RF #11	570435	765622	(9.88"@78')	78.0	(6"@78') PVC Pipe Grouted	78.0	50	C / Gel, Polymer Mud
UE-25 UZ #4	566139	768716	(6"@244') (4.25"@367.5')	367.5	(5.50"@60")	60.0	-	O-115 / Air
UE-25 UZ #5	566135	768591	(6.00"@365')	365.0	(5.50"@18')	18.0	-	O-115 / Air
UE-25 UZN #1	565224	769329	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air
UE-25 UZN #2	566114	768606	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air
UE-25 UZN #3	566119	768630	(6"@15')	15.0	(5.50"@15')	15.0	-	O-115 / Air
UE-25 UZN #4	566127	768663	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
UE-25 UZN #5	566134	768689	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air
UE-25 UZN #6	566137	768706	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
UE-25 UZN #7	566141	768724	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
UE-25 UZN #8	566147	768743	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
UE-25 UZN #9	566156	768782	(6"@40')	40.0	(5.50"@40')	40.0	-	O-115 / Air
UE-25 UZN #10	564744	769869	(6"@94') (4.25"@99')	99.0	(5.50"@94')	94.0	-	O-115 / Air
UE-25 UZN #12	566695	768651	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air
UE-25 UZN #13	568255	768025	(6"@65')	65.0	(5.50"@65')	65.0	-	O-115 / Air
UE-25 UZN #14	568233	767967	(6"@55')	55.0	(5.50"@55')	55.0	-	O-115 / Air

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
Borehole ID	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
UE-25 UZN #16	559626	778151		60.0		55.0	-	O-115 / Air
UE-25 UZN #18	565247	766472	(6"@61')	61.0	(5.50"@61')	61.0	-	O-115 / Air
UE-25 UZN #28	565320	763091	(6"@25') (4"@26')	26.0	(5.50"@25')	25.0	-	O-115 / Air
UE-25 UZN #29	565173	762613	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
UE-25 UZN #30	565233	762048	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
UE-25 UZN #56	565480	760394	(6"@60')	60.0	(5.50"@60')	60.0	-	O-115 / Air
UE-25 UZN #60	566567	759757	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
UE-25 UZN #97	565321	763094	(6"@60')	60.0	(5.50"@60')	60.0	-	O-115 / Air
UE-25 UZNC #1	566159	764671		5.0				
UE-25 UZNC #2	566158	764668		5.0				
UE-25 WT #4	568040	768512	See Appendix B	1,580.0	See Appendix B	48.0	28	C / Air Foam
UE-25 WT #5	574250	761826	See Appendix B	1,330.0	See Appendix B	40.0	162	C / Air Foam
UE-25 WT #13	578757	756715	See Appendix B	1,160.0	See Appendix B	222.0	386	C / Air Foam
UE-25 WT #14	575210	761651	See Appendix B	1,310.0	See Appendix B	120.0	378	C / Air Foam
UE-25 WT #15	579806	766117	See Appendix B	1,360.0	See Appendix B	127.0	430	C / Air Foam
UE-25 WT #17	566212	748420	See Appendix B	1,453.0	See Appendix B	55.0	75	C / Air Foam
UE-25 WT #18	564855	771167	See Appendix B	2,043.0	See Appendix B	86.0	108	C / Air Foam
UE-25A #1	566350	764900	See Appendix B	2,501.0	See Appendix B	2,450.0	50	C / Mud

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
UE-25A #4	564472	767972	See Appendix B	500.0	See Appendix B	119.0	108	C / Air Foam - Bentonite
UE-25A #5	564755	766956	See Appendix B	487.0	See Appendix B	120.0	75	C / Revert Mud - Bentonite Mud
UE-25A #7	565469	766250	See Appendix B	1,002.0	See Appendix B	134.0	90	C / Air Foam, Bentonite Mud
UE-25B #1	566416	765243	See Appendix B	4,002.0	See Appendix B	1,700.0	1,035	C / Air Foam
UE-25C #1	569680	757096	See Appendix B	3,000.0	See Appendix B	1,365.0	1,312	C / Air Foam
UE-25C #2	569634	756849	See Appendix B	3,000.0	See Appendix B	1,365.0	1,153	C / Air Foam
UE-25C #3	569555	756910	See Appendix B	3,000.0	See Appendix B	1,323.0	1,396	C / Air Foam
UE-25P #1	571485	756171	See Appendix B	5,923.0	See Appendix B	4,256.0	3,176	C / Air Foam, and Water, Polymer
USW G-1	561000	770500	See Appendix B	6,000.0	See Appendix B	1,016.0	350	C / Bentonite, Air Foam, Polymer
USW G-2	560504	778824	See Appendix B	6,006.0	See Appendix B	795.0	470	C / Polymer - Air Foam
USW G-3	558483	752780	See Appendix B	5,031.0	See Appendix B	2,598.0	190	C / Air Foam - Polymer Mud
USW GA-1	559247	779365	See Appendix B	551.0	See Appendix B	148.0	2	C / Polymer Mud-Water-Polymer
USW GU-3	558501	752690	See Appendix B	2,644.0	See Appendix B	1,144.0	45	C / Polymer-Mud- Bentonite Mud
USW H-1	562388	770254	See Appendix B	6,000.0	See Appendix B	2,255.0	1,186	C / Air Foam

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
USW H-3	558452	756542	See Appendix B	4,000.0	See Appendix B	2,600.0	829	C / Air Foam
USW H-6	554075	763299	See Appendix B	4,002.0	See Appendix B	1,906.0	1,415	C / Air Foam
USW UZ-1	560221	771276	See Appendix B	1,270.0	See Appendix B	39.5	432	RAV / Air
USW UZ-13	558489	751953	(6"@410') (3.94"@430')	430.0	(5"@330')	330.0	-	O-115 / Air
USW UZ-16	564857	760535		1,663.0				RAV / Air
USW UZ-N11	559021	780574		84.4			-	O-115 / Air
USW UZ-N15	559552	778091		59.9			-	O-115 / Air
USW UZ-N17	559995	778224		59.9			-	O-115 / Air
USW UZ-N27	558872	771570		202.4			-	O-115 / Air
USW UZ-N33	562100	770000		75.0			-	O-115 / Air
USW UZ-N34	562100	770200		84.1			-	O-115 / Air
USW UZ-N36	563583	773900		59.8			-	O-115 / Air
USW UZ-N46	559748	772262	(6"@99')	99.0	(5.50"@99')	99.0	-	O-115 / Air
USW UZ-N47	559784	771968	(6"@85') (4.25"@86')	86.0	(5.50"@85')	85.0	-	O-115 / Air
USW UZ-N53	564237	760096		234.5			-	O-115 / Air
USW UZ-N54	564262	760272		244.7			-	O-115 / Air
USW UZ-N55	564248	760503		255.3			-	O-115 / Air
USW UZ-N65	562537	758627	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
USW UZ-N66	561881	758434	(6"@50')	50.0	(5.50"@50')	50.0	-	O-115 / Air
USW UZ-N67	563799	753634	(6"@25')	25.0	(5.50"@25')	25.0	-	O-115 / Air
USW UZ-N68	564006	753962	(6"@55')	55.0	(5.50"@55')	55.0	-	O-115 / Air
USW UZ-N69	564402	754461	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N70	560165	769251	(6"@35')	35.0	(5.50"@35')	35.0	-	O-115 / Air
USW UZ-N77	554397	755526	(6"@50')	50.0	(5.50"@50')	30.0	-	O-115 / Air
USW UZ-N78	556262	757558	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N79	556334	757733	(6"@32')	32.0	(5.50"@32')	32.0	-	O-115 / Air
USW UZ-N80	557201	757634	(6"@52')	52.0	(5.50"@52')	52.0	-	O-115 / Air
USW UZ-N81	555595	757807	(6"@70')	70.0	(5.50"@70')	70.0	-	O-115 / Air
USW UZ-N82	554690	757498	(6"@40')	40.0	(5.50"@40')	40.0	-	O-115 / Air
USW UZ-N83	556349	760624	(6"@70')	70.0	(5.50"@70')	70.0	-	O-115 / Air
USW UZ-N84	555888	760717	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW UZ-N86	556460	760615	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N87	555887	760714	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW UZ-N88	556551	760797	(6"@30')	30.0	(5.50"@30')	30.0	-	O-115 / Air
USW UZ-N89	555589	760610	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW UZ-N90	555587	760608	(6"@45')	45.0	(5.50"@45')	45.0	-	O-115 / Air
USW WT-1	563739	753941	See Appendix B	1,689.0	See Appendix B	32.5	189	C / Air Foam

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
USW WT-7	553891	755570	See Appendix B	1,610.0	See Appendix B	52.0	162	C / Air Foam
USW WT-10	553302	748771	See Appendix B	1,413.0	See Appendix B	114.0	378	C / Air Foam
US-25 #1	565424	762631	(8.75"@53')	53.0	(5.50"@50')	50.0	-	C / Polymer[b]
US-25 #2	566427	762403	(8.75"@53')	53.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #3	572454	762075	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #4	567853	762458	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #5	567853	762432	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #6	568551	762377	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #7	568551	762354	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #8	569332	762317	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #9	569329	762285	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #10	570112	762251	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #11	570111	762226	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #12	570894	762198	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #13	570891	762168	(8.75"@52')	52.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #14	571675	762137	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #15	571670	762106	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #16	572453	762046	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #17	573627	761986	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

Borehole ID	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
US-25 #18	574709	761895	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #19	576242	761746	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #20	577175	761613	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
US-25 #21	578543	761628	(8.75"@50')	50.0	(6"@50')	50.0	-	C / Polymer[b]
U-25 SEISMIC #1	560457	778913	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #2	560363	779089	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #3	560268	779265	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam[c]
U-25 SEISMIC #4	560174	779441	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam[c]
U-25 SEISMIC #5	560079	779618	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam[c]
U-25 SEISMIC #6	559985	779794	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air, Air Foam[c]
U-25 SEISMIC #7	559891	779970	(6.13"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam[c]
U-25 SEISMIC #8	559796	780146	(6.25"@4') (6.13"@200')	200.0	(4.5"@200')	200.0	-	C / Air, Air Foam[c]
U-25 SEISMIC #9	559702	780323	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #13	560551	778736	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #14	560740	778384	(6.13"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]

Refer to footnotes at end of table.

Table A-2 *(Continued)*

Borehole Construction Information
Existing Boreholes Outside of Potential Repository Boundary and Within Potential Repository Restricted Area

	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique/ Circulating Media[a]
Borehole ID	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
U-25 SEISMIC #15	560834	778208	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #16	560929	778031	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #17	561023	777855	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #18	561118	777679	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #19	561212	777503	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[c]
U-25 SEISMIC #21	569427	746904	(15"@5') (10.63"@140')	140.0	(8.25"@140')	140.0	-	C / Air Foam[c]
Total Number 138			Total Footage	86,367				

---

[a] Drilling techniques include conventional rotary (C), ODEX 115 (O-115), and ODEX 165 (O-165).

[b] Conventional drilling/polymer mud (circulating media), flexible plastic hose emplaced, backfilled, and shot.

[c] Cased with PVC, backfilled, and shot.

Table A-3

Borehole Construction Information
Existing Boreholes Outside of Repository Restricted Area

	Borehole Coordinates		Borehole Size Diameter-Location	Total Depth	Casing Size Diameter-Location	Casing Depth	Grout Volume	Drilling Technique / Circulating Media[a]
Borehole ID	East	North	(in.-ft.)	(ft)	(in.-ft.)	(ft)	(ft^3)	
J-13	579651	749209	(9.88"@1561') (9"@2020') (7.63"@3488')	3,488.0	(18"@444') (13.38"&11.75"@1546') (5.5"@1484'-3385')			
UE-25 UZN #85	577568	750716	(6"@80')	80.0	(5.50"@80')	80.0	-	O-115 / Air
UE-25 WT #3	573384	745995	See Appendix B	1,142.0	See Appendix B	40.0	284	C / Air Foam
UE-25 WT #6	564524	780576	See Appendix B	1,256.5	See Appendix B	251.0	216	C / Air Foam
UE-25 WT #12	567011	739726	See Appendix B	1,308.0	See Appendix B	70.0	162	C / Air Foam
UE-25 WT #16	570395	774420	See Appendix B	1,710.0	See Appendix B	102.0	324	C / Air Foam
UE-29 UZN #92	583559	778010	(6"@105') (4.25@120')	120.0	(5.50"@105')	105.0	-	O-115 / Air
USW WT-11	558377	739070	See Appendix B	1,446.0	See Appendix B	44.5	81	C / Air Foam
U-25 SEISMIC #10	559607	780499	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[b]
U-25 SEISMIC #11	559513	780675	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam[b]
U-25 SEISMIC #12	559419	780851	(6.25"@200')	200.0	(4.5"@200')	200.0	-	C / Air Foam, Polymer[b]
U-25 SEISMIC #23	580246	741126	(13.38"@5') (12.25"@145')	145.0	(8.25"@139.5')	139.5	-	C / Air Foam[b]
U-25 SEISMIC #24	580907	769057	(15"@5') (12.25"@147')	147.0	(4.5"@140')	140.0	-	C / Air Foam[b]
Total Number 13	Total Footage			11,443				

[a] Drilling techniques include conventional rotary (C), ODEX 115 (O-115), and ODEX 165 (O-165).

[b] Cased with PVC, backfilled, and shot

Table A-4

Borehole Construction Information
Proposed Boreholes within Potential Repository Boundary

Borehole ID	Borehole Coordinates		Proposed Diameter (in.)	Proposed Depth (ft)	Total Footage (ft)	Notes
	East	North				
LPRS 2	559048	761353	6.00	35.0	350.0	a
LPRS 4	561881	760434	6.00	35.0	350.0	a
LPRS 5	562321	760860	6.00	35.0	350.0	a
SPRS 2	558406	761026	6.00	5.0	20.0	b
SPRS 3	558403	759446	6.00	5.0	20.0	b
SPRS 4	559048	761353	6.00	5.0	20.0	b
SPRS 7	561881	760434	6.00	5.0	20.0	b
SPRS 8	562321	760860	6.00	5.0	20.0	b
SPRS 12	564545	763973	6.00	5.0	20.0	b
SPRS 13	560100	766400	6.00	5.0	20.0	b
SPRS 14	562859	765729	6.00	5.0	20.0	b
SRG-5	558315	758175	6.00	150.0	150.0	
USW SD-2	560665	767875	12.25	2,300.0	2,300.0	c
USW SD-3	559345	764760	12.25	2,610.0	2,610.0	c
USW SD-4	562375	764390	12.25	2,100.0	2,100.0	c
USW SD-5	564195	763175	12.25	2,030.0	2,030.0	c
USW SD-6	559375	762230	12.25	2,580.0	2,580.0	c
USW UZ-2	558180	759769	12.25	2,800.0	2,800.0	c
USW UZ-3	558220	759625	12.25	2,800.0	2,800.0	c
USW UZ-6A	558325	759731	12.25	1,800.0	1,800.0	d
USW UZ-7A	562911	760836	12.25	1,575.0	1,575.0	e, f
USW UZ-8	562294	760762	12.25	1,772.0	1,772.0	f, g
UE-25 UZ-15 (UE-25 VSP-1)	558325	759732	12.25	1,460.0	1,460.0	f
USW UZ-N31	562850	764000	6.00	180.0	180.0	
USW UZ-N32	562850	764050	6.00	180.0	180.0	
USW UZ-N35	562350	762200	6.00	100.0	100.0	
Total Number 26	Total Footage				25,647.0	

[a] Large Plot Rainfall Study (LPRS) hole depth from Table 3.1-2 of YMP-USGS-SP 8.3.1.2.2.3. Each LPRS cluster has ten holes.

[b] Each Small Plot Rainfall Study (SPRS) cluster has four holes.

[c] SD and UZ hole depths (unless otherwise noted) are assumed equal to the depth to the groundwater table plus 300 ft. Values of the distance to the groundwater table are taken from SNL *CALMA system, Product 288. All hole depths are rounded to the nearest 10-ft depth.*

[d] Assumed to be in close proximity to USW UZ-6. Coordinates given are for USW UZ-6.

[e] Close proximity to USW UZ-7—30 ft north or south of USW UZ-7 location.

[f] Depth for UE-25 VSP-1 (UE-25 UZ-15), USW UZ-7A, and deepened USW UZ-8 from Table 3.2-3 of YMP-USGS-SP 8.3.1.2.2.3

[g] USW UZ-8 is a shallow existing hole of 57 ft.

Table A-5
Borehole Construction Information
Proposed Boreholes Outside of Potential Repository Boundary and Within Restricted Area

Borehole ID	Borehole Coordinates		Proposed Diameter (in.)	Proposed Depth (ft)	Total Footage (ft)	Notes
	East	North				
LPRS 1	559300	751400	6.00	35.0	350.0	a
LPRS 3	559990	757200	6.00	35.0	350.0	a
LPRS 6	565300	765500	6.00	35.0	350.0	a
LPRS 7	560150	755550	6.00	35.0	350.0	a
LPRS 8	562300	770450	6.00	35.0	350.0	a
LPRS 9	557950	765500	6.00	35.0	350.0	a
LPRS 10	557950	765750	6.00	35.0	350.0	a
LPRS 11	565320	763091	6.00	35.0	350.0	a
LPRS 12	565233	762048	6.00	35.0	350.0	a
LPRS 13	565173	762613	6.00	35.0	350.0	a
LPRS 14	556600	760150	6.00	35.0	350.0	a
NRG 2	569000	765800	6.00	210.0	210.0	
NRG 3	568195	766380	6.00	475.0	475.0	
NRG 4	566900	766830	6.00	735.0	735.0	
NRG 5	564700	767850	6.00	1,000.0	1,000.0	
NRG 6	564187	776726	6.00	1,100.0	1,100.0	
SPRS 1	559300	751400	6.00	5.0	20.0	b
SPRS 5	559990	757200	6.00	5.0	20.0	b
SPRS 6	557675	765700	6.00	5.0	20.0	b
SPRS 9	565300	765500	6.00	5.0	20.0	b
SPRS 10	565173	762613	6.00	5.0	20.0	b
SPRS 11	564250	760550	6.00	5.0	20.0	b
SPRS 15	560150	755550	6.00	5.0	20.0	b
SPRS 16	562300	770450	6.00	5.0	20.0	b
SPRS 17	556600	760150	6.00	5.0	20.0	b
SPRS 18	556400	760000	6.00	5.0	20.0	b
SPRS 19	557950	765500	6.00	5.0	20.0	b
SPRS 20	556250	759350	6.00	5.0	20.0	b
SPRS 21	560400	755120	6.00	5.0	20.0	b

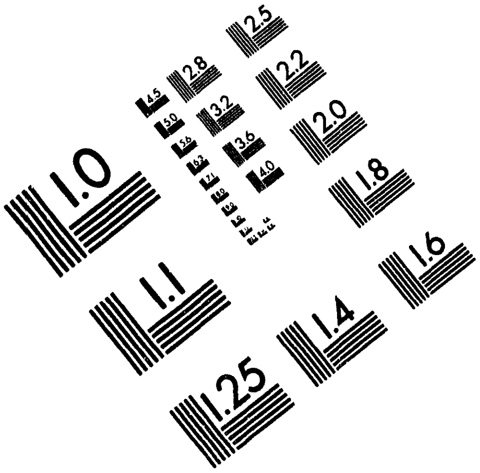
Refer to footnotes at end of table.

Table A-5 *(Continued)*

Borehole Construction Information
Proposed Boreholes Outside of Potential Repository Boundary and Within Restricted Area

Borehole ID	Borehole Coordinates		Proposed Diameter (in.)	Proposed Depth (ft)	Total Footage (ft)	Notes
	East	North				
SPRS 22	565320	763091	6.00	5.0	20.0	b
SPRS 23	565233	762048	6.00	5.0	20.0	b
SRG 1	566483	756691	6.00	150.0	150.0	
SRG 2	565096	756778	6.00	325.0	325.0	
SRG 3	563580	757100	6.00	250.0	250.0	
SRG 4	561258	757562	6.00	600.0	600.0	
STC #1	NA	NA	12.25	3,000.0	3,000.0	c
STC #2	NA	NA	12.25	3,000.0	3,000.0	c
STC #3	NA	NA	7.00	3,000.0	3,000.0	c
STC #4	NA	NA	7.00	3,000.0	3,000.0	c
UE-25 PH#1	569300	766000	3.75	60.0	615.0	d
UE-25 FM#1	581695	766450	12.25	500.0	500.0	
UE-25 FM#2	579975	756065	12.25	500.0	500.0	
UE-25 UZ#4A	556139	768716	12.25	1,860.0	1,860.0	e, f
UE-25 UZ#5A	566135	768591	12.25	1,860.0	1,860.0	e, f
UE-25 UZ#9	564750	760600	12.25	1,920.0	1,920.0	e
UE-25 UZ#9A	564800	760600	12.25	1,920.0	1,920.0	e
UE-25 UZ#9B	564850	760600	12.25	1,910.0	1,910.0	e
UE-25 UZ#10	561123	750139	12.25	2,380.0	2,380.0	e
UE-25 UZ#11	555800	757400	12.25	2,140.0	2,140.0	e
UE-25 UZ#12	556055	757400	12.25	2,140.0	2,140.0	e
USW UZ-13A	558489	751953	12.25	1,700.0	1,700.0	g
UE-25 UZ#14	560220	771275	12.25	1,700.0	1,700.0	e
USW SD-1	563370	768220	12.25	2,100.0	2,100.0	e
USW SD-7	561060	758605	12.25	2,330.0	2,330.0	e
USW SD-8	564010	761415	12.25	2,000.0	2,000.0	e
UE-25 SD#9	564625	761160	12.25	1,990.0	1,990.0	e
USW SD-10	563610	760681	12.25	2,050.0	2,050.0	e

Refer to footnotes at end of table.

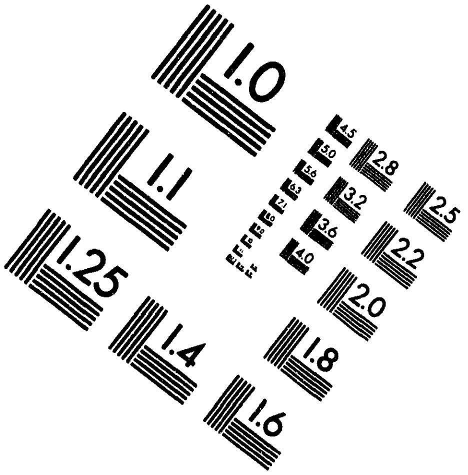


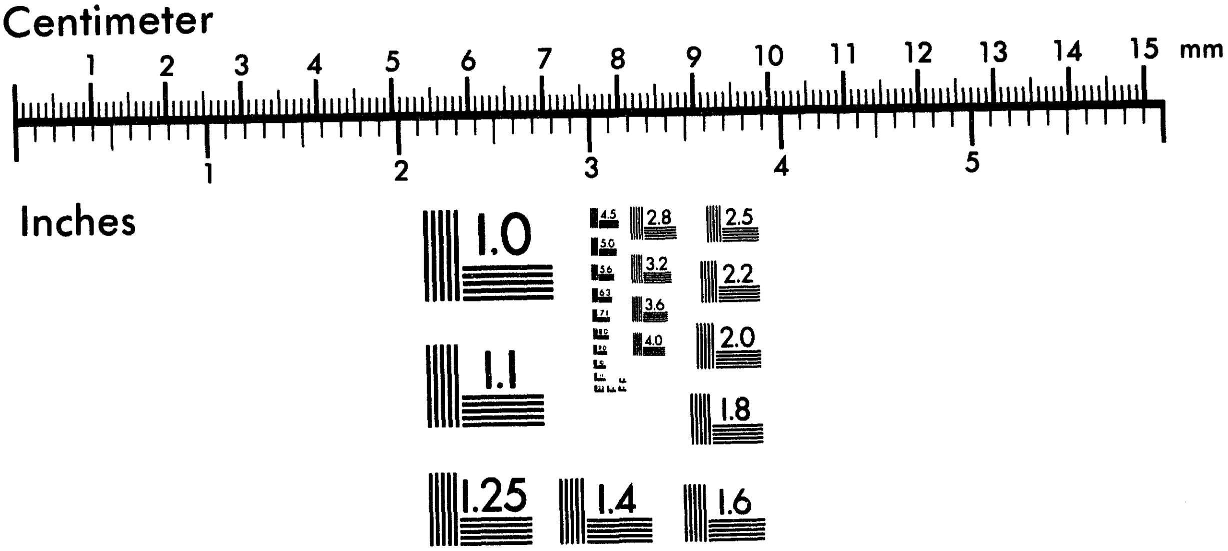
AIIM

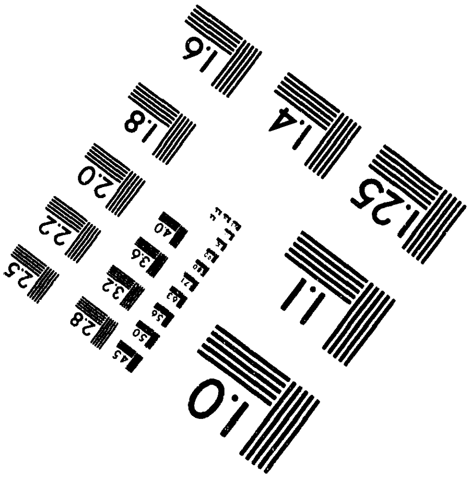
Association for Information and Image Management

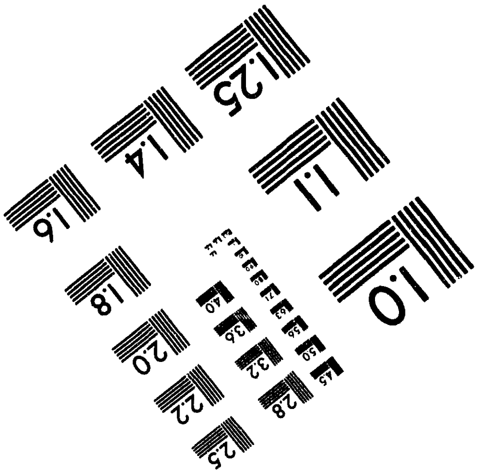
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202









MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

4 of 6

Table A-5 *(Continued)*

Borehole Construction Information
Proposed Boreholes Outside of Potential Repository Boundary and Within Restricted Area

Borehole ID	Borehole Coordinates		Proposed Diameter (in.)	Proposed Depth (ft)	Total Footage (ft)	Notes
	East	North				
USW SD-11	564132	760670	12.25	2,000.0	2,000.0	e
USW SD-12	564260	760030	12.25	1,970.0	1,970.0	e
USW H-7	557074	763298	8.00	3,000.0	3,000.0	
USW UZ-N57	561100	755075	6.00	120.0	120.0	
USW UZ-N58	561250	755200	6.00	120.0	120.0	
USW UZ-N59	561400	755300	6.00	120.0	120.0	
USW UZ-N61	561500	755450	6.00	120.0	120.0	
USW UZ-N62	558800	755200	6.00	60.0	60.0	
USW UZ-N63	566200	768800	6.00	60.0	60.0	
USW WT-8	557049	762283	12.25	1,870.0	1,870.0	e
USW WT-9	557642	769477	12.25	1,880.0	1,880.0	e
USW WT-21	550328	760086	12.25	2,010.0	2,010.0	e
USW WT-23	560220	771275	12.25	1,990.0	1,990.0	e
USW WT-24	565449	776622	12.25	1,880.0	1,880.0	e
Total Number 71			Total Footage		69,810.0	

[a] LPRS hole depth from Table 3.1-2 of YMP-USGS-SP8.3.1.2.2.3. Each LPRS cluster has ten holes.

[b] Each Small Plot Rainfall Study (SPRS) cluster has four holes.

[c] Southern Tracer Complex Studies (STC) holes are to be located southeast of the potential repository block.

[d] Calcite-Silica Study cluster has six holes—five holes approximately 60 ft deep, and one slanted hole approximately 315 ft long, for a total of 615 ft of borehole.

[e] SD and UZ hole depths (unless otherwise noted) are assumed equal to the depth to the groundwater table plus 300 ft. WT hole depths are assumed equal to the depth to the groundwater table plus 100 ft. Values of the distance to the groundwater table are taken from SNL CALMA system, Product 288. All hole depths are rounded to the nearest 10-ft depth.

[f] Holes are to be located 30 ft north or south of the indicated coordinates.

[g] Total depth of USW UZ-13A is estimated based on proposed depth of other UZ holes.

Table A-6

Borehole Construction Information
Proposed Boreholes Outside of Restricted Area Boundary

Borehole ID	Borehole Coordinates		Proposed Diameter (in.)	Proposed Depth (ft)	Total Footage (ft)	Notes
	East	North				
FMN 1	NA	NA	6.25	33.0	33.0	a
FMN 2	NA	NA	6.25	33.0	33.0	a
FMN 3	NA	NA	6.25	33.0	33.0	a
FMN 4	NA	NA	6.25	33.0	33.0	a
FMN 5	NA	NA	6.25	33.0	33.0	a
FMN 6	NA	NA	6.25	33.0	33.0	a
FMN 7	NA	NA	6.25	33.0	33.0	a
FMN 8	NA	NA	6.25	33.0	33.0	a
FMN 9	NA	NA	6.25	33.0	33.0	a
FMN 10	NA	NA	6.25	33.0	33.0	a
ISS-1	NA	NA	6.25	1,000.0	1,000.0	b
UE-25 FM#3	572300	710445	12.25	500.0	500.0	
USW G-5	563008	781930	3.98	5,000.0	5,000.0	
USW G-6	548922	778722	3.98	5,000.0	5,000.0	
USW G-7	566090	724586	3.98	5,000.0	5,000.0	
USW G-8	NA	NA	12.25	1,600.0	1,600.0	c
USW UZ-N39	614500	756500	6.00	125.0	125.0	
USW WT-19	589975	747980	12.25	1,100.0	1,100.0	
USW WT-20	565145	728300	12.25	1,000.0	1,000.0	
USW WT-22	528373	778858	12.25	1,300.0	1,300.0	
V-1	518000	729600	6.25	1,000.0	1,000.0	
V-2	572900	683450	6.25	1,000.0	1,000.0	
V-3	567848	658100	6.25	1,000.0	1,000.0	
V-4	569502	654056	6.25	1,000.0	1,000.0	
V-5	NA	NA	6.25	1,000.0	1,000.0	d
Total Number 25			Total Footage		26,955.0	

[a] FMN holes are part of the Forty-Mile Wash Recharge Study. The location coordinates of each has not yet been determined, but all FMN holes will be located in Forty Mile Wash.

[b] ISS-1 is part of the In Situ Stress Study. The hole will be located either on Little Skull Mountain or the Striped Hills.

[c] The location coordinates for Geologic hole G-8 are not yet known. The hole's approximate location is Forty Mile Wash near the main road to Yucca Mountain.

[d] The location coordinates for volcanic hole V-5 are not yet known but are anticipated to be outside the Restricted Area Boundary.

Table A-7
Borehole Deviations/Existing Boreholes Within Potential Repository

		Top Borehole Coordinates		Total Depth	Bottom Borehole Coordinates		Spatial Deviation	Angular Deviation
Location	Borehole ID	East	North	(ft)	East	North	(ft)	(–)
Within Potential Repository	USW UZ-6	558325	759731	1887	558337	759734	11.8	0.4
	USW H-5	558909	766634	4000	558876	766609	41.7	0.6
	USW H-4	563911	761644	4000	563870	761659	43.4	0.6
	USW WT-2	561924	760661	2060	561872	760600	79.6	2.2
	USW G-4	563082	765807	3003	562864	765667	258.9	4.9
Within Restricted Boundary	UE-25 WT #13	578757	756715	1160	578752	756716	4.8	0.2
	UE-25 WT #5	574250	761826	1330	574254	761833	7.6	0.3
	UE-25C #2	569634	756849	3000	569650	756852	16.6	0.3
	USW WT-7	553891	755570	1610	553893	755553	16.8	0.6
	UE-25 WT #18	564855	771167	2043	564847	771152	17.3	0.5
	USW WT-10	553302	748771	1413	553285	748767	17.8	0.7
	UE-25 WT #16	570395	774420	1710	570389	774442	22.6	0.8
	UE-25 WT #14	575210	761651	1310	575185	761641	27.1	1.2
	UE-25C #3	569555	756910	3000	569557	756879	31.1	0.6
	USW WT-11	558377	739070	1446	558391	739041	32.4	1.3
	UE-25C #1	569680	757096	3000	569704	757124	37.0	0.7
	UE-25 WT #12	567011	739726	1308	566988	739694	39.6	1.7
	UE-25 WT #15	579806	766117	1360	579766	766110	40.6	1.7
	UE-25 WT #3	573384	745995	1142	573344	745971	47.2	2.4
	USW H-6	554075	763299	4002	554023	763300	52.4	0.8
	USW WT-1	563739	753941	1689	563722	753890	53.2	1.8
	UE-25 WT #6	564524	780576	1257	564552	780621	53.9	2.5
	UE-25 WT #4	568040	768512	1580	567992	768474	61.3	2.2
	UE-25 WT #17	566212	748420	1453	566180	748364	64.2	2.5
	USW H-3	558452	756542	4000	558371	756569	84.9	1.2
	USW H-1	562388	770254	6000	562298	770219	96.9	0.9
	UE-25P #1	571485	756171	5920	571493	756069	102.5	1.0
	UE-25A #1	566350	764900	2501	566228	764829	141.3	3.2
	UE-25B #1	566416	765243	4002	566097	765151	332.3	4.7

Table A-8

Correlation Between Borehole Conditions and Where Condition is Encountered

Location	Condition
WT holes 1, 4, 6, 7, 10 to 19; UE-25 a#6; UE-25 a#7; UE-25 a#7; USW GU-3, G-2	Removal of 2.875-inch outside diameter tubing (OD) (or other size) with 12-ft screen; free standing.
WT holes 1, 5, 6, 7, 10 to 19; UE-25 a#4, a#5, a#6; UE-25 b#1; UE-25 c#1, c#2, c#3; UE-25 p#1; USW G-1, GA-1, GU-3, G-2, G-4; USW H-1, H-3, H-4, H-5; USW UZ-1; USW UZ-6	Steel casing grouted in at surface.
WT holes 4, 5, 6, 10 to 19; UE-25 c#1, c#2 (including a 4-ft hole at 940 ft), c#3; UE-25 p#1; USW G-1, GA-1, GU-3, G-2, G-4; USW H-1, H-4, H-5, H-6, USW UZ-1, UZ-6	Eroded zones and sloughing holes.
WT hole 18; UE-25 a#1, a#4, a#5, a#7; UE-25 b#1; USW G-1, GA-1, GU-3, G-2, G-4; USW H-1, H-5, H-6	Lost circulation.
UE-25 a#1; UE-25 WT#6; USW G-1; USW GA-1; USW GU-3; USW UZ-6s; USW UZ-7	Uncemented steel casing in deeper holes.
Neutron holes	Uncemented steel casing in shallow neutron holes, 20 to 120 tt in depth.
UE-25 a#6; UE-25 b#1; UE-25 c#1; USW G-1; USW H-1; USW UZ-6	Cement on wall, typically neat cement plus 2 percent $CaCl_2$. Cement was placed and then drilled out.
UE-25 a#7; UE-25 RF#10, RF-11, RF-9	PVC pipe grouted at the surface.
UE-25b#1	Perforated casing cemented.
USW H-3; USW H-4; USW H-5, H-6; USW G-4	Perforated casing uncemented.
UE-25 b#1; UE-25 c#1, c#2, c#3; UE-25 p#1; USW H-1, H-3, H-4, H-5, H-6; USW UZ-6; USW G-4	Steel casing spot-grouted at the bottom or along selected areas over the length of the casing.
USW GU-3 (need to review all logs for this occurrence)	Water inflows.
Vertical Seismic Profile (VSP) holes	VSP holes dealing with the removal of the seismometers.
All new UZ holes	Instruments in the UZ holes.
All wells to varying degrees	Deviations in the surface and the at-depth coordinates.

Table A-9
Specific Conditions Encountered in Existing Boreholes

Location	Condition
UE-25 WT#18	Electrical tool lost below 200 ft.
UE-25 WT#5	Bowen overshot, crossover sub, and Bowen bumper sub left at 1036 ft with top at 1018 ft; additional junk below 1036 ft.
UE-25 a#1	19.5 ft of HQ drill rod and 13 ft of HQ core barrel and core bit left in hole from 1264.5 to 1297 ft, and U.S. Geological Survey (USGS) fluid probe stuck in hole at 2495 ft.
UE-25 a#4	Seven piezometers (0.25 in. outside diameter (OD) plastic tubing); sand and bentonite above and below the end of the tubing; upper portion of the tubing (0 to 113.5 ft) filled with sand, bentonite gel, and dry Cal-Seal cement; from 397 to 113.7 ft Cal-Seal cement; bottom of the hole 397 to 500 ft predominantly sand and small amount of bentonite gel.
UE-25 p#1	– 1.9 in. OD tubing with bottom plugged; landed at 1355 ft. – 1.9 inches OD open-ended tubing landed at 1371 ft. – Two 0.125 x 3 x 18 in. caliper arms lost in hole at about 3934 ft. – Float shoe, float collar, two metal petal baskets; upper-stage collar, lower-stage collar; baker line liner hanger.
USW H-4	– 1.9 in. OD tubing set at 1725 ft. – TAM packer on 2.875 in. OD tubing set at 3876 ft with bottom of slotted and bull-nosed tubing at 3896 ft.
USW G-3	Plug in hole (1160 to 1362 ft) comprised neat cement plus 2 percent calcium chloride.
USW UZ-1	– 2.375 in. OD fiberglass tubing 1213.4 ft to surface; stemmed to surface with layers of bentonite, 12 to 16 mesh sand, and silica flour. – Junk in hole cemented into the bottom of the hole 1221 to 1270 ft (globe basket and crossover sub).
USW G-3	– Source on NAIL tool lost in first hole between 1247 and 1250 ft. – 986 ft of 3.5 in. drill pipe and drilling assembly left in hole with top of junk at 1362 ft.

Table A-9 *(Continued)*

Specific Conditions Encountered in Existing Boreholes

Location	Condition
UE-25 c#2	Centrilift pump set in hole at 2364 ft; monitor line at 2365 ft; retrievable bridge plug set at 2485 ft.
EU-25 c#3	Packer in hole with center at 2469.5 ft; monitor line at 2270.5 ft.
USW H-1	– 3 piezometers 2.0625 in. OD tubing with Johnson screen; ends are stemmed with Chevro gravel and cement is in the remainder of the hole 2207 to 5851 ft. – NCQ rods grouted in hole form 4160 to 5250 ft.
USW H-3	– Dyna-Drill drive shaft and 12.25 in. bit in rat hole at 43 ft.
USW H-6	– Packer set at 2468 ft on 2.875 in. tubing; bottom of packer assembly bull plugged with circulation sub below element. – Open 1.9 in. monitor line landed at 1752 ft.
UE-25 b#1	TAM packer at 3,935 ft on 2.875 in. tubing.
USW G-1	2 13/16 in. bit and sub, total length 1.25 ft, depth unknown.
USW G-4	Core barrel and bit (13-ft long) below 365 ft.
USW GU-3	24-in. pipe wrench body in hole.
UE-25 UZN#28	Drive sampler tube.
USW UZ-N76	Casing drive shoe below casing.
UE-25 UZ#4	One 5-ft joint of 5.5-in. casing and 2.3 ft casing shoe downhole (top of tish at 231 ft).

Table A-10

Casing Thicknesses of the Existing Boreholes at the Upper Sealing Location PTn/TSw1 Contact

Borehole ID	PTn/TSw1 Contact Depth (ft)	PTn/TSw1 Contact Elevation (ft)	Casing Thickness at Contact (in.)	Casing Diameter (OD) at Contact (in.)	Borehole Diameter at Contact (in.)	Diameter to Thickness Ratio	Remarks
UE-25a #6	247.6	3805.3	a	a	5.5	-----	Uncased at proposed seal location.
USW G-4	246.3	3920.6	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall.
USW H-4	254.5	3842.0	0.495	16.000	20	32.323	Hole double cased at this depth and outer casing (shown here) is cemented at proposed seal location.
"	320	3776.5	0.400	10.750	14.75	26.875	Hole only single cased at this depth; Minimum 2.0-in. gap between casing and original hole wall.
USW H-5	569.6	4281.2	0.350	10.750	14.75	30.714	Minimum 2.0-in. gap between casing and original hole wall.
USW UZ-62	585.1	4339.9	a	a	17.5	-----	Uncased at proposed seal location.
USW UZ-6s	(assume 609)^b	(assume 4340)^b	b	b	b	-----	Borehole does not reach contact.
USW WT-2	266.5	4003.2	a	a	8.75	-----	Uncased at proposed seal location.
UE-25a #1	422.1	3512.0	c	2.375	3.875	-----	Minimum 0.75-in. gap between casing and original hole wall.
"	277	3657.1	c	2.375	3.875	-----	Minimum 0.75-in. gap between casing and original hole wall.
UE-25a #4	316.8	3783.9	a	a	6.125	-----	Hole uncased but grouted around piezometers.
UE-25a #5	277.3	3779.2	a	a	6.125	-----	Uncased at proposed seal location.
UE-25a #7	284.2	3720.4	a	a	5.5	-----	Uncased at proposed seal location 2.375 in OD Hydril tubing in hole at seal location.
UE-25b #1	280	3659.0	0.495	16.000	18.5	32.323	Hole double-cased at this depth, and outer casing (shown here) is cemented at proposed seal location.
"	320	3619.0	0.352	9.625	12.25	27.344	Hole only single-cased at this depth; minimum 1.3-in. gap between casing and original hole wall.
USW G-1	292.5	4056.1	0.250	4.500	6.25	18.000	Minimum 0.87-in. gap between casing and original hole wall.

Refer to footnotes at end of table.

Table A-10 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Upper Sealing Location (PTn/TSw1 Contact)

Borehole ID	PTn/TSw1 Contact Depth (ft)	PTn/TSw1 Contact Elevation (ft)	Casing Thickness at Contact (in.)	Casing Diameter (OD) at Contact (in.)	Borehole Diameter at Contact (in.)	Diameter to Thickness Ratio	Remarks
USW H-1	332.4	3942.0	0.438	16.000	20	36.530	Hole double-cased at this depth, and outer casing (shown here) is cemented at proposed seal location.
•	385	3889.4	0.352	9.625	13.25	27.344	Hole only single cased at this depth; minimum 1.8-in. gap between casing and original hole wall.
USW H-3	450.7	4415.7	0.400	10.750	14.75	26.875	Minimum 2.0-in. gap between casing and original hole wall.
USW UZ-1	d	d	a	a	17.5	-----	Hole alternately stemmed and grouted at probable seal location.
USW UZ-7	b	b	a	a	6	-----	Hole uncased and presently only 207 ft deep. Future plans call for hole to be deepened considerably.
UE-25c #1	(<368)[d]	(>3341)[d]	0.438	16.000	24	36.530	Hole double-cased at this depth, and outer casing (shown here) is cemented from 362 ft to surface.
•	(368 to 1260)[d]	(3341 to 2449)[d]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
UE-25c #2	(<320)[d]	(>3394)[d]	0.495	16.000	24	32.323	Hole double-cased at this depth, and outer casing (shown here) is cemented from 320 ft to surface.
•	(320 to 1365)[d]	(3394 to 2349)[d]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
UE-25c #3	(<315)[d]	(>3399)[d]	0.495	16.000	24	32.323	Hole double-cased at this depth, and outer casing (shown here) is cemented from 315 ft to surface.
•	(315 to 1323)[d]	(3399 to 2391)[d]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
UE-25p #1	(<341)[d]	(<3314)[d]	0.438	16.000	22	36.530	Hole double-cased at this depth, and outer casing (shown here) is cemented from 326 ft to surface
•	(341 to 1487)[d]	(3314 to 2168)[d]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall

Refer to footnotes at end of table.

Table A-10 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Upper Sealing Location (PTn/TSw1 Contact)

Borehole ID	PTn/TSw1 Contact Depth (ft)	PTn/TSw1 Contact Elevation (ft)	Casing Thickness at Contact (in.)	Casing Diameter (OD) at Contact (in.)	Borehole Diameter at Contact (in.)	Diameter to Thickness Ratio	Remarks
UE-25 WT-3	d	d	a	a	8.75	-----	Hole 8.75 in and uncased from depth of 41 to 1142 ft.
UE-25 WT-4	d	d	a	a	8.75	-----	Hole 8.75 in and uncased from depth of 50 to 1580 ft.
UE-25 WT-5	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 40 to 1330 ft.
UE-25 WT-6	(<251)[d]	(>4061)[d]	0.328	7.625	9.875	23.247	Casing not cemented; minimum 1 1 in gap between casing and original hole wall.
"	(>251)[d]	(<4061)[d]	a	a	6.75	-----	Hole 6.75 in. and uncased from depth of 251 to 1257 ft.
UE-25 WT-12	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 70 to 1308 ft.
UE-25 WT-13	(<224)[d]	(>3162)[d]	0.350	10.750	14.75	30 714	Casing cemented from 222 ft depth to surface
"	(>224)[d]	(<3162)[d]	a	a	8.75	-----	Hole 8.75 in and uncased from depth of 224 to 1160 ft.
UE-25 WT-14	d	d	a	a	8.75	-----	Hole 8.75 in and uncased from depth of 126 to 1310 ft.
UE-25 WT-15	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 130 to 1360 ft.
UE-25 WT-16	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 102 to 1710 ft.
UE-25 WT-17	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 55 to 1453 ft.
UE-25 WT-18	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 88 to 2043 ft.
USW GA-1	(<148)[d]	(>5039)[d]	0.250	4.500	6.25	18.000	Minimum 0 8 in gap between casing and original hole wall
"	(>148 ft)[d]	(<5039)[d]	a	a	3.937	- - -	Hole 3 937 in. and uncased from 148 to 551 ft

Refer to footnotes at end of table

Table A-10 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Upper Sealing Location (PTn/TSw1 Contact)

Borehole ID	PTn/TSw1 Contact Depth (ft)	PTn/TSw1 Contact Elevation (ft)	Casing Thickness at Contact (in.)	Casing Diameter (OD) at Contact (in.)	Borehole Diameter at Contact (in.)	Diameter to Thickness Ratio	Remarks
USW G-2	762	4336.4	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall.
USW G-3	430	4426.5	0.275	5.500	8.75	20.000	Minimum 1.6-in. gap between casing and original hole wall.
USW GU-3	(assume 430)[d]	4426.6	0.275	5.500	6.75	20.000	Minimum 0.6-in. gap between casing and original hole wall.
USW H-6	332	3938.6	0.450	10.750	22	23.889	Hole changes size at 335 ft depth, minimum 5.6-in. gap between casing and original hole wall.
"	336	3934.6	0.450	10.750	14.75	23.889	Hole changes size at 335 ft depth, minimum 2.0-in. gap between casing and original hole wall.
USW WT-1	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 33.5 to 1689 ft.
USW WT-7	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 53 to 1610 ft.
USW WT-10	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 116 to 1413 ft.
USW WT-11	d	d	a	a	8.75	-----	Hole 8.75 in. and uncased from depth of 45 to 1446 ft.

[a] Borehole not cased at this contact.
[b] Borehole does not reach contact.
[c] Borehole cased with NQ drill steel.
[d] Elevation not directly available.

Refer to footnotes at end of table.

Table A-11

Casing Thicknesses of the Existing Boreholes at the Repository Horizon

Borehole ID	Approximate Repository Depth (ft)	Approximate Repository Elevation (ft)	Casing Thickness at Contact (in)	Casing Diameter (OD) at Contact (in)	Hole Diameter at Contact (in)	Casing Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach Repository Horizon.
USW G-4	1030.5	3136.4	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall.
USW H-4	980.3	3116.2	0.400	10.750	14.75	26.875	Minimum 2.0-in. gap between casing and original hole wall.
USW H-5	1473.2	3377.6	0.350	10.750	14.75	30.714	Minimum 2.0-in. gap between casing and original hole wall
USW UZ-6	1271.2	3653.8	b	b	17.5	-----	Borehole not cased at repository horizon.
USW UZ-6s	a	a	a	a	a	-----	Borehole does not reach repository horizon.
USW WT-2	944.4	3325.3	b	b	8.75	-----	Borehole not cased at repository horizon.
UE-25a #5	a	a	a	a	a	-----	Borehole does not reach repository horizon.
UE-25a #7	a	a	a	a	a	-----	Borehole does not reach repository horizon.
UE-25b #1	c	c	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall.
USW G-1	(<1016)[c]	(>3333)[c]	0.250	4.500	6.25	18.000	Hole cased to depth of 1016 ft; minimum 0.8-in. gap between casing and original hole wall.
-	(>1016)[c]	(<3333)[c]	b	b	3.875	-----	Hole uncased below 1016 ft
USW H-1	c	c	0.352	9.625	13.25	27.344	Minimum 1 8-in. gap between casing and original hole wall.
USW H-3	c	c	0.4	10.75	14.75	26.875	Minimum 2.0-in gap between casing and original hole wall.
USW UZ-1	c	c	b	b	17.5	-----	Hole alternately stemmed and grouted at probable seal location
USW UZ-7	a	a	b	b	6	-----	Hole uncased and presently only 207 ft deep Future plans call for hole to be deepened considerably.

Refer to footnotes at end of table.

Table A-11 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Repository Horizon

Borehole ID	Approximate Repository Depth (ft)	Approximate Repository Elevation (ft)	Casing Thickness at Contact (in)	Casing Diameter (OD) at Contact (in)	Hole Diameter at Contact (in)	Casing Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach Repository Horizon.
UE-25c #1	(<1260)[c]	(>2449)[c]	0.350	10.750	14.75	30.714	Minimum 2.0-in. gap between casing and original hole wall.
"	(1260 to 1365)[c]	(2449 to 2344)[c]	0.350	10.750	14.75	30.714	Casing annulus cemented from 1260 to 1365 ft.
"	(1365 to 1515)[c]	(2344 to 2194)[c]	b	b	14.75	-----	Hole uncased below 1365 ft.
"	(>1515)[c]	(<2194)[c]	b	b	9.875	-----	Borehole not cased.
UE-25c #2	(320 to 1365)[c]	(3394 to 2349)[c]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
"	(1365 to 1520)[c]	(2349 to 2194)[c]	b	b	14.75	-----	Hole uncased below 1365 ft.
"	(1520 to 3000)[c]	(2194 to 714)[c]	b	b	9.875	-----	Borehole not cased.
UE-25c #3	(315 to 1323)[c]	(3399 to 2391)[c]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
"	(1323 to 1368)[c]	(2391 to 2346)[c]	b	b	14.75	-----	Hole cemented below casing, then drilled out to 9.875-in. OD.
"	(1368 to 1520)[c]	(2346 to 2194)[c]	b	b	14.75	-----	Hole uncased below 1365 ft.
"	(1520 to 3000)[c]	(2194 to 714)[c]	b	b	9.875	-----	Borehole not cased.
UE-25p #1	(341 to 1487)[c]	(3314 to 2168)[c]	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
"	(1487 to 1564)[c]	(2168 to 2091)[c]	0.350	10.750	14.75	30.714	Hole double-cased at this depth, and outer casing (shown here) is cemented from 1517 to 1590 ft)
"	(1564 to 4210)[c]	(2091 to −555)[c]	0.328	7.625	9.875	23.247	Hole single-cased within this depth range; minimum 1.1-in. gap between casing and original hole wall.

Refer to footnotes at end of table.

Table A-11 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Repository Horizon

Borehole ID	Approximate Repository Depth (ft)	Approximate Repository Elevation (ft)	Casing Thickness at Contact (in)	Casing Diameter (OD) at Contact (in)	Hole Diameter at Contact (in)	Casing Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach Repository Horizon.
UE-25 WT-3	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 41 to 1142 ft.
UE-25 WT-4	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 50 to 1580 ft.
UE-25 WT-5	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 40 to 1330 ft.
UE-25 WT-6	(>251)[c]	(<4061)[c]	b	b	6.75	-----	Hole 6.75 in. and uncased from depth of 251 to 1257 ft.
UE-25 WT-12	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 70 to 1308 ft.
UE-25 WT-13	(>224)[c]	(<3162)[c]	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 224 to 1160 ft.
UE-25 WT-14	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 126 to 1310 ft.
UE-25 WT-15	611.5	2941.0	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 130 to 1360 ft.
UE-25 WT-16	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 102 to 1710 ft.
UE-25 WT-17	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 55 to 1453 ft.
UE-25 WT-18	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 88 to 2043 ft.
USW GA-1	(>148)[c]	(<5039)[c]	b	b	3.937	-----	Hole 3.937 in. and uncased from 148 to 551 ft
USW G-2	1831.4	3267.0	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 795 to 2670 ft.

Refer to footnotes at end of table

Table A-11 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Repository Horizon

Borehole ID	Approximate Repository Depth (ft)	Approximate Repository Elevation (ft)	Casing Thickness at Contact (in)	Casing Diameter (OD) at Contact (in)	Hole Diameter at Contact (in)	Casing Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach Repository Horizon
USW G-3	c	c	0.275	5.500	8.75	20.000	Hole cased from 2600 ft to surface; hole sidetracked at 1144 ft; minimum 1.6-in. gap between casing and original hole wall.
USW GU-3	(<1144)[c]	(>3713)[c]	0.275	5.500	6.75	20.000	Minimum 0.6-in. gap between casing and original hole wall.
•	(>1144)[c]	(<3713)[c]	b	b	3.937	-----	Hole 3.937 in. and uncased from 1144 to 1768 ft
USW H-6	c	c	0.450	10.750	14.75	23.889	Minimum 2.0-in. gap between casing and original hole wall.
USW WT-1	286.4	3656.0	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 33 5 to 1689 ft.
USW WT-7	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 53 to 1610 ft.
USW WT-10	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 116 to 1413 ft.
USW WT-11	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 45 to 1446 ft.

[a] Borehole does not reach contact.
[b] Borehole not cased at this contact.
[c] Elevation not directly available.

Table A-12

Casing Thicknesses of the Existing Boreholes at the Lower Sealing Location

Borehole ID	TSw3/CHn1 Contact Depth (ft)	TSw3/CHn1 Contact Elev. (ft)	Casing Thickness at Contact (in)	Diameter at Contact (in)	Diameter at Contact (in)	Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach contact.
USW G-4	1350.4	2816.5	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall
USW H-4	1219	2877.5	0.400	10.750	14.75	26.875	Minimum 2.0-in. gap between casing and original hole wall.
USW H-5	1656.4	3194.4	0.350	10.750	14.75	30.714	Minimum 2.0-in. gap between casing and original hole wall.
USW UZ-6	1458.3	3466.7	b	b	17.5	-----	Borehole uncased at contact
USW UZ-6s	a	a	a	a	a	-----	Borehole does not reach contact.
USW WT-2	1194.8	3074.9	b	b	8.75	-----	Borehole not cased at contact.
UE-25a #1	1461.1	2473.0	**	2.375	2.98	-----	Minimum 0.3-in. gap between steel and original hole wall.
"	1317	2617.1	**	2.375	2.98	-----	Minimum 0.3-in. gap between steel and original hole wall.
UE-25a #4	a	a	a	a	a	-----	Borehole does not reach contact.
UE-25a #5	a	a	a	a	a	-----	Borehole does not reach contact.
UE-25a #7	a	a	a	a	a	-----	Borehole does not reach contact.
UE-25b #1	1330	2609.0	0.352	9.625	12.25	27.344	Minimum 1.3-in. gap between casing and original hole wall.
USW G-1	1342.4	3006.2	b	b	3.875	-----	Hole uncased below 1016 ft.
USW H-1	1411.9	2862.5	0.352	9.625	13.25	27.344	Minimum 1.8-in. gap between casing and original hole wall.
USW H-3	1252.9	3613.5	0.400	10.750	14.75	26.875	Minimum 2.0-in. gap between casing and original hole wall.
USW UZ-1	(<1270)^c	(>3156)^c	b	b	17.5	-----	Hole alternately stemmed and grouted at probable seal location. Total depth of hole 1270 ft.
USW UZ-7	a	a	b	b	6	-----	Hole uncased and presently only 207 ft deep. Future plans call for hole to be deepened considerably.
UE-25c #1	(<1260)^c	(>2449)^c	0.350	10.750	14.75	30.714	Minimum 2.0-in. gap between casing and original hole wall.
"	(1260 to 1365)^c	(2449 to 2344)^c	0.350	10.750	14.75	30.714	Casing annulus cemented from 1260 to 1365 ft.
"	(1365 to 1515)^c	(2344 to 2194)^c	b	b	14.75	-----	Hole uncased below 1365 ft.
"	(>1515)^c	(<2194)^c	b	b	9.875	-----	Borehole not cased.
UE-25c #2	(320 to 1365)^c	(3394 to 2349)^c	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in gap between casing and original hole wall.
"	(1365 to 1520)^c	(2349 to 2194)^c	b	b	14.75	-----	Hole uncased below 1365 ft.
"	(1520 to 3000)^c	(2194 to 714)^c	b	b	9.875	-----	Borehole not cased.
UE-25c #3	(315 to 1323)^c	(3399 to 2391)^c	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in gap between casing and original hole wall.
"	(1323 to 1368)^c	(2391 to 2346)^c	b	b	14.75	-----	Hole cemented below casing, then drilled out to 9.875-in OD.
"	(1368 to 1520)^c	(2346 to 2194)^c	b	b	14.75	-----	Hole uncased below 1365 ft.

Refer to footnotes at end of table

Table A-12 *(Continued)*

Casing Thicknesses of the Existing Boreholes at the Lower Sealing Location

Borehole ID	TSw3/CHn1 Contact Depth (ft)	TSw3/CHn1 Contact Elev. (ft)	Casing Thickness at Contact (in)	Diameter at Contact (in)	Diameter at Contact (in)	Diameter to Thickness Ratio	Remarks
UE-25a #6	a	a	a	a	a	-----	Borehole does not reach contact.
"	(1520 to 3000)^c	(2194 to 714)^c	b	b	9.875	-----	Borehole not cased
UE-25p #1	(341 to 1487)^c	(3314 to 2168)^c	0.350	10.750	14.75	30.714	Hole single-cased within this depth range; minimum 2.0-in. gap between casing and original hole wall.
"	(1487 to 1564)^c	(2168 to 2091)^c	0.350	10.750	14.75	30.714	Hole double-cased at this depth and outer casing (shown here) is cemented from 1517 to 1590 ft.
"	(1564 to 4210)^c	(2091 to −555)^c	0.328	7.625	9.875	23.247	Hole single-cased within this depth range; minimum 1.[illegible] gap between casing and original hole wall.
UE-25 WT-3	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 41 to 1142 ft.
UE-25 WT-4	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 50 to 1580 ft
UE-25 WT-5	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 40 to 1330 ft
UE-25 WT-6	(>251)^c	(<4061)^c	b	b	6.75	-----	Hole 6.75 in. and uncased from depth of 251 to 1257 ft.
UE-25 WT-12	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 70 to 1308 ft
UE-25 WT-13	(>224)^c	(<3162)^c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 224 to 1160 ft.
UE-25 WT-14	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 126 to 1310 ft
UE-25 WT-15	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 130 to 1360 ft
UE-25 WT-16	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 102 to 1710 ft.
UE-25 WT-17	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 55 to 1453 ft.
UE-25 WT-18	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 88 to 2043 ft.
USW GA-1	(>148)^c	(<5039)^c	b	b	3.937	-----	Hole 3.937 in. and uncased from 148 to 551 ft.
USW G-2	1669	3429.4	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 795 to 2670 ft.
USW G-3	1269	3587.5	0.275	5.500	8.75	20.000	First hole may also need to be resealed at this contact. Minimum 1.6-in. gap between casing and original hole wall.
USW GU-3	(<1144)^c	(>3713)^c	0.275	5.500	6.75	20.000	Minimum 0.6-in. gap between casing and original hole wall.
"	(>1144)^c	(<3713)^c	b	b	3.937	-----	Hole 3.937 in. and uncased from 1144 to 1768 ft.
USW H-6	1310	2960.6	0.450	10.750	14.75	23.889	Minimum 2.0-in. gap between casing and original hole wall.
USW WT-1	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 33.5 to 1689 ft.
USW WT-7	c	c	b	b	8.75	-----	Hole 8.75 in. and uncased from depth of 53 to 1610 ft.
USW WT-10	c	c	b	b	8.75	-----	Hole 8 75 in. and uncased from depth of 116 to 1413 ft.
USW WT-11	c	c	b	b	8.75	-----	Hole 8.75 in and uncased from depth of 45 to 1446 ft

[a] Borehole does not reach contact.
[b] Borehole not cased at this contact.
[c] Elevation not directly available.

Refer to footnotes at end of table.

APPENDIX B

STRATIGRAPHIC AND DRILLING LOGS FOR SELECTED BOREHOLES

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

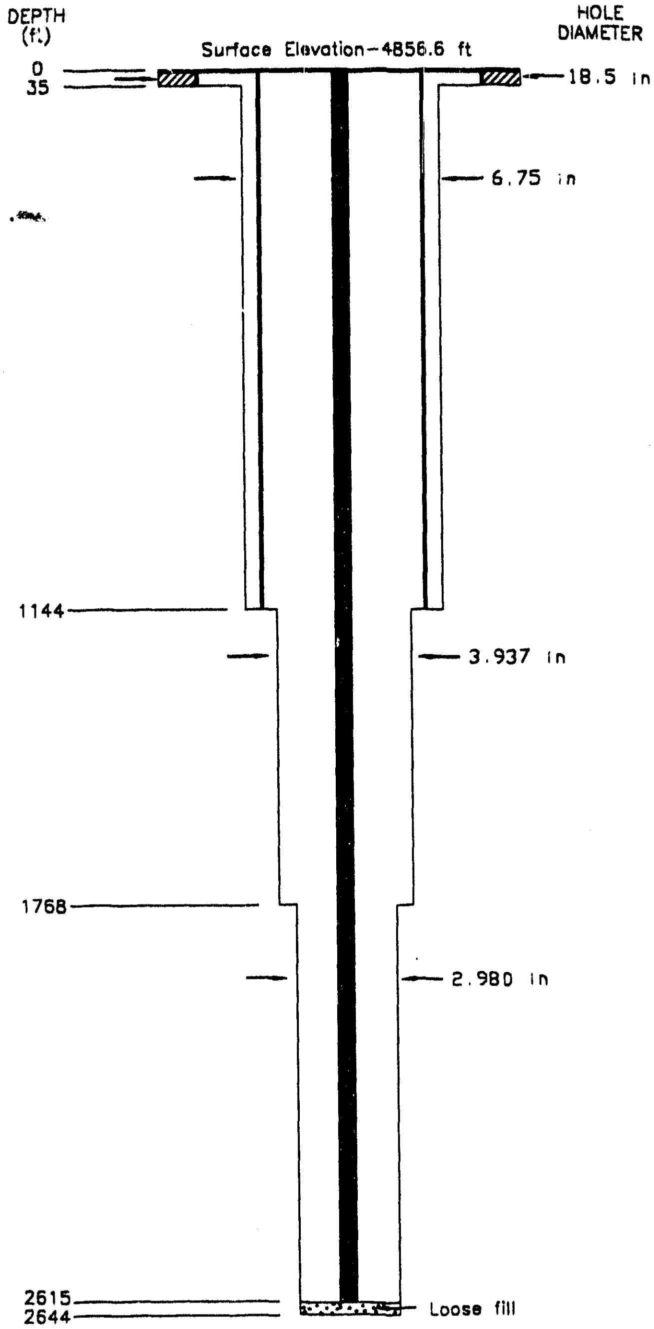
CEMENTING AND CASING INFORMATION

Annulus cemented with 45 ft^3 of neat cement plus 2% $CaCl_2$ and 10% sand from 35 ft to surface.

OD = 13.375 in
ID = 12.615 in
T_c = 0.380 in
Set at 34 ft

Annulus not cemented.

OD = 5.500 in
ID = 4.950 in
T_c = 0.275 in
Set at 1144 ft



ER

in

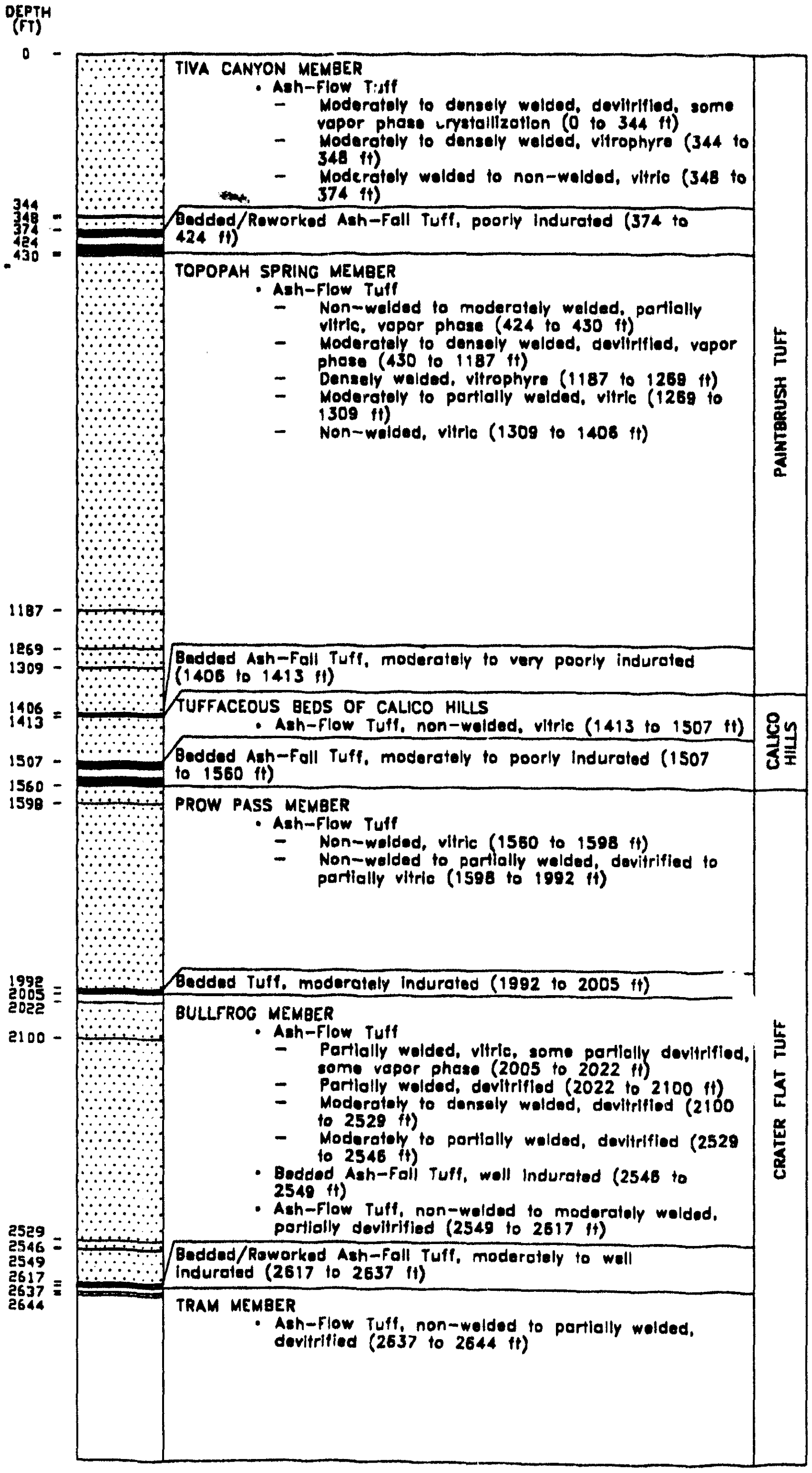
USW GU-3

GENERALIZED STRATIGRAPHIC LOG

(Modified from Scott and Castellanos, 1984)

HOLE INFORMATION

266 281 283	● Caliper log indicated eroded zone between 266 and 283 ft with maximum hole enlargement of 32 in at 281ft.
358 378 425	● Gradual washout zone between 358 and 425 ft with maximum hole enlargement of 31.5 in at 378 ft.
501	▲ TV camera log indicated small stream of water going down hole at 501 ft.
516	△ Large quantities of lost circulation material and mud added to hole at hole depth of 516 ft to maintain mud level in hole.
504 542 562 568	● Caliper log indicated hole enlargement from 504 to 568 ft with maximum hole enlargement of 23 in at 542 and 562 ft.
2615	■ 1.6 in OD tubing was landed at 2615 ft with 2.75 in x 15 in cage around wiper plug shoe.



TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified, some vapor phase crystallization (0 to 344 ft)
  - Moderately to densely welded, vitrophyre (344 to 348 ft)
  - Moderately welded to non-welded, vitric (348 to 374 ft)

Bedded/Reworked Ash-Fall Tuff, poorly indurated (374 to 424 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded to moderately welded, partially vitric, vapor phase (424 to 430 ft)
  - Moderately to densely welded, devitrified, vapor phase (430 to 1187 ft)
  - Densely welded, vitrophyre (1187 to 1269 ft)
  - Moderately to partially welded, vitric (1269 to 1309 ft)
  - Non-welded, vitric (1309 to 1406 ft)

Bedded Ash-Fall Tuff, moderately to very poorly indurated (1406 to 1413 ft)

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded, vitric (1413 to 1507 ft)

Bedded Ash-Fall Tuff, moderately to poorly indurated (1507 to 1560 ft)

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (1560 to 1598 ft)
  - Non-welded to partially welded, devitrified to partially vitric (1598 to 1992 ft)

Bedded Tuff, moderately indurated (1992 to 2005 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partially welded, vitric, some partially devitrified, some vapor phase (2005 to 2022 ft)
  - Partially welded, devitrified (2022 to 2100 ft)
  - Moderately to densely welded, devitrified (2100 to 2529 ft)
  - Moderately to partially welded, devitrified (2529 to 2546 ft)
- Bedded Ash-Fall Tuff, well indurated (2546 to 2549 ft)
- Ash-Flow Tuff, non-welded to moderately welded, partially devitrified (2549 to 2617 ft)

Bedded/Reworked Ash-Fall Tuff, moderately to well indurated (2617 to 2637 ft)

TRAM MEMBER
- Ash-Flow Tuff, non-welded to partially welded, devitrified (2637 to 2644 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987d)

CEMENTING AND CASING INFORMATION

Annulus cemented with 350 ft^3 of 75% neat cement and 25% gypsum cement from 41 ft to surface.

OD = 30.625 in
ID = 30.000 in
T_c = 0.3125 in
Set at 38.5 ft

Annulus cemented with 806 ft^3 of neat cement plus 2% $CaCl_2$ from 335 ft to surface. Hole cased with 5 joints of J-55 slip joint casing plus 4 joints of H-40 casing on top.

H-40	J-55
OD = 16.000 in	OD = 16.000 in
ID = 15.250 in	ID = 15.124 in
T_c = 0.375 in	T_c = 0.438 in

Set at 334.2 ft

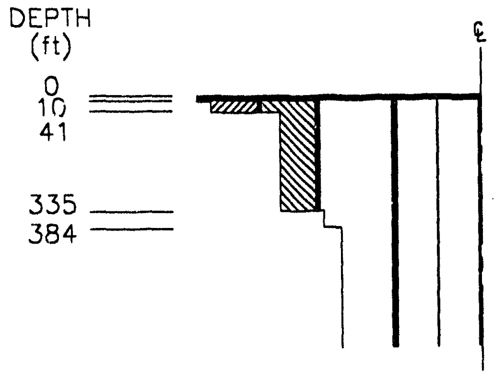
Hole cemented from 347 ft to 315 ft with 30 ft^3 of neat cement plus 3 % $CaCl_2$, then drilled out to 15 inches diameter.

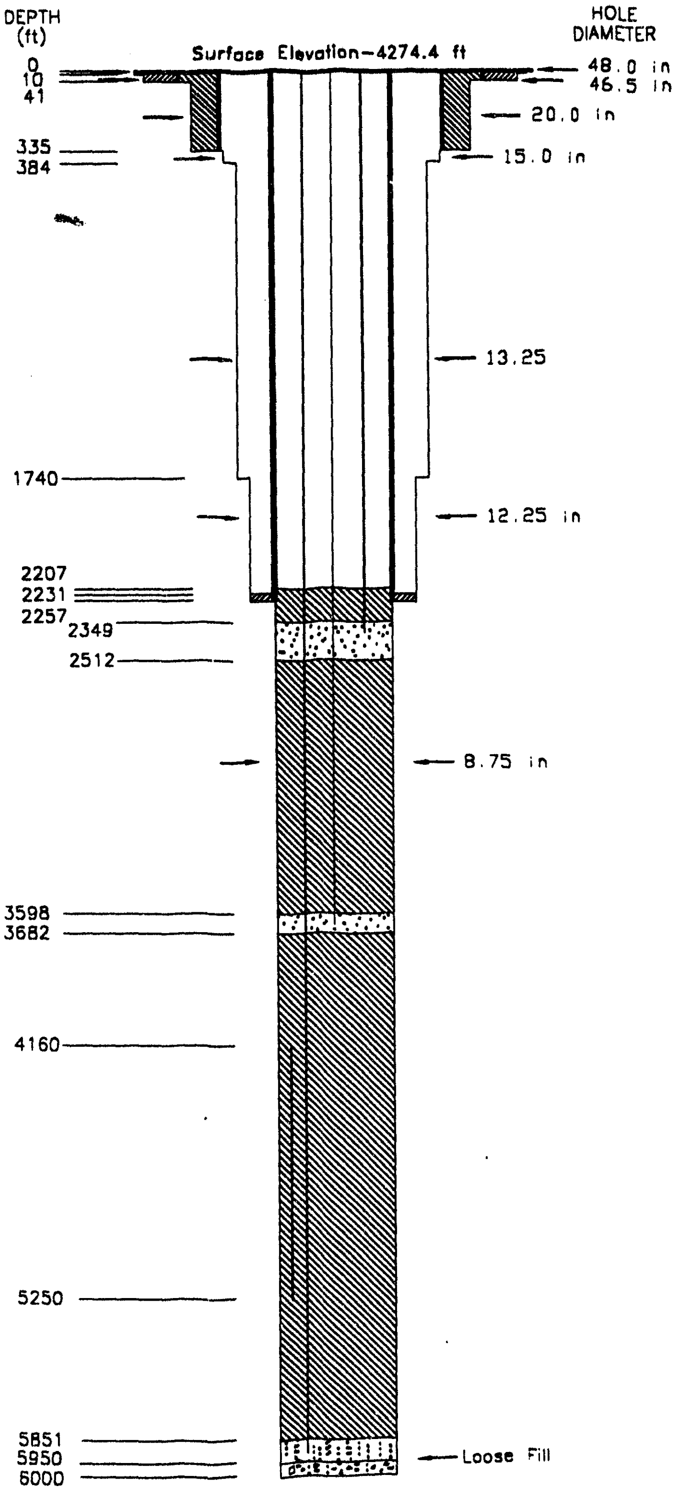
Annulus cemented with 30 ft^3 of neat cement from 2257 to 2231 ft.

OD = 9.625 in
ID = 8.921 in
T_c = 0.352 in
Set at 2255.0 ft

Three strings of 2.0625 in OD tubing with Johnson screen and piezometer set at various depths (string #1 at 5925 ft, #2 at 3657 ft, and #3 at 2431 ft) and extending to the surface. Each piezometer was stemmed with 0.125 in x 0.250 in Chevro gravel: string #1 - from 5950 to 5851 ft with 42 ft^3; String #2 - from 3682 to 3598 ft with 40 ft^3; and String #3 - from 2512 to 2349 ft with 110 ft^3. Each annulus was cemented with neat cement plus 2% $CaCl_2$: String #1 - from 5851 to 3682 ft with 625 ft^3; String #2 - from 3598 to 2512 ft with 570 ft^3; String #3 - from 2349 to 2207 ft with 145 ft^3.

NCQ rods left in hole from 5250 to 4160 ft.





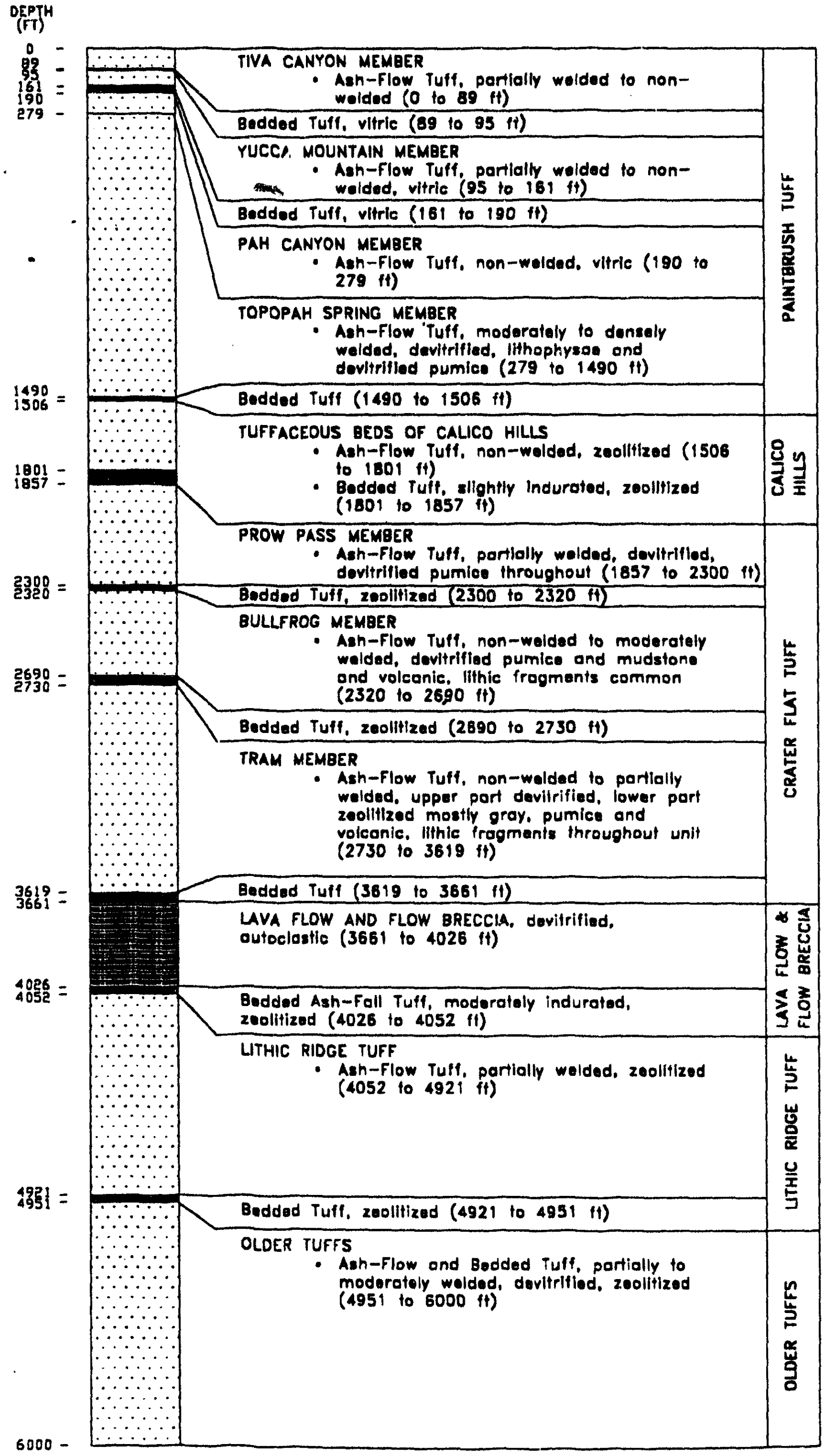
USW H-1

GENERALIZED STRATIGRAPHIC LOG

(From Rush, et al.,1983)

HOLE INFORMATION

280 320	△ Lost circulation from 280 ft to 320 ft.
2292 2371 2554	● Caliper log indicated slightly eroded area from 2292 to 2554 ft with maximum hole enlargement of 13.75 in at 2371 ft.
3995 4035 4041	● Caliper log indicated eroded area from 3995 to 4041 ft with maximum hole enlargement of 18.25 in at 4035 ft.



TIVA CANYON MEMBER
- Ash-Flow Tuff, partially welded to non-welded (0 to 89 ft)

Bedded Tuff, vitric (89 to 95 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, partially welded to non-welded, vitric (95 to 161 ft)

Bedded Tuff, vitric (161 to 190 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric (190 to 279 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff, moderately to densely welded, devitrified, lithophysae and devitrified pumice (279 to 1490 ft)

Bedded Tuff (1490 to 1506 ft)

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded, zeolitized (1506 to 1801 ft)
- Bedded Tuff, slightly indurated, zeolitized (1801 to 1857 ft)

PROW PASS MEMBER
- Ash-Flow Tuff, partially welded, devitrified, devitrified pumice throughout (1857 to 2300 ft)

Bedded Tuff, zeolitized (2300 to 2320 ft)

BULLFROG MEMBER
- Ash-Flow Tuff, non-welded to moderately welded, devitrified pumice and mudstone and volcanic, lithic fragments common (2320 to 2690 ft)

Bedded Tuff, zeolitized (2890 to 2730 ft)

TRAM MEMBER
- Ash-Flow Tuff, non-welded to partially welded, upper part devitrified, lower part zeolitized mostly gray, pumice and volcanic, lithic fragments throughout unit (2730 to 3619 ft)

Bedded Tuff (3619 to 3661 ft)

LAVA FLOW AND FLOW BRECCIA, devitrified, autoclastic (3661 to 4026 ft)

Bedded Ash-Fall Tuff, moderately indurated, zeolitized (4026 to 4052 ft)

LITHIC RIDGE TUFF
- Ash-Flow Tuff, partially welded, zeolitized (4052 to 4921 ft)

Bedded Tuff, zeolitized (4921 to 4951 ft)

OLDER TUFFS
- Ash-Flow and Bedded Tuff, partially to moderately welded, devitrified, zeolitized (4951 to 6000 ft)

U

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986c)

CEMENTING AND CASING INFORMATION

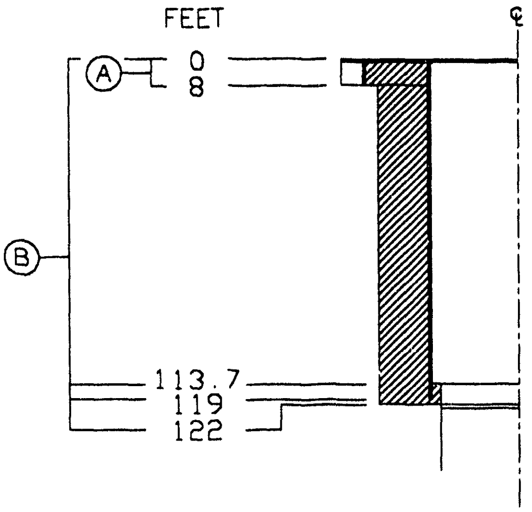
Ⓐ Annulus not cemented.

OD = 13.375 in
ID = 12.615 in
T_c = 0.38 in
Set at 8 ft

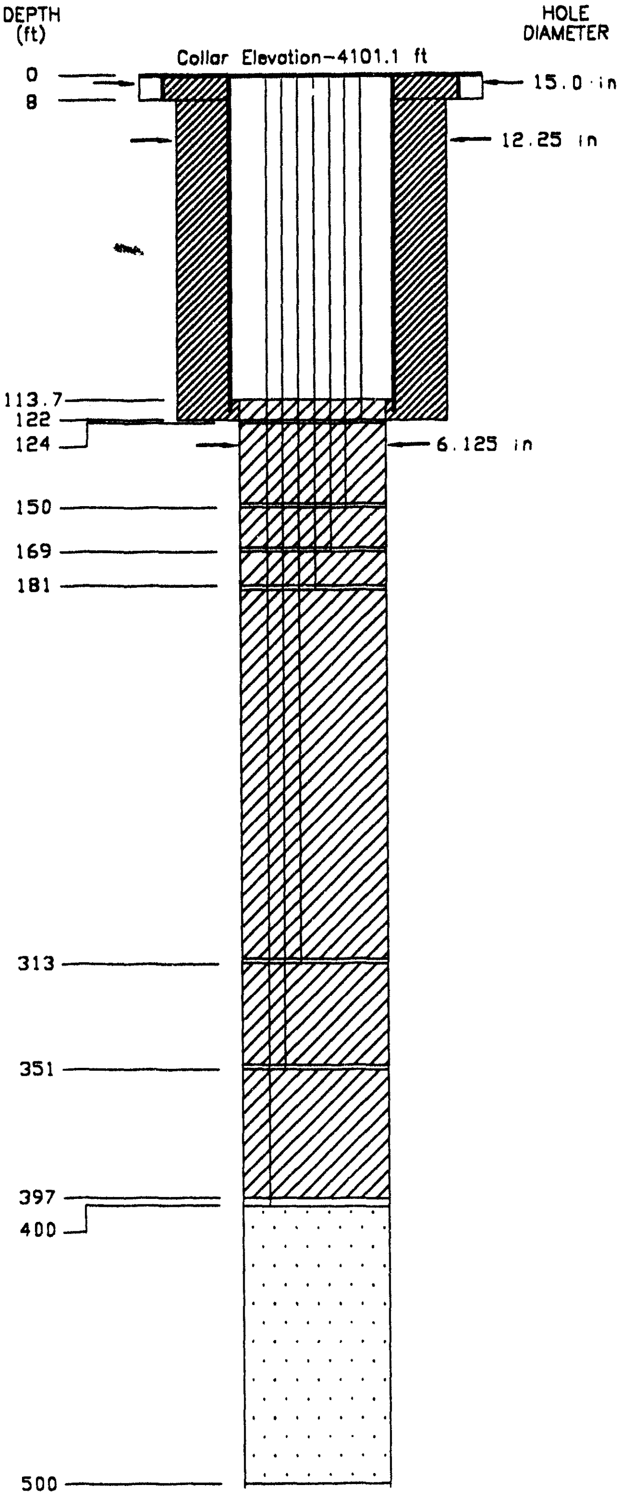
Ⓑ Annulus cemented with 108 ft^3 Gyp-Seal cement from 119 ft to surface.

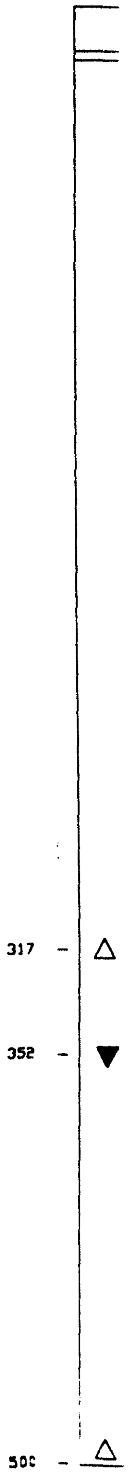
OD = 8.625 in
ID = 7.625 in
T_c = 0.5 in
PVC-plastic pipe
Set at 119 ft

7 piezometers installed on 7 continuous strings of 0.25 in OD plastic tubing; 1 ft^3 of sand and a small amount of bentonite used to stem 1 ft below and 2 ft above piezometers; hole filled with a total of 307 ft^3 of Cal-Seal cement from 397 to 113.7 ft. Piezometers set at 400, 351, 313, 181, 169, 150 and 124 ft. Hole is stemmed from 113.7 ft to surface with 17 sacks of sand, 11 sacks of bentonite gel and 25 ft^3 of dry Cal-Seal cement.



Bottom of hole filled with 18.5 sacks of Monterey sand and 0.5 sacks of bentonite gel.

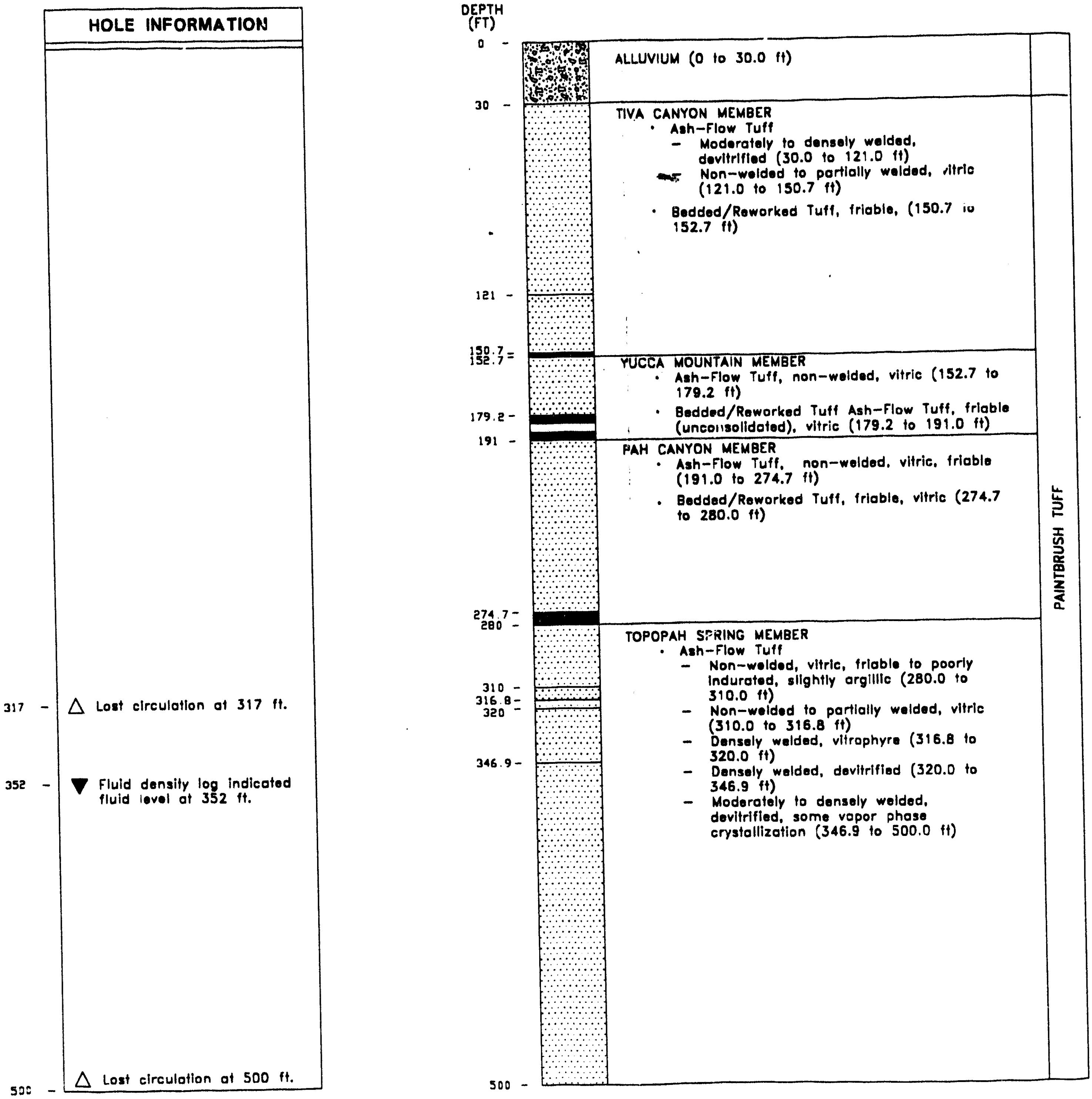




UE-25a #4

GENERALIZED STRATIGRAPHIC LOG

(Modified from Spengler and Rosenbaum, 1980)



317 – △ Lost circulation at 317 ft.

352 – ▼ Fluid density log indicated fluid level at 352 ft.

500 – △ Lost circulation at 500 ft.

ALLUVIUM (0 to 30.0 ft)

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified (30.0 to 121.0 ft)
  - Non-welded to partially welded, vitric (121.0 to 150.7 ft)
- Bedded/Reworked Tuff, friable, (150.7 to 152.7 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, non-welded, vitric (152.7 to 179.2 ft)
- Bedded/Reworked Tuff Ash-Flow Tuff, friable (unconsolidated), vitric (179.2 to 191.0 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric, friable (191.0 to 274.7 ft)
- Bedded/Reworked Tuff, friable, vitric (274.7 to 280.0 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric, friable to poorly indurated, slightly argillic (280.0 to 310.0 ft)
  - Non-welded to partially welded, vitric (310.0 to 316.8 ft)
  - Densely welded, vitrophyre (316.8 to 320.0 ft)
  - Densely welded, devitrified (320.0 to 346.9 ft)
  - Moderately to densely welded, devitrified, some vapor phase crystallization (346.9 to 500.0 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986c)

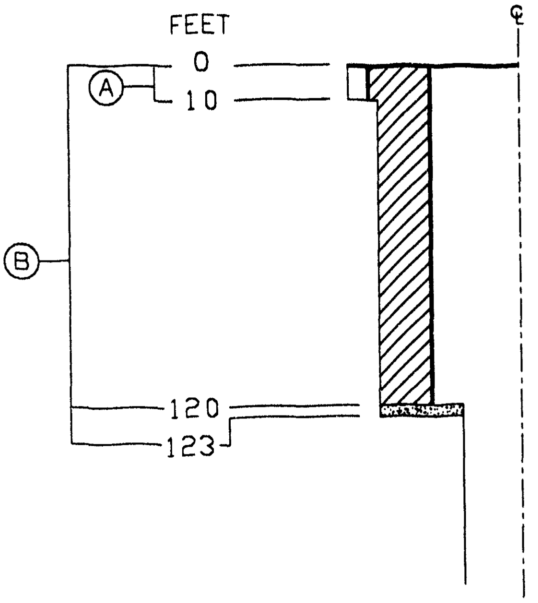
CEMENTING AND CASING INFORMATION

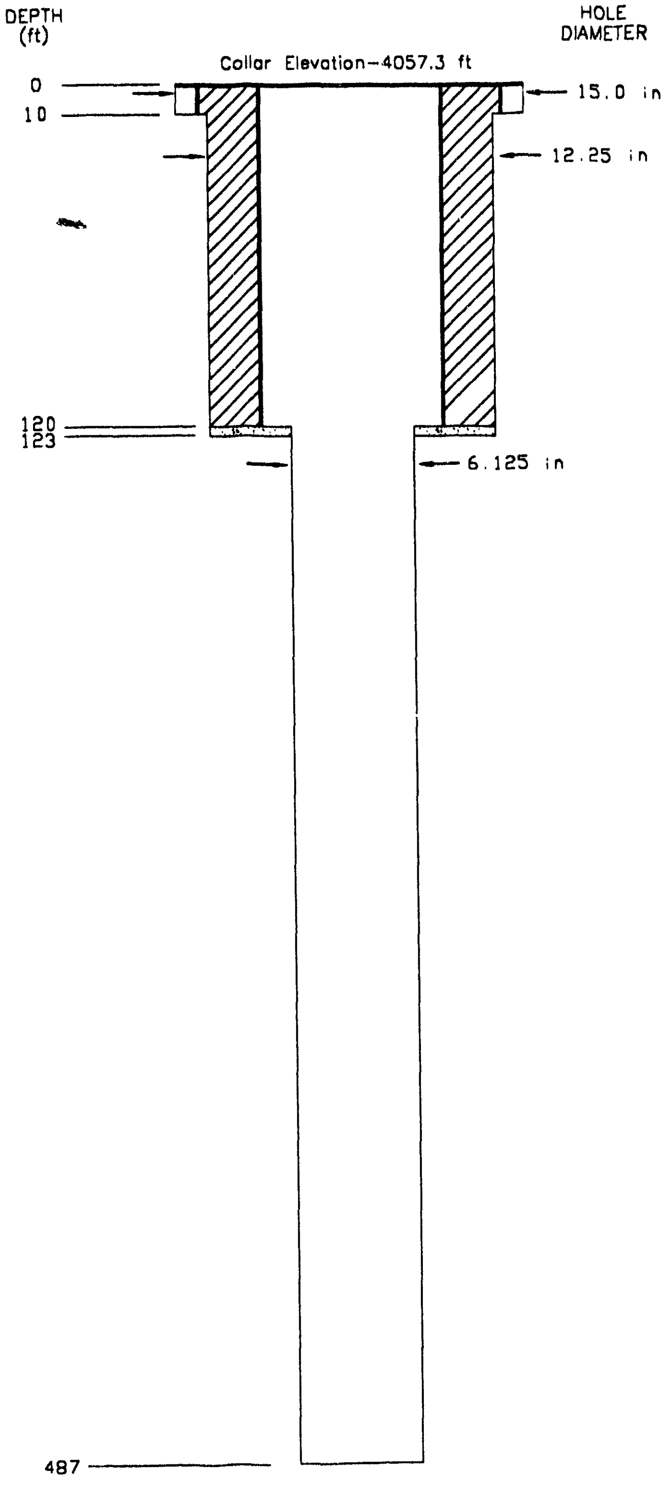
Ⓐ Annulus not cemented.

OD = 13.375 in
ID = 12.615 in
T_e = 0.380 in
Set at 10. ft

Ⓑ Annulus cemented with 75 ft^3 of Gyp-Seal gypsum cement from 120 ft to surface.

OD = 8.825 in
ID = 7.625 in
T_e = 0.5 in
PVC-plastic pipe
Set at 120 ft





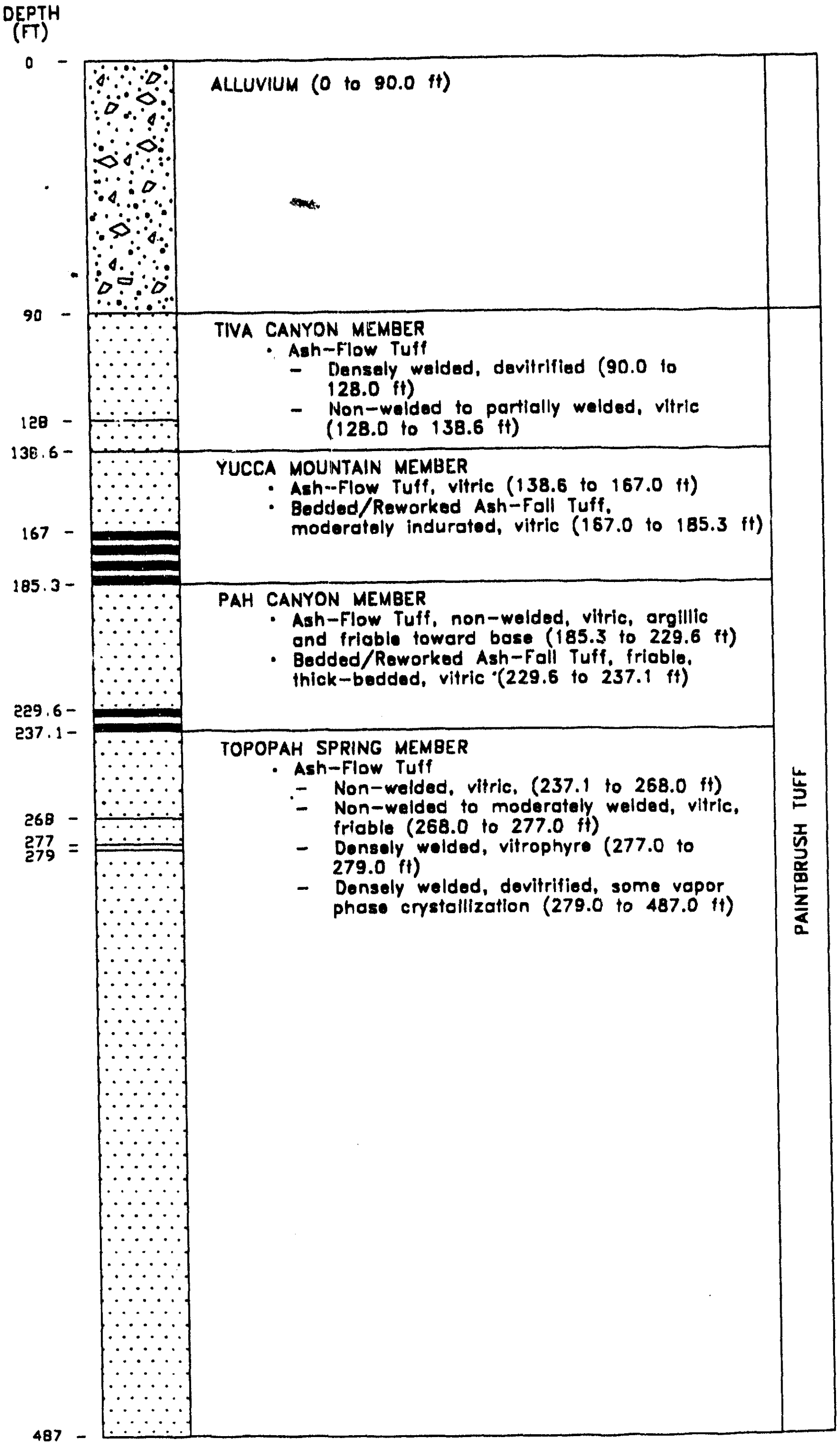
UE-25a # 5

GENERALIZED STRATIGRAPHIC LOG

(Modified from Spengler and Rosenbaum, 1980)

HOLE INFORMATION

123	△ Lost circulation at 123 ft.
245	△ Lost circulation from 245 to 288 ft.
288	
464	△ Lost circulation at 464 ft.



ALLUVIUM (0 to 90.0 ft)

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (90.0 to 128.0 ft)
  - Non-welded to partially welded, vitric (128.0 to 138.6 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, vitric (138.6 to 167.0 ft)
- Bedded/Reworked Ash-Fall Tuff, moderately indurated, vitric (167.0 to 185.3 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric, argillic and friable toward base (185.3 to 229.6 ft)
- Bedded/Reworked Ash-Fall Tuff, friable, thick-bedded, vitric (229.6 to 237.1 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric, (237.1 to 268.0 ft)
  - Non-welded to moderately welded, vitric, friable (268.0 to 277.0 ft)
  - Densely welded, vitrophyre (277.0 to 279.0 ft)
  - Densely welded, devitrified, some vapor phase crystallization (279.0 to 487.0 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987d)

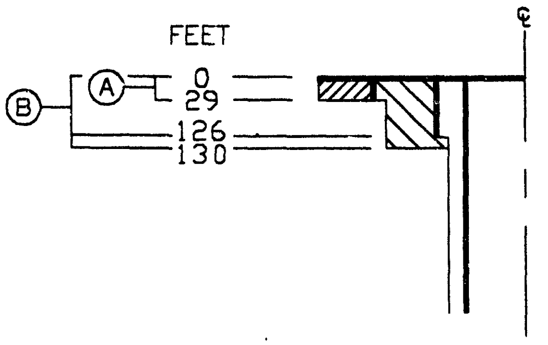
CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 81 ft^3 of neat cement plus 2% $CaCl_2$ and 10% sand from 29 ft to surface.

OD = 31 in
ID = 30 in
T_e = 0.50 in
Set at 29 ft

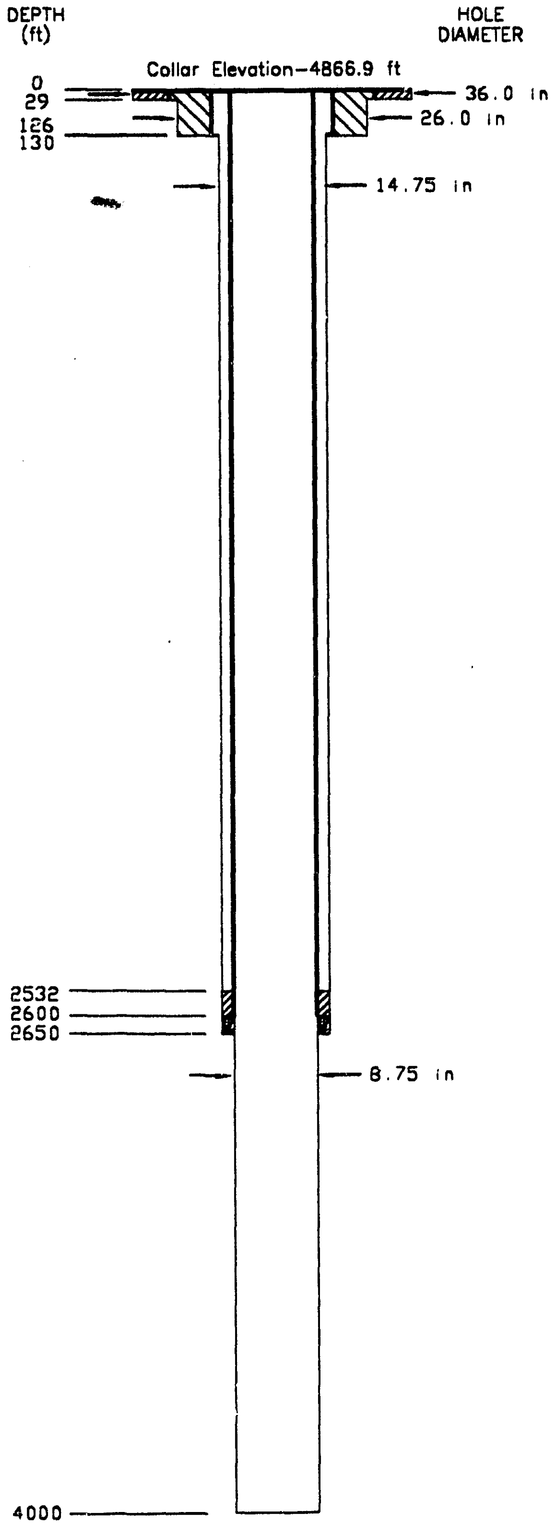
Ⓑ Annulus cemented with 673 ft^3 of neat cement +2% $CaCl_2$ from 127 ft to surface.

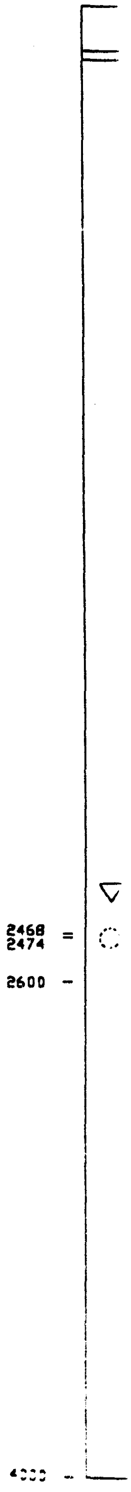
OD = 16 in
ID = 15.01 in
T_e = 0.495 in
Set at 126 ft



Annulus cemented with 75 ft^3 of neat cement +2% $CaCl_2$ from 2600 ft to 2532 ft.

OD = 10.75 in
ID = 9.950 in
T_e = 0.40 in
Set at 2600 ft

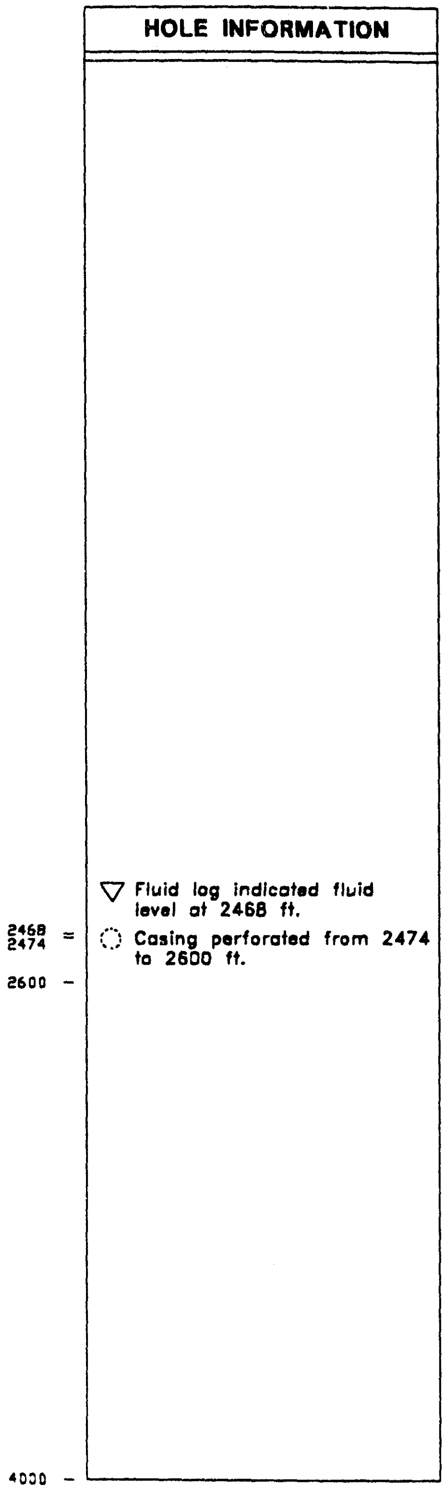




USW H-3

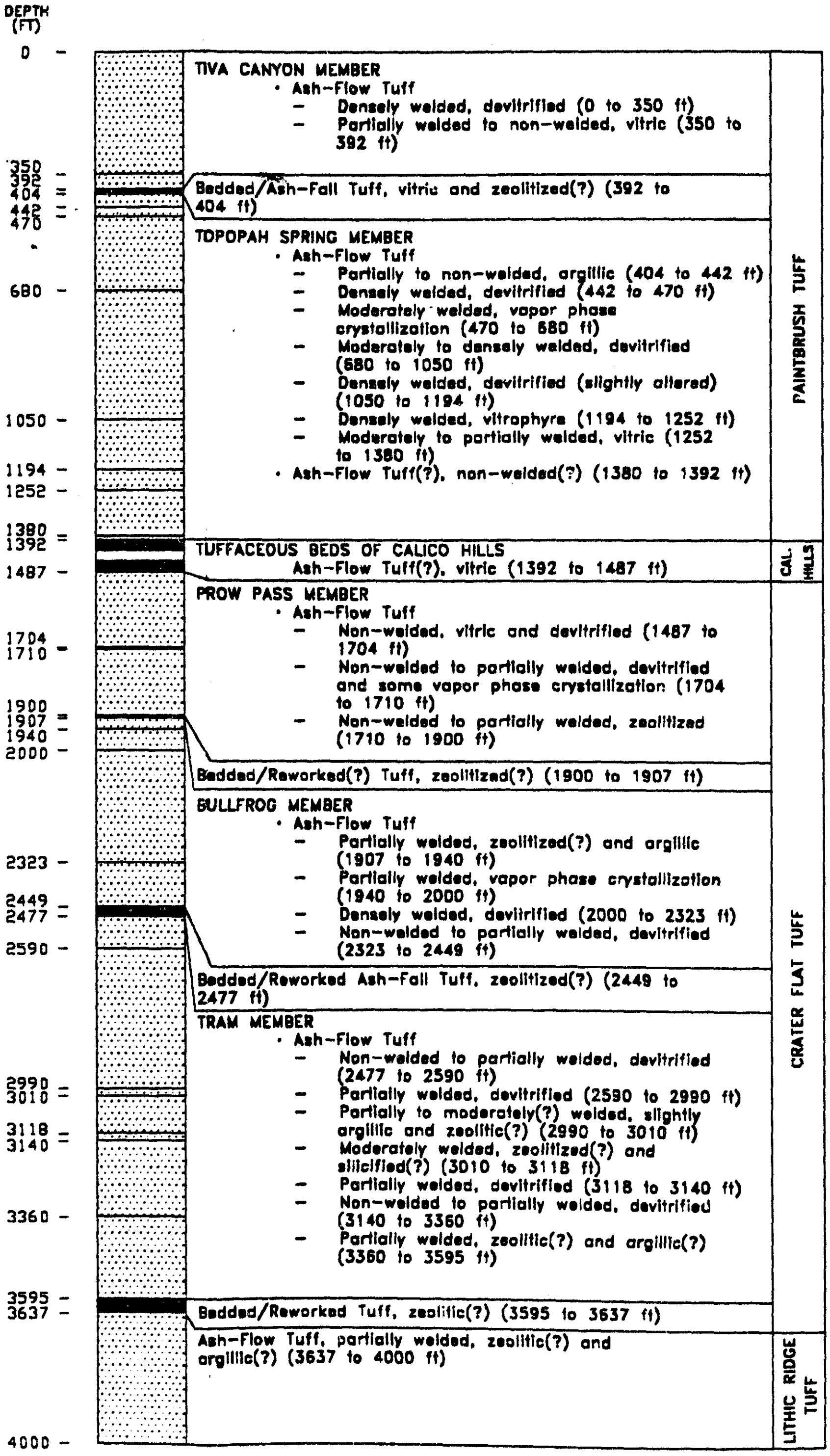
GENERALIZED STRATIGRAPHIC LOG

(Modified from Thordarson et al., 1984)



▽ Fluid log indicated fluid level at 2468 ft.

◌ Casing perforated from 2474 to 2600 ft.



TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (0 to 350 ft)
  - Partially welded to non-welded, vitric (350 to 392 ft)

Bedded/Ash-Fall Tuff, vitric and zeolitized(?) (392 to 404 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Partially to non-welded, argillic (404 to 442 ft)
  - Densely welded, devitrified (442 to 470 ft)
  - Moderately welded, vapor phase crystallization (470 to 680 ft)
  - Moderately to densely welded, devitrified (680 to 1050 ft)
  - Densely welded, devitrified (slightly altered) (1050 to 1194 ft)
  - Densely welded, vitrophyre (1194 to 1252 ft)
  - Moderately to partially welded, vitric (1252 to 1380 ft)
- Ash-Flow Tuff(?), non-welded(?) (1380 to 1392 ft)

TUFFACEOUS BEDS OF CALICO HILLS

Ash-Flow Tuff(?), vitric (1392 to 1487 ft)

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric and devitrified (1487 to 1704 ft)
  - Non-welded to partially welded, devitrified and some vapor phase crystallization (1704 to 1710 ft)
  - Non-welded to partially welded, zeolitized (1710 to 1900 ft)

Bedded/Reworked(?) Tuff, zeolitized(?) (1900 to 1907 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partially welded, zeolitized(?) and argillic (1907 to 1940 ft)
  - Partially welded, vapor phase crystallization (1940 to 2000 ft)
  - Densely welded, devitrified (2000 to 2323 ft)
  - Non-welded to partially welded, devitrified (2323 to 2449 ft)

Bedded/Reworked Ash-Fall Tuff, zeolitized(?) (2449 to 2477 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified (2477 to 2590 ft)
  - Partially welded, devitrified (2590 to 2990 ft)
  - Partially to moderately(?) welded, slightly argillic and zeolitic(?) (2990 to 3010 ft)
  - Moderately welded, zeolitized(?) and silicified(?) (3010 to 3118 ft)
  - Partially welded, devitrified (3118 to 3140 ft)
  - Non-welded to partially welded, devitrified (3140 to 3360 ft)
  - Partially welded, zeolitic(?) and argillic(?) (3360 to 3595 ft)

Bedded/Reworked Tuff, zeolitic(?) (3595 to 3637 ft)

Ash-Flow Tuff, partially welded, zeolitic(?) and argillic(?) (3637 to 4000 ft)

GENERALIZED DRILLER'S LOG

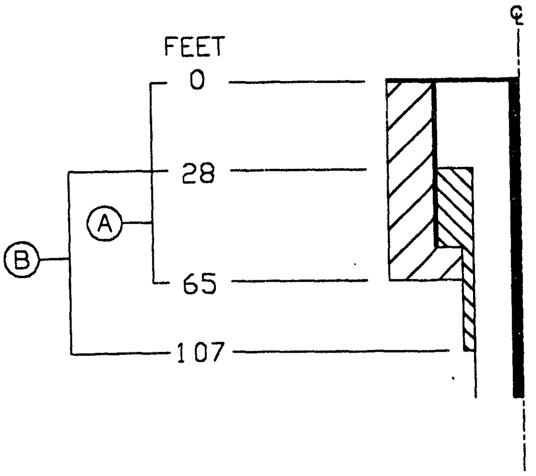
(From Fenix and Scisson, 1986c)

CEMENTING AND CASING INFORMATION

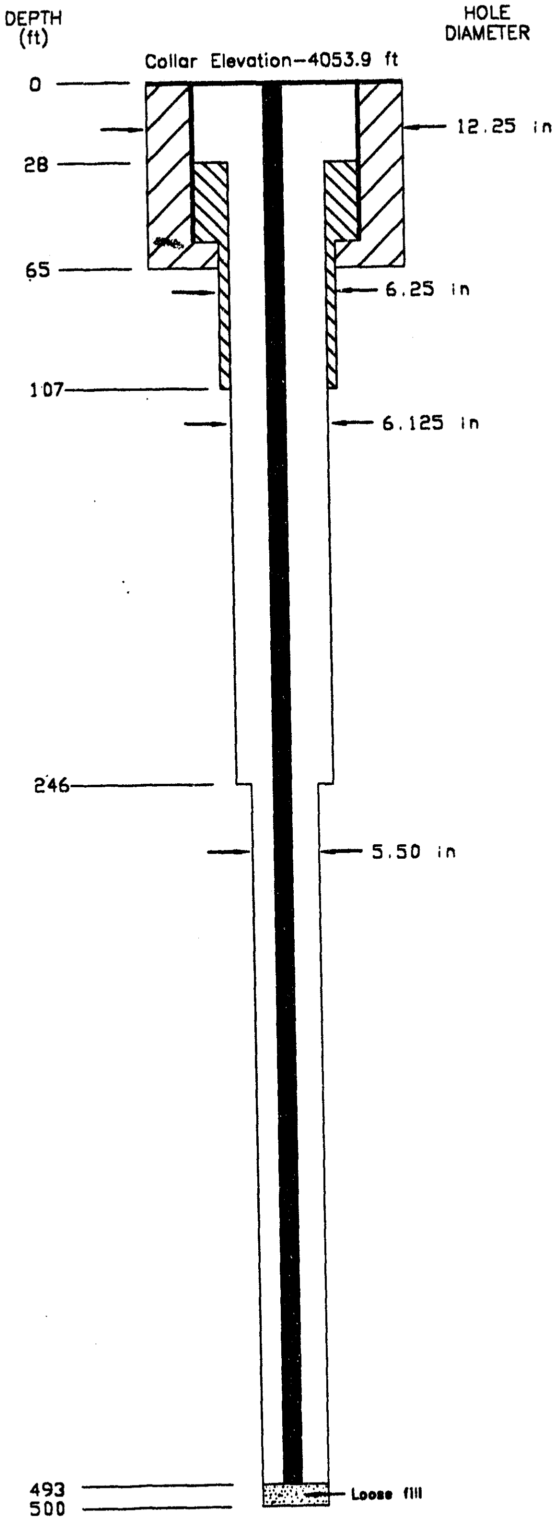
Ⓐ Annulus cemented with 126 ft^3 of gypsum cement from 57 ft to surface.

OD = 8.625 in
ID = 7.625 in
T_e = 0.50 in
PVC–plastic pipe
Set at 57 ft

Ⓑ Hole cemented from 28.5 to 107 ft with 25 ft^3 of neat cement plus 2% $CaCl_2$ in order to stabilize hole, then drilled out.



2.375 in OD Hydril tubing set at 493 ft.

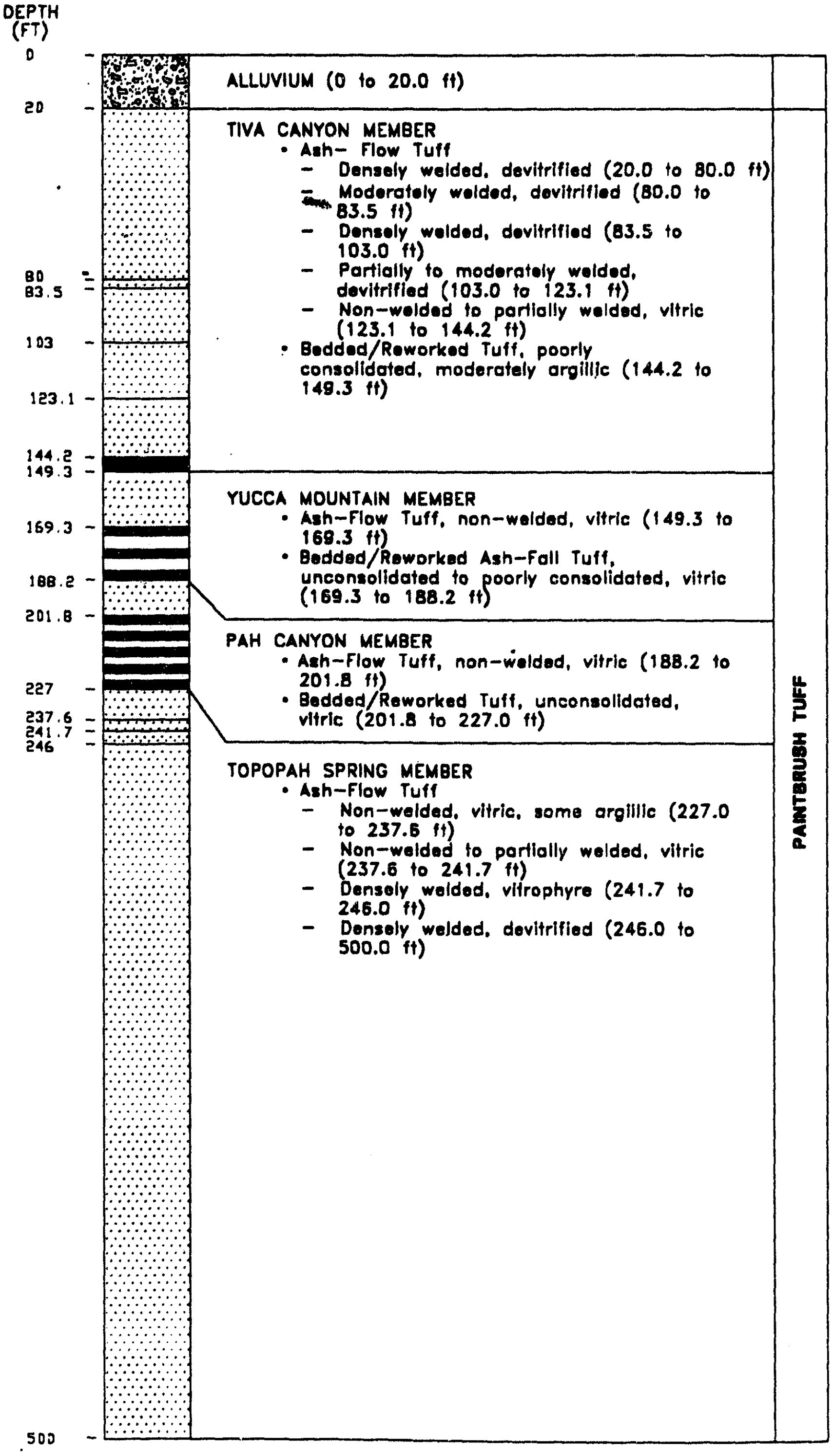


HOLE INF

UE-25a #6

GENERALIZED STRATIGRAPHIC LOG
(Modified from Spengler and Rosenbaum, 1980)

HOLE INFORMATION



ALLUVIUM (0 to 20.0 ft)

TIVA CANYON MEMBER
- Ash- Flow Tuff
  - Densely welded, devitrified (20.0 to 80.0 ft)
  - Moderately welded, devitrified (80.0 to 83.5 ft)
  - Densely welded, devitrified (83.5 to 103.0 ft)
  - Partially to moderately welded, devitrified (103.0 to 123.1 ft)
  - Non-welded to partially welded, vitric (123.1 to 144.2 ft)
- Bedded/Reworked Tuff, poorly consolidated, moderately argillic (144.2 to 149.3 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, non-welded, vitric (149.3 to 169.3 ft)
- Bedded/Reworked Ash-Fall Tuff, unconsolidated to poorly consolidated, vitric (169.3 to 188.2 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric (188.2 to 201.8 ft)
- Bedded/Reworked Tuff, unconsolidated, vitric (201.8 to 227.0 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric, some argillic (227.0 to 237.6 ft)
  - Non-welded to partially welded, vitric (237.6 to 241.7 ft)
  - Densely welded, vitrophyre (241.7 to 246.0 ft)
  - Densely welded, devitrified (246.0 to 500.0 ft)

UE

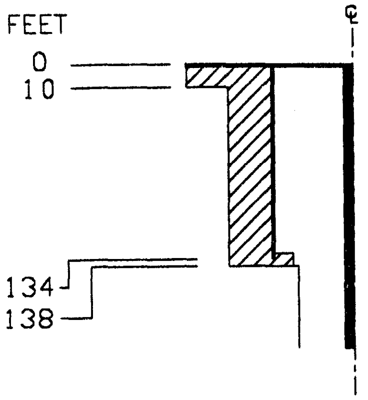
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986c)

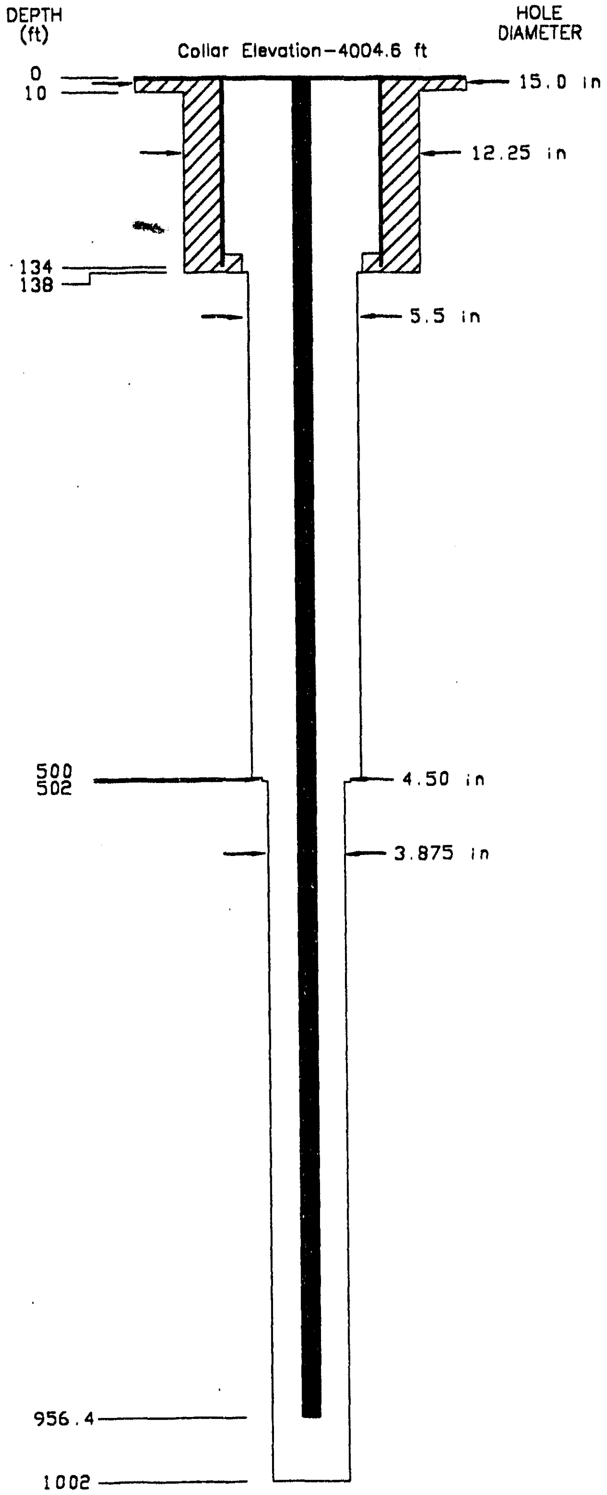
CEMENTING AND CASING INFORMATION

Annulus cemented with 90 ft^3 of Gyp-Seal gypsum cement from 135 ft to surface.

OD = 8.625 in
ID = 7.625 in
T_c = 0.5 in
PVC-plastic pipe
Set at 134 ft



2.375 in OD Hydril tubing set at 956.4 ft.



20 – ● Ho
at

119 – △ Lo
128 – △ Lo

508 – △ Lc

1002 –

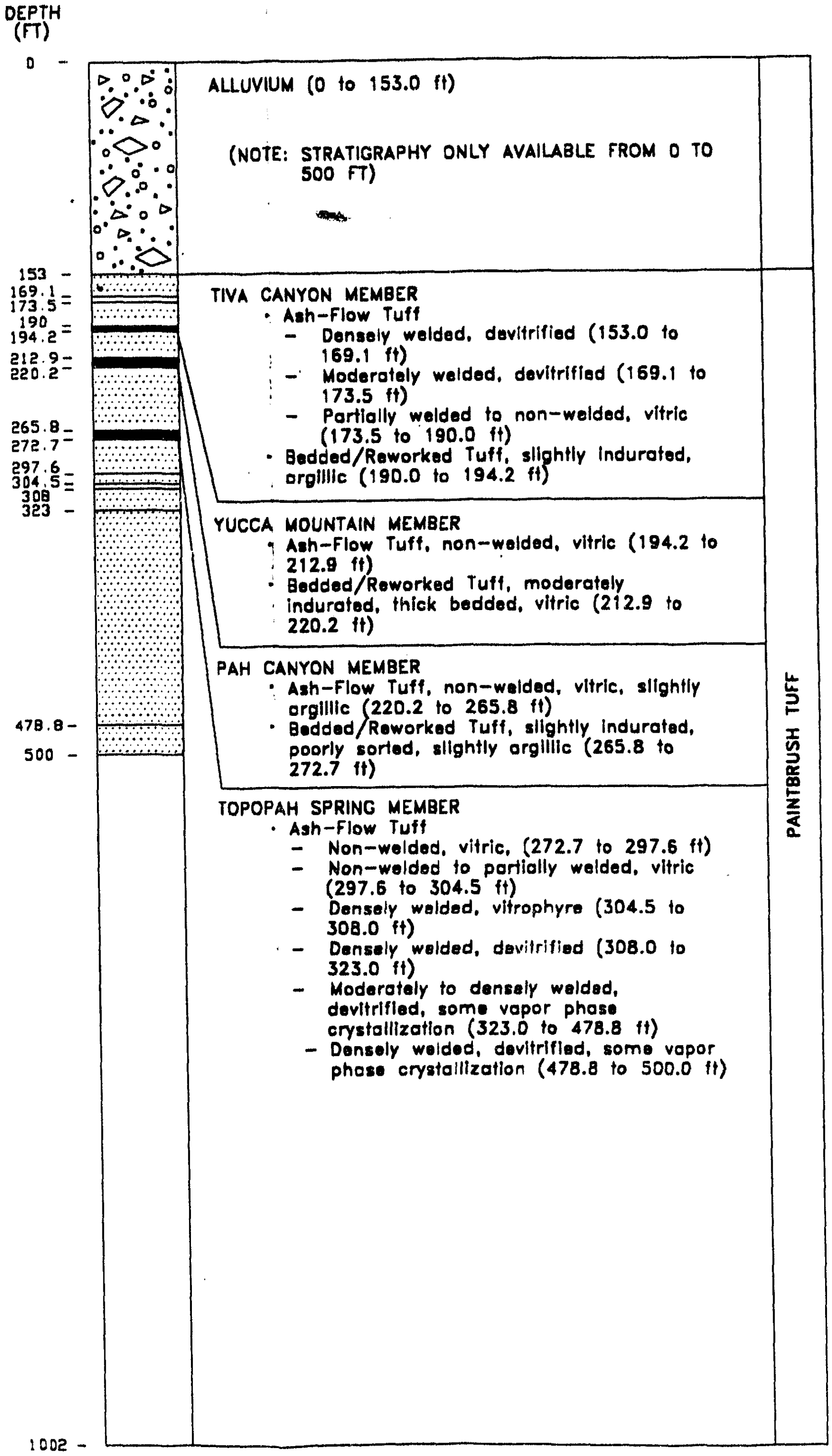
UE-25a #7

GENERALIZED STRATIGRAPHIC LOG

(Modified from Spengler and Rosenbaum, 1980)

HOLE INFORMATION

20	● Hole enlargement to 17.5 in at 20 ft.
119	△ Lost circulation at 119 ft.
128	△ Lost circulation at 128 ft.
508	△ Lost circulation at 508 ft.
1002	



ALLUVIUM (0 to 153.0 ft)

(NOTE: STRATIGRAPHY ONLY AVAILABLE FROM 0 TO 500 FT)

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (153.0 to 169.1 ft)
  - Moderately welded, devitrified (169.1 to 173.5 ft)
  - Partially welded to non-welded, vitric (173.5 to 190.0 ft)
- Bedded/Reworked Tuff, slightly indurated, argillic (190.0 to 194.2 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, non-welded, vitric (194.2 to 212.9 ft)
- Bedded/Reworked Tuff, moderately indurated, thick bedded, vitric (212.9 to 220.2 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric, slightly argillic (220.2 to 265.8 ft)
- Bedded/Reworked Tuff, slightly indurated, poorly sorted, slightly argillic (265.8 to 272.7 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric, (272.7 to 297.6 ft)
  - Non-welded to partially welded, vitric (297.6 to 304.5 ft)
  - Densely welded, vitrophyre (304.5 to 308.0 ft)
  - Densely welded, devitrified (308.0 to 323.0 ft)
  - Moderately to densely welded, devitrified, some vapor phase crystallization (323.0 to 478.8 ft)
  - Densely welded, devitrified, some vapor phase crystallization (478.8 to 500.0 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986d)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 300 ft^3 of neat cement plus 2% $CaCl_2$ from 35 ft to surface.

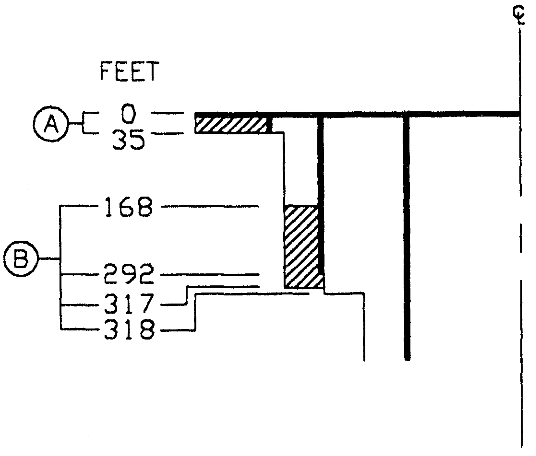
OD = 20.5 in
ID = 20 in
T_a = 0.25 in
Set at 34 ft

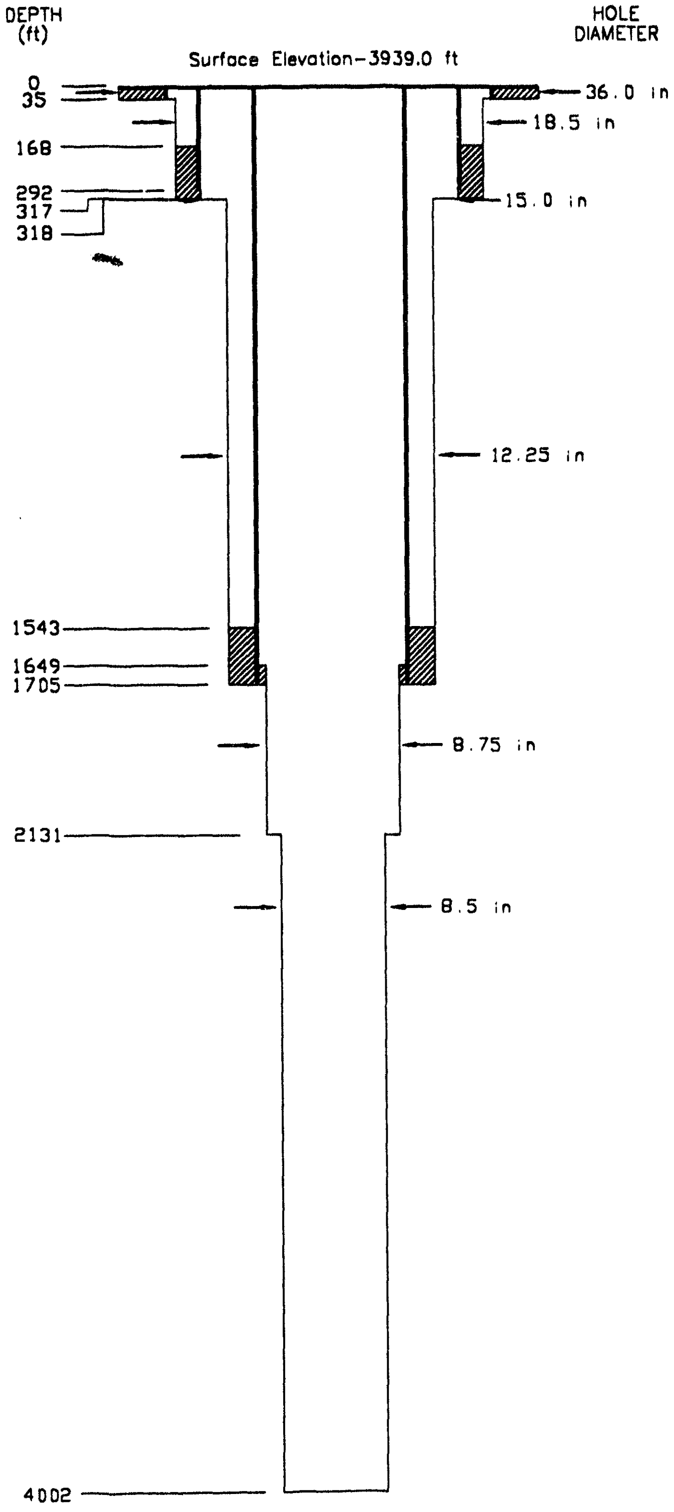
Ⓑ Annulus cemented with 635 ft^3 of neat cement plus 2% $CaCl_2$ from 317 ft to 168 ft.

OD = 16 in
ID = 15.010 in
T_a = 0.495 in
Set at 292 ft

Annulus spot cemented with 100 ft^3 of neat cement plus 2% $CaCl_2$ from 1705 ft to 1543 ft.

OD = 9.625 in
ID = 8.921 in
T_a = 0.352 in
Set at 1700 ft





UE-25b #1

GENERALIZED STRATIGRAPHIC LOG

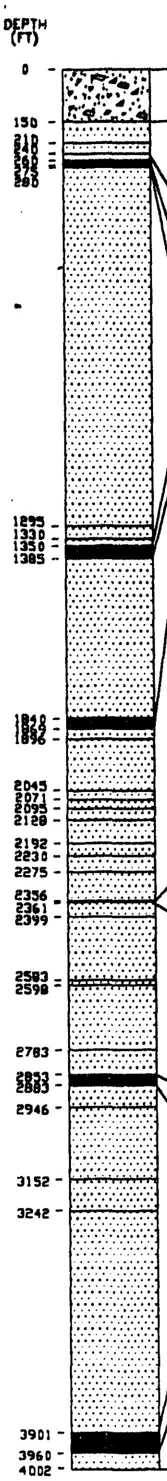
(From Lobmeyer et al., 1983)

)LE
ETER

.0 in

HOLE INFORMATION

	■ Hole caving from approximately 1100 to 1550 ft. Hole cemented from 1105 to 1200 ft with 1000 ft^3 of neat cement plus 2% $CaCl_2$ and 0.5 lbs/ft^3 LCM, then drilled out leaving 922 ft^3 of cement to stabilize borehole wall.
1105 –	
1190 1200 1205 =	△ Lost circulation and tight hole from 1190 to 1205 ft.
	▽ Fluid level indicated at 1550 ft.
1550 1564 =	◌ Casing perforated from 1564 to 1644 ft.
1644 –	
3908 –	● Hole caved in at 3908 ft.
4002 –	



ALLUVIUM (0 to 150 ft)	
TIVA CANYON MEMBER • Ash-Flow Tuff – Densely welded (150 to 210 ft) – Partially to non-welded, vitric (210 to 240 ft)	PAINTBRUSH TUFF
PAH CANYON MEMBER • Ash-Flow Tuff, non-welded, vitric (240 to 260 ft)	
Bedded/Reworked Tuff, vitric and devitrified, rich in pumice (260 to 275 ft)	
TOPOPAH SPRING MEMBER • Ash-Flow Tuff – Densely welded, vitrophyre (275 to 280 ft) – Densely welded, devitrified (280 to 1295 ft) – Densely welded, vitrophyre (1295 to 1330 ft) – Moderately to partially welded, vitric (1330 to 1350 ft)	
Bedded/Reworked Tuff, altered (1350 to 1385 ft)	
TUFFACEOUS BEDS OF CALICO HILLS • Ash-Flow Tuff, non-welded, zeolitized (1385 to 1840 ft) • Bedded Ash-Fall Tuff (1840 to 1869 ft)	CALICO HILLS
PROW PASS MEMBER • Ash-Flow Tuff – Non-welded to partially welded, zeolitized (1869 to 1896 ft) – Partially to moderately welded, devitrified (1896 to 2045 ft) – Partially welded to non-welded, devitrified, slightly argillic (2045 to 2071 ft) – Non-welded, devitrified, some vapor phase, partially zeolitized (2071 to 2095 ft) – Partially welded, devitrified (2095 to 2128 ft) – Partially welded, devitrified, zeolitized and silicified (2128 to 2192 ft) – Partially to moderately welded, devitrified, moderately to highly silicified and zeolitized (2192 to 2230 ft) – Partially welded, devitrified (2230 to 2275 ft) – Non-welded, devitrified, zeolitized (2275 to 2356 ft)	CRATER FLAT TUFF
Bedded/Reworked Ash-Fall Tuff, devitrified, some beds silicified/zeolitized (2356 to 2361 ft)	
BULLFROG MEMBER • Ash-Flow Tuff – Partially welded, devitrified (2361 to 2399 ft) – Partially welded, vapor phase (2399 to 2583 ft) • Ash-Fall(?) Tuff, partially welded(?) (2583 to 2598 ft) • Ash-Flow Tuff – Moderately welded, devitrified (2598 to 2783 ft) – Partially welded to non-welded, moderately zeolitic, slightly argillic (2783 to 2853 ft)	
Bedded/Reworked Tuff, zeolitized (2853 to 2883 ft)	
TRAM MEMBER • Ash-Flow Tuff – Non-welded to partially welded, zeolitic (2883 to 2946 ft) – Partially welded, devitrified (2946 to 3152 ft) – Moderately welded, devitrified, slightly to moderately silicified (3152 to 3242 ft) – Partially to moderately welded, devitrified, some zeolitized and argillic (3242 to 3901 ft)	
Bedded/Reworked Tuff, moderately to highly indurated, zeolitic (3901 to 3960 ft)	
LITHIC RIDGE TUFF • Ash-Flow Tuff, moderately welded, devitrified, argillic and zeolitized (3960 to 4002 ft)	LITHIC RIDGE

US

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 50 ft^3 of neat cement plus 3% $CaCl_2$ from 27 ft to surface.

OD = 20 in
ID = 19 in
T_e = 0.5 in
Set at 27 ft

Ⓑ Annulus cemented with 300 ft^3 of neat cement plus 3% $CaCl_2$ from 280 ft to surface.

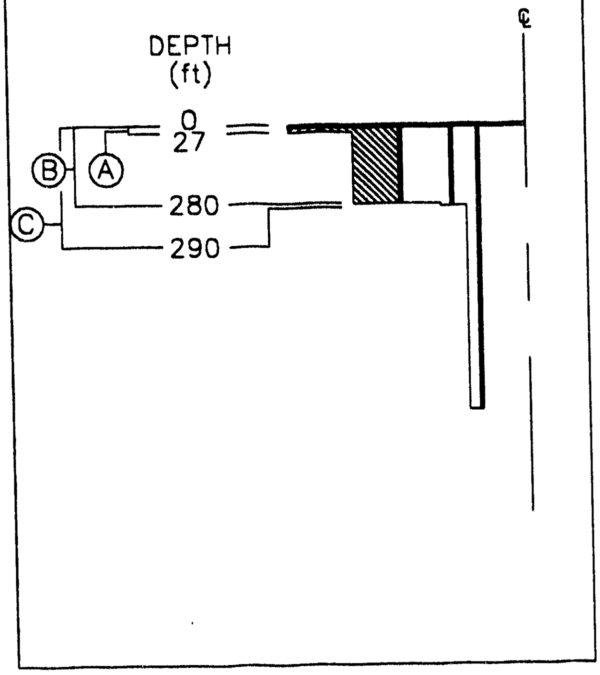
OD = 13.375 in
ID = 12.615 in
T_e = 0.380 in
Set at 280 ft

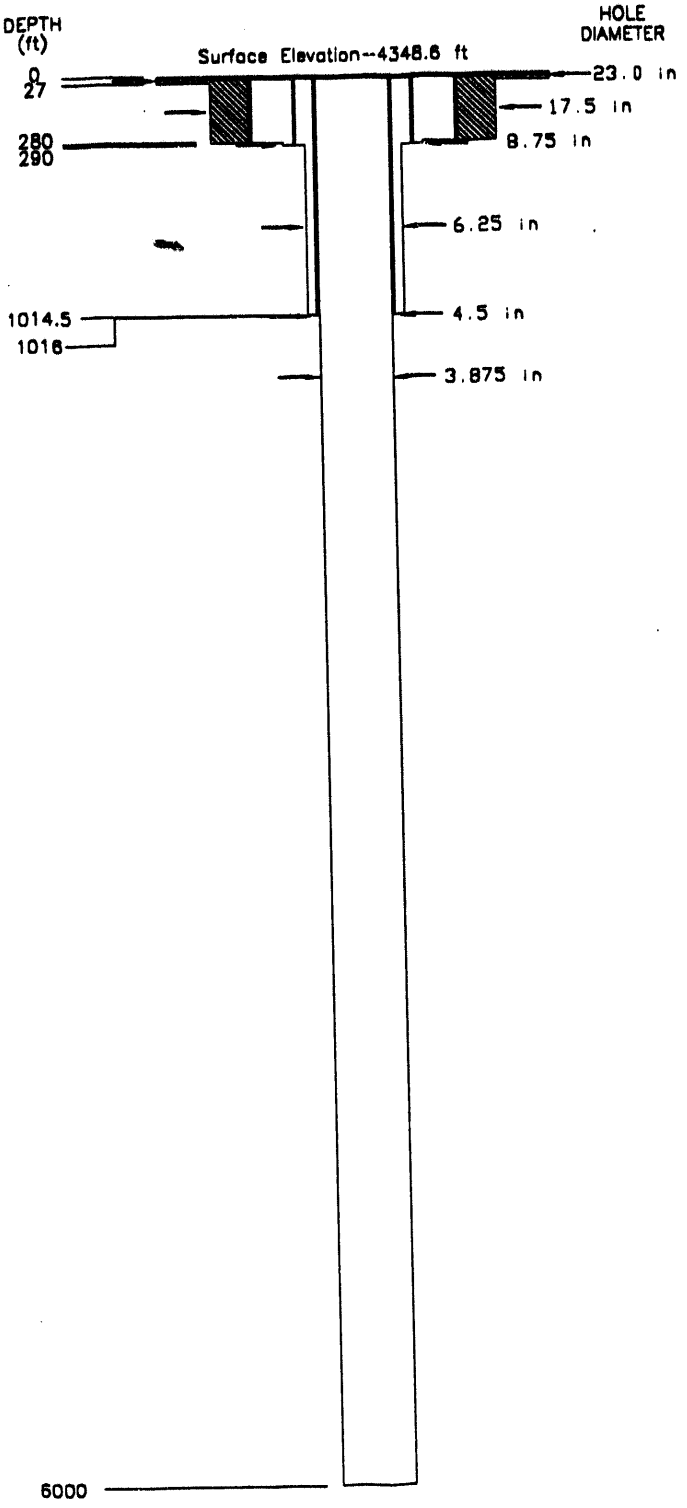
Ⓒ Annulus not cemented.

OD = 7.625 in
ID = 6.75 in
T_e = 0.438 in
Set at 290 ft

Annulus not cemented.

OD = 4.5 in
ID = 4.0 in
T_e = 0.25 in
Set at 1016 ft





785
786
1013
1382

USW G-1

GENERALIZED STRATIGRAPHIC LOG

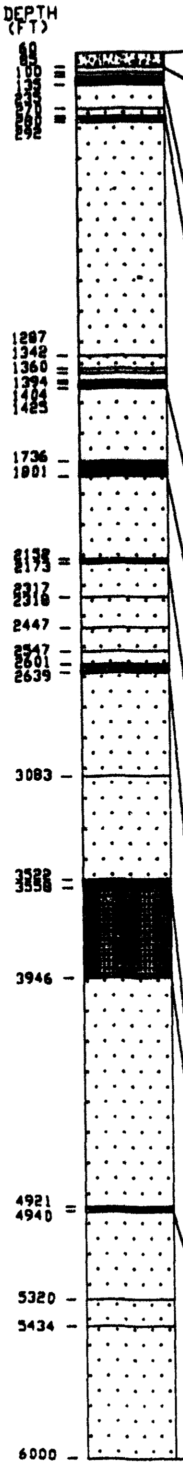
(Modified from Spengler et al., 1981)

HOLE INFORMATION

785
786 – ● Hole enlargement of 23.5 in at 786 ft.

1013 – ■ Hole cemented from 785 to 1013 ft with 100 ft^3 of cement. Cement drilled out with 52 ft^3 remaining on side of hole to stabilize.

1382 – △ Lost circulation at 1382 ft.



PAINTBRUSH TUFF

ALLUVIUM (0.0 to 80.0 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff
  - Partially welded, vapor phase crystallization (80.0 to 85.0 ft)
  - Non-welded, vitric (85.0 to 100.0 ft)
- Bedded/Reworked Tuff, poorly consolidated, vitric (100.0 to 135.0 ft)

PAH CANYON MEMBER
- Ash-Fall Tuff, non-welded, vitric (135.0 to 235.0 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (235.0 to 270.0 ft)
  - Densely welded, vitrophyre (270.0 to 280.0 ft)
  - Densely welded, vitric (280.0 to 292.5 ft)
  - Densely welded, devitrified (292.5 to 1287.0 ft)
  - Densely welded, vitrophyre (1287.0 to 1342.4 ft)
  - Moderately welded, vitric (1342.4 to 1360.5 ft)
  - Partially welded to non-welded, vitric (1360.5 to 1394.3 ft)
  - Non-welded, devitrified (1394.3 to 1403.9 ft)
- Bedded/Reworked Tuff, vitric (1403.9 to 1425.5 ft)

CALICO HILLS

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded to partially welded, devitrified and zeolitized (1425.5 to 1736.4 ft)
- Bedded/Reworked Ash-Fall Tuff (Tuffaceous Sandstone), zeolitized to silicified (1736.4 to 1801.5 ft)

CRATER FLAT TUFF

PROW PASS MEMBER
- Ash-Flow Tuff partially to moderately welded, devitrified, some vapor phase crystallization, some pumice vitric (1801.5 to 2152.0 ft)
- Bedded/Reworked Ash-Fall Tuff (Tuffaceous Sandstone), zeolitized, slightly argillic (2152.0 to 2173.0 ft).

BULLFROG MEMBER
- Ash-Flow Tuff, Non-welded to partially welded devitrified, some argillic (2173.0 to 2317.4 ft)
- Bedded/Reworked Tuff, moderately indurated (2317.4 to 2317.9 ft)
- Ash-Flow Tuff
  - Partially welded, vapor phase crystallization (2317.9 to 2447.0 ft)
  - Moderately to densely welded, devitrified (2447.0 to 2547.1 ft)
  - Moderately to partially welded, devitrified (2547.1 to 2601.6 ft)
- Bedded/Reworked Tuff (2601.6 to 2639.4 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Partially to moderately welded, devitrified (2639.4 to 3083.0 ft)
  - Non-welded to partially welded, zeolitic and argillic (3083.0 to 3522.0 ft)
- Bedded/Reworked Ash-Fall Tuff and Tuffaceous Sandstone, moderately indurated (3522.0 to 3558.2 ft)

Flow Breccia (Tuff, Breccia, and Lava Flows) (3558.2 to 3945.8 ft)

LITHIC RIDGE TUFF

LITHIC RIDGE TUFF
- Ash-Flow Tuff, partially welded, well indurated, argillic and zeolitic (3945.8 to 4920.7 ft)
- Bedded/Reworked Ash-Fall Tuff, moderately indurated (4920.7 to 4940.2 ft)

OLDER TUFFS

Ash-Flow and Bedded Tuff (Undivided)
- Unit A (4940.2 to 5320.0 ft)
- Unit B (5320.0 to 5434.0 ft)
- Unit C (5434.0 to 6000.0 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987d)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 205 ft³ of neat cement plus 2% $CaCl_2$ from 35 ft to 18 ft and 36 ft³ of Redi-Mix from 18 ft to surface.

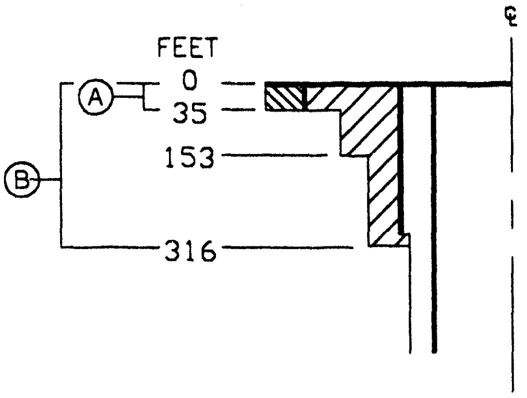
OD = 30.000 in
ID = 29.250 in
T_s = 0.375 in
Set at 35 ft

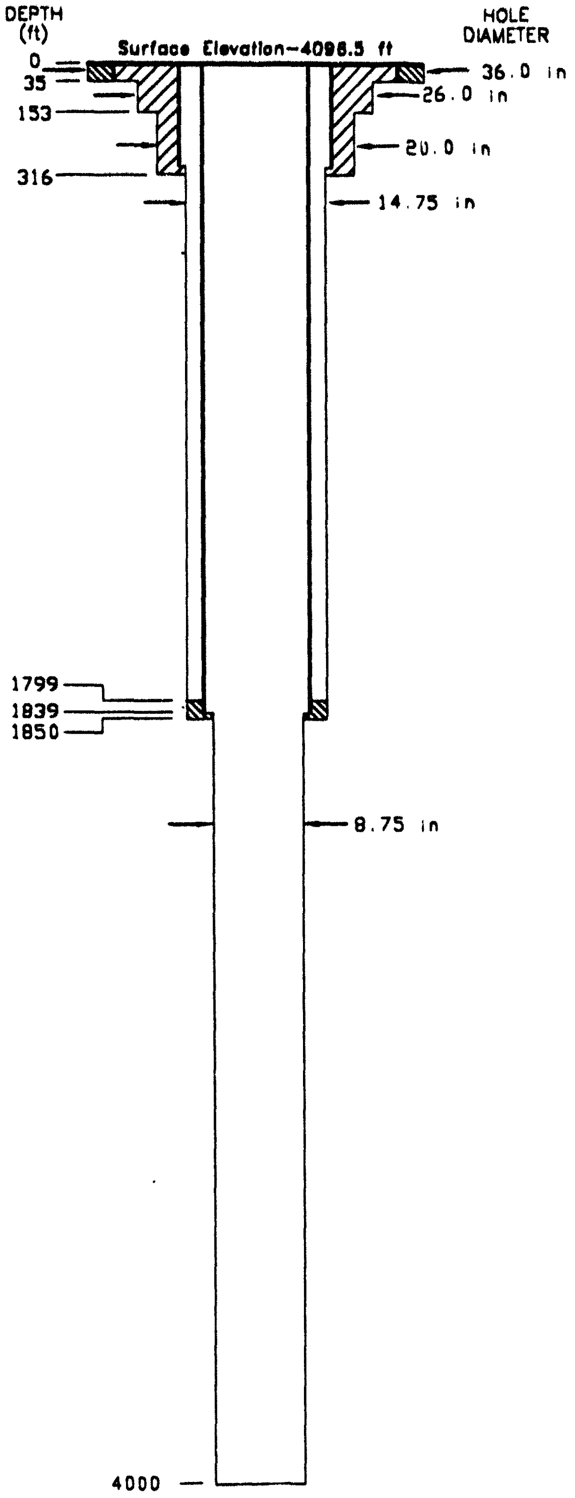
Ⓑ Annulus cemented with 720 ft³ of neat cement plus 3% $CaCl_2$ from 316 ft to 3.5 ft.

OD = 16.000 in
ID = 15.010 in
T_s = 0.495 in
Set at 311 ft

Annulus cemented with 100 ft³ of neat cement plus 3% $CaCl_2$ from 1850 ft to approximately 1799 ft.

OD = 10.75 in
ID = 9.95 in
T_s = 0.40 in
Set at 1839 ft





USW H-4

GENERALIZED STRATIGRAPHIC LOG

(Modified from Whitfield et al., 1984)

HOLE INFORMATION

232 = 243 — ● Caliper log indicates hole enlargement to 22 in from 232 to 243 ft.

330 —

1060 — ● Below 330 ft several eroded areas with maximum hole enlargement of 29 in at 1060 ft.

1650 — 1750 = 1770 = 1777 = 1860 — ● Gradual washout to 22 in from 1650 to 1777 ft.

■ 1.9 in OD tubing set at 1725 ft.

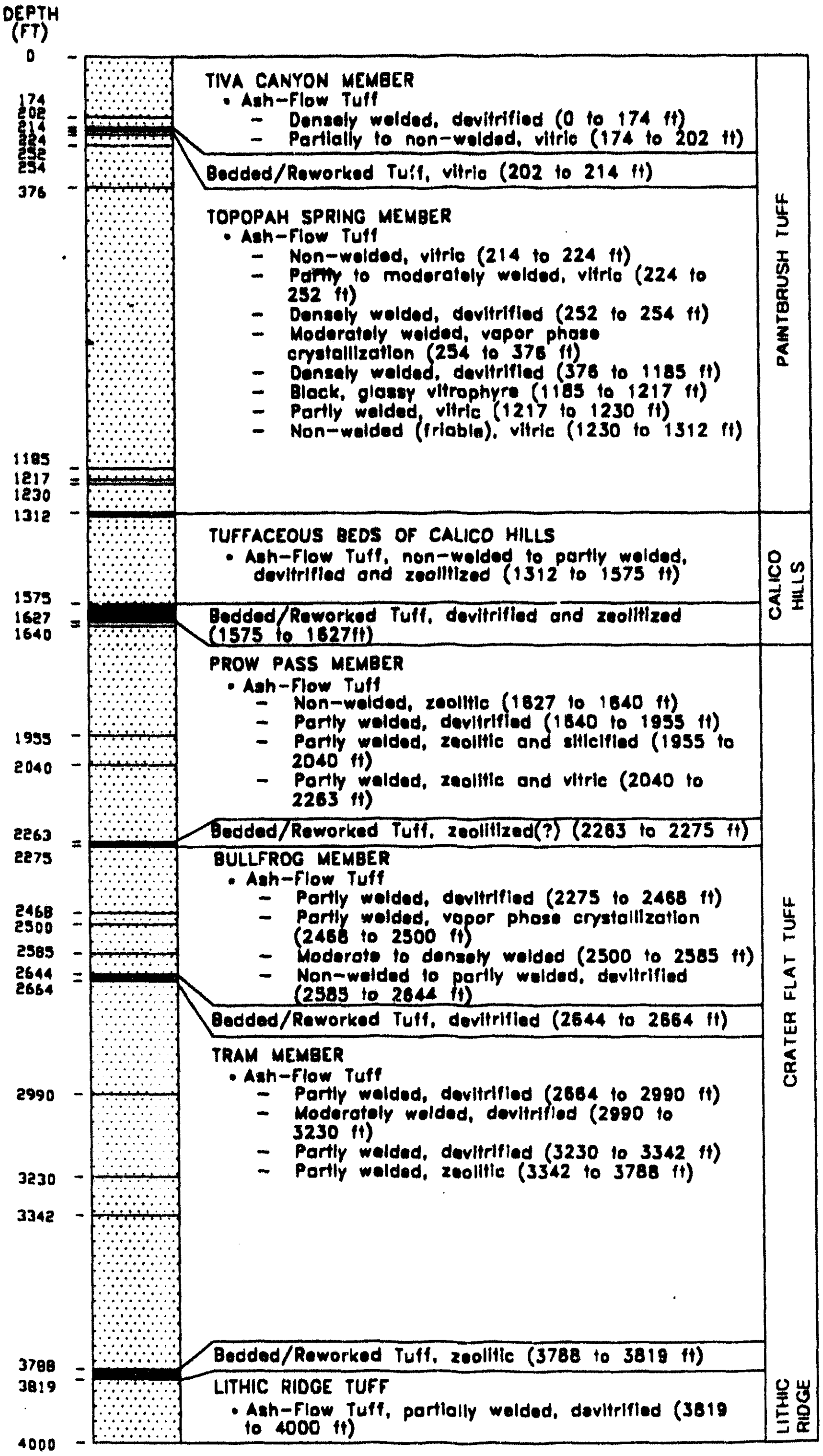
◌ Casing perforated from 1750 to 1770 ft.

2261 = 2274 — ▲ Increase in formation water noted at 2261 ft.

● Gradual washout from 1860 to 2870 ft with maximum hole enlargement of 19.75 in at 2274 ft.

2870 —

3876 = 3896 — ■ Tam packer on 2.875 in OD tubing set at 3876 ft with bottom of slotted and bull nosed tubing at 3896 ft.



TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (0 to 174 ft)
  - Partially to non-welded, vitric (174 to 202 ft)

Bedded/Reworked Tuff, vitric (202 to 214 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (214 to 224 ft)
  - ~~Partly~~ to moderately welded, vitric (224 to 252 ft)
  - Densely welded, devitrified (252 to 254 ft)
  - Moderately welded, vapor phase crystallization (254 to 376 ft)
  - Densely welded, devitrified (376 to 1185 ft)
  - Black, glassy vitrophyre (1185 to 1217 ft)
  - Partly welded, vitric (1217 to 1230 ft)
  - Non-welded (friable), vitric (1230 to 1312 ft)

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded to partly welded, devitrified and zeolitized (1312 to 1575 ft)

Bedded/Reworked Tuff, devitrified and zeolitized (1575 to 1627ft)

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, zeolitic (1627 to 1640 ft)
  - Partly welded, devitrified (1640 to 1955 ft)
  - Partly welded, zeolitic and silicified (1955 to 2040 ft)
  - Partly welded, zeolitic and vitric (2040 to 2263 ft)

Bedded/Reworked Tuff, zeolitized(?) (2263 to 2275 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partly welded, devitrified (2275 to 2468 ft)
  - Partly welded, vapor phase crystallization (2468 to 2500 ft)
  - Moderate to densely welded (2500 to 2585 ft)
  - Non-welded to partly welded, devitrified (2585 to 2644 ft)

Bedded/Reworked Tuff, devitrified (2644 to 2664 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Partly welded, devitrified (2664 to 2990 ft)
  - Moderately welded, devitrified (2990 to 3230 ft)
  - Partly welded, devitrified (3230 to 3342 ft)
  - Partly welded, zeolitic (3342 to 3788 ft)

Bedded/Reworked Tuff, zeolitic (3788 to 3819 ft)

LITHIC RIDGE TUFF
- Ash-Flow Tuff, partially welded, devitrified (3819 to 4000 ft)

U

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 90 ft^3 of neat cement plus 2% $CaCl_2$ from 38 ft to surface.

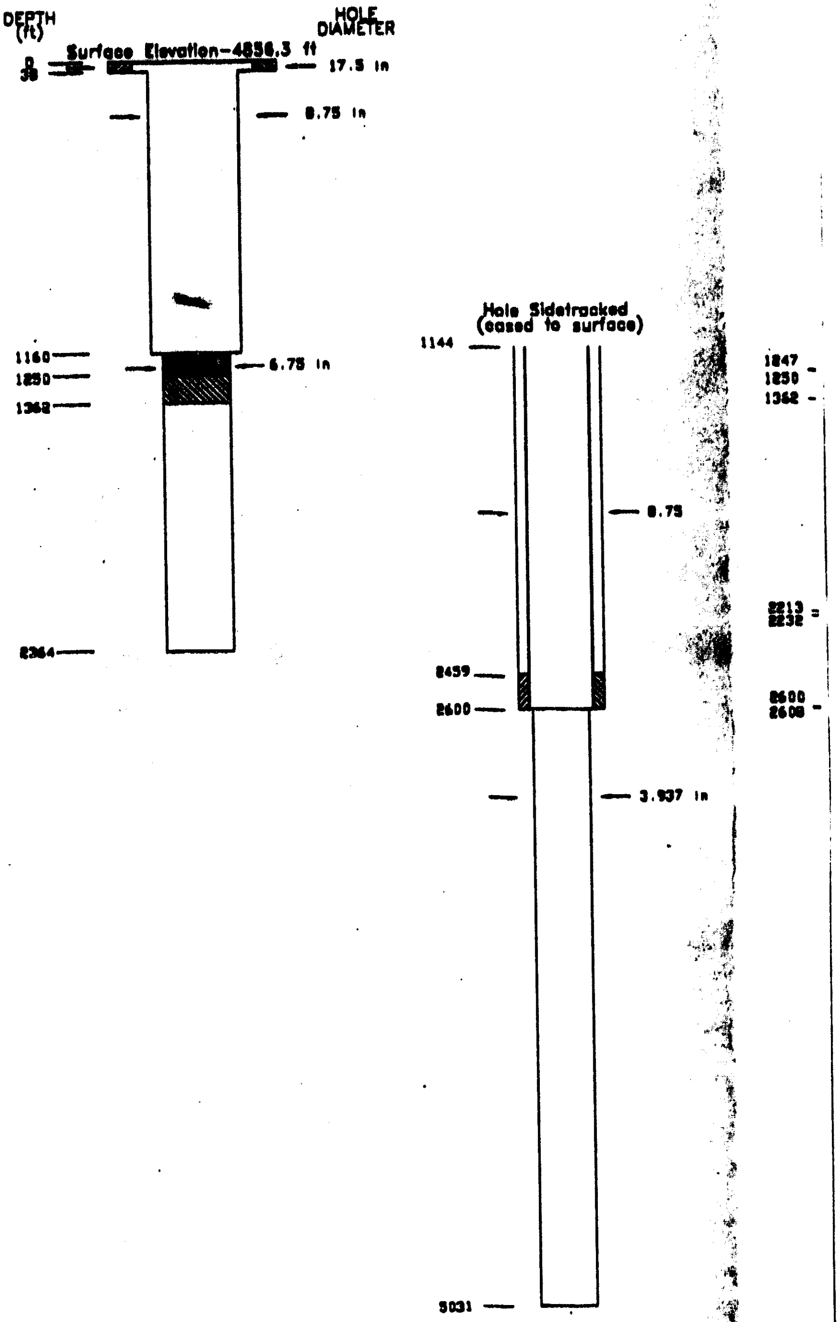
OD = 13.375 in
ID = 12.615 in
T_e = 0.380 in
Set at 36 ft

Hole filled with 65 ft^3 of neat cement plus 2% $CaCl_2$ plus 10% sand from 1250 to 1160 ft.

Hole filled with 1425 ft^3 of neat cement plus 2% $CaCl_2$ from 1362 to 1250 ft.

Annulus cemented with 100 ft^3 of neat cement plus 2% $CaCl_2$ from 2600 to 2459 ft (calculated).

OD = 5.500 in
ID = 4.950 in
T_e = 0.275 in
Set at 2598 ft



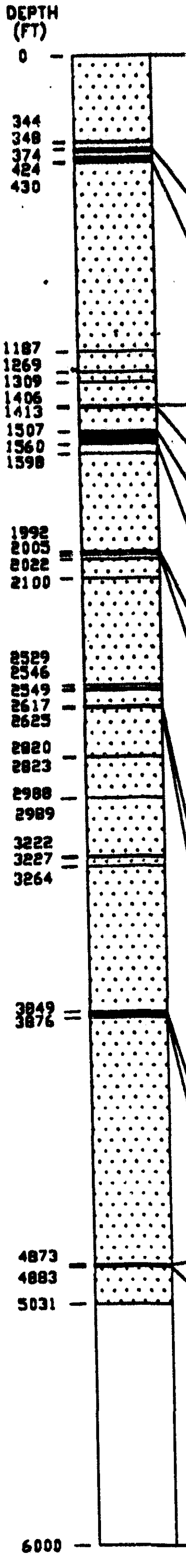
USW G-3

GENERALIZED STRATIGRAPHIC LOG

(Modified from Scott and Castellanos, 1984)

HOLE INFORMATION

1247 - 1250	■	Source on NAIL tool lost in first hole between 1247 and 1250 ft.
1362 -	■	986 ft of 3.5 in drill pipe and drilling assembly left in hole with top of junk at 1362 ft.
2213 = 2232	△	Lost returns from 2213 to 2231 ft in first hole and from 2230 to 2232 ft in second hole.
2600 - 2608	●	Hole 4.75 in diameter between 2600 and 2608 ft.



PAINTBRUSH TUFF

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified, some vapor phase crystallization (0 to 344 ft)
  - Moderately to densely welded, vitrophyre (344 to 348 ft)
  - Moderately welded to non-welded, vitric (348 to 374 ft)

Bedded/Reworked Ash-Fall Tuff, poorly indurated (374 to 424 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded to moderately welded, partially vitric, vapor phase (424 to 430 ft)
  - Moderately to densely welded, devitrified, vapor phase (430 to 1187 ft)
  - Densely welded, vitrophyre (1187 to 1289 ft)
  - Moderately to partially welded, vitric (1289 to 1309 ft)
  - Non-welded, vitric (1309 to 1406 ft)

Bedded Ash-Fall Tuff, moderately to very poorly indurated (1406 to 1413 ft)

CALICO HILLS TUFF

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded, vitric (1413 to 1507 ft)

Bedded Ash-Fall Tuff, moderately to poorly indurated (1507 to 1560 ft)

CRATER FLAT TUFF

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (1560 to 1598 ft)
  - Non-welded to partially welded, devitrified to partially vitric (1598 to 1992 ft)

Bedded Tuff, moderately indurated (1992 to 2005 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partially welded, vitric, some partially devitrified, some vapor phase (2005 to 2022 ft)
  - Partially welded, devitrified (2022 to 2100 ft)
  - Moderately to densely welded, devitrified (2100 to 2529 ft)
  - Moderately to partially welded, devitrified (2529 to 2546 ft)
- Bedded Ash-Fall Tuff, well indurated (2546 to 2549 ft)
- Ash-Flow Tuff, non-welded to moderately welded, partially devitrified (2549 to 2617 ft)

Bedded/Reworked Ash-Fall Tuff, moderately to well indurated (2617 to 2625 ft)

TRAM MEMBER
- Ash-Flow Tuff, non-welded to partially welded, devitrified (2625 to 2820 ft)
- Bedded Tuff, well indurated (2820 to 2823 ft)
- Ash-Flow Tuff, non-welded to moderately welded, devitrified (2823 to 2988 ft)
- Bedded/Reworked Tuff, well indurated (2988 to 2989 ft)
- Ash-Flow Tuff, partially to densely welded
  - Devitrified (2989 to 3222 ft)
  - Vitrophyre (3222 to 3227 ft)
  - Partially vitric (3227 to 3264 ft)
  - Devitrified (3264 to 3849 ft)

Bedded/Reworked Tuff, moderately to well indurated (3849 to 3876 ft)

LITHIC RIDGE TUFF

LITHIC RIDGE TUFF
- Ash-Flow Tuff, non-welded to moderately welded, devitrified, some vapor phase (3876 to 4873 ft)

Bedded/Reworked Tuff, poorly to well indurated (4873 to 4883 ft)

Older Tuffs (Unit A?) (4883 to 5031 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986f)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 25 ft^3 of Gyp-Seal cement from 38 to 33 ft and 440 ft^3 of neat cement plus 2% $CaCl_2$ from 33 ft to surface.

OD = 24.0 in
ID = 23.25 in
T_e = 0.375 in
Set at 36 ft

Ⓑ Annulus cemented with 1325 ft^3 of neat cement plus 2% $CaCl_2$ and LCM from 326 ft to surface.

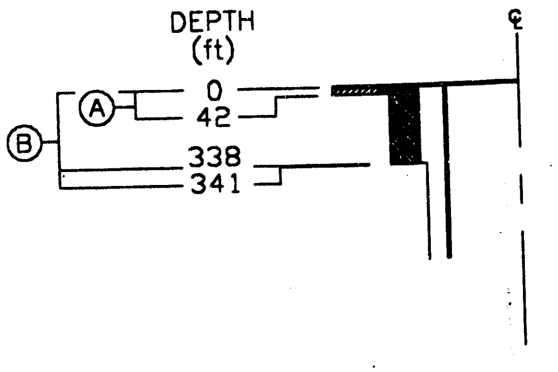
OD = 16.000 in
ID = 15.124 in
T_e = 0.438 in
Set at 325 ft

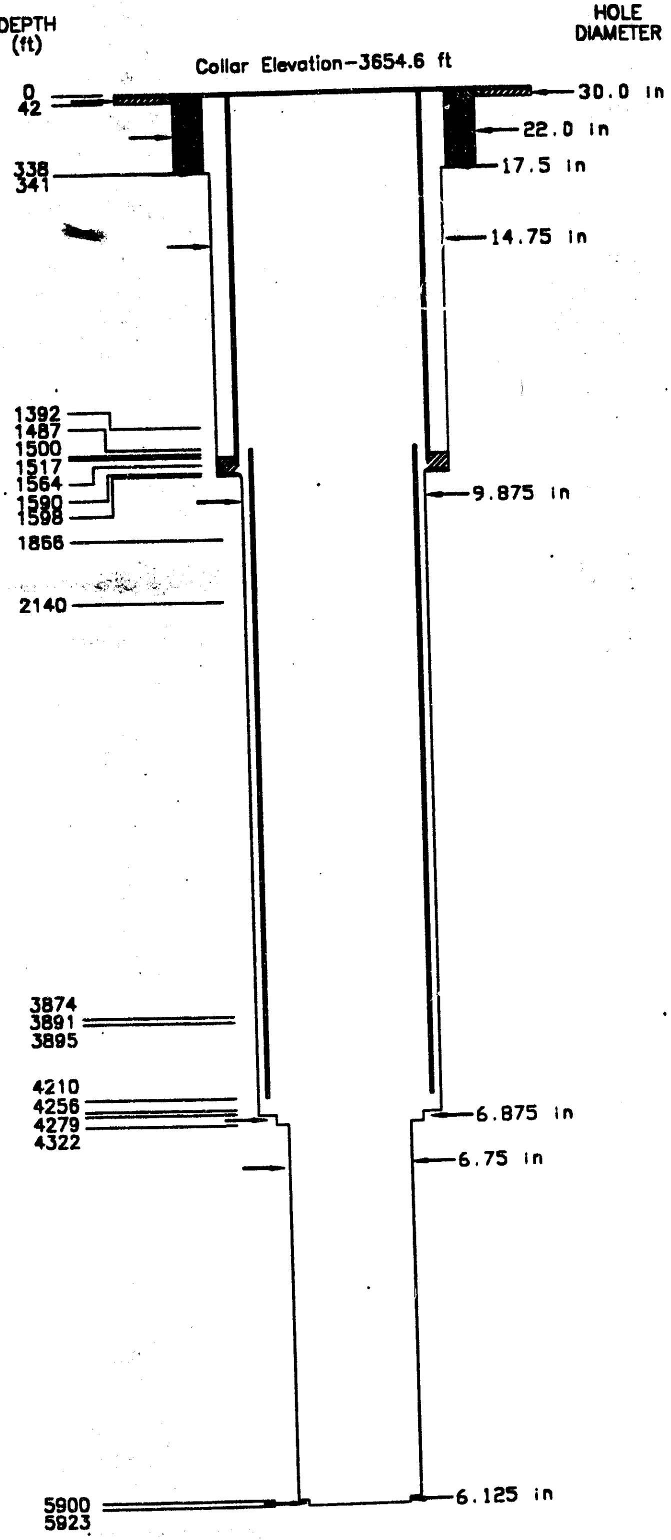
Annulus cemented with 125 ft^3 of neat cement plus 2% $CaCl_2$ from 1590 to 1517 ft.

OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 1564 ft

Annulus cemented in 4 stages. Float collar set at 4210 ft, lower stage collar set at 3875 ft, and upper stage collar set at 2140 ft. Two metal petal baskets at 3891 and 3895 ft. Stage 1–51^3 ft of neat cement plus 2% $CaCl_2$ at 4256 ft. Stage 2–755 ft^3 of class A cement plus 20% DAICEL D plus 2% $CaCl_2$ at 3874 ft. Stage 3–380 ft^3 of class A cement plus 20% DIACEL D plus 2% $CaCl_2$ at 2116 ft. Stage 4–Drillable bridge plug set at 1500 ft inside 7.625 in liner and 10.75 in squeeze packer set at 1392 ft, cemented with 75 ft^3 of neat cement plus 2% $CaCl_2$.

OD = 7.625 in
ID = 6.969 in
T_e = 0.328 in
Set at 4256 ft
extending to 1487 ft





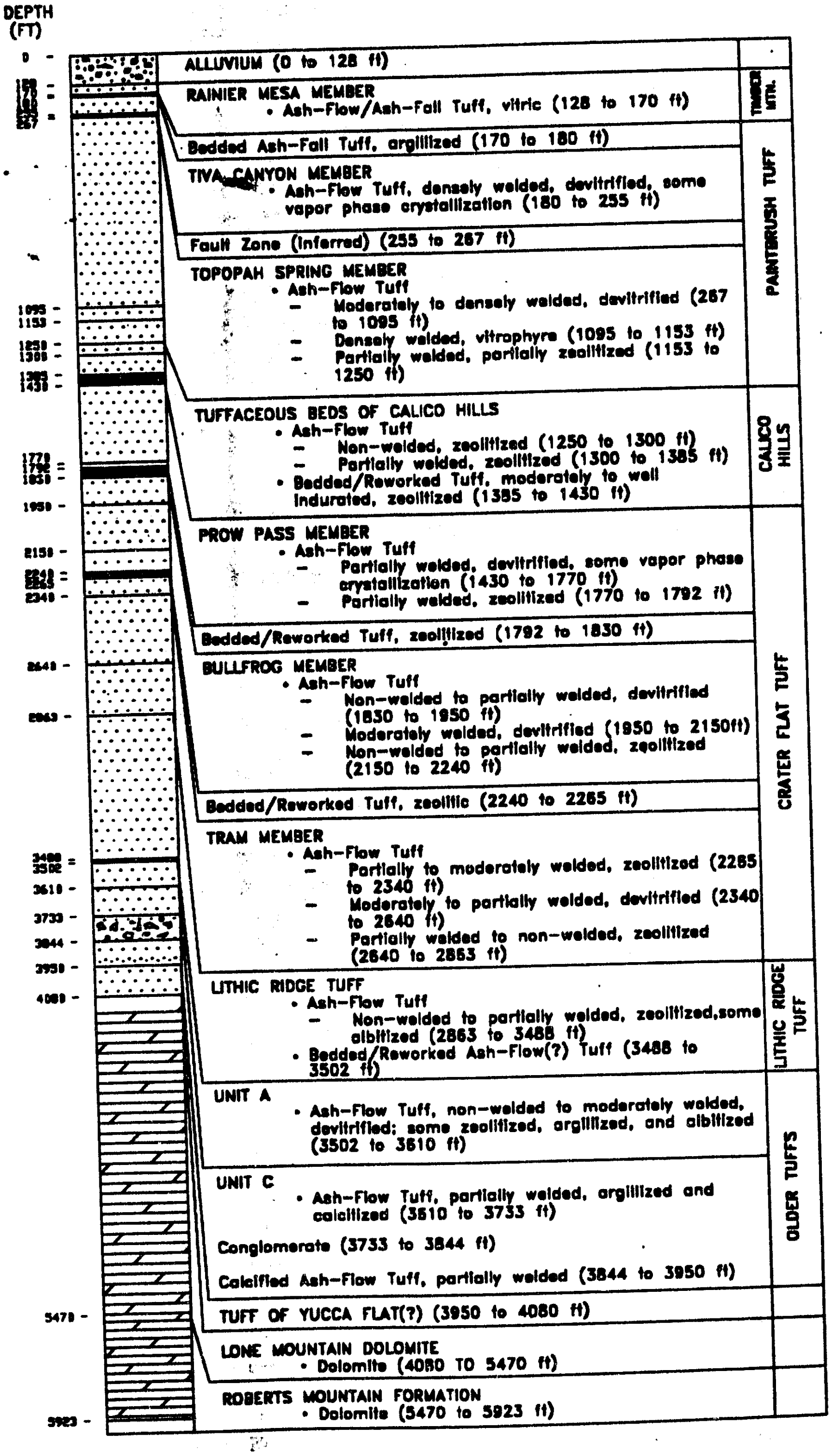
UE-25 p #1

GENERALIZED STRATIGRAPHIC LOG

(Modified from Carr et al., 1986)

HOLE INFORMATION

326	● Hole eroded to 32.75 in at 326 ft.
1190 1262 1355 1371	▽ Initial fluid density log indicated fluid level at 1262 ft. Final fluid level measured at 1190 ft. ■ 1.9 in OD tubing with bottom plugged landed at 1355 ft. 1.9 in OD open ended tubing landed at 1371 ft.
2862	● Hole eroded to 30.5 in at 2862 ft.
3925 3930 3934	● Hole eroded to greater than 34.75 in from 3925 to 3930 ft. ■ Two 0.125 in x 3 in x 18 in caliper arms lost in hole at approximately 3934 ft.
4256 4568	● Caliper log indicated eroded hole from base of 7.625 in casing (4256 ft) to 5076 ft with maximum hole enlargement of 11.5 in at 4568 ft.
5076	



ALLUVIUM (0 to 128 ft)

RAINIER MESA MEMBER
- Ash-Flow/Ash-Fall Tuff, vitric (128 to 170 ft)

Bedded Ash-Fall Tuff, argillized (170 to 180 ft)

TIVA CANYON MEMBER
- Ash-Flow Tuff, densely welded, devitrified, some vapor phase crystallization (180 to 255 ft)

Fault Zone (inferred) (255 to 287 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified (287 to 1095 ft)
  - Densely welded, vitrophyre (1095 to 1153 ft)
  - Partially welded, partially zeolitized (1153 to 1250 ft)

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff
  - Non-welded, zeolitized (1250 to 1300 ft)
  - Partially welded, zeolitized (1300 to 1385 ft)
- Bedded/Reworked Tuff, moderately to well indurated, zeolitized (1385 to 1430 ft)

PROW PASS MEMBER
- Ash-Flow Tuff
  - Partially welded, devitrified, some vapor phase crystallization (1430 to 1770 ft)
  - Partially welded, zeolitized (1770 to 1792 ft)

Bedded/Reworked Tuff, zeolitized (1792 to 1830 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified (1830 to 1950 ft)
  - Moderately welded, devitrified (1950 to 2150ft)
  - Non-welded to partially welded, zeolitized (2150 to 2240 ft)

Bedded/Reworked Tuff, zeolitic (2240 to 2265 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Partially to moderately welded, zeolitized (2265 to 2340 ft)
  - Moderately to partially welded, devitrified (2340 to 2640 ft)
  - Partially welded to non-welded, zeolitized (2640 to 2863 ft)

LITHIC RIDGE TUFF
- Ash-Flow Tuff
  - Non-welded to partially welded, zeolitized, some albitized (2863 to 3488 ft)
- Bedded/Reworked Ash-Flow(?) Tuff (3488 to 3502 ft)

UNIT A
- Ash-Flow Tuff, non-welded to moderately welded, devitrified; some zeolitized, argillized, and albitized (3502 to 3610 ft)

UNIT C
- Ash-Flow Tuff, partially welded, argillized and calcitized (3610 to 3733 ft)

Conglomerate (3733 to 3844 ft)

Calcified Ash-Flow Tuff, partially welded (3844 to 3950 ft)

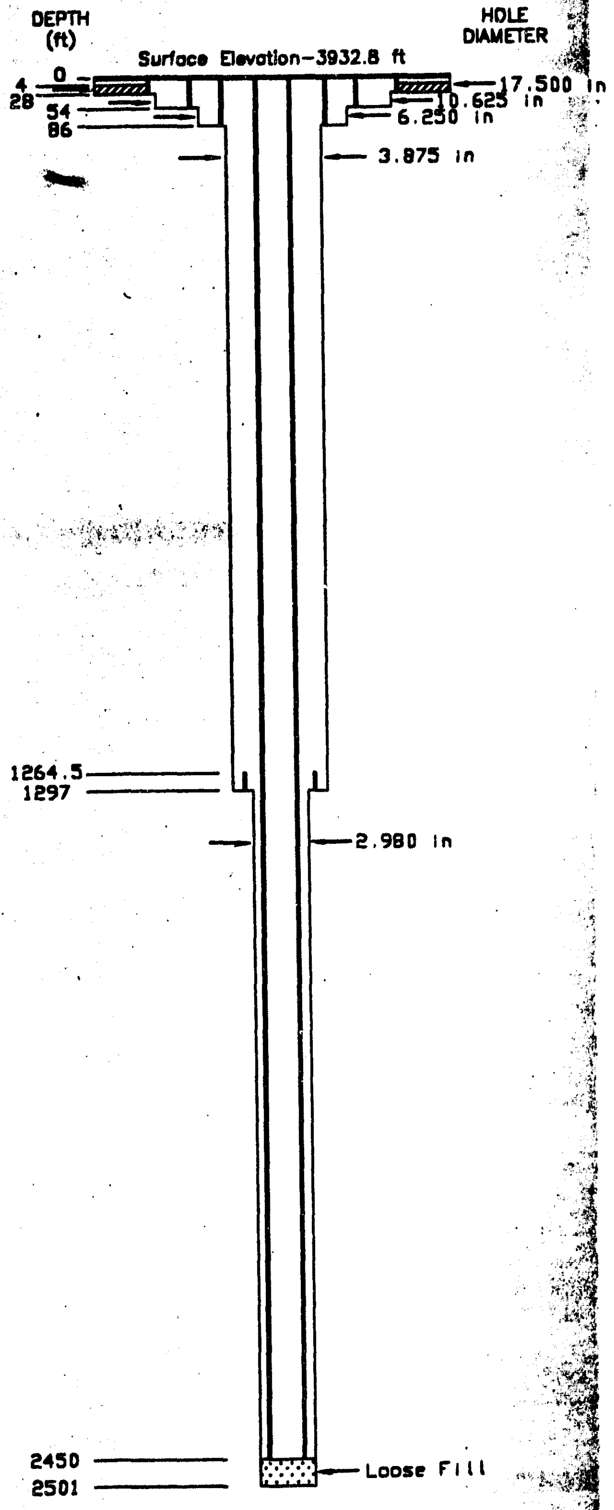
TUFF OF YUCCA FLAT(?) (3950 to 4080 ft)

LONE MOUNTAIN DOLOMITE
- Dolomite (4080 TO 5470 ft)

ROBERTS MOUNTAIN FORMATION
- Dolomite (5470 to 5923 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986c)



CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 50 ft^3 of GYP-Seal cement from 28 ft to 4 ft.

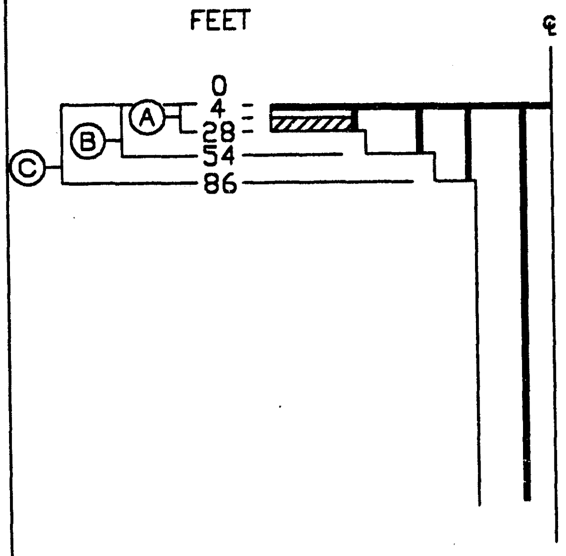
OD = 13.375 in
ID = 12.615 in
T_e = 0.380 in
Set at 28 ft

Ⓑ Annulus not cemented.

OD = 7.625 in
ID = 6.969 in
T_e = 0.328 in
Set at 54 ft

Ⓒ Annulus not cemented.

OD = 4.500 in
ID = 4.000 in
T_e = 0.250 in
Set at 86 ft



Ⓓ Annulus not cemented. NQ rods with casing shoe used as casing from 2450 ft to surface.

OD = 2.375 in

Set at 2450 ft

804
833
836
905
934
974
1024
1064
1264.5
1297
2495

UE-25a #1

GENERALIZED STRATIGRAPHIC LOG

(Modified from Spengler et al., 1979)

HOLE INFORMATION

804 - 833 = 836 — △ Partial loss of circulation at 804 ft, 833 ft and 836 ft.

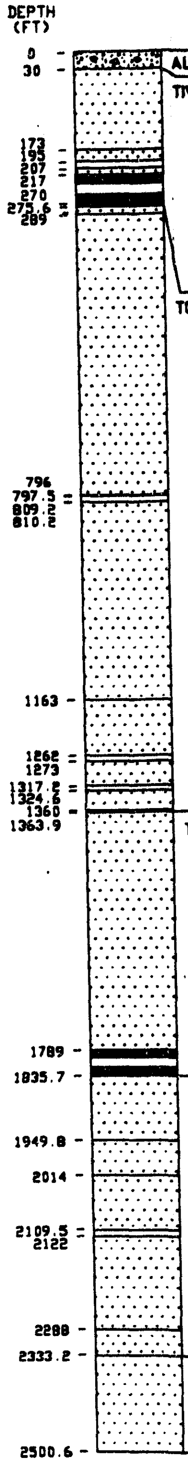
905 - 934 - — △ Lost circulation between 905 and 934 ft.

974 - 1024 - — △ Lost circulation at 974 and 1024 ft.

1064 - — △ Lost circulation at approximately 1064 ft.

1264.5 - 1297 - — ■ 19.5 ft of HQ drill rod and 13 ft of HQ core barrel and core bit left in hole from 1264.5 to 1297 ft.

2495 - — ■ USGS fluid probe stuck in hole at 2495 ft.



ALLUVIUM (0.0 to 30.0 ft)

PAINTBRUSH TUFF

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (30.0 to 173.0 ft)
  - Moderately welded, vapor phase crystallization (173.0 to 195.0 ft)
  - Partially welded, vitric, partly argillized (195.0 to 207.0 ft)
  - Non-welded to partially welded, argillized (207.0 to 217.0 ft)
- Bedded Tuff, reworked ash-fall and ash-flow, non-welded, vitric (217.0 to 270.0 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (270.0 to 275.6 ft)
  - Densely welded, vitric (275.6 to 289.0 ft)
  - Moderately to densely welded, devitrified, some vapor phase crystallization (289.0 to 796.0 ft)
  - Partially to moderately welded, devitrified (796.0 to 797.5 ft)
  - Densely welded, devitrified (797.5 to 809.2 ft)
  - Partially to moderately welded, devitrified vapor phase crystallization, (809.2 to 810.2 ft)
  - Densely welded, devitrified (810.2 to 1163.0 ft)
  - Moderately to densely welded, devitrified (1163.0 to 1262.0 ft)
  - Moderately to densely welded, vitric (1262.0 to 1273.0 ft)
  - Densely welded, vitrophyre (1273.0 to 1317.2 ft)
  - Partially welded, vitric (1317.2 to 1324.6 ft)
  - Non-welded to partially welded, devitrified (1324.6 to 1360.0 ft)
- Ash-Fall Tuff, reworked, slightly indurated (1360.0 to 1363.9 ft)

CALICO HILLS TUFF

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded, devitrified (1363.9 to 1789.0 ft)
- Bedded/Reworked Tuff, moderately to highly indurated, occasionally silicified (1789.0 to 1835.7 ft)

CRATER FLAT TUFF

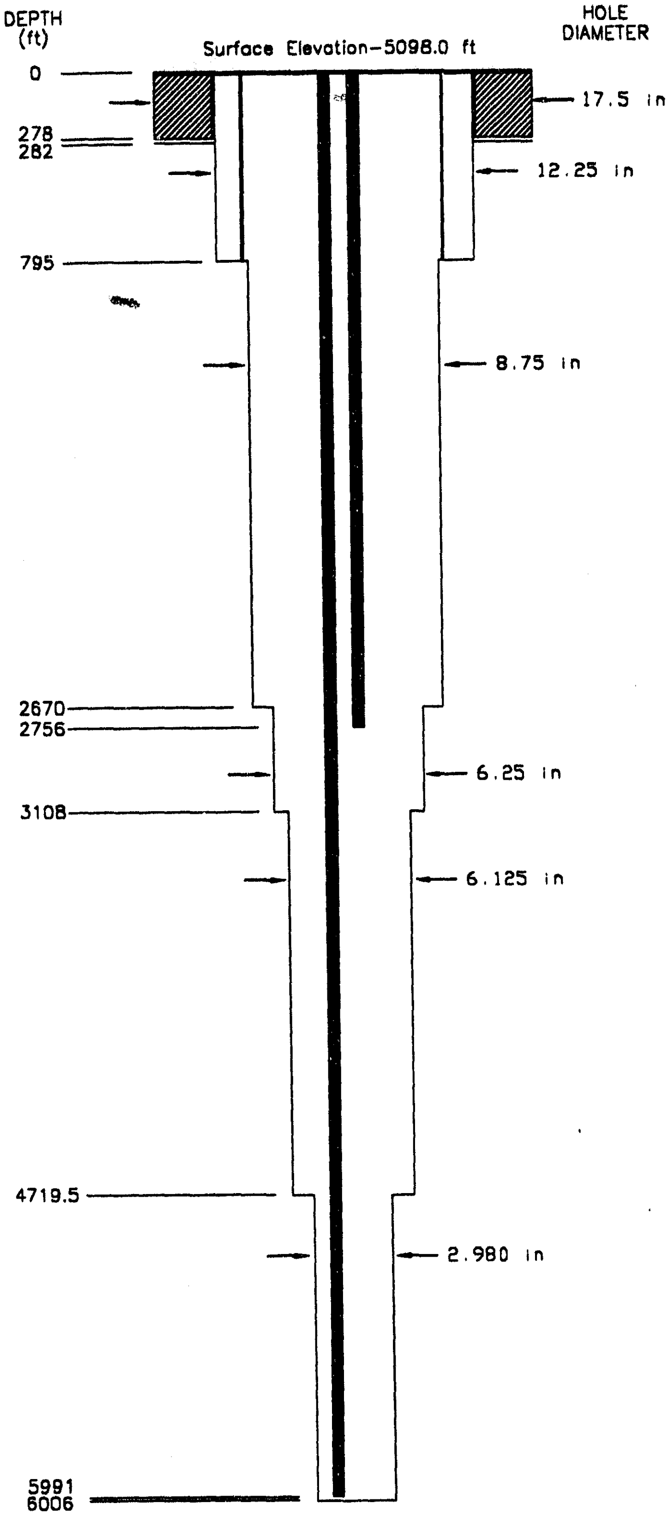
PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified (1835.7 to 1949.8 ft)
  - Moderately welded, devitrified (1949.8 to 2014.0 ft)
  - Partially welded, partially devitrified (2014.0 to 2109.5 ft)
  - Moderately welded, vitric (2109.5 to 2122.0 ft)
  - Partially welded, devitrified, slightly zeolitic (2122.0 to 2288.0 ft)
  - Non-welded to partially welded, slightly zeolitized (2288.0 to 2333.2 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partially to moderately welded, devitrified (2333.2 to 2500.6 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

CEMENTING AND CASING INFORMATION
Annulus cemented with 470 ft^3 of neat cement plus 2% $CaCl_2$ from 278 ft to surface. OD = 13.375 in ID = 12.615 in T_e = 0.380 in Set at 278 ft
Annulus not cemented. OD = 9.625 in ID = 8.921 in T_e = 0.352 in Set at 795 ft



USW G-2

GENERALIZED STRATIGRAPHIC LOG

(Modified from Maldonado and Koether, 1983)

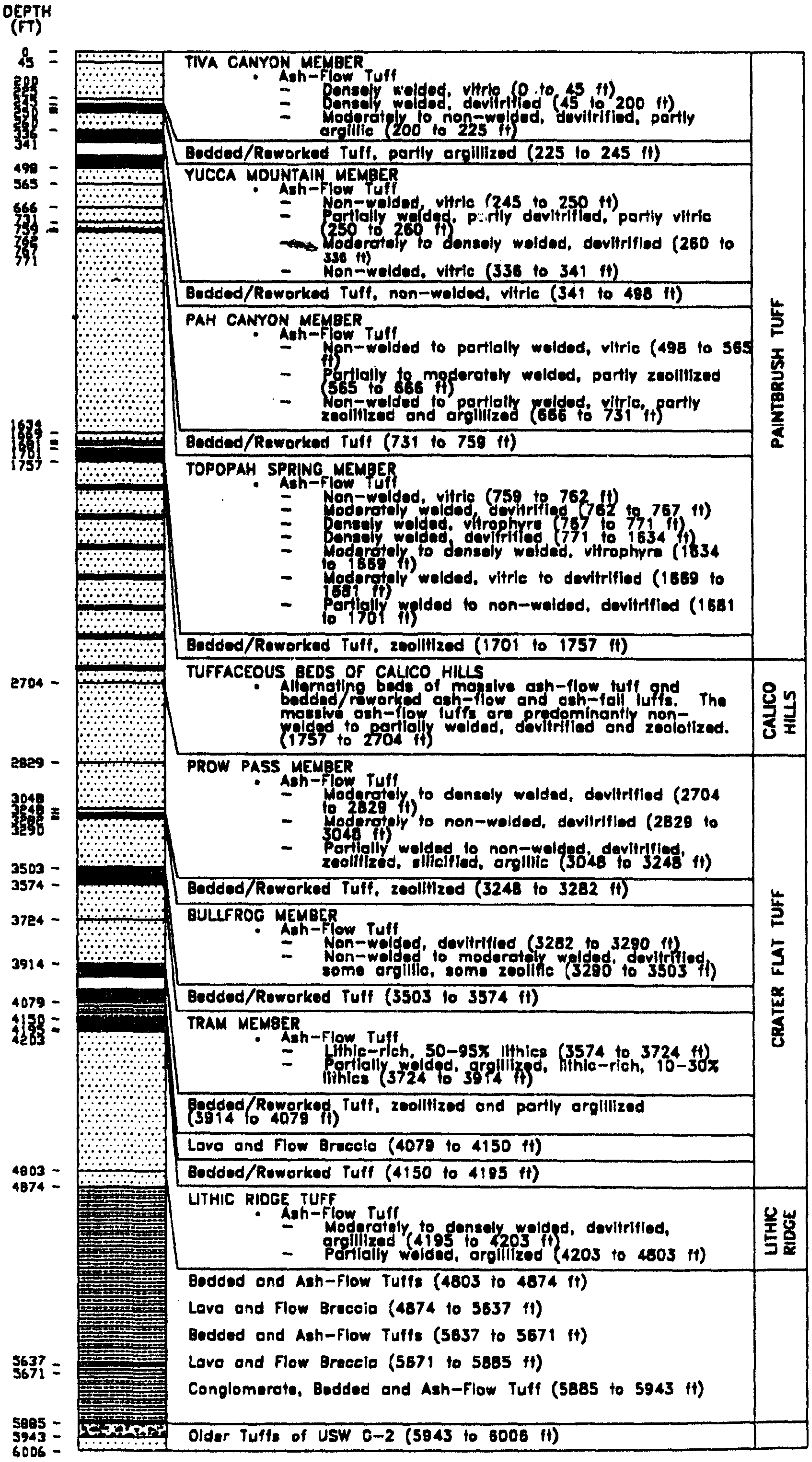
HOLE INFORMATION

314.5 = 329 = ● Hole sloughing between 314.5 and 329 ft.

889 – ▽ Lost circulation at 889 ft.

2756 – ■ 1.9 in OD tubing set at 2756 ft to surface.

5991 – ■ 1.9 in OD tubing set at 5991 ft to surface.



TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, vitric (0 to 45 ft)
  - Densely welded, devitrified (45 to 200 ft)
  - Moderately to non-welded, devitrified, partly argillic (200 to 225 ft)

Bedded/Reworked Tuff, partly argillized (225 to 245 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (245 to 250 ft)
  - Partially welded, partly devitrified, partly vitric (250 to 260 ft)
  - Moderately to densely welded, devitrified (260 to 336 ft)
  - Non-welded, vitric (336 to 341 ft)

Bedded/Reworked Tuff, non-welded, vitric (341 to 498 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, vitric (498 to 565 ft)
  - Partially to moderately welded, partly zeolitized (565 to 666 ft)
  - Non-welded to partially welded, vitric, partly zeolitized and argillized (666 to 731 ft)

Bedded/Reworked Tuff (731 to 759 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (759 to 762 ft)
  - Moderately welded, devitrified (762 to 767 ft)
  - Densely welded, vitrophyre (767 to 771 ft)
  - Densely welded, devitrified (771 to 1634 ft)
  - Moderately to densely welded, vitrophyre (1634 to 1669 ft)
  - Moderately welded, vitric to devitrified (1669 to 1681 ft)
  - Partially welded to non-welded, devitrified (1681 to 1701 ft)

Bedded/Reworked Tuff, zeolitized (1701 to 1757 ft)

TUFFACEOUS BEDS OF CALICO HILLS
- Alternating beds of massive ash-flow tuff and bedded/reworked ash-flow and ash-fall tuffs. The massive ash-flow tuffs are predominantly non-welded to partially welded, devitrified and zeolotized. (1757 to 2704 ft)

PROW PASS MEMBER
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified (2704 to 2829 ft)
  - Moderately to non-welded, devitrified (2829 to 3048 ft)
  - Partially welded to non-welded, devitrified, zeolitized, silicified, argillic (3048 to 3248 ft)

Bedded/Reworked Tuff, zeolitized (3248 to 3282 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Non-welded, devitrified (3282 to 3290 ft)
  - Non-welded to moderately welded, devitrified, some argillic, some zeolific (3290 to 3503 ft)

Bedded/Reworked Tuff (3503 to 3574 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Lithic-rich, 50-95% lithics (3574 to 3724 ft)
  - Partially welded, argillized, lithic-rich, 10-30% lithics (3724 to 3914 ft)

Bedded/Reworked Tuff, zeolitized and partly argillized (3914 to 4079 ft)

Lava and Flow Breccia (4079 to 4150 ft)

Bedded/Reworked Tuff (4150 to 4195 ft)

LITHIC RIDGE TUFF
- Ash-Flow Tuff
  - Moderately to densely welded, devitrified, argillized (4195 to 4203 ft)
  - Partially welded, argillized (4203 to 4803 ft)

Bedded and Ash-Flow Tuffs (4803 to 4874 ft)

Lava and Flow Breccia (4874 to 5637 ft)

Bedded and Ash-Flow Tuffs (5637 to 5671 ft)

Lava and Flow Breccia (5671 to 5885 ft)

Conglomerate, Bedded and Ash-Flow Tuff (5885 to 5943 ft)

Older Tuffs of USW G-2 (5943 to 6006 ft)

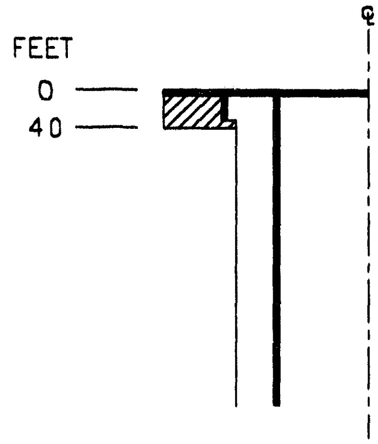
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

CEMENTING AND CASING INFORMATION

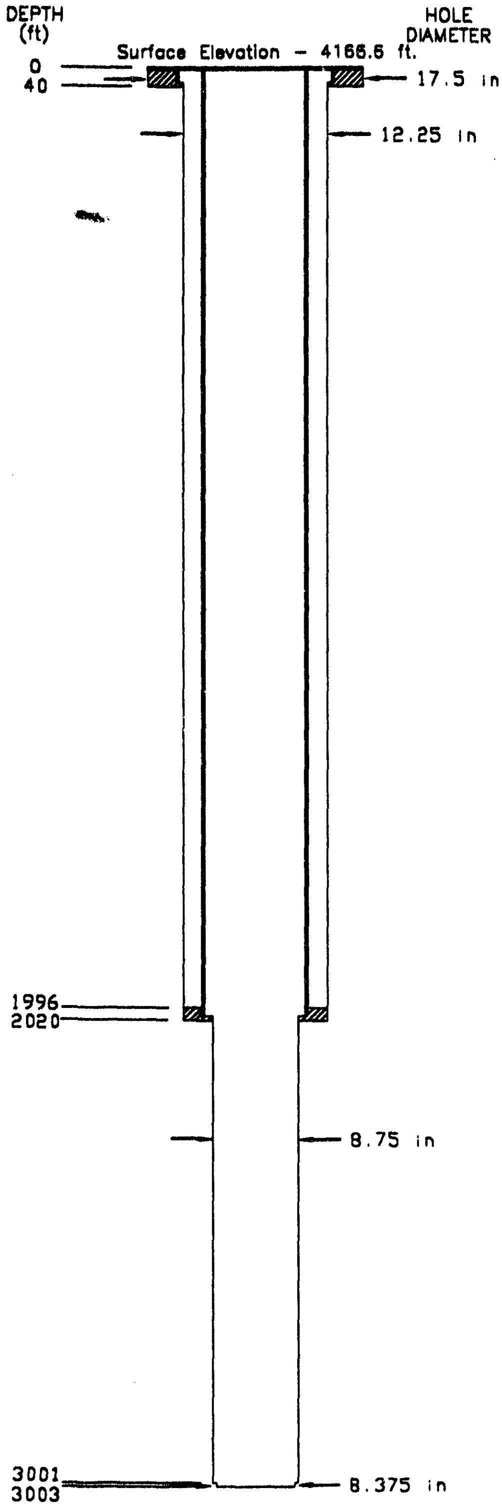
Annulus cemented with 43 ft^3 of neat cement plus 2% $CaCl_2$.

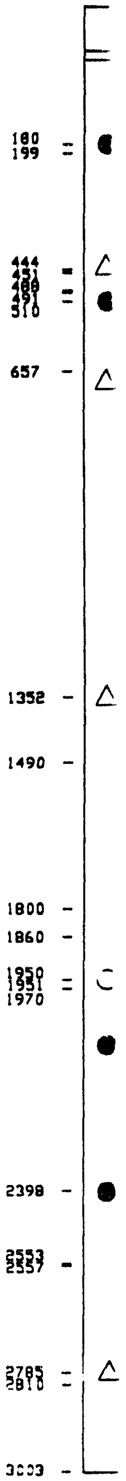
OD = 13.375 in
ID = 12.615 in
T_e = 0.380 in
Set at 39 ft



Annulus cemented with 20 ft^3 of neat cement plus 2% $CaCl_2$. Bottom of casing belled and centralizers located at 2013.5 and 2000 ft.

OD = 9.625 in
ID = 8.921 in
T_e = 0.352 in
Set at 2017 ft





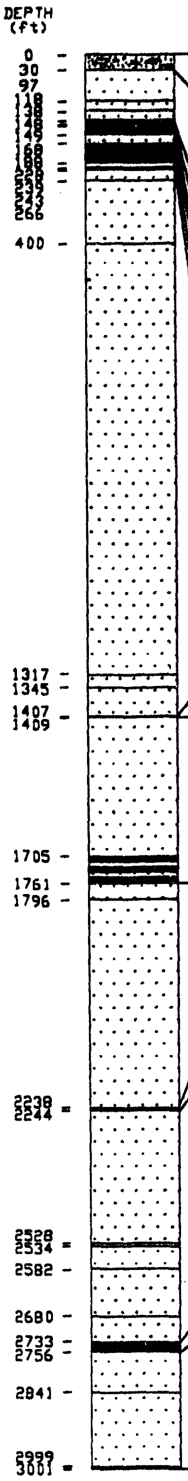
USW G-4

GENERALIZED STRATIGRAPHIC LOG

(Modified from Spengler et al., 1984)

HOLE INFORMATION

180 – 199	● Hole enlarged greater than 34.25 in between 180 to 199 ft.
444 – 451	△ Lost circulation from 444 to 451 ft.
488 – 491 – 510	● Hole eroded between 488 and 510 ft with a maximum hole enlargement of 27.5 in at 491 ft.
657	△ Lost circulation at 657 ft.
1352	△ Lost circulation from 1352 to 1490 ft.
1490	
1800	
1860	
1950 – 1951 – 1970	◌ Casing perforated from 1950 to 1970 ft and from 1800 to 1860 ft.
	● Hole enlarged to 29.5 in at 1951 ft.
2398	● Hole enlarged from 2398 to 2557 ft with a maximum enlargement of 15.75 in at 2553 ft.
2553 – 2557	
2785 – 2810	△ Sporadic loss of circulation from 2785 to 2810 ft.
3003	



PAINTBRUSH TUFF

ALLUVIUM, boulder- to silt-size fragments of non-welded to welded tuff (0 to 30 ft)

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (30 to 97 ft)
  - Moderately welded, devitrified (97 to 118 ft)
  - Partially to non-welded, vitric (118 to 138 ft)

Bedded Ash-~~Fall~~ Tuff, moderately indurated, vitric (138 to 148 ft)

YUCCA MOUNTAIN MEMBER
- Ash-Flow Tuff, non-welded, vitric (148 to 149 ft)

Bedded/Reworked Ash-Fall Tuff, vitric (149 to 168 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric (168 to 188 ft)

Bedded/Reworked Tuff, poorly consolidated, vitric (188 to 228 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (228 to 239 ft)
  - Densely welded, vitrophyre (239 to 243 ft)
  - Densely welded, devitrified, (caprock) (243 to 266 ft)
  - Moderately to densely welded, devitrified, vapor phase crystallization (266 to 400 ft)
  - Densely welded, devitrified (400 to 1317 ft)
  - Densely welded, vitrophyre (1317 to 1345 ft)
  - Non-welded to partially welded, vitric (1345 to 1407 ft)

Bedded/Reworked Ash-Fall Tuff, moderately indurated, zeolitic (1407 to 1409 ft)

CALICO HILLS

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow/Ash-Fall Tuff, non-welded to partially welded, zeolitic (1409 to 1705 ft)
- Bedded/Reworked Ash-Fall Tuff, tuffaceous sandstone, zeolitic (1705 to 1761 ft)

CRATER FLAT TUFF

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, zeolitic (1761 to 1796 ft)
  - Non-welded to partially welded, devitrified, zeolitic in areas (1796 to 2238 ft)

Bedded/Reworked Ash-Fall Tuff, slightly to moderately zeolitic (2238 to 2244 ft)

BULLFROG MEMBER
- Ash-Flow Tuff, partially welded, devitrified, some vapor phase crystallization (2244 to 2528 ft)
- Ash-Fall Tuff, (interbedded with ash-flow), well indurated, devitrified (2528 to 2534 ft)
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified (2534 to 2582 ft)
  - Moderately to densely welded, devitrified (2582 to 2680 ft)
  - Non-welded to partially welded, devitrified, argillic or zeolitic (2680 to 2733 ft)

Bedded/Reworked Ash-Fall Tuff (2733 to 2756 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified (2756 to 2841 ft)
  - Devitrified, vapor phase crystallization (2841 to 2999 ft)
  - Moderately welded, devitrified (2999 to 3001 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987d)

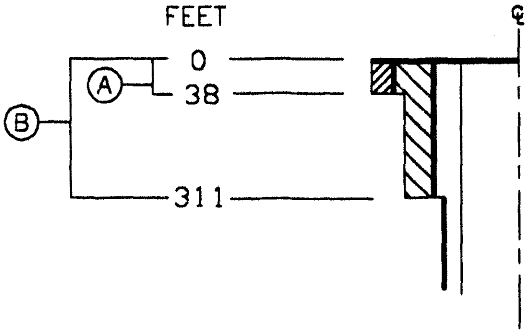
CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 9 ft^3 of gypsum cement from 38 ft to 37.8 ft and 189 ft^3 of Redi-Mix from 37.8 ft to surface.

OD = 30 in
ID = 29.25 in
T_e = 0.375 in
Set at 38 ft

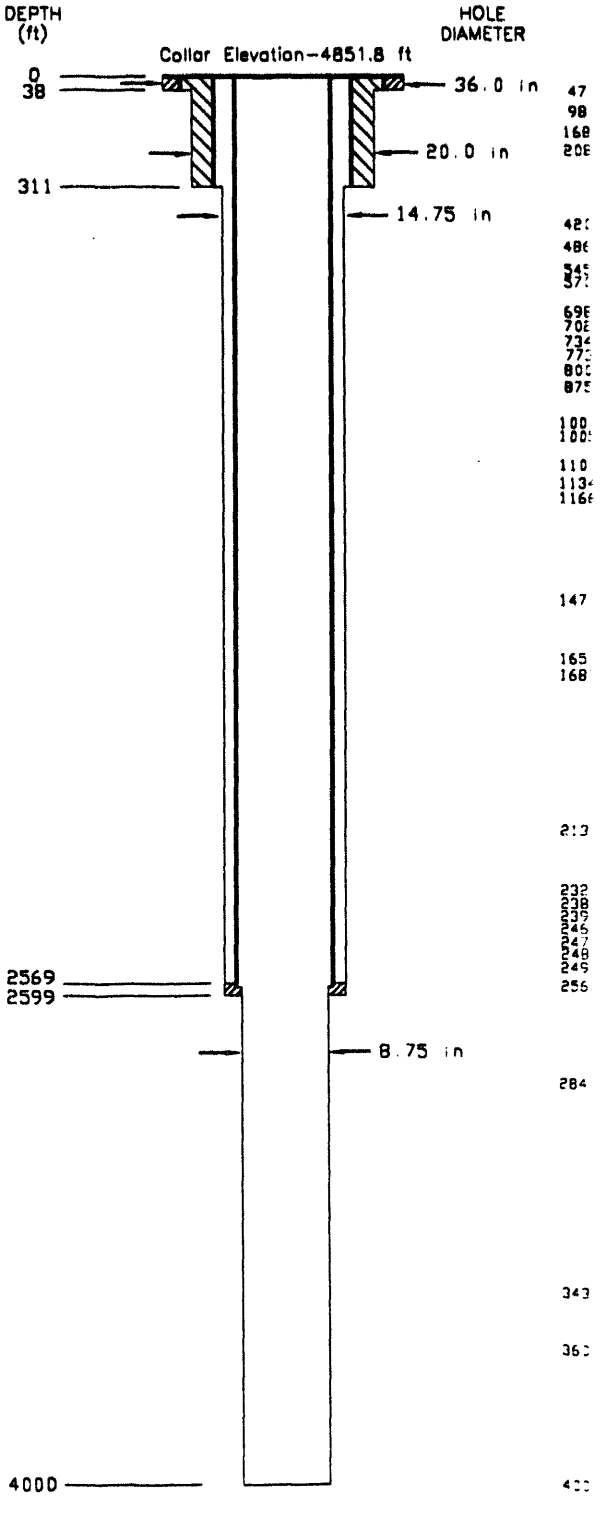
Ⓑ Annulus cemented with 20 ft^3 of gypsum cement from 311 ft to 301 ft and 1050 ft^3 of neat cement plus 2% $CaCl_2$ from 301 ft to surface.

OD = 16 in
ID = 15.01 in
T_e = 0.495 in
Set at 311 ft



Annulus cemented with 100 ft^3 of neat cement plus 3% $CaCl_2$ from 2587 ft to 2569 ft.

OD = 10.75 in
ID = 10.05 in
T_e = 0.35 in
Set at 2585 ft



USW H-5

GENERALIZED STRATIGRAPHIC LOG
(Modified from Bentley et al., 1983)

HOLE INFORMATION

47 – 98 – 168 – 208 –
- ● Hole erosion from 47 ft to 208 ft with maximum hole enlargement of 36 in at 98 ft and 168 ft.

420 – 486 – 545 – 570 –
- ● Gradual wash out from 420 ft to 570 ft with maximum hole enlargement to 24.75 in between 486 ft and 545 ft.

698 – 702 – 734 – 773 –
- ● Hole erosion between 698 and 773 ft with hole enlargements of 26.5 in at 702 ft and 33 in at 734 ft.

800 – 875 – 1000 –
- ● Hole erosion between 800 ft and 1000 ft with hole enlargement of 26.25 in at 875 ft.

1005 –
- △ Lost circulation at 1005 ft.

1100 – 1134 – 1166 –
- ● Hole erosion between 1100 ft and 1658 ft with hole enlargement to 27.5 in at 1134 ft.
- △ Lost circulation from 1166 ft to 1476 ft.

1476 –

1658 – 1683 –
- ● Gradual wash out between 1683 ft and 2496 ft with hole enlargement to 26 in at 2481 ft.

2135 –
- △ Lost circulation at 2135 ft.
- ◌ Casing perforated from 2320 ft to 2565 ft.

2320 – 2386 – 2396 – 2465 – 2475 – 2481 – 2496 –
- △ Lost circulation from 2386 ft 2396 ft and 2465 ft to 2475 ft.

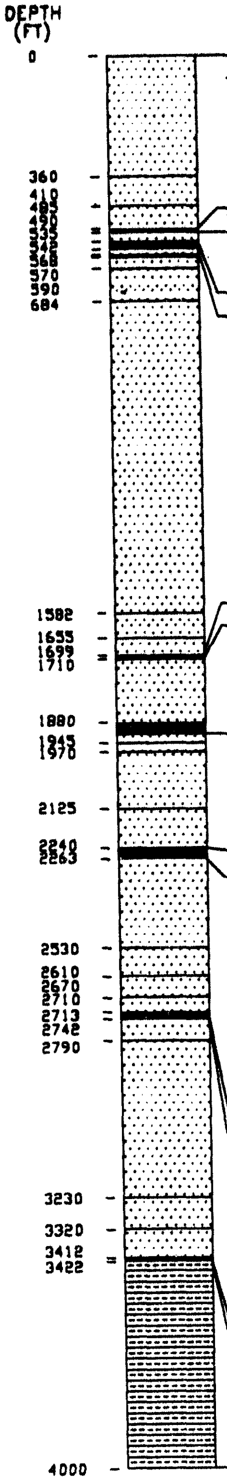
2565 –

2848 –
- ● Hole enlargements to 13 in at 2848 ft, 20.5 in at 3436 ft and 15.25 in at 3604 ft.

3436 –

3604 –

4000 –



PAINTBRUSH TUFF

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (0 to 360 ft)
  - Moderately to partially welded, devitrified (360 to 410 ft)
  - Non-welded, vitric (410 to 485 ft)

Bedded/Ash-Fall(?) Tuff, vitric (485 to 490 ft)

PAH CANYON MEMBER
- Ash-Flow Tuff, non-welded, vitric (490 to 535 ft)

Bedded Tuff, vitric (535 to 542 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (542 to 568 ft)
  - Densely welded, vitrophyre (568 to 570 ft)
  - Densely welded, devitrified (570 to 590 ft)
  - Moderately welded, vapor phase crystallization (590 to 684 ft)
  - Densely welded, devitrified (684 to 1582 ft)
  - Densely welded, vitrophyre (1582 to 1655 ft)
  - Moderately to partially welded, vitric (1655 to 1699 ft)

Bedded/Ash-Fall Tuff, vitric (1699 to 1710 ft)

CALICO HILLS

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded to partially welded, vitric (1710 to 1880 ft)
- Bedded/Reworked Ash-Fall Tuff, zeolitic (1880 to 1945 ft)

CRATER FLAT TUFF

PROW PASS MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (1945 to 1970 ft)
  - Partially welded, devitrified and vapor phase crystallization (1970 to 2125 ft)
  - Non-welded, zeolitized (2125 to 2240 ft)

Bedded Tuff, zeolitic(?) (2240 to 2263 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Partially welded, vapor phase crystallization (2263 to 2530 ft)
  - Partially welded, devitrified (2530 to 2610 ft)
  - Partially to moderately welded, devitrified and zeolitic (2610 to 2670 ft)
  - Moderately to densely welded, devitrified (2670 to 2710 ft)
  - Partially welded, devitrified and zeolitic (2710 to 2713 ft)

Bedded/Reworked Tuff (2713 to 2742 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Moderately welded(?), devitrified (2742 to 2790 ft)
  - Partially welded, devitrified (2790 to 3230 ft)
  - Partially welded, devitrified, slightly zeolitic(?) (3230 to 3320 ft)
  - Partially welded, zeolitic (3320 to 3412 ft)

Bedded/Reworked Tuff, zeolitic (3412 to 3422 ft)

Lava (unnamed) (3422 to 4000 ft)

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987d)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 315 ft^3 of neat cement plus 2% $CaCl_2$ from 33 ft to surface.

OD = 30.0 in
ID = 29.376 in
T_e = 0.312 in
Set at 31 ft

Ⓑ Annulus cemented with 1000 ft^3 of neat cement plus 2% $CaCl_2$ from 312 ft to surface.

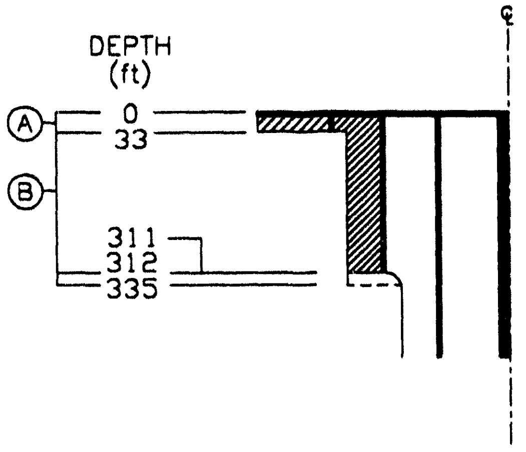
OD = 16 in
ID = 15.010 in
T_e = 0.495 in
Set at 311 ft

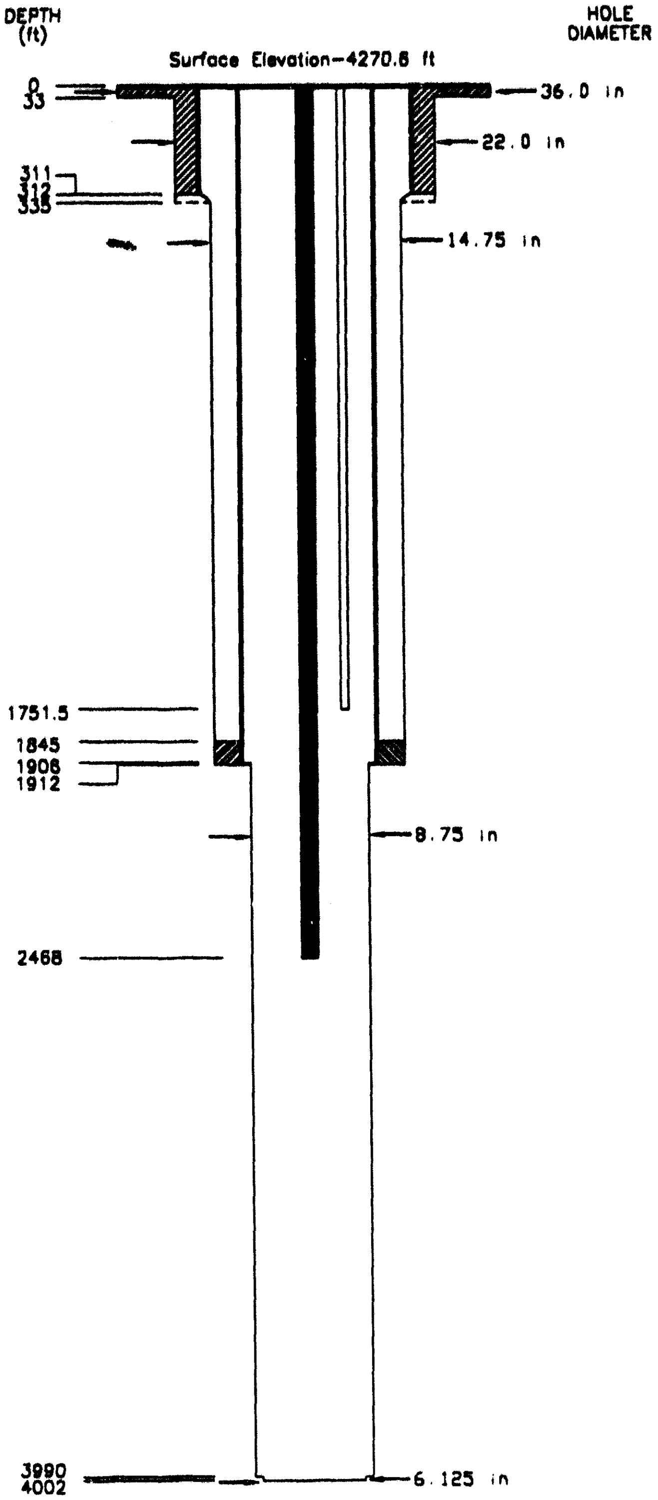
Annulus cemented with 100 ft^3 of neat cement plus 2% $CaCl_2$ from 1912 ft to approximately 1845 ft.

OD = 10.75 in
ID = 9.850 in
T_e = 0.45 in
Set at 1906 ft
Baker float collar at 1884.4 ft

Monitor line (1.9 in OD) landed at 1751.5 ft.

Packer set at 2468 ft on 2.875 in OD tubing. Bottom of packer assembly bull plugged with circulating sub below elements open.





USW H-6

HOLE INFORMATION

96 – 134 – ● Hole enlargement greater than 30 in between 96 and 134 ft and 250 and 309 ft.

250 – 309 – 311 – 320 ● Hole enlargement greater than 30 in from 311 to 320 ft.

1740 – ◌ Casing perforated from 1740 to 1876 ft.

1806 – ● Maximum hole enlargement of 27 in at 1806 ft.

1876 – 1906 – ● Hole fairly uniform from 1906 to 3973 ft with maximum hole enlargement of 20 in at 2024 ft.

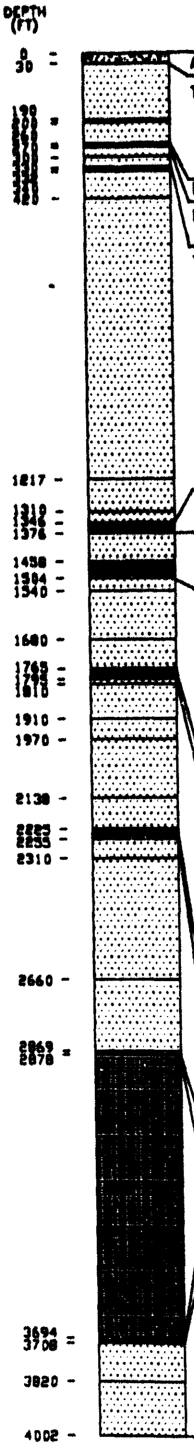
2024 – 2044 – ▲ Indication of water at 2044ft.

3709 – △ Lost circulation at 3709 ft.

3973 –

GENERALIZED STRATIGRAPHIC LOG

\(Modified from Craig et al., 1984)



PAINTBRUSH TUFF

ALLUVIUM (0 to 30 ft)

TIVA CANYON MEMBER
- Ash-Flow Tuff
  - Densely welded, devitrified (30 to 190 ft)
  - Moderately welded(?), vitric (190 to 200 ft)
  - Partially welded, vitric (200 to 260 ft)

Bedded/Ash-Fall Tuff, vitric (260 to 270 ft)

PAH CANYON MEMBER
- Ash-Fall Tuff, non-welded, vitric (270 to 300 ft)

TOPOPAH SPRING MEMBER
- Ash-Flow Tuff
  - Non-welded, vitric (300 to 330 ft)
  - Densely welded, vitrophyre (330 to 332 ft)
  - Densely welded, devitrified (332 to 340 ft)
  - Moderately welded, vapor phase crystallization (340 to 420 ft)
  - Densely welded, devitrified (420 to 1217 ft)
  - Densely welded, vitrophyre (1217 to 1310 ft)
  - Partially welded to non-welded, vitric (1310 to 1346 ft)

Bedded/Reworked Ash-Fall Tuff, vitric, slightly to moderately indurated(?) (1346 to 1376 ft)

CALICO HILLS

TUFFACEOUS BEDS OF CALICO HILLS
- Ash-Flow Tuff, non-welded to partially welded, vitric (1376 to 1458 ft)
- Bedded/Reworked Tuff, zeolitic (1458 to 1504 ft)

CRATER FLAT TUFF

PROW PASS MEMBER
- Ash-Flow Tuff
  - Partially welded, vitric (1504 to 1540 ft)
  - Partially welded, devitrified and vapor phase crystallization (1540 to 1680 ft)
  - Partially welded, devitrified, zeolitic(?) (1680 to 1765 ft)

Bedded/Reworked Tuff, zeolitic(?) (1765 to 1795 ft)

BULLFROG MEMBER
- Ash-Flow Tuff
  - Non-welded to partially welded, devitrified 1795 to 1810 ft)
  - Partially welded, vapor phase crystallization (1810 to 1910 ft)
  - Partially welded, devitrified (1910 to 1970 ft)
  - Partially to moderately welded, devitrified (1970 to 2138 ft)
  - Partially welded to non-welded, devitrified, moderately altered (2138 to 2225 ft)

Bedded/Reworked Tuff (2225 to 2255 ft)

TRAM MEMBER
- Ash-Flow Tuff
  - Non-welded, devitrified (2255 to 2310 ft)
  - Devitrified, dominantly vapor phase crystallization (2310 to 2660 ft)
  - Non-welded, zeolitic and argillic (2660 to 2869 ft)

Bedded/Reworked Tuff, moderately indurated, zeolitic(?) (2869 to 2878 ft)

Lava (Unnamed) (2878 to 3694 ft)

Bedded/Reworked Tuff (tuffaceous sandstone) (3694 to 3708 ft)

LITHIC RIDGE TUFF

LITHIC RIDGE TUFF
- Ash-Flow Tuff
  - Partially welded, zeolitic and argillic (3708 to 3820 ft)
  - Non-welded to partially welded, moderately zeolitic (3820 to 4002 ft)

UE-25 WT #6

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

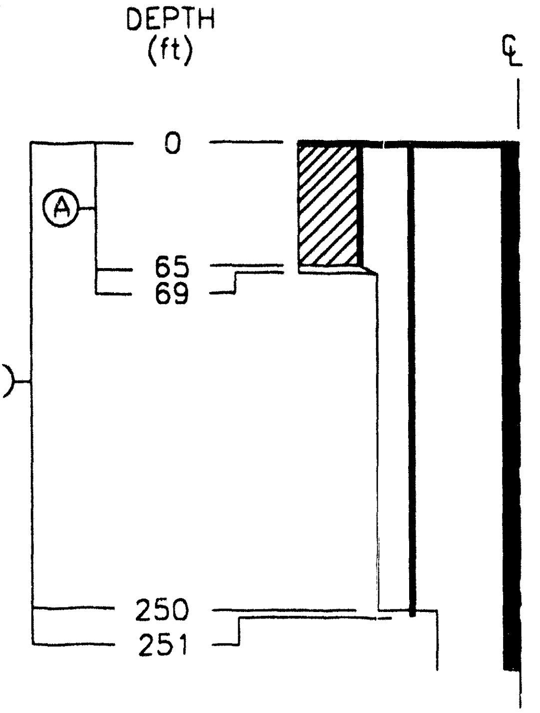
CEMENTING AND CASING INFORMATION

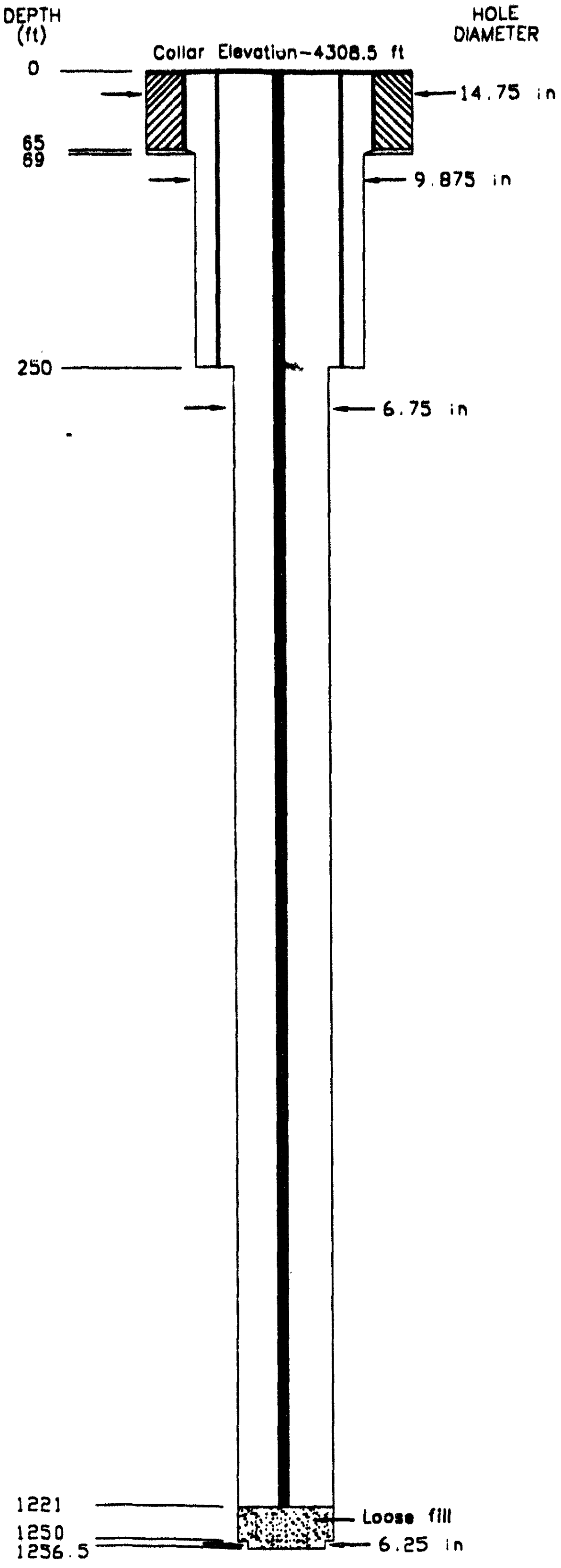
Annulus cemented with 218 ft^3 of Redi-Mix from 65 ft to surface.

OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 65 ft

Annulus not cemented.

OD = 7.625 in
ID = 6.969 in
T_e = 0.328 in
Set at 251 ft





HOLE INFC

135 – 163 – ● Hole sloughing
163 ft.

296 – 426 – ● Caliper log inc
eroded zone f
426 ft with a
enlargement o

874 – ▽ Fluid density l
fluid level at

990 – 1021 – ▲ Water flowing
990 to 1021

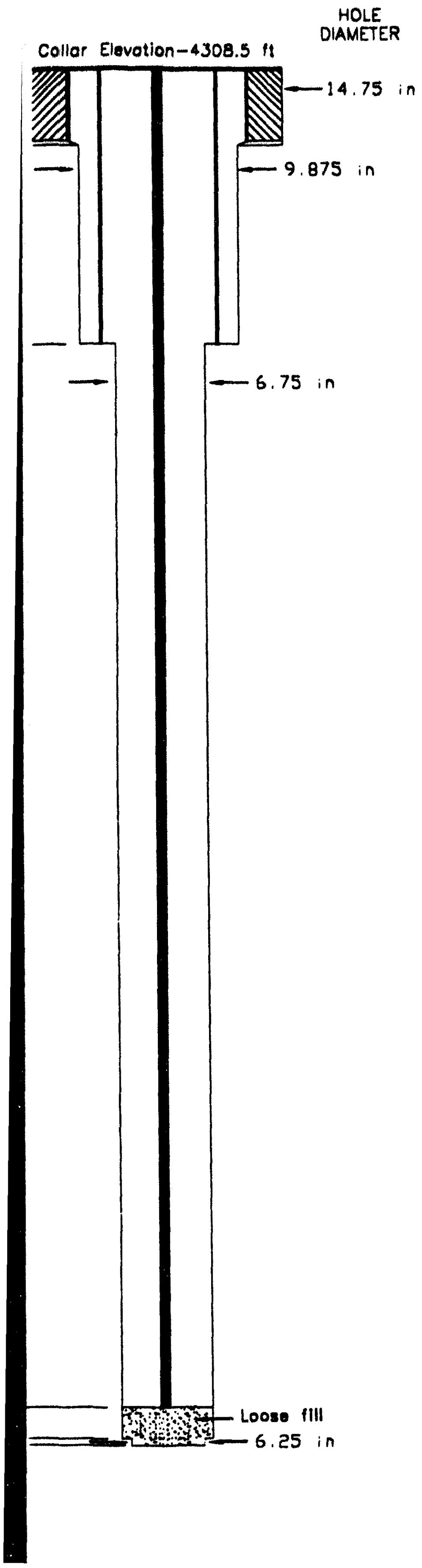
1202 – 1208 – ● Caliper log inc
zone from 12
with maximum
ment of 8.875

1220.7 – ■ 2.875 in OD
12 ft screen
1220.7 ft.

JE-25 WT #6

ALIZED DRILLER'S LOG

n Fenix and Scisson, 1986a)



HOLE INFORMATION

135 163	● Hole sloughing from 135 to 163 ft.
296 426	● Caliper log indicated an eroded zone from 296 to 426 ft with a maximum hole enlargement of 10.5 in.
874	▽ Fluid density log indicated fluid level at 874 ft.
990 1021	▲ Water flowing into hole from 990 to 1021 ft.
1202 1208	● Caliper log indicated eroded zone from 1202 to 1208 ft with maximum hole enlargement of 8.875 at 1208 ft.
1220.7	■ 2.875 in OD tubing with 12 ft screen landed at 1220.7 ft.

USW UZ-1

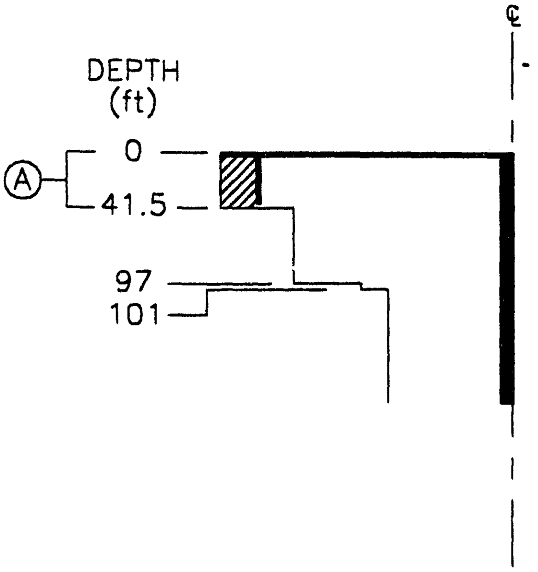
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987f)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 432 ft^3 of Redi-Mix cement from 41.5 ft to surface.

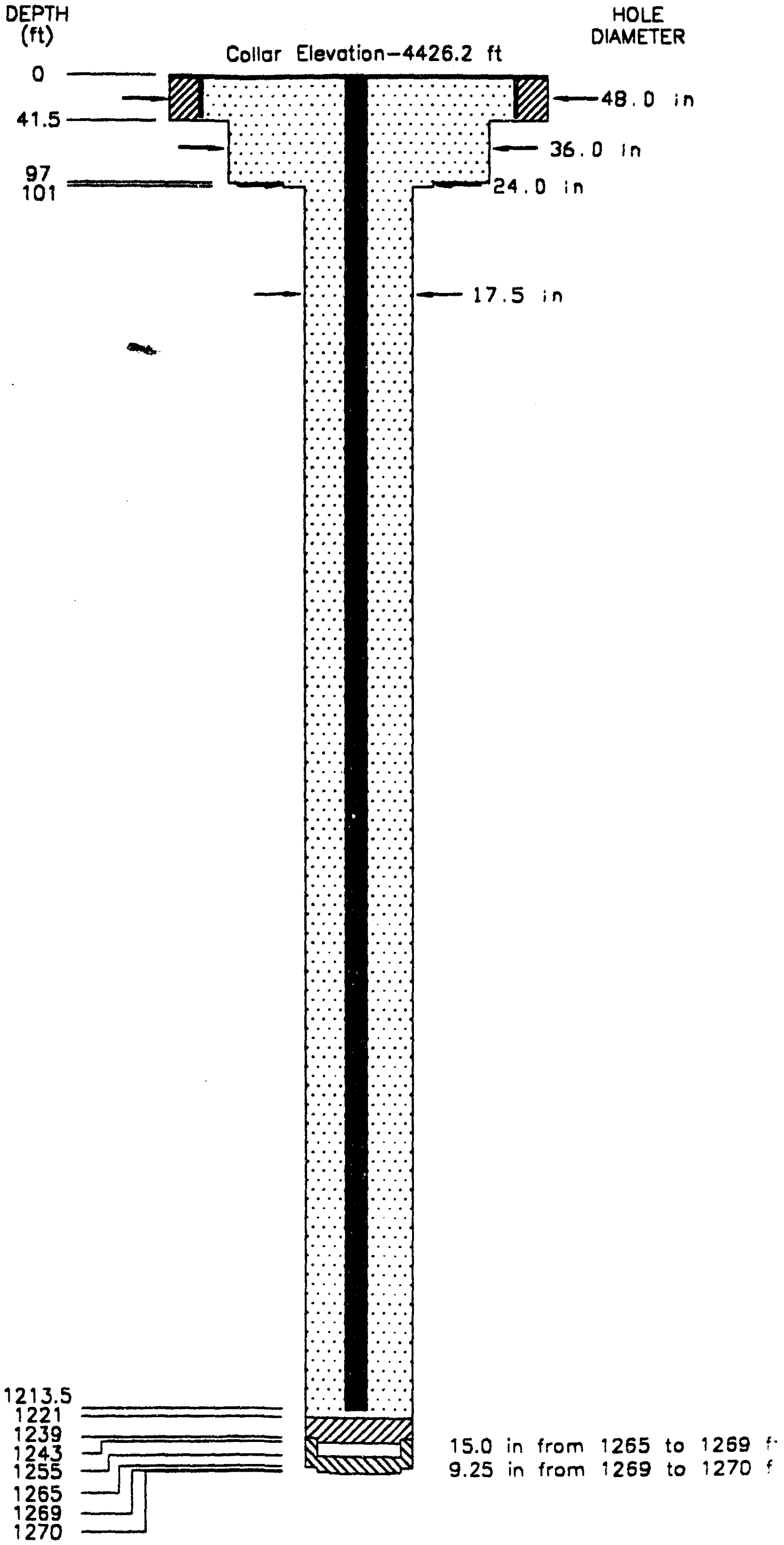
OD = 42.0 in
ID = 41.0 in
T_e = 0.5 in
Set at 39.5 ft



Hole cemented with 75 ft^3 of W-60 gypsum cement from fill at 1268 ft to 1221 ft, then drilled out to 1239 ft with 17.5 in bit and to 1255 ft with 15 in bit.

Hole cemented above junk left in hole at 1243 ft with 35 ft^3 of neat cement plus 2% $CaCl_2$ from 1243 to 1221 ft.

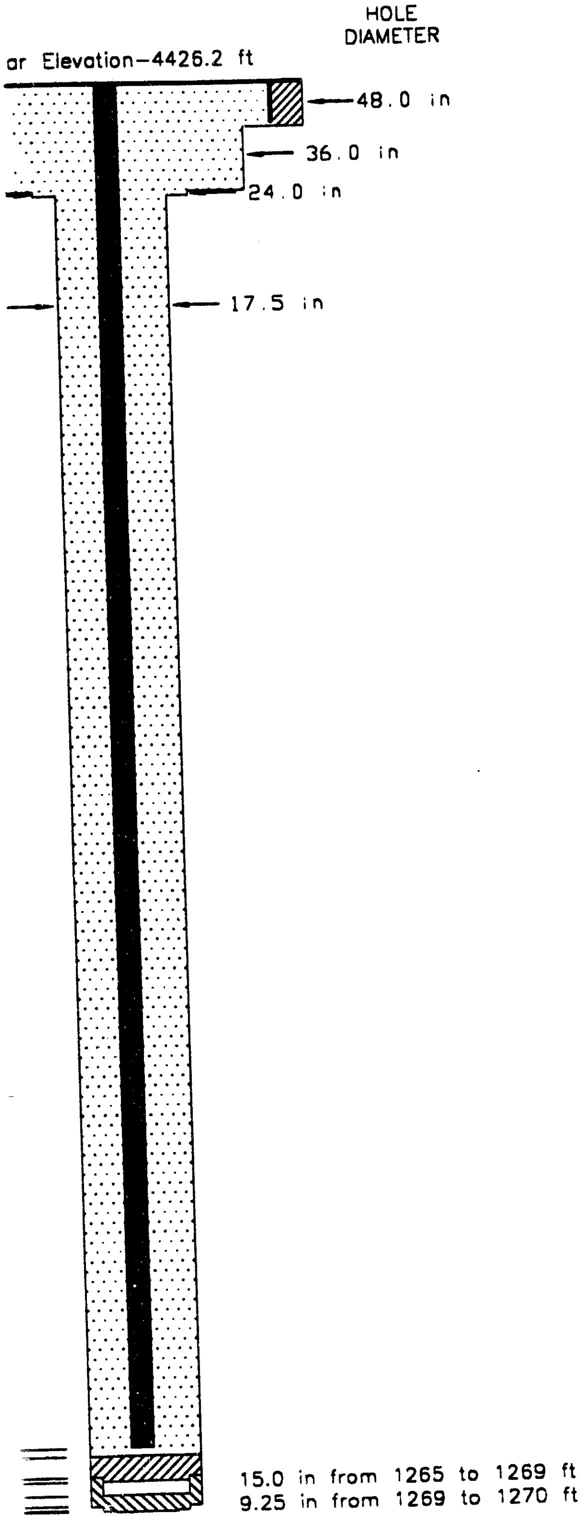
Instruments on 2.375 in OD fiberglass tubing set at 1213.35 ft. Alternately stemmed and grouted hole from 1217.5 ft to surface (total of 27 layers of grout, 30 layers of stemming). Stemming material includes layers of bentonite, 12-16 mesh sand and silica flour.



W UZ-1

ED DRILLER'S LOG

x and Scisson, 1987f)



HOLE INFORMATION

56 58	△ Lost circulation from 56 to 58 ft. (No Returns)
242 248 249	● Caliper log indicated eroded zone from 242 to 249 ft with maximum hole enlargement of 26 in at 248 ft.
492 493 517	● Eroded zone from 492 to 517 ft with maximum hole enlargement of 24 in at 493 ft.
846 869	● Eroded zone from 846 to 869 ft with maximum hole enlargement to 23.75 in.

USW UZ-6s

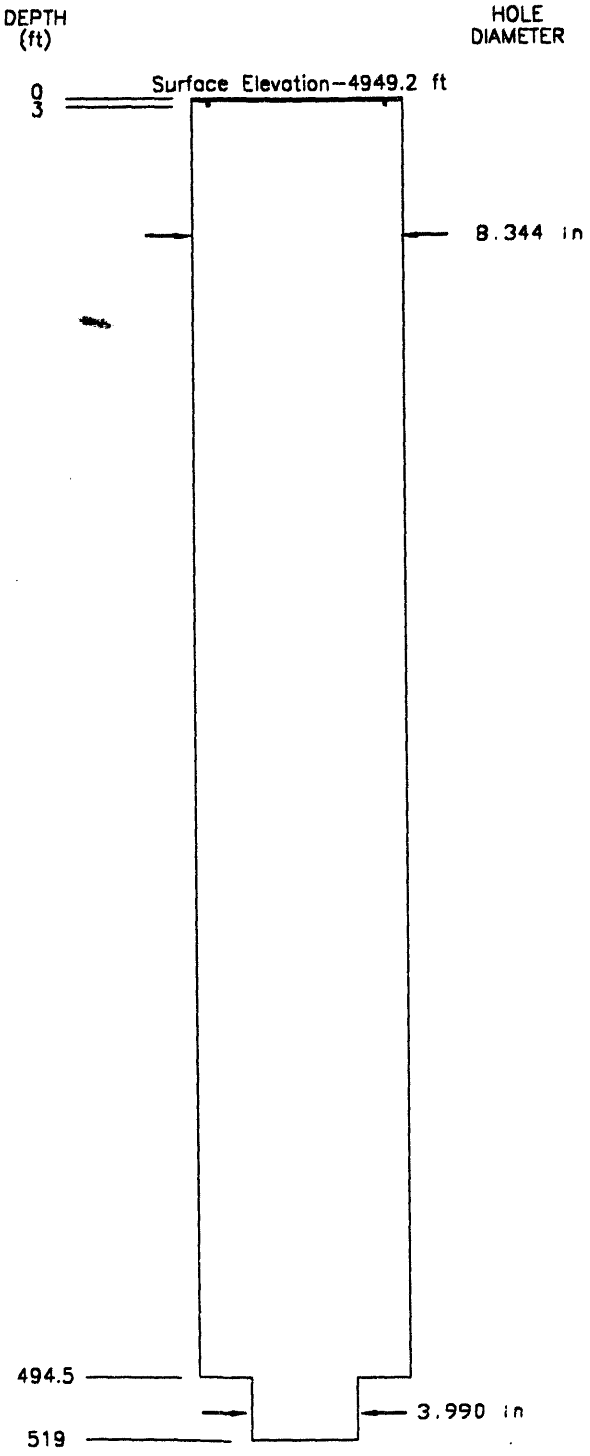
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987f)

CEMENTING AND CASING INFORMATION

Annulus not cemented-casing welded to plate at surface.

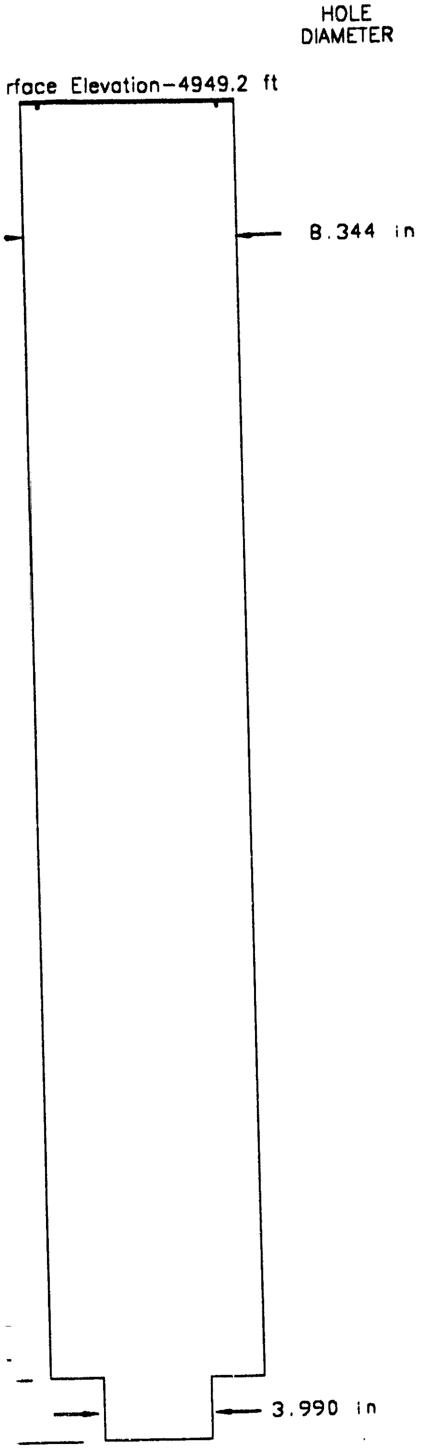
OD = 7.625 in
ID = 6.969 in
T_c = 0.328 in
Set at 3 ft



W UZ-6s

ED DRILLER'S LOG

< and Scisson, 1987f)



HOLE INFORMATION

USW UZ-6

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987f)

CEMENTING AND CASING INFORMATION

Annulus cemented with 189 ft^3 of Redi-Mix cement from 40 ft to surface.

OD = 26.75 in
ID = 26.00 in
T_c = 0.375 in
Set at 40 ft

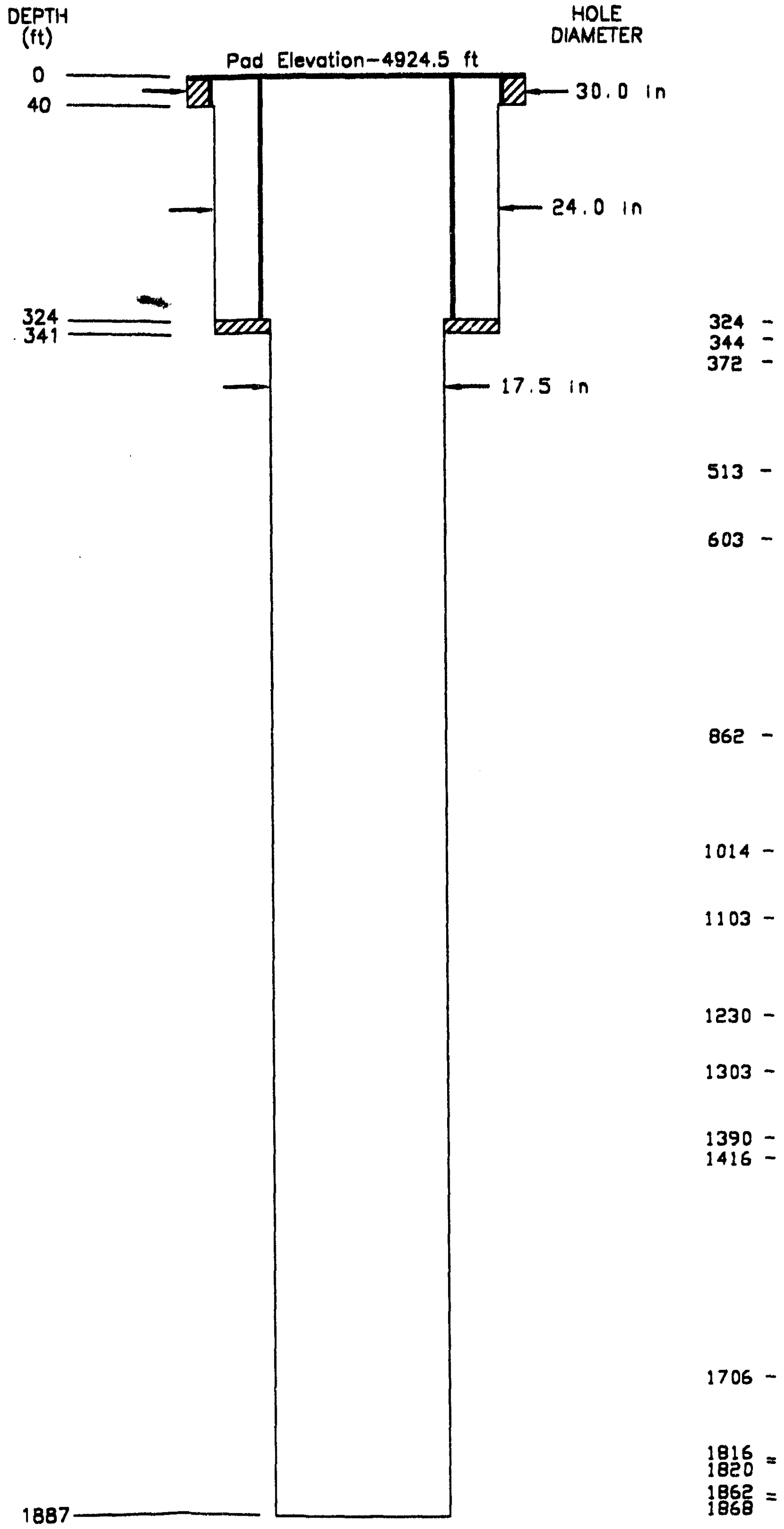
Annulus not cemented.

From 324 ft to 101 ft
OD = 20.0 in
ID = 19.25 in
T_c = 0.375 in
Set at 324 ft

From 101 ft to surface
OD = 20.0 in
ID = 19.0 in
T_c = 0.5 in

Hole cemented from 322 to 328 ft with 200 ft^3 of neat cement plus 150 lbs D-19 friction reducer to stabilize the hole, then drilled out.

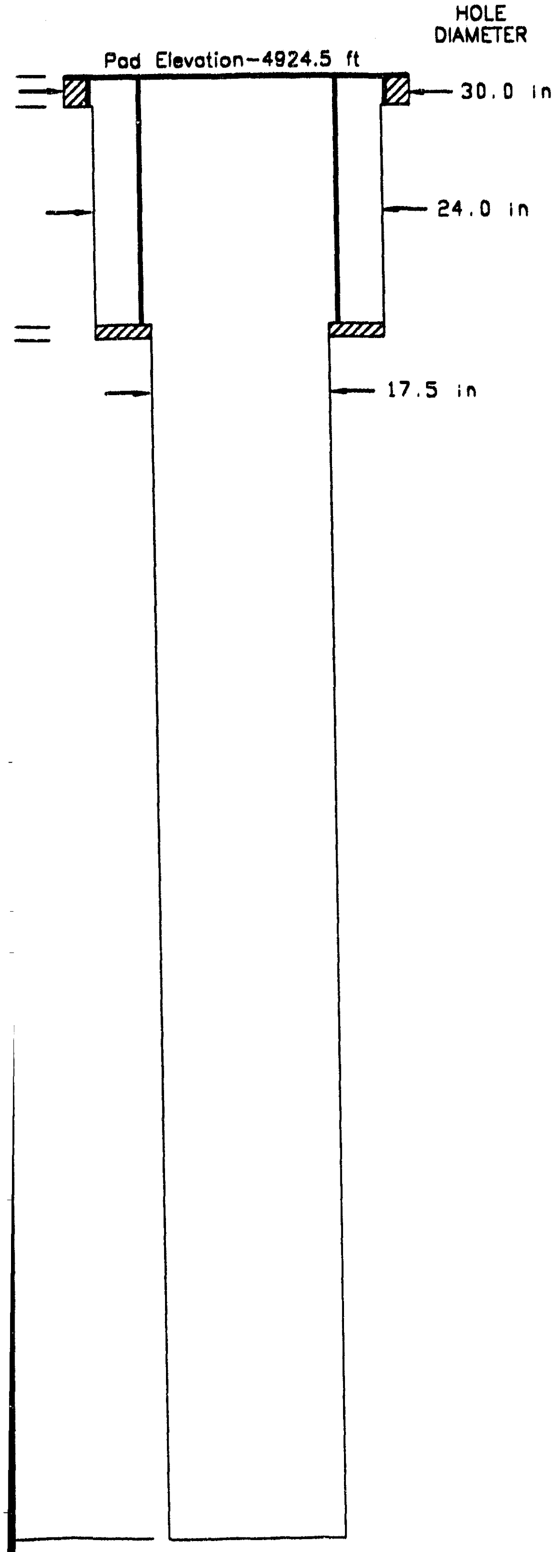
Hole again cemented, from 324 to 331 ft with 210 ft^3 of neat cement plus 2200 lbs Gilsonite and 150 lbs D-19, then drilled out.



USW UZ-6

RALIZED DRILLER'S LOG

m Fenix and Scisson, 1987f)



HOLE INFORMATION

324 - 344 - 372 -	● Caliper log indicated eroded zone from bottom of 20 in casing (324 ft) to 372 ft with maximum hole enlargement to 38.25 in at 344 ft.
513 - 603 -	● Eroded hole to 1103 ft with maximum hole enlargements of 29.25 in at 513, 36.75 in at 603 ft, 33.75 in at 862 ft and 36.5 in at 1014 ft.
862 -	
1014 -	
1103 -	
1230 - 1303 -	● Eroded zone from 1230 to 1390 ft with maximum hole enlargement of 29 in at 1303 ft.
1390 - 1416 -	● Eroded zones from 1416 to 1706 ft and 1816 to 1820ft.
1706 -	▽ Fluid density log indicated no fluid (log ran to 1862 ft).
1816 1820 =	
1862 1868 =	● Formation change indicated at 1868 ft.

UE-25c #2

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986b)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 189 ft^3 of Redi-Mix cement from 40 ft to surface.

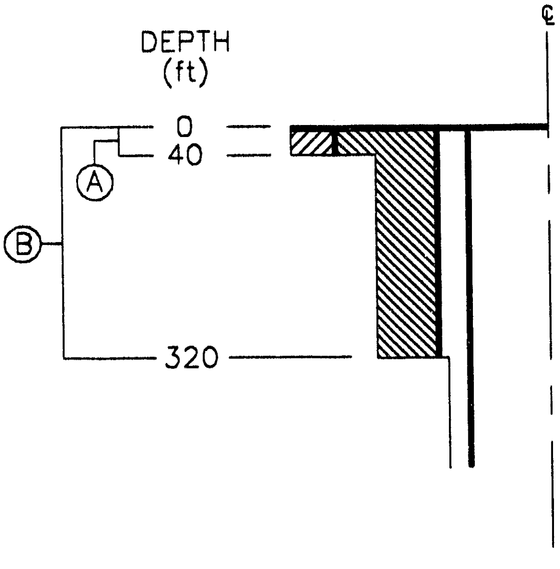
OD = 30.0 in
ID = 29.0 in
T_e = 0.5 in
Set at 39.5 ft

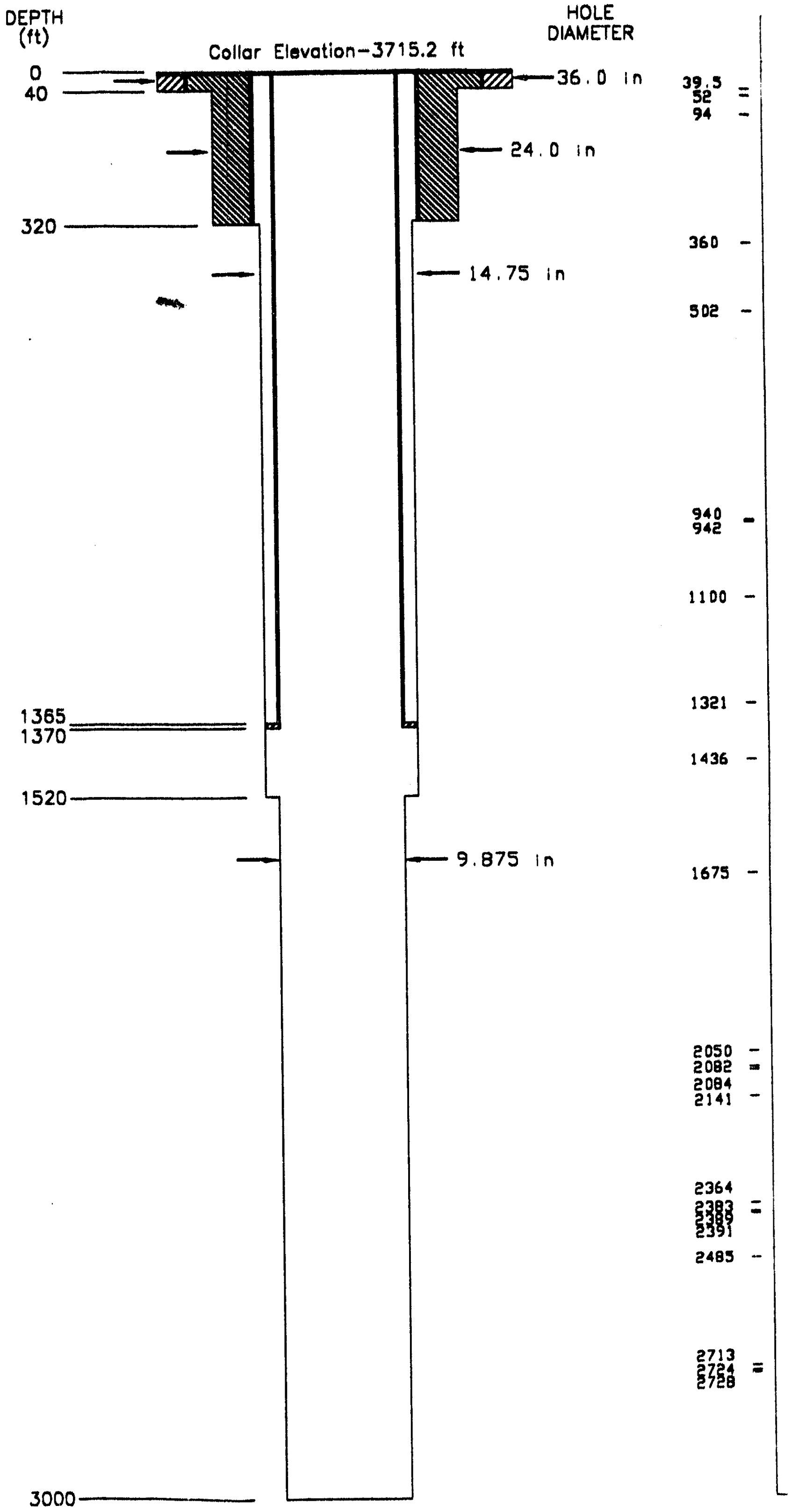
Ⓑ Annulus cemented with 864 ft^3 of Redi-Mix cement from 320 ft to surface.

OD = 16.000 in
ID = 15.010 in
T_e = 0.495 in
Set at 319 ft

Annulus spot cemented with 100 ft^3 of neat cement plus 2% $CaCl_2$ from 1370 ft to an unknown depth.

OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 1365 ft

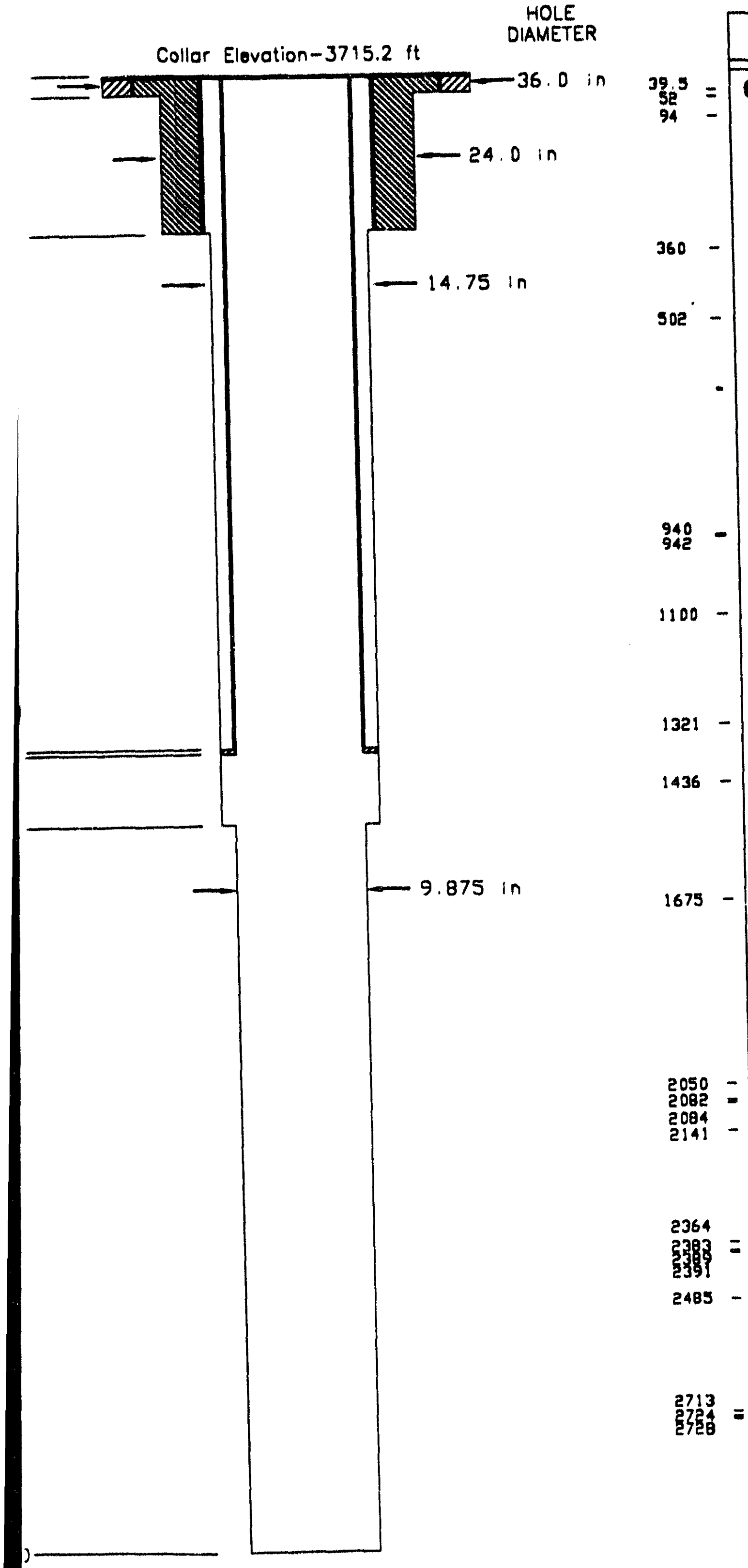




UE-25c #2

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986b)



HOLE INFORMATION

- ● Caliper log indicated eroded zone from bottom of casing at 39.5 ft to 94 ft with maximum hole enlargement of greater than 38.33 in at 52 ft.
- ● Several eroded zones indicated to 1436 ft with maximum hole enlargements of 23 in at 360 ft, 23.75 in at 502 ft, 27.25 in at 942 ft and 22.25 in at 1100 ft.
- ● Drill encountered 4 ft void at 940 ft.
- ▽ Fluid level checked at 1321ft.
- ● Slight hole erosion to 17.5 in at 1675 ft.
- ● Eroded zones indicated between 2050 and 2141 ft, 2383 and 2391 ft, and between 2713 and 2728 ft with maximum hole enlargements of 16 in at 2082 and 2084 ft, 14.5 in at 2389 ft and 15.25 in at 2724 ft.
- ■ Centrilift pump was set in hole with intake at 2364 ft and monitor line at 2365 ft.
- ■ Retrievable bridge plug was set at 2485 ft.

USW UZ-7

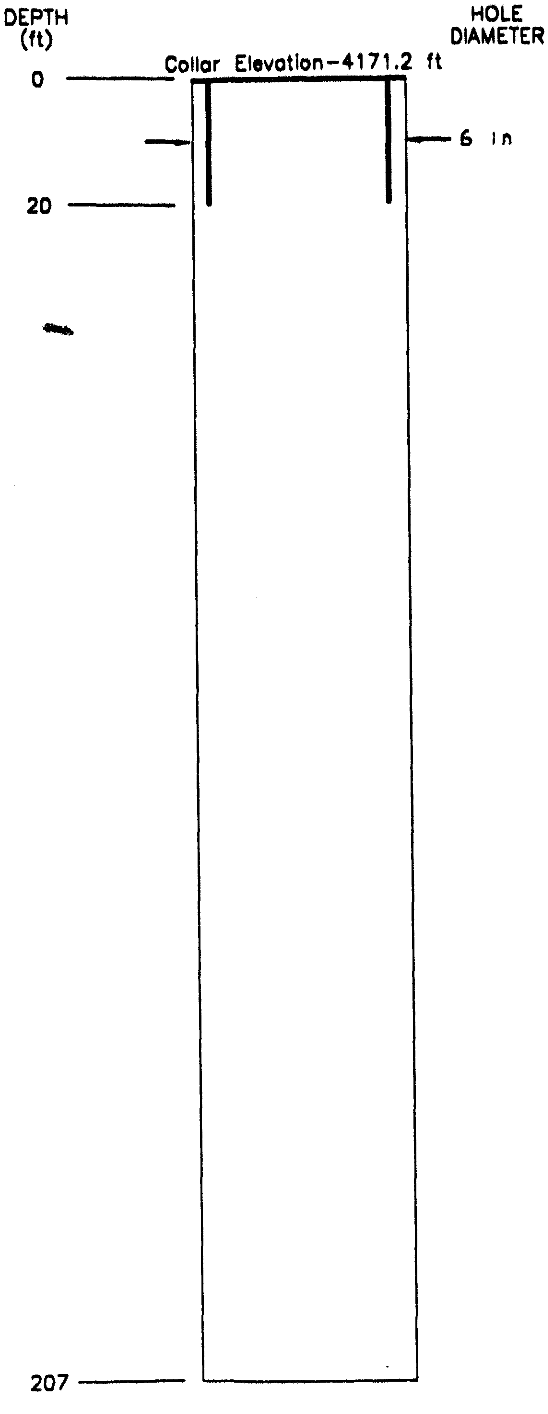
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987f)

CEMENTING AND CASING INFORMATION

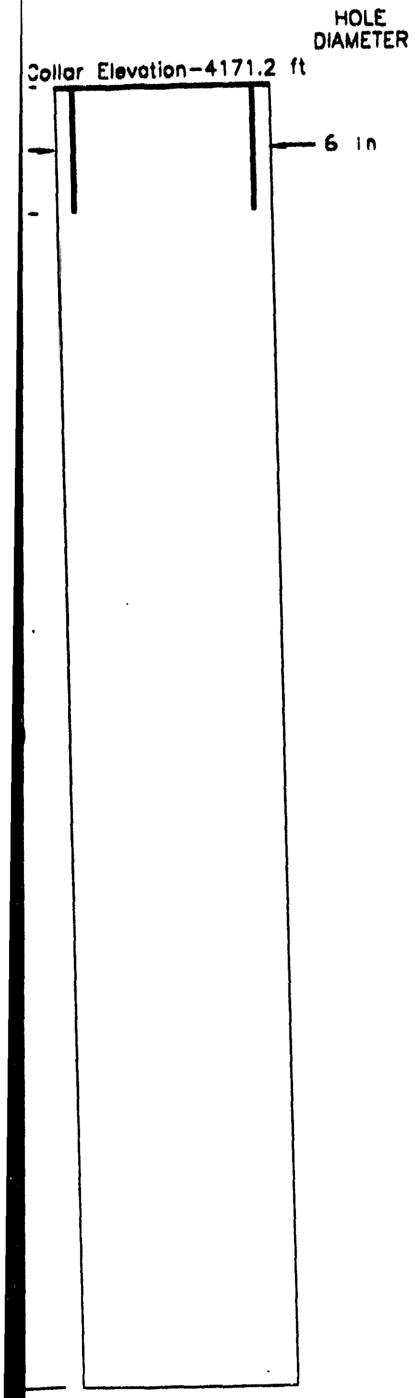
Annulus not cemented.

OD = 5.5 in
ID = 5.0 in
T_e = 0.25 in
Set at 20 ft



301820.01.01 823

SW UZ-7
ZED DRILLER'S LOG
nix and Scisson, 1987f)



HOLE INFORMATION

UE-25c #1

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986b)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 200 ft^3 of neat cement plus 2% $CaCl_2$ from 30 ft to surface.

OD = 30.0 in
ID = 29.25 in
T_s = 0.375 in
Set at 30 ft

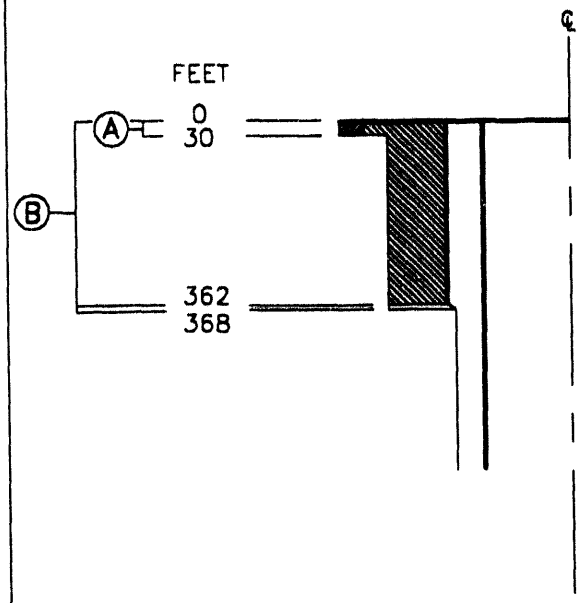
Hole cemented from 74 ft to 27 ft with 1030 ft^3 neat cement plus 2% $CaCl_2$ because of sloughing. Hole drilled out.

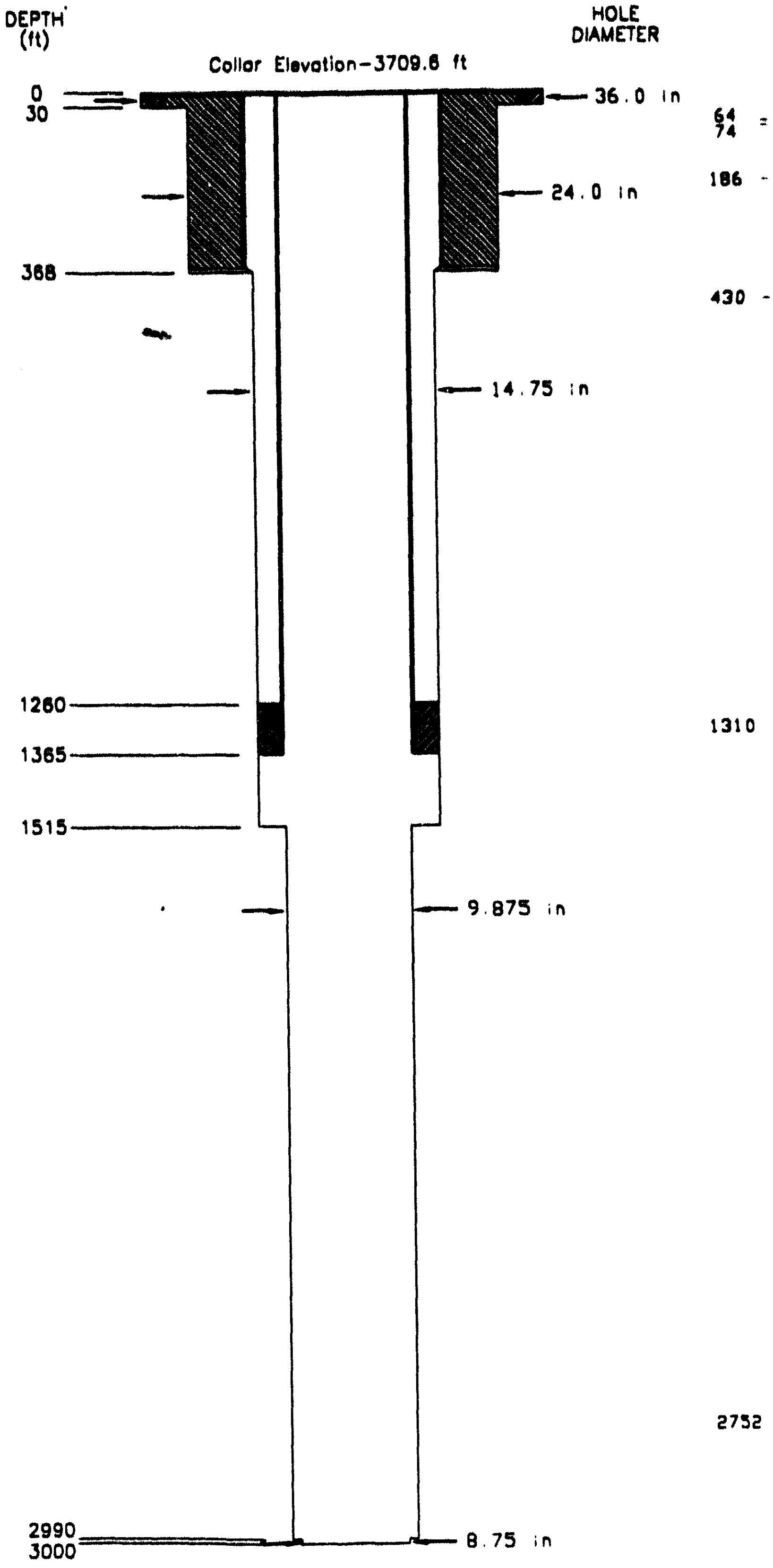
Ⓑ Annulus cemented with 972 ft^3 of Redi-Mix cement plus 2% $CaCl_2$ from 362 ft to surface.

OD = 16.000 in
ID = 15.124 in
T_s = 0.438 in
Set at 362 ft

Annulus cemented with 140 ft^3 of neat cement plus 2% $CaCl_2$ from 1365 to 1260 ft.

OD = 10.750 in
ID = 10.050 in
T_s = 0.350 in
Set at 1365 ft

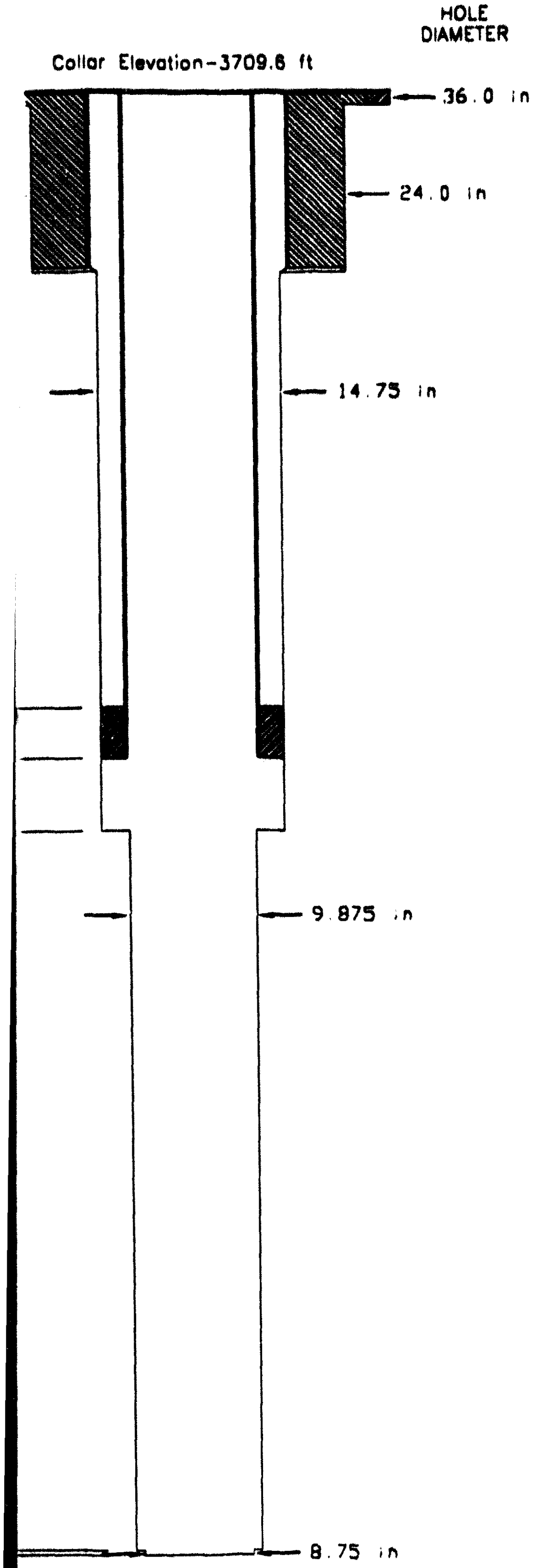




JE-25c #1

IZED DRILLER'S LOG

enix and Sclsson, 1986b)



HOLE INFORMATION

64 = 74	● Hole sloughing from 64 to 74 ft.
186 -	● Caliper log indicated maximum hole enlargement of 34 in at 186 ft.
430 -	● Hole enlargement to 28.5 in at 430 ft.
1310 -	▽ Fluid level at 1310 ft.
2752 -	● Hole enlargement to 22 in indicated at 2752 ft.

UE-25 WT #3

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

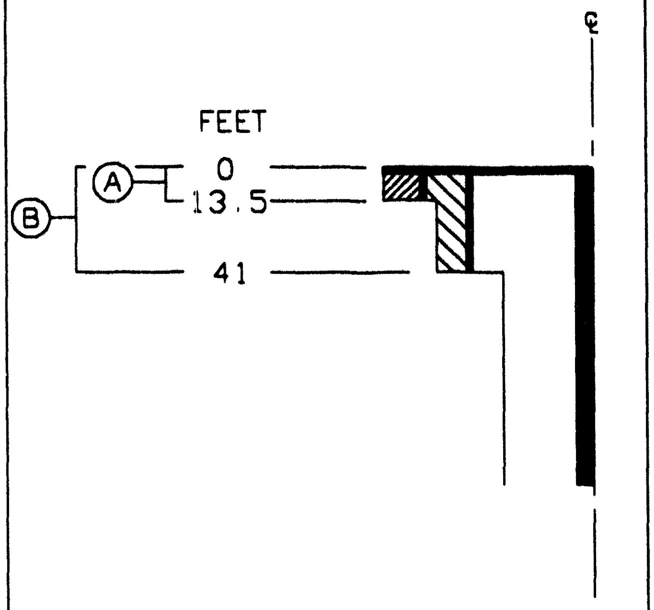
CEMENTING AND CASING INFORMATION

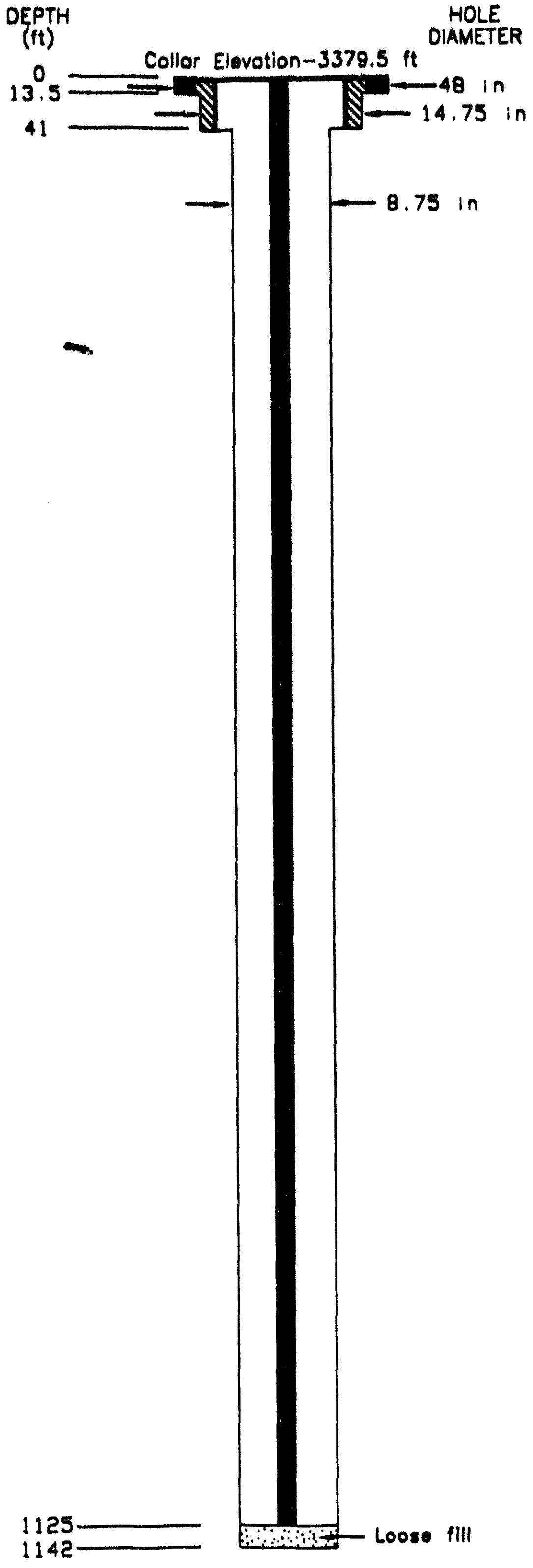
Ⓐ Annulus cemented with 216 ft^3 of Redi-Mix from 13.5 ft to surface.

OD = 16 in
ID = 15.010 in
T_e = 0.495 in
Set at 13.5 ft

Ⓑ Annulus cemented with 68 ft^3 of Redi-Mix from 41 ft to surface.

OD = 10.75 in
ID = 10.05 in
T_e = 0.35 in
Set at 40 ft

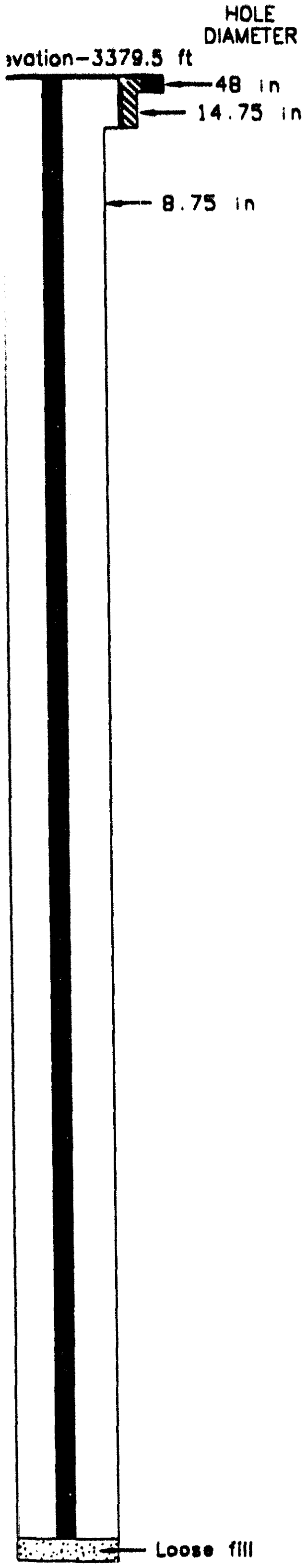




5 WT #3

D DRILLER'S LOG

and Scisson, 1986a)



HOLE INFORMATION

40 –
82 –
● Caliper log indicated hole enlargement between 40 and 140 ft with a maximum hole enlargement of 21.5 in at 82 ft.

140 –

983 – ▽ Fluid level in hole measured at 983.

1125 – ■ 2.875 in OD tubing with 12 ft screen landed at 1125 ft.

UE-25c #3

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986b)

CEMENTING AND CASING INFORMATION

Ⓐ Annulus cemented with 432 ft^3 of Redi-Mix cement from 39 to 2.5 ft.

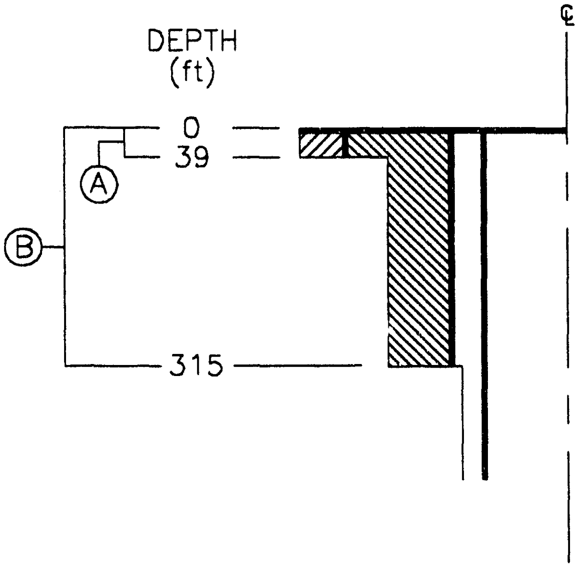
OD = 30.0 in
ID = 29.25 in
T_c = 0.375 in
Set at 39 ft

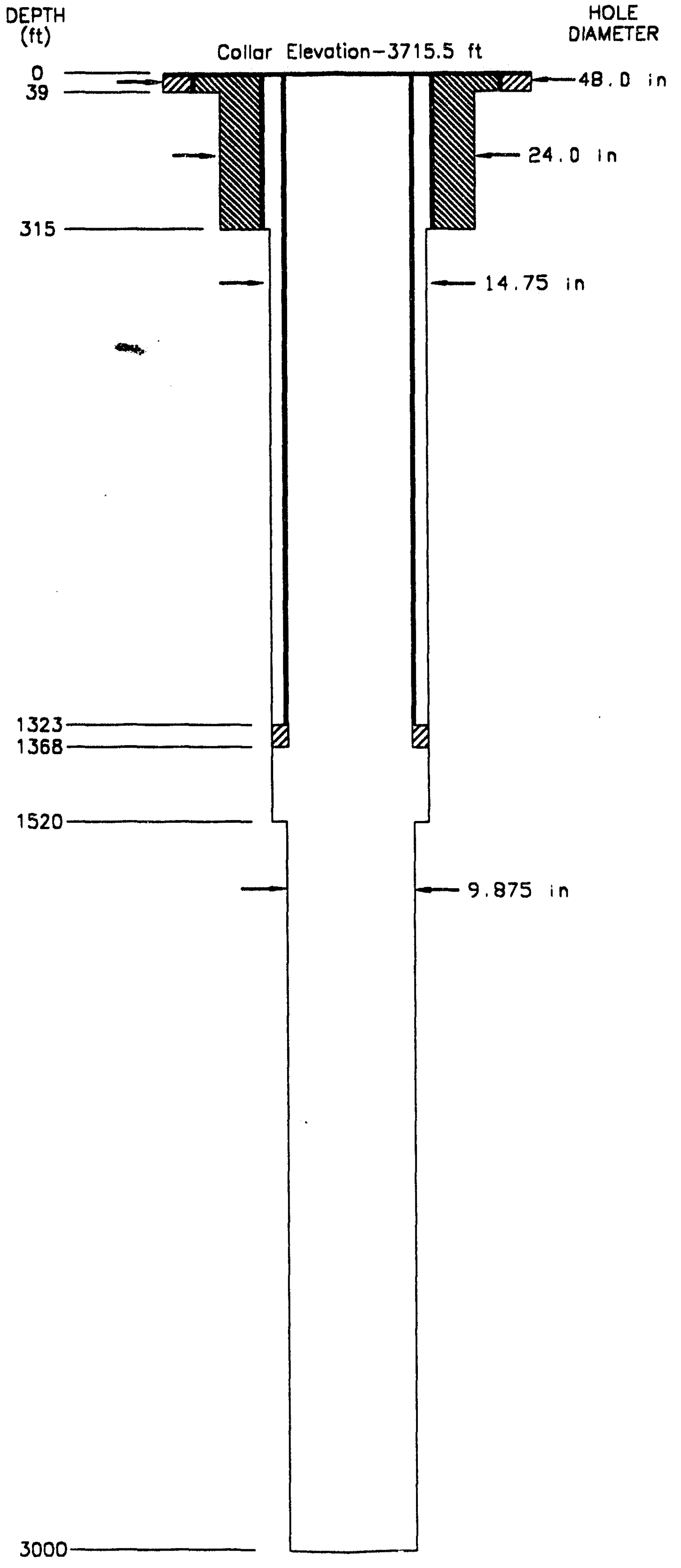
Ⓑ Annulus cemented with 864 ft^3 of Redi-Mix cement from 313 to surface.

OD = 16.000 in
ID = 15.010 in
T_c = 0.495 in
Set at 313 ft

Annulus spot cemented with 100 ft^3 of neat cement plus 2% $CaCl_2$ from 1368 to an unknown depth.

OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 1323 ft

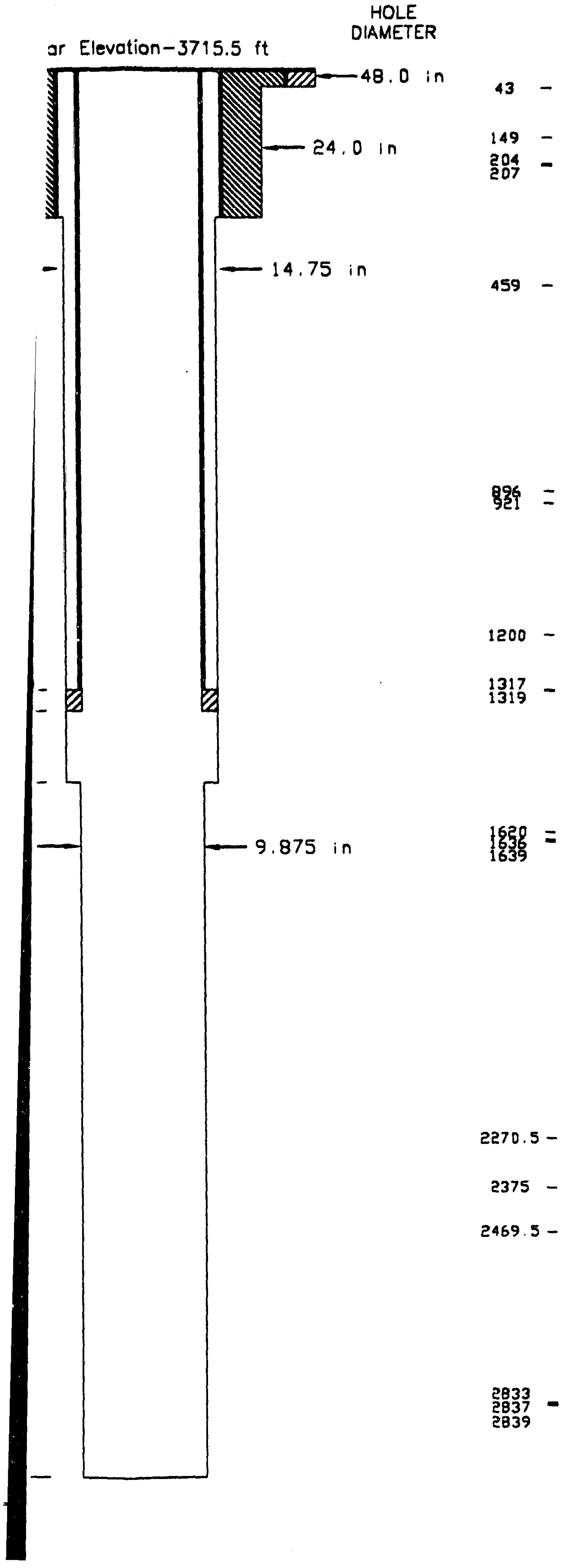




:-25c #3

ZED DRILLER'S LOG

ix and Scisson, 1986b)



HOLE INFORMATION

● Caliper log indicated hole eroded to 207 ft with maximum hole enlargements of 38.75 in at 43 ft, 28.75 in at 149 ft and 29 in at 204 ft.

● Hole eroded to 1200 ft with maximum hole enlargements of 25.75 in at 459 ft and 25.5 in at 896 and 921 ft.

▲ Formation water indicated at 1317 ft.

▽ Fluid density log indicated fluid level at 1319 ft.

● Hole eroded between 1620 and 1639 ft with maximum hole enlargement greater than 31.75 in at 1636 ft.

▲ Water inflow increase at 2375 ft.

■ Dual element packer was set in hole with center at 2469.5 ft and 2.375 in monitor line at 2270.5 ft.

● Eroded zone indicated between 2833 and 2839 ft with maximum hole enlargement of 23.25 in at 2837 ft.

UE-25 WT #4

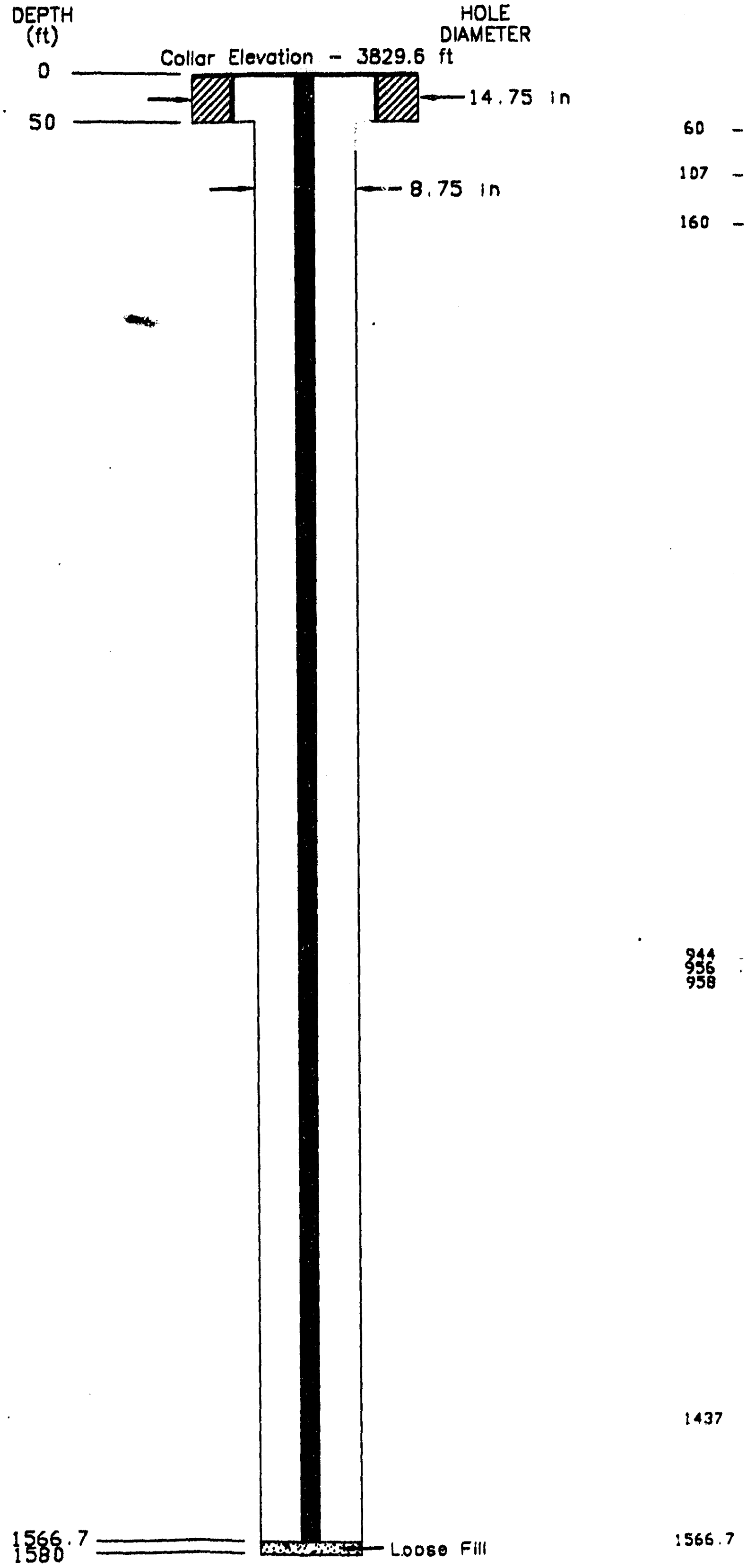
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 28 ft^3 of 75% neat cement, 25% gypsum cement from 50 ft to surface.

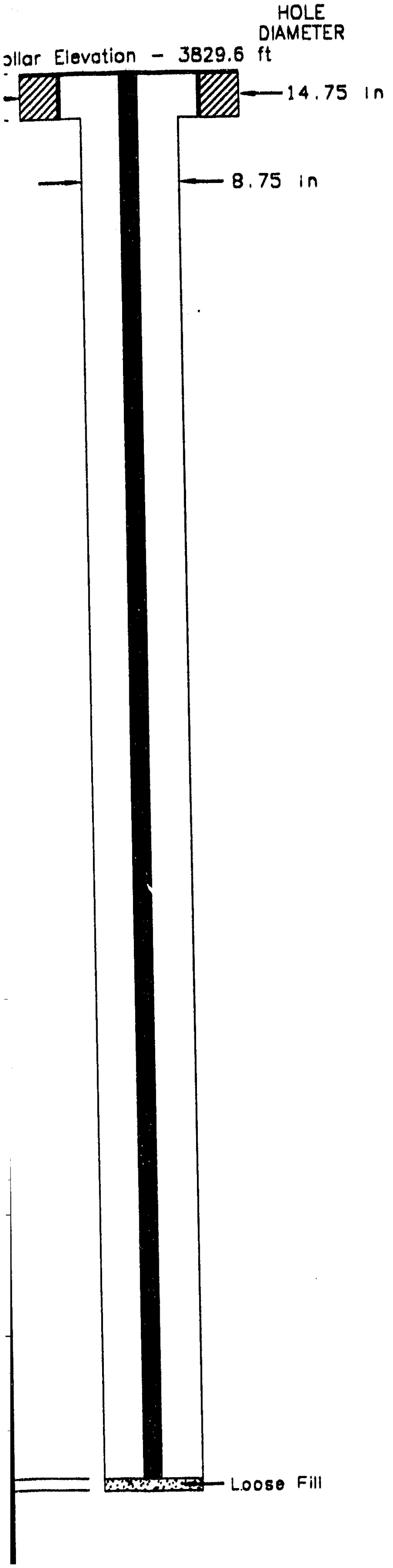
OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 48 ft



E-25 WT #4

LIZED DRILLER'S LOG

Fenix and Scisson, 1986a)



HOLE INFORMATION

60 107 160	● Caliper log indicated eroded zone from 60 to 160 ft with maximum hole enlargement of 18 in at 107 ft.
944 956 958	● Caliper log indicated hole enlargement from 944 to 958 ft with maximum hole enlargement of 16.5 in at 956 ft.
1437	▽ Fluid density log indicated fluid level at 1437 ft.
1566.7	■ 2.875 in OD tubing with 12 ft screen landed at 1566.7 ft.

UE-25 WT #12

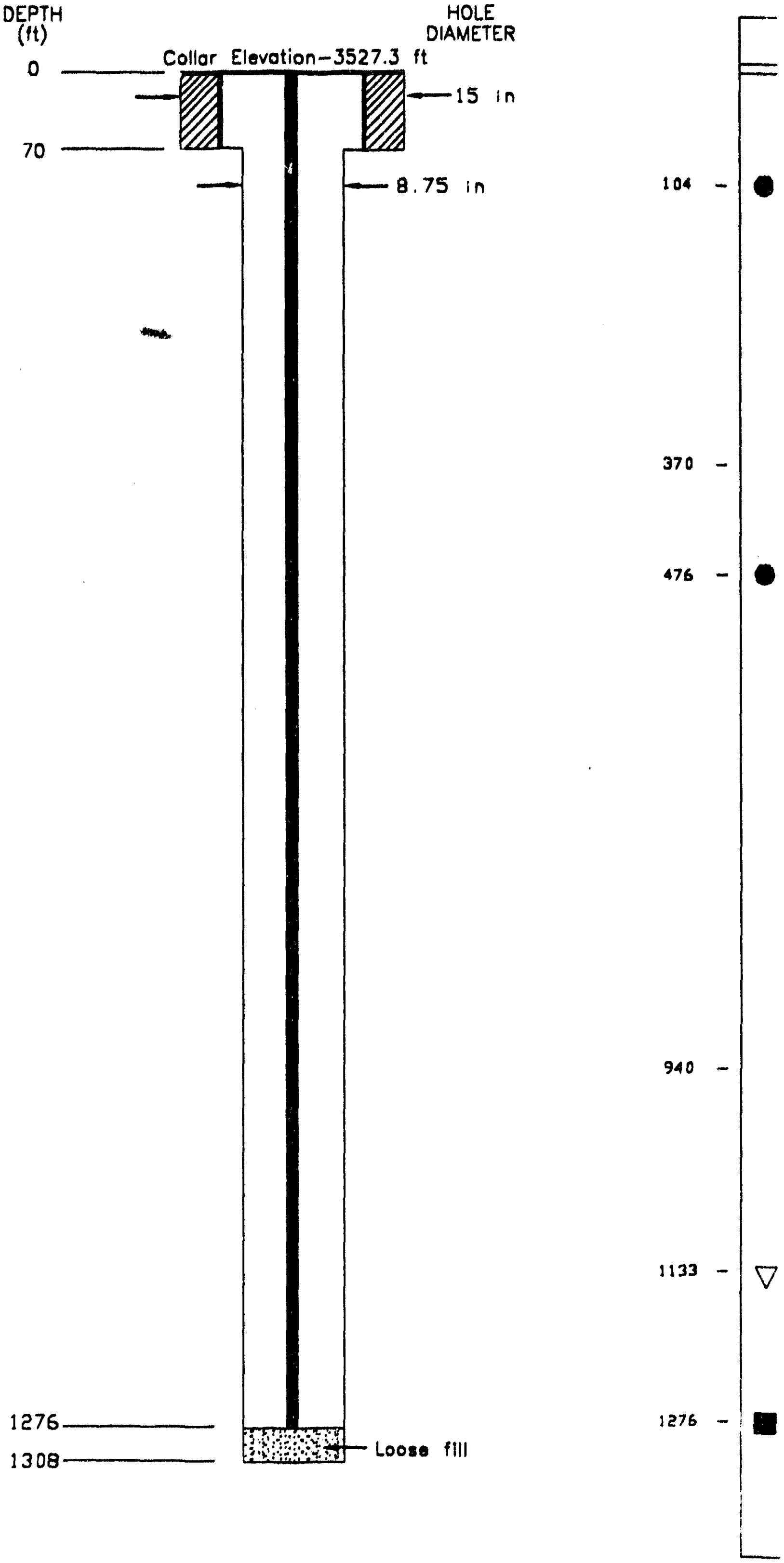
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 162 ft^3 of Redi-Mix cement from 70 ft to surface.

OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 70 ft

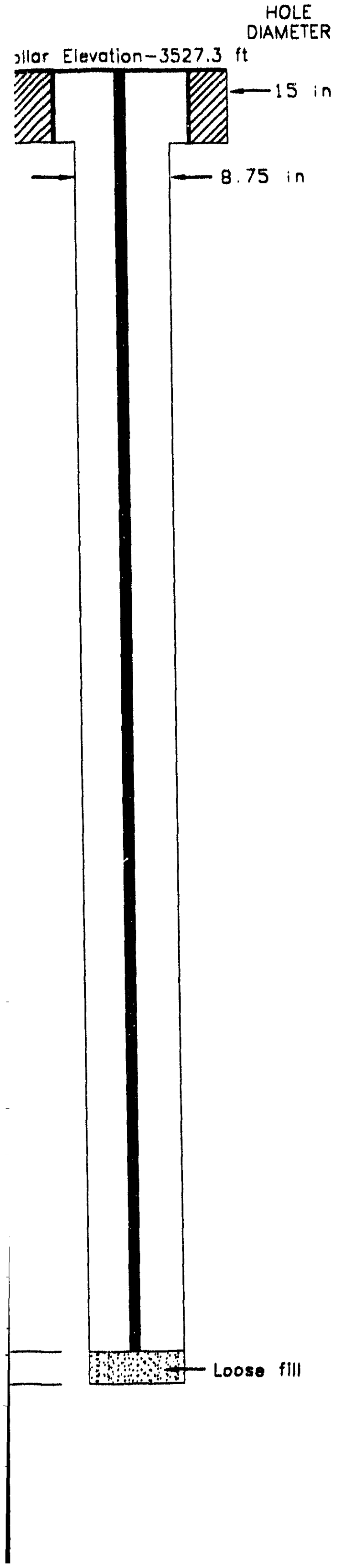


301620.01.01 B28

·25 WT #12

IZED DRILLER'S LOG

:nix and Scisson, 1986a)



HOLE INFORMATION

104 –	● Caliper log indicated eroded zone from 104 to 370 ft with maximum hole enlargement of 21.5 in.
370 –	
476 –	● Caliper log indicated eroded zone from 476 to 940 ft with maximum hole enlargement of 17.75 in.
940 –	
1133 –	▽ Fluid density log indicated fluid level at 1133 ft.
1276 –	■ 2.875 in OD tubing with 11.65 ft screen landed at 1276 ft.

UE-25 WT #13

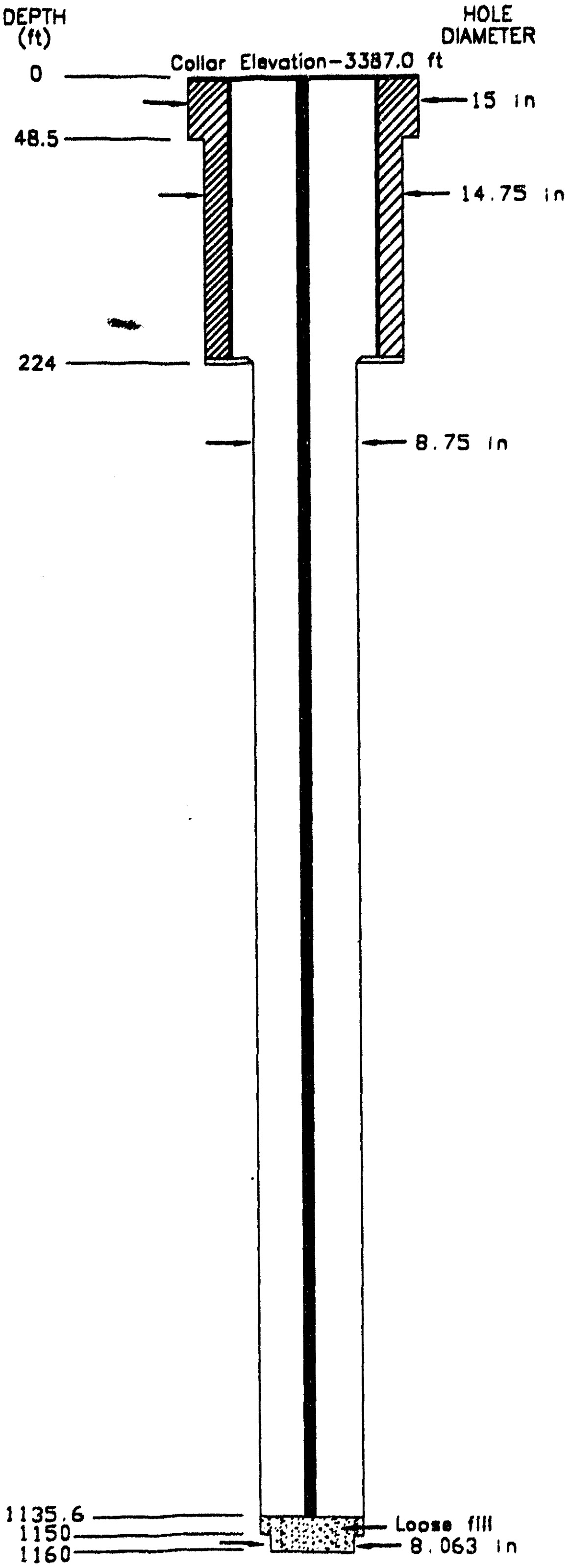
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 381 ft^3 of neat cement plus 3% $CaCl_2$ from 222 ft to 3 ft and 5 ft^3 of Cal-Seal cement from 3 ft to surface.

OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 222 ft



492
497 =

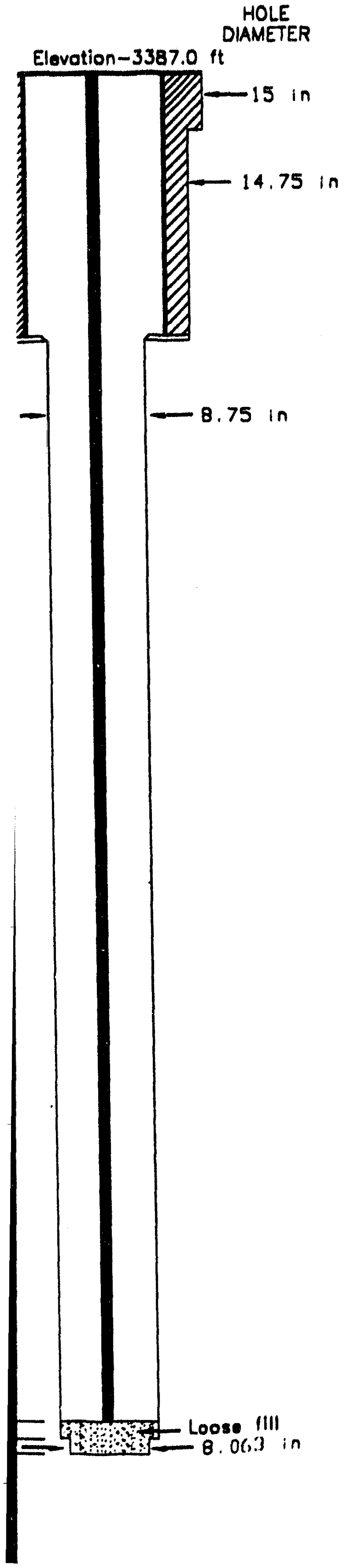
994 -
1024 -
1090 -
1135 6 -

301620.01.01 B29

5 WT #13

:D DRILLER'S LOG

and Scisson, 1986a)



HOLE INFORMATION

492
497 = ● Caliper log indicated hole enlargement from 492 to 497 ft with maximum hole enlargement of 16.75 in.

994 – ▽ Fluid density log indicated fluid level at 994 ft.

1024 – ● Caliper log indicated eroded zone from 1024 to 1090 ft with maximum hole enlargement of 17.75 in.

1090 –

1135.6 – ■ 2.875 in OD tubing with 12 ft screen sub and 1.5 ft orange peeled sub landed at 1135.6 ft.

UE-25 WT #15

GENERALIZED DRILLER'S LOG

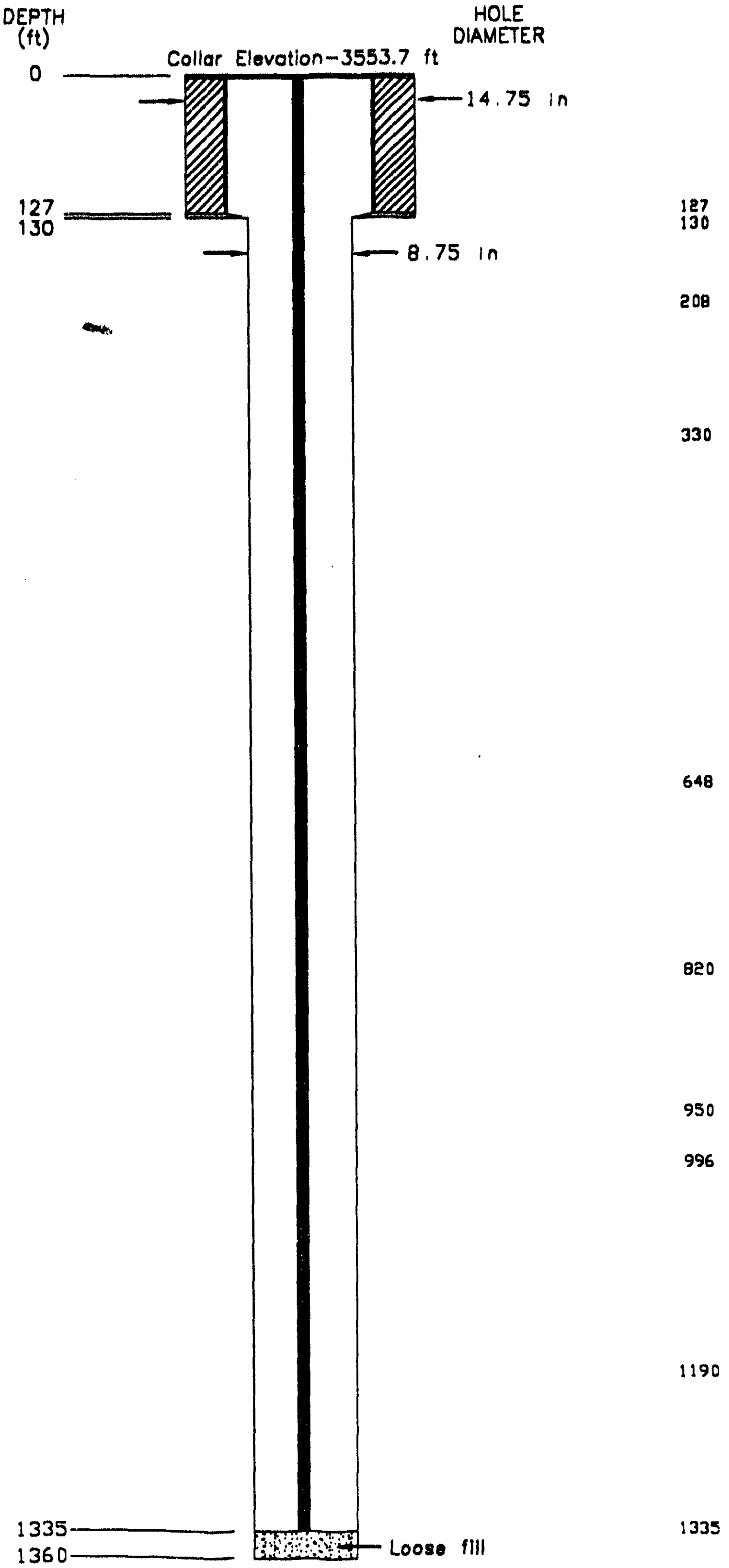
(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Hole cemented from 35 ft to surface with 725 ft^3 of neat cement plus 2% $CaCl_2$, then drilled out because of excessive sloughing.

Annulus cemented with 430 ft^3 of neat cement plus 2% $CaCl_2$ from 127 ft to surface.

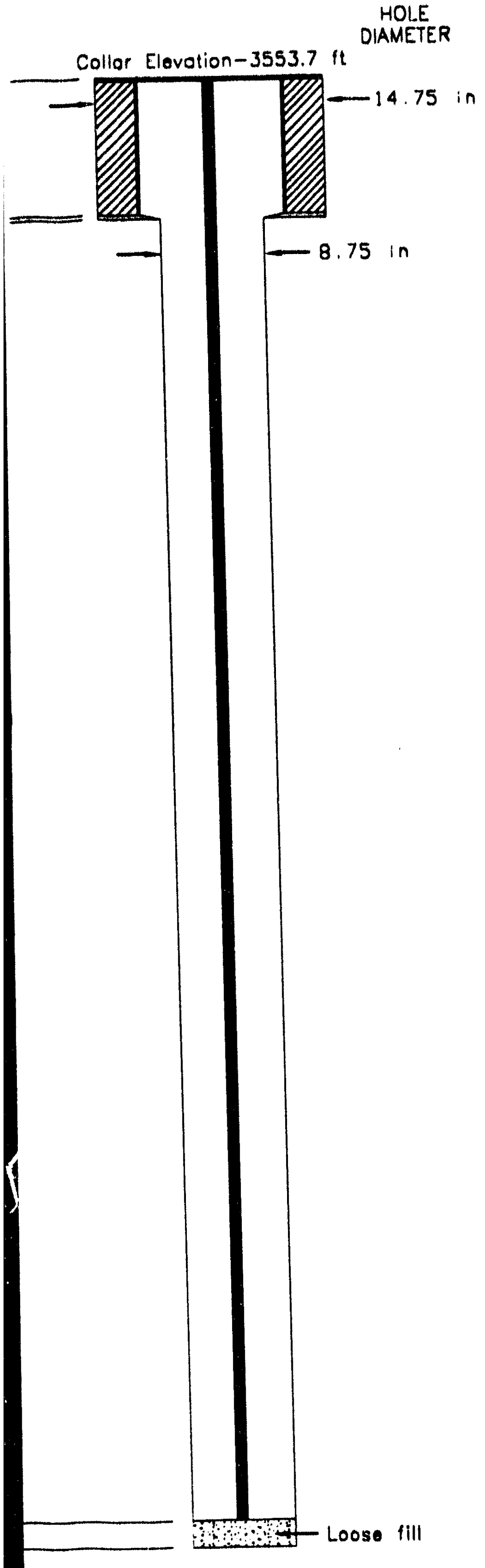
OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 127 ft



UE-25 WT #15

:RALIZED DRILLER'S LOG

·om Fenix and Scisson, 1986a)



HOLE INFORMATION

127 130	●	Caliper log indicated eroded zone from 127 ft to 208 ft with maximum hole enlargement of 30 in at 130 ft.
208		
330	●	Caliper log indicated eroded zone from 330 ft to 820 ft with maximum hole enlargement of 17.25 ft at 648 ft.
648		
820		
950		
996	●	Caliper log indicated slightly eroded hole below 950 ft with maximum hole enlargement of 15.75 ft at 996 ft.
1190	▽	Fluid density log indicated fluid level at 1190 ft.
1335	■	2.875 in OD tubing with 12 ft screen landed at 1335 ft.

UE-25 WT #14

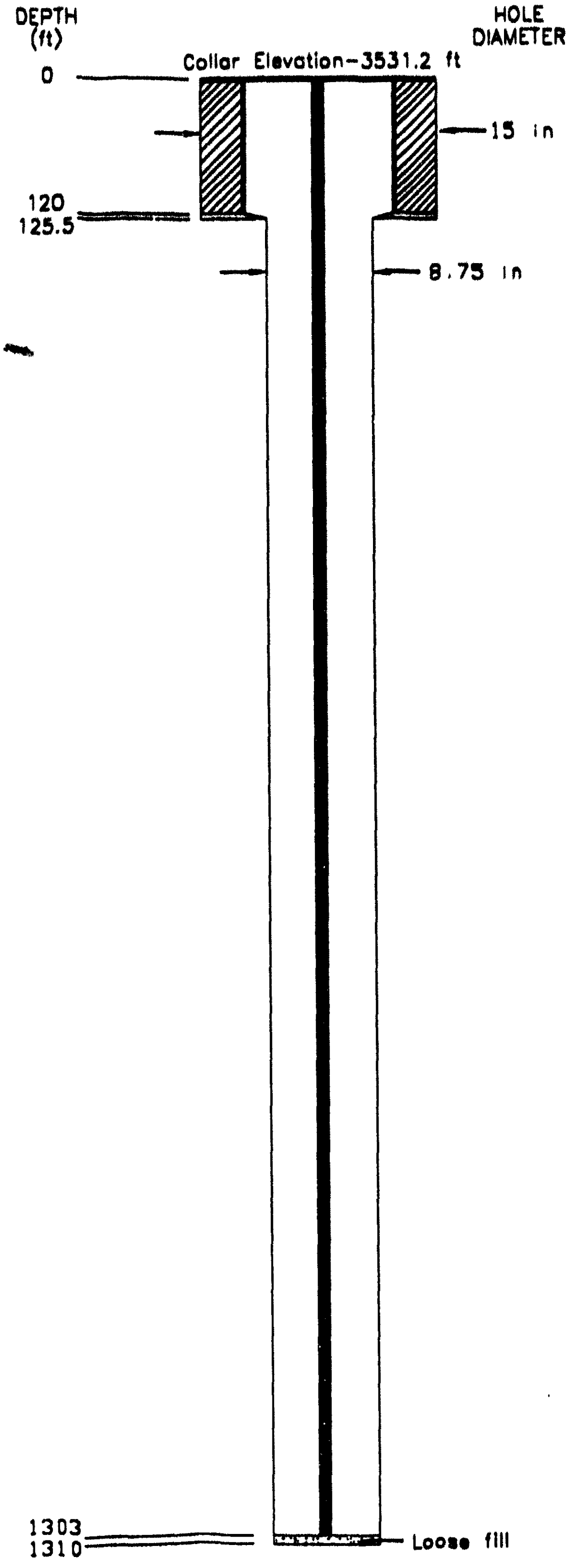
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 378 ft^3 of Redi-Mix cement from 120 ft to surface.

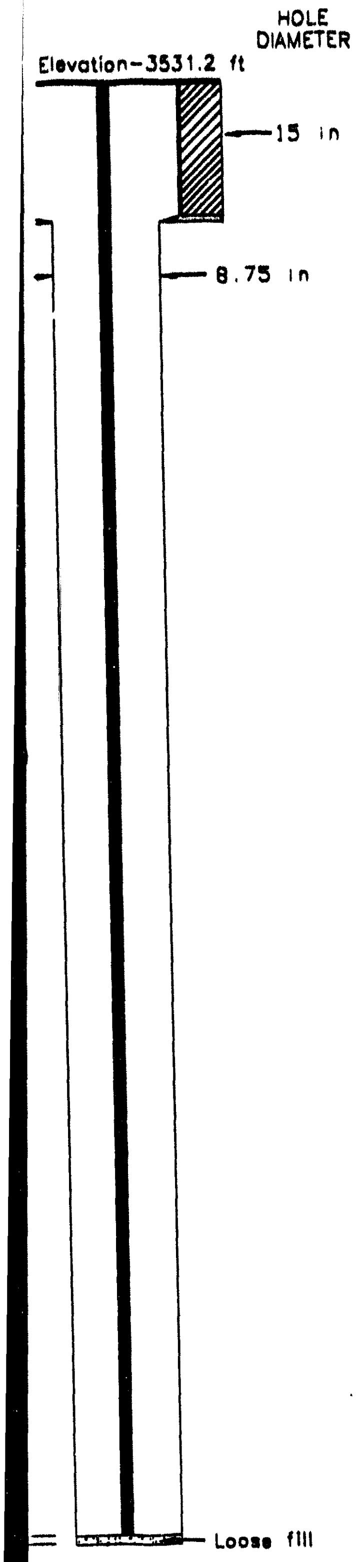
OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 120 ft



5 WT #14

D DRILLER'S LOG

and Scisson, 1986a)



HOLE INFORMATION

190 – ● Caliper log indicated a slightly eroded hole with maximum hole enlargements of 19.75 in at 190 ft, 19 in at 585 ft, 18 in at 930 ft and 14.5 in at 1037 ft.

585 –

930 –

1037 –

1130 – ▽ Fluid level marked at 1130 ft.

1303 – ■ 2.875 in OD tubing with 12.1 ft steel screen landed at 1303 ft.

UE-25 WT #18

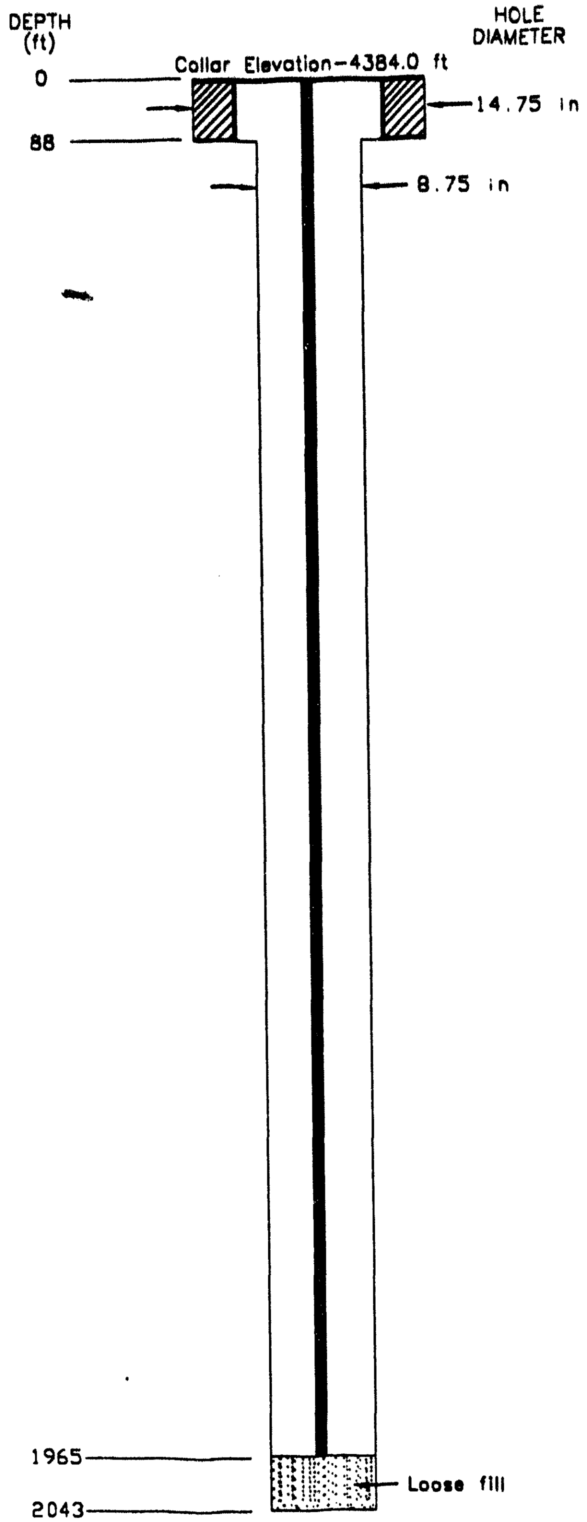
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 108 ft^3 of Redi-Mix cement from 87 ft to surface.

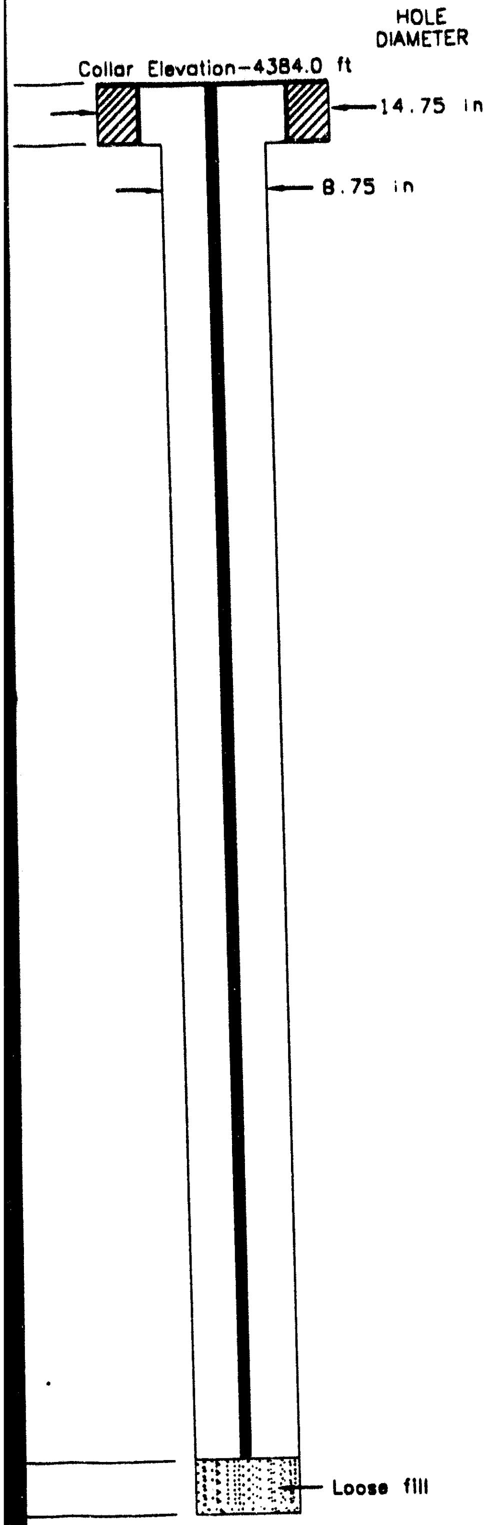
OD = 10.750 in
ID = 10.050 in
T_s = 0.350 in
Set at 86 ft



UE-25 WT #18

ERALIZED DRILLER'S LOG

'rom Fenix and Scisson, 1986a)



HOLE INFORMATION

200	■ Electric log tool was lost in hole below 200 ft.
465 471 481 505 522 564	● Hole sloughed below 465 ft. ● Caliper log indicated slightly eroded zone from 471 to 505 ft with maximum hole enlargement greater than 29.75 in at 481 ft. ● Lost circulation (returns) below 522 ft to 564 ft.
937 1078 1086	● Hole eroded between 937 and 1086 ft with maximum hole enlargement of 16.75 in at 1078 ft.
1515 1556	● Lost circulation (returns) between 1515 and 1556 ft.
1860	▽ Last density log indicated fluid level at 1860 ft.
1965	■ 2.875 in OD tubing with 12 ft screen landed on fill at 1965 ft.

UE-25 WT #16

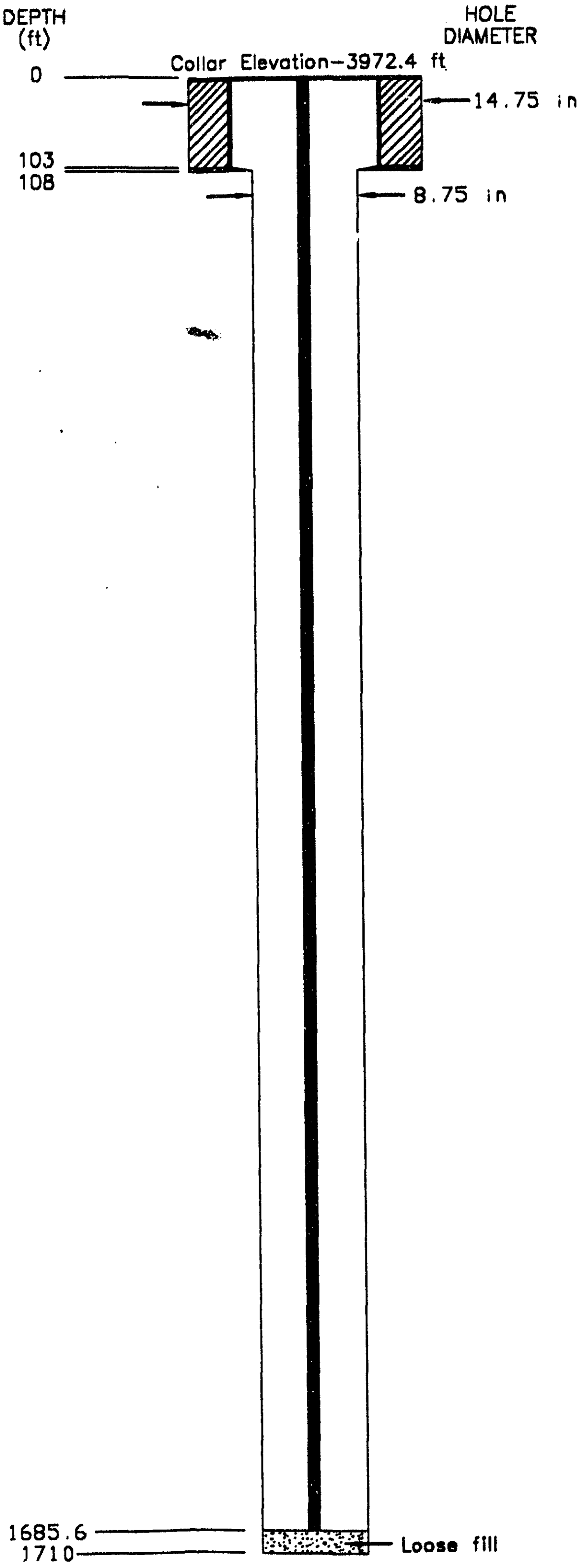
GENERALIZED DRILLER'S LOG

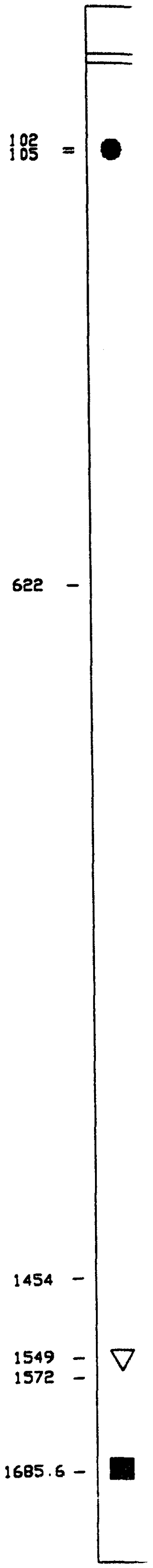
(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 324 ft^3 of Redi-Mix cement from 103 ft to surface.

OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 102 ft

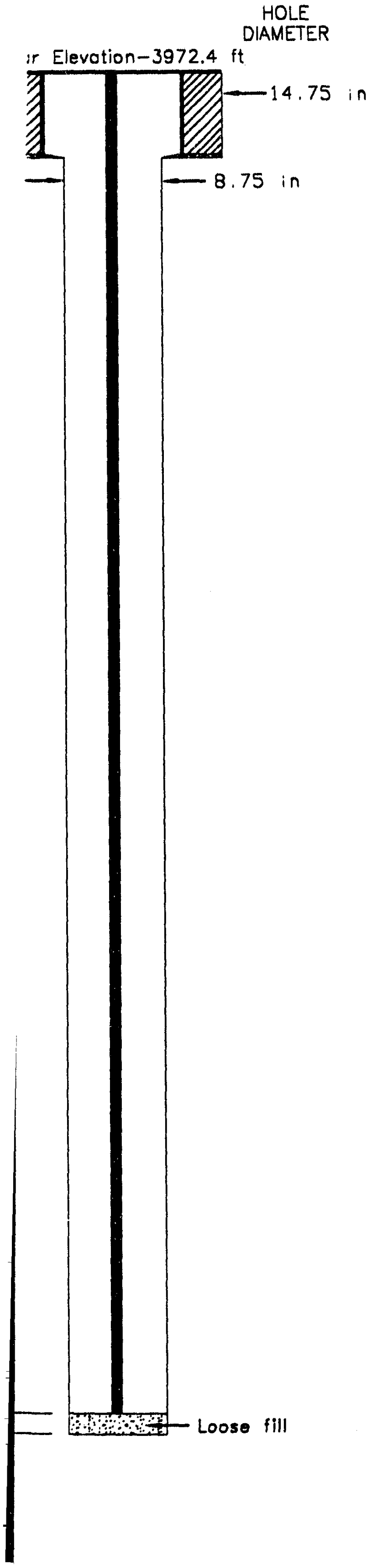




5 WT #16

ƎD DRILLER'S LOG

and Scisson, 1986a)



HOLE INFORMATION

102 105	● Caliper log indicated several eroded zones at 102 ft to 1572 ft with maximum hole enlargements of 27.75 in at 105 ft, 18.5 in at 622 ft, and 18.75 in at 1454 ft.
622	
1454	
1549 1572	▽ Fluid density log indicated fluid level at 1549 ft.
1685.6	■ 2.875 in OD tubing with 12 ft screen landed at 1685.6 ft.

UE-25 WT # 17

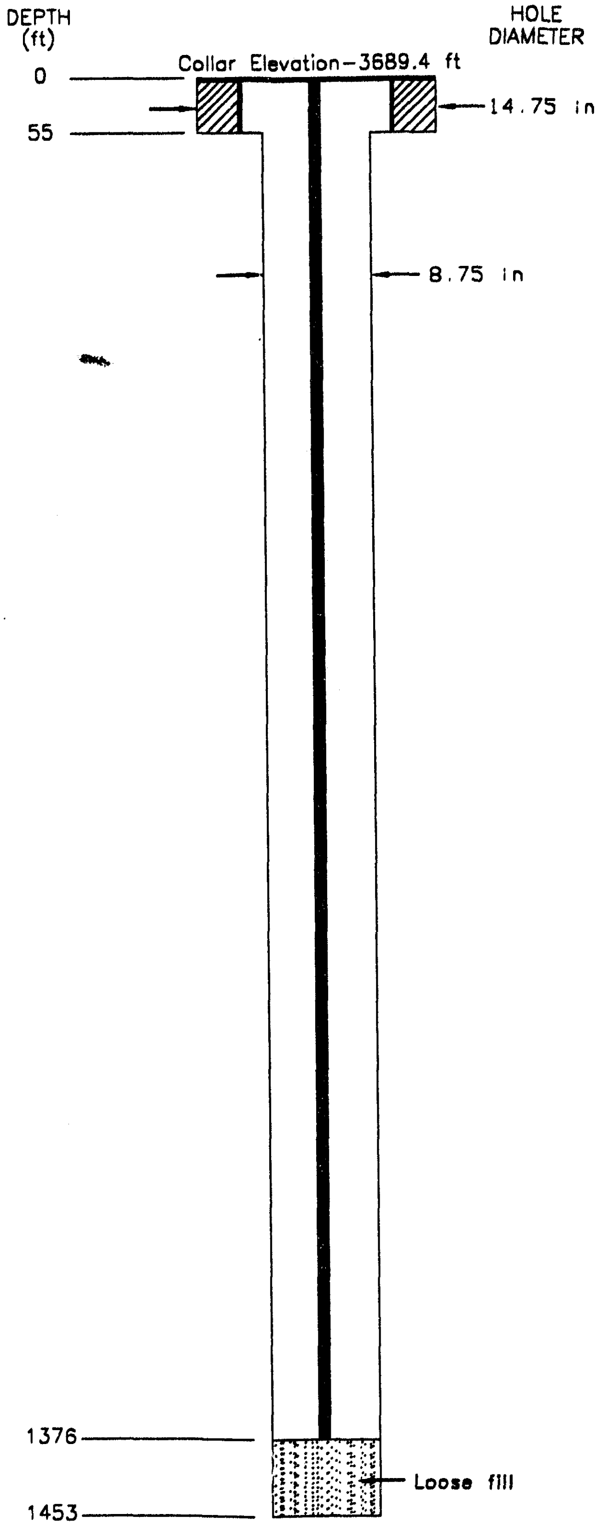
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 75 ft^3 of neat cement plus 2% $CaCl_2$ from 55 ft to surface.

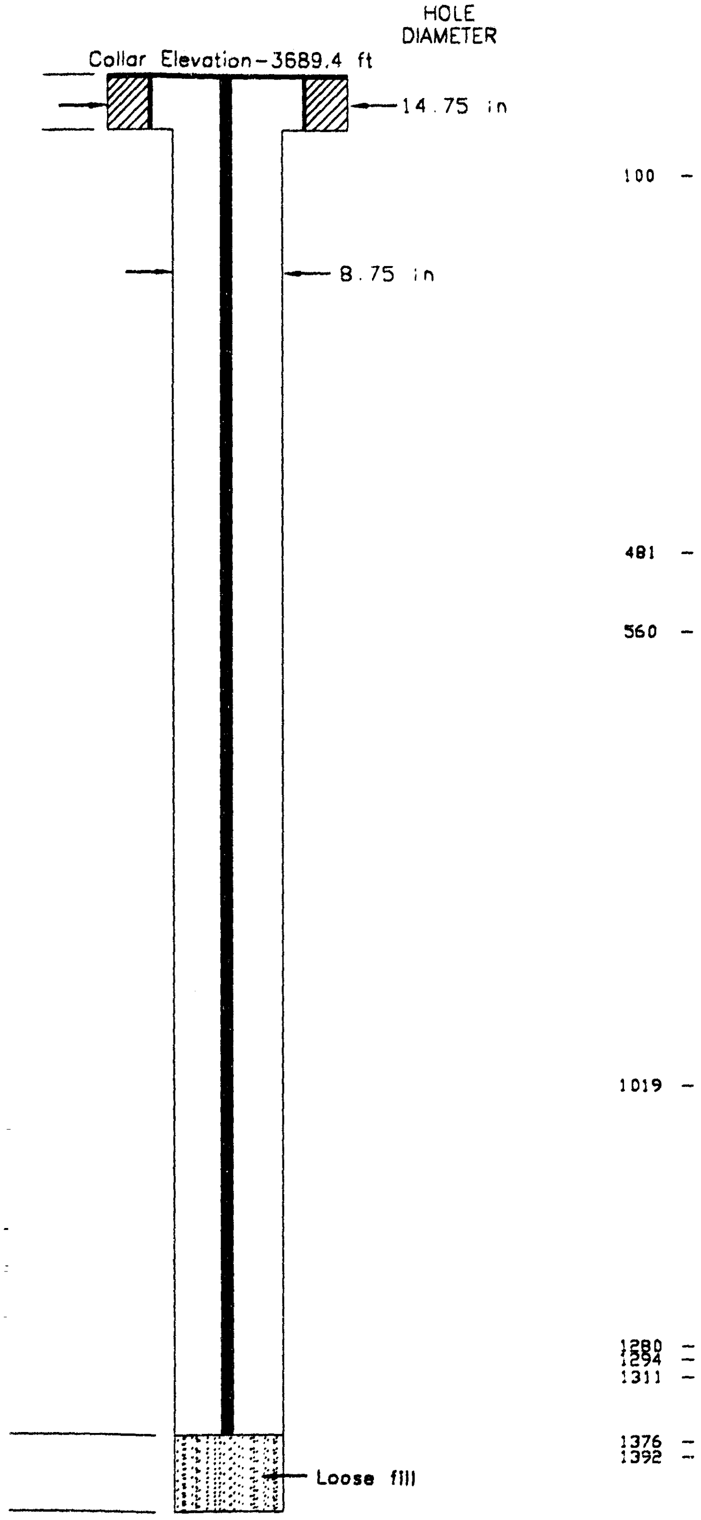
OD = 10.750 in
ID = 10.050 in
T_a = 0.350 in
Set at 55 ft



JE-25 WT # 17

RALIZED DRILLER'S LOG

m Fenix and Scisson, 1986a)



HOLE INFORMATION

- ● Caliper log indicated hole eroded from surface to 1019 ft with maximum hole enlargements of 23.25 in at 100 ft, greater than 33 in at 481 ft and 23.75 in at 560 ft.
- ● Slightly eroded hole from 1280 to 1392 ft with maximum hole enlargement of 21.75 in at 1311 ft.
- ▽ Fluid density log indicated fluid level at 1294 ft.
- ■ 2.875 in OD tubing with 12 ft screen landed on bottom fill at 1376 ft.

USW GA-1

GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1987e)

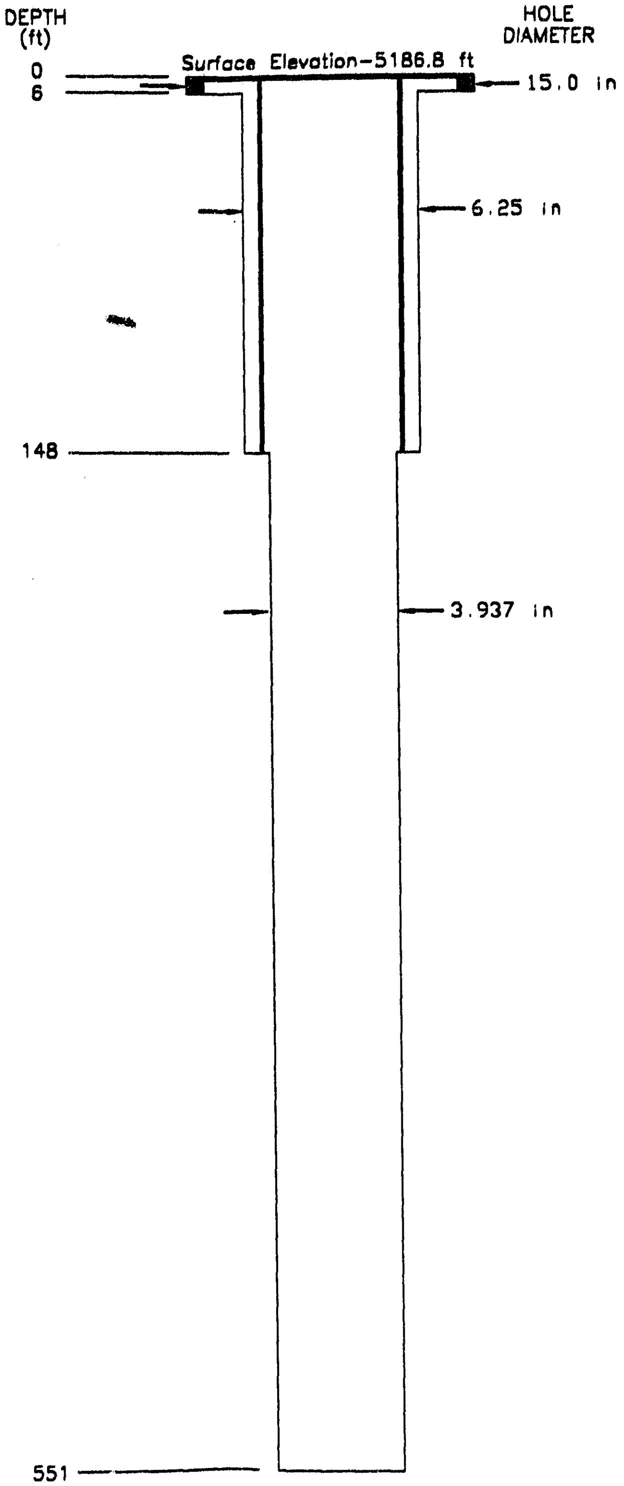
CEMENTING AND CASING INFORMATION

Annulus cemented with 2 ft^3 of gypsum plaster from 6 ft to surface.

OD = 13.375 in
ID = 12.615 in
T_a = 0.380 in
Set at 6 ft

Annulus not cemented.

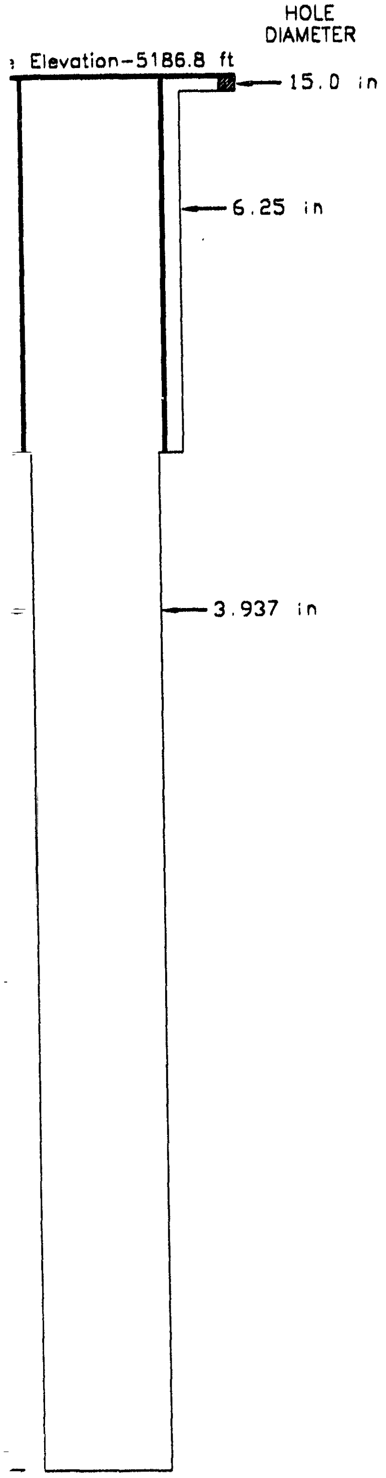
OD = 4.500 in
ID = 4.000 in
T_a = 0.250 in
Set at 148 ft



;W GA-1

ED DRILLER'S LOG

and Scisson, 1987e)



HOLE INFORMATION

317 –	● Formation fractured at 317 ft.
327 –	● Formation badly fractured & caving from 327 to 407 ft.
407 –	
528 –	△ Lost circulation at 528 ft.

UE-25 WT # 5

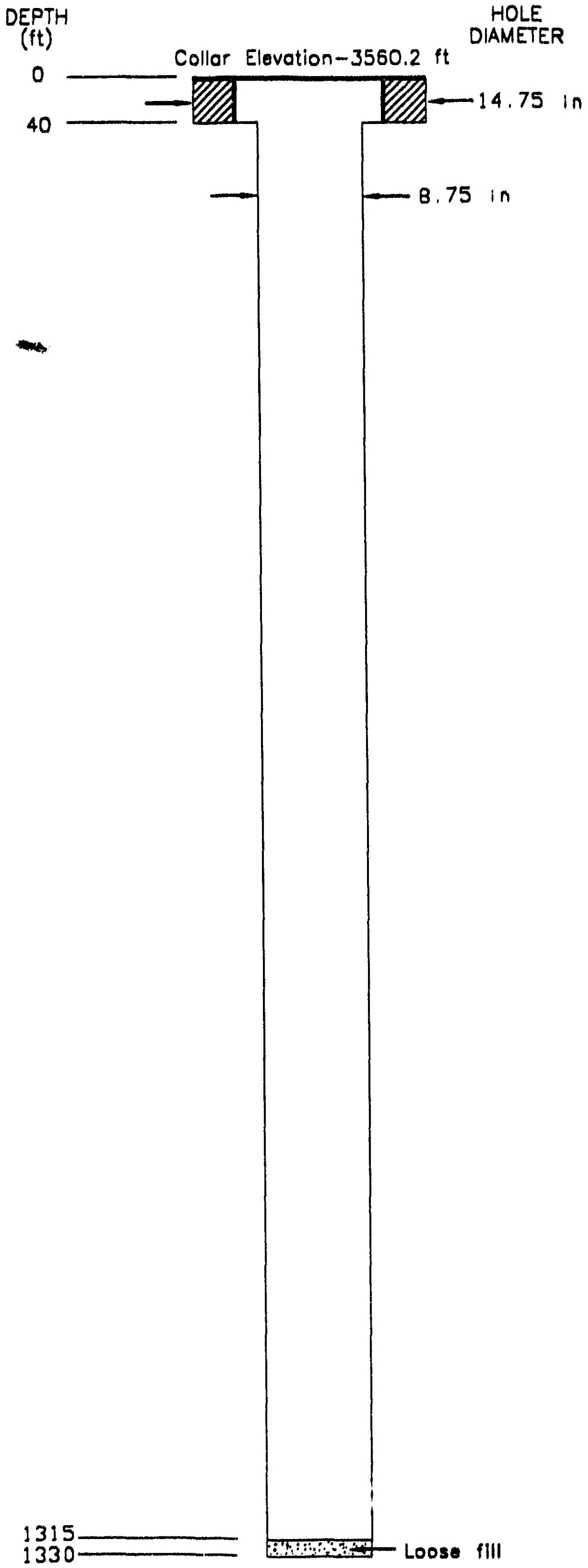
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 162 ft^3 of Redi-Mix cement from 40 ft to surface.

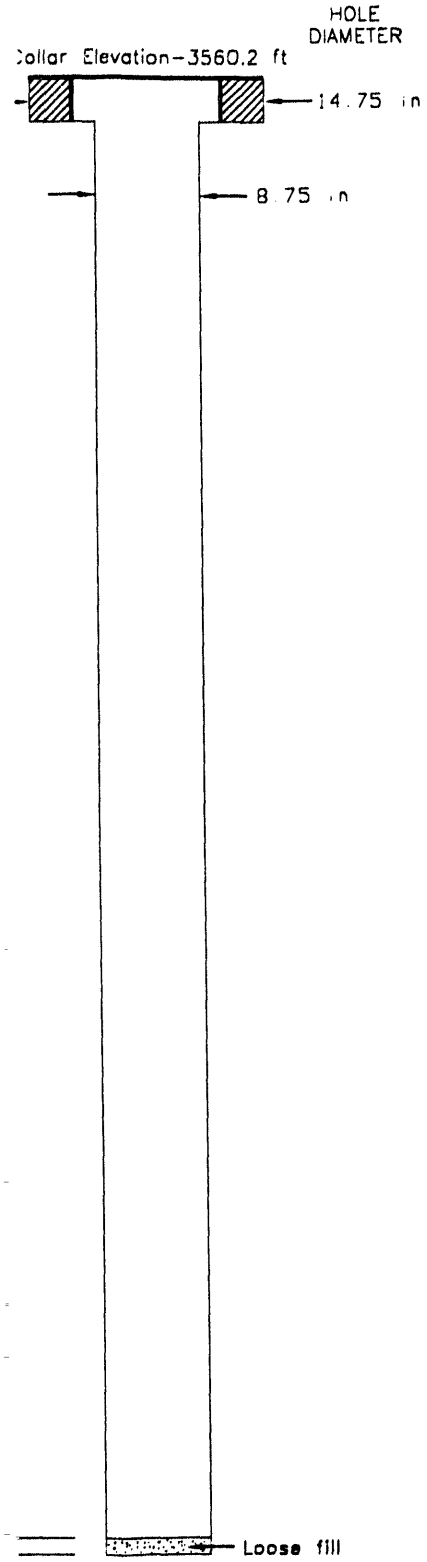
OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 40 ft



-25 WT # 5

IZED DRILLER'S LOG

enix and Scisson, 1986a)



HOLE INFORMATION

105 – ● Hole sloughed from 105 ft to bottom. Hole was abandoned 6/18/83.

1018 –
1036 – ■ Bowen overshot, crossover sub, and Bowen bumper sub were left in the hole at 1036 ft with top at 1018 ft.

1180 – ▲ Water inflow indicated at 1180ft.

USW WT-2

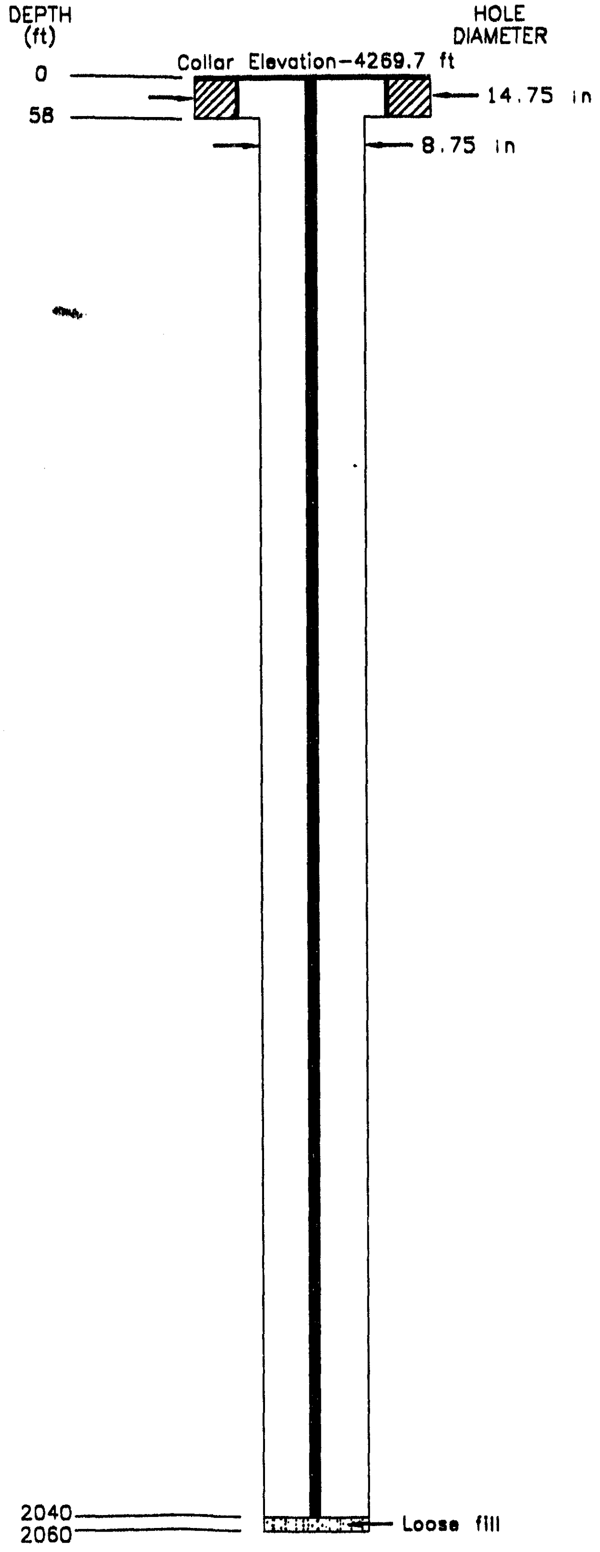
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 100 ft^3 of neat cement plus 3% $CaCl_2$ plus 1 ft^3 Cal-Seal cement from 58 ft to surface.

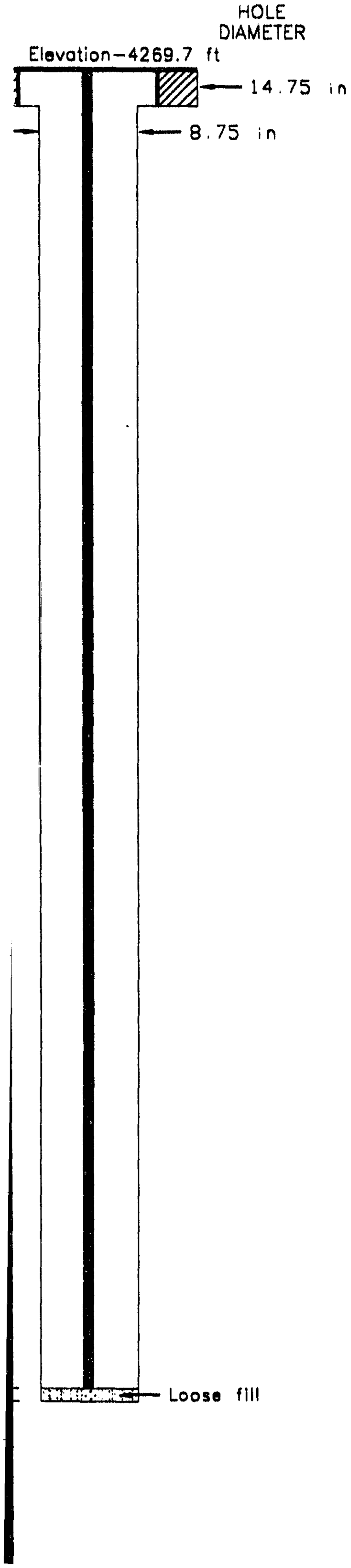
OD = 10.750 in
ID = 10.050 in
T_o = 0.350 in
Set at 58 ft



N WT-2

D DRILLER'S LOG

and Scisson, 1986a)



HOLE INFORMATION

200	● Caliper log indicated eroded hole from 200 to 1300 ft with maximum hole enlargements of 22 in at 782 ft, 18.25 in at 1001 ft and 16.5 ft at 1110 ft.
782	
1001	
1110	
1300	
1873	▽ Fluid density log indicated fluid level at 1873 ft.
1940	● Hole enlargement below 1940 ft with maximum hole enlargement of 16.5 in at 2040 ft.
2040	■ 2.875 in OD tubing with 12 ft screen landed on fill at 2040 ft.

USW WT-10

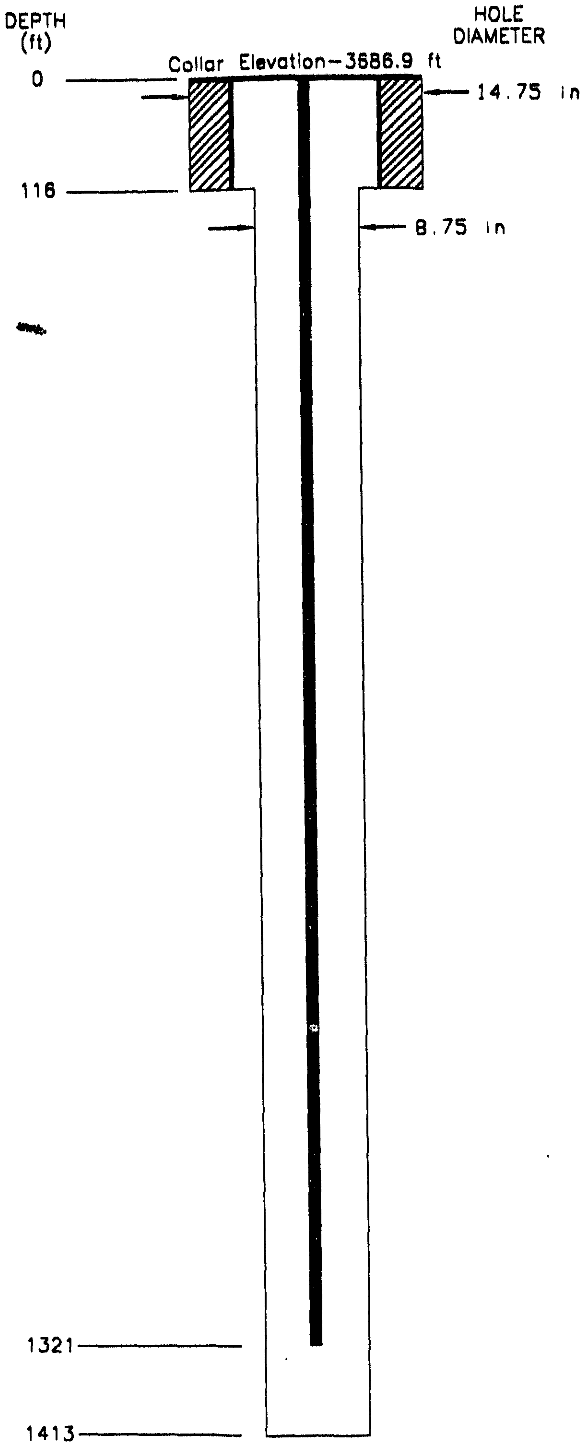
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 378 ft^3 of Redi-Mix cement from 116 ft to surface.

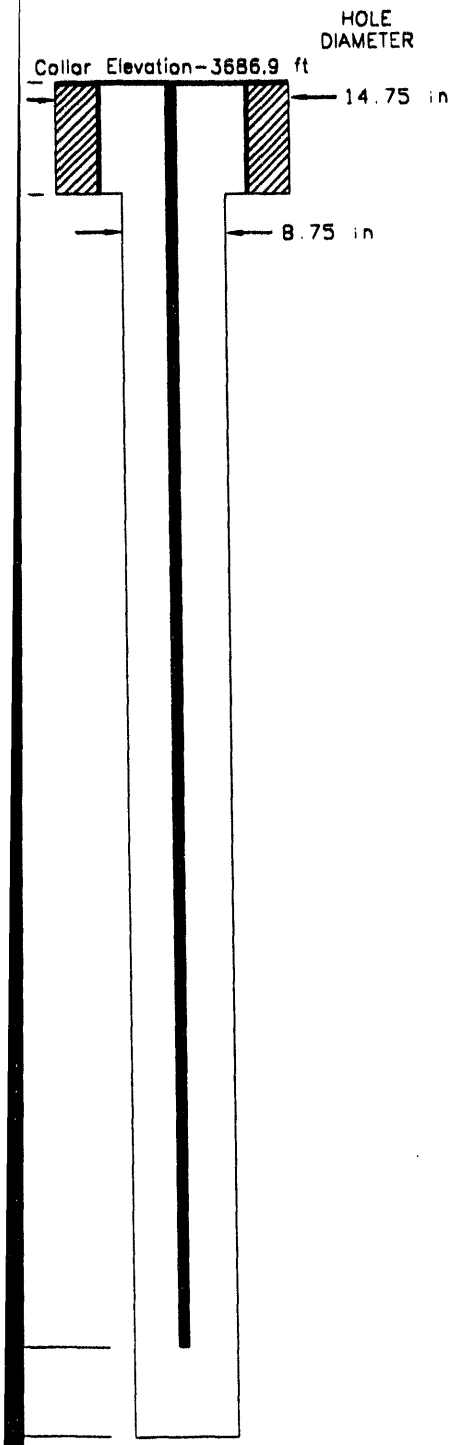
OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 114 ft



JSW WT-10

LIZED DRILLER'S LOG

Fenix and Scisson, 1986a)



HOLE INFORMATION

139	● Caliper log indicated slightly eroded hole with maximum hole enlargements of 17.25 in at 139 ft and 17.25 in at 1262 ft.
1140	▽ Fluid density log indicated fluid level at 1140 ft.
1262	
1321	■ 2.875 in OD tubing with 12 ft screen sub landed on fill at 1321 ft.

USW WT-1

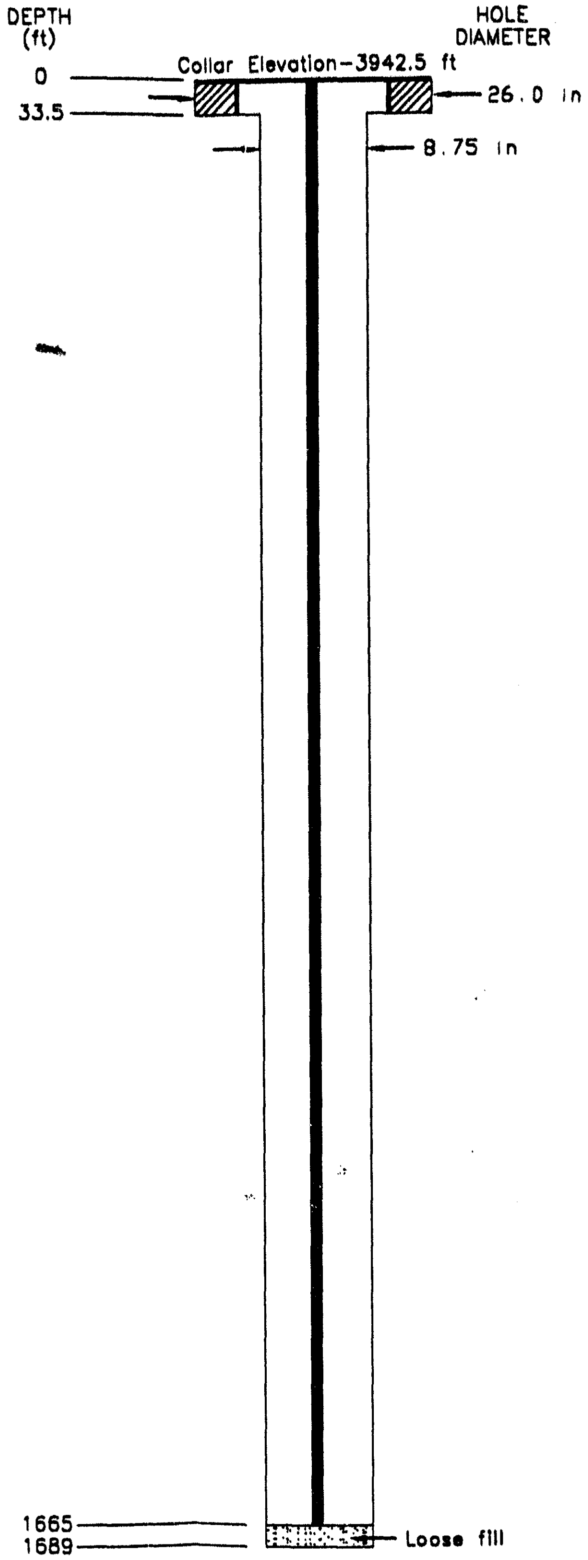
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 189 ft^3 of Redi-Mix cement from 33.5 ft to surface.

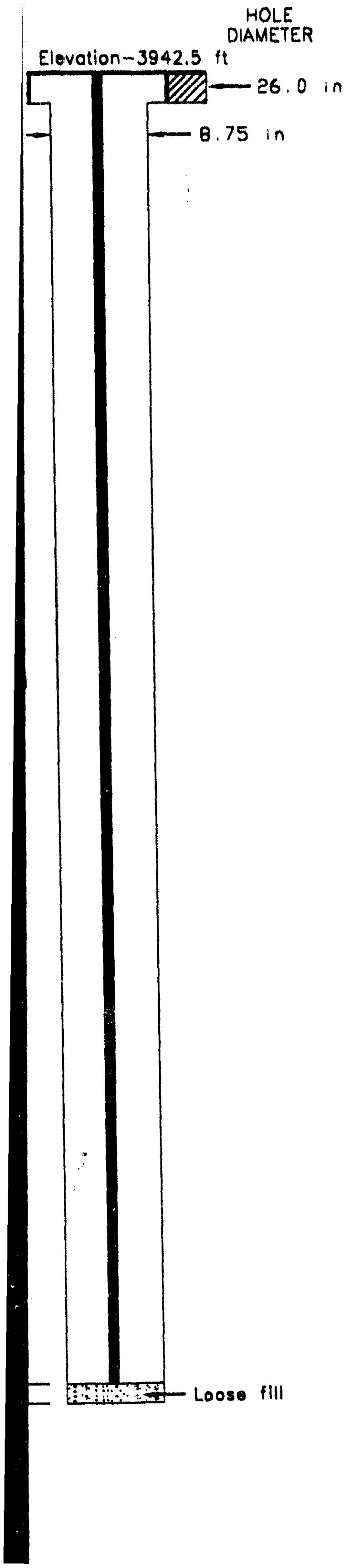
OD = 10.750 in
ID = 10.050 in
T_e = 0.350 in
Set at 32.5 ft



W WT-1

ED DRILLER'S LOG

and Scisson, 1986a)



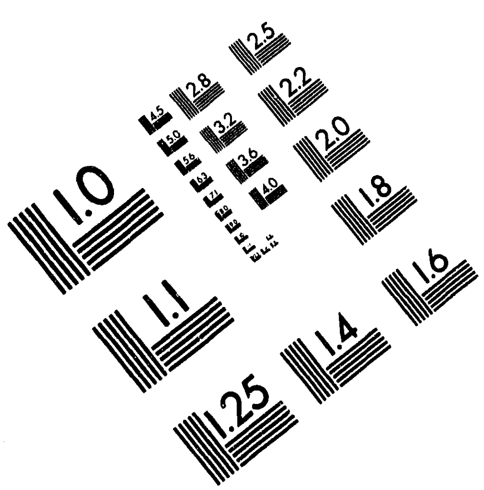
HOLE INFORMATION

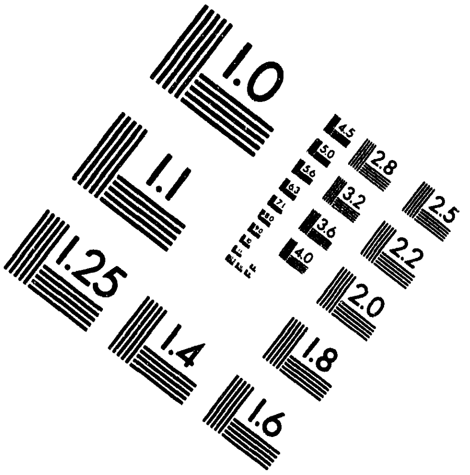
1542	▽ Fluid density log indicated fluid level at 1542 ft.
1560	▲ Small water inflow indicated at 1560 ft while drilling.
1665	■ 2.875 in OD tubing with 12 ft screen landed on fill at 1665 ft.

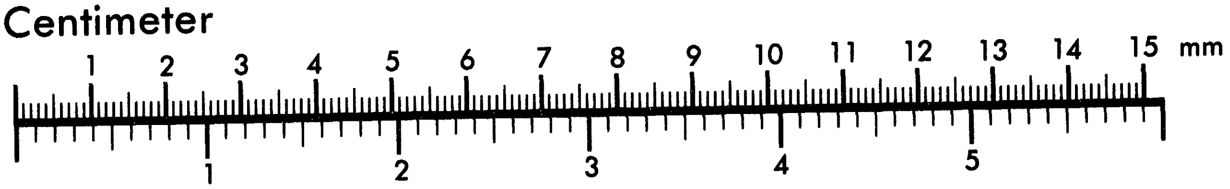
AIIM

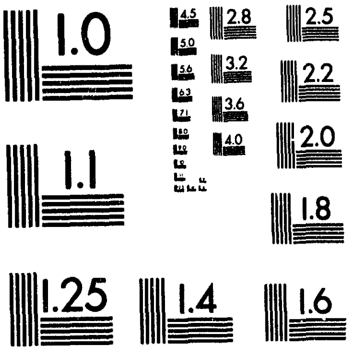
Association for Information and Image Management

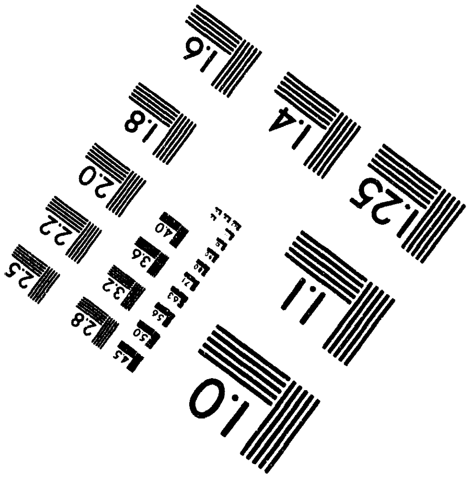
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

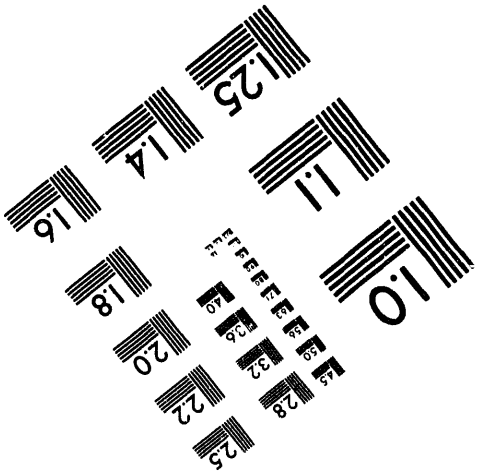












MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

5 of 6

USW WT-11

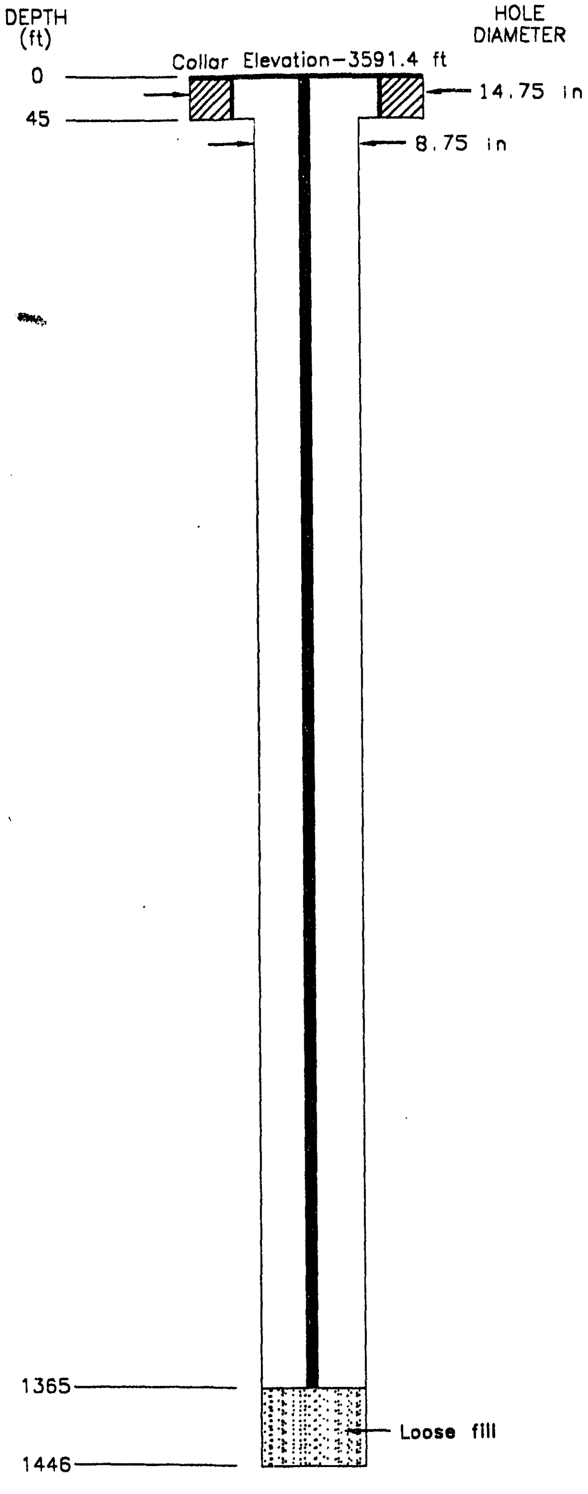
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 81 ft^3 of Redi-Mix cement from 45 ft to surface.

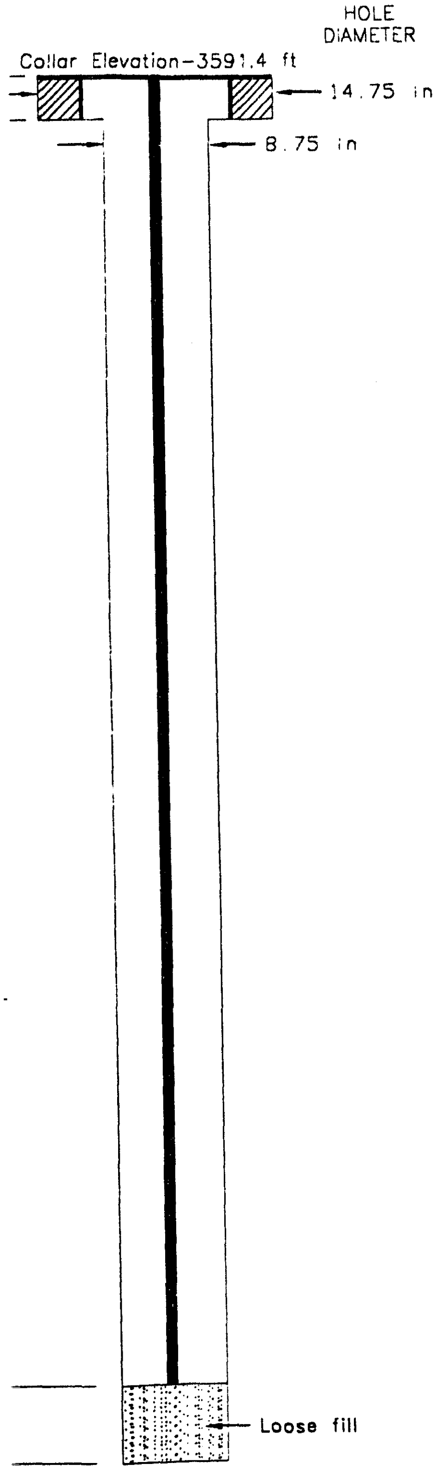
OD = 10.750 in
ID = 10.050 in.
T_c = 0.350 in
Set at 44.5 ft



SW WT-11

IZED DRILLER'S LOG

enix and Scisson, 1986a)



HOLE INFORMATION

428 – ● Caliper log indicated several eroded zones with maximum hole enalrgements of 21 in at 428 ft, 18 in at 810 ft and 14.25 in at 1218 ft.

810 –

1193 – ▽ Fluid density log indicated fluid level at 1193 ft.

1218 –

1365 – ■ 2.875 in OD tubing with 12 ft screen sub landed on fill at 1365 ft.

USW WT-7

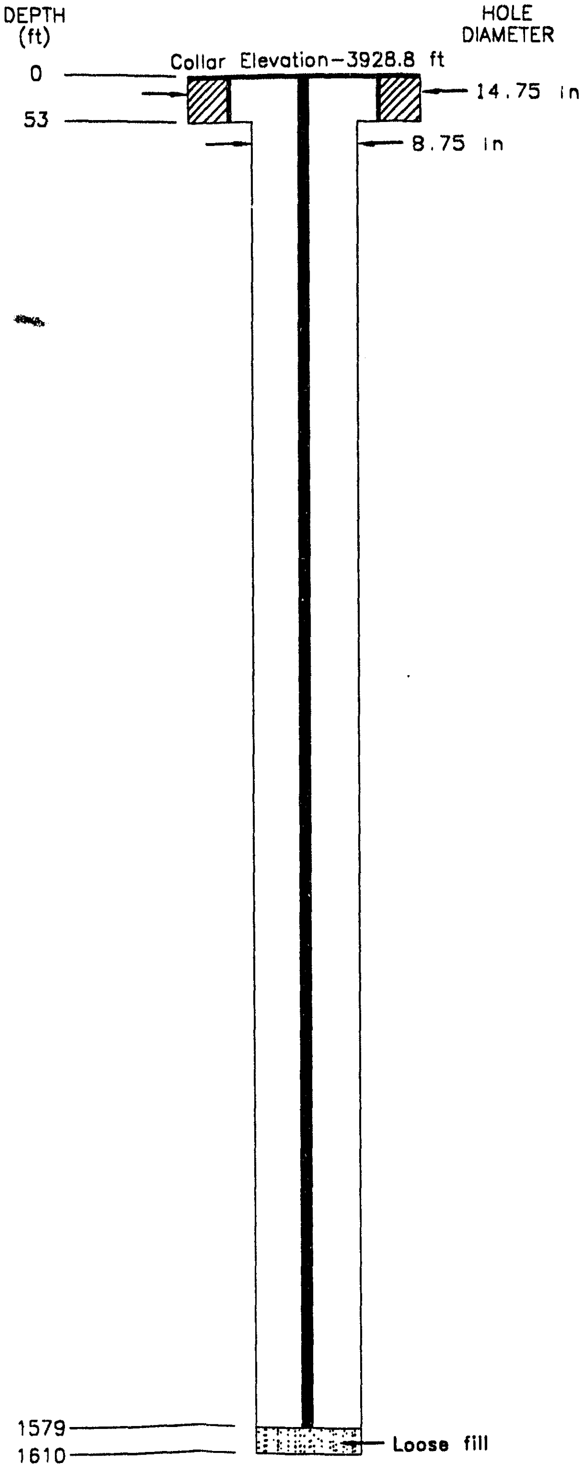
GENERALIZED DRILLER'S LOG

(From Fenix and Scisson, 1986a)

CEMENTING AND CASING INFORMATION

Annulus cemented with 162 ft^3 of Redi-Mix cement from 53 ft to surface.

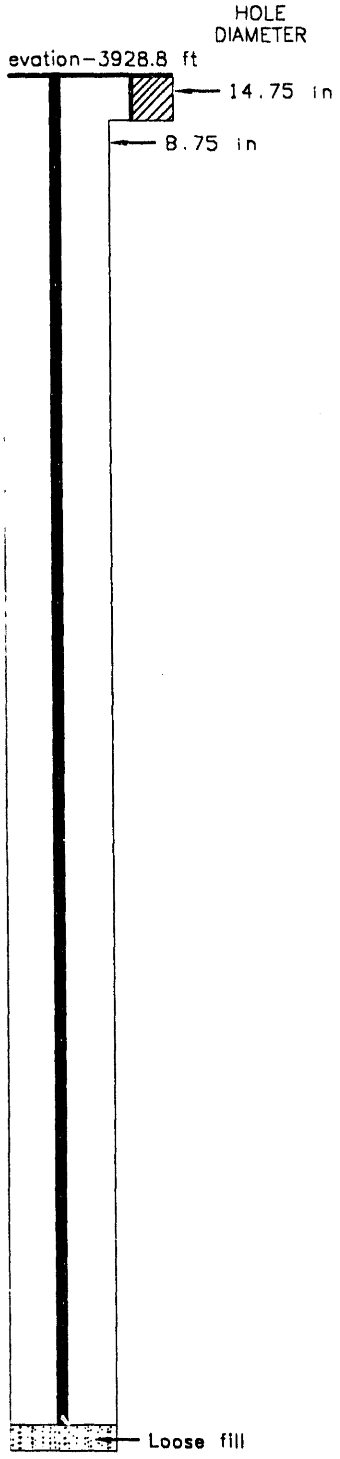
OD = 10.750 in
ID = 10.050 in
T_c = 0.350 in
Set at 52 ft



/ WT-7

) DRILLER'S LOG

nd Scisson, 1986a)



HOLE INFORMATION

● Caliper log indicated hole erosion to 1292 ft with maximum hole enlargements of 29 in at 212 ft and 20 in at 825 ft.

212 –
230 –
246 –

● Hard formation encountered from 230 to 246 ft.

825 –

1292 –

1380 – ▽ Fluid density log indicated fluid level at 1380 ft.

1579 – ■ 2.875 in OD tubing with 12 ft screen sub landed on fill at 1579 ft.

APPENDIX C

GEOLOGIC DESCRIPTION AND CROSS SECTIONS THERMAL/MECHANICAL STRATIGRAPHY

Appendix C
Geologic Description and Cross Sections Thermal/Mechanical Stratigraphy

This appendix provides a basic understanding of the physical and chemical modifications that occur to various units of tuff following deposition. These units include the Tiva Canyon Member, the Yucca Mountain and Pah Canyon Members, the Topopah Spring Member, and the tuffaceous beds of the Calico Hills. There are three types of deposition that occur at Yucca Mountain: ash fall, which is deposited directly from the air; ash flow, which contains high temperature mixtures of gas and pyroclastic materials and flows down the slope as an avalanche; and bedded and reworked tuffs, which form from the erosion and redeposition of either the ash-fall or the ash-flow tuffs. Also, this section presents cross-sections through the potential repository block.

C.1 Tiva Canyon Member

The basal portion of this member consists of air-fall tuff marking the initial stages of eruption. This portion of the member is nonwelded and virtually unaltered, with slightly altered rhyolite shards and pumice pyroclasts (termed the ccs). Overlying this nonwelded tuff is a densely included vitric tuff (Bish et al., 1982). Above this is a devitrified zone, the central portion of which includes the hackly, lower lithophysal clinkerstone and the upper lithophysal zone. At the top of both the Tiva Canyon and the Topopah Spring Members is the caprock unit, which exhibits low values of porosity (2 to 3 percent) and high values of bulk density. The caprock unit of the Tiva Canyon appears to be absent from much of the actual potential repository site (Rautman and Flint, 1992).

C.2 Yucca Mountain and Pah Canyon Members

The nonwelded tuff between the Tiva Canyon and Topopah Spring Members is typically considered the Paintbrush nonwelded tuff. It includes the nonwelded and partially welded base of the Tiva Canyon Member, the Yucca Mountain Member, the Pah Canyon Member, the nonwelded and partially welded upper part of the Topopah Spring Member, and the associated bedded tuff. Tuffs of this unit are generally vitric, nonwelded, very porous, slightly indurated, and in part bedded (Montazer and Wilson, 1984). Within the potential repository area, the cumulative thickness generally thins to the southeast.

The Yucca Mountain Member is a nonwelded to partially welded ash-flow tuff. In borehole USWG-2, it consists of a basal, reworked, bedded tuff overlain by six subunits. These tuffs are among the most highly altered, some containing between 30 and 60 percent smectite. The Pah Canyon consists of a thin, reworked, air-fall tuff overlain by five ash-flow subunits (Bish et al., 1982). This sequence forms a single cooling unit, with a moderately welded central zone. Bish et al. (1982) describe this member as follows: the upper and lower portions contain fresh glass, and the groundmass glass in the upper vitric zone is pervasively altered to smectite. However, the lower vitric zone contains more smectite (up to 50 percent) and less glass than the upper zone. Between the upper and lower vitric zones is a zone of devitrification and zeolitization that coincides with a zone of moderate welding. The presence of zeolites is unusual this far above the water table and is not a pervasive occurrence.

C.3 Topopah Spring Member

The Topopah Spring Member is a compound cooling unit made up of multiple ash flows. In general, this member is made up of a thick, densely welded crystallized interior. It contains a thin upper vitrophyre and a thicker lower vitrophyre. The lower or basal vitrophyre consists predominantly of unaltered, densely welded, rhyolitic glass with a silica content of 74 to 77 percent (Fox et al., 1990). It grades downward into moderately welded to nonwelded ash-flow and reworked tuff and grades upward into the thick, densely welded interior of the member. The upper vitrophyre grades upward into moderately welded to nonwelded ash-flow bedded tuff. Beneath the upper vitrophyre is the thick, moderately to densely welded, devitrified, vapor-phase altered ash flows. Lithophysal cavities are abundant in the areas of intense vapor-phase development. These cavities are 1 to 3 cm in diameter and occur in discrete zones near the middle of the member. The upper lithophysal zone contains the most cavities, contributing an additional 10 to 30 percent porosity (Fox et al., 1990). Furthermore, these lithophysal cavity zones are generally continuous but vary appreciably in thickness and stratigraphic position (Montazer and Wilson, 1984). Fractures are common in the middle and the lower portions of the central interior zone. The fracture filling varies from calcite or silica to none. The lowermost portion of the Topopah Spring Member is a partly welded to nonwelded, heavily zeolitized ash flow (Bish et al., 1982).

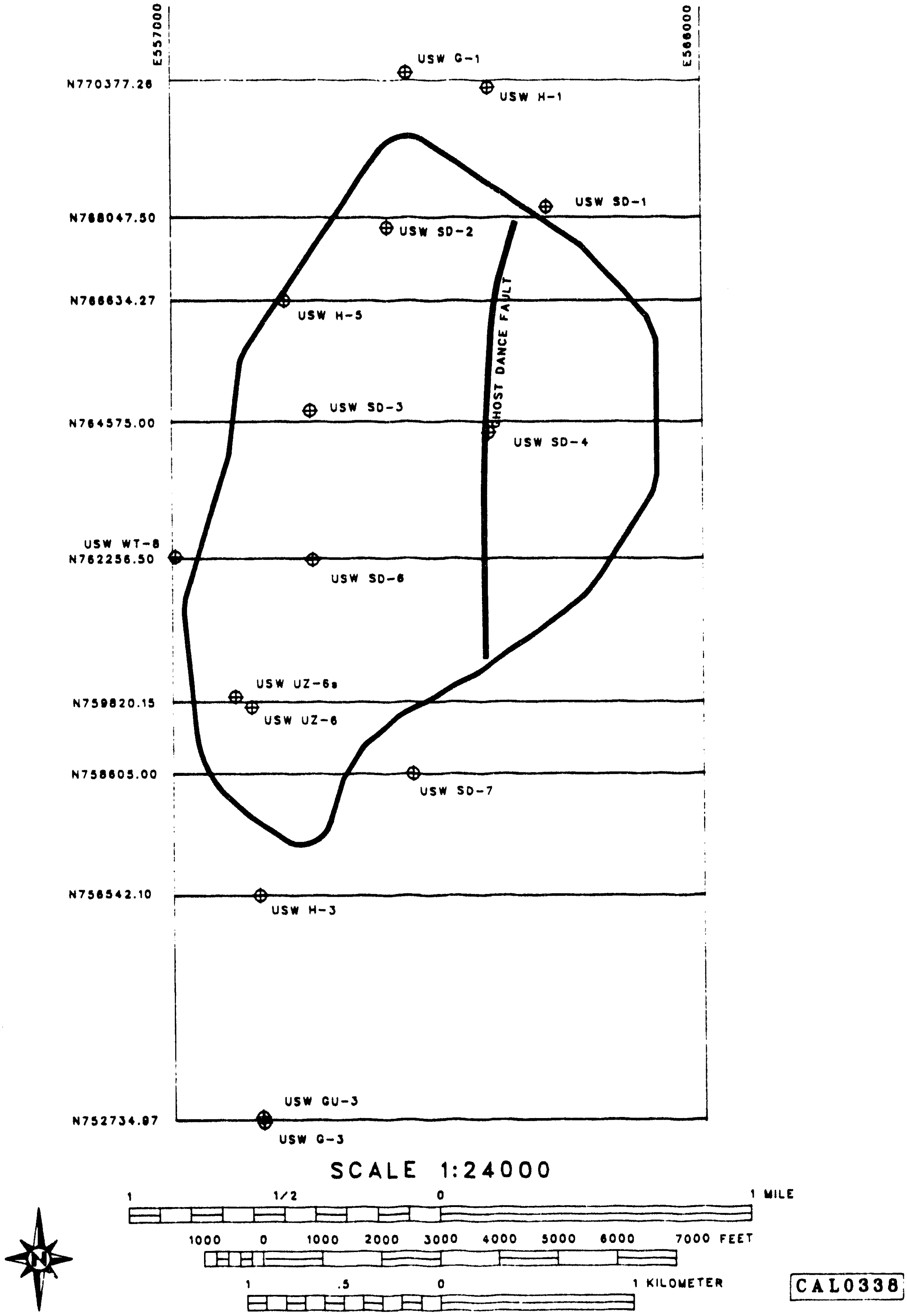
C.4 Tuffaceous Beds of Calico Hills

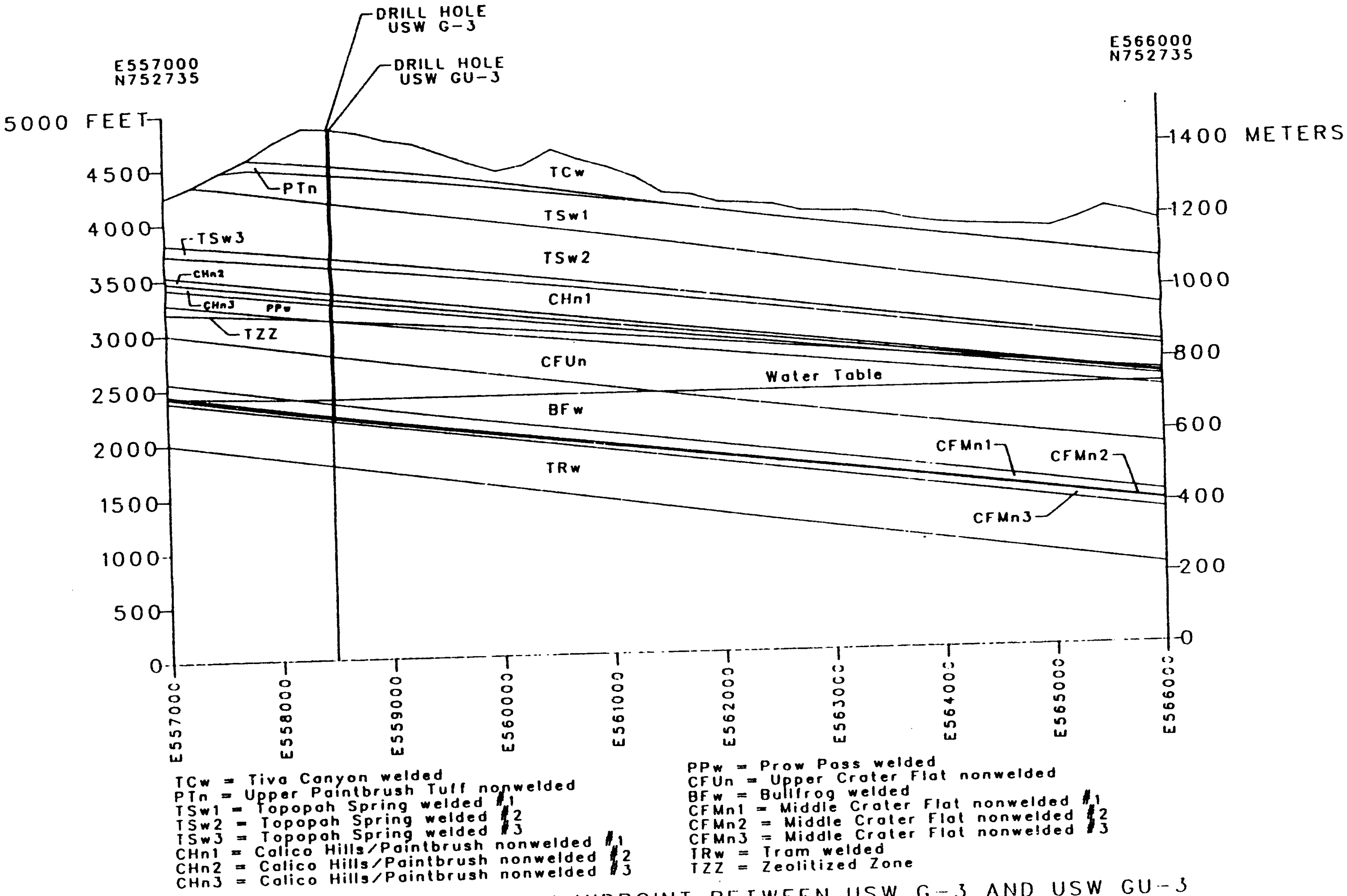
The tuffaceous beds of Calico Hills are dissimilar to many other units because they are not only mainly ash-flow tuff but also consist of bedded (air-fall) and rhyolitic flows (Scott et al., 1983). They are variable and are comprised of up to 16 nonwelded, zeolitized ash flows with thin, bedded to massive, reworked and air-fall tuffs separating each of the ash flows (Bish et al., 1982). Both vitric and devitrified facies occur within the Calico Hills nonwelded unit. Alteration products in the devitrified facies include zeolites (most abundant), clay, and calcite (rare). Because of the pervasiveness of the zeolites in the devitrified facies, it is referred to as the zeolitic facies. The thickness of the zeolitic facies generally increases from the southwest to the northeast beneath Yucca Mountain. While the vitric facies beneath Yucca Mountain tend to increase from the northeast to the southwest. Both facies are very porous, with a mean porosity of about 37 percent for the vitric and 31 percent for the zeolitic facies (Montazer and Wilson, 1984).

Following deposition, modifications to the tuffs depend on the temperature and pressure conditions, rate of cooling, original composition of the tuff, thickness of the tuffaceous deposit, and subsequent exposure to groundwater. As a result, the modifications that can result include the following:

- Varying degrees of welding, ranging from nonwelded to densely welded tuff
- Petrographic differences in the tuff, which can be classified on the basis of three physical components—glass, crystals, and lithic fragments
- Lithophysae development
- Fracture development
- Digenetic alterations of the tuff, including smectite and zeolite development.

Each of these modifications to the geology must be considered during the design, emplacement, and evaluation of each borehole seal for the YMP. Detailed geologic and drillers logs for numerous boreholes are presented in Appendix B.

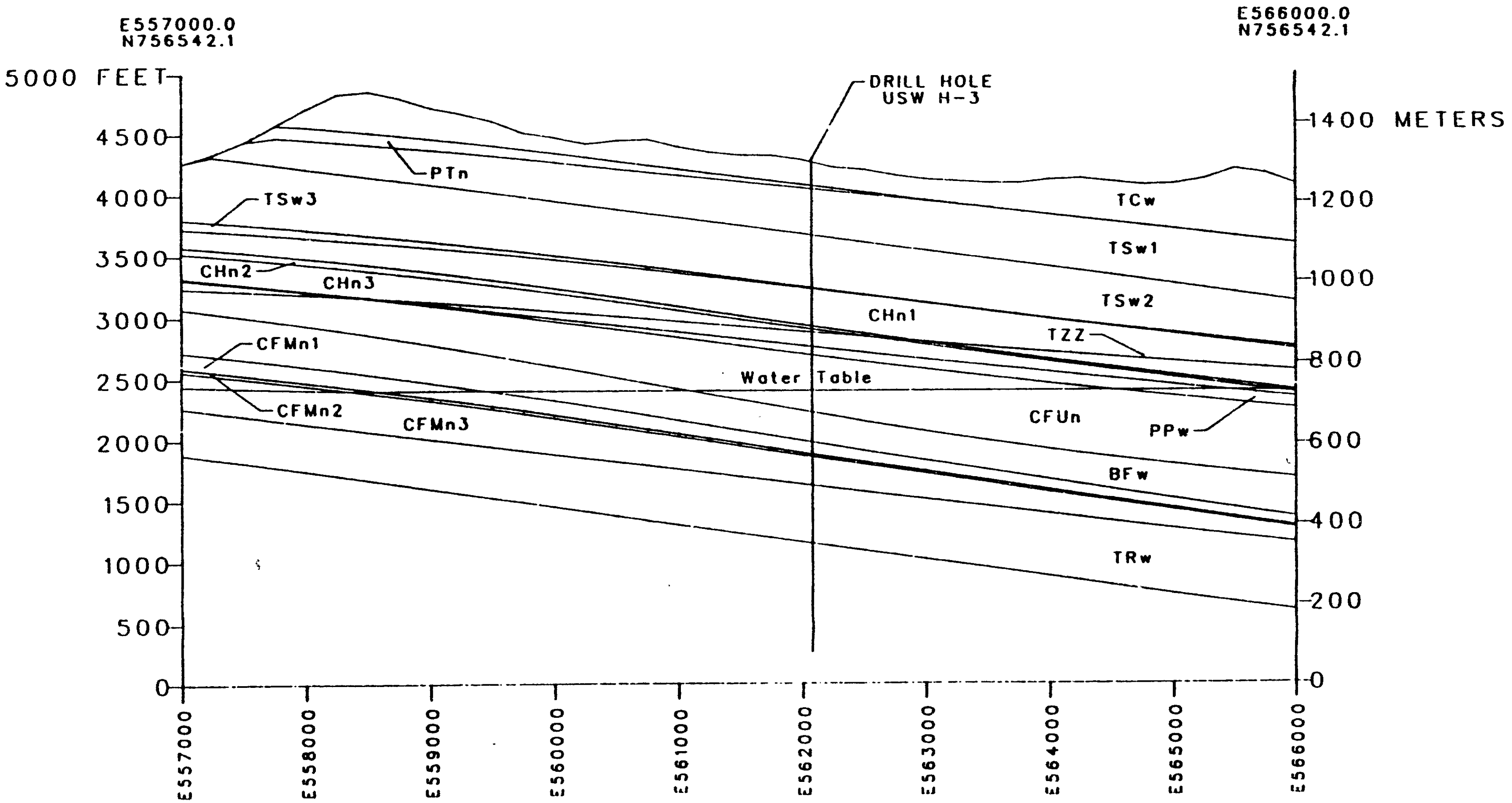
E557000
E566000
N770377.26
USW G-1
USW H-1
N768047.50
USW SD-1
USW SD-2
N766634.27
USW H-5
GHOST DANCE FAULT
N764575.00
USW SD-3
USW SD-4
USW WT-8
N762256.50
USW SD-6
USW UZ-6s
N759820.15
USW UZ-6
N758605.00
USW SD-7
N756542.10
USW H-3
USW GU-3
N752734.97
USW G-3
SCALE 1:24000
1
1/2
0
1 MILE
1000
0
1000
2000
3000
4000
5000
6000
7000 FEET
1
.5
0
1 KILOMETER
N
CAL0338



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

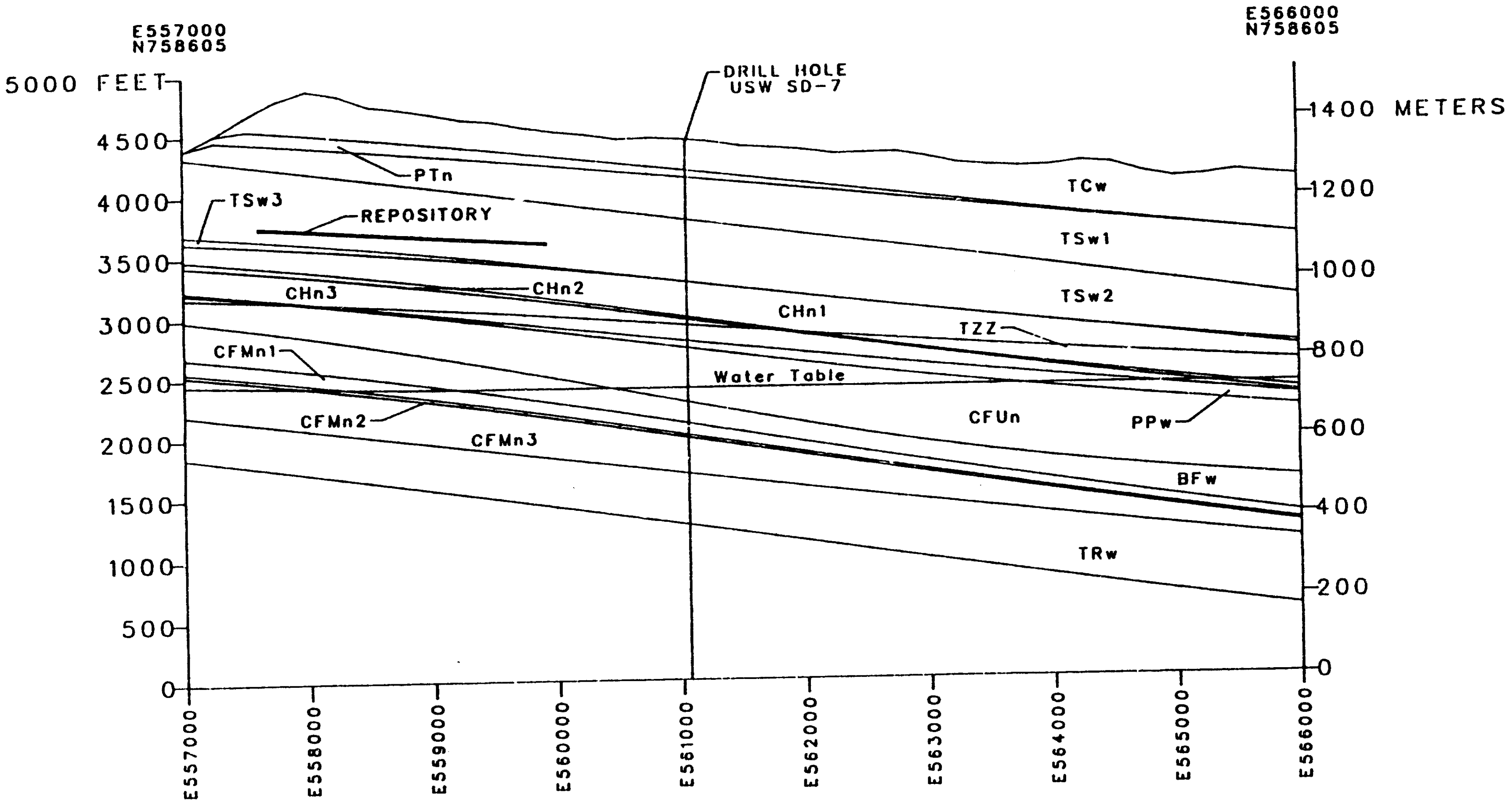
PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

WEST-EAST SECTION THROUGH MIDPOINT BETWEEN USW G-3 AND USW GU-3



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3
PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

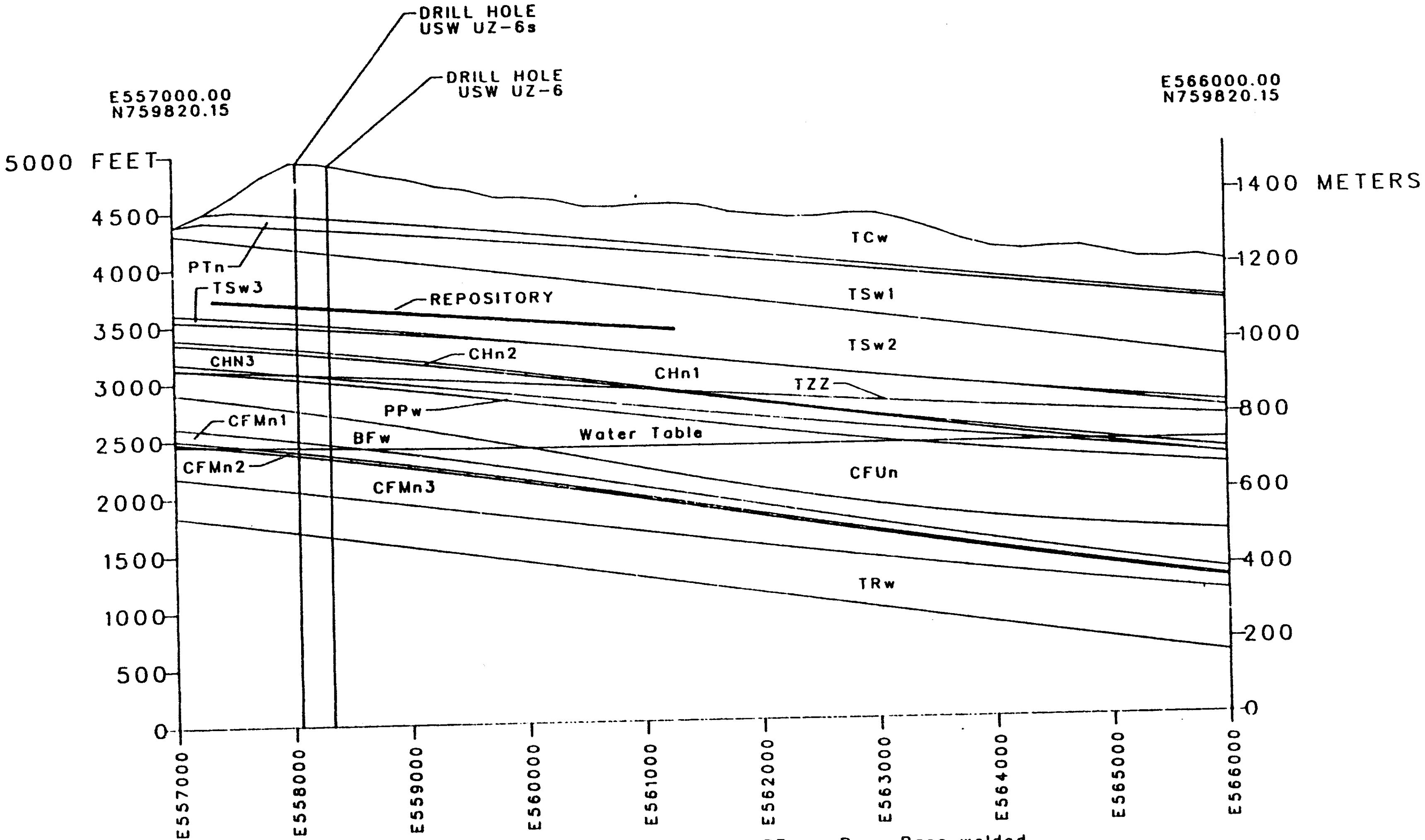
WEST-EAST SECTION THROUGH USW H-3



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

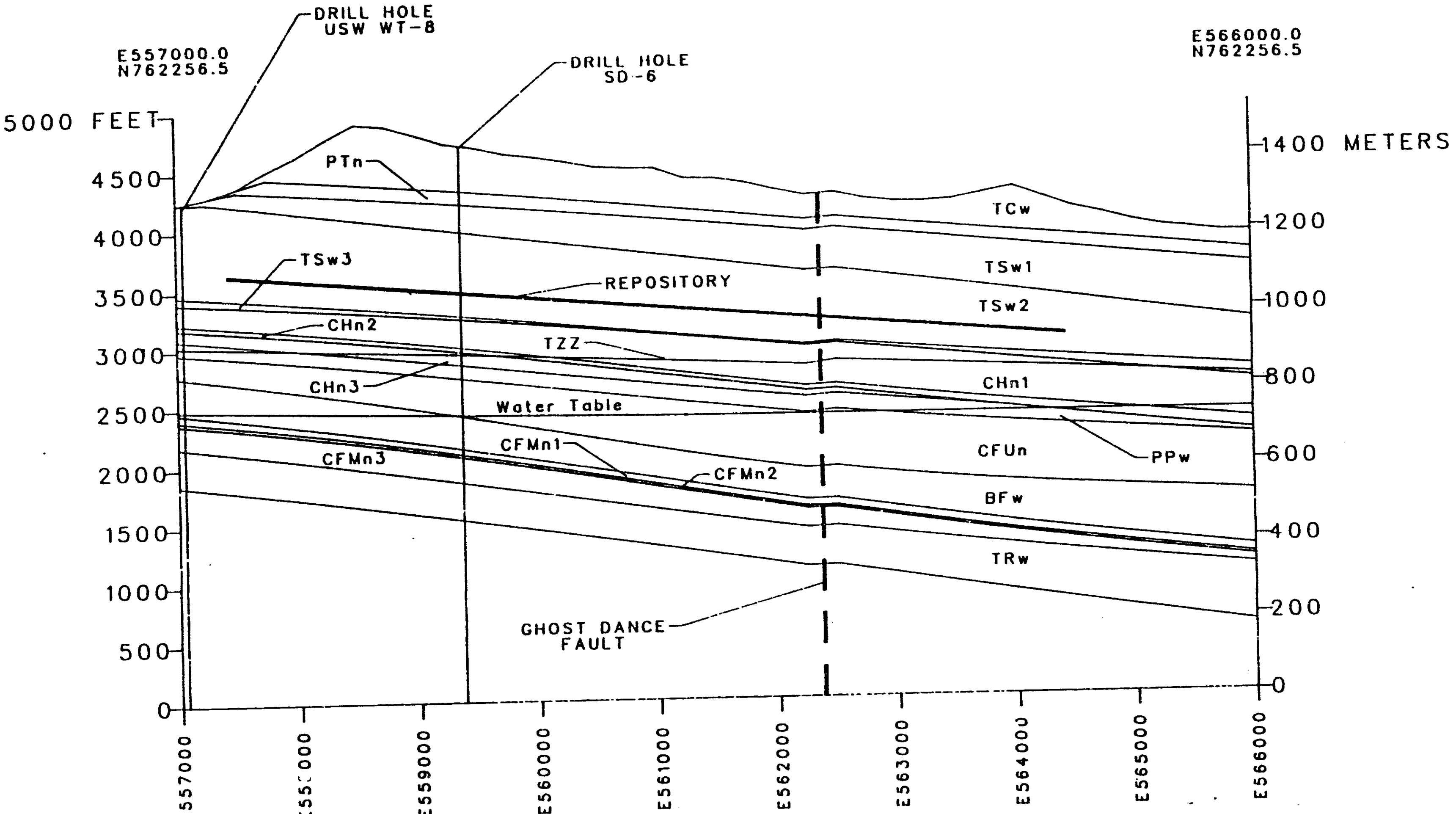
WEST-EAST SECTION THROUGH USW SD-7



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

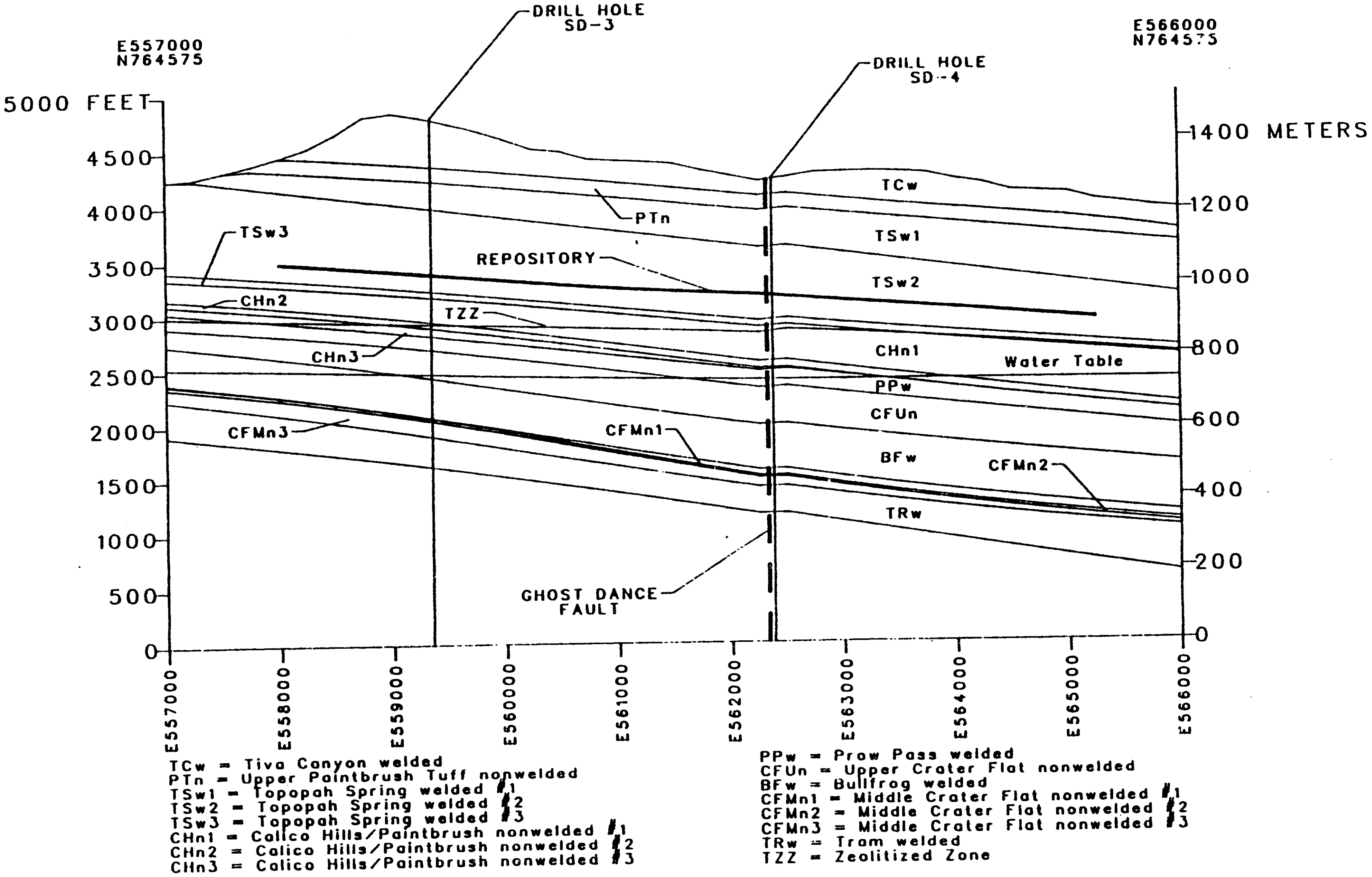
WEST-EAST SECTION THROUGH MIDPOINT BETWEEN USW UZ-6 AND USW UZ-6s



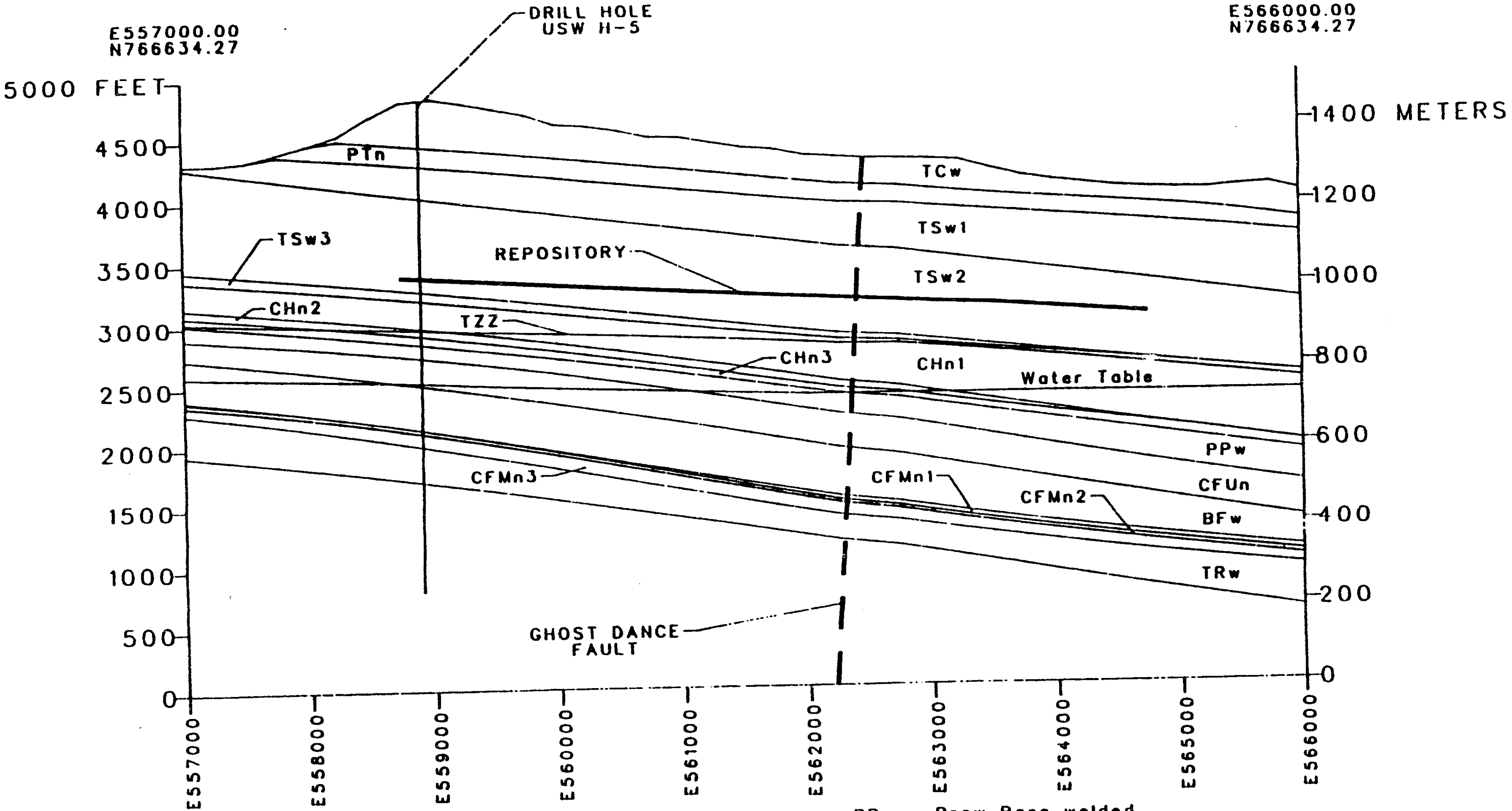
TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

WEST-EAST SECTION THROUGH MIDPOINT BETWEEN USW WT-8 AND SD-6



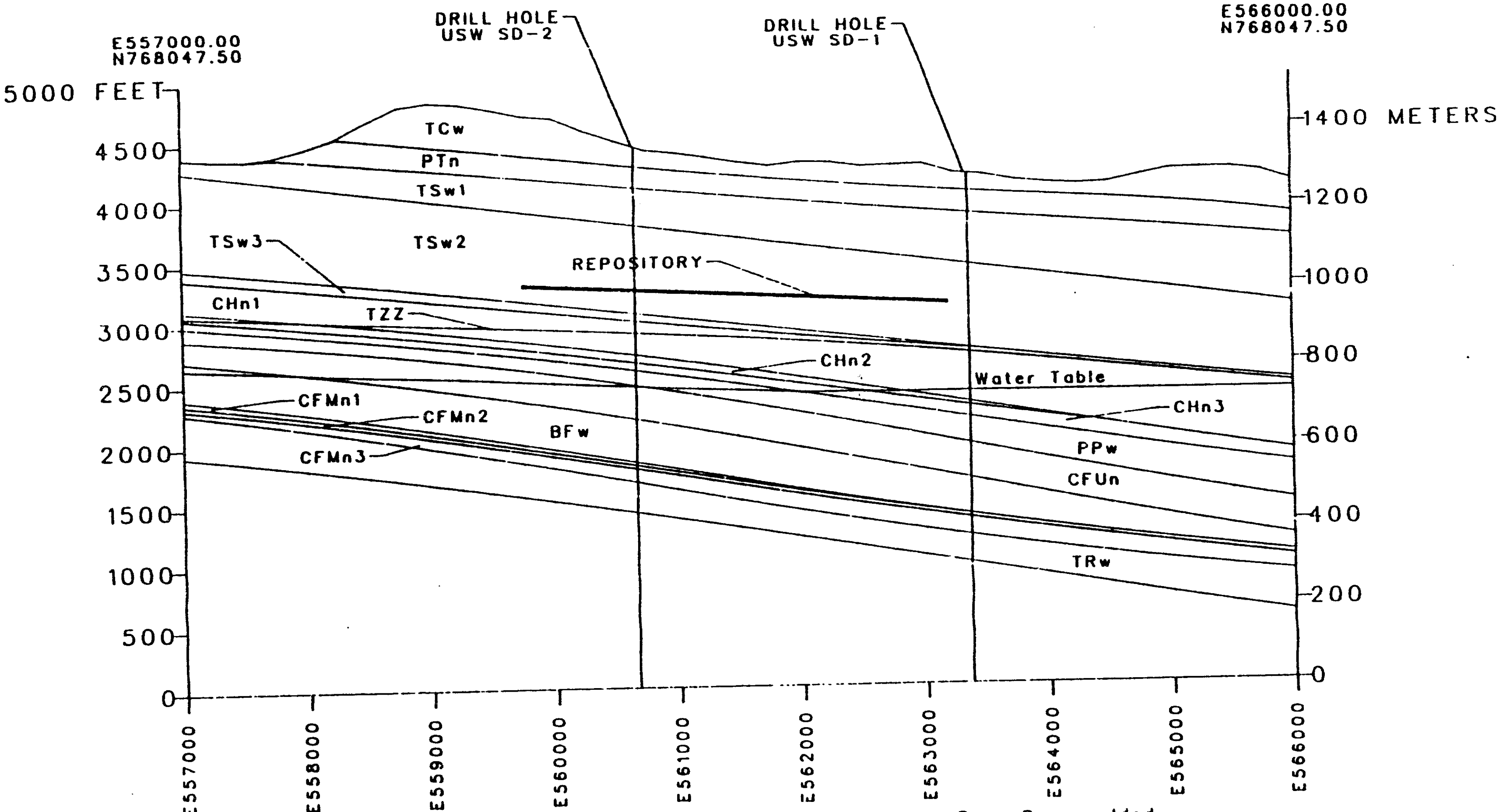
WEST-EAST SECTION THROUGH MIDPOINT BETWEEN SD-3 AND SD-4



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

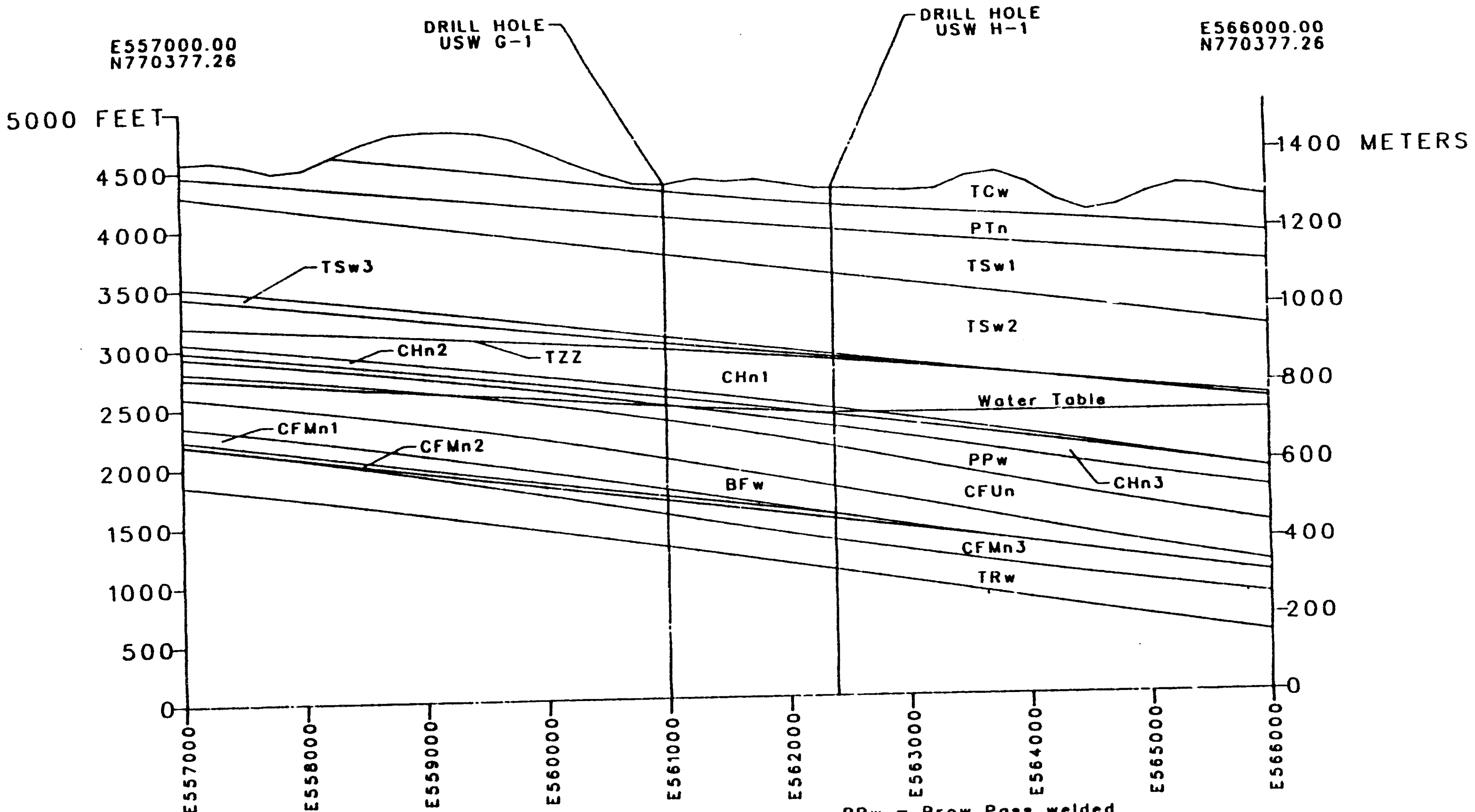
WEST-EAST SECTION THROUGH USW H-5



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
Tsw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFmn2 = Middle Crater Flat nonwelded #2
CFmn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

WEST-EAST SECTION THROUGH MIDPOINT BETWEEN SD-1 AND SD-2



TCw = Tiva Canyon welded
PTn = Upper Paintbrush Tuff nonwelded
TSw1 = Topopah Spring welded #1
TSw2 = Topopah Spring welded #2
TSw3 = Topopah Spring welded #3
CHn1 = Calico Hills/Paintbrush nonwelded #1
CHn2 = Calico Hills/Paintbrush nonwelded #2
CHn3 = Calico Hills/Paintbrush nonwelded #3

PPw = Prow Pass welded
CFUn = Upper Crater Flat nonwelded
BFw = Bullfrog welded
CFMn1 = Middle Crater Flat nonwelded #1
CFMn2 = Middle Crater Flat nonwelded #2
CFMn3 = Middle Crater Flat nonwelded #3
TRw = Tram welded
TZZ = Zeolitized Zone

WEST-EAST SECTION THROUGH MIDPOINT BETWEEN USW G-1 AND USW H-1

APPENDIX D

CORRELATION OF BOREHOLE WALL CATEGORY WITH THE STRATIGRAPHY FOR SELECTED BOREHOLES

Appendix D

Correlation of Borehole Wall Category with the Stratigraphy for Selected Boreholes

Introduction

Selected borehole video logs were reviewed as a direct means of assessing the wall condition. Boreholes were selected based on their location and the availability of borehole video logging. Nine locations were selected over a broad area to capture a range of subsurface geologic conditions. Following a preliminary review of all video logs, a classification scheme was developed based on smoothness of the borehole wall, lithophysae presence, degree of fracturing, and hole enlargement. The qualitative criteria for the classification scheme are:

- Category C1. Excellent, typically symmetrical hole with a smooth surface; no hole enlargement; none to few lithophysae; no pronounced fractures; minor "pluckouts."
- Category C2. Good, typically symmetrical hole with a smooth surface; hole enlargement small or intermediate[a] but infrequent; none to few fractures; uniform lithophysae can be present.
- Category C3. Poor, typically a rough surface; hole enlargement is intermediate and frequent, but it is possible for hole to be symmetrical; lithophysae can be prevalent, large, and nonuniformly distributed; fractures are frequent.
- Category C4. Extremely poor, typically a nonsymmetrical hole having an extremely irregular surface; hole enlargement is large; large lithophysae can be present; fractures are frequent and pronounced.

Following this initial step, each of the borehole video logs were reviewed in detail, and sections of the borehole were placed in the C1, C2, C3, or C4 categories of the report. Additionally, these categories were correlated with a simplified stratigraphic log. More detailed information on the results of video-logging is presented in Chapter 3.0 and in the correlations in Figures D-1 through D-10. Additionally, Tables D-1 through D-10 contain a summary of the percentage of

---

[a] Intermediate hole enlargement is equivalent to up to one-half of the hole diameter. Large hole enlargement is equivalent to one-half or greater than the hole diameter. This logic also applies to the size of the lithophysae.

for each stratigraphic unit for which video was available. Based upon these categories, the generalized hole conditions were found to be as follows:

- A high percentage of Categories C3 and C4 occur in the densely welded, devitrified tuff in the Tiva Canyon and Topopah Spring Units.
- Category C1 occurs in the Paintbrush nonwelded tuff.
- Categories C1 and C2 occur in the upper portion of Topopah Spring Unit.
- Categories C1 and C2 occur in the nonwelded vitric and zeolitic portions of the Calico Hills Unit.

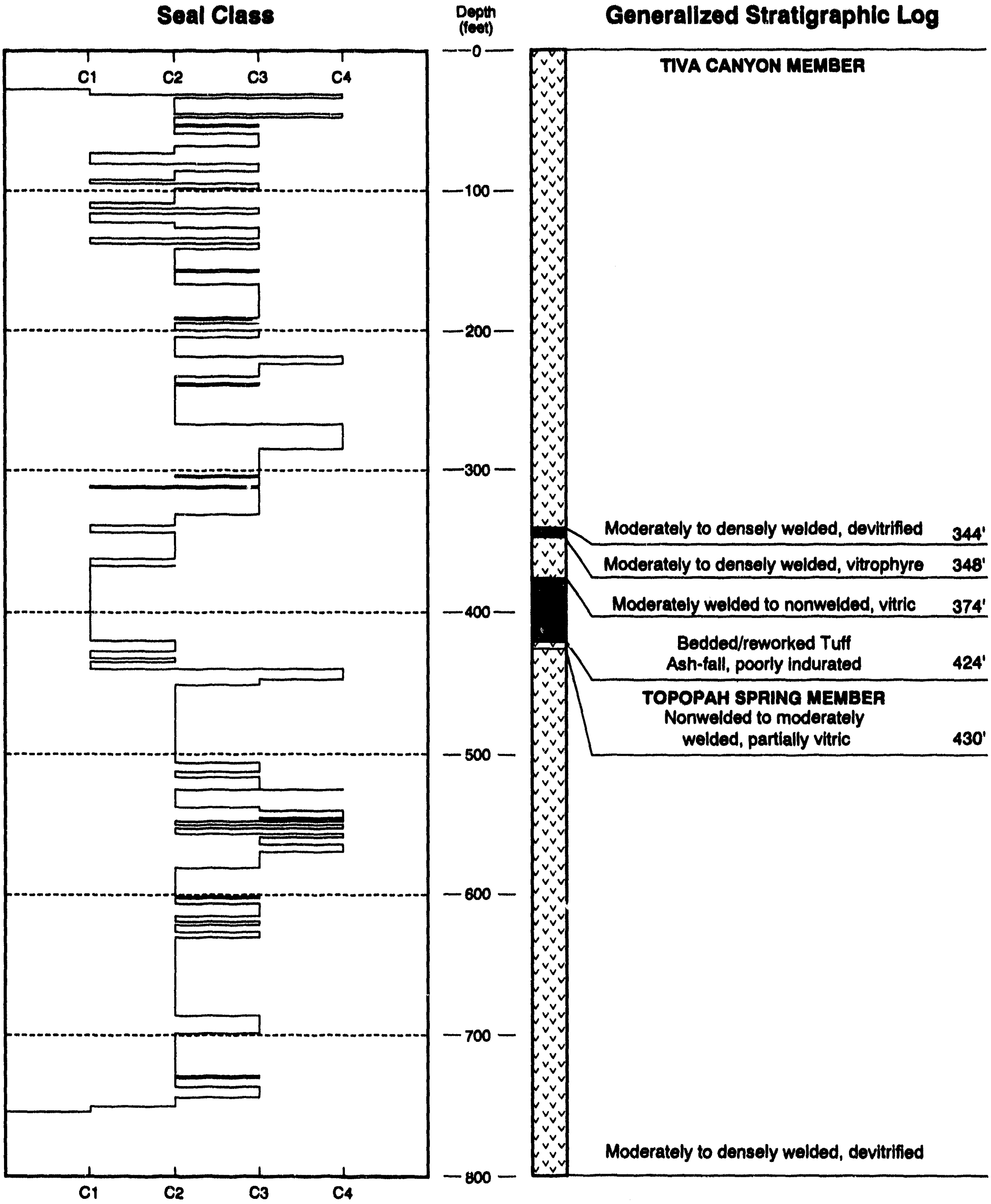


Figure D-1
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW GU-3

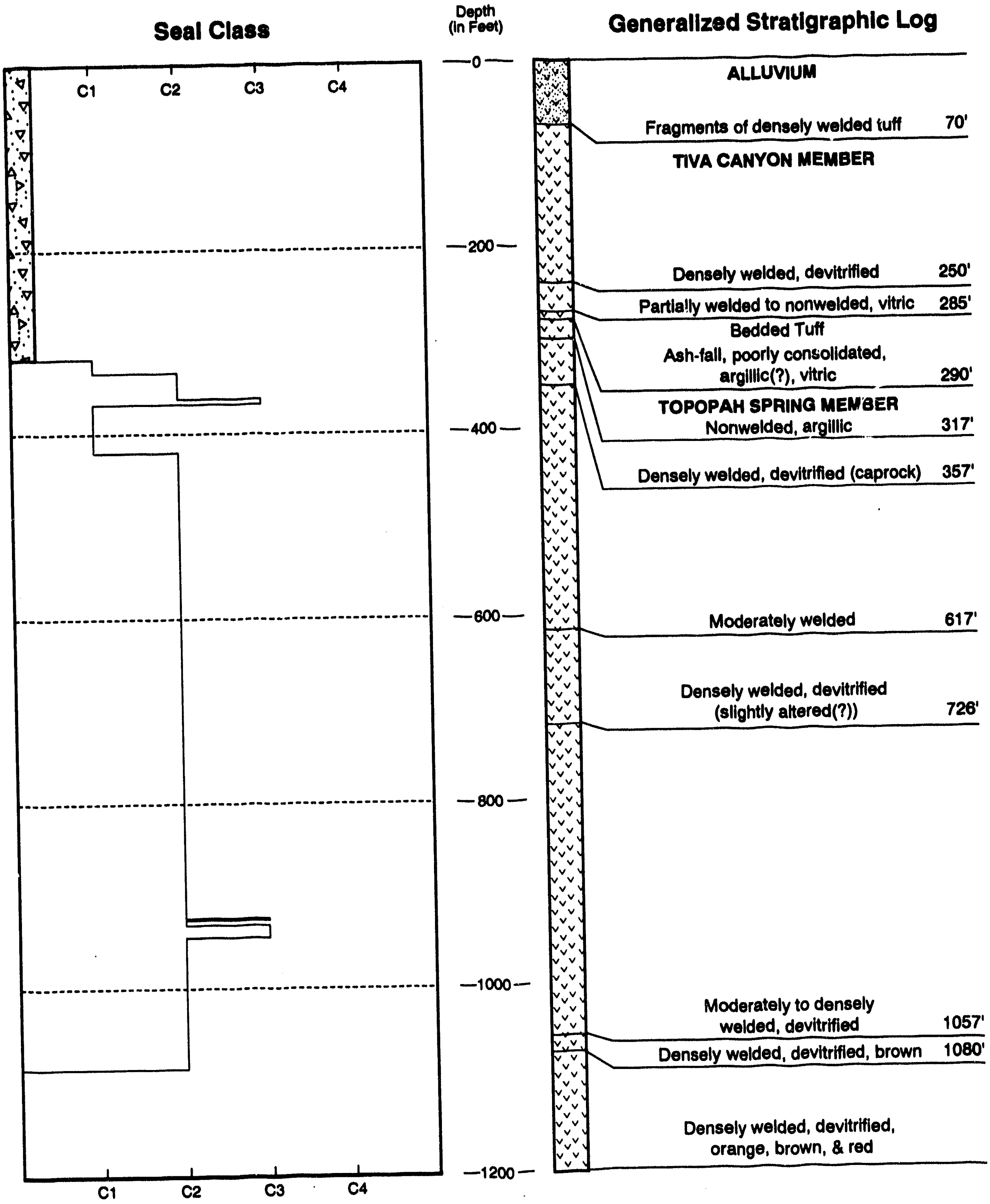


Figure D-2
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole UE-25 C-2

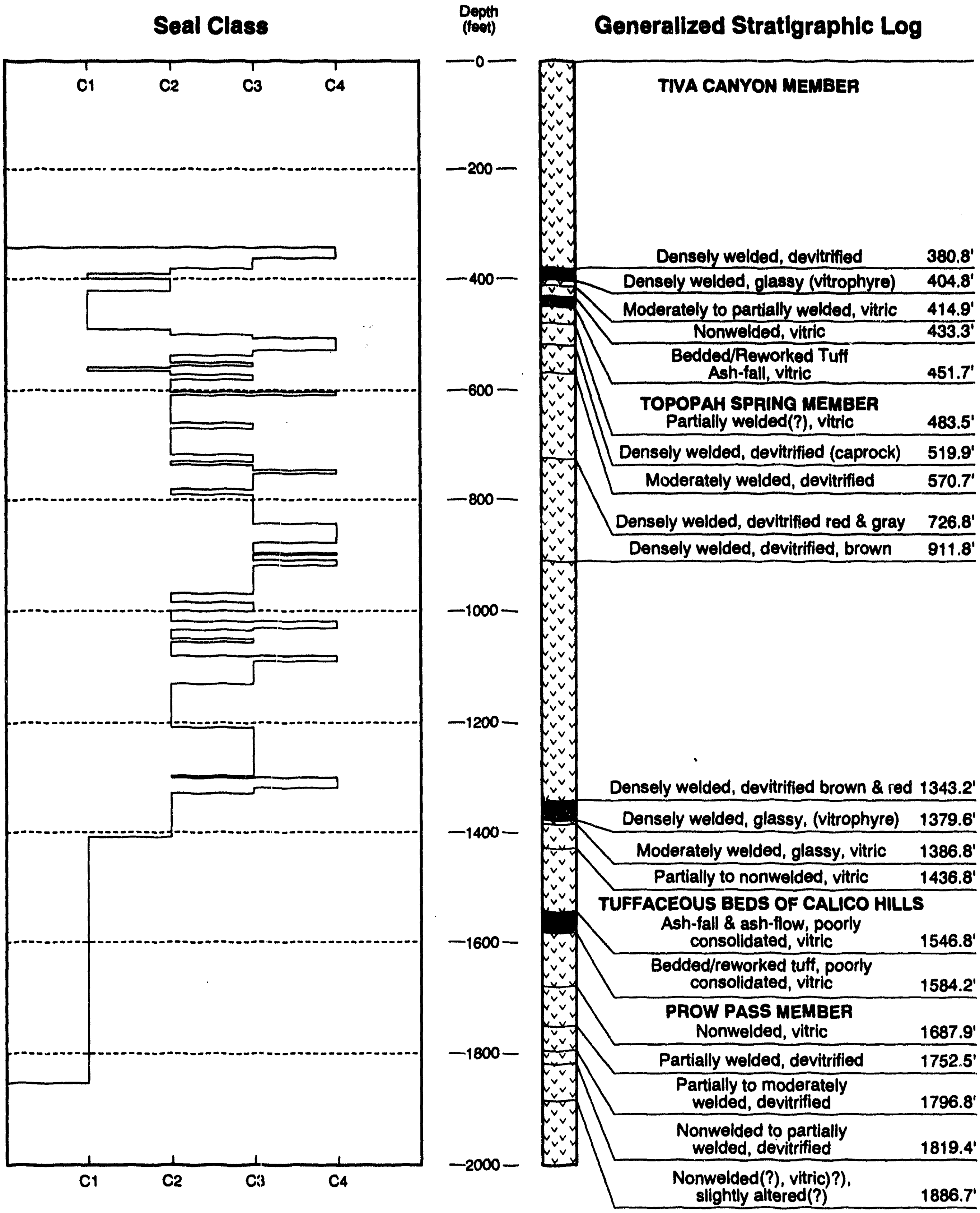


Figure D-3
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW UZ-6

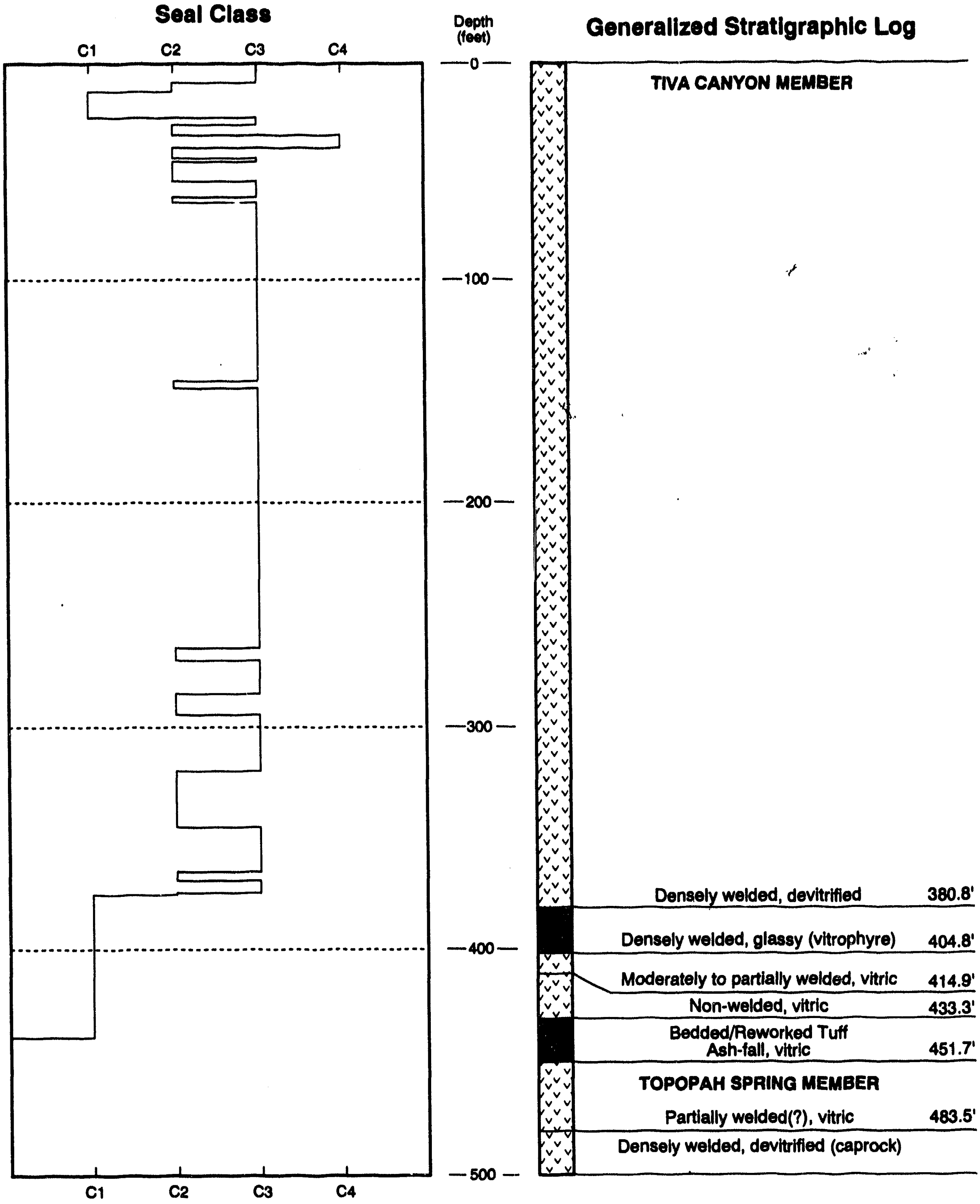


Figure D-4
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole UZ-6s

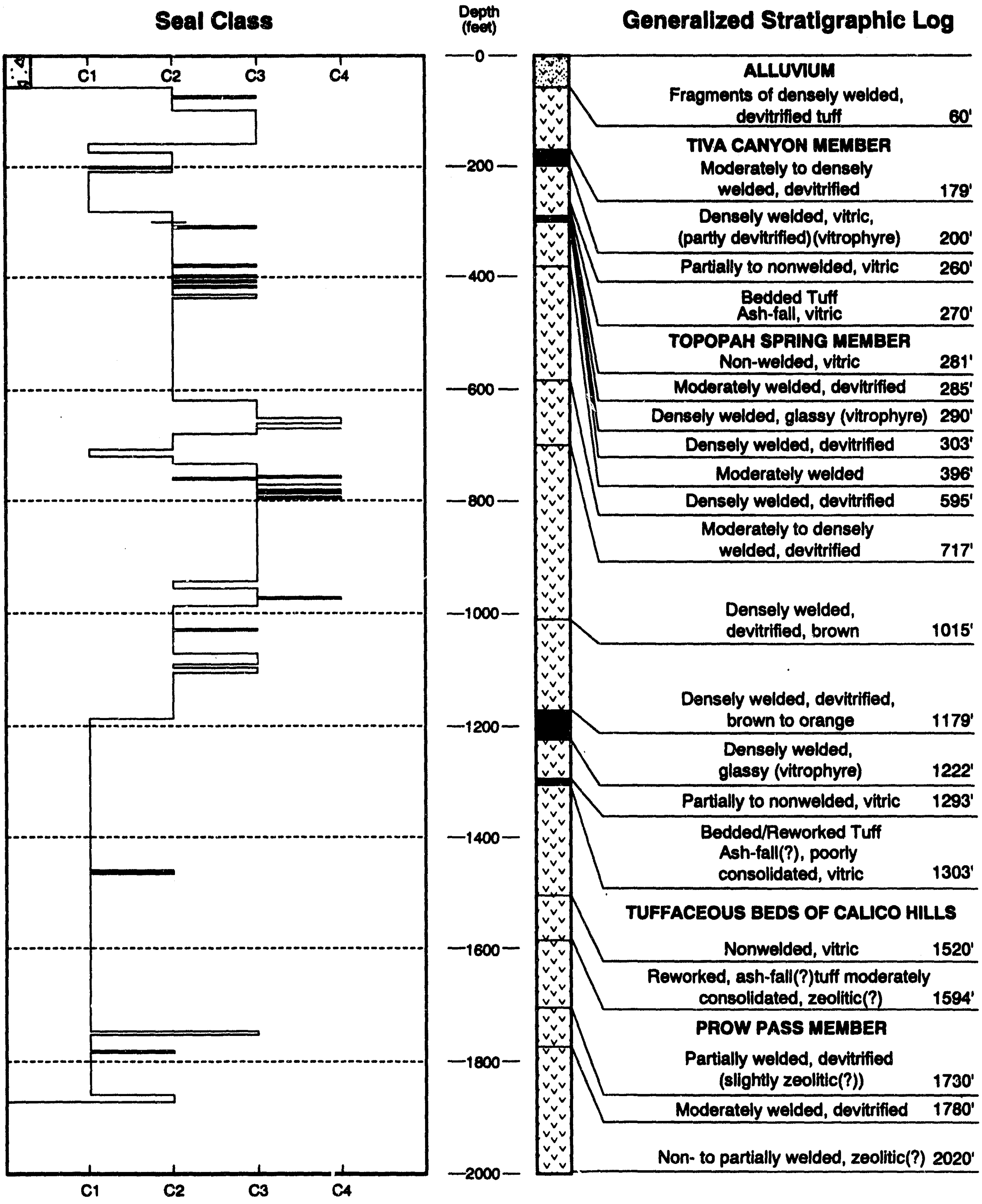


Figure D-5
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW WT-2

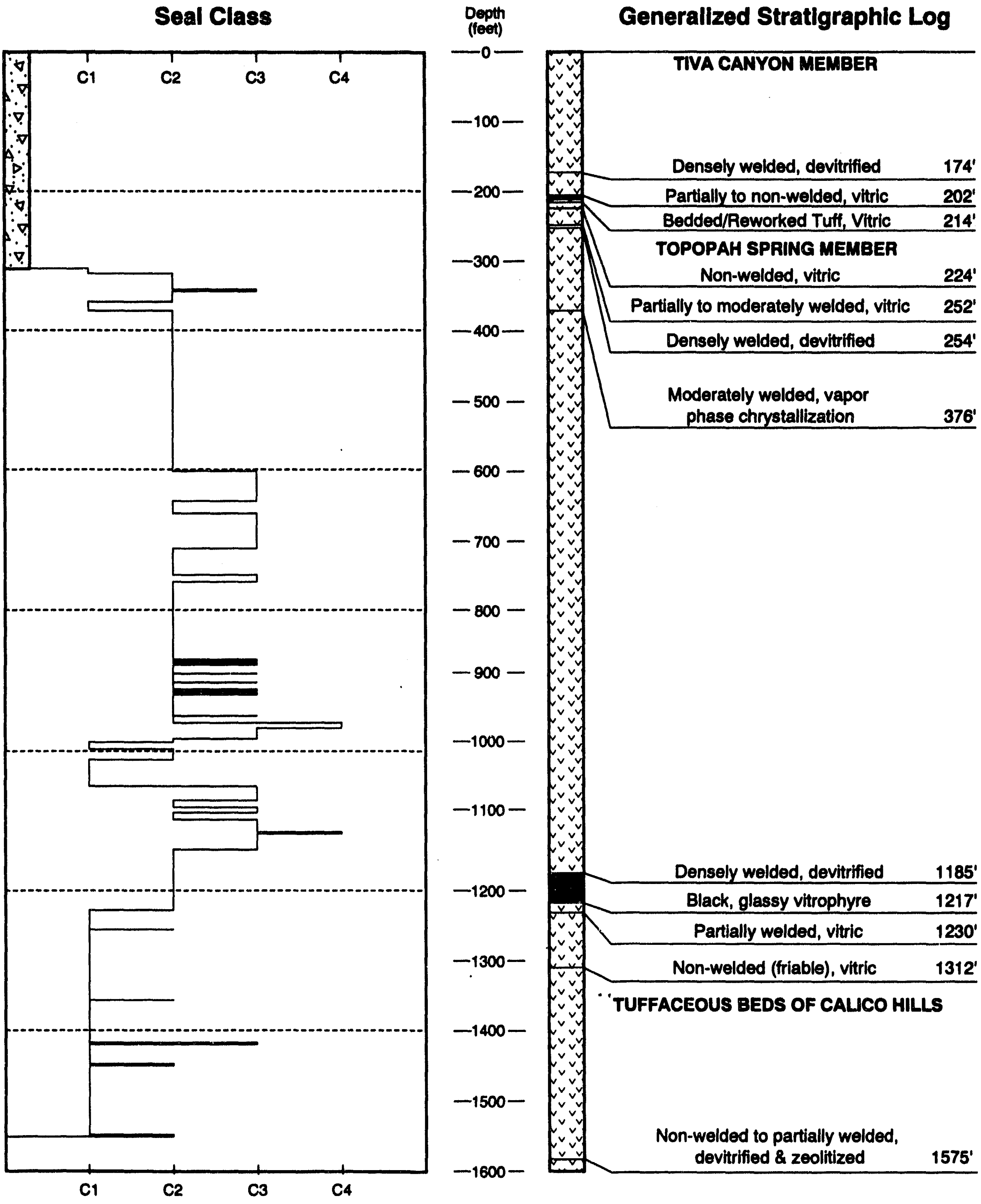


Figure D-6
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW H-4

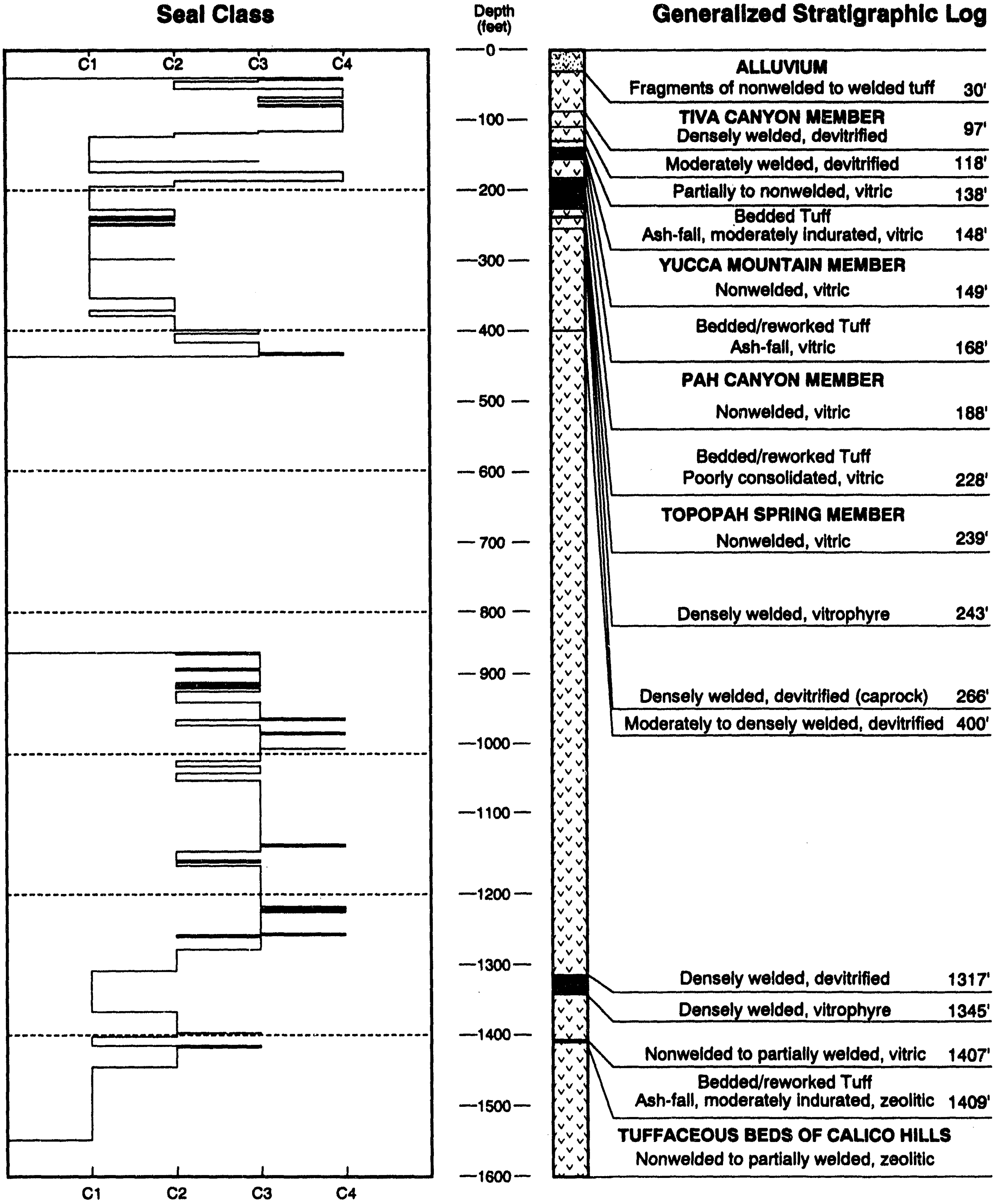


Figure D-7
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW G-4

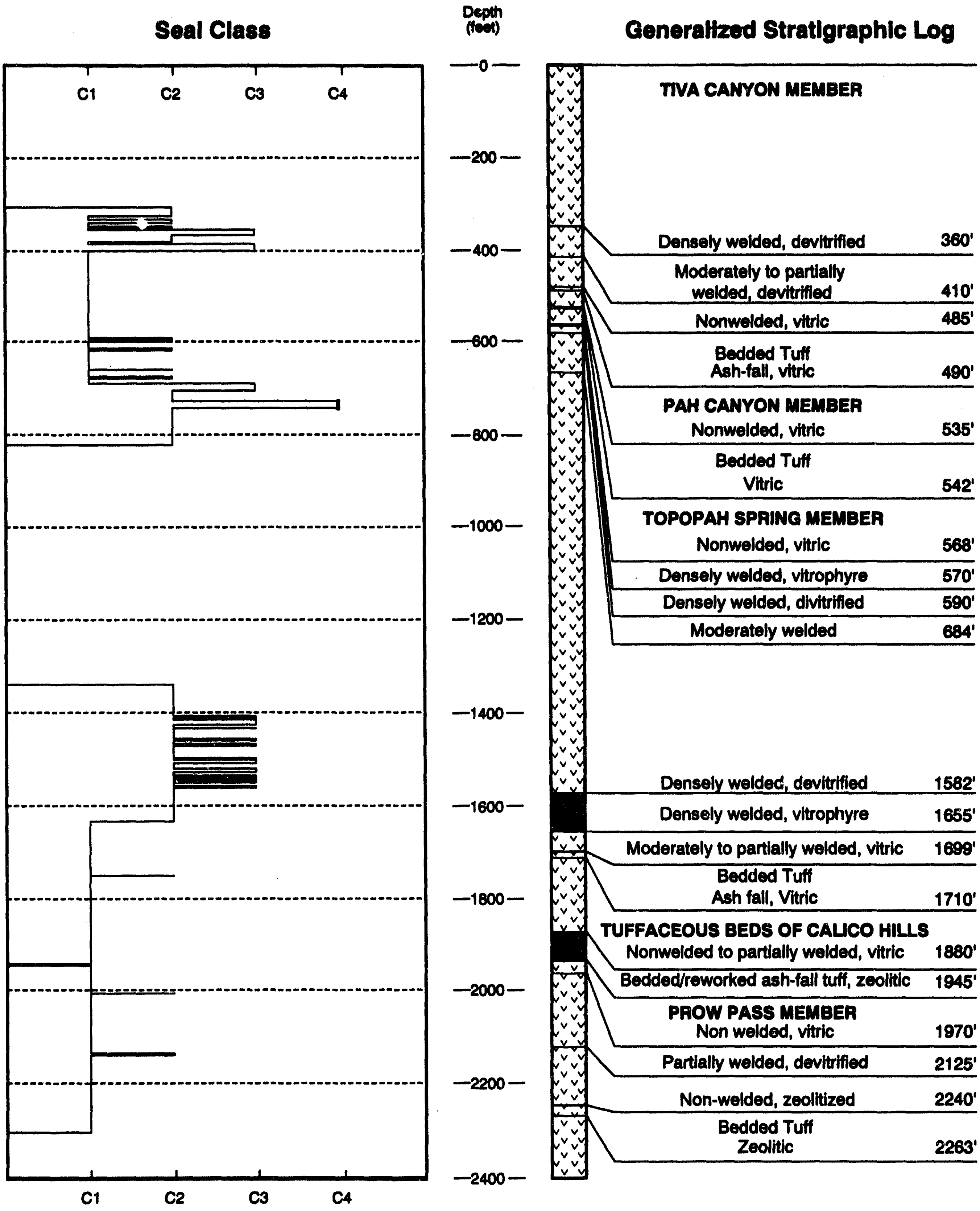


Figure D-8
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW H-5

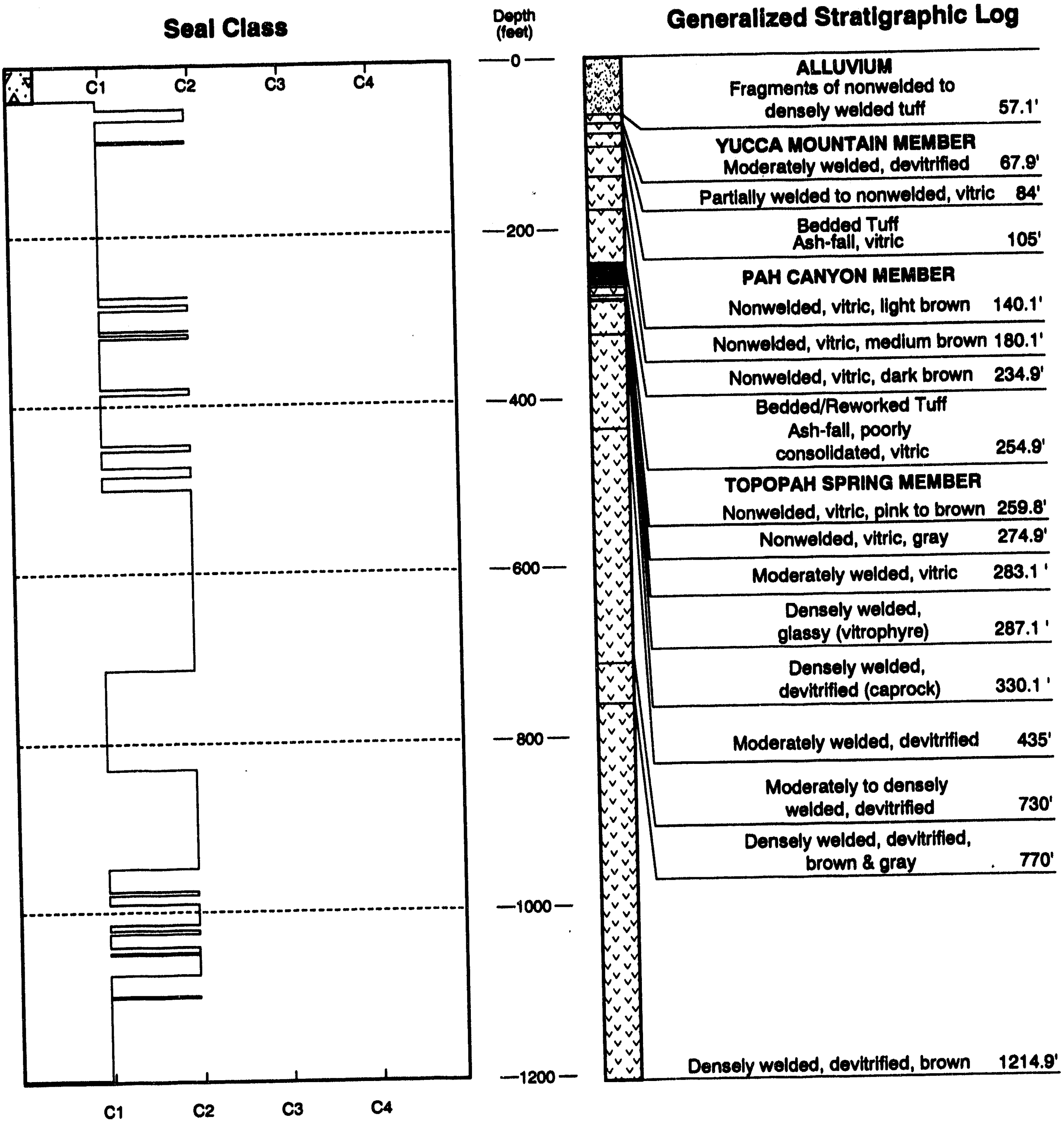


Figure D-9
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole USW UZ-1

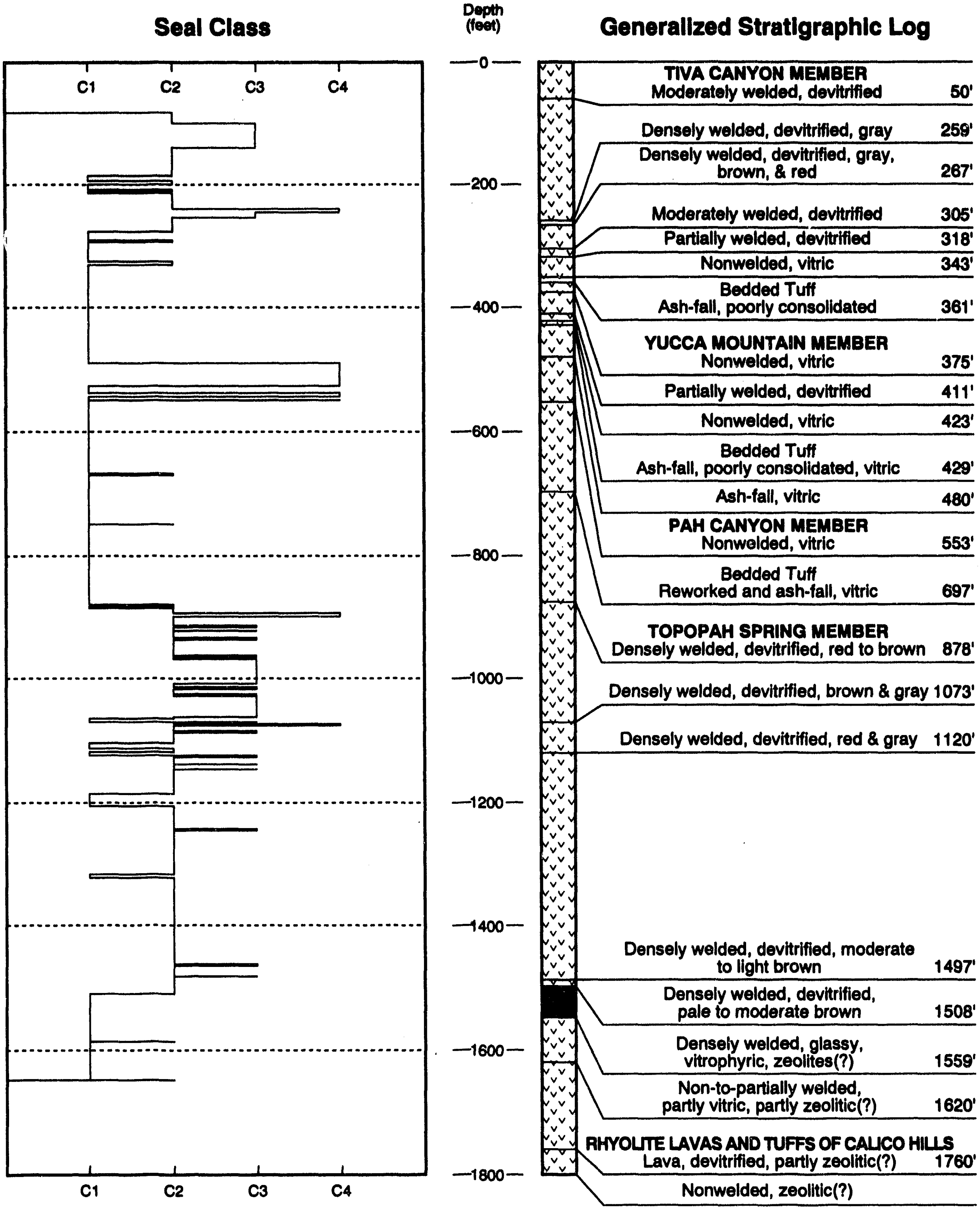


Figure D-10
Correlation Between the Borehole Wall Category and Stratigraphy for Borehole UE-25 WT 18

Table D-1

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW GU-3

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Moderately to densely welded, devitrified	344	344	35	135	118	28	11.1%	42.7%	37.3%	8.9%
Moderately to densely welded, vitrophyre	348	4	0	4	0	0	0.0%	100.0%	0.0%	0.0%
Moderately welded to non-welded, vitric	374	26	11	15	0	0	42.3%	57.7%	0.0%	0.0%
Bedded/reworked tuff—ash-fall, poorly indurated	424	50	46	4	0	0	92.0%	8.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Non-welded to moderately welded, partially vitric	430	6	3	3	0	0	50.0%	50.0%	0.0%	0.0%
Moderately to densely welded, devitrified	1187	757	12	212	76	24	3.7%	65.4%	23.5%	7.4%
Densely welded, vitrophyre	1269	82								
Moderately to partially welded, vitric	1309	40								
Non-welded, vitric	1406	97								
Bedded tuff—ash-fall, moderately to very poorly indurated	1413	7								
TUFFACEOUS BEDS OF CALICO HILLS										
Non-welded, vitric	1507	94								
Bedded tuff—ash-fall, moderately to poorly indurated	1560	53								
PROW PASS MEMBER										
Non-welded, vitric	1598	38								
Non-welded to part. welded, devitrified to part. vitric	1992	394								
Bedded tuff—moderately indurated	2005	13								

Table D-1 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW GU-3

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
BULLFROG MEMBER										
Partially welded, vitric, some partially devitrified	2022	17								
Partially welded, devitrified	2100	78								
Moderately to densely welded, devitrified	2529	429								
Moderately to partially welded, devitrified	2546	17								
Bedded tuff, ash-fall, well indurated	2549	3								
Non-welded to moderately welded, part. devitrified	2617	68								
Bedded/reworked tuff—ash-fall, moderately to well indurated	2637	20								
TRAM MEMBER										
Non-welded to partially welded, devitrified	2644	7								

Table D-2

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole UE-25 C-2

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
ALLUVIUM										
Fragments of densely welded tuff	70	70								
TIVA CANYON MEMBER										
Densely welded, devitrified	250	180								
Partially welded to nonwelded, vitric	285	35								
Bedded tuff—ash-fall, poorly consolidated, argillic(?), vitric	290	5								
TOPOPAH SPRING MEMBER										
Non-welded, argillic	317	27								
Densely welded, devitrified (caprock)	357	40	17	23	0	0	42.5%	57.5%	0.0%	0.0%
Moderately welded	617	260	52	201	7	0	20.0%	77.3%	2.7%	0.0%
Densely welded, devitrified (slightly altered (?))	726	109	0	109	0	0	0.0%	100.0%	0.0%	0.0%
Moderately to densely welded, devitrified	1057	331	0	318	13	0	0.0%	96.1%	3.9%	0.0%
Densely welded, devitrified, brown	1080	23	0	23	0	0	0.0%	100.0%	0.0%	0.0%
Densely welded, devitrified, orange, brown, and red	1206	126	0	6	0	0	0.0%	100.0%	0.0%	0.0%
Densely welded, glassy (vitrophyre)	1260	54								
Moderately welded, vitric	1289	29								
Partially to nonwelded, partially vitric and zeolitic(?)	1316	27								
TUFFACEOUS BEDS OF CALICO HILLS										
Nonwelded, zeolitic	1593	277								

Table D-2 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole UE-25 C-2

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
Reworked ash-fall, mod. to highly indurated, zeolitic	1671	78								
PROW PASS MEMBER										
Nonwelded to part, welded, devitrified, slightly altered	1810	139								
Moderately welded, devitrified	1840	30								
Nonwelded, devitrified	1955	115								
Nonwelded, intensely zeolitic	2109.5	154.5								
Bedded/reworked tuff—moderately indurated, zeolitic(?)	2138	28.5								
BULLFROG MEMBER										
Nonwelded to partially welded, devitrified	2240	102								
Moderately welded, devitrified	2270	30								
Moderately to densely welded, devitrified	2390	120								
Moderately welded, devitrified	2460	70								
Partially to nonwelded, devitrified	2560	100								
Nonwelded, zeolitic (?)	2667	107								
Bedded/reworked tuff—moderately indurated	2719	52								
TRAM MEMBER										
Partially welded, devitrified	2775	56								
Breccia, moderately indurated, devitrified	2935	160								
Partially welded, devitrified	3000	65								

Table D-3

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW UZ-6

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Densely welded, devitrified	380.8	380.8	0.0	0.8	20.0	20.0	0.0%	2.0%	49.0%	49.0%
Densely welded, glassy (vitrophyre)	404.8	24.0	10.0	14.0	0.0	0.0	41.7%	58.3%	0.0%	0.0%
Moderately to partially welded, vitric	414.9	10.1	0.0	10.1	0.0	0.0	0.0%	100.0%	0.0%	0.0%
Non-welded, vitric	433.3	18.4	13.3	5.1	0.0	0.0	72.3%	27.7%	0.0%	0.0%
Bedded/reworked tuff—ash-fall, vitric	451.7	18.4	18.4	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Partially welded(?), vitric	483.5	31.8	31.8	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Densely welded, devitrified (caprock)	519.9	36.4	6.5	10.0	7.0	12.9	17.9%	27.5%	19.2%	35.4%
Moderately welded, devitrified	570.7	50.8	8.0	18.0	18.7	6.1	15.7%	35.4%	36.8%	12.0%
Densely welded, devitrified, red and gray	726.8	156.1	0.0	120.0	31.1	5.0	0.0%	76.9%	19.9%	3.2%
Densely welded, devitrified, brown	911.8	185.0	0.0	15.0	122.2	47.8	0.0%	8.1%	66.1%	25.8%
Densely welded, devitrified, brown and red	1343.2	431.4	0.0	167.2	215.0	49.2	0.0%	38.8%	49.8%	11.4%
Densely welded, glassy (vitrophyre)	1379.6	36.4	0.0	36.4	0.0	0.0	0.0%	100.0%	0.0%	0.0%
Moderately welded, glassy, vitric	1386.8	7.2	0.0	7.2	0.0	0.0	0.0%	100.0%	0.0%	0.0%
Partially to nonwelded, vitric	1436.6	49.8	26.6	23.2	0.0	0.0	53.4%	46.6%	0.0%	0.0%

Table D-3 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW UZ-6

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TUFFACEOUS BEDS OF CALICO HILLS										
Ash-fall and ash-flow, poorly consolidated, vitric	1546.8	110.2	110.2	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Bedded/reworked tuff, poorly consolidated, vitric	1584.2	37.4	37.4	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
PROW PASS MEMBER										
Nonwelded, vitric	1687.9	103.7	103.7	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Partially welded, devitrified	1752.5	64.6	64.6	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Partially to moderately welded, devitrified	1796.8	44.3	44.3	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Nonwelded to partially welded, devitrified	1819.4	22.6	22.6	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Nonwelded(?), vitric(?), slightly altered(?)	1886.7	67.3	33.6	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%

Table D-4

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW UZ-6s

Description (Stratigraphic Column from USW UZ-6)	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Densely welded, devitrified	380.8	380.8	17.8	72.0	283.0	5.0	4.7%	19.1%	74.9%	1.3%
Densely welded, glassy (vitrophyre)	404.8	24.0	24.0	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Moderately to partially welded, vitric	414.9	10.1	10.1	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Non-welded, vitric	433.3	18.4	18.4	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
Bedded/reworked tuff—ash-fall, vitric	451.7	18.4	5.7	0.0	0.0	0.0	100.0%	0.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Partially welded(?), vitric	483.5	31.8								
Densely welded, devitrified (caprock)	519.9	36.4								
Moderately welded, devitrified	570.7	50.8								
Densely welded, devitrified, red and gray	726.8	156.1								
Densely welded, devitrified, brown	911.8	185.0								
Densely welded, devitrified, brown and red	1343.2	431.4								
Densely welded, glassy (vitrophyre)	1379.6	36.4								
Moderately welded, glassy, vitric	1386.8	7.2								
Partially to nonwelded, vitric	1436.6	49.8								
TUFFACEOUS BEDS OF CALICO HILLS										
Ash-fall and ash-flow, poorly consolidated, vitric	1546.8	110.2								
Bedded/reworked tuff, poorly consolidated, vitric	1584.2	37.4								
PROW PASS MEMBER										
Nonwelded, vitric	1687.9	103.7								
Partially welded, devitrified	1752.5	64.6								
Partially to moderately welded, devitrified	1796.8	44.3								
Nonwelded to partially welded, devitrified	1819.4	22.6								

Table D-4 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW UZ-6s

Description (Stratigraphic Column from USW UZ-6)	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
Nonwelded(?), vitric(?), slightly altered(?)	1886.7	67.3								

Table D-5

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW WT-2

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
ALLUVIUM										
Fragments of densely welded, devitrified tuff	60	60	0	2	0	0	0.0%	100.0%	0.0%	0.0%
TIVA CANYON MEMBER										
Moderately to densely welded, devitrified	179	119	16	42	61	0	13.4%	35.3%	51.3%	0.0%
Densely welded, vitric (partly devitrified)(vitrophyre)	200	21	0	21	0	0	0.0%	100.0%	0.0%	0.0%
Partially to nonwelded, vitric	260	60	54	6	0	0	90.0%	10.0%	0.0%	0.0%
Bedded tuff—ash-fall, vitric	270	10	10	0	0	0	100.0%	0.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Non-welded, vitric	281	11	11	0	0	0	100.0%	0.0%	0.0%	0.0%
Moderately welded, devitrified	285	4	0	4	0	0	0.0%	100.0%	0.0%	0.0%
Densely welded, glassy (vitrophyre)	290	5	0	5	0	0	0.0%	100.0%	0.0%	0.0%
Densely welded, devitrified	303	13	0	13	0	0	0.0%	100.0%	0.0%	0.0%
Moderately welded	396	93	0	90	3	0	0.0%	96.8%	3.2%	0.0%
Densely welded, devitrified	595	199	0	189	10	0	0.0%	95.0%	5.0%	0.0%
Moderately to densely welded, devitrified	717	122	10	52	48	12	8.2%	42.6%	39.3%	9.8%
Densely welded, devitrified, brown	1015	298	2	57	221	18	0.7%	19.1%	74.2%	6.0%
Densely welded, devitrified, brown to orange	1179	164	0	134	30	0	0.0%	81.7%	18.3%	0.0%
Densely welded, glassy (vitrophyre)	1222	43	33	10	0	0	76.7%	23.3%	0.0%	0.0%
Partially to nonwelded, vitric	1293	71	71	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded/reworked tuff—ash-fall(?), poorly consolidated, vitric	1303	10	10	0	0	0	100.0%	0.0%	0.0%	0.0%
TUFFACEOUS BEDS OF CALICO HILLS										
Nonwelded, vitric	1520	217	215	2	0	0	99.1%	0.9%	0.0%	0.0%

Table D-5 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW WT-2

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
Reworked, ash-fall(?) tuff, mod. consolid., zeolitic(?)	1594	74	74	0	0	0	100.0%	0.0%	0.0%	0.0%
PROW PASS MEMBER										
Partially welded, devitrified (slightly zeolitic(?))	1730	136	136	0	0	0	100.0%	0.0%	0.0%	0.0%
Moderately welded, devitrified	1780	50	44	0	6	0	88.0%	0.0%	12.0%	0.0%
Non- to partially welded, zeolitic(?)	2020	240	75	18	0	0	80.6%	19.4%	0.0%	0.0%
Moderately to densely welded, devitrified	2060	40								

Table D-6

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW H-4

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Densely welded, devitrified	174	174								
Partially to non-welded, vitric	202	28								
Bedded/reworked tuff—vitric	214	12								
TOPOPAH SPRING MEMBER										
Non-welded, vitric	224	10								
Partly to moderately welded, vitric	252	28								
Densely welded, devitrified	254	2								
Moderately welded, vapor phase crystallization	376	122	17	45	2	0	26.6%	70.3%	3.1%	0.0%
Densely welded, devitrified	1185	809	45	553	199	12	5.6%	68.4%	24.6%	1.5%
Black, glassy vitrophyre	1217	32	0	32	0	0	0.0%	100.0%	0.0%	0.0%
Partly welded, vitric	1230	13	0	13	0	0	0.0%	100.0%	0.0%	0.0%
Nonwelded (friable), vitric	1312	82	81	1	0	0	98.8%	1.2%	0.0%	0.0%
TUFFACEOUS BEDS OF CALICO HILLS										
Nonwelded to partly welded, devitrified & zeolitized	1575	263	226	9	3	0	95.0%	3.8%	1.3%	0.0%
Bedded/reworked tuff—devitrified and zeolitized	1627	52								
PROW PASS MEMBER										
Nonwelded, zeolitic	1640	13								
Partly welded, devitrified	1955	315								
Partly welded, zeolitic, and silicified	2040	85								
Partly welded, zeolitic, and vitric	2263	223								
Bedded/reworked tuff—zeolitized(?)	2275	12								

Table D-6 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW H-4

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
BULLFROG MEMBER										
Partly welded, devitrified	2468	193								
Partly welded	2500	32								
Moderately to densely welded	2585	85								
Non-welded to partly welded, devitrified	2644	59								
Bedded/reworked tuff—devitrified	2664	20								
TRAM MEMBER										
Partly welded, devitrified	2990	326								
Moderately welded, devitrified	3230	240								
Partly welded, devitrified	3342	112								
Partly welded, zeolitic	3788	446								
Bedded/reworked tuff—zeolitic	3819	31								
LITHIC RIDGE TUFF										
Partially welded, devitrified	4000	181								

Table D-7

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW G-4

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
ALLUVIUM										
Fragments of nonwelded to welded tuff	30	30								
TIVA CANYON MEMBER										
Densely welded, devitrified	97	67	0	12	11	34	0.0%	21.1%	19.3%	59.6%
Moderately welded, devitrified	118	21	0	0	0	21	0.0%	0.0%	0.0%	100.0%
Partially to nonwelded, vitric	138	20	14	3	3	0	70.0%	15.0%	15.0%	0.0%
Bedded tuff—ash-fall, moderately indurated, vitric	148	10	10	0	0	0	100.0%	0.0%	0.0%	0.0%
YUCCA MOUNTAIN MEMBER										
Nonwelded, vitric	149	1	1	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded/reworked tuff—ash-fall, vitric	168	19	18	0	1	0	94.7%	0.0%	5.3%	0.0%
PAH CANYON MEMBER										
Nonwelded, vitric	188	20	7	1	0	12	35.0%	5.0%	0.0%	60.0%
Bedded/reworked tuff—poorly consolidated, vitric	228	40	31	9	0	0	77.5%	22.5%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Nonwelded, vitric	239	11	1	10	0	0	9.1%	90.9%	0.0%	0.0%
Densely welded, vitrophyre	243	4	1	3	0	0	25.0%	75.0%	0.0%	0.0%
Densely welded, devitrified (caprock)	266	23	21	2	0	0	91.3%	8.7%	0.0%	0.0%
Moderately to densely welded, devitrified	400	134	97	37	0	0	72.4%	27.6%	0.0%	0.0%
Densely welded, devitrified	1317	917	9	113	364	13	1.8%	22.6%	72.9%	2.6%
Densely welded, vitrophyre	1345	28	28	0	0	0	100.0%	0.0%	0.0%	0.0%
Nonwelded to partially welded, vitric	1407	62	28	33	1	0	45.2%	53.2%	1.6%	0.0%
Bedded/reworked tuff—ash-fall, moderately indurated, zeolitic	1409	2	2	0	0	0	100.0%	0.0%	0.0%	0.0%

Table D-7 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW G-4

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TUFFACEOUS BEDS OF CALICO HILLS										
Nonwelded to partially welded, zeolitic	1705	296	112	27	1	0	80.0%	19.3%	0.7%	0.0%
Bedded/reworked ash-fall tuff, zeolitic	1761	56								
PROW PASS MEMBER										
Nonwelded, zeolitic	1796	35								
Nonwelded to partially welded, devitrified, zeolitic	2238	442								
Bedded/reworked tuff—ash-fall, slightly to moderately zeolitic	2244	6								
BULLFROG MEMBER										
Partially welded, devitrified	2528	284								
Ash-fall tuff, well indurated, devitrified	2534	6								
Nonwelded to partially welded, devitrified	2582	48								
Moderately to densely welded, devitrified	2680	98								
Nonwelded to partially welded, devitrified, argillic or zeolitic	2733	53								
Bedded/reworked tuff—ash-fall	2756	23								
TRAM MEMBER										
Nonwelded to partially welded, devitrified	2841	85								
Devitrified	2999	158								
Moderately welded, devitrified	3001	2								

Table D-8

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW H-5

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Densely welded, devitrified	360	360	17	31	2	0	34.0%	62.0%	4.0%	0.0%
Moderately to partially welded, devitrified	410	50	15	15	20	0	30.0%	30.0%	40.0%	0.0%
Nonwelded, vitric	485	75	75	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded tuff—ash-fall(?), vitric	490	5	5	0	0	0	100.0%	0.0%	0.0%	0.0%
PAH CANYON MEMBER										
Non-welded, vitric	535	45	45	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded tuff—vitric	542	7	7	0	0	0	100.0%	0.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Non-welded, vitric	568	26	26	0	0	0	100.0%	0.0%	0.0%	0.0%
Densely welded, vitrophyre	570	2	2	0	0	0	100.0%	0.0%	0.0%	0.0%
Densely welded, devitrified	590	20	20	0	0	0	100.0%	0.0%	0.0%	0.0%
Moderately welded	684	94	76	18	0	0	80.9%	19.1%	0.0%	0.0%
Densely welded, devitrified	1582	898	5	303	60	14	1.3%	79.3%	15.7%	3.7%
Densely welded, vitrophyre	1655	73	23	50	0	0	31.5%	68.5%	0.0%	0.0%
Moderately to partially welded, vitric	1699	44	44	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded tuff—ash-fall, vitric	1710	11	11	0	0	0	100.0%	0.0%	0.0%	0.0%
TUFFACEOUS BEDS OF CALICO HILLS										
Non-welded to partially welded, vitric	1880	170	169	1	0	0	99.4%	0.6%	0.0%	0.0%
Bedded/reworked ash-fall tuff, zeolitic	1945	65	60	0	0	0	100.0%	0.0%	0.0%	0.0%

Table D-8 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole USW H-5

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
PROW PASS MEMBER										
Nonwelded, vitric	1970	25	25	0	0	0	100.0%	0.0%	0.0%	0.0%
Partially welded, devitrified	2125	155	153	2	0	0	98.7%	1.3%	0.0%	0.0%
Nonwelded, zeolitized	2240	115	113	2	0	0	98.3%	1.7%	0.0%	0.0%
Bedded tuff—zeolitic(?)	2263	23	23	0	0	0	100.0%	0.0%	0.0%	0.0%
BULLFROG MEMBER										
Partially welded	2530	267	41	0	0	0	100.0%	0.0%	0.0%	0.0%
Partially welded, devitrified	2610	80								
Partially to moderately welded, devitrified	2670	60								
Moderately to densely welded, devitrified	2710	40								
Partially welded, devitrified, and zeolitic	2713	3								
Bedded/reworked tuff	2742	29								
TRAM MEMBER										
Moderately welded(?), devitrified	2790	48								
Partially welded, devitrified	3230	440								
Partially welded, devitrified, slightly zeolitic(?)	3320	90								
Partially welded, zeolitic	3412	92								
Bedded/reworked tuff—zeolitic	3422	10								
Lava (unnamed)	4000	578								

Table D-9

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole USW UZ-1

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
ALLUVIUM										
Fragments of non-welded to densely welded tuff	57.1	57.1	11.5	4.1	0	0	73.7%	26.3%	0.0%	0.0%
YUCCA MOUNTAIN MEMBER										
Moderately welded, devitrified	67.9	10.8	1.4	9.4	0	0	13.0%	87.0%	0.0%	0.0%
Partially welded to nonwelded, vitric	84	16.1	16.1	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded tuff—ash-fall, vitric	105	21	17	4	0	0	81.0%	19.0%	0.0%	0.0%
PAH CANYON MEMBER										
Non-welded, vitric, light brown	140.1	35.1	35.1	0	0	0	100.0%	0.0%	0.0%	0.0%
Non-welded, vitric, medium brown	180.1	40	40	0	0	0	100.0%	0.0%	0.0%	0.0%
Non-welded, vitric, dark brown	234.9	54.8	54.8	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded/reworked tuff—ash-fall, poorly consolidated, vitric	254.9	20	20	0	0	0	100.0%	0.0%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Non-welded, vitric, pink to brown	259.8	4.9	4.9	0	0	0	100.0%	0.0%	0.0%	0.0%
Non-welded, vitric, gray	274.9	15.1	15.1	0	0	0	100.0%	0.0%	0.0%	0.0%
Moderately welded, vitric	283.1	8.2	6.1	2.1	0	0	74.4%	25.6%	0.0%	0.0%
Densely welded, glassy (vitrophyre)	287.1	4	0	4	0	0	0.0%	100.0%	0.0%	0.0%
Densely welded, devitrified (caprock)	330.1	43	36.1	6.9	0	0	84.0%	16.0%	0.0%	0.0%
Moderately welded, devitrified	435	104.9	96.9	8	0	0	92.4%	7.6%	0.0%	0.0%
Moderately to densely welded, devitrified	730	295	65	230	0	0	22.0%	78.0%	0.0%	0.0%
Densely welded, devitrified, brown and gray	770	40	40	0	0	0	100.0%	0.0%	0.0%	0.0%
Densely welded, devitrified, brown	1214.9	444.9	242.5	185.5	0	0	56.7%	43.3%	0.0%	0.0%

Table D-10

Borehole Wall Categorization As a Percentage for Stratigraphy of Borehole UE-25 WT#18

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
TIVA CANYON MEMBER										
Moderately welded, devitrified	50	50								
Densely welded, devitrified, gray	259	209	19.5	103.5	43	7	11.3%	59.8%	24.9%	4.0%
Densely welded, devitrified, gray, brown, and red	267	8	0	8	0	0	0.0%	100.0%	0.0%	0.0%
Moderately welded, devitrified	305	38	26	12	0	0	68.4%	31.6%	0.0%	0.0%
Partially welded, devitrified	318	13	13	0	0	0	100.0%	0.0%	0.0%	0.0%
Nonwelded, vitric	343	25	18	7	0	0	72.0%	28.0%	0.0%	0.0%
Bedded tuff—ash-fall, poorly consolidated	361	18	18	0	0	0	100.0%	0.0%	0.0%	0.0%
YUCCA MOUNTAIN MEMBER										
Nonwelded, vitric	375	14	14	0	0	0	100.0%	0.0%	0.0%	0.0%
Partially welded, devitrified	411	36	36	0	0	0	100.0%	0.0%	0.0%	0.0%
Nonwelded, vitric	423	12	12	0	0	0	100.0%	0.0%	0.0%	0.0%
Bedded tuff—ash-fall, poorly consolidated, vitric	429	6	6	0	0	0	100.0%	0.0%	0.0%	0.0%
Ash-fall, vitric	480	51	51	0	0	0	100.0%	0.0%	0.0%	0.0%
PAH CANYON MEMBER										
Nonwelded, vitric	553	73	34	0	0	39	46.6%	0.0%	0.0%	53.4%
Bedded tuff—reworked and ash-fall, vitric	697	144	142	2	0	0	98.6%	1.4%	0.0%	0.0%
TOPOPAH SPRING MEMBER										
Densely welded, devitrified, red to brown	878	181	179	2	0	0	98.9%	1.1%	0.0%	0.0%
Densely welded, devitrified, brown and gray	1073	195	8	89	93	5	4.1%	45.6%	47.7%	2.6%
Densely welded, devitrified, red and gray	1120	47	14	31	1	1	29.8%	66.0%	2.1%	2.1%
Densely welded, devitrified, mod. to light brown	1497	377	29	336	12	0	7.7%	89.1%	3.2%	0.0%
Densely welded, devitrified, pale to mod. brown	1508	11	1	10	0	0	9.1%	90.9%	0.0%	0.0%
Densely welded, glassy, vitrophyric, zeolites(?)	1559	51	51	0	0	0	100.0%	0.0%	0.0%	0.0%

Table D-10 *(Continued)*

Borehole Wall Categorization as a Percentage for Stratigraphy of Borehole UE-25 WT#18

Description	Depth to Bottom	Thickness	Class C1	Class C2	Class C3	Class C4	% Class C1	% Class C2	% Class C3	% Class C4
Non-to partially welded, partly vitric, partly zeolitic(?)	1620	61	59	2	0	0	96.7%	3.3%	0.0%	0.0%
RHYOLITE LAVAS AND TUFFS OF CALICO HILLS										
Lava, devitrified, partly zeolitic(?)	1760	140	29	1	0	0	96.7%	3.3%	0.0%	0.0%
Nonwelded, zeolitic(?)	2043	283								

APPENDIX E

LATERAL EXTENT OF FLOODING FROM A POTENTIAL REPOSITORY

Appendix E
Lateral Extent of Flooding From a Potential Repository

This appendix presents two calculations for a drift intercepted by several sets of fractures. The conceptual design report (DOE, 1992) presents information on fracture frequency for various dip angles. The analysis assumes that the tensor contribution of all joints may be added for each fracture orientation. For the orientation at angle α

$$Kxx(\alpha) = \frac{\rho g}{\mu} N(\alpha) \frac{b^3}{12}$$

$$Kyy = K_m$$

where

ρ = mass density,
b = fracture aperture,
μ = absolute viscosity,
$N(\alpha)$ = fracture frequency as a functioning of dip angle, and
K_m = matrix conductivity

The permeability tensor is defined for the fracture set oriented at angle α

$$K(\alpha) = \begin{bmatrix} Kxx(\alpha) & 0 \\ 0 & Kyy \end{bmatrix}$$

The matrix of direction cosines is defined as

$$A(\alpha) = \begin{bmatrix} \cos(\alpha) & -\sin(d) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

The second order tensor transformation is given by

$$K(\alpha) = A\ (\alpha)\ K(\alpha)\ A(\alpha)^T$$

These calculations are presented in Tables E-1 and E-2 for the mean fracture frequency as a function of dip angle, and for a more conservative case in which a lower fracture frequency for the high angled fractures is combined with a higher fracture frequency for the low angled fractures. After calculating the values for conductivity along the fractures for each orientation, and transforming the conductivities to the xy orientation, the values are summed following the approach outlined in Chapter 4.0 of this report. The principal permeabilities can then be calculated, and the orientation of the major and minor principal permeabilities determined. In the first case evaluated, the vertical fracture are dominant, the principal major permeability is oriented vertically, and flow would be directed vertically downward. In the second case, the principal major permeability orients at an angle of 28°. Lateral spreading occurs at this angle of about 28° as illustrated by the flow-net analysis.

Table E-1
Fracture Conductivity Calculations[a,b]

Orientation (Degrees)	Fracture Frequency (m^{-1})	Equivalent Conductivity (m/s)	Kxx	Kyy	Kxy
5	0.2	1.44 x 10^{-7}	1.43 x 10^{-7}	1.10 x 10^{-9}	1.25 x 10^{-8}
15	0.2	1.44 x 10^{-7}	1.35 x 10^{-7}	9.66 x 10^{-9}	3.60 x 10^{-8}
25	0.2	1.44 x 10^{-7}	1.18 x 10^{-7}	2.58 x 10^{-8}	5.52 x 10^{-8}
35	0.1	7.21 x 10^{-8}	4.84 x 10^{-8}	2.37 x 10^{-8}	3.39 x 10^{-8}
45	0.2	1.44 x 10^{-7}	7.21 x 10^{-8}	7.21 x 10^{-8}	7.21 x 10^{-8}
55	0.2	1.44 x 10^{-7}	4.74 x 10^{-8}	9.67 x 10^{-8}	6.77 x 10^{-8}
65	0.3	2.16 x 10^{-7}	3.86 x 10^{-8}	1.78 x 10^{-7}	8.28 x10^{-8}
75	1.7	1.223 x 10^{-6}	8.21 x 10^{-8}	1.14 x 10^{-6}	3.06 x 10^{-7}
85	13.2	9.51 x 10^{-6}	7.22 x 10^{-8}	9.44 x 10^{-6}	8.26 x 10^{-7}
Total			7.57 x 10^{-7}	1.09 x 10^{-5}	1.49 x 10^{-6}

[a] Mean values for fracture spacing are used.
[b] The fracture apertures are uniform and equal to 89 microns.

Table E-2

Fracture Hydraulic Conductivity Calculations High Frequency for Low-Angled Fractures[a,b]

Orientation (Degrees)	Fracture Frequency (m^{-1})	Equivalent Conductivity (m/s)	Kxx	Kyy	Kxy
5	0.5	3.60×10^{-7}	3.58×10^{-7}	2.74×10^{-9}	3.13×10^{-8}
15	0.6	4.32×10^{-7}	4.03×10^{-7}	2.90×10^{-8}	1.08×10^{-7}
25	0.6	4.32×10^{-7}	3.55×10^{-7}	7.72×10^{8}	1.66×10^{-7}
35	0.3	2.16×10^{-7}	1.45×10^{-7}	7.11×10^{-8}	1.02×10^{-7}
45	0.4	2.88×10^{-7}	1.44×10^{-7}	1.44×10^{-7}	1.44×10^{-7}
55	0.5	3.60×10^{-7}	1.19×10^{-7}	2.42×10^{-7}	1.69×10^{-7}
65	0.1	7.21×10^{-7}	1.29×10^{-8}	5.92×10^{-8}	2.76×10^{-8}
75	0.7	5.05×10^{-7}	3.38×10^{-8}	4.71×10^{-7}	1.26×10^{-7}
85	2.5	1.80×10^{-6}	1.37×10^{-8}	1.79×10^{-6}	1.56×10^{-7}
Total			1.58×10^{-6}	2.88×10^{-6}	1.03×10^{-6}

[a] Mean values for fracture spacing are used.

[b] The fracture apertures are uniform and equal to 89 microns.

APPENDIX F
SATURATION OF ALLUVIUM

Appendix F

Saturation of Alluvium

A simple method for calculating vertical infiltration is the Green and Ampt solution (Hillel, 1971), which gives good results for cases of infiltration into an initially dry soil. Green and Ampt's solution makes several principal assumptions: (1) the wetting is distinct and precisely definable, (2) the matrix suction at the wetting front remains effectively constant despite time and position, and (3) the soil behind the wetting front is uniformly wet and of constant conductivity. The wetting-front plane separates a uniformly wetted zone from a dry zone. With gravity considered (i.e., vertical infiltration), the Green and Ampt solution gives the following:

$$t = \frac{\left(L_f - \left(H_p - H_f\right) \ln \left(1 + \frac{L_f}{H_p - H_f} \right) \right) \Delta\theta}{K_B}$$

where

K_B = Saturated hydraulic conductivity of the alluvium (m/s)
t = Time(s)
$\Delta\theta$ = Change in moisture content ($\theta_f - \theta_i$)
θ_f = Transmissive-zone, volumetric water content
θ_i = Initial water content
L_f = Distance from the surface to the wetting front (i.e., length of the wetted zone [m])
H_P = Pressure head at the entry surface (m)
H_f = Initial pressure head at the wetting front (m).

The initial pressure at the wetting front is determined from the initial moisture content and the suction properties of the soil. The soil properties used include the Van Genuchten curve-fit parameters used widely for predicting soil water content as a function of pressure head. Carsel and Parrish (1988) express the Van Genuchten model as follows:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n \right)^m}$$

where

θ_r = Residual water content
θ_s = Saturated water content
h = Capillary head

α = Van Genuchten curve-fit parameter
n = Van Genuchten curve-fit parameter
m = $1-1/n$ = Van Genuchten curve-fit parameter.

The volumetric water-content logs performed in neutron access holes in Coyote Wash determine the initial saturation and show several alternating wet and dry zones. Hillel (1982) presents the concept of field capacity as the property that distinguishes between wet and dry zones as 1/3 to 1/10 bars matrix suction potential. According to Dane and Wierenga (1975), for a material that is similar in physical characteristics to the alluvium, this point occurs at approximately 5 percent volumetric moisture content. This value was selected, and the weighted averages of saturation determined over three layers. The results of the analysis show a wet top layer 2 ft thick with an approximate degree of saturation of 24 percent, a dry layer approximately 4 ft thick with a degree of saturation of 8 percent, and a wet bottom layer 15 ft thick with a degree of saturation of 18 percent. The weighted average saturation for the three layers is approximately 20 percent. A subsequent calculation assumes that the saturation is higher at 70 percent.

The soil properties determine the initial suction potential in the Green and Ampt solution. To provide a range of conditions, properties for a clay loam, loamy sand, and sand (reported by Carsel and Parrish [1988]) are presented.

	Sand (%)	Clay (%)	θ_s	θ_r	K (cm/s)	Alpha $(cm)^{-1}$	n
Clay Loam	29.8	32.6	.41	.095	$7x10^{-5}$	.019	1.31
Sand	42.7	2.9	.43	.045	$8x10^{-3}$	.145	2.68
Loamy Sand	80.9	6.4	.41	.057	$4x10^{-3}$	.124	2.28

Using the Van Genuchten relationships for different types of soils (Figure F-1), the initial suction potential corresponding to the saturations were selected. The height of the water at ground surface varies from 0.1 m, which might correspond to an upper bound for sheet flow. A value of 1.0 m more adequately represents flow in the arroyos.

Limited information exists on the thickness of the alluvium at borehole locations. The following information was derived from several core logs in the northwestern portion of the potential repository and reflects alluvial thicknesses in areas where the east-west trending streams fan out.

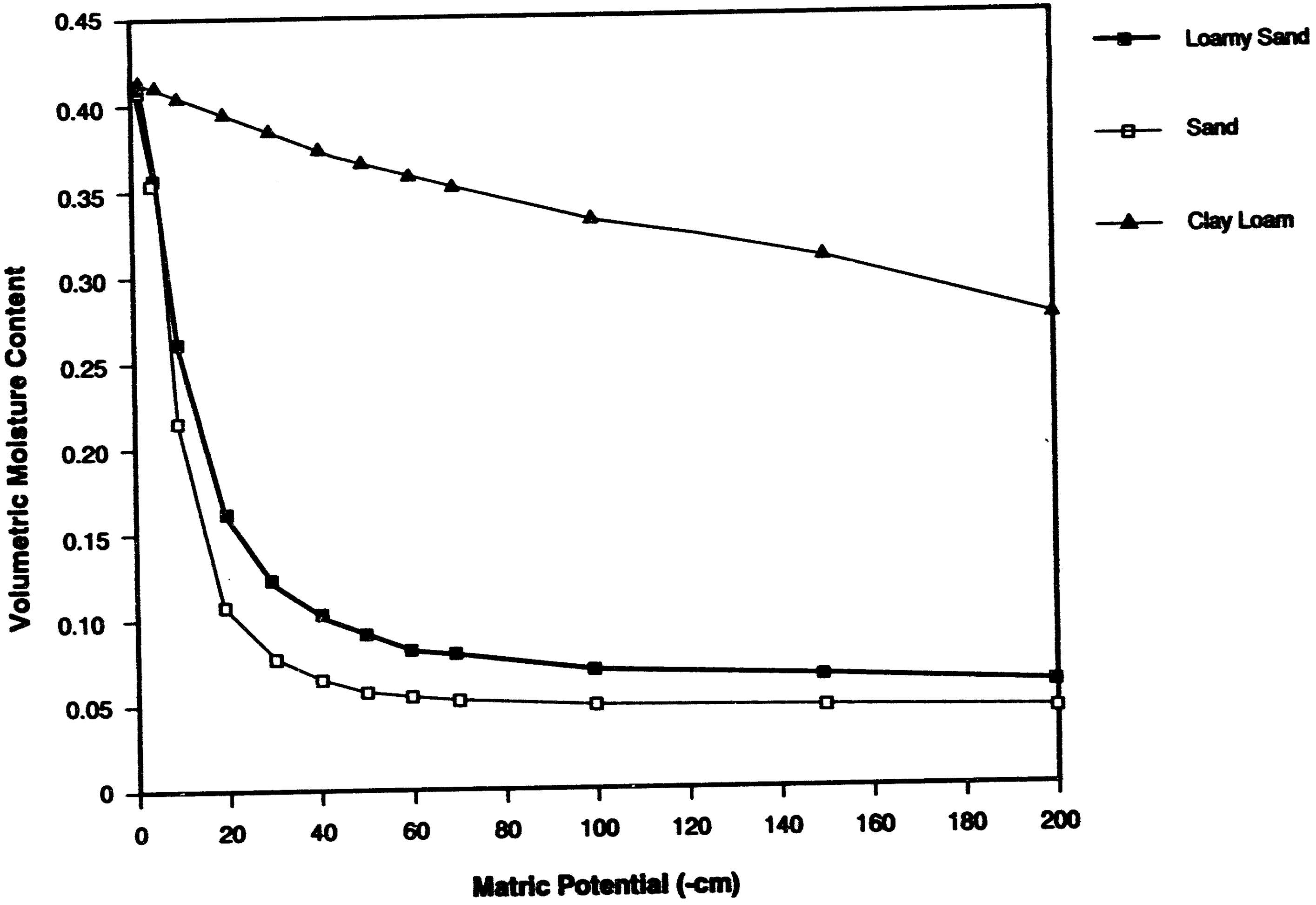


Figure F-1
Volumetric Moisture Content vs. Matric Potential

Borehole	Thickness (m)
UE 25 A#4	9.1
UE 25 A#5	27.4
UE 25 A#6	6.1
UE 25 A#7	46.6
USW G-1	18.3
USW G-4	9.1

UE 25 A#7 is northwest of the potential repository in Drillhole Wash, while USW G-4 is at a higher elevation at the confluence of two smaller washes. The alluvial thickness, approximately 50 m, is typical outside the potential repository boundary, while 10 m is more typical of the four washes traversing the potential repository. Using several additional neutron holes and boreholes UE 25 A#5, UE 25 A#6, and USW G-4, an approximate profile of the alluvium across the wash can be constructed. The bedrock outcrops in steeper terrain, while the alluvium is thicker in flat areas, as would be expected of alluvial fan areas. This observation allows for the development of a linear relationship between alluvial thickness and slope.

The analysis results are expressed as the time for the infiltration front to move a vertical distance as illustrated in Figures F-2a through F-3b. These analyses were performed for the sand and the clay, considering depths of flow ranging from 10 to 100 cm, with initial moisture contents ranging from 20 to 70 percent. The results indicate that the time required for penetration of 10 m is on the order of 5 to 10 hr for sand and 100 to 300 hr for the clay loam. Given the general duration of storms of the order of 10 to 20 hrs, the results show that sandy alluvial areas would saturate during the flooding event, which would result in potential perched water in boreholes. This is much less likely for finer-grained soils.

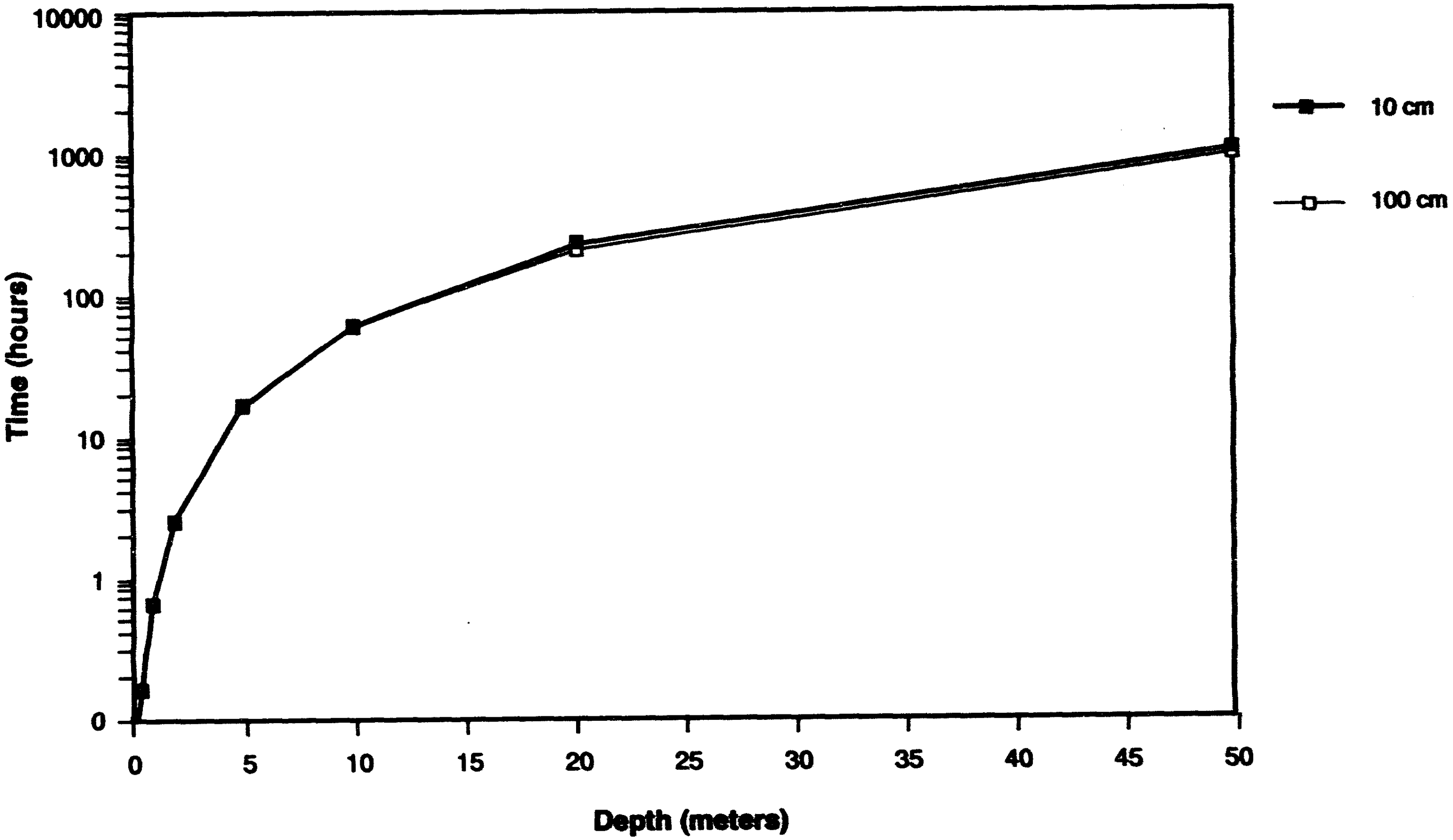


Figure F-2a
Saturation Front Travel Time
(a) Clay Loam, Low Initial Saturation (0.20) and
(b) Clay Loam, High Initial Saturation (0.70)

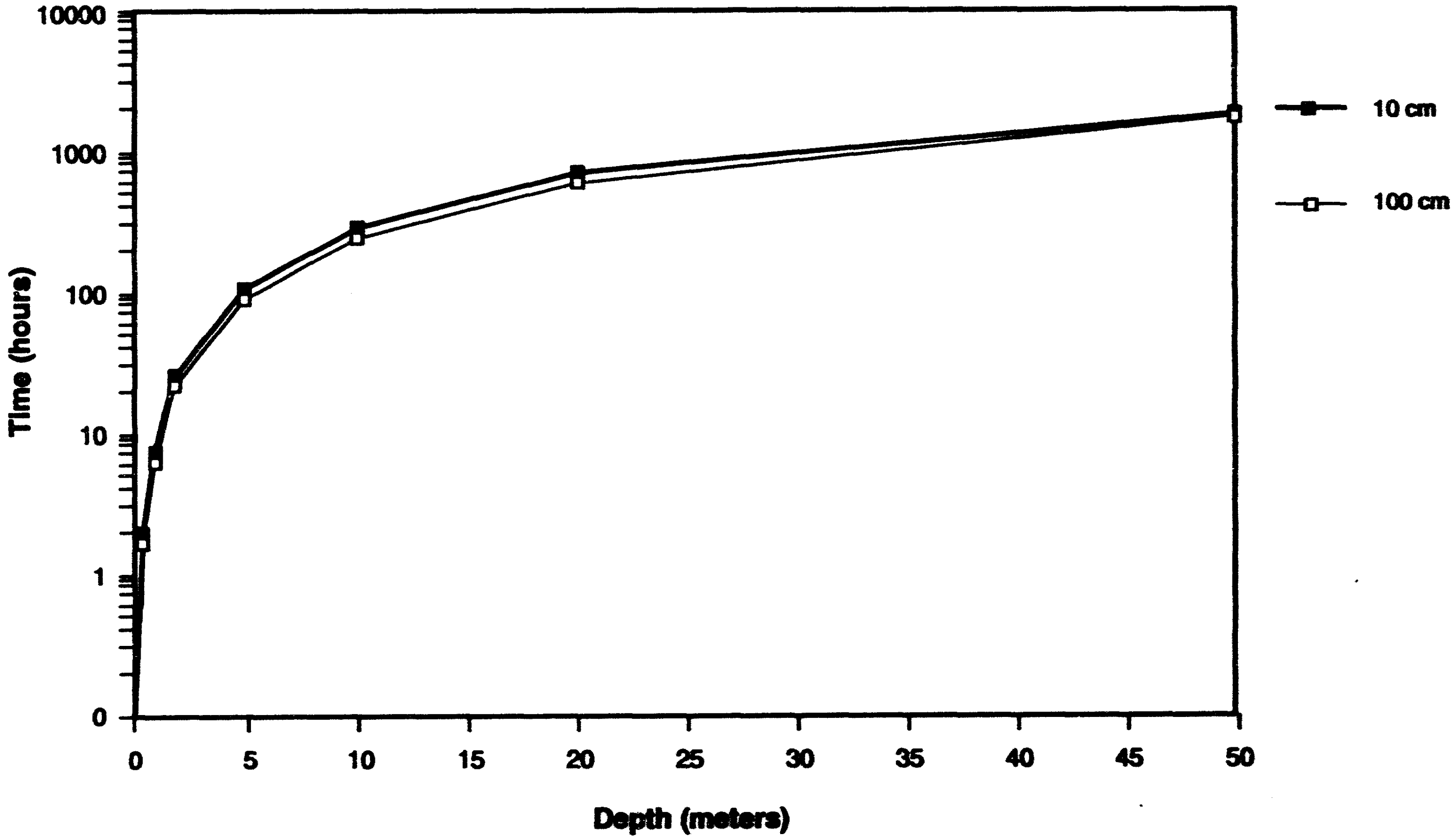


Figure F-2b
Saturation Front Travel Time
(a) Clay Loam, Low Initial Saturation (0.20) and
(b) Clay Loam, High Initial Saturation (0.70)

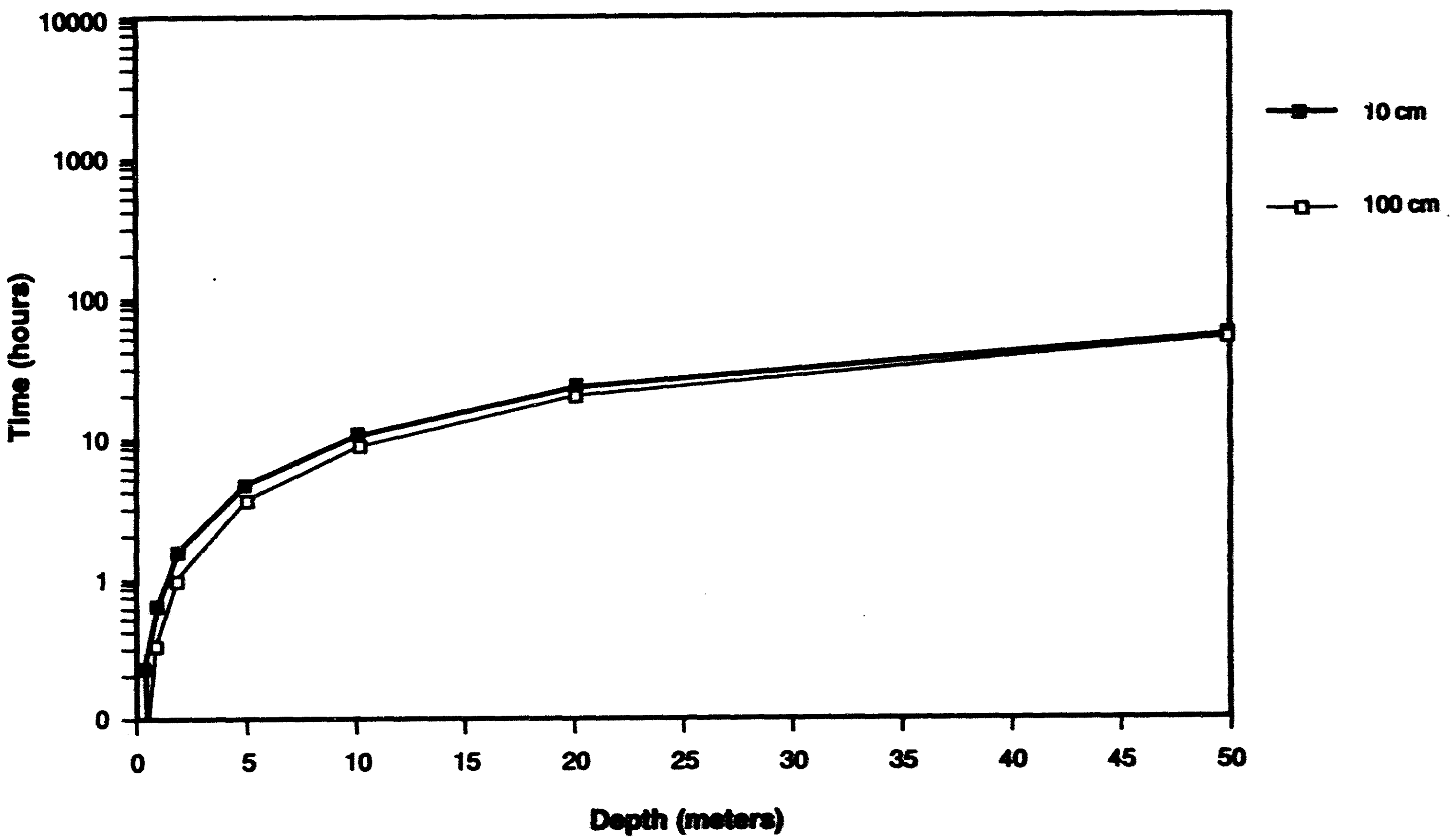


Figure F-3a
Saturation Front Travel Time
(a) Sand, Low Initial Saturation (0.20) and
(b) Sand, High Initial Saturation (0.70)

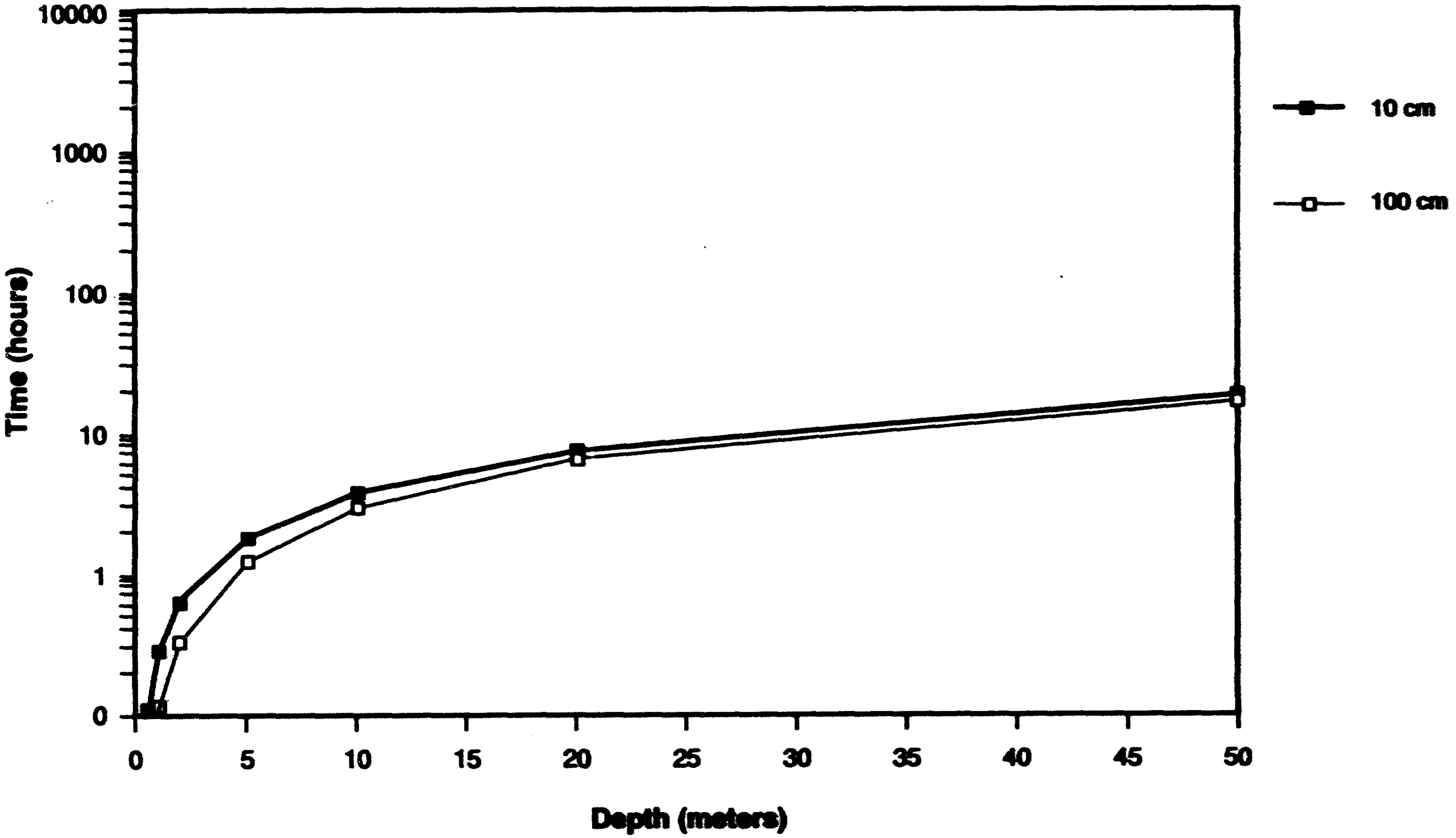


Figure F-3b
Saturation Front Travel Time
(a) Sand Low Initial Saturation (0.20) and
(b) Sand High Initial Saturation (0.70)

APPENDIX G

ADVECTION/DISPERSION ANALYSIS

Appendix G
Advection/Dispersion Analysis

This appendix presents the solution for the advection/dispersion relation for contaminant transport presented in Chapter 4.0 of this report. The potential repository can be modeled as a single-line source that is perpendicular to the flow direction and approximately the width of the potential repository (2a). If the concentration of the solute diminishes exponentially with time, the initial and boundary conditions for the model can be written as follows:

$$C(0,y,t) = C_o\, e^{-\alpha t} \qquad -a \leq y \leq a$$

and for other values of y:

$$C(0,y,t) = 0$$

$$\lim_{y \to \pm\infty} \frac{\partial C}{\partial y} = 0$$

$$\lim_{x \to \infty} \frac{\partial C}{\partial x} = 0 \; .$$

Javandel et al. (1984) presented the following analytical solution to this problem:

$$C(x,y,t) = \frac{C_o x}{4(\pi D_L)^{1/2}} \exp\left(\frac{vx}{2D_L} - \alpha t\right)$$

$$\cdot \int_0^{t/r} \exp\left[-\left(\lambda R - \alpha R + \frac{v^2}{4D_L}\right)\tau - \frac{x^2}{4D_L \tau}\right] \tau^{-3/2}$$

$$\cdot \left[\operatorname{erf}\left(\frac{a - y}{2(D_T \tau)^{1/2}}\right) + \operatorname{erf}\left(\frac{a + y}{2(D_T \tau)^{1/2}}\right)\right] d\tau$$

where

C_o = Initial concentration

α = Decay constant for concentration

x, y = Spatial coordinates
r = Retardation
t = Time
τ = Variable for integration
a = Repository half width
D_L = $D^* + \alpha_L v$
D_T = $D^* + \alpha_T v$.
α_L, α_T = longitudinal and transverse dynamic dispersivities
D^* = the coefficient of molecular diffusion.

As pointed out by Freeze and Cherry (1979), nearly all studies of dispersion have involved relatively homogeneous sandy materials under controlled laboratory conditions. Values of α_L are typically 0.1 to 10 mm, with α_T values normally lower by a factor of 5 to 20. In field systems, the α_L and α_T are significantly larger. Values of α_L as large as 100 m and values of α_T as large as 50 m have been used in mathematical simulation studies of large contaminant plumes in sandy aquifers. Also, Ghislain de Marsily (1979) summarized several studies. In one study the α_L and α_T (field scale) were reported as 30 and 20 m, respectively, for an accidental tritium release at Hanford. In a second case, chlorides and tritium polluted an aquifer made up of fractured basalt and interlayered sedimentary deposits. The model used fitted well with α_L and α_T values of 91 and 137 m, respectively. In the third case cited, a tracer experiment with tritium in 150-m-thick fractured rock, the α_L was quoted as 150 m. While these values are associated with hydrodynamic dispersion of contaminated plumes in a saturated fractured rock environment, the authors feel that these field values of α are more appropriate to use than those reported in laboratory-scale studies. Further, because of the uncertainty in the dispersive nature of the fractured tuff, variations in α_L and α_T are assumed. To maximize dispersion, the α_L and α_T values are assumed to be 100 m. In other cases evaluated, the α_L is fixed at 100 m, while the α_T is reduced to 1 m. Given the anisotropic nature of the welded tuffs (i.e., the low permeability of the matrix and the predominance of fractures), the latter set of assumptions may be more reflective of the actual dispersive nature of the rock.

The hydrodynamic dispersion coefficients were calculated from the average linear velocity. The velocity values were computed using the following formula:

$$T = \frac{\sum_{i=1}^{3} n_i L_i \sum_{i=1}^{3} \frac{L_i}{K_i}}{G * L}$$

where

n_i = Porosities of the ith unit

G = Gradient for airflow
L = Total flow path length
L_i = Flow path length of the ith component
K_i = Hydraulic conductivity of the ith component
T = Total travel time through the stratigraphic column, and the other parameters are as defined previously.

The average linear velocity was computed using the relationship:

$$J = \frac{L}{T} .$$

Note that while three discrete values for average linear velocity are used, the selection of the three models also reflects a broad range in velocities.

The results of the analyses are a series of concentration profiles at various times (Figures G-1 through G-12).

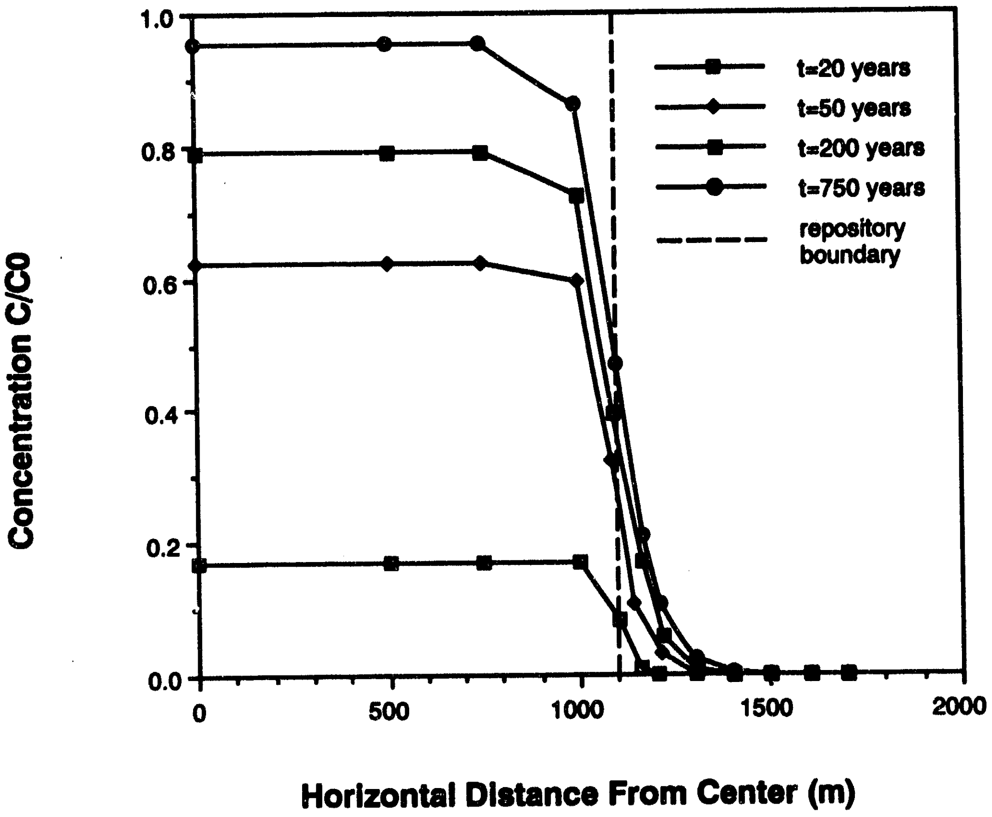


Figure G-1
Concentration Versus Distance at Various Times at a Vertical Distance of 60 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = .37 m/year for Model 1) (Note that the potential repository half width is 1,100 m.)

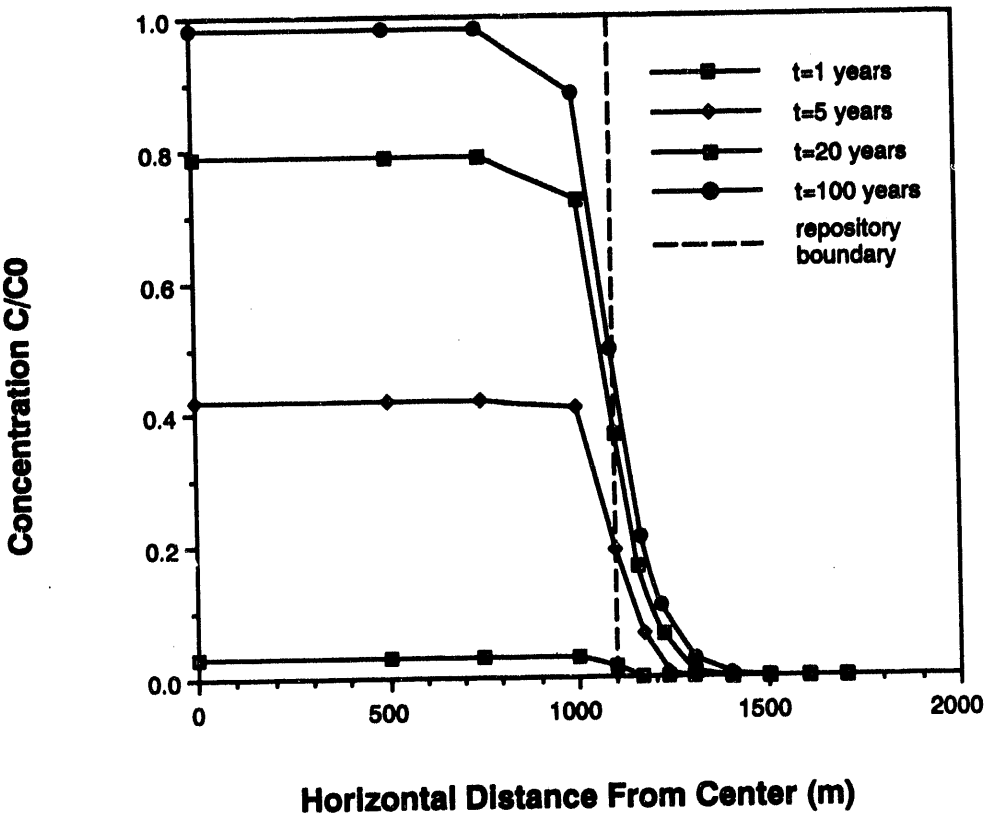


Figure G-2
Concentration Versus Distance at Various Times at a Vertical Distance of 60 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = 3.7 m/year for Model 2)
(Note that the potential repository half width is 1,100 m.)

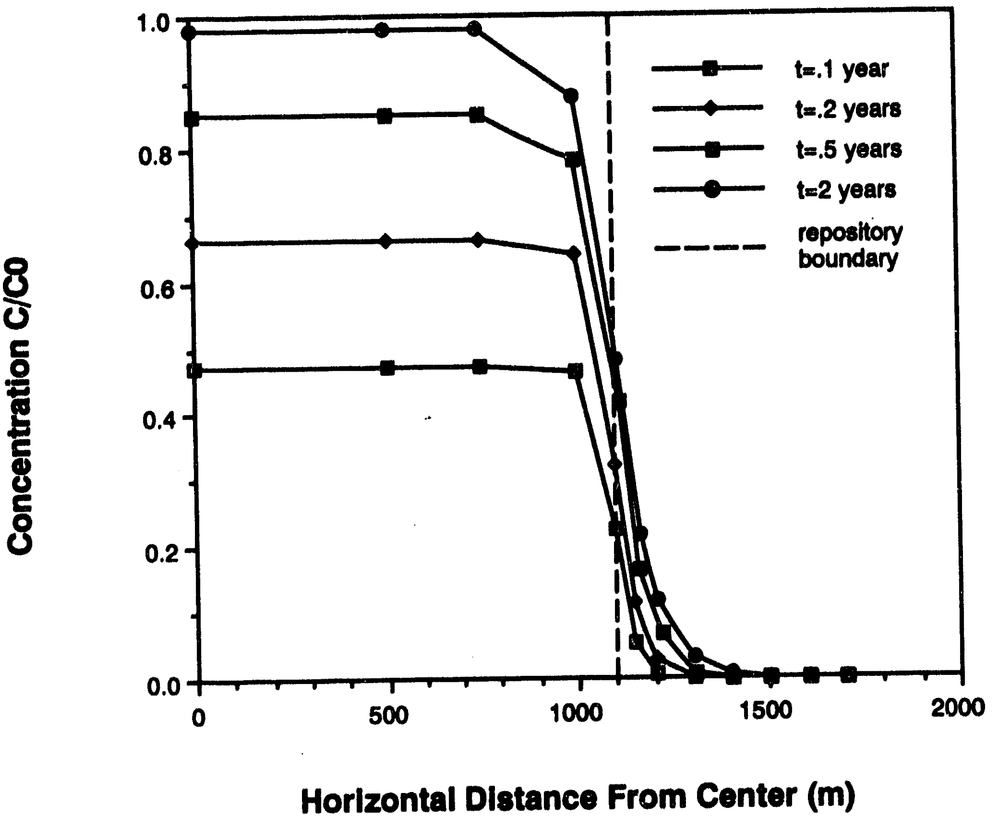


Figure G-3
Concentration Versus Distance at Various Times at a Vertical Distance of 60 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = 210 m/year for Model 3)
(Note that the potential repository half width is 1,100 m.)

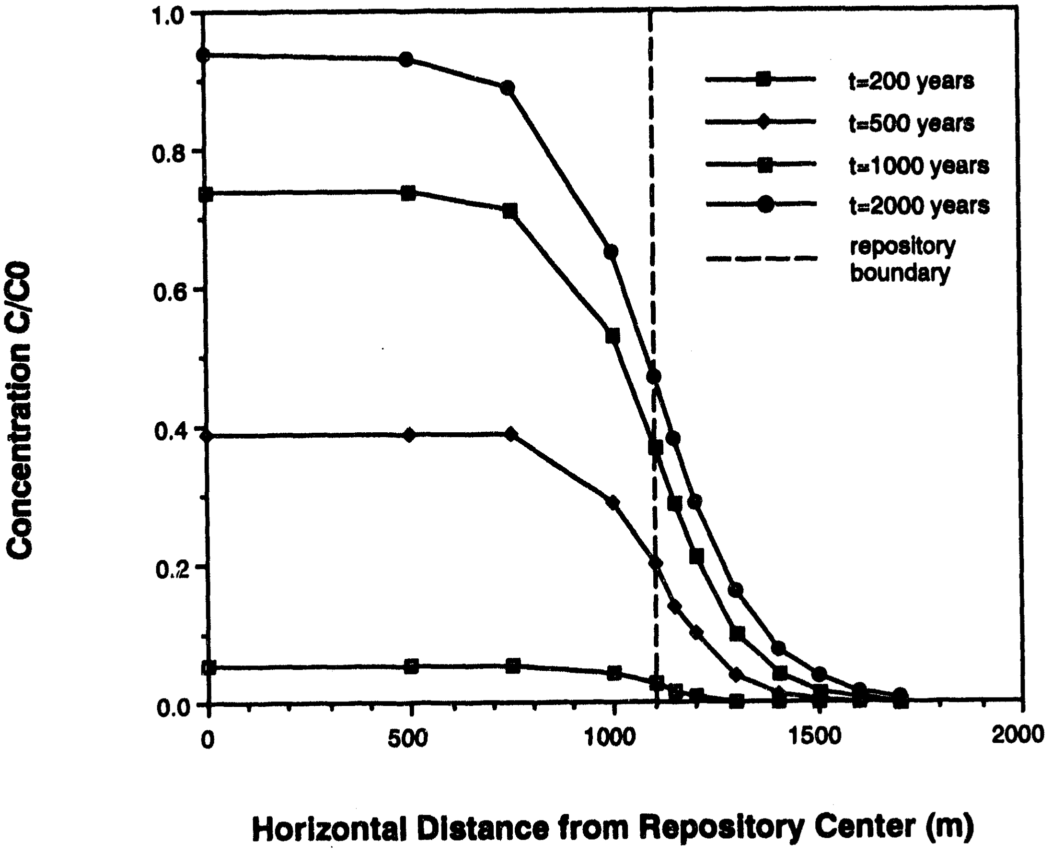


Figure G-4
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = 0.37 m/year for Model 1) (Note that the potential repository half width is 1,100 m.)

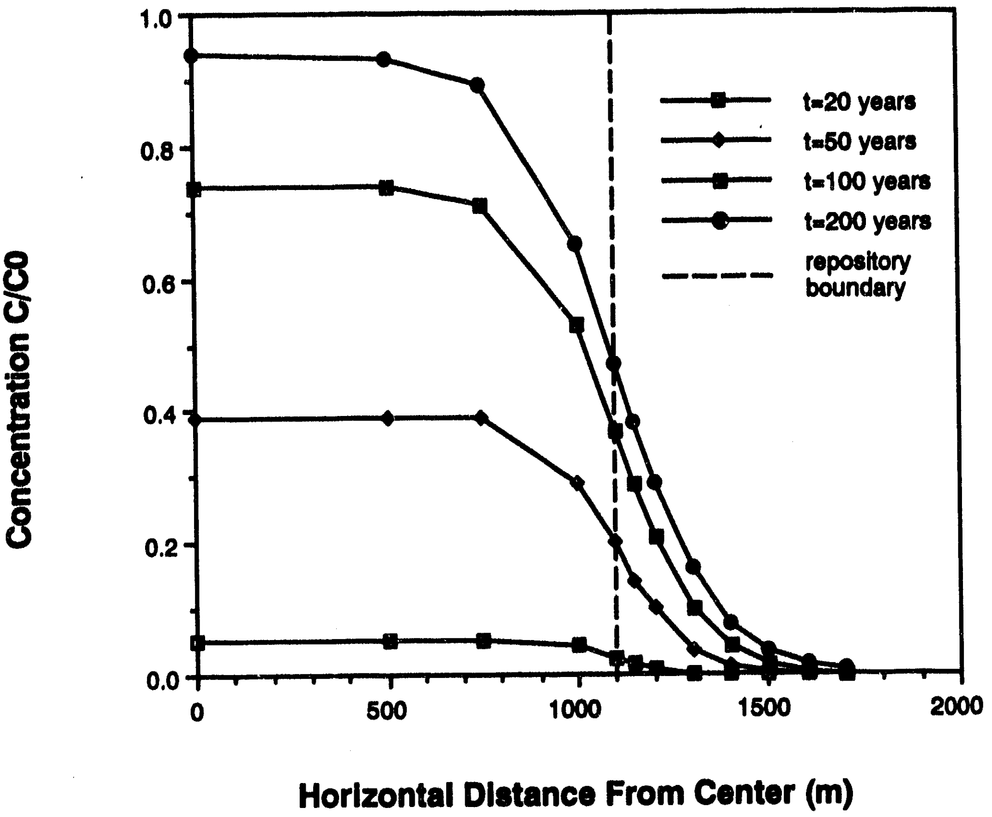


Figure G-5
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = 0.37 m/year for Model 2) (Note that the potential repository half width is 1,100 m.)

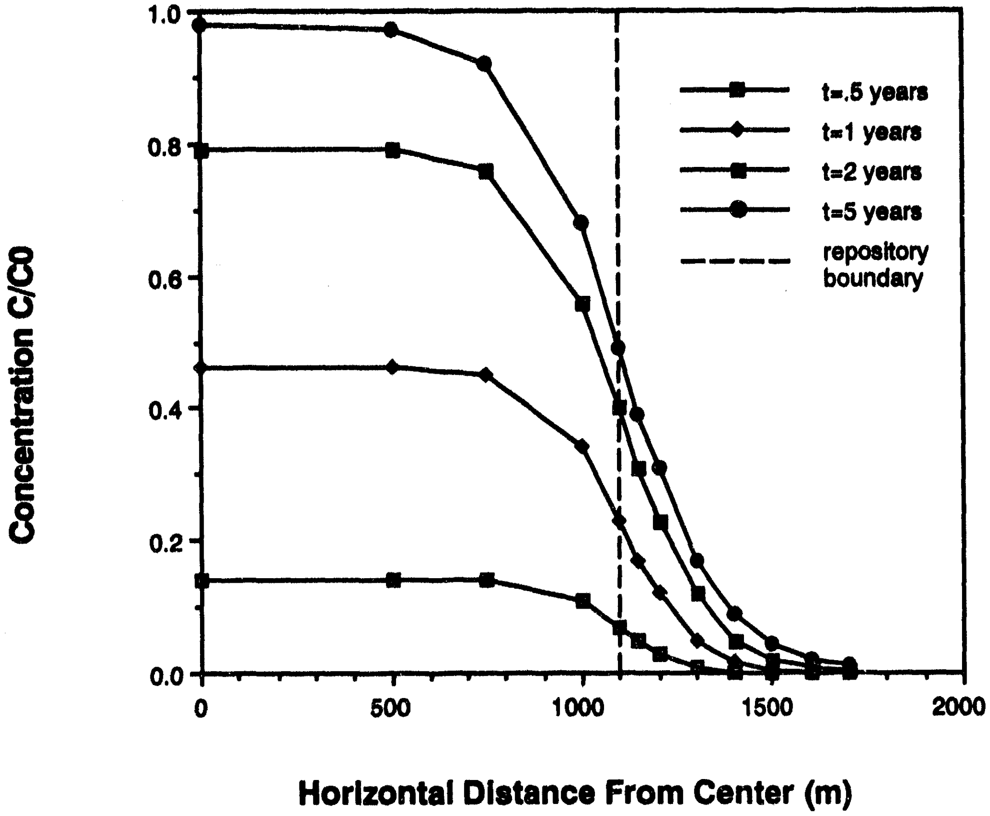


Figure G-6
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 100 m, Fluid Velocity = 210 m/year for Model 3) (Note that the potential repository half width is 1,100 m.)

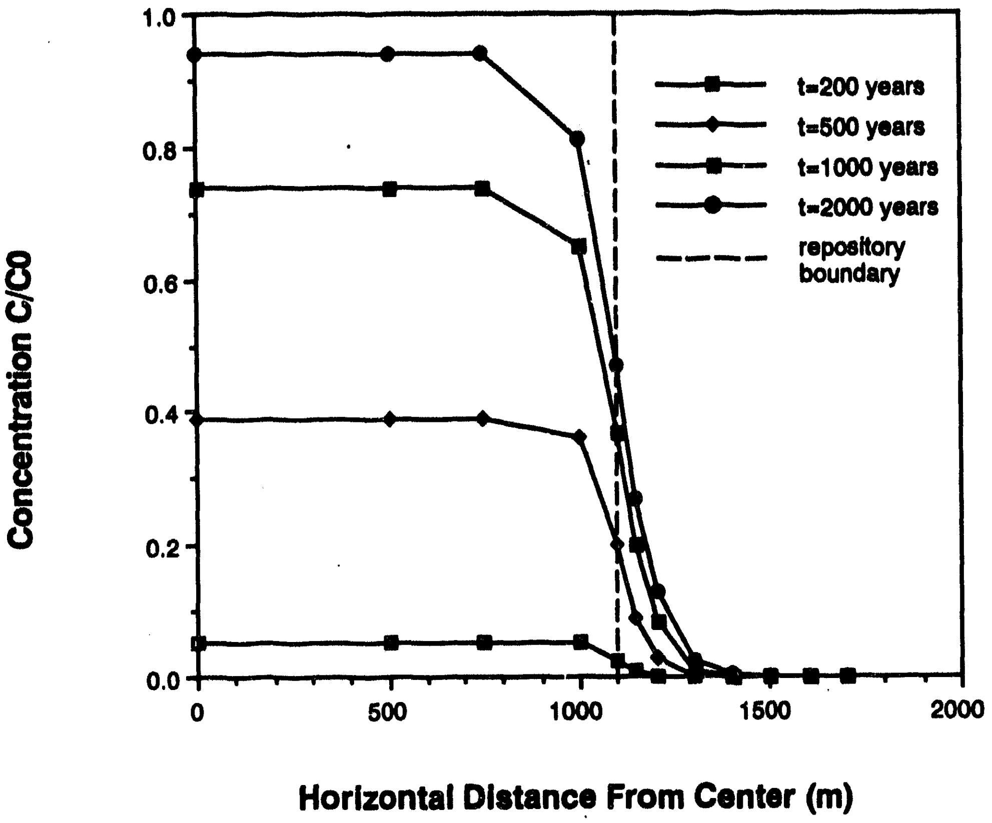


Figure G-7
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 20 m, Fluid Velocity = 0.37 m/year for Model 1) (Note that the potential repository half width is 1,100 m.)

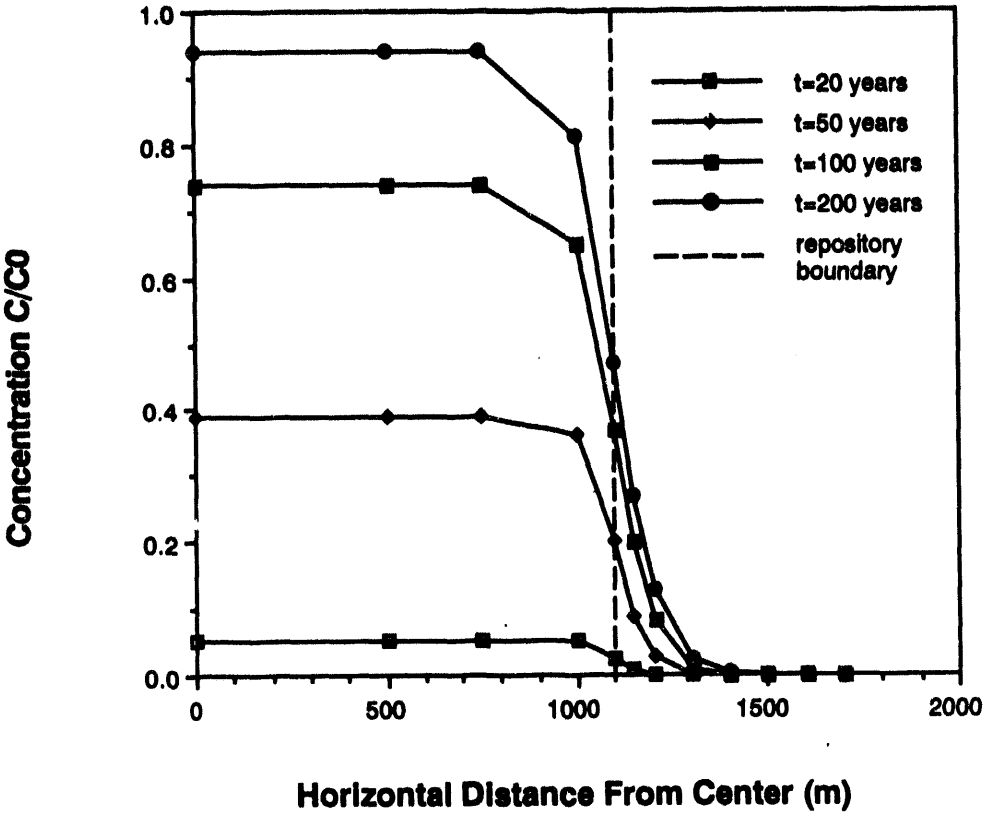


Figure G-8
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 20 m, Fluid Velocity = 3.7 m/year for Model 2) (Note that the potential repository half width is 1,100 m.)

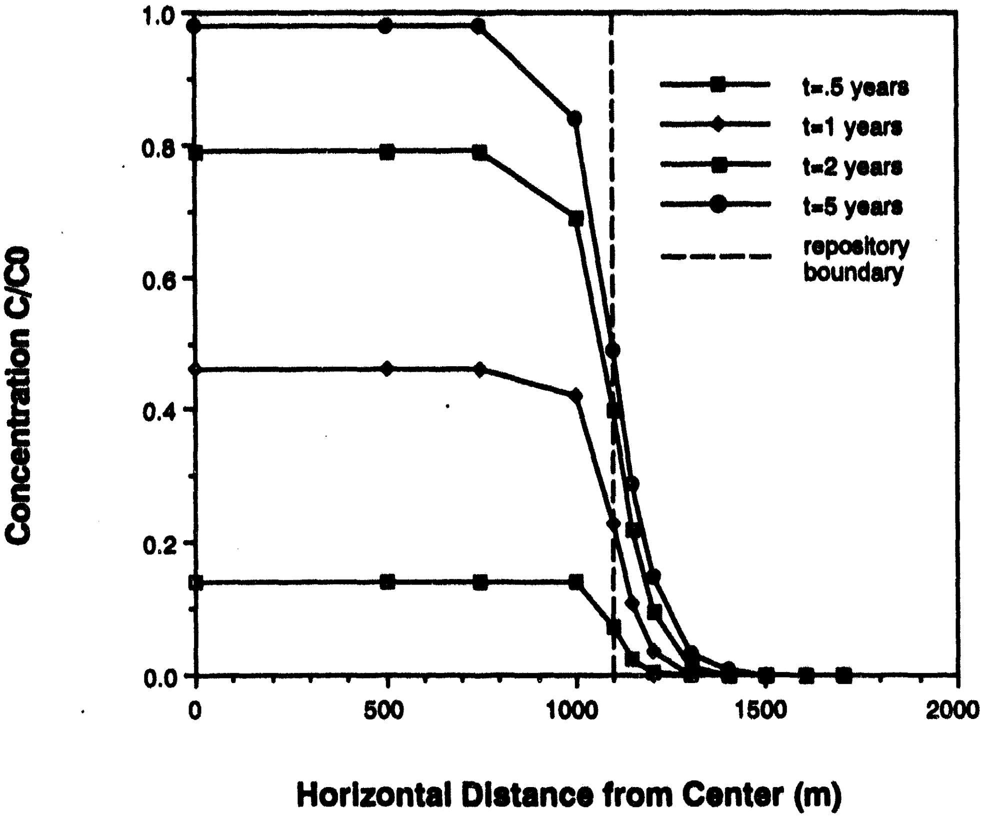


Figure G-9
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 20 m, Fluid Velocity = 210 m/year for Model 3) (Note that the potential repository half width is 1,100 m.)

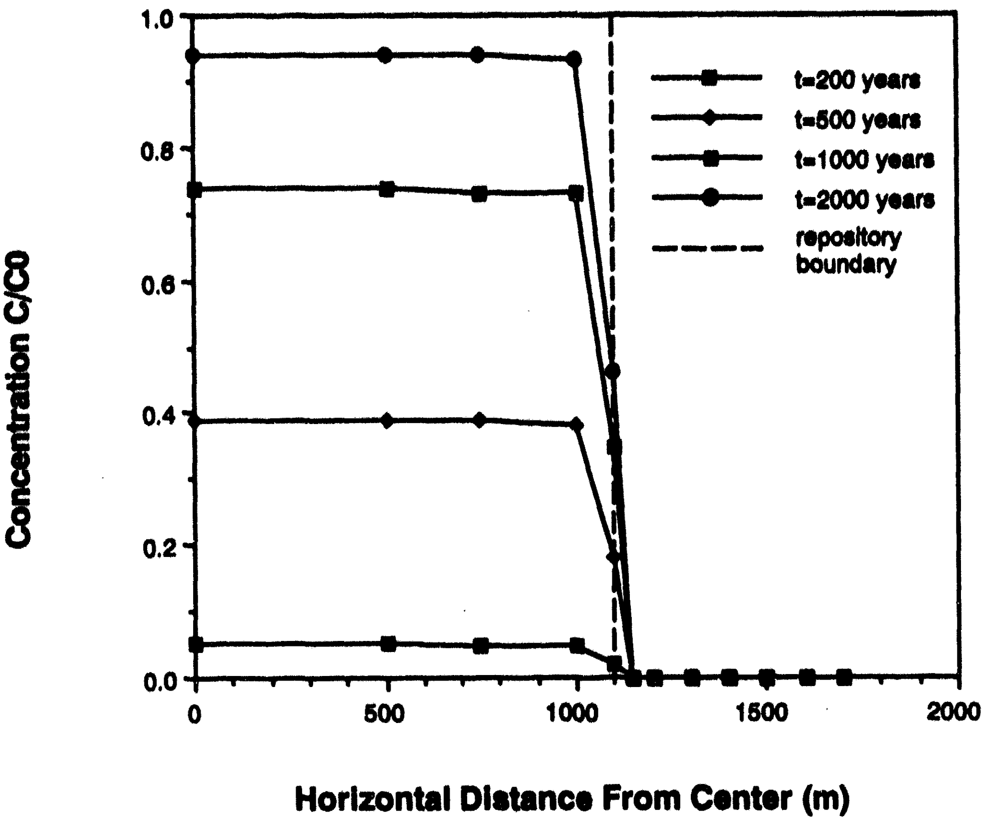


Figure G-10
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 1 m, Fluid Velocity = 0.37 m/year for Model 1)
(Note that the potential repository half width is 1,100 m.)

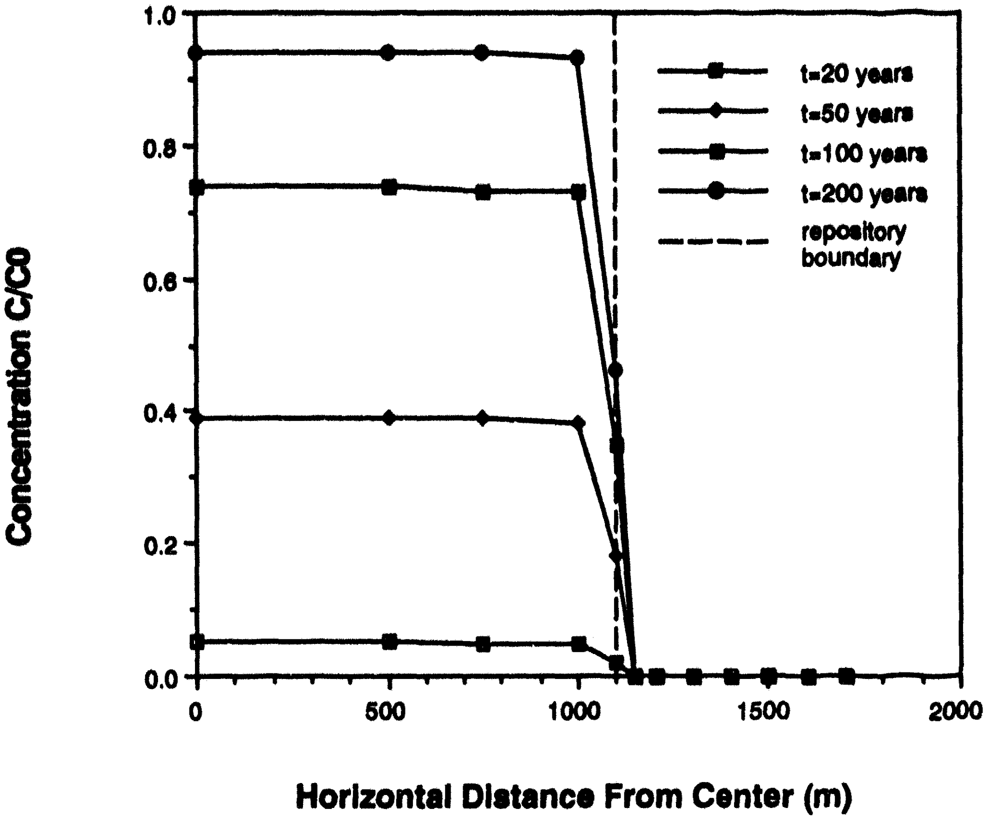


Figure G-11
Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 1 m, Fluid Velocity = 3.7 m/year for Model 2)
(Note that the potential repository half width is 1,100 m.)

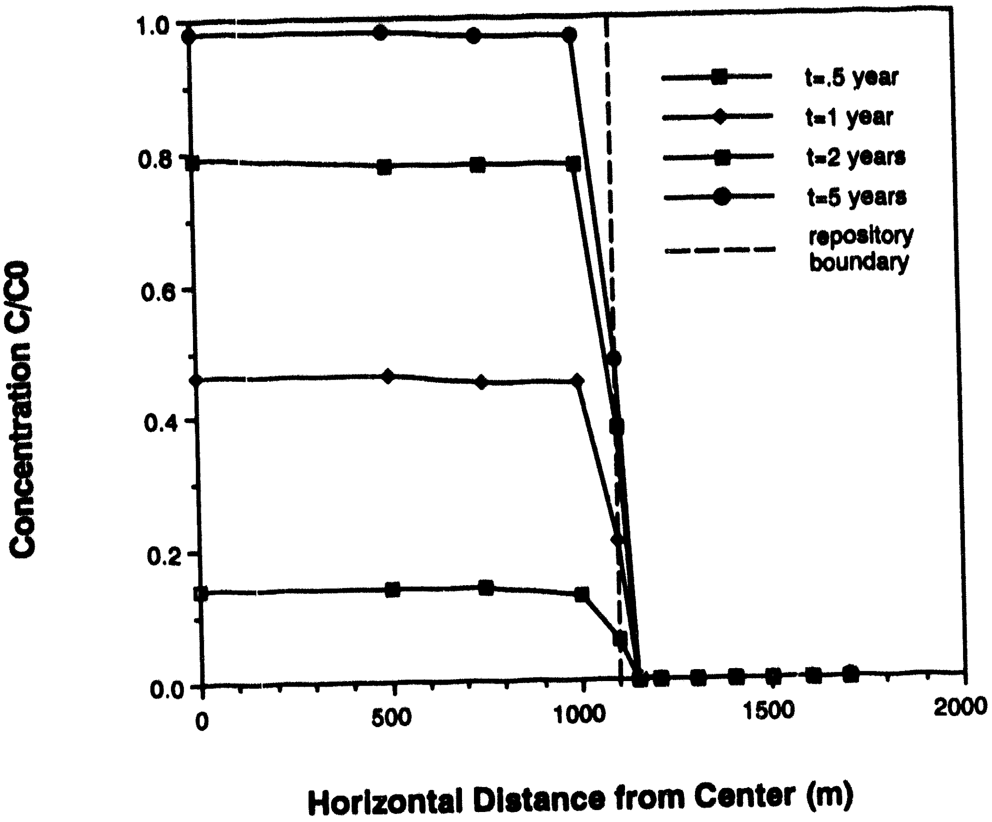


Figure G-12

Concentration Versus Distance at Various Times at a Vertical Distance of 300 m (Longitudinal Dispersivity = 100 m, Transverse Dispersivity = 1 m, Fluid Velocity = 210 m/year for Model 3) *(Note that the potential repository half width is 1,100 m.)*

APPENDIX H

AIRFLOW PERFORMANCE REQUIREMENTS AND THE SIGNIFICANCE OF BOREHOLES

Appendix H

Airflow Performance Requirements and the Significance of Boreholes

This appendix presents a calculation to assess the relative significance between shallow and deep boreholes. In Figure H-1, boreholes are illustrated that are sealed using the same seal material for both deep and shallow boreholes. The seal material equivalent vertical conductivity satisfies the relationship.

$$.01(d*c_x)*\ A*\ i\ =\sum_{i=1}^{n}(K_b*A_b)i \qquad \text{(H-1)}$$

where

d = Mean depth of potential repository to the ground surface
c_x = Mean conductance of the rock model
K_b = Equivalent vertical conductivity of the backfill
A_b = Cross-sectional area of boreholes near the surface depth
A = Area of the repository
i = Airflow gradient.

The equivalent conductivity for airflow may be expressed for series flow as

$$\frac{t}{K_b}=\left[\sum_{i=1}^{n}\left(\frac{t_i}{K_i}\right)\right]+\frac{t_s}{K_s} \qquad \text{(H-2)}$$

t = Depth of ground surface to the potential repository horizon
t_i = Thickness of the ith unit not penetrated by the borehole
t_s = Depth of the seal
K_i = Rock conductivity of the ith unit not penetrated by the borehole
K_s = Seal conductivity.

The above relationship may be explained as follows. If the borehole is deep and intercepts the potential repository horizon then all units are penetrated and n = O and

$$\frac{t}{K_b}=\frac{t_s}{K_s} \qquad \text{(H-3)}$$

The effective seal conductivity equals the equivalent vertical conductivity. If the borehole is shallow then all units below are not penetrated and

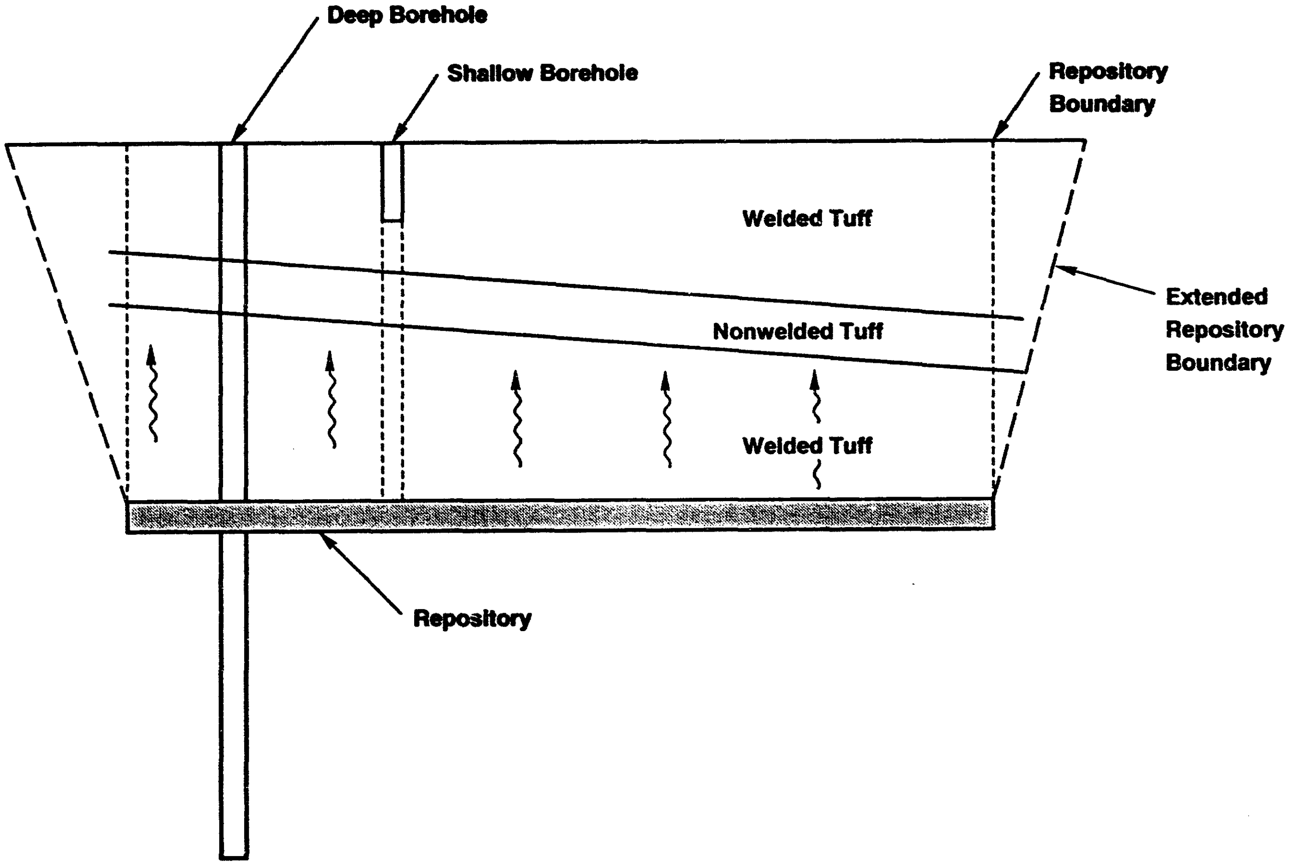


Figure H-1
Air Dispersion From the Repository

$$\frac{t}{K_b} = \frac{t_1}{K_1} + \frac{t_2}{K_2} + \frac{t_3}{K_3} + \frac{t_4}{K_4} + \frac{t_s}{K_s} \qquad \text{(H-4)}$$

Noting that for a borehole penetrating a shallow welded unit that if

$$K_1 < < K_s, K_2 < < K_s, K_3 < < K_s, K_4 < < K_s \qquad \text{(H-5)}$$

then

$$\frac{t_1}{K_1} > > \frac{t_s}{K_s}, \frac{t_2}{K_2} > > \frac{t_s}{K_s}, \frac{t_3}{K_3} > > \frac{t_s}{K_s}, \frac{t_4}{K_4} > > \frac{t_s}{K_s} \qquad \text{(H-6)}$$

if t_1, t_2, t_3, t_4 and t_s are comparable. The harmonic sum presented above is dominated by the term with the lowest conductivity, or flow resistance is dominantly through the rock where the seal conductivity is greater then the rock conductivity.

The flow rate through a shallow borehole would then be much less significant than the flow rate through a deep borehole. Table H-1 presents these calculations for each borehole for each of the three models. The conductance which is the product of K_b*A_b represents a "flow rate" that allows for comparison among the boreholes. In this table, the boreholes are sorted by borehole length.

The cumulative distribution of the "flow rate" for the 116 boreholes for each rock model is presented in Figures H-2 through H-4. The cumulative flow rate plotted as a function of borehole length for each model is illustrated in Figures H-5 through H-7. The flow rate is plotted on a "log" scale because the product K_b*A_b varies over several orders of magnitude. The results show that the "flow rates" for the shallow boreholes are much less significant than the deep boreholes by about five to six orders of magnitude. On each plot the performance requirement for each is shown for all boreholes that satisfies Equation H-1.

The calculations presented above allow for evaluation of a single borehole that is abandoned or left untreated. For purposes of evaluation, the existing UZ-6 borehole has the largest diameter at the potential repository horizon. Also, it should be considered that the effective hydraulic conductivity of an abandoned borehole equals 10 cm/s (equivalent to 0.4 meter per minute). This conductance can be compared to the cumulative conductance for the three models.

The relative significance depends on the rock model employed. For the low conductivity model (Model 1), a single abandoned borehole provides a greater conductance than 100 combined together (or 30 boreholes penetrating through the potential repository horizon). For Model 2, the

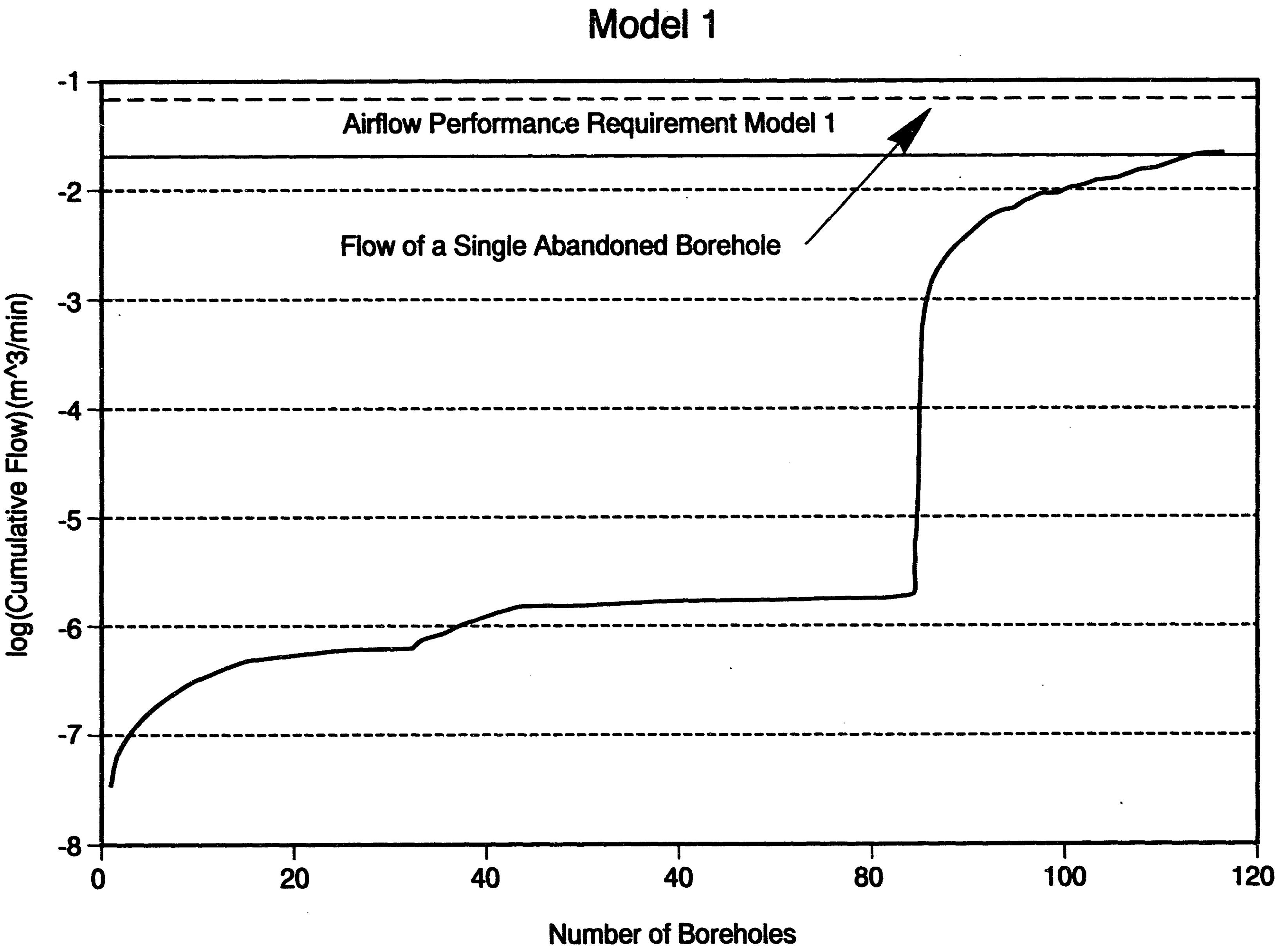


Figure H-2
Cumulative Flow for Model 1

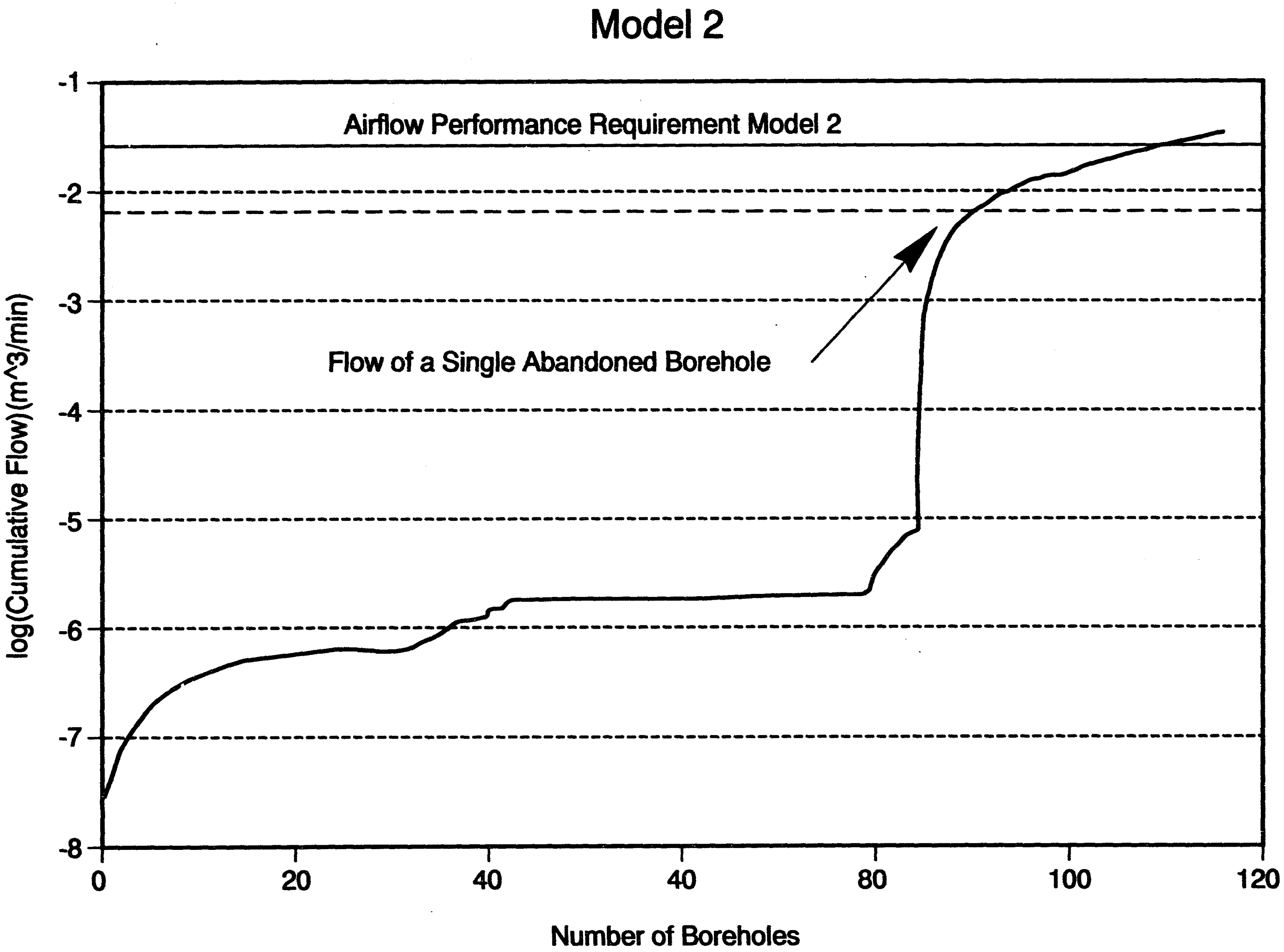


Figure H-3
Cumulative Flow for Model 2

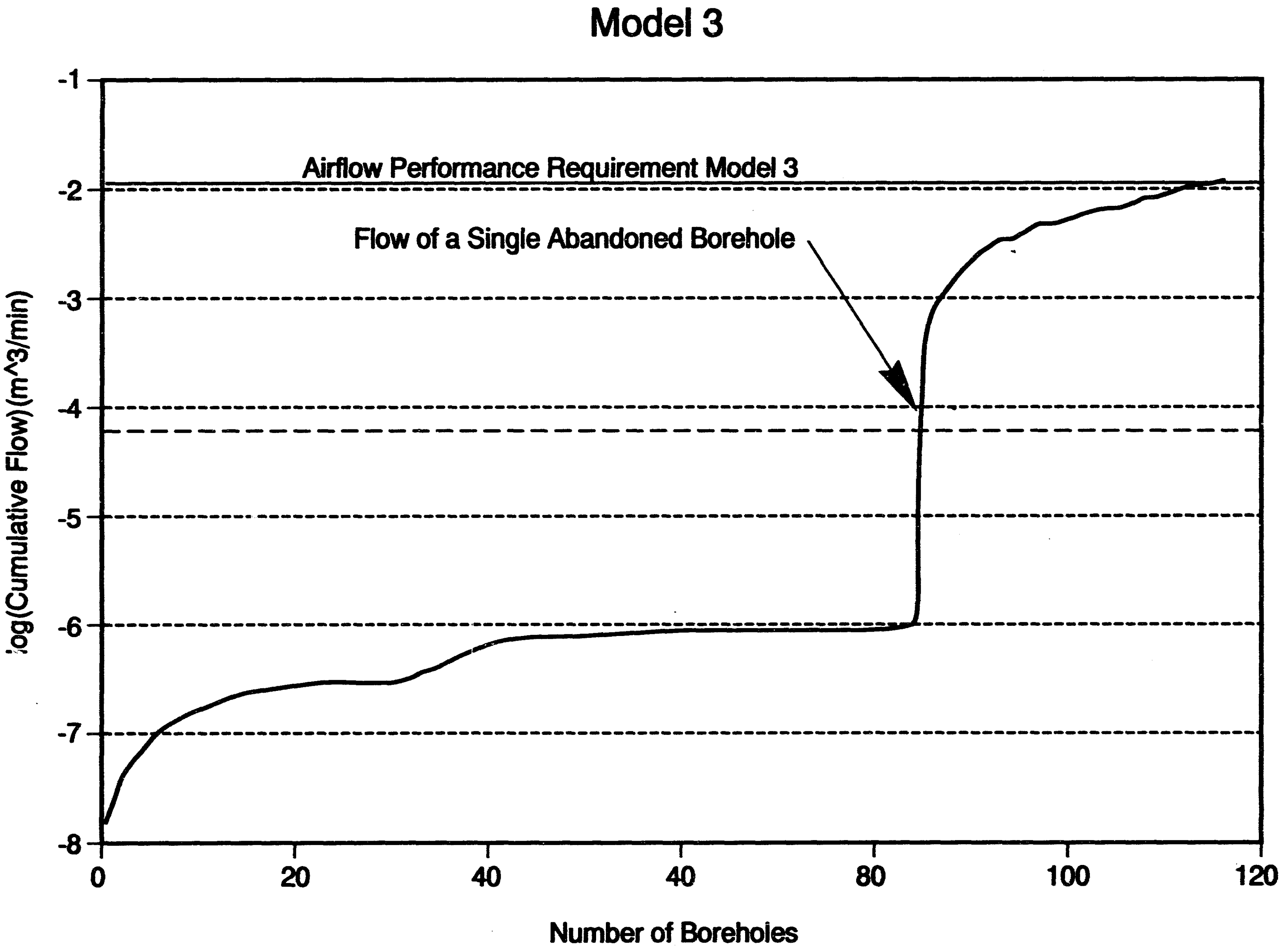


Figure H-4
Cumulative Flow for Model 3

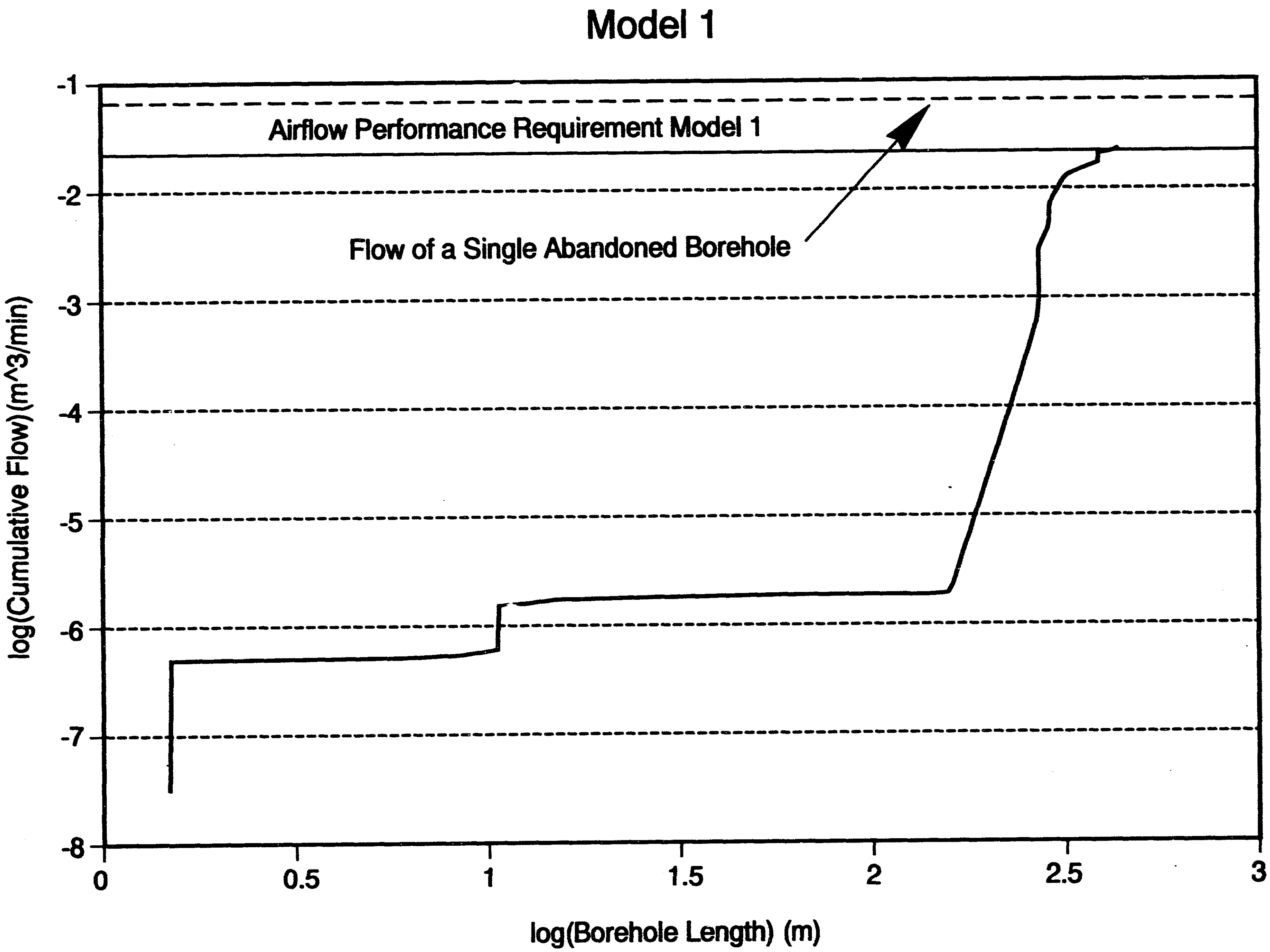


Figure H-5
Cumulative Flow Versus Borehole Length – Model 1

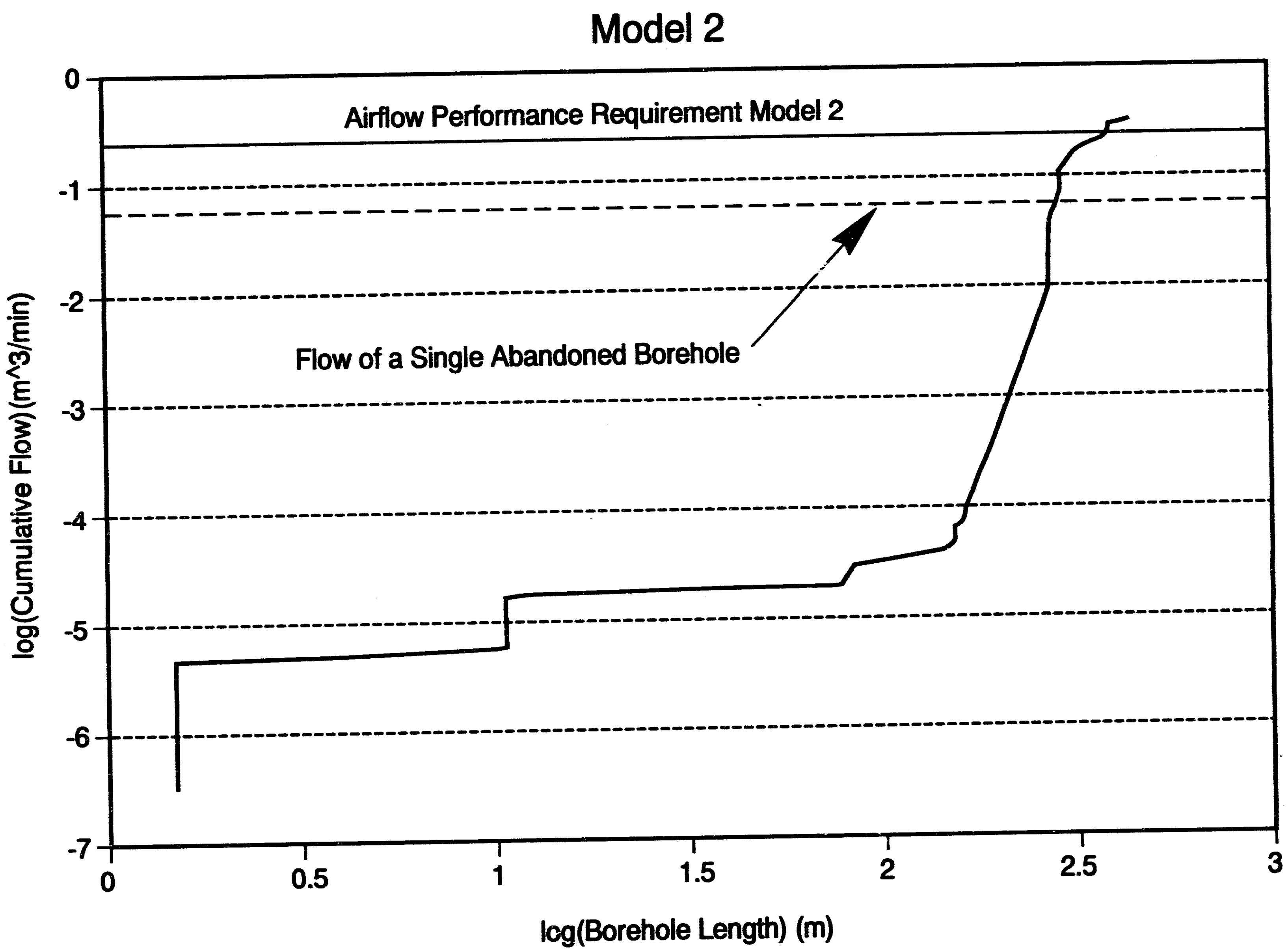


Figure H-6
Cumulative Flow Versus Borehole Length – Model 2

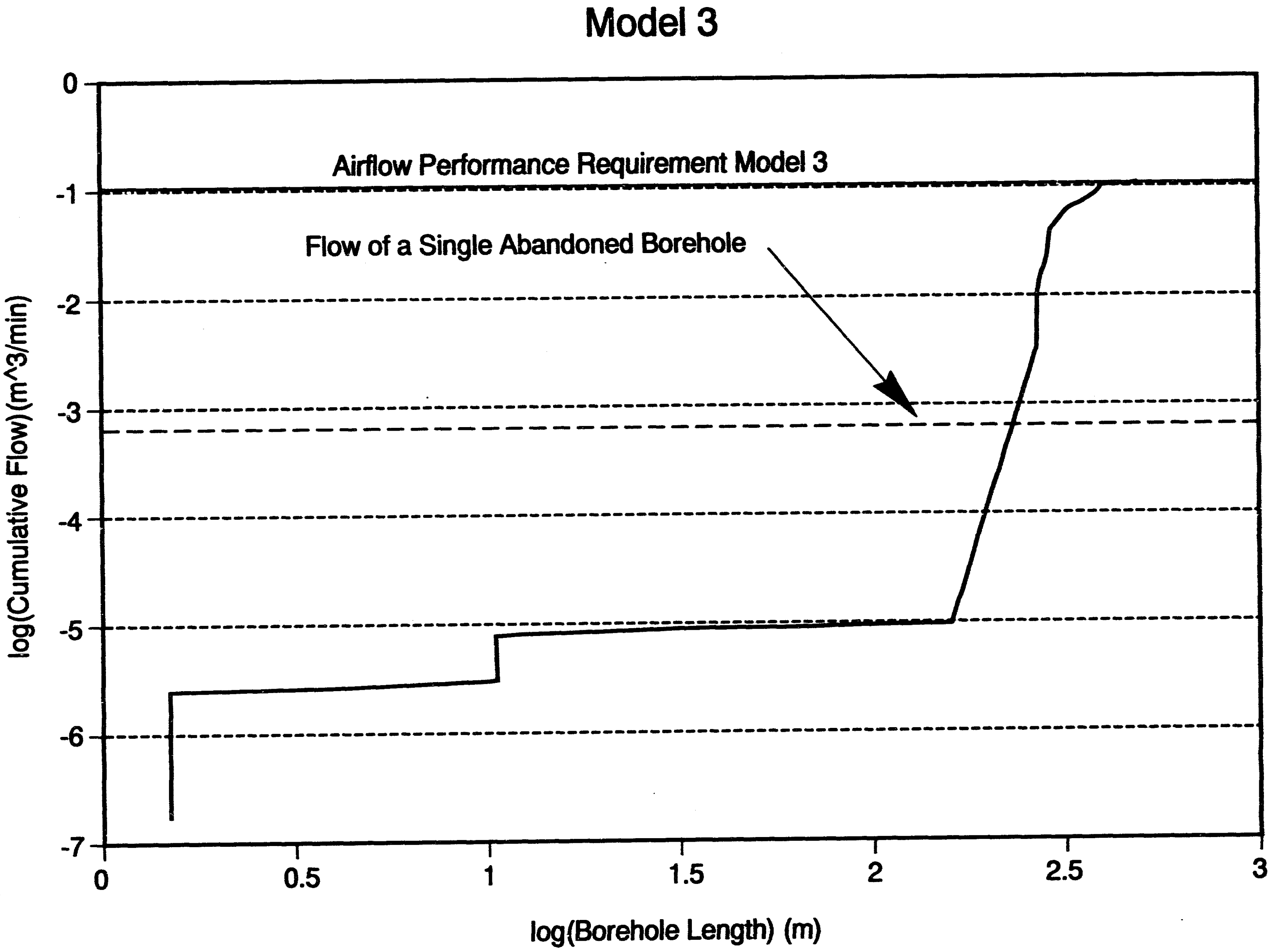


Figure H-7
Cumulative Flow Versus Borehole Length – Model 3

conductance of a single abandoned borehole represents about 10 percent of the total flow. For the most conductive model (Model 3) the flow through a single abandoned borehole is not significant, in that the design requirement expressed as a hydraulic conductivity for seals is of the order of 100 cm/s.

Table H-1
Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
SPRS-02[*a]	6.00	0.15	0.07	1.5	150.7	32.8	215.4	400.4	2.93e-08	3.52e-07	1.68e-05
SPRS-03[*a]	6.00	0.15	0.07	1.5	132.7	31.0	208.0	373.2	2.93e-08	3.47e-07	1.67e-05
SPRS-04[*a]	6.00	0.15	0.07	1.5	134.9	32.1	218.9	387.5	2.93e-08	3.48e-07	1.68e-05
SPRS-05[*a]	6.00	0.15	0.07	1.5	84.0	22.7	181.8	290.1	2.93e-08	3.68e-07	1.72e-05
SPRS-07[*a]	6.00	0.15	0.07	1.5	76.2	19.1	204.8	301.6	2.93e-08	4.55e-07	1.87e-05
SPRS-08[*a]	6.00	0.15	0.07	1.5	62.0	19.4	208.1	290.9	2.93e-08	4.32e-07	1.83e-05
SPRS-09[*a]	6.00	0.15	0.07	1.5	66.0	36.6	236.6	340.8	2.93e-08	2.69e-07	1.49e-05
SPRS-10[*a]	6.00	0.15	0.07	1.5	39.9	37.6	216.6	295.6	2.93e-08	2.28e-07	1.36e-05
SPRS-11[*a]	6.00	0.15	0.07	1.5	75.3	14.6	191.7	283.1	2.93e-08	5.55e-07	2.00e-05
SPRS-12[*a]	6.00	0.15	0.07	1.5	42.8	42.1	233.6	320.0	2.93e-08	2.20e-07	1.34e-05
SPRS-13[*a]	6.00	0.15	0.07	1.5	88.8	47.7	262.1	400.2	2.93e-08	2.43e-07	1.41e-05
SPRS-14[*a]	6.00	0.15	0.07	1.5	35.0	39.1	240.8	316.5	2.93e-08	2.34e-07	1.38e-05
SPRS-16[*a]	6.00	0.15	0.07	1.5	37.6	67.3	222.6	329.0	2.93e-08	1.42e-07	1.03e-05
SPRS-19[*a]	6.00	0.15	0.07	1.5	0.0	19.3	269.8	290.6	2.93e-08	4.34e-07	1.83e-05
SPRS-22[*a]	6.00	0.15	0.07	1.5	39.1	41.4	219.9	301.9	2.93e-08	2.11e-07	1.31e-05
SPRS-23[*a]	6.00	0.15	0.07	1.5	43.0	31.7	208.0	284.2	2.93e-08	2.60e-07	1.46e-05
USW UZ-N50	6.00	0.15	0.02	6.1	57.3	17.3	206.8	287.5	7.45e-09	1.20e-07	4.80e-06

Refer to footnotes at end of table.

Table H-1 *(Continued)*

Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
USW UZ-N51	6.00	0.15	0.02	6.1	59.1	17.8	208.7	291.7	7.45e-09	1.18e-07	4.77e-06
USW UZ-N95	6.00	0.15	0.02	6.1	139.3	32.0	209.4	386.8	7.41e-09	8.72e-08	4.22e-06
USW UZ-N52	6.00	0.15	0.02	7.6	58.3	18.0	209.5	293.4	7.49e-09	1.17e-07	4.78e-06
UE-25 UZN #28	6.00	0.15	0.02	7.9	32.7	41.4	219.9	301.9	7.49e-09	5.29e-08	3.30e-06
USW UZ-N72	6.00	0.15	0.02	9.1	137.2	32.4	216.0	394.7	7.47e-09	8.78e-08	4.25e-06
USW UZ-N73	6.00	0.15	0.02	9.1	122.3	31.7	216.5	379.7	7.48e-09	8.64e-08	4.22e-06
USW UZ-N94	6.00	0.15	0.02	9.1	135.6	31.7	208.9	385.4	7.47e-09	8.77e-08	4.25e-06
LPRS 2[a,b]	6.00	0.15	0.18	10.7	123.1	32.1	218.9	384.9	7.50e-08	8.65e-07	4.23e-05
LPRS 3[a,b]	6.00	0.15	0.18	10.7	74.9	22.7	181.8	290.1	7.57e-08	9.21e-07	4.37e-05
LPRS 4[a,b]	6.00	0.15	0.18	10.7	62.8	19.0	204.7	297.2	7.57e-08	1.12e-06	4.74e-05
LPRS 5[a,b]	6.00	0.15	0.18	10.7	56.6	19.3	207.8	294.5	7.57e-08	1.10e-06	4.69e-05
LPRS 6[a,b]	6.00	0.15	0.18	10.7	56.9	36.6	236.6	340.8	7.53e-08	6.73e-07	3.77e-05
LPRS 8[a,b]	6.00	0.15	0.18	10.7	28.5	67.3	222.6	329.0	7.54e-08	3.55e-07	2.60e-05
LPRS 9[a,b]	6.00	0.15	0.18	10.7	0.0	10.1	269.8	290.6	7.57e-08	2.04e-06	5.71e-05
LPRS 10[a,b]	6.00	0.15	0.18	10.7	0.0	9.9	274.4	294.9	7.57e-08	2.12e-06	5.77e-05
LPRS 11[a,b]	6.00	0.15	0.18	10.7	30.0	41.4	219.9	301.9	7.56e-08	5.29e-07	3.32e-05
LPRS 12[a,b]	6.00	0.15	0.18	10.7	33.9	31.7	208.0	284.2	7.58e-08	6.49e-07	3.71e-05

Refer to footnotes at end of table.

Table H-1 *(Continued)*

Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
LPRS 13[a,b]	6.00	0.15	0.18	10.7	30.7	37.6	216.6	295.6	7.57e-08	5.70e-07	3.46e-05
UE-25 UZN #23	6.00	0.15	0.02	10.7	33.7	42.1	233.6	320.0	7.55e-09	5.51e-08	3.39e-06
UE-25 UZN #29	6.00	0.15	0.02	10.7	30.7	37.6	216.6	295.6	7.57e-09	5.70e-08	3.46e-06
UE-25 UZN #30	6.00	0.15	0.02	10.7	33.9	31.7	208.0	284.5	7.58e-09	6.49e-08	3.71e-06
USW UZ-N26	6.00	0.15	0.02	10.7	29.9	58.6	252.1	351.2	7.52e-09	4.35e-08	2.95e-06
USW UZ-N40	6.00	0.15	0.02	10.7	26.3	37.8	235.3	310.0	7.56e-09	5.95e-08	3.54e-06
USW UZ-N48	6.00	0.15	0.02	10.7	52.2	208.9	290.7	562.5	7.44e-09	1.96e-08	1.69e-06
USW UZ-N70	6.00	0.15	0.02	10.7	52.9	63.5	269.8	396.9	7.50e-09	4.54e-08	3.02e-06
USW UZ-N96	6.00	0.15	0.02	10.7	123.5	31.0	208.0	373.2	7.51e-09	8.69e-08	4.24e-06
USW UZ-N44	6.00	0.15	0.02	11.0	29.8	38.9	236.6	316.2	7.56e-09	5.90e-08	3.52e-06
USW UZ-N49	6.00	0.15	0.02	11.0	52.5	19.4	208.1	290.9	7.58e-09	1.08e-07	4.67e-06
USW UZ-N41	6.00	0.15	0.02	11.3	27.5	36.7	238.6	314.1	7.57e-09	6.20e-08	3.62e-06
USW UZ-N74	6.00	0.15	0.02	11.3	143.0	33.1	217.4	404.8	7.50e-09	8.82e-08	4.27e-06
USW UZ-N75	6.00	0.15	0.02	11.3	125.4	32.3	219.7	388.8	7.51e-09	8.68e-08	4.24e-06
UE-25 UZN #19	6.00	0.15	0.02	12.2	30.0	42.0	231.5	315.7	7.59e-09	5.45e-08	3.38e-06
USW UZ-N42	6.00	0.15	0.02	12.2	24.4	39.1	240.8	316.5	7.59e-09	5.86e-08	3.52e-06
USW UZ-N76	6.00	0.15	0.02	12.2	124.3	32.1	218.9	387.5	7.53e-09	8.71e-08	4.26e-06

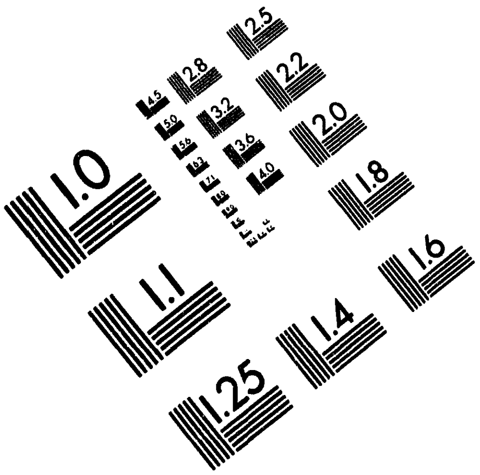
Refer to footnotes at end of table.

Table H-1 *(Continued)*

Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
USW UZ-N93	6.00	0.15	0.02	12.2	127.9	31.4	208.6	380.1	7.54e-09	8.75e-08	4.27e-06
UE-25 UZN #20	6.00	0.15	0.02	12.5	26.6	42.2	231.9	313.2	7.60e-09	5.38e-08	3.36e-06
UE-25 UZN #21	6.00	0.15	0.02	12.8	27.8	42.2	232.2	314.9	7.60e-09	5.41e-08	3.37e-06
USW UZ-N43	6.00	0.15	0.02	13.7	21.4	37.7	237.3	310.1	7.63e-09	5.96e-08	3.56e-06
USW UZ-N45	6.00	0.15	0.02	13.7	21.8	37.1	237.6	310.3	7.63e-09	6.05e-08	3.59e-06
USW UZ-N65	6.00	0.15	0.02	15.2	90.0	10.5	183.8	299.5	7.69e-09	2.02e-07	5.76e-06
USW UZ-N66	6.00	0.15	0.02	15.2	0.0	183.1	275.5	473.9	7.54e-09	1.89e-08	1.64e-06
USW UZ-N71	6.00	0.15	0.02	15.8	136.4	32.8	215.4	400.4	7.60e-09	8.81e-08	4.30e-06
US-25 SEISMIC #1	8.75	0.22	0.04	16.2	23.9	38.0	212.0	290.0	1.64e-08	1.18e-07	7.31e-06
USW UZ-08	6.00	0.15	0.02	17.4	43.1	18.9	206.6	286.0	7.77e-09	1.09e-07	4.75e-06
USW UZ-N25	6.00	0.15	0.02	18.0	20.5	56.8	249.3	344.6	7.70e-09	4.41e-08	3.00e-06
UE-25 UZN #97	6.00	0.15	0.02	18.3	22.4	41.4	219.9	302.0	7.77e-09	5.29e-08	3.36e-06
USW UZ-N64	6.00	0.15	0.02	18.3	106.7	44.8	267.2	437.0	7.61e-09	7.05e-08	3.88e-06
UE-25 UZN #18	6.00	0.15	0.02	18.6	23.0	40.8	225.1	307.5	7.77e-09	5.47e-08	3.42e-06
USW UZ-N24	6.00	0.15	0.02	22.9	2.5	54.6	238.3	318.2	7.86e-09	4.24e-08	2.95e-06
USW UZ-N33	6.00	0.15	0.02	22.9	6.1	64.8	228.4	322.1	7.85e-09	3.61e-08	2.66e-06
USW UZ-N98	6.00	0.15	0.02	22.9	2.8	54.5	237.9	318.1	7.86e-09	4.24e-08	2.95e-06

Refer to footnotes at end of table.

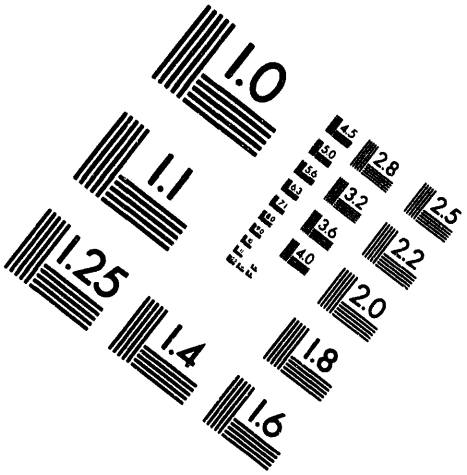


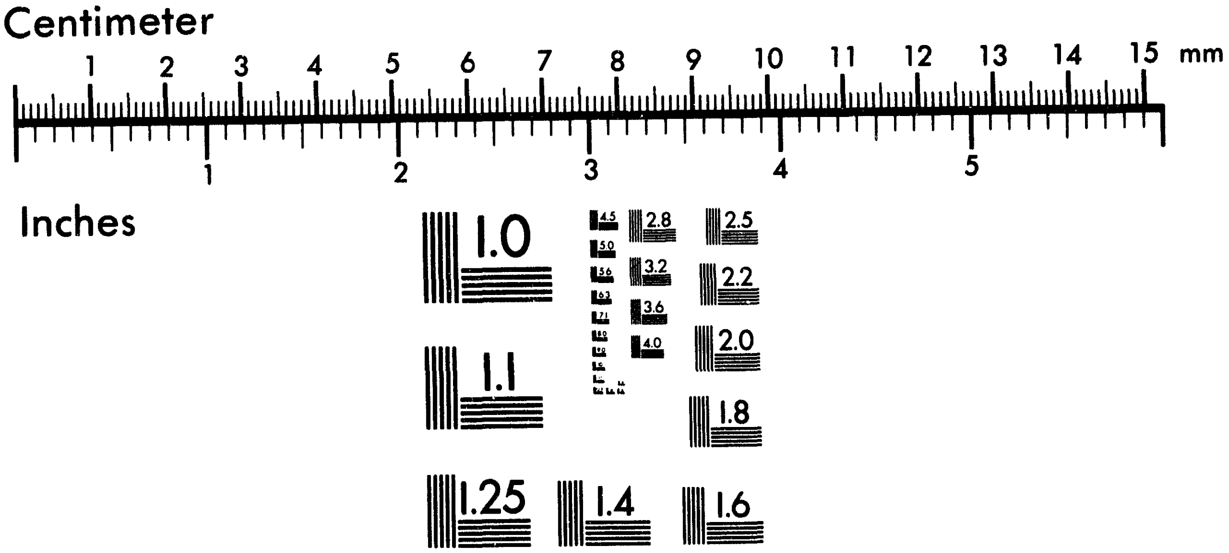
AIIM

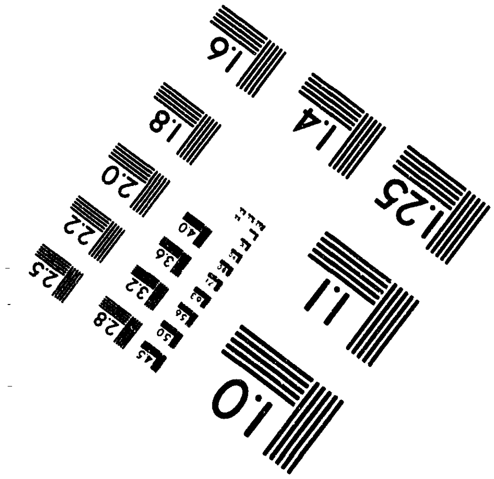
Association for Information and Image Management

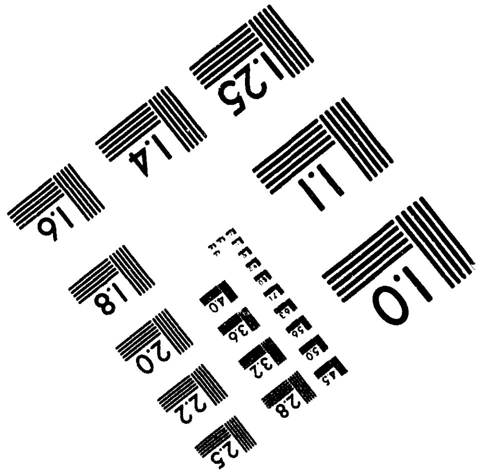
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202









MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

6 of 6

Table H-1 *(Continued)*

Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
USW UZ-N34	6.00	0.15	0.02	25.6	10.7	65.7	227.5	329.6	7.91e-09	3.64e-08	2.68e-06
USW UZ-N38	6.00	0.15	0.02	28.7	3.8	49.7	227.9	310.1	8.04e-09	4.53e-08	3.11e-06
UE-25 UZN #22	6.00	0.15	0.02	29.0	14.0	42.3	232.6	317.9	8.03e-09	5.45e-08	3.46e-06
USW UZ-N35*	6.00	0.15	0.02	30.5	38.6	27.7	224.4	321.2	8.06e-09	8.38e-08	4.34e-06
SRG-5*	6.00	0.15	0.02	45.7	73.3	30.8	203.0	352.8	8.38e-09	8.29e-08	4.41e-06
USW UZ-N31*	6.00	0.15	0.02	54.9	0.0	29.9	241.4	326.2	8.77e-09	7.90e-08	4.40e-06
USW UZ-N32*	6.00	0.15	0.02	54.9	0.0	26.3	241.5	322.7	8.79e-09	8.86e-08	4.66e-06
USW UZ-07	6.00	0.15	0.02	63.1	1.6	17.7	208.2	290.5	9.32e-09	1.19e-07	5.49e-06
USW UZ-N53	6.00	0.15	0.02	71.5	0.0	10.1	186.6	268.2	9.95e-09	1.90e-07	6.81e-06
USW UZ-N54	6.00	0.15	0.02	74.6	0.0	6.9	188.5	270.0	1.01e-08	2.79e-07	7.65e-06
USW UZ-N55	6.00	0.15	0.02	77.8	0.0	11.7	190.7	280.3	1.01e-08	1.72e-07	6.64e-06
USW UZ-N37	6.00	0.15	0.02	82.7	0.0	0.0	223.6	306.3	9.99e-09	9.98e-06	9.99e-06
UE-25A #5	6.13	0.16	0.02	148.4	0.0	0.0	157.6	306.0	1.48e-08	1.47e-05	1.48e-05
UE-25A #6	5.50	0.14	0.02	152.4	0.0	0.0	159.8	312.2	1.20e-08	1.19e-05	1.20e-05
UE-25A #4	6.13	0.16	0.02	152.4	0.0	0.0	151.5	303.9	1.52e-08	1.52e-05	1.52e-05
USW UZ-6S	8.34	0.21	0.04	158.2	0.0	17.0	209.1	384.3	2.40e-08	3.14e-07	1.43e-05
NRG-5*	6.00	0.15	0.02	304.8	0.0	0.0	2.7	307.5	8.28e-07	6.29e-04	8.25e-04

Refer to footnotes at end of table.

Table H-1 *(Continued)*

Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses			Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
					T1 (m)	T2 (m)	T3 (m)				
UE-25A #7	5.50	0.14	0.02	305.4	0.0	0.0	2.1	307.5	8.73e-07	6.25e-04	8.69e-04
UE-25 VSP-1 (UZ-15)*[c]	12.25	0.31	0.08	445.0	0.0	0.0	0.0	384.5	6.84e-04	1.06e-02	3.73e-01
USW UZ-7A*	12.25	0.31	0.08	480.0	0.0	0.0	0.0	290.5	6.84e-04	1.06e-02	3.73e-01
USW UZ-16	12.25	0.31	0.08	506.9	0.0	0.0	0.0	383.6	6.84e-04	1.06e-02	3.73e-01
USW UZ-8*	12.25	0.31	0.08	540.1	0.0	0.0	0.0	286.0	6.84e-04	1.06e-02	3.73e-01
USW UZ-06A*	12.25	0.31	0.08	548.6	0.0	0.0	0.0	384.5	6.84e-04	1.06e-02	3.73e-01
USW UZ-6	17.50	0.44	0.16	575.1	0.0	0.0	0.0	383.6	1.40e-03	2.17e-02	7.60e-01
UE-25 UZ#9B*	12.25	0.31	0.08	582.1	0.0	0.0	0.0	271.2	6.84e-04	1.06e-02	3.73e-01
UE-25 UZ#9*	12.25	0.31	0.08	585.2	0.0	0.0	0.0	272.3	6.84e-04	1.06e-02	3.73e-01
UE-25 UZ#9A*	12.25	0.31	0.08	585.2	0.0	0.0	0.0	271.8	6.84e-04	1.06e-02	3.73e-01
USW SD-12*	12.25	0.31	0.08	600.4	0.0	0.0	0.0	272.9	6.84e-04	1.06e-02	3.73e-01
UE-25 SD#9*	12.25	0.31	0.08	606.5	0.0	0.0	0.0	290.1	6.84e-04	1.06e-02	3.73e-01
USW SD-11*	12.25	0.31	0.08	609.6	0.0	0.0	0.0	287.6	6.84e-04	1.06e-02	3.73e-01
USW SD-8*	12.25	0.31	0.08	609.6	0.0	0.0	0.0	298.5	6.84e-04	1.06e-02	3.73e-01
USW SD-5*	12.25	0.31	0.08	618.7	0.0	0.0	0.0	337.4	6.84e-04	1.06e-02	3.73e-01
USW SD-10*	12.25	0.31	0.08	624.8	0.0	0.0	0.0	292.3	6.84e-04	1.06e-02	3.73e-01
USW WT-2	8.75	0.22	0.04	627.9	0.0	0.0	0.0	290.7	3.49e-04	5.43e-03	1.90e-01

Refer to footnotes at end of table.

Table H-1 *(Continued)*
Borehole Seal Significance—Airflow

Hole ID	Diameter (in.)	Diameter (m)	Area (m^2)	Borehole Length (m)	Effective Thicknesses T1 (m)	T2 (m)	T3 (m)	Potential Repository Depth (T4) (m)	Model 1 $K_b A_b$ (m^3/min)	Model 2 $K_b A_b$ (m^3/min)	Model 3 $K_b A_b$ (m^3/min)
USW SD-1*	12.25	0.31	0.08	640.0	0.0	0.0	0.0	323.9	6.84e-04	1.06e-02	3.73e-01
USW SD-4*	12.25	0.31	0.08	640.0	0.0	0.0	0.0	312.6	6.84e-04	1.06e-02	3.73e-01
USW SD-2*	12.25	0.31	0.08	701.0	0.0	0.0	0.0	376.0	6.84e-04	1.06e-02	3.73e-01
USW SD-7*	12.25	0.31	0.08	710.1	0.0	0.0	0.0	281.3	6.84e-04	1.06e-02	3.73e-01
USW SD-6*	12.25	0.31	0.08	786.3	0.0	0.0	0.0	367.2	6.84e-04	1.06e-02	3.73e-01
USW SD-3*	12.25	0.31	0.08	795.5	0.0	0.0	0.0	429.1	6.84e-04	1.06e-02	3.73e-01
USW UZ-2*	12.25	0.31	0.08	853.4	0.0	0.0	0.0	386.3	6.84e-04	1.06e-02	3.73e-01
USW UZ-3*	12.25	0.31	0.08	853.4	0.0	0.0	0.0	381.6	6.84e-04	1.06e-02	3.73e-01
USW G-4	12.25	0.31	0.08	915.3	0.0	0.0	0.0	313.2	6.84e-04	1.06e-02	3.73e-01
USW H-3	14.75	0.37	0.11	1219.1	0.0	0.0	0.0	352.1	9.92e-04	1.54e-02	5.40e-01
USW H-4	14.75	0.37	0.11	1219.1	0.0	0.0	0.0	303.0	9.92e-04	1.54e-02	5.40e-01
USW H-5	14.75	0.37	0.11	1219.1	0.0	0.0	0.0	440.8	9.92e-04	1.54e-02	5.40e-01
USW G-1	6.25	0.16	0.02	1828.7	0.0	0.0	0.0	339.0	1.78e-04	2.77e-03	9.70e-02
USW H-1	13.25	0.34	0.09	1828.7	0.0	0.0	0.0	325.7	8.01e-04	1.25e-02	4.36e-01

*Proposed borehole.

[a] SPRS holes are a cluster of four boreholes.

[b] LPRS holes are a cluster of ten boreholes.

[c] The shading denotes borehole penetrating through the potential repository horizon.

APPENDIX I
CEMENT HYDRATION ANALYSIS

Appendix I
Cement Hydration Analysis

This appendix presents the results of the SHAFT.SEAL Code to evaluate the hydration of cementitious materials. The following sections describe the input properties that include the seal properties, the tuff properties, and environmental conditions at the time of seal emplacement.

I.1 Input Properties

The input properties include the thermal and thermomechanical properties of the seal, the thermal and thermomechanical properties of the rock, and the environmental conditions at depth. Each of these is evaluated at the upper and sealing locations and at the potential repository horizon. Table I-1 presents the properties used to evaluate seals 0.2 to 0.3 m in radius. Table I-2 presents the properties of the host rock at sealing locations. Table I-3 presents environmental conditions at the time of emplacement.

I.1.1 Seal Properties

The water-to-cement ratio, humidity, and containment (or addition) of moisture during the curing process control the design-mix moisture content. The design mixes and their associated hydration properties for the cementitious seals were selected based on such factors as the water-to-cement ratio, aggregate size (grout versus concrete), and temperature and moisture environments at depth.

The hydration of plain concrete or grout results in an exothermic reaction and the release of heat. While concrete continues to hydrate for years, most of the hydration occurs within 28 days and is practically complete after 1,000 days. The hydration of concrete depends on the following:

- Type of cement
- Cement content
- Moisture and temperature environment.

The type of cement will control the amount of heat liberated during hydration. Figure I-1 presents hydration data for two types of cements used in the analysis: Type II cement and Type K cement. In this analysis, admixtures that increase expansivity, workability, or retard the set of concrete are assumed not to effect the heat of hydration. The heat of hydration also depends on the cement content of the concrete or grout. The analysis assumes that the grout is 33.8 percent by weight cement resulting in a bulk density of 1,950 kg/m^3.

In this analysis, the seal volumetric expansion and Young's modulus of the concrete are modeled as functions of time. Other properties are assumed to be independent of time. Figure I-2 presents the time relationship for Young's modulus. During the initial mixing and emplacement

Table I-1
Summary of Seal Properties

Property	Units	Upper Seal Location	Potential Repository Horizon	Lower Seal Location
Borehole Radius	(m)	0.30	0.22	0.22
Ultimate Young's Modulus	MPa	6,890	6,890	6,890
Poisson's Ratio	(-)	0.2	0.2	0.2
Thermal Expansion Coefficient	1/°C	12.6×10^{-6}	12.6×10^{-6}	12.6×10^{-6}
Bulk Density	(kg/m^3)	1,950	1,950	1,950
Thermal Conductivity	(J/m-day-°C)	259,200	259,200	259,200
Specific Heat Capacity	(J/kg-°C)	962.8	962.8	962.8
Ultimate Volumetric Expansion	(-)	0.6% for Type K 0.03% for Type II	0.6% for Type K 0.03% for Type II	0.6% for Type K 0.03% for Type II

Table I-2

Summary of Properties of Welded and Nonwelded Tuff

Property	Units	Upper Sealing Location	Potential Repository Horizon	Lower Sealing Location
Density*	(g/cm^3)	1.000	1.000	1.000
Rock Mass Thermal Conductivity	(J/m Day-K°)	113,443	158,890	111,024
Thermal Capacitance	(J/m-day-°C)	1.97×10^6	2.055×10^6 @ 29.2°C 3.770×10^6 @ 60.8°C 7.770×10^6 @ 87.2°C	1.880×10^6 @ 29.8°C 1.970×10^6 @ 42.3°C
Elastic Modulus	(MPa)	7,800	16,400	7,900
Poisson's Ratio	(-)	0.16	0.26	0.17

*Since the data for specific heat is expressed as thermal capacitance, the analysis uses the bulk density set equal to 1.0.

Table I-3

Summary of Environmental Conditions

Property	Units	Upper Seal Location	Potential Repository Horizon	Lower Seal Location
Minimum Horizontal Stress	(MPa)	1.2	3.64	4.37
Ambient Temperature	(°C)	22.7	29.2	29.8
Elevated Temperature	(°C)	22.7	60.8 and 87.2	42.3
Maximum Injection Pressure	(MPa)	0.60	1.82	2.19

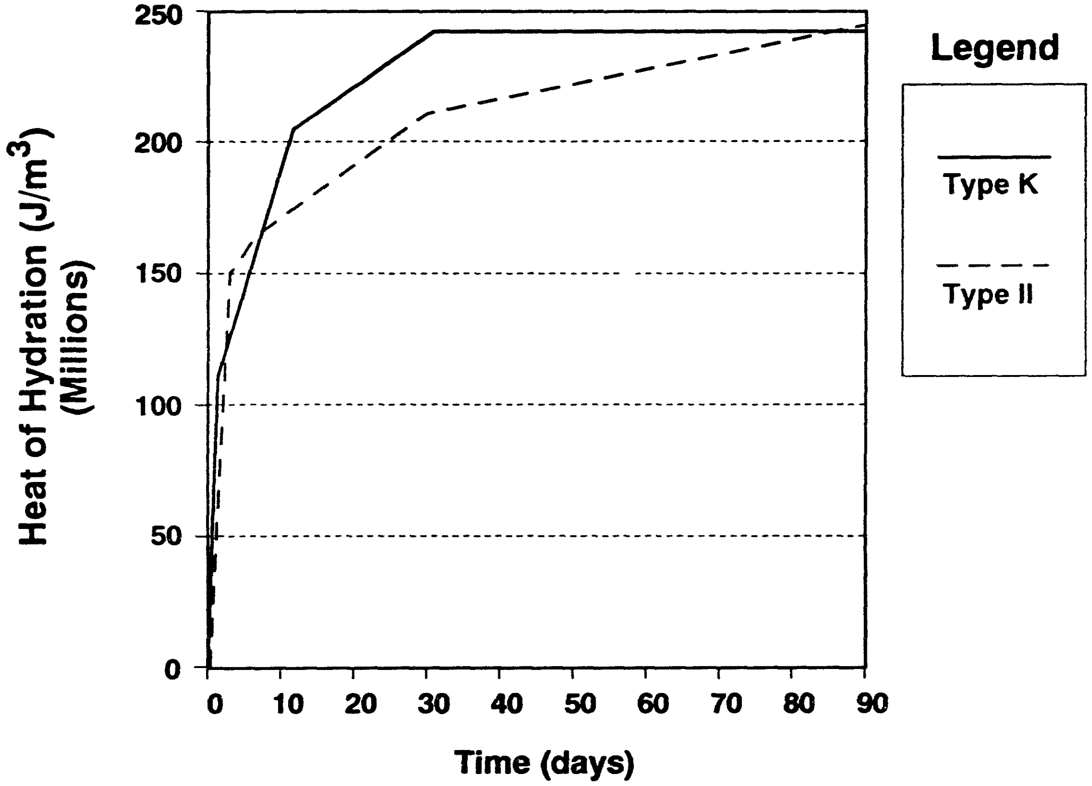


Figure I-1

Heat of Hydration of Cementitious Materials for Type II and Type K Cements

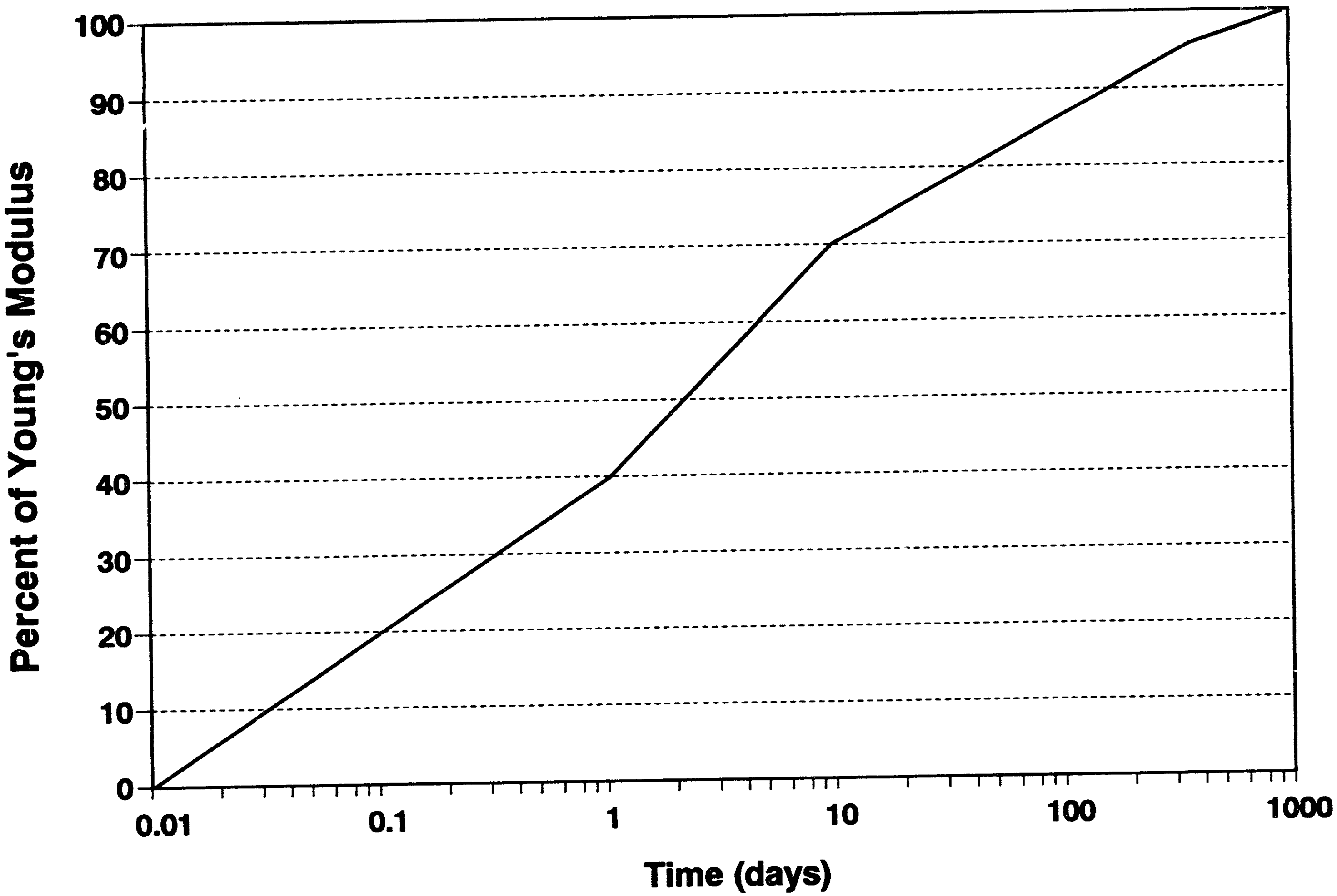


Figure I-2

Evolution of Young's Modulus for a Cementitious Material phase, the ultimate volumetric expansion for either Type II or Type K cement occurs after seven days. At this time, the Young's modulus attains about two-thirds of its ultimate value.

The thermal expansion coefficient of concrete might affect the early-age development of residual thermal stresses, depending on the temperature history of the plug. If the plug cools during curing (e.g., because the rock temperature is low), a low value for the thermal coefficient is desirable. On the other hand, if the cooling stage is eliminated, a high value may be desirable. The analysis uses a value of 12.6 X 10^{-6} $(°C)^{-1}$.

I.1.2 Tuff Properties

The analyses used input parameters for tuff thermal and thermomechanical properties at specific sealing locations, as determined from laboratory studies (DOE, 1992).

I.1.3 Environmental Conditions

The geothermal conditions at depth and potential repository heating determine the temperature of the surrounding rock at selected sealing locations in welded and nonwelded tuff. The analyses used rock-mass temperatures ranging from ambient geothermal temperature (23°C) to elevated temperatures caused by potential repository heating (61° or 87°C).

During the tests, the placement temperature was varied to evaluate initial temperature effects on interface stress development relative to the surrounding host-rock temperature. The placement temperatures ranged from 4°C to the ambient geothermal temperature at depth. This range in temperatures would be achieved by cooling the aggregate or circulating water through the seal.

The injection pressures ranged from 0 to 50 percent of the minimum horizontal stress at different sealing locations in welded and nonwelded tuff.

I.1.4 Analysis Results

Tables I-4 through I-9 present the results at the sealing locations for parametric variations in the type of cement (heat of hydration and expansivity), placement temperature, and injection pressure.

Table I-4

Upper Seal Location at Ambient Temperature

Analysis				Seal				Rock			
Cement	Placement Temperature	Injection Pressure	Temp (°C)	Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	23.98	4.09	4.28	5.46	0.69	4.09	0.55	3.39	1.77
Type K	25°C	50%	23.98	4.69	4.68	6.06	0.69	4.69	-0.05	3.39	2.37
Type K	4°C	0%	23.97	4.55	4.52	5.86	0.67	4.55	0.25	3.39	2.15
Type K	4°C	50%	23.97	5.15	5.12	6.46	0.67	5.15	-0.35	3.39	2.75
Type II	25°C	0%	23.15	-0.28	-0.12	-0.42	0.15	-0.28	4.92	3.39	2.60
Type II	25°C	50%	23.15	0.32	0.48	0.18	0.15	0.32	4.32	3.39	2.00
Type II	4°C	0%	23.14	0.19	0.12	-0.03	0.11	0.19	4.62	3.39	2.22
Type II	4°C	50%	23.14	0.79	0.72	0.57	0.11	0.79	4.02	3.39	1.62

Table I-5

Potential Repository Horizon at Ambient Temperature

Analysis			Temp (°C)	Seal				Rock			
Cement	Placement Temperature	Injection Pressure		Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	29.68	5.19	5.28	6.15	0.48	5.19	8.89	9.21	2.01
Type K	25°C	50%	29.68	7.01	7.10	7.97	0.48	7.01	7.07	9.21	1.10
Type K	4°C	0%	29.68	5.64	5.56	6.50	0.47	5.64	9.19	9.21	1.79
Type K	4°C	50%	29.68	7.46	7.38	8.32	0.47	7.46	7.37	9.21	0.92
Type II	25°C	0%	29.35	-0.07	-0.01	-0.10	0.05	-0.07	14.28	9.21	7.18
Type II	25°C	50%	29.35	1.75	1.81	1.72	0.05	1.75	12.46	9.21	5.36
Type II	4°C	0%	29.35	0.38	0.27	0.25	0.07	0.38	14.57	9.21	7.10
Type II	4°C	50%	29.35	2.20	2.09	2.07	0.07	2.20	12.75	9.21	5.28

Table I-6

Potential Repository Horizon at Elevated Temperature

Analysis				Seal				Rock			
Cement	Placement Temperature	Injection Pressure	Temp (°C)	Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	61.28	5.88	5.70	6.69	0.50	5.88	9.14	9.21	1.67
Type K	25°C	50%	61.28	7.70	7.52	8.51	0.50	7.70	7.32	9.21	0.95
Type K	4°C	0%	61.28	6.29	5.93	6.98	0.53	6.29	9.23	9.21	1.47
Type K	4°C	50%	61.28	8.11	7.75	8.80	0.53	8.11	7.41	9.21	0.90
Type II	25°C	0%	60.95	0.60	0.39	0.41	0.11	0.60	14.49	9.21	6.95
Type II	25°C	50%	60.95	2.42	2.21	2.23	0.11	2.42	12.67	9.21	5.13
Type II	4°C	0%	60.95	1.02	0.63	0.71	0.20	1.02	14.57	9.21	6.78
Type II	4°C	50%	60.95	2.84	2.45	2.53	0.20	2.84	12.75	9.21	4.96

Table I-7

Potential Repository Horizon at Panel Temperature

Analysis			Temp (°C)	Seal				Rock			
Cement	Placement Temperature	Injection Pressure		Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangen-tial (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	87.70	6.36	5.94	7.00	0.53	6.36	9.01	9.21	1.43
Type K	25°C	50%	87.70	8.18	7.76	8.82	0.53	8.18	7.19	9.21	1.01
Type K	4°C	0%	87.69	6.74	6.12	7.23	0.56	6.74	8.98	9.21	1.24
Type K	4°C	50%	87.69	8.56	7.94	9.05	0.56	8.56	7.16	9.21	1.03
Type II	25°C	0%	87.39	1.07	0.61	0.71	0.23	1.07	14.33	9.21	6.63
Type II	25°C	50%	87.39	2.89	2.43	2.53	0.23	2.89	12.51	9.21	4.81
Type II	4°C	0%	87.38	1.45	0.79	0.94	0.33	1.45	14.30	9.21	6.43
Type II	4°C	50%	87.38	3.27	2.61	2.76	0.33	3.27	12.48	9.21	4.61

Table I-8

Lower Seal Location at Ambient Temperature

Analysis			Temp (°C)	Seal				Rock			
Cement	Placement Temperature	Injection Pressure		Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	30.48	4.32	4.40	5.73	0.71	4.32	12.87	10.42	4.28
Type K	25°C	50%	30.48	6.51	6.59	7.92	0.71	6.51	10.68	10.42	2.09
Type K	4°C	0%	30.48	4.73	4.64	6.09	0.73	4.73	12.97	10.42	4.12
Type K	4°C	50%	30.48	6.92	6.83	8.28	0.73	6.92	10.78	10.42	1.93
Type II	25°C	0%	30.01	-0.05	0.00	-0.16	0.08	-0.05	17.31	10.42	8.68
Type II	25°C	50%	30.01	2.14	2.19	2.03	0.08	2.14	15.12	10.42	6.49
Type II	4°C	0%	30.01	0.36	0.25	0.21	0.08	0.36	17.41	10.42	8.53
Type II	4°C	50%	30.01	2.55	2.44	2.40	0.08	2.55	15.22	10.42	6.34

Table I-9

Lower Seal Location at Elevated Temperature

Analysis			Temp (°C)	Seal				Rock			
Cement	Placement Temperature	Injection Pressure		Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)	Radial (MPa)	Tangential (MPa)	Vertical (MPa)	Shear (MPa)
Type K	25°C	0%	42.98	4.57	4.55	5.95	0.70	4.57	12.93	10.42	4.18
Type K	25°C	50%	42.98	6.76	6.74	8.14	0.70	6.76	10.74	10.42	1.99
Type K	4°C	0%	42.98	4.97	4.79	6.31	0.76	4.97	13.02	10.42	4.03
Type K	4°C	50%	42.98	7.16	6.98	8.50	0.76	7.16	10.83	10.42	1.84
Type II	25°C	0%	42.51	0.20	0.15	0.07	0.07	0.20	17.36	10.42	8.58
Type II	25°C	50%	42.51	2.39	2.34	2.26	0.07	2.39	15.17	10.42	6.39
Type II	4°C	0%	42.51	0.60	0.39	0.43	0.11	0.60	17.46	10.42	8.43
Type II	4°C	50%	42.51	2.79	2.58	2.62	0.11	2.79	15.27	10.42	6.24

APPENDIX J
BACKFILL LOADING ANALYSIS

Appendix J
Backfill Loading Analysis

This appendix presents a backfill loading analysis for a cementitious seal, in which the loading is resisted in uniform shear and the backfill below the plug has settled. Section J.1 presents backfill loading under unsaturated conditions. Section J.2 presents loading under saturated conditions, and Section J.3 presents a dynamic analysis using a pseudo static method.

J.1 Backfill Loading Under Unsaturated Conditions

Consider the plug that resists dead load and loads transmitted from above in uniform shear. The total load resisted in uniform shear is as follows:

$$P_d = (\sigma_z)\ \pi a^2 + g\rho_c\ \pi\ a^2\ 1$$

where

P_d = Total load on the plug
σ_z = Vertical stress on the plug from the backfill at the top of the seal
ρ_c = Mass density of the seal
a = Seal radius
g = Acceleration constant
1 = Plug length.

The vertical stress from the backfill on the plug can be calculated by considering the equilibrium of an element of backfill (Figure J-1). If the backfill is dry and unsaturated, the governing differential equation is as follows:

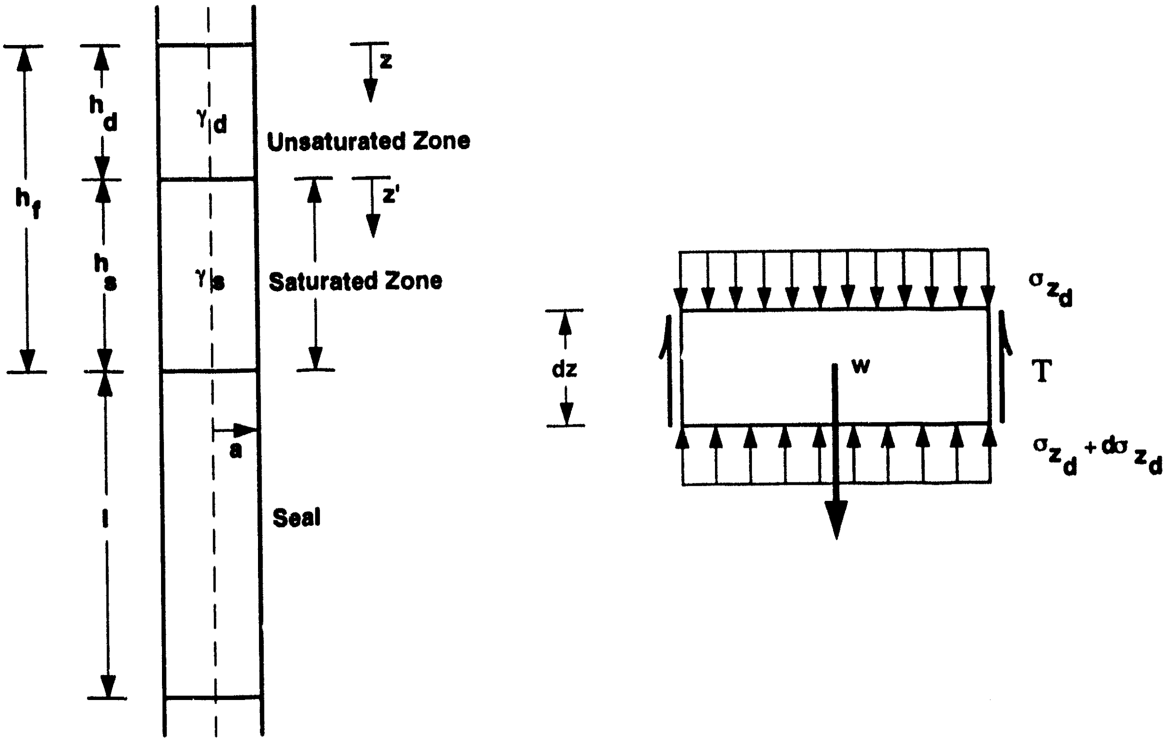
$$\frac{d\sigma_z}{dz} + \frac{2K(\tan(\phi))}{a}\sigma_z = g\rho_d$$

where

z = Vertical coordinate
tan ϕ = Friction angle
ρ_d = Mass unit weight
K = Active earth pressure coefficient.

The vertical stress is calculated by solving the first-order differential equation with the boundary condition that the vertical stress is zero at the top of the fill. The solution to the above equation follows:

Considering the condition below the water level, the governing differential equation becomes:



Seal Geometry

Force Equilibrium in the Vertical Direction

σ_{z_d} = Vertical Stress in the Unsaturated Zone

h_d = Height of Unsaturated Zone

h_s = Height of Saturated Zone

z = Vertical Coordinate from Top of the Unsaturated Zone

z' = Vertical Coordinate from Top of the Saturated Zone

g = Acceleration Due to Gravity

T = Shear Stress

l = Length of the Seal

w = Weight

σ_{z_d} = Vertical Stress in the Unsaturated Zone

g = Acceleration of Gravity

l = Length of the Seal

Figure J-1
Structural Analysis of Rockfill Loading

$$\sigma_z = \frac{a\rho_d g}{2(\tan(\phi))K} * \left(1 - e^{\frac{-2(\tan(\phi))}{a}z}\right).$$

$$\frac{d\sigma_z}{dz'} + \frac{2(\tan(\phi))K}{a}\sigma_z = 2(\tan(\phi))\frac{K}{a}u_w + g\rho_s .$$

The pore pressure equals:

$$u_w = \rho_w g z'$$

Substituting this relationship into the above differential equation yields:

$$\frac{d\sigma_z}{dz'} + \frac{2K(\tan(\phi))}{a}\sigma_z = \frac{2K(\tan(\phi))}{a}\rho_w g z' + g\rho_s .$$

The solution to the above equation is obtained by applying the boundary condition at the water level as follows:

$$\sigma_z = g\rho_w h_s + \frac{g(\rho_s - \rho_w)a}{2K(\tan(\phi))}\left(1 - e^{\frac{-2K(\tan(\phi))}{a}h_s}\right) + \frac{ag\rho_d}{2K(\tan(\phi))}\left(1 - e^{\frac{-2K(\tan(\phi))}{a}h_d}\right)e^{\frac{-2K(\tan(\phi))}{a}h_s}$$

where

K = Active earth pressure coefficient
ϕ = Internal friction angle
ρ_s = Density of saturated backfill
ρ_w = Density of water
h_s = Height of the saturated backfill
ρ_d = Density of dry backfill
h_d = Height of unsaturated backfill, h_f - h_s
h_f = Total height of the backfill.

J.2 Backfill Loading Under Saturated Conditions

It is assumed that the vertical loading on the plug to be resisted in uniform shear along the periphery of the plug is as follows:

$$\tau_{rz} = \frac{a}{2l}(\sigma_z + g\rho_c l) \; .$$

The above relationships are used to evaluate shear stress as a function of seal length for various loadings (Figures J-2 through J-4).[1] Table J-1 presents the assumed height used in the analyses for each seal location.

Table J-1
Height of Backfill

Seal Location	Height of Backfill (m)
Upper Seal Location	178
Potential Repository Horizon	454
Lower Seal Location	552

The analysis results show that the uniform shear stress that develops on the periphery of the plug depends on the plug length and the height of the saturated column. The principal loading results from the pore water pressure under saturated conditions. There is also considerable reduction in shear stress for plug lengths from 1 to 10 m and less reduction for plugs greater than 10 m in length.

J-3 Dynamic Loadings

For seismic analysis, the plug may be analyzed as a lumped-mass, single-degree-of-freedom system with damping for vertical ground movement. The response spectrum for maximum acceleration for periodic (sine or cosine) ground movements is most appropriate because the seal system is rigid or stiff. Ground movements might be predominantly vertical and not result in changes in seal confinement. Shearing stresses increase with no change or possibly a loss of confinement and potential failure along the plug boundary:

$$\tau_{rz} = \frac{a}{2l}(\sigma_z + \chi g \gamma_c l)$$

where

τ_{rz} = Shear stress on the rock/seal interface
a = Seal radius

---

[1] The calculations assume typical properties for the backfill. This includes a dry density of 1,750 kg/m^3; a wet density of 2,090 kg/m^3; and a friction angle of 30 degrees.

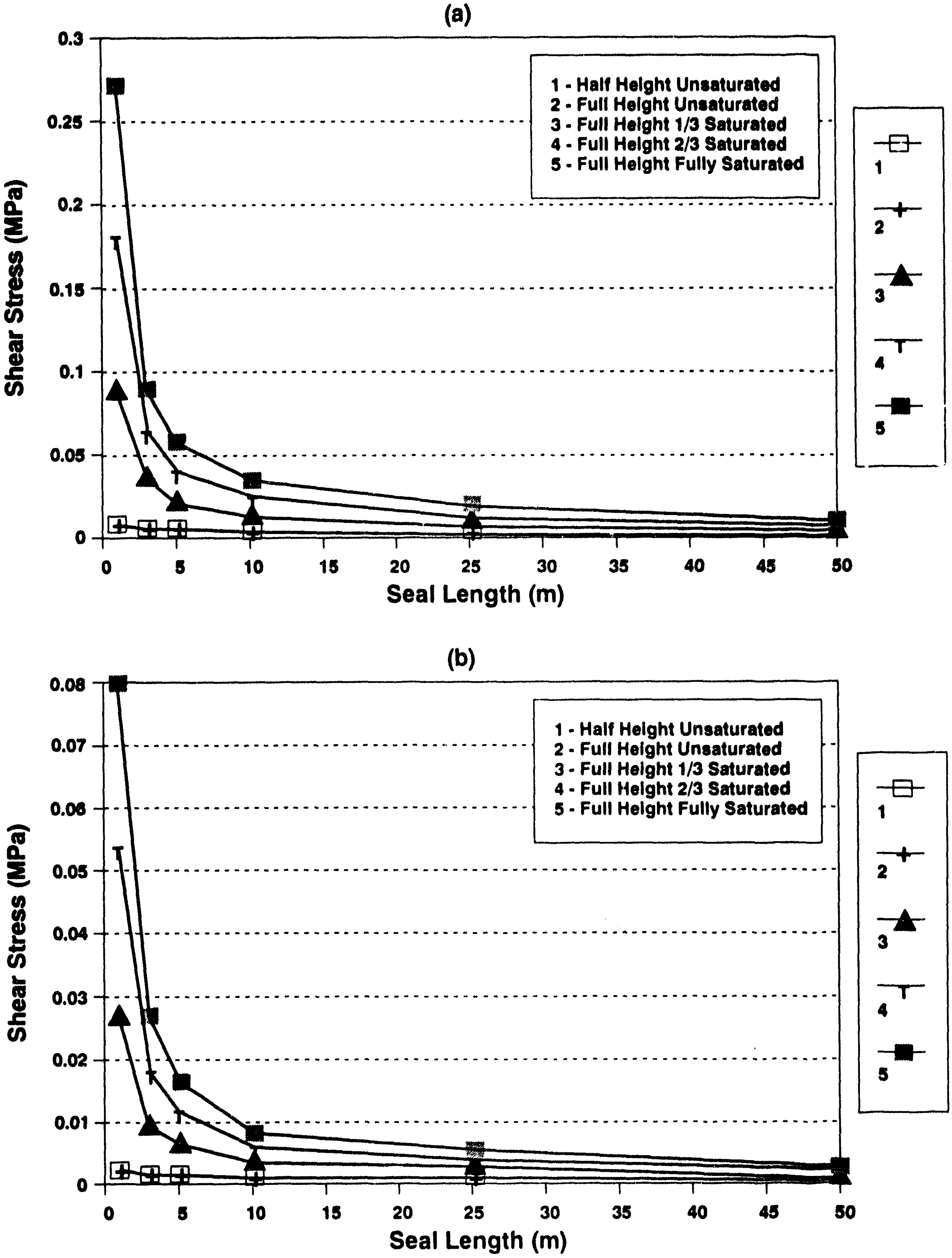


Figure J-2

Structural Analysis of Rockfill at Upper Seal Location
(a) Static Loading and (b) Dynamic Loading

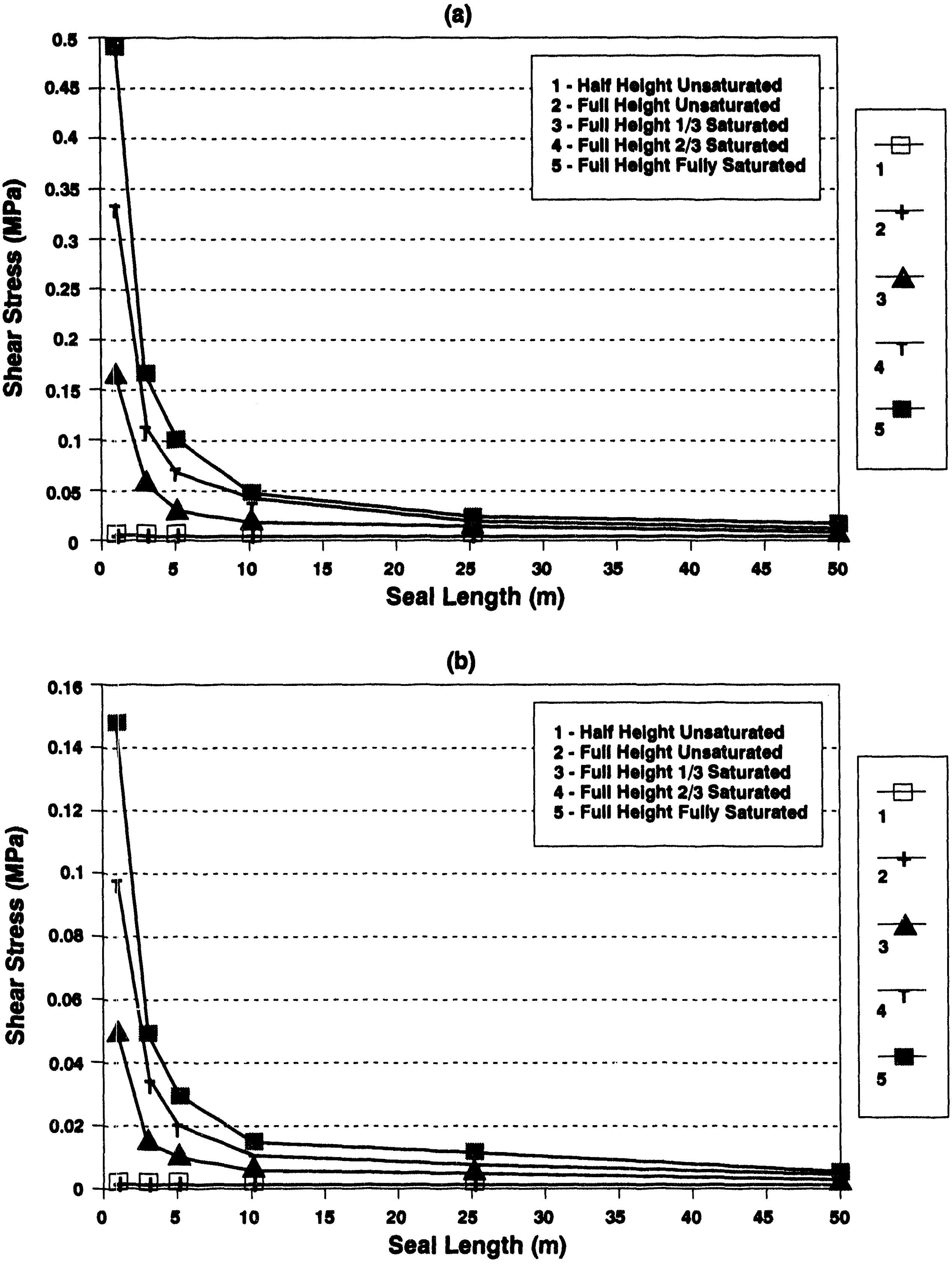


Figure J-3

Structural Analysis of Rockfill at the Potential Repository Horizon (a) Static Loading and (b) Dynamic Loading

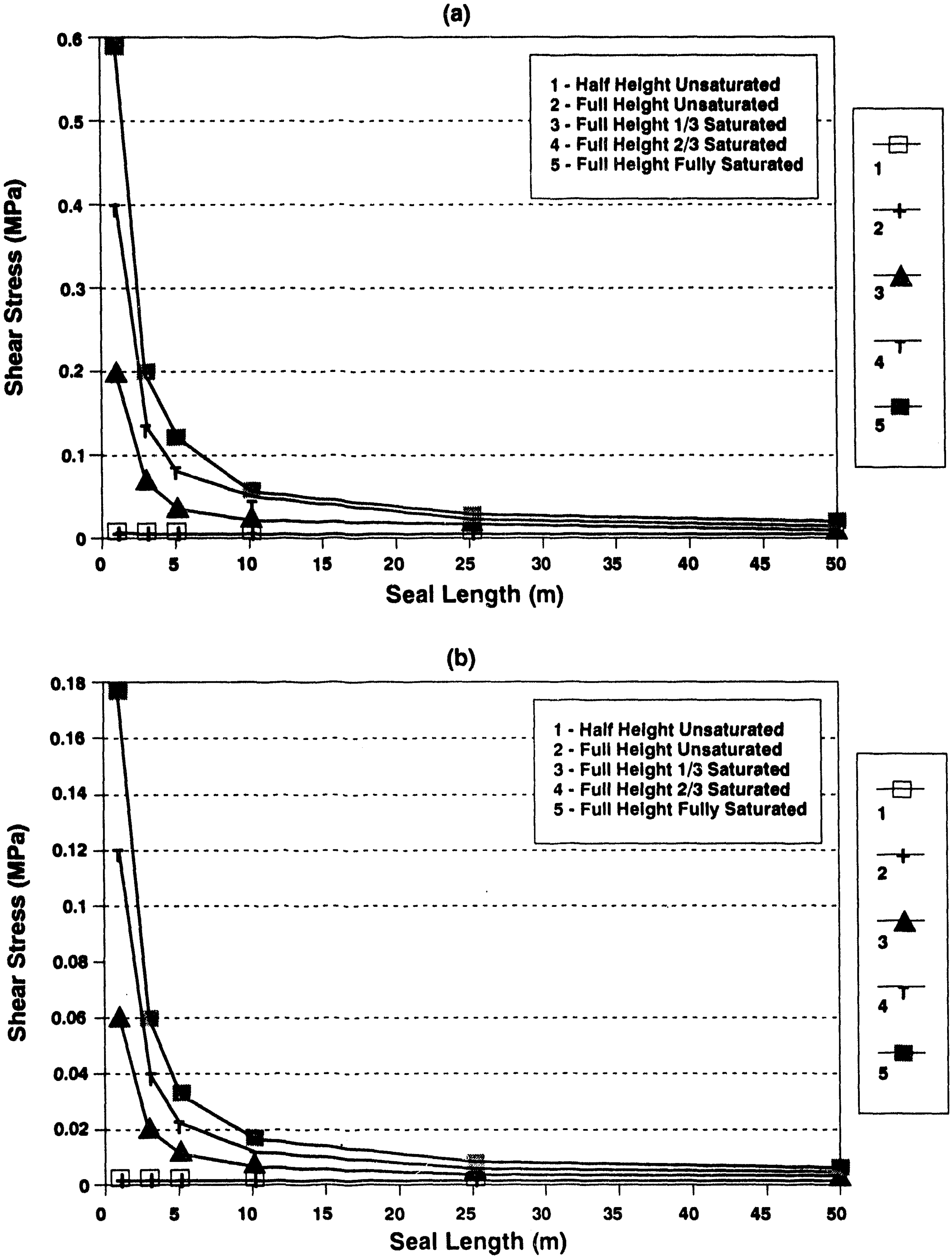


Figure J-4

Structural Analysis of Rockfill at Lower Sealing Location
(a) Static Loading and (b) Dynamic Loading

l = Length of the seal
σ_z = Vertical stress on the top of the seal
χ = Acceleration ratio
g = Acceleration of gravity
γ_c = Density of the seal.

The vertical stress for seismic loading becomes:

$$\sigma_z = \frac{a}{2k} \chi g \rho_b \left(1 - e^{-2\frac{k}{a}h_s}\right) + \chi \rho_w \, g h_s + \frac{a}{2k} \chi g \rho_d \left(1 - e^{-2\frac{k}{a}h_d}\right) e^{-2\frac{k}{a}h_s}$$

where

k = $K_a \tan(\phi)$
ρ_b = Buoyant density of backfill, $\gamma_s = \gamma_w$
h_s = Height of the saturated backfill
ρ_d = Density of dry backfill
h_d = Height of unsaturated backfill, $h_f - h_s$
h_f = Total height of the backfill.

Figures J-2 through J-4 present the analysis results. The vertical seismic loads result in shear stress that is approximately one-third of the total loading that would be expected for an acceleration of 0.3 g. The results also show little reduction in shear stress for seal lengths greater than 10 m.

APPENDIX K

MATERIALS USED IN THE OIL SEALING AND GAS INDUSTRY

Appendix K
Materials Used in the Oil Sealing and Gas Industry

This appendix presents information on cementitious materials and drilling muds used in the oil sealing and gas industry. Section K.1 presents information on cementitious materials, while Section K.1.1 presents information for cementitious materials in high-temperature environments. Section K.1.2 presents information on drilling muds. One alternative strategy being pursued is to load the potential repository in a way that would cool the temperature of the waste and the potential repository rock near the boiling point of water to keep moisture away from the waste (GAO, 1993). Seal temperature at the upper and lower sealing locations would be higher than the temperatures presented in this report, and the discussion in this appendix would be relevant.

K.1 Cementitious Materials

The API provides standards for well cements, well-cement additives, and well-cement testing procedures under API Specification 10 (API, 1979), "Specification for Materials and Testing for Well Cements." This specification considers eight classes of well cements and aids in the procurement of standardized equipment and materials. API Specification 10 does not specifically address requirements of cements for well-plugging applications, but it does provide standardized tests and testing procedures that address test-sample preparation, normal and minimum water content, density, compressive strength, thickening time, fluid loss, and rheological properties of the slurry, as well as the permeability of the set cement to water. These tests may be employed to evaluate blends of cement for a particular application and as one quality control measure of field blends against the design specification for a particular application. The development of semiautomated slurry blending units means the achievement to reproduce the desired portions of admixtures. Sampling of the blended slurry normally takes place at predetermined points throughout the mixing process.

Cement-slurry composition can be tailored to specific applications by selection of an API-classified cement and proper use of one or more additives and the addition of the required volume of water. Examples of applications where special cement formulations may be needed in the sealing of boreholes include expansion and sealing properties, extreme temperatures, and highly permeable or "thief" zones that may be encountered. In wells where the hydrostatic head of a full column of cement would exceed the fracture pressure of the weakest formation, cement is either emplaced in stages, or lightweight cements are used in noncritical portions of the borehole. Stage cementing is the emplacement of the desired total amount of cement in reduced volumes, from individual ascending positions after the previous stage has cured.

Most of the cement used in oil wells is portland cement (Suman and Ellis, 1977; Western Company, undated). Limestone, clay, sand, and iron ore, which are finely ground and blended, comprise portland cement. The mixture is fired in a rotary kiln to about 2600°F. These materials fuse into glass-like balls or clinkers of complex silicate, which are then reground with gypsum.

Portland cement consists primarily of tricalcium aluminate, tetracalcium aluminoferite, tricalcium silicate, and dicalcium silicate. These four principal components affect the early strength, sulfate resistance, hydration, swelling, and cracking during cure and/or rate of hardening. The API established nine classifications of portland cement with the maximum percent of the four principal components designated. These classifications allow for various pressure/temperature conditions, early strength, sulfate resistance, and adaptability to modification with accelerators and retarders. Table K-1 presents the API classifications (API, 1979).

The published depth range of cements is based on laboratory determinations of thickening time and minimum compressive strength development in wells with a geothermal gradient of 1.5°F/100 ft (Suman and Ellis, 1977). Since the actual geothermal temperature gradient may differ from those in the laboratory, the depth ranges may not always be applicable. For instance, the geothermal temperature gradients range from about 0.8 to 2.4°F/100 ft in various parts of the southeastern United States. Normal cure time, or WOC time, after placement of plugs ranges from 12 to 24 hr.

There is much potential for creation of new cements or tailoring of standard classes of cement to meet specific design objectives, given the number of developed additives. The major cement additives that might be considered for sealing of potential repository boreholes include additives to prevent strength retrogression at high temperatures and density reducers to help prevent the loss of slurry to weak formations during cementing. These additives are discussed below.

K.1.1 Cementitious Materials in a High-Temperature Environment

One problem that may be encountered is a high-temperature environment for boreholes near or penetrating through the nuclear waste potential repository.[1] Cured portland cement exhibits severe compressive strength loss (retrogression) and an increase in permeability at temperatures above 230°F (110°C). Silica flour (minus 200 mesh) and coarse silica (50 to 150 mesh) can be used to avoid strength retrogression in high-temperature wells where the temperature exceeds this value. Coarse silica performs best where densified slurries are required, due to its reduced water requirements, as compared to silica flour. The silica flour can be used in all types of heavy or lightweight compositions. Table K-2 presents the effects of temperature and silica flour content on compressive strength and cement permeability. With the addition of bentonite and a high water-ratio material, the potential exists for the loss of strength and permeability. At least 30 to 35 percent silica flour by weight is needed to prevent retrogression, but concentrations of up to 80 percent have been used in geothermal well applications (Shryock and Smith, 1980).

---

[1] Alternative potential repository designs are being evaluated and include the concept of a "high-temperature" environment to drive off moisture and protect waste canisters. This discussion is relevant to such a high-temperature environment.

Table K-1
API Oil Well Cements

Class	Soundness Maximum %	Fineness Minimum (m²/kg)	Free Water Maximum (ml)	Depth Range (ft)	Water % by Weight of Cement	Characteristics
A	.80	150	--	0-6,000	46	Common cement when special properties are not required, similar to ASTM C 150, Type I.
B	.80	160	--	0-6,000	46	Provides moderate to high sulphate resistance, available in moderate (similar to ASTM C 150, Type II) and high sulfate-resistant types.
C	.80	220	--	0-6,000	56	Provides high early strength. Available in ordinary and moderate (similar to ASTM C 150, Type III) and high sulfate-resistant types.
D	.80	--	--	6,000-10,000	38	Coarse grind, retarded. Available in both moderate and high sulfate-resistant types.
E	.80	--	--	10,000-14,000	38	Same as D.
F	.80	--	--	10,000-16,000	38	Same as D.
G	.80	--	3.5	0-8,000	44	Intended for use as a basic cement or can be used with accelerators and retarders to cover a range of well depths and temperatures. No additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture. Available in moderate and high sulfate-resistant types, primarily in western United States.
H	.80	--	3.5	0-8,000	38	Intended for use as a basic cement as manufactured or can be used with accelerators and retarders to cover. See Appendix B for chemical and physical range of well depths and temperatures. No requirements for API Cements. Additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture. Available in moderate and high sulfate-resistant types, primarily in Gulf Coast and midcontinent regions.

Table K-2
Permeability of Hydrated API Class H Cement[a]

Silica (%)	Bentonite (%)	Hematite (%)	Curing Time: 3 Days at 320°F		Curing Time: 28 Days at 320°F	
			Compressive Strength (%)	Permeability (md)	Compressive Strength (%)	Permeability (md)
0	0	0	2,165	0.031	2,590	4,580
20	0	0	9,590	0.001	5,450	<0.001
30	0	0	8,325	0.001	5,390	<0.001
40	0	0	8,165	<0.001	11,330	<0.001
0	4	0	590	0.548	370	9.720
30	4	0	4,275	<0.001	3,050	<0.001
40	4	0	3,750	<0.001	4,140	<0.001
0	0	28	2,205	0.030	1,600	3.890
30	0	45	9,925	<0.001	7,015	<0.001
40	0	50	8,525	<0.001	8,450	<0.001

[a] From Smith, 1990.

Sand is used to densify slurries in plugback cements. Densified slurries are used to minimize the effects of "mud" contamination and are generally for plugback cements (Smith, 1990). During pumping, low-density cement slurries decrease the likelihood of breaking down a formation and causing lost circulation due to the hydrostatic force of a cement-slurry column. Density reduction can result from additives that increase the water content of the slurry (i.e., bentonite) or by the addition of lightweight solid particles (i.e., gilsonite and perlite). More common density-reduction additives are discussed below.

The principal additive for producing lightweight "filler" cementing slurries is bentonite, a colloidal clay that absorbs large quantities of water. The amount of bentonite (or gel) used in cement varies from 1 to 25 percent, with 4 percent being the most common ratio used in the field. Table K-3 presents the API Specification 10 requirements for bentonite. High percentages of bentonite cause a reduction of pumping time and compressive strength. Gel cements also have reduced sulfate resistance and are more permeable (Suman and Ellis, 1977).

The oil industry uses blends of pozzolans in oil well cement to create a lighter cement slurry with improved pumpability and increased brine and sulfate resistance. Generally, pozzolans are mixed in equal portions (by absolute volume) with portland cements. Pozzolan's cement can be accelerated or retarded in the same manner as portland cement. For low-weight, high-temperature applications, a mixture of pozzolan and lime (without portland cement) has been used (Montgomery and Smith, 1961). This composition applies to wells having bottom-hole temperatures from 140 to 400°F (60 to 204°C), requiring no strength retrogression.

Table K-3

Physical and Chemical Requirements for Bentonite According to API Specifications

Name	Property
Dry-screen analysis	100% through U.S. Standard No. 40 sieve (420 μm)
Wet-screen analysis	2.5% maximum retained on U.S. Standard No. 200 sieve (74 μm)
Moisture content (as received)	10%, maximum
Viscometer reading[a]	22, minimum at 600 rpm
Yield point[a] (lbf/100 ft^2)	3 x plastic viscosity, maximum
Filtration properties[a]	15.0 mL, maximum (100 psi paper)
pH[a]	9.5 maximum

[a] Based on 22.5 g bentonite in 350-mL distilled water; equivalent to approximately 80 bbl/ton yield clay.

The addition of gilsonite, which is a lightweight (specific gravity 1.07) bridging material added to oil well cement slurries, reduces slurry density and helps to control losses to permeable formations. Its addition to a cement composition produces a higher compressive strength at all ages at the same slurry weight. Table K-4 illustrates the quantities of gilsonite to produce various slurry weights in portland cement with and without bentonite or pozzolan cements.

Perlite is a volcanic composition that, after being mined, screened, and heated under pressure, forms a cellular product of low density. It provides bridging for lost circulation zones and reduces the weight of cement slurries. It can be used with common portland or retarding-type cements and generally contains small amounts of bentonite (4 percent) to help prevent flotation or settling of perlite particles.

Table K-4
Effects of Gilsonite on Cement Density

Gilsonite (lb/sack)	Portland Cement (lb/gal)	Portland 4% Gel (lb/gal)	Pozzolan Cement (lb/gal)
0	15.6	14.1	14.2
25	13.6	12.7	12.5
50	12.5	11.9	11.7
100	11.3	11.0	10.8

Due to some severe environments that are not commonplace, several investigations solved cementing problems associated with these environments. These investigations resulted in the development of special cementing blends. Some findings and the cement applications follow below.

Geopressured geothermal resources are found in sedimentary basins under high temperature and pressure. Temperatures and pressures range to more than 600°F (315.5°C) (Lipman, 1987; Shryock and Smith, 1980) and from 9,000 to 15,000 psi (Geraghty and Miller, 1982). Shyrock and Smith (1980), in writing on the state-of-the-art of geothermal well cementing, summarized the research and studies of various companies, agencies, and committees and technical papers published in both the United States and Europe related to cement compositions used in geothermal wells. The basic findings are as follows:

1. All (portland) cement (slurries and in cured state) undergo a retrogression of compressive strength when temperatures increase above 230°F (110°C).

2. When curing time increases at high temperatures, between 200 and 300°C, the compressive strength of the slurries rapidly decreases. Only Class G type cement with 40 percent silica flour showed sufficient compressive strength and durability with time (to support well casing).

3. API Class G Cement can be used up to 170°F (77°C), whereas at higher temperatures (up to 600°F [315°C]), it is necessary to add a retarder depending on the temperature (to maintain pumpability during emplacement).

4. The fluid loss of this composition almost equals the filtrate of a neat cement slurry that is approximately 1,000 cm^3/30 min, based on the API test. The addition of other products, such as the retarding agents, bentonite, mica, and gilsonite, does not greatly affect the fluid loss; however, filtration control agents will reduce fluid loss to less than 60 cm^3/30 min.

5. The rheological characteristics of API Class G Cement with silica flour are not much different from those of a neat cement slurry and are further improved (made easier to pump) by the addition of the retarding agent and/or friction reducing materials.

6. Class G Cement with silica flour and proper water composition can reduce the flow of water found in geothermal wells and is ideal for bonding, sealing, and zonal isolation.

High-temperature cements are available for use in wells when exceeding the upper effective limit of portland cements (700°F) (Suman and Ellis, 1977). In completing in situ coal-conversion wells, high-temperature combustion zones occur where temperatures may reach 2735°F (1500°C) for several hours. During ignition, the base of the injection well will undergo an initial thermal cycle reaching as high as 1112°F (600°C). Combustion of coal near any commonly used casing material (carbon steel) will cause rapid deterioration due to sulfidation, oxidation, melting, or thermal expansion (Geraghty and Miller, 1982).

Calcium aluminate cement (Cement Fondu™ or Luminite™) has been used in in situ combustion wells where temperatures may reach 2000°F. Calcium aluminate cement is manufactured from limestone and bauxite ores. Neat calcium aluminate cement has a high heat of reaction and attains an ultimate compressive strength of 12,000 psi (83 MPa) in 24 hr. Additives include fire brick, fly ash, and silica flour (40 percent to improve strength retrogression).

Calcium aluminate cements may be considered for portions of the wellbores that penetrate or locate near the potential repository, where the heat from radioactive materials may reach a temperature of 302°F (150°C). Other specialty cements sometimes used in the construction or abandonment of industrial injection wells include latex cements and synthetic resin cements.

Epoxy-resin cements offer chemical resistance in injection wells with more aggressive waste streams. The addition of silica flour to the epoxy resin results in a low-viscosity epoxy-resin blend that is easily pumped and attains a compressive strength of over 2000 psi very soon after initial set takes place (Ostroot and Ramos, 1972). Epoxy cements are effective in wells with bottom-hole temperatures of 60 to 200°F (Smith, 1990). Special precautions must be used to remove all water from in front of the cements as epoxy water accelerates the setting of the epoxy. Once the epoxy starts to thicken, thickening time (pumpability) is essentially over.

A unique property of these cements is that when applying pressure to the slurry, the resin phase may be squeezed into a permeable zone and form a seal within the formation. These specialty cements are used in wells in small volumes. Manufacturers use different trademarks for epoxy cements. Halliburton's Epseal Cement™ and Dowell's Synthetic Cement™ (Dowell, 1972) are examples of epoxy-resin cements.

Expanding cements are a blend of portland cement and expansion aids, such as sodium sulfate, sodium chloride, pozzolan, calcium sulfoaluminate, or a combination of these admixtures (Carter et al., 1966). These cements expand during and following setting. This expansion improves bonding between cement and casing or formation. The permeability of some expanding cements is equivalent to that of API Class A neat cement (0.0001 millidarcies to water) (Dowell, 1973). Expanding cements are limited to temperatures below 200 to 290°F (93 to 143°C), depending on formulation, and may be detrimentally affected by conventional retarders.

One type of expanding cement available from Dowell (1972) is known as regulated fill-up cement. This thixotropic cement is thin when mixed but becomes thick when pumping stops. This property transfers hydrostatic pressure to the walls of the formation rather than to the bottom of the hole and thus can prevent the loss of slurry into weak and highly permeable zones. Regulated fill-up cement is highly sulfate-resistant and has permeabilities between 0.0038 and .0050 md (to water), depending on the percentage of water added (60 and 70 percent, respectively).

Chemical additives improve the stability of cements in the presence of various influent streams in industrial injection wells. Most standard cementing compositions are not resistant to inorganic acids. Latex can be mixed directly into a portland cementing composition as an aid to improving resistance to attack by organic acids and weak solutions of hydrochloric acid, nitric, and mixed acids (not sulfuric).

K.1.2 Drilling.Muds

Drilling fluids (muds) containing bentonite or other natural clays serve to prevent vertical fluid migration from deep reservoir horizons into shallow, saturated horizons (freshwater or potential underground sources of drinking water). The following discusses the major mud properties that affect the ability of drilling fluids to prevent vertical fluid migration in abandoned wellbores.

The fluid density of a drilling mud prevents inflow of formation fluids into a wellbore. The fluid density serves this purpose by exerting hydrostatic pressure differentials that are preferential to the formation and as such can prevent formation collapse due to tectonic stresses or settling. Formation fluid density can be adjusted to accomplish these objectives, either by increasing the salinity of brines or by the addition of insoluble solids, such as barite, for use as weighing material.

Gel strength is the thixotropic property of a drilling mud and primarily serves two functions relative to vertical fluid movement. The first major function of gel strength is to keep the insoluble weighing materials suspended in the fluid for extended periods. The second major function, long-term gel strength, provides additional resistance to vertical fluid movement due to the increased pressure required to shear or initiate vertical fluid movement.

There are two primary classifications of gel strength: progressive- and fragile-type gels. A progressive gel is one that starts low initially but consistently increases with time. The progressive gel is strong or firm and hard to break and often occurs because of high solids concentrations in the drilling fluid. From a drilling fluid standpoint, they are usually undesirable because they can create problems, such as excessive pump pressures to shear the fluid to initiate circulation resulting in potential loss of circulation. Conversely, as a plugging material, the increased gel strength that develops over time provides additional resistance to vertical fluid movement. The fragile gel may start with a high initial gel and only increase slightly in time. From a plugging-agent standpoint, the fragile gel may limit the additional resistance of the drilling mud to arrest vertical movement.

Drilling fluids may eventually dehydrate and crack, resulting in a channel that could permit fluid movement within a penetration. Rogers (1963) demonstrates that most clays in general and specifically smectite clays will adsorb water. They determined fluid permeabilities due to compressing water out of clay samples to be about 10^{-6} darcies (Rogers, 1963).

If a mud plug dehydrates, due to emplacement in the unsaturated zone at the Yucca Mountain Mined Geologic Disposal System, radionuclide gases would permeate the plug. Yet, if the permeability of the unsaturated zone is greater than that of the dehydrated mud plug, gases could permeate the formation surrounding the borehole. Desiccation/ dehydration and subsequent cracking of drilling muds could pose a problem in the unsaturated zone.

Filtercake buildup is the result of loss of fluid (usually water and chemical additions) from the mud into the formation when the formation permeability is such that fluid passage through pores occurs. Depending on the size of the pore openings, if the openings are large enough, the first event to occur would be a mud spurt that enters these openings at the wellbore face. As additional fluid is lost, a buildup of mud solids (filtercake) develops (Magcobar 1977). For treating the enhanced permeability development of the disturbed rock zone, the combination of filtration control and density can decrease the hoop stresses in the wellbore and exert a confining pressure on the face of the hole (Darley, 1981).

The water well industry uses bentonite seals in the presence of water. They are inapplicable to unsaturated zones, where it will dry and shrink or crack. In wet, static conditions, bentonite provides a flexible impermeable seal; bentonite seals cannot hold fluid pressure (Driscoll, 1989).

The literature shows that only qualitative judgements have been made in studies to date regarding standards for adequate zone isolation. These usually relate to the hydraulic bond that indicates the adhesion between cement and casing or between cement and formation. The actual relationship between hydraulic bond measurements in the laboratory, and downhole zone isolation has not been reported.

Laboratory studies for evaluating bond strength of cement to formation rock in deep boreholes are not common. One laboratory investigation (Evans and Carter, 1962), in which cement was placed in contact with formation cores and the interface was tapped by a simulated perforation, evaluated the effect of various contact surfaces and applied squeeze pressure. The study showed that, when cement was squeezed against dry cores, bond strength approached or exceeded compressive strength, yet test results were not provided for low-compressive-strength formation materials, such as tufted shales.

Based more on the lack of verifiable data rather than evidence to the contrary, it appears safer to rely on cement plugs for seal support than as a primary barrier to water infiltration, when other sealing materials are feasible. Table K-5 presents a summary of sealing materials—their advantages and disadvantages.

Table K-5
Summary of Seal Materials

Material	Advantage	Disadvantage
Bentonite	• Flexible when wet • No heat of hydration • Sorptive • Mud contamination less critical	• Shrinks/cracks in unsaturated zones • Cannot hold fluid pressure • Minimal structural support • 20-min thickening/set time • May disperse/erode in moving water • Well must be static during placement • Not self-supporting • Cannot tag for a test
Cement	• Tailored to fit need • Provides structural support • Does not dry in unsaturated zones • Holds fluid pressure • Thickening time may be adjusted • Can be expansive • Designed to reduce mud contamination effects • Self-supporting after hydration • Can tag for test	• Shrinks during hydration • May crack during hydration • Expands/shrinks with thermal cycles • Some blends very sensitive to mud contamination • Well must be static during placement • Retrogression over time • Not self-supporting as a slurry
Drilling Mud	• Holds pressure • Provides structural support when saturated • Sorptive	• May dehydrate in unsaturated zone • Shrinks/cracks when dehydrated • Loss of structural support when dehydrated • Contaminated by cement slurry

APPENDIX

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Geographic Nodal Information Study and Evaluation System

This report contains no candidate information for the Geographic Nodal Information Study and Evaluation System.

YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT

DISTRIBUTION LIST

1 D.A. Dreyfus (RW-1)
Director
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 L.H. Barrett (RW-2)
Acting Deputy Director
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 J.D. Saltzman (RW-4)
Office of Strategic Planning and International Programs
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 J.D. Saltzman (RW-5)
Office of External Relations
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 Samuel Rousso (RW-10)
Office of Program and Resource Mgt.
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 J. C. Bresee (RW-10)
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

1 R.M. Nelson (RW-20)
Office of Geologic Disposal
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 S. J. Brocoum (RW-22)
Analysis and Verification Division
OCRWM
US Department of Energy
1000 Independence Avenue SW
Washington, DC 2585

1 D. Shelor (RW-30)
Office of Systems and Compliance
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 J. Roberts (RW-33)
Director, Regulatory Compliance Division
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 G. J. Parker (RW-332)
Reg. Policy/Requirements Branch
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 R. A. Milner (RW-40)
Office of Storage and Transporation
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 S. Rousso (RW-50)
Office of Contract Business Management
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

1 T. Wood (RW-52)
Director, M&O Management Division
OCRWM
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

4 Victoria F. Reich, Librarian
Nuclear Waste Technical Review Board
1100 Wilson Blvd, Suite 910
Arlington, VA 22209

5 R.M. Nelson Jr, Acting Project Manager
Yucca Mountain Site
Characterization Project Office
US Department of Energy
P.O. Box 98608--MS 523
Las Vegas, NV 89193-8608

1 C. L. West, Director
Office of External Affairs
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

8 Technical Information Officer
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

1 P. K. Fitzsimmons, Technical Advisor
Office of Assistant Manager for Environmental Safety and Health
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

1 D. R. Elle, Director
Environmental Protection and Division
DOE Nevada Field Office
US Department of Energy
P.O. Box 98518
Las Vegas, NV 89193-8518

1 Repository Licensing & Quality Assurance
Project Directorate
Division of Waste Management
US NRC
Washington, DC 20555

1 Senior Project Manager for Yucca Mountain
Repository Project Branch
Division of Waste Management
US NRC
Washington, DC 20555

1 NRC Document Control Desk
Division of Waste Management
US NRC
Washington, DC 20555

1 Philip S. Justus
NRC Site Representive
301 E Stewart Avenue, Room 203
Las Vegas, NV 89101

1 E. P. Binnall
Field Systems Group Leader
Building 50B/4235
Lawrence Berkeley Laboratory
Berkeley, CA 94720

1 Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
Drawer 28510
San Antonio, TX 78284

3 W. L. Clarke
Technical Project Officer - YMP
Attn: YMP/LRC
Lawrence Livermore National Laboratory
P.O. Box 5514
Livermore, CA 94551

1 **J. A. Blink**
Deputy Project Leader
Lawrence Livermore National Laboratory
101 Convention Center Drive
Suite 820, MS 527
Las Vegas, NV 89109

4 **J. A. Canepa**
Technical Project Officer - YMP
N-5, Mail Stop J521
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

1 **H. N. Kalia**
Exploratory Shaft Test Manager
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr., #820
Las Vegas, NV 89101

1 **N. Z. Elkins**
Deputy Technical Project Officer
Los Alamos National Laboratory
Mail Stop 527
101 Convention Center Dr., #820
Las Vegas, NV 89101

5 **L. E. Shephard**
Technical Project Officer - YMP
Sandia National Laboratories
Organization 6302, M/S 1333
P.O. Box 5800
Albuquerque, NM 87185

1 **J. F. Devine**
Asst Director of Engineering Geology
US Geological Survey
106 National Center
12201 Sunrise Valley Drive
Reston, VA 22092

1 **L. R. Hayes**
Technical Project Officer
Yucca Mountain Project Branch
MS 425
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 **V. R. Schneider**
Asst. Chief Hydrologist--MS 414
Office of Program Coordination and Technical Support
US Geological Survey
12201 Sunrise Valley Drive
Reston, VA 22092

1 **J. S. Stuckless**
Geologic Division Coordinator
MS 913
Yucca Mountain Project
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 **D. H. Appel, Chief**
Hydrologic Investigations Program
MS 421
US Geological Survey
P.O. Box 25046
Denver, CO 80225

1 **E. J. Helley**
Branch of Western Regional Geology
MS 427
US Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

1 **R. W. Craig, Chief**
Nevada Operations Office
US Geological Survey
101 Convention Center Drive
Suite 860, MS 509
Las Vegas, NV 89109

1 **D. Zesiger**
US Geological Survey
101 Conventional Center Drive
Suite 860, MS 509
Las Vegas, NV 89109

1 **G. L. Ducret, Associate Chief**
Yucca Mountain Project Division
US Geological Survey
P.O. Box 25046
421 Federal Center
Denver, CO 80225

1 A. L. Flint
US Geological Survey
MS 721
P.O. Box 327
Mercury, NV 89023

1 D. A. Beck
Water Resources Division, USGS
6770 S Paradise Road
Las Vegas, NV 89119

1 P. A. Glancy
US Geological Survey
Federal Building, Room 224
Carson City, NV 89701

1 Sherman S.C. Wu
US Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001

1 J. H. Sass - USGS
Branch of Tectonophysics
2255 N Gemini Drive
Flagstaff, AZ 86001

1 DeWayne Campbell
Technical Project Officer - YMP
US Bureau of Reclamation
Code D-3790
P.O. Box 25007
Denver, CO 80225

1 J. M. LaMonaca
Records Specialist
US Geological Survey
421 Federal Center
P.O. Box 25046
Denver, CO 80225

1 W. R. Keefer - USGS
913 Federal Center
P.O. Box 25046
Denver, CO 80225

1 M. D. Voegele
Technical Project Officer - YMP
SAIC
101 Convention Center Drive
Suite 407
Las Vegas, NV 89109

2 L. D. Foust
Nevada Site Manager
TRW Environmental Safety
Systems
101 Convention Center Drive
Suite 540, MS 423
Las Vegas, NV 89109

1 C. E. Ezra
YMP Support Office Manager
EG&G Energy Measurements Inc
MS V-02
P.O. Box 1912
Las Vegas, NV 89125

1 E. L. Snow, Program Manager
Roy F. Weston Inc
955 L'Enfant Plaza SW
Washington, DC 20024

1 Technical Information Center
Roy F. Weston Inc
955 L'Enfant Plaza SW
Washington, DC 20024

1 D. Hedges, Vice President, QA
Roy F. Weston Inc
4425 Spring Mountain Road
Suite 300
Las Vegas, NV 89102

1 D. L. Fraser, General Manager
Reynolds Electrical &
Engineering Co, Inc
MS 555
P.O. Box 98521
Las Vegas, NV 89193-8521

1 B. W. Colston, President and
General Manager
Las Vegas Branch
Raytheon Services Nevada
MS 416
P.O. Box 95487
Las Vegas, NV 89193-5487

1 R. L. Bullock
Technical Project Officer - YMP
Raytheon Services Nevada
Suite P-250, MS 403
101 Convention Center Drive
Las Vegas, NV 89109

1 Paul Eslinger, Manager
PASS Program
Pacific Northwest Laboratories
P.O. Box 999
Richland, WA 99352

1 A. T. Tamura
Science and Technology Division
OSTI
US Department of Energy
P.O. Box 62
Oak Ridge, TN 37831

1 Carlos G. Bell Jr
Professor of Civil Engineering
Civil and Mechanical Engineering Dept.
University of Nevada, Las Vegas
4505 S Maryland Parkway
Las Vegas, NV 89154

1 P. J. Weeden, Acting Director
Nuclear Radiation Assessment Div.
US EPA
Environmental Monitoring
Systems Lab
P.O. Box 93478
Las Vegas, NV 89193-3478

1 ONWI Library
Battelle Columbus Laboratory
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201

1 T. Hay, Executive Assistant
Office of the Governor
State of Nevada
Capitol Complex
Carson City, NV 89710

3 R. R. Loux
Executive Director
Agency for Nuclear Projects
State of Nevada
Evergreen Center, Suite 252
1802 N. Carson Street
Carson City, NV 89710

1 C.H. Johnson
Technical Program Manager
Agency for Nuclear Projects
State of Nevada
Evergreen Center, Suite 252
1802 N. Carson Street
Carson City, NV 89710

1 John Fordham
Water Resources Center
Desert Research Institute
P.O. Box 60220
Reno, NV 89506

1 David Rhode
Desert Research Institute
P.O. Box 60220
Reno, NV 89506

1 Eric Anderson
Mountain West Research-
Southwest Inc
2901 N Central Avenue #1000
Phoenix, AZ 85012-2730

1 The Honorable Cyril Schank
Chairman
Churchill County Board of
Commissioners
190 W First Street
Fallon, NV 89406

1 Dennis Bechtel, Coordinator
Nuclear Waste Division
Clark County Department of
Comprehensive Planning
301 E Clark Avenue, Suite 570
Las Vegas, NV 89101

1 Juanita D. Hoffman
Nuclear Waste Repository
Oversight Program
Esmeralda County
P.O. Box 490
Goldfield, NV 89013

1 Eureka County Board of Commissioners
Yucca Mountain Information
Office
P.O. Box 714
Eureka, NV 89316

1 **Brad Mettam**
Inyo County Yucca Mountain
Repository Assessment Office
Drawer L
Independence, CA 93526

1 **Lander County Board of Commissioners**
315 South Humbolt
Battle Mountain, NV 89820

1 **Vernon E. Poe**
Office of Nuclear Projects
Mineral County
P.O. Box 1026
Hawthorne, NV 89415

1 **Les W. Bradshaw**
Program Manager
Nye County Nuclear Waste
Repository Program
P.O. Box 153
Tonopah, NV 89049

1 **Florindo Mariani**
White Pine County Nuclear
Waste Project Office
457 Fifth Street
Ely, NV 89301

1 **Judy Foremaster**
City of Caliente Nuclear Waste
Project Office
P.O. Box 158
Caliente, NV 89008

1 **Phillip A. Niedzielski-Eichner**
Nye County Nuclear Waste
Repository Project Office
P.O. Box 221274
Chantilly, VA 22022-1274

1 **Jason Pitts**
Lincoln County Nuclear Waste
Project Office
Lincoln County Courthouse
Pioche, NV 89043

1 **Economic Development Dept.**
City of Las Vegas
400 E. Stewart Avenue
Las Vegas, NV 89101

1 **Commmunity Planning and Development**
City of North Las Vegas
P.O. Box 4086
North Las Vegas, NV 89030

1 **Community Development and Planning**
City of Boulder City
P.O. Box 61350
Boulder City, NV 89006

1 **Commission of the European Communities**
200 Rue de la Loi
B-1049 Brussells
BELGIUM

2 **M. J. Dorsey, Librarian**
YMP Research and Study Center
Reynolds Electrical &
Engineering Co Inc
MS 407
P.O. Box 98521
Las Vegas, NV 89193-8521

1 **Amy Anderson**
Argonne National Laboratory
Building 362
9700 S Cass Avenue
Argonne, IL 60439

1 **Steve Bradhurst**
P.O. Box 1510
Reno, NV 89505

1 **Michael L. Baughman**
35 Clark Road
Fiskdale, MA 01518

1 **Glenn Van Roekel**
Director of Community
Development
City of Caliente
P.O. Box 158
Caliente, NV 89008

1 Ray Williams, Jr
P.O. Box 10
Austin, NV 89310

1 Nye County District Attorney
P.O. Box 593
Tonopah, NV 89049

1 William Offutt
Nye County Manager
Tonopah, NV 89049

1 Charles Thistlethwaite, AICP
Associate Planner
Inyo County Planning Department
Drawer L
Independence, CA 93526

1 R. F. Pritchett
Technical Project Officer - YMP
Reynolds Electrical &
Engineering Company Inc
MS 408
P.O. Box 98521
Las Vegas, NV 89193-8521

1 Dr. Moses Karakouzian
1751 E Reno #125
Las Vegas, NV 89119

1 John B. Case
IT Corporation
5301 Central Avenue NE
Suite 700
Albuquerque, NM 87108

5 J.F.T. Agapito and Associates
715 Horizon Drive
Suite 340
Grand Junction, CO 81506

20 Thomas W. Bjerstedt
Yucca Mountain Site
Characterization Project
MS 523
101 Convention Center Drive
Las Vegas, NV 89109

	MS	
1	1325	L.S. Costin, 6313
2	1330	G.M. Gerstner-Miller, 6352 100/12461/SAND93-1184/QA
2	1330	G.M. Gerstner-Miller, 6352 DRMS Files
20	1330	WMT Library, 6352
1	1324	P.B. Davies, 6115
1	0827	P.J. Hommert, 1502
1	1375	D.A. Dahlgren, 4400
1	0751	W.R. Wawersik, 6117
1	1322	F.D. Hansen, 6121
1	1322	J.R. Tillerson, 6121
1	1341	A.L. Stevens, 6306
1	1325	R.E. Finley, 6213
1	0726	J. Woodward, 6600
1	0715	R. Luna, 6603
1	1315	T.E. Blejwas, 7500
10	1348	J.A. Fernandez, 7583
1	1348	G.L. Peace, 7585
1	9018	Central Technical Files, 8523-2
5	0899	Technical Library, 7141
1	0619	Technical Publications, 7151
10	0100	Document Processing for DOE/OSTI, 7613-2

DATE
FILMED
8/4/94

END