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Identification of Characteristics Which Influence Repository Design – Tuff

Final Report (Task 1)
June 1981 - March 1982

Prepared by G. Rawlings, G. Antonnen, D. Findley, R. Hoffmann, C. Soto,
J. Rowe, F. Marinelli, W. Roberds, D. Pentz, K. Jones

Golder Associates

Prepared for
U.S. Nuclear Regulatory
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NRC FIN B6983

ABSTRACT

This report represents the results of Task 1, Subtask 1.2 of NRC Contract NRC-02-81-037, "Technical Assistance for Repository Design."

The purpose of the complete project is to provide NRC with technical assistance for the following reasons:

- To enable the focused, adequate review by NRC of the aspects related to design and construction of an underground test facility and final geologic repository, as presented in DOE Site Characterization Reports (SCR)
- To ascertain that the DOE site characterization program will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a license application for construction authorization.

The results of that part of the study presented in this report cover the identification of characteristics which influence design and construction of a geologic repository in tuff. Much of the report is therefore media-specific and the results are then applied to the repository sites being considered by DOE in tuff at the Nevada Test Site (NTS).

In order to satisfy the performance criteria (EPA and NRC), certain issues related to the design and ultimate construction of a geologic repository in tuff must be addressed during an SCR review. This report has identified five key issues, i.e., constructability, thermal response, mechanical response, hydrological response, and geochemical response. These issues involve both short-term (up to closure) and long-term (post-closure) effects.

The characteristics of tuff and its environment are described under the general headings of stratigraphic/structural, tectonic, mechanical, thermal and hydrologic. Characteristics have been separated into those which can be quantified and measured (parameters) and those which can only be described qualitatively (factors).

The characteristics are subjectively ranked in terms of their influence on the key issues as critical, major, minor or insignificant. This ranking took into account the following attributes of each characteristic: availability and suitability of conservative design/construction techniques, uncertainty in model and the model sensitivity to characteristic, and finally, potential for reducing uncertainty in characteristic.

Thus, recommendations are provided for a focused, adequate SCR review by NRC of the design and construction aspects of a nuclear waste repository in tuff.

EXECUTIVE SUMMARY

1. INTRODUCTION

1.1 This report represents the results of Task 1, Subtask 1.2 of NRC Contract NRC-02-81-037, "Technical Assistance for Repository Design."

The purpose of the complete project is to provide NRC with technical assistance for the following reasons:

- To enable the focused, adequate review by NRC of the aspects related to design and construction of an underground test facility and final geologic repository, as presented in DOE Site Characterization Reports (SCR)
- To ascertain that the DOE site characterization program will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a license application for construction authorization.

1.2 The results of that part of the study presented here cover the identification and ranking of characteristics which influence design and construction of a geologic repository in tuff. It is a companion report to the two previous Golder Associates' reports on bedded salt and granite/basalt (1979 a and c, respectively) and a similar report which considers characteristics for a repository located in domal salt (Subtask 1.1 of this study). Much of this report is directed towards generic aspects of tuff at the Nevada Test Site (NTS), specifically Yucca Mountain tuffs, and the conclusions from that part of the study are applied to selected horizons in tuff, the Bullfrog and Tram members, being studied by DOE.

2. STUDY PROCEDURES

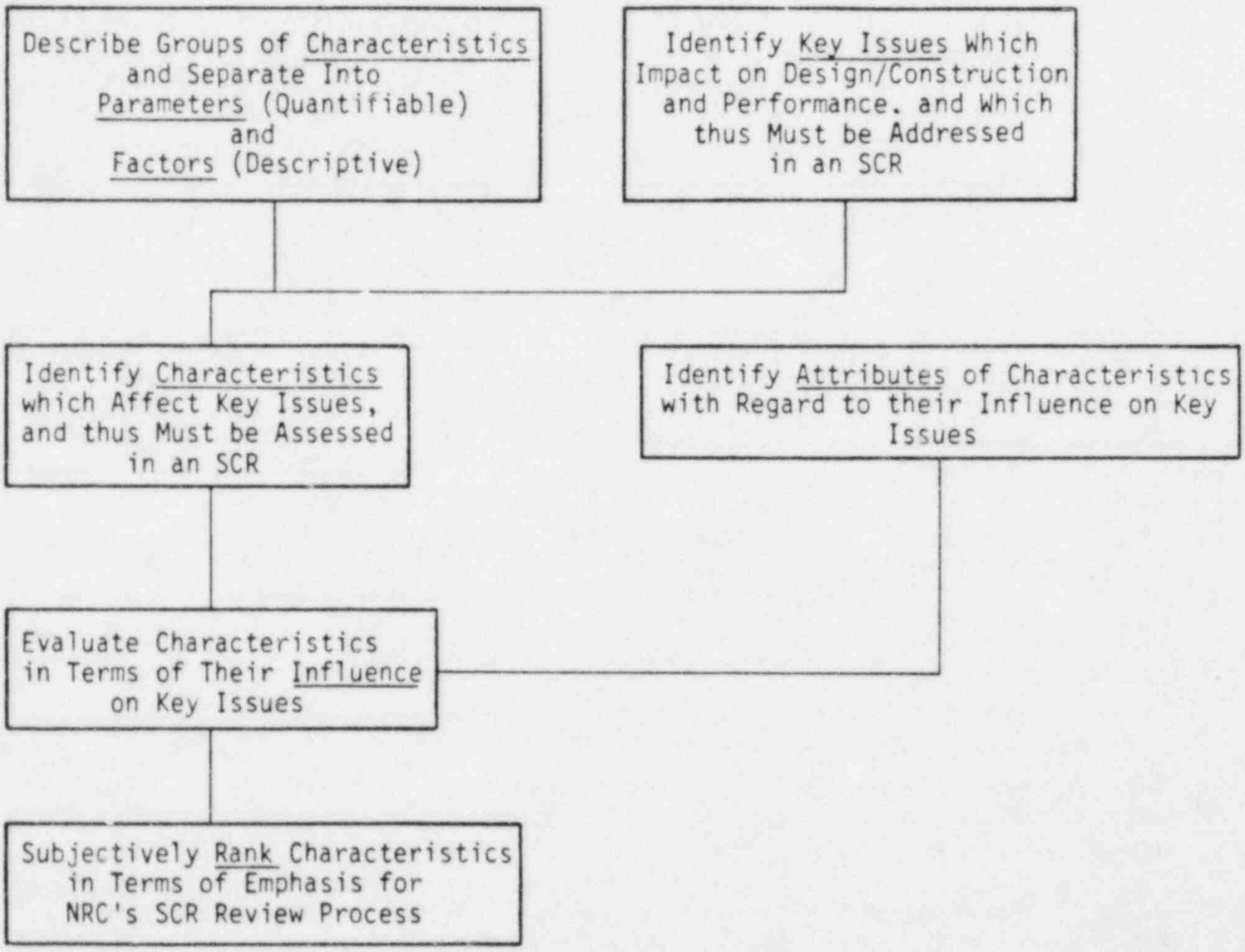
2.1 Figure 1 shows a flow chart which represents the process used during the study to identify the priority of characteristics to be emphasized in the NRC's review of an SCR. The components of the process are discussed individually below.

2.2 In order to satisfy the performance criteria (EPA and NRC), both short-term construction/operation and long-term containment/isolation, certain issues related to the design and ultimate construction of a geologic repository in tuff must be addressed. During an SCR review it will be necessary to evaluate the level of information presented in the SCR about a particular characteristic; i.e., is the information presented sufficient to answer the following five questions or key issues.

- Constructability. Can the facility be constructed in a timely and safe fashion, and so that it will not jeopardize the long-term containment and isolation capability of the facility? The

TASK-1 ACTIVITY FLOW CHART

Figure 1



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construction of the facility will entail the unavoidable creation of a disturbed zone of rock around underground openings and the construction of engineered barriers, both of which will have an effect on the response of the repository.

- Thermal Response. Can the temperature field be adequately predicted as a function of time to use as input to the mechanical, hydrological and geochemical models?

- Mechanical Response. Can the stability and deformation of underground openings be adequately predicted for the periods of short-term construction/operation and long-term containment/isolation?

- Hydrological Response. Can an adequate prediction be made regarding the resaturation time of the repository (post-closure) and of the groundwater flow through the repository over the long-term? Of lesser importance is the question of the amount of inflow into the repository during operation, i.e., over the short-term.

- Geochemical Response. Can an adequate prediction be made of the extent and effect of geochemical alteration of the engineered barriers and the rock where there is a potential for radionuclide migration to occur? Can the quantity and rate of migration of specific radionuclides over the long-term be adequately predicted?

2.3 The characteristics of tuff which must be assessed in order to address the above key issues were divided into five groups:

- Stratigraphic/structural
- Tectonic
- Mechanical
- Thermal
- Hydrologic.

The characteristics which could be quantified and measured are referred to as "parameters," and those which can only be qualitatively described are termed "factors."

2.4 These characteristics (i.e., parameters and factors) were subjectively evaluated in terms of their influence on each of the key issues in design and construction. Based on past experience, this evaluation has taken into account the following categories of attributes:

- Availability of design and construction techniques which allow for a conservative assumption of the value of the characteristic

- Uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value

- Cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values.

Certain combinations of the above attributes for a characteristic indicate that the characteristic should have the highest priority during NRC's review of an SCR; such a characteristic is termed critical. Similarly, other combinations of attributes suggest lower priorities during SCR review; such characteristics are termed, in decreasing order of priority, major, minor, and insignificant. The combinations of attributes which comprise each priority level have been subjectively assessed based on our experience.

Thus, recommendations are provided for the level of emphasis to be placed on each characteristic in tuff during the SCR review process. This will allow for a focused, adequate review by NRC of the design and construction aspects of a nuclear waste repository in tuff.

2.5 The tuff sites at NTS currently being studied in detail by DOE were reviewed on the basis of the characteristics identified during the project.

3. CONCLUSIONS

3.1 The relative influence of each characteristic of tuff on the resolution of the key issues has been subjectively assessed, based on the cumulative practical experience and judgement of Golder Associates personnel in the design and construction of underground openings, the modeling of the physical processes involved, and the difficulty of assessing the characteristics. This assessment and the recommended priority of each characteristic in NRC's review process of an SCR in tuff are summarized in Table 1. It is recommended that those characteristics which have the most significant influence on the key issues (i.e., designated as critical) have the highest priority in NRC's review of DOE submitted SCR(s) for site(s) in tuff. Similarly, those designated as major, minor, and insignificant should have decreasing priority in NRC's SCR review. This prioritization of characteristics will allow for a focused, adequate review by NRC and, although subjective, the process by which it has been achieved is exposed and trackable.

3.2 The relative importance of each characteristic to each issue does not change when going from the generic study (i.e., Yucca Mountain tuffs) to the site specific study (i.e., the Bullfrog and Tram members). Of course, the relative importance could change when more detailed data is available. Areas of particular concern because of lack of available data are:

- The lack of information on
  - stratigraphic continuity and thickness of the horizons over the Yucca Mountain site

TABLE 1

RECOMMENDED PRIORITIES IN THE REVIEW BY NRC OF AN SCR IN TUFF

CRITICAL CHARACTERISTICS FOR REVIEW

	CHARACTERISTICS	KEY ISSUES WHICH IMPACT ON DESIGN AND CONSTRUCTION: CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Stratigraphic/Structural	Lithology/Mineralogy	Major	Major	Critical	Critical	Critical
	Stratigraphic Sequence	Major	Major	Critical	Critical	Critical
	Faulting/Jointing	Critical	Minor	Critical	Critical	Critical
	Alteration			Major	Major	Critical
Tectonic	Seismicity	Major		Critical	Minor	
	Crustal Instability			Major	Minor	
	Volcanism (Continuing)		Major	Major		Major
	Faulting	Major		Critical	Major	Major
Mechanical	Rock Mass Strength	Major		Major	Minor	Minor
	Deformation Moduli			Major	Minor	
	Creep/Plasticity			Major	Minor	Minor
	Discontinuities	Major	Minor	Critical	Critical	Critical
	Density		Minor			
	Moisture Content		Minor		Major	Major
	In Situ Stresses	Minor	Minor	Major	Major	Major
Thermal	In Situ Temperature	Minor	Major	Major	Major	Major
	Thermal Conductivity		Major			
	Heat Capacity		Major			Minor
	Thermal Expansion		Minor	Major		
Hydrologic	Hydraulic Conductivity	Major	Minor		Critical	Critical
	Hydraulic Gradient	Major	Minor	Major	Critical	Critical
	Porosity		Major	Major	Major	Major
	Specific Storage				Major	
	Dispersivity					Minor
	Adsorption					Critical
	Pore Fluid Composition					Major

KEY: *

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 2.4, and Section 1.3.5 and Table 1.1 in the text for definitions

- vertical faults and discontinuities
- in situ stresses, temperatures, heat capacities and vertical hydraulic conductivities over the site
- the three-dimensional distribution of hydraulic head
- the mechanical and thermal properties of the Lower Tram formation

- The effects of increased temperature or groundwater movement on the mechanical properties of the Yucca Mountain tuffs

- The reaction of sodium montmorillonite to heating and drying

- The presence or absence of the lower carbonate aquifer postulated by Winograd and Thordarson (1975) beneath the tuff section.

3.3 To some extent, the impact of the currently perceived adverse characteristics of tuff can be decreased by appropriate design and construction strategies. Mitigating measures which should be considered include:

- Optimizing repository orientation and geometry
- Choosing suitable stratigraphic formations for the repository horizon, to include possibly widely separated multiple levels
- Selecting optimum excavation methods
- Selecting tunnel lining and support systems
- Varying the waste package emplacement design
- Varying the room spacing and design
- Selecting appropriate engineered barriers
- Designing a suitable ventilation/cooling system
- Controlling inflows by seals, plugs, grouting and pumping
- Limiting extraneous boreholes and excavations
- Controlling hydraulic gradients by drainage.

Specific mitigating strategies can be selected using information from the in situ testing and monitoring program.

3.4 We have determined that site suitability is sensitive to the following two points:

- There appears to potentially be a great deal of lateral and vertical variability in individual ash flows as indicated by the wide range in porosity values measured on small intact core samples. Because the mechanical and hydrologic characteristics especially have been found to be highly correlated with porosity, it would be expected that there will be large variability over relatively short distances in these characteristics. Hence, measurements of these characteristics in situ will be scale and location specific and difficult to extrapolate to either other locations or other scales. The resulting uncertainty in the determination of characteristics will be transmitted through performance assessment models to produce potentially large uncertainty in the prediction of performance. Clearly this variability within tuff members must be assessed. Thus, the uncertainty in predicted performance has built in a substantial uncertainty due to natural variability as well as the uncertainty due to models, testing etc.

- Generically, tuff has relatively poor mechanical characteristics, especially for higher porosities. This includes relatively low strength and potentially swelling materials and is due, in part, to the presence of disseminated montmorillonite. As temperature has a generally adverse effect on mechanical characteristics, as well as causing alteration of tuff (which has an additional adverse effect on mechanical characteristics), thermal loadings may have to be relatively low in order to ensure satisfactory mechanical (and thus hydrologic and geochemical) response. Low thermal loadings require increased waste package spacing, and thus increased lateral extent of the repository for a given waste package inventory. The necessity for reduced thermal loadings will have a significant cost impact and, therefore, must be addressed.

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ACKNOWLEDGMENTS

This report was made possible by the cooperation of the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE), particularly the Nevada Operations Office and their contractors. Personal communications with D. Vanimin, Los Alamos National Laboratories; E. Hoek, Golder Associates; and Fenix and Scisson are referenced as appropriate and are gratefully acknowledged. The Fenix and Scisson data was provided on a site visit to the Nevada Test Site on August 28, 1981, and included the lithologic log of core hole USW-G1 labeled Table 1.

Much of the data presented in this report was presented by DOE and their contractors in a preliminary draft unpublished form at the Nevada Nuclear Waste Storage Investigations (NNWSI) Peer Review held at the Riviera Hotel, Las Vegas, Nevada, August 24-28, 1981 under the direction of DOE Nevada Operations Office. The authors wish to express their appreciation for the invitation to attend. Presentations were made on behalf of DOE and their contractors by the following:

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NRC and Golder Associates look forward to the publication of information in the appropriate form. Although the authors acknowledge the cooperation of others, the responsibility for the accuracy of the presentation in this report rests with the authors and Golder Associates.

1. INTRODUCTION

1.1 TERMS OF REFERENCE

This report represents the results of Task 1, Subtask 1.2 of NRC Contract NRC-02-81-037, "Technical Assistance for Repository Design."

The purpose of the complete project is to provide the U.S. Nuclear Regulatory Commission (NRC) with technical assistance for the following reasons:

- To enable the focused, adequate review by NRC of the aspects related to design and construction of an underground test facility and final geologic repository, as presented in DOE Site Characterization Reports (SCR)
- To ascertain that the DOE site characterization* program will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a license application for construction authorization.

The results of that part of the study presented here cover the identification and ranking of characteristics which influence design and construction of a geologic repository in tuff. By identifying and ranking these characteristics, suitable emphasis can be placed in NRC's review of DOE submitted SCR(s) and license application(s) for site(s) in tuff. This ensures an NRC review process which is focused (and thus efficient) and yet still sufficient.

Much of this report is directed towards generic aspects of tuff at the Nevada Test Site (NTS), specifically Yucca Mountain tuffs, and the conclusions from that part of the study are applied to selected horizons in tuff, specifically the Bullfrog and Tram members, currently being studied by DOE. It is a companion report to the two previous Golder Associates' reports on bedded salt and granite/basalt (1979 a and c, respectively)** and a similar report which considers characteristics for a repository located in domal salt (Subtask 1.1 of this study).

1.2 SITE CHARACTERIZATION PROCESS

The site selection process weights site suitability criteria to permit rational choices to be made. The suitability of any site for potential use as a nuclear waste repository is addressed by a Site Characterization Report (SCR) submitted by the DOE to the NRC. The primary requirement of such a report is to identify and assess those characteristics of a site which will have a significant influence on the ability

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*Technical terms and those terms with a particular significance in waste disposal parlance are defined in the Glossary, Section 8.

**For references see Section 9.

of a site to meet the established performance criteria formulated by EPA and NRC for waste storage (both the short-term construction/operation and the long-term containment/isolation). In addition, the SCR will contain a conceptual repository design and an in situ testing plan for the completion of detailed characterization.

Characterization is generally performed by a combination of investigation methods: surface, borehole, laboratory and in situ tests. The simpler and cheaper methods are generally utilized in earlier phases of characterization when site selection is at issue. More accurate and expensive methods, especially in situ test methods, will be utilized to provide the more detailed characterization required to plan, design and construct the repository such that the performance criteria are satisfied. This detailed characterization will also serve to help verify the earlier characterization for site selection. However, because of the concentration of effort within the repository horizon and access shafts, verification of the far-field characterization is not generally achieved by site characterization for design and construction.

It will be necessary for the NRC to review DOE submitted SCR(s) and evaluate whether the characterization is, or will be subsequent to in situ testing, sufficient to establish that the performance criteria will be satisfied.

1.3 RATIONALE FOR EMPHASIS IN SCR REVIEW

1.3.1 Rationale Process

Figure 1.1 is a flow chart which represents the process used during the study to identify the priority of characteristics to be emphasized in NRC's review of an SCR. The components of the process, which are discussed individually in the following sections, include primarily:

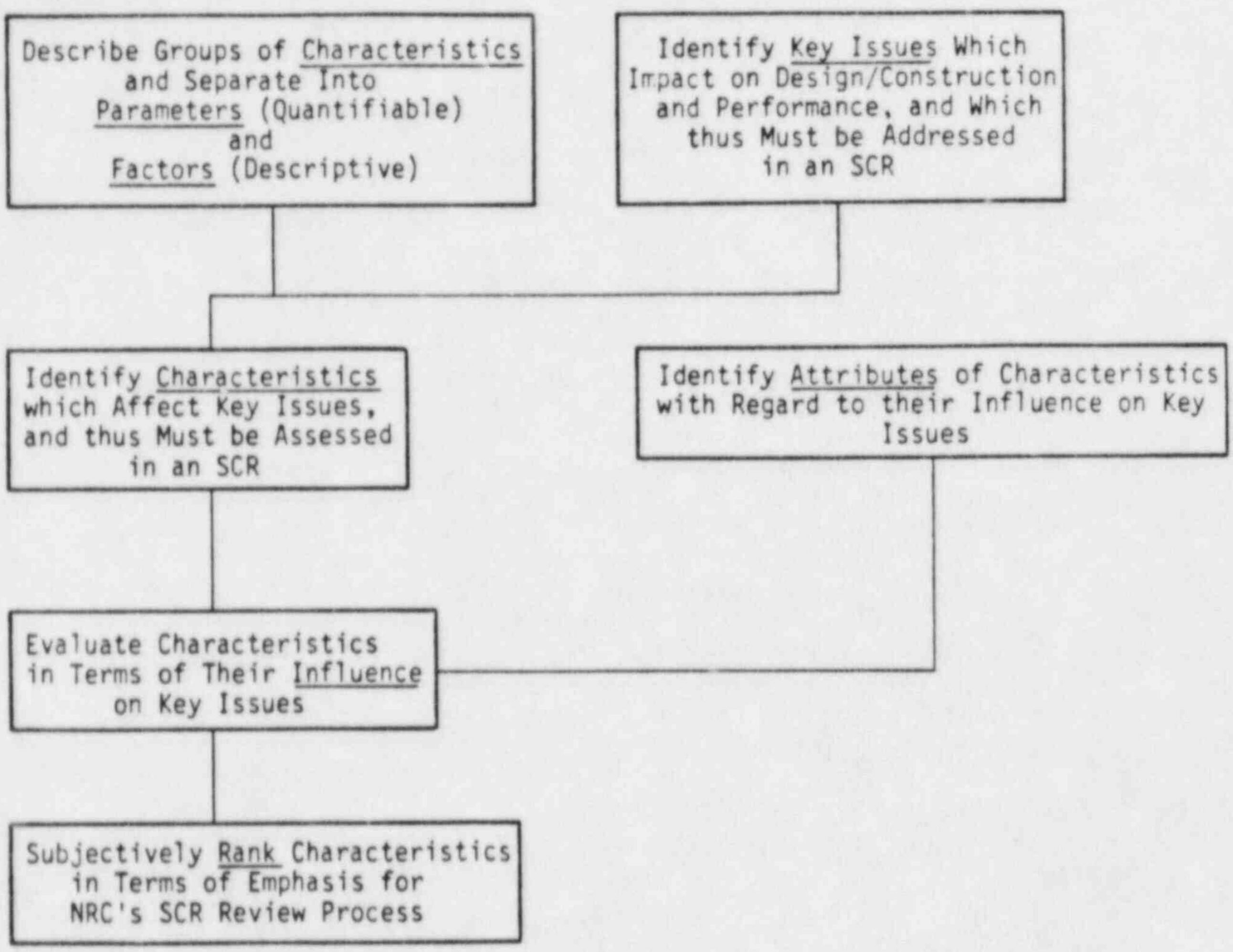
- Identification of key issues related to the design and construction of a repository in tuff
- Identification of characteristics of tuff which influence key issues
- Evaluation of the influence of characteristics of tuff on key issues
- Ranking of characteristics of tuff in terms of their influence on the key issues.

1.3.2 Key Issues

In order to satisfy the performance criteria (EPA and NRC), both short-term construction and operation and long-term containment and

TASK-1 ACTIVITY FLOW CHART

Figure 1.1



isolation, certain considerations related to the design and ultimate construction of a geologic repository in tuff must be addressed and ultimately resolved. These considerations can be summarized by the following five key issues:

- Constructability. Can the facility be constructed in a timely and safe fashion, and so that it will not jeopardize the long-term containment and isolation capability of the facility? The construction of the facility will entail the unavoidable creation of a disturbed zone of rock around underground openings and the construction of engineered barriers, both of which will have an effect on the response of the repository.

- Thermal Response. Can the temperature field be adequately predicted as a function of time to use as input to the mechanical, hydrological and geochemical models?

- Mechanical Response. Can the stability and deformation of underground openings be adequately predicted for the periods of short-term construction/operation and long-term containment/isolation?

- Hydrological Response. Can an adequate prediction be made regarding the resaturation time of the repository (post-closure) and of the groundwater flow through the repository over the long-term? Of lesser importance is the question of the amount of inflow into the repository during operation, i.e., over the short-term.

- Geochemical Response. Can an adequate prediction be made of the extent and effect of geochemical alteration of the engineered barriers and the rock where there is a potential for radionuclide migration to occur? Can the quantity and rate of migration of specific radionuclides over the long-term be adequately predicted?

During an SCR review it will be necessary to evaluate the level of information presented in the SCR, especially as it pertains to the above key issues.

1.3.3 Characteristics

The satisfactory resolution of each key issue identified in Section 1.3.2 will necessitate the adequate assessment of certain characteristics. A full suite of characteristics was drawn up which covered all potential aspects of tuff and its environment. The previous Golder Associates' reports on bedded salt (1979a) and granite/basalt (1979c) were used for guidance in this effort. This list of characteristics has been divided into five groups as follows:

- Stratigraphic/structural
  - lithology/mineralogy
  - stratigraphic sequence
  - faulting/jointing
  - alteration

- Tectonic
  - seismicity
  - crustal instability
  - volcanism (continuing)
  - faulting

- Mechanical
  - rock mass strength
  - moduli
  - creep/plasticity
  - discontinuities
  - density
  - moisture content
  - in situ stresses

- Thermal
  - in situ temperature
  - thermal conductivity
  - heat capacity
  - thermal expansion

- Hydrologic
  - hydraulic conductivity
  - hydraulic gradient
  - porosity
  - specific storage
  - dispersivity
  - adsorption
  - pore fluid composition.

The characteristics which can be quantified and measured are referred to herein as "parameters," and those which can only be qualitatively described are termed "factors."

1.3.4 Influence

Each of the characteristics identified in Section 1.3.3 has some influence on each of the key issues, although in some cases this influence may be insignificant. Certain attributes of characteristics can be identified and utilized to evaluate the level of influence of each characteristic on each key issue. Based on past experience, these attributes have been divided into the following three categories.

- Availability of design and construction techniques which allow for a conservative assumption of the value of the characteristic:

a) reasonable techniques are not available (i.e., high cost impact)
b) some techniques are available, but at moderate cost impact
c) reasonable techniques are available (i.e., little cost impact)

- Uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:

d) model has low uncertainty (i.e., is very representative) and has high sensitivity to characteristic
e) model has moderate uncertainty and moderate sensitivity
f) model has high uncertainty or low sensitivity

- Cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic value:

g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
h) uncertainty can be reduced, but only during in situ testing
i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization).

The influence of each characteristic on each key issue can thus be evaluated by assessing the characteristic's attributes in each of the above three categories; for example:

- In the first category, if a conservative assumption can be made for a characteristic value with little cost impact (i.e., repository design/construction techniques are available which allow for the performance criteria to be met, even with a conservative value of the characteristic - attribute c) then the characteristic has little influence. Conversely, if a conservative assumption for a characteristic value results in a high cost impact (i.e., repository design/construction techniques are not readily available which allow for the performance criteria to be met with a conservative value of the characteristics - attribute a), then the characteristic has significant influence.

- In the second category, if the model used to represent the real world is very poor (regardless of the uncertainty in the characteristics used as input) or if the model is very insensitive to a characteristic (i.e., attribute f), then that characteristic has little influence on the resolution of key issues. Conversely, if the model represents the real world relatively well (not taking into account the uncertainty in the characteristics used as input) and if the model is very sensitive to a characteristic (i.e., attribute d), then that characteristic has significant influence.

- In the third category, if the uncertainty in a characteristic cannot be significantly reduced in a cost-effective or timely manner (i.e., the characteristic has an inherent uncertainty which has little potential for being reasonably reduced prior to construction and operation of a repository - attribute i), then that characteristic has little influence in resolving the key issues during NRC's SCR and construction authorization review process. Conversely, if the uncertainty in the characteristic can be significantly reduced in a cost-effective and timely manner (i.e., the characteristic has an inherent uncertainty that can be reduced using available surface, borehole, or laboratory tests prior to SCR submittal - attribute g), then that characteristic may have significant influence in resolving the key issues during NRC's SCR review process.

1.3.5 Ranking

Certain combinations of the above attributes for a characteristic indicate that the characteristic would have a significant influence on the key issues and thus should have the highest priority during NRC's review of an SCR; such a characteristic is termed critical. Similarly, other combinations of attributes suggest less influence and thus lower priorities during SCR review; such characteristics are termed, in decreasing order of priority, major, minor, and insignificant.

For example, if a conservative assumption of a characteristic value has high cost impact (attribute a), if the model utilized is very representative of the real world and is very sensitive to that characteristic (attribute d), and if the uncertainty in the characteristic can be significantly reduced cost effectively prior to SCR submittal (attribute g), then clearly that characteristic will have a very significant influence on the resolution of key issues. Such a critical characteristic should thus have highest priority in NRC's SCR review process. Conversely, if a conservative assumption of a characteristic value has little or no cost impact (attribute c), if the model utilized is not representative of the real world or is insensitive to that characteristic (attribute f), and if the uncertainty in the characteristic cannot be significantly reduced prior to repository construction (attribute i), then clearly that characteristic will have an insignificant influence on the resolution of key issues. Such an insignificant characteristic should thus have lowest priority in NRC's review process.

Between the above two extreme examples are various combinations of attributes, each with a certain level of influence. The combinations of attributes which comprise each level of influence, and thus each recommended priority level, have been subjectively assessed, as presented in Table 1.1. Although, due to the subjective nature of this assessment there may be some disagreement in the rankings, it is felt that priority levels will not vary by more than one level. For example, if a characteristic has been assessed as insignificant, it is not likely

TABLE 1.1
PRIORITY LEVELS OF CHARACTERISTIC AS A FUNCTION OF THEIR ATTRIBUTES

	Availability of Conservative Design/Construction Techniques	Uncertainty in Model and its Sensitivity to Characteristic	Potential for Reducing Uncertainty in Characteristic
Critical	a	d	g
	a	d	h
	a	d	i
	a	e	g
	b	d	g
Major	a	e	h
	a	e	i
	a	f	g
	b	d	h
	b	d	i
	b	e	g
	b	e	h
	b	f	g
	c	d	g
Minor	a	f	h
	a	f	i
	b	e	i
	b	f	h
	b	f	i
	c	d	h
	c	d	i
	c	e	g
	c	e	h
	c	e	i
Insignificant	c	f	g
	c	f	h
	c	f	i

to be critical or even major. Similarly, if a characteristic has been assessed as critical, it is not likely to be insignificant or even minor.

Thus, recommendations are provided for the emphasis to be placed on each characteristic in tuff during the SCR review process. This will allow for a focused, adequate review by NRC of the design and construction aspects of a nuclear waste repository in tuff.

1.4 REPORT FORMAT

The report has been organized on the basis of the five groups of characteristics, namely:

- Stratigraphic/structural
- Tectonic
- Mechanical
- Thermal
- Hydrologic.

In each of the five sections the significant characteristics are described from a generic standpoint for tuff, their importance considered from the point of view of the key issues and a comparative ranking of importance produced. Matrix diagrams summarize the conclusions at the end of the generic part of each section.

Also in each section, an attempt has been made to consider the higher priority characteristics for tuff, as identified in the text and matrix diagrams, for each site currently being considered by DOE. However, because much of the characterization at NTS has been solely for site selection purposes, some difficulty was experienced in this respect because of the limitations of the available data on the characteristics for the two repository horizons. It was decided that it would nevertheless be preferable to preserve the same format as in the related Golder Associates report on domal salt to permit this current report to be updated as new site specific data is acquired.

2. STRATIGRAPHIC/STRUCTURAL CHARACTERISTICS

2.1 GENERAL

2.1.1 Selection of Characteristics

The stratigraphic/structural characteristics which must be considered for repository design and construction relate primarily to the basic geology of a candidate area. Most of the characteristics may be treated as factors as they cannot be quantified and will require description and geological/geotechnical survey techniques for their assessment.

These aspects of the site assessment for design are considered to be fundamental and represent the framework to which all the subsequent parameters are related. Only by obtaining a full understanding of the repository site stratigraphic and structural characteristics can the correct perspective be placed on measured data, i.e., parameters as defined in this report.

Analysis of the available stratigraphic/structural data for the tuff at Yucca Mountain has shown that it is not adequate to fully define these characteristics. Data being acquired is still at the site selection stage and gaps in the knowledge are identified. Mapping, assessment, monitoring and sampling will be necessary during excavations for a shaft and test facility and, ultimately, the repository.

The key issues of design and construction are affected by the stratigraphic/structural characteristics in the following ways:

Issue 1: Constructability
- lithology/mineralogy
- stratigraphic sequence
- faulting/jointing

Issue 2: Thermal Response
- lithology/mineralogy
- stratigraphic sequence
- faulting/jointing

Issue 3: Mechanical Response
- lithology/mineralogy
- stratigraphic sequence
- alteration
- faulting/jointing

Issue 4: Hydrological Response
- lithology/mineralogy
- stratigraphic sequence
- alteration
- faulting/jointing

Issue 5: Geochemical Response
lithology/mineralogy
stratigraphic sequence
alteration
faulting/jointing

Bedding and discontinuities are described in the following sections from a geological point of view but, because of their prime importance for the mechanical properties of the rock mass, they have been included in the overall assessment as part of the mechanical characteristics.

The stratigraphic/structural characteristics of tuff cannot be considered without an understanding of the depositional environment of a typical tuff sequence and modes of alteration. These peripheral aspects are covered in the following subsections which critically examine the stratigraphic/structural characteristics of tuff to assess their relative importance for a repository excavated in that medium. A matrix diagram is presented at the end of this section of the report summarizing the assessments. The site specific study which follows the generic study assesses the importance of the identified characteristics for the tuff repository horizons being currently considered by DOE within Yucca Mountain.

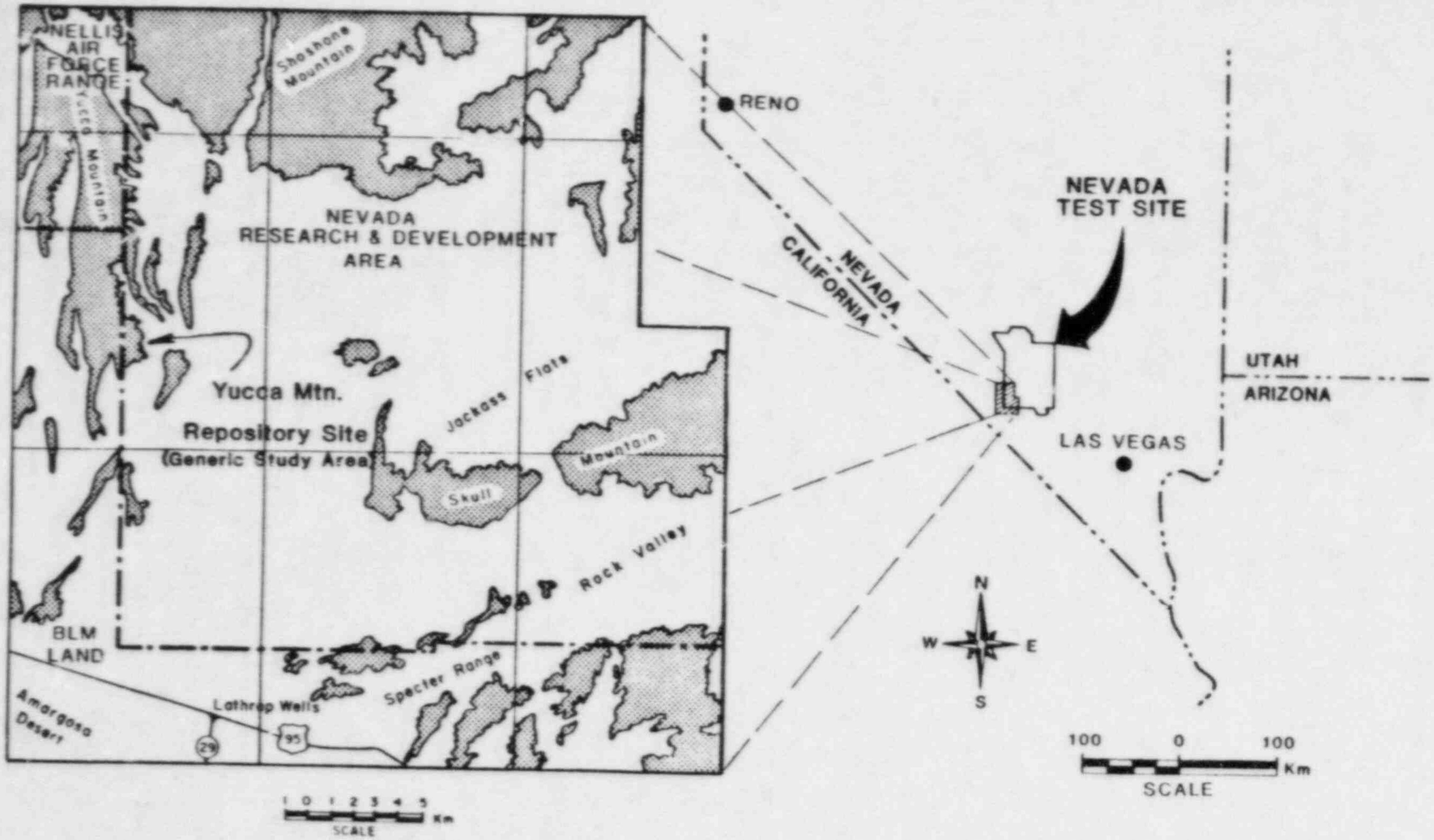
2.1.2 Yucca Mountain (Generic Area for Tuff)

The generic area for this study is Yucca Mountain, located in the southwest quadrant of the Nevada Test Site (NTS). The NTS comprises a 1400 square mile area located approximately 79 km (50 miles) northwest of Las Vegas (Figure 2.1). The area is within the south-central part of the Great Basin section of the Basin and Range province. Yucca Mountain is bordered on the south and east by Jackass Flats, on the west by Crater Flat, and on the north by Beatty Wash. Forty Mile Canyon separates Yucca Mountain from the adjacent Shoshone Mountain to the northeast.

The floors of the basins vary in elevation from 915 m to 1372 m (3000 to 4500 feet) above sea level. The highest point on the Yucca Mountain block is 2046 m (6708 feet), located just outside the northwest corner of the waste repository study area. The tuff generic area is traversed by northwest-southeast trending Yucca Wash, which averages 2.42 km (1.5 miles) in width. Topographic relief between Yucca Wash and the surrounding mountain averages 427 m (1400 feet).

2.2 MODE OF TUFF FORMATION

The mode of formation of tuffs is important to the siting of a waste repository because it directly affects the horizontal and vertical continuity of the lithologic units, the degree of fracturing and



After DOE, Aug. 1981

LOCATION OF GENERIC STUDY AREA WITHIN NTS

Figure 2.1

jointing, and the amount and type of alteration within the tuff units. Thus, the geology directly relates to the degree of continuity and predictability of the thermal, mechanical, hydrological, and geochemical responses of a potential repository placed in tuff.

Tuffs are pyroclastic deposits produced when the gas content of a magma is explosively lost; they may be deposited either directly from explosive volcanic eruptions or as reworked and redeposited sediments. Magma composition may range from basic to acidic, although intermediate and acidic tuffs are the most common. Because of the explosive origin of acidic tuffs, these deposits tend to be more widespread than basic tuffs. In the Basin and Range Province, accumulation of tuff locally exceeds 3000 m (9840 ft) in thickness, and individual units may be tens of kilometers in lateral extent. This mode of origin results in a high degree of variation between different tuff deposits and hence the need to restrict the area of the generic study.

On eruption, silicic (acidic) magmas most commonly contain less than 10 percent primary phenocrysts and less than 10 percent lithic fragments. The remaining 80 percent of the ejecta is volcanic glass. Pyroclastic ejecta deposited above 500°C compact and weld by viscous deformation of the glass. Compacted material that cools rapidly (weeks to months) may remain glassy, but materials that cool more slowly usually crystallize to cristobalite, quartz, and a mixture of feldspars. Glassy material may devitrify within geologic time.

Pyroclastic materials may be classified according to size. Debris more than 32 mm (1.25 in.) across are called bombs if they were partly or wholly molten when discharged and resulted in sub-rounded margins, and blocks if they were entirely solid and predominantly angular (Williams et al, 1954). Fragments measuring between 4mm (0.16 in.) and 32 mm (1.25 in.) in diameter are classified as lapilli, no matter what their condition on discharge; those of smaller diameter are termed ashes. By compaction, recrystallization and cementation the pyroclastic debris becomes lithified. Deposits composed chiefly of bombs become agglomerates and those consisting of angular blocks produce volcanic breccias. Lithification of ash yields tuffs, and those rich in lapilli become lapilli tuffs.

Tuffs may also be classified by composition depending on their content of glass, crystal, and rock debris. Those composed mainly of glass particles are known as vitric tuff; those made up chiefly of crystals are designated crystal tuff; and those in which accessory and accidental rock fragments (originating from the pre-existing rocks) predominate are termed lithic tuffs. Most pyroclastic ejecta, particularly those derived from acid and intermediate magmas, reveal the effects of gravity sorting both by size and by composition. Ejecta generally become finer away from the eruptive vents, though exceptions to this rule may result from changes in wind velocity during transport and from differences in density of the flying particles. Generally, lithic and crystal rich fragments fall nearest the source, while the less dense glassy fragments (especially vesicula fragments) tend to be carried afar. At any one locality, the products of a single ash fall may exhibit graded bedding. The coarser, more crystalline, and more basic minerals and those richer in mafic minerals grade upward into finer materials richer in glass, feldspar and quartz to form layers with a more siliceous composition. Corresponding lateral transitions may often be observed as a layer of tuff is followed away from the parent source.

Most vitric tuffs form by being blown high into the atmosphere and cool before they are deposited upon the surface forming air fall tuffs. Some ashes are discharged as a nuees ardente (glowing, turbulent, gas-charged avalanches) that move rapidly downslope from a crater or fissure forming ash flow tuffs. These gas-charged masses are extremely mobile and consequently may spread over vast areas. Because these ash flows are deposited so rapidly and accumulate to great thicknesses, many remain hot for a long time, especially in the central part of the flows. The shards of volcanic glass, while still hot and under high overburden pressures, are squeezed and flattened and at the same time pumiceous lapilli are deformed into disks, some paper thin. All the constituents thus become firmly annealed to form a welded tuff. The majority of the tuffs discussed in this report at Yucca Mountain are ash flow tuffs with some air fall tuffs.

Tuff deposits that cool as a single entity are commonly referred to as a cooling unit (Figures 2.2 and 2.3). Such a deposit typically has a core of welded material, most of which may have devitrified to quartz and feldspars with or without cristabalite. The welded zone is characterized by a lack of bedding, columnar jointing, and spherulitic structures. At the base of the welded zone, there is typically a layer of densely welded material that has not devitrified, but, instead, remains a dense glass called a vitrophyre. The degree of welding decreases outward from the core so that the welded zone is surrounded by zones of decreasing density, thermal conductivity, competence, and strength. An unsorted, nonwelded horizon of loosely aggregated pumice and ash similar to the air fall unit described previously is commonly present at the base of the ash flow deposit. The transition between the soft unwelded upper portion and the hard jointed, welded zone is commonly gradational, but over a very narrow interval.

Because the surface of the deposit is loose and poorly consolidated, it is readily reworked by surface processes and may be redeposited by streams, in ponds, or as volcanic mud flows (lahars). Such processes give rise to sorted, bedded deposits termed bedded tuffs. A wide gradation exists between true tuffs and sedimentary deposits with a tuffaceous content.

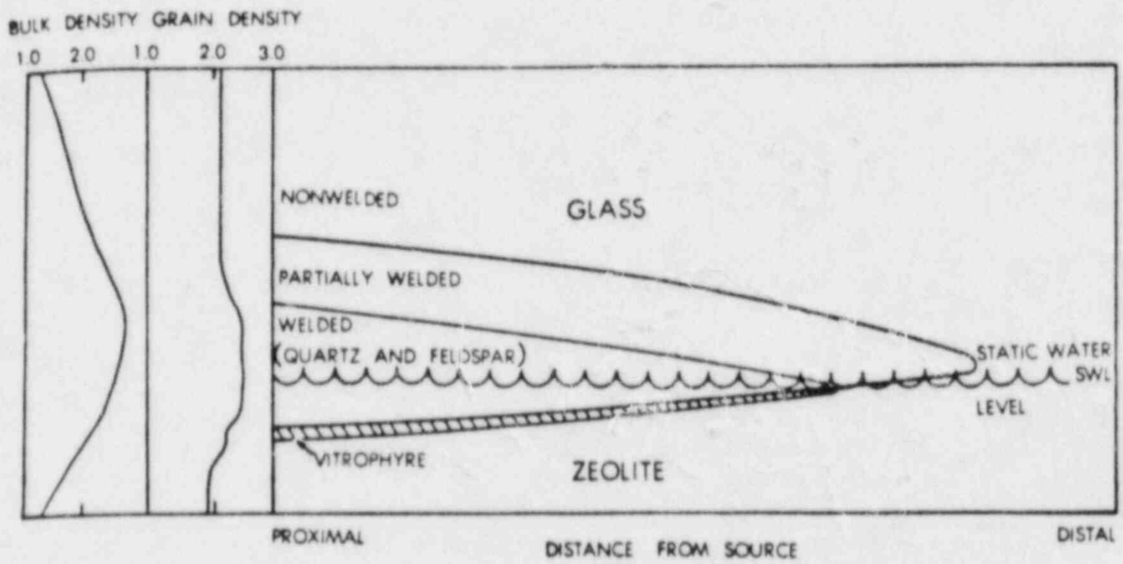
2.3 YUCCA MOUNTAIN GENERIC STUDY

2.3.1 Stratigraphic Sequence

The stratigraphy of the generic study area at Yucca Mountain is based on the series of holes that has been drilled for investigation of potential

SCHEMATIC CROSS SECTION THROUGH AN ASH FLOW TUFF COOLING UNIT WITH TYPICAL BULK AND GRAIN DENSITIES

Figure 2.2



After Smyth and Sykes, 1980

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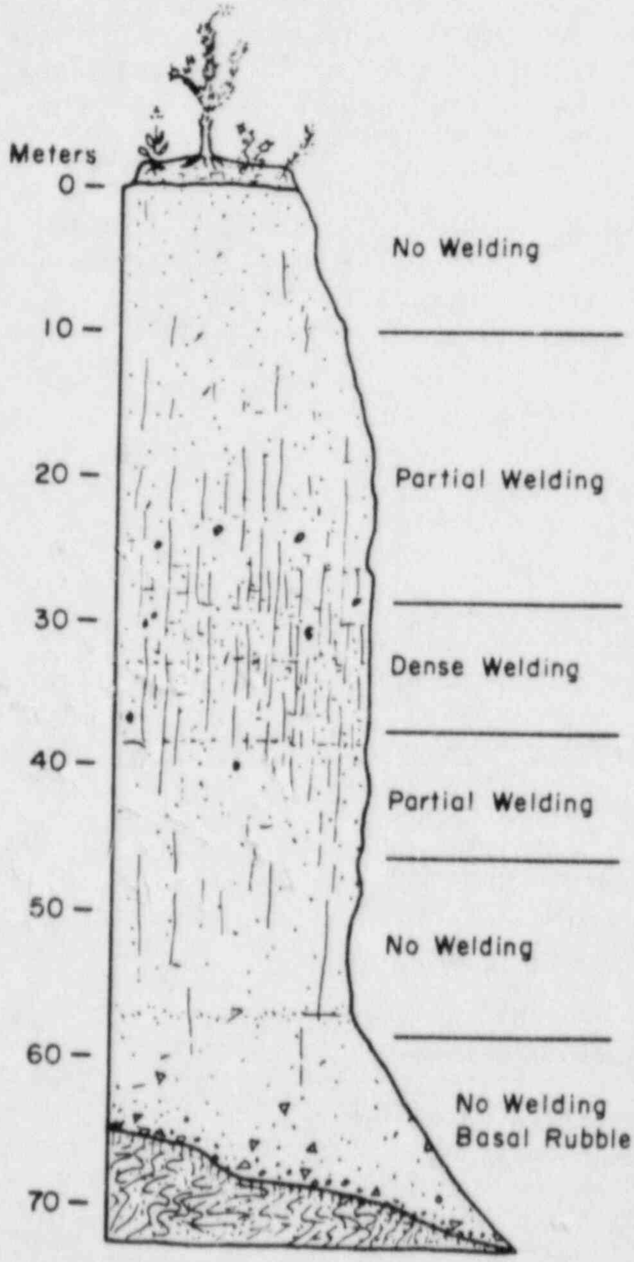
SCHEMATIC STRUCTURAL SECTION THROUGH A SINGLE ASH FLOW TUFF BED

Figure 2.3



After Winograd, 1971

repository sites by NNWSI. Five holes have been drilled within or immediately adjacent to the Yucca Mountain block: UE25a-1, UE25b-1, USW-H1, USW-G1, and USW-G2, but the only official drillhole data available to this study were from UE25a-1 and USW-G1. The location of the holes is shown in Figure 2.4 and a typical stratigraphic sequence is shown in Figure 2.5. The three drillholes shown on Figure 2.5 are regarded as the type-sequence for the generic study area. Much of the laboratory testing has been carried out on samples from these locations and some in situ testing has been undertaken within the holes. While the detail from these investigations is adequate for site selection purposes it needs to be considerably extended for characterization for design and construction requirements. Figure 2.5 gives brief stratigraphic descriptions for the main members of the sequence and indicates the five horizons being considered as potential repositories.

Based on very limited subsurface data, the tuff units at Yucca Mountain, with one notable exception, appear to be fairly uniform in thickness and continuity. The lithic rich upper Tram Member is missing in hole G2. The strata dip between 5° and 7° between drillholes G1 and H1. However, the Bullfrog and Tram Members thin from drillholes G1 and H1 toward drill hole G2.

Because it is desirable to confine the repository to a particular tuff horizon, the stratigraphic sequence becomes a critical characteristic for design.

2.3.2 Lithology and Mineralogy

The lithology and mineralogy of the repository horizon are extremely important because they strongly influence the continuity and predictability of the measured parameters, e.g., thermal, mechanical, and hydrological properties of the host rock.

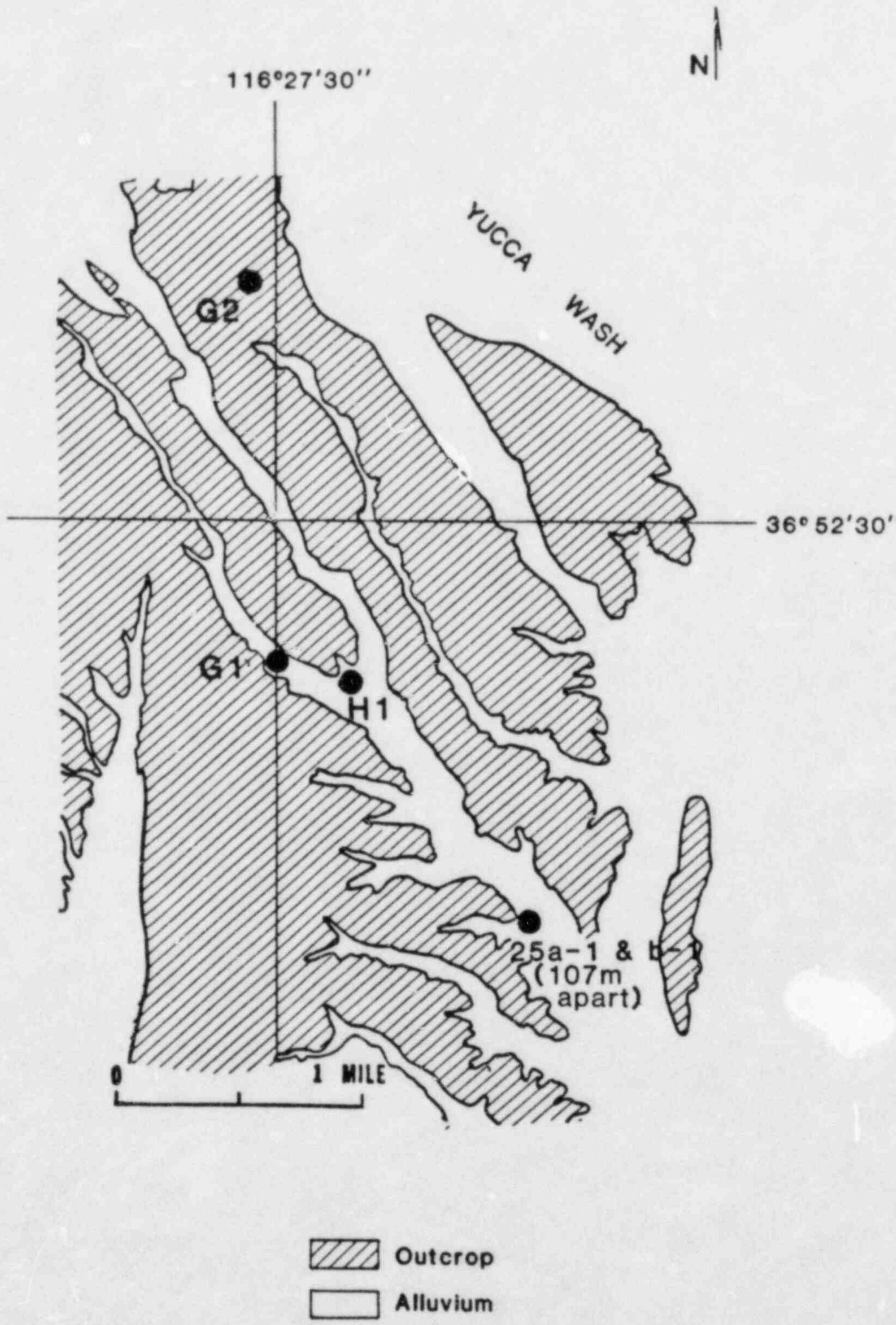
Tuffs are usually well lithified and commonly cemented with carbonate, but quartz, tridymite, and zeolites are also possible cementing agents. When exposed to weathering, the carbonate cement is leached from the tuff, and the original porous nature of the deposit is exposed.

Tuffs are highly variable in their physical properties. However, based on the current available data, it is not possible to quantify with any degree of certainty the limits, i.e., distances laterally or with depth, where similar conditions are likely to be found. While some tuffs are massive, most are usually well bedded. The bedding may be obscured by shearing. When tuffs are interbedded with more competent volcanic flows, the shearing may be concentrated in these relatively incompetent rocks.

Many of the tuffs at Yucca Mountain contain secondary zeolite minerals which may act as effective barriers to radionuclide migration because of their favorable cation sorptive characteristics. However, zeolite

DRILL HOLE LOCATIONS
AT YUCCA MOUNTAIN AREA

Figure 2.4



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ALLUVIUM (Qa) Gravel, sand, silt, containing fragments of densely welded Tiva Canyon Member, and partially welded Yucca Mtn. Member.

PAINTBRUSH TUFF

TIVA CANYON MEMBER (Tpc): A nonwelded to partially welded, vitric tuff; pumice.

YUCCA MTN. MEMBER (Tpy): A nonwelded vitric ashflow tuff; pumice.

PAH CANYON MEMBER (Tpp): A nonwelded, vitric ashflow tuff.

TOPOPAH SPRINGS MEMBER (Tpt): Densely welded, devitrified ashflow tuff (upper 68.6 meters are glassy). Lithophysae between 133.6 - 217.6 meters and 248.5 - 365.8 meters in hole USW-G1.

TUFFACEOUS BEDS OF CALICO HILLS (Tct): Nonwelded, zeolitized ashflow tuff with occasional layers of bedded and reworked tuff. Zeolitization locally ranges from 10 to 80 percent.

CRATER FLAT TUFF

PROW PASS MEMBER (Tcfp): Primarily a partially to moderately welded, devitrified tuff; locally exhibits vapor phase crystalization and argillic pumice. A bedded and reworked zeolitized horizon is located between 656.4 and 662.8 meters in hole USW-G1.

BULLFROG MEMBER (Tcfb): Partially to moderately welded, devitrified tuff with local vapor phase crystalization, slightly argillic between 673.5 and 707 meters in hole USW-G1. Zeolitized pumice horizon between 793.5 and 805 meters in hole USW-G1.

TRAM MEMBER (Tcft): Partially to moderately welded, devitrified tuff (locally nonwelded); argillic and zeolitized between 981.6 and 1074.2 meters in hole USW-G1. Upper contains concentrations of lithic fragments and is partially to moderately welded. Lower is nonwelded to partially welded, zeolitized argillic.

FLOW BRECCIA (Tfb): Interstratified breccia, rhyodacite lava, bedded/reworked tuff, and ashfall tuff; primarily devitrified; moderately to well indurated; lower 7.9 meters (25.8 feet) of unit is argillic; basal 1 meter (3.4 feet) of unit is zeolitized.

LITHIC-RICH TUFF (Tfu): A thick, 319 meter (1046 feet) thick ashflow tuff over a bedded/reworked tuff. The ashflow tuff is partially welded and well indurated with 5 to 15 percent rhyolitic and intermediate lithic fragments, lithics decrease in size and abundance in lower 12.2 meters (40 feet) of interval; argillic and zeolitic. The bedded/reworked tuff is moderately indurated and devitrified; individual beds range from 4 cm to 1.5 meters (0.13 to 5 feet). Lowermost bed, .3 meter (1.2 feet) thick, contains 30-40 percent lithic fragments.

ASHFLOW AND BEDDED TUFF (Tfa): A thick sequence, 323 meters (1060 feet), of ashflow tuffs, airfall tuffs, bedded/reworked tuff, and tuffaceous sandstone. Induration varies from partially to well indurated. The degree of welding in the ashflow and airfall tuffs ranges from nonwelded to densely welded. Nearly all horizons within the unit are zeolitic and/or argillic. Individual beds within the bedded/reworked horizons range from 2 cm to 2.4 meters (0.01 to 8 feet).

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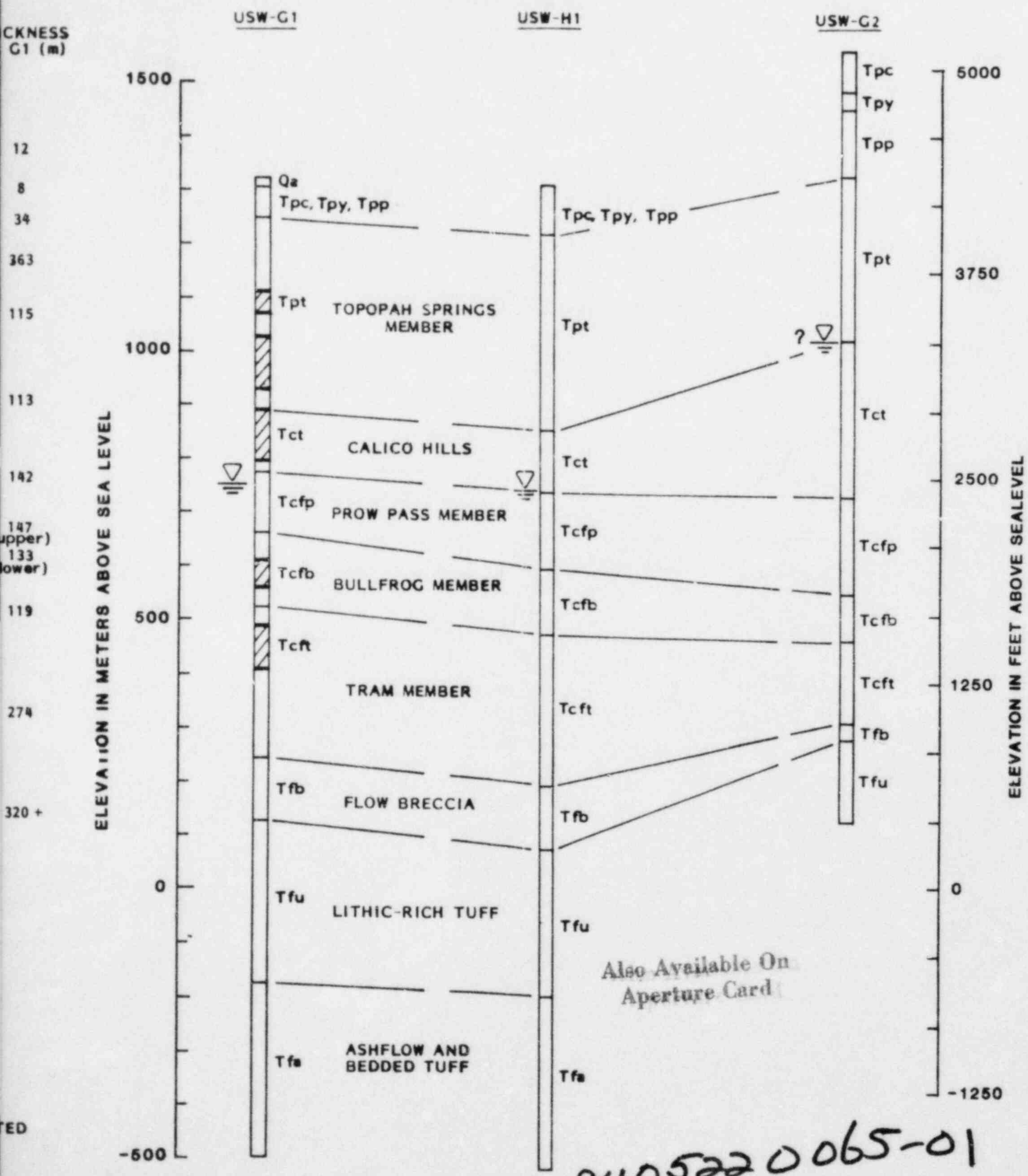
STRATIGRAPHIC SEQUENCE IN GENERIC STUDY AREA

Figure 2.5



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minerals are temperature sensitive and, upon heating, may alter to secondary phases with less favorable sorptive qualities. Alteration is treated more fully in Sections 2.3.3 and 2.3.4.

Because of the high degree of possible variations in lithology and mineralogy within any tuff horizon, it is necessary to select a flow of acceptable and uniform characteristics. For this reason, lithology and mineralogy are critical characteristics in design.

2.3.3 Alteration

Pyroclastic rocks, particularly fine-grained varieties, are readily altered, both chemically and physically. This is because of their high porosity, the large surface area of constituent particles, and the inherently unstable nature of the glassy fragments. Their alteration may be due to simple surface weathering or may result from the influence of circulating groundwater either in the waning stages of the volcanic activity or subsequently.

Devitrification of glass is the initial alteration phase and usually occurs fairly rapidly. In the case of nuee ardente, deuteric alteration may occur while the ejecta are still hot and permeated by fumarolic gases. The glass of some welded tuffs may thus be changed to crypto- and microcrystalline aggregates of tridymite, sanidine or albite while pores may be coated with tridymite, cristobalite, and hematite. In other vitric tuffs, the glass may be replaced by dense felsic mixtures of quartz and orthoclase or sodic plagioclase.

Deuteric alteration of acid and intermediate glasses to opal and clay minerals is widespread. Opalization is usually confined to hot spring areas, but clay may form in any environment. One of the more common products of devitrification is the expansive clay mineral montmorillonite (which is of the smectite group). Montmorillonite is an expanding-lattice clay mineral which exhibits swelling on wetting and shrinking upon drying due to the introduction or removal of interlayer water.

Clay minerals at NTS are reported as sodium saturated montmorillonite-beidellites (DOE, August 1981). The presence of sodium saturated montmorillonite is extremely important in that this particular form of montmorillonite has a significantly higher swelling potential than the other common variety of montmorillonite which is composed of adsorbed calcium cations. The swelling potential is approximately three times greater for sodium than calcium montmorillonites. Similarly, the potential for a volume decrease upon drying would be greater for sodium montmorillonite than calcium montmorillonite. Associated with a volume decrease upon drying is the development of dessication cracks and the widening of joint apertures. This could have an adverse impact upon radionuclide migration routes if the repository horizon were not located sufficiently far from any sodium montmorillonite zones. However, these clays are reportedly ubiquitous at Yucca Mountain. The reaction of ubiquitous sodium montmorillonite to heating and drying is currently unknown and deserves further study.

The presence of sodium as an exchangeable cation leads to high plastic limits and extremely high liquid limits relative to calcium montmorillonites. Since the limit values for montmorillonites vary substantially with the nature of the adsorbed cation, any change in the environment in which such clays existed during or after construction could lead to a significant change in their mechanical properties. In other words, properties might be significantly different from those determined for original undisturbed clay (Grim and Guven, 1978).

Feldspars, as well as glass, may alter to clay or sericite. Mafic constituents tend to be replaced by chlorite and iron oxides.

If porosity is high and water of suitable composition is present, glass may alter completely to zeolites in as little as 10,000 years, even at temperatures below 100°C (Shepard and Starkey, 1964). Zeolite mineral assemblages may therefore be considered as characteristic of low-temperature groundwater alterations of glass in an open hydrologic system (Sykes et al, 1979). If water is not present, or if the porosity is low, as in vitrophyres, alteration will not occur and the material may remain glassy for millions of years. There is no evidence that material once crystalized to quartz and feldspar will later alter to zeolites in the geochemical environment commonly present in these rocks. However, feldspars may alter slowly to clays, particularly in the presence of acidic groundwater. Many acidic and intermediate tuffs are extensively silicified due to deposition of quartz, chalcedony, or opal from groundwater enriched in silica during devitrification of the glass.

Alteration of tuffs, particularly to zeolites of high sorptive properties with respect to radionuclides (see Section 2.3.4), indicates that alteration is a characteristic upon which the repository design will critically depend.

2.3.4 Geochemistry

The presence of zeolites and clays in some tuff units results in highly favorable mineralogic compositions from the standpoint of inhibiting radionuclide migration. However, the complex chemistry and mineralogic variability of tuff units will require extensive individual testing of specific candidate horizons to adequately assess their potential for geochemically retarding radioactive contaminants that escape from the waste package.

Zeolites and Clays

Most welded tuff does not contain a high percentage of zeolites and is thermodynamically stable. A welded, devitrified tuff typically contains as little as 1 to 2 percent absorbed water; constituent phases are generally anhydrous and stable at high temperatures. Nonwelded tuffs contain more zeolites than welded tuffs because they are generally more porous. Zeolite formation requires both high porosity and pore waters of suitable composition. Because of their high porosity, nonwelded tuffs may contain up to 18 percent structurally bonded water. They are thermodynamically unstable at relatively low temperatures.

The principal zeolite phase is high silica clinoptilolite. Calcium tends to be the dominant large radius cation, but grains with dominant potassium or sodium cations are not uncommon, particularly with increasing depth (Sykes et al, 1979). Compositional variations in clinoptilolite may be due to groundwater composition or original pyroclast composition. Minor amounts of mordenite that is characterized by lower silica content and high alkali content occur as vug fillings at depths below 550 m (168 feet) in hole UE25a-1. The presence of mordenite may indicate slightly elevated alteration temperatures, but more likely reflects enrichment of groundwater in alkalis with depth.

Recent work by Los Alamos National Laboratory has shown the mineralogic phase change in zeolites (clinoptilolite-analcime-albite) is very temperature sensitive. Clinoptilolite, which is very sorptive, begins to alter to less sorptive analcime at approximately 100°C. Therefore, to utilize clinoptilolite's very good cation sorption qualities, temperatures within zeolite horizons should be limited to less than 125°C. These breakdown reactions, as well as dehydration of zeolites, result in the formation of denser, less hydrous phases. Thermal effects in zeolitized tuff could potentially cause volume loss leading to shrinkage fractures, and evolution of water vapor (Sandia Laboratories, 1980).

As mentioned in Section 2.3.3, the primary clay minerals at Yucca Mountain are sodium saturated montmorillonite-beidellites with some illite. Zeolites are generally more abundant than clays and are stratified. Clays are ubiquitous throughout the tuff units due to the mode of alteration of the units. Montmorillonite has a high cation exchange capacity, and its presence in the repository rock horizon could provide an additional barrier to the migration of radionuclides. At the present time the temperature effects on clays at Yucca Mountain are not known. However, the capacity of both clays and zeolites to trap ions becomes reduced with continued passage of radionuclides migrating in solution at temperatures greater than 100°C. Thus, the effects of heating will diminish the near-field effectiveness of clays for retarding radionuclide migration through the repository rock horizon.

Adsorption

Adsorption of radionculides by zeolites and clays present in tuff units can cause retardation of migrating radioactive contaminants that are released from the waste package over time. Adsorption is covered in detail in Section 6.

2.3.5 Structure

Structural features which could have an influence on design and construction and must be considered in the selection of a repository horizon are:

- Bedding
- Discontinuities
- Folding
- Faulting/shearing.

2.3.5.1 Bedding

The thickness of an ash flow tuff depends on the volume of material erupted and the topographic configuration over which it is deposited. Over a gentle surface, it will tend to spread laterally and form thinner units; if confined to drainage courses, it will flow further from the source than it it were flowing over a broad plain. Ash flow tuffs tend to have even upper surfaces with very low original dip angles. By contrast, the base of an ash flow tuff may be quite irregular, especially if it was deposited upon uneven topography. It may exhibit evidence of flow around obstacles and down drainages. Successive depositional surfaces within a particular flow become progressively more level as topographic irregularities are filled. This pattern differs markedly from the overall blanketing of the topography by air fall tuffs units, whose thickness depends on the distance from the eruptive center and the wind velocity at the time of eruption.

A principal characteristic of ash flow tuffs is the common occurrence of nonsorted and nonbedded materials. This characteristic is in direct contrast to air fall tuffs in which pronounced bedding is commonly present (Ross and Smith, 1960.)

The NNWSI Peer Review (DOE, August 1981) suggested that the tuffs at Yucca Mountain, being of ash flow origin, are laterally continuous and of sufficient thickness for the siting of a repository within one of the flow horizons. Bedding dips reportedly are relatively shallow and range from 9 to 12 degrees relative to the core axis at the base of the Prow Pass Member in hole USW-G1. However the spatial arrangement of drillholes is considered to be too extensive to evaluate stratigraphic continuity at this time.

Bedding should be treated as a type of discontinuity. Due to its probable irregular and nonuniform disposition at the bottom of a flow, it is considered that it should be treated as a characteristic of minor significance only.

2.3.5.2 Discontinuities

Discontinuities can be defined as any natural or induced fractures or planes of separation in the rock mass, which may or may not show relative displacement. This term includes bedding planes, joints, faults, and fractures. Faults and shears are both fractures upon which relative displacement has occurred. Different terms reflect the amount and extent of displacement, for example, shears are smaller scale features than faults. Bedding plane faults are covered elsewhere, both in this section and in Section 4.

Columnar jointing is a common feature of many welded tuffs and in those parts of ash flows indurated by vapor phase minerals. They normally do not occur in noncrystalline nonwelded parts of the ash flow units. Columnar joints form in response to tensional forces active during the cooling of a flow. Joint spacing may range between 4 to 5 cm and 1 m. The more closely spaced joints are usually found in the zones of most intense welding. In any given locality, the joints appear to be uniformly spaced, although the spacing will vary greatly over several miles. Spacing of joints is controlled by several factors such as the rate of cooling, thickness, and degree of welding. The spacing of joints in outcrops of the Piapi Canyon Group at the NTS (which includes the Paintbrush Tuff) ranges from a centimeter or less in the glassy densely welded zones to approximately a meter in the zone of partial welding; the nonwelded zones contain few visible joints (Winograd and Thordarson, 1975).

Vertical jointing is the most common type, but departures from the vertical are not uncommon. Some welded tuffs have developed fan jointing, while others have distorted vertical joints that give rise to bent or warped columns. These features are probably related to local deviations in the isotherms during cooling.

According to Ross and Smith (1960), many welded tuffs show a horizontal platy jointing in or near the zone of maximum compaction. This platy structure is accentuated by weathering. It should not be confused with the platy structure that is commonly developed by weathering along foliation planes in zones of partial to complete welding and compaction and in zones where devitrification has increased the variation in hardness inherent in the banded nature of these rocks. Ross and Smith (1960) state that platy jointing marks the zone of maximum flattening. However, in some rocks, this jointing is best developed slightly below that zone. In some welded tuffs, vertical joints do not extend below this zone of horizontal joints. In other instances, vertical joints continue downward through the zone of horizontal joints and die out at the top of a nonwelded tuff that forms the base of the unit. Unlike columnar joints in lava flows, which characteristically form 5- or 6-sided polygonal columns, columnar joints in welded tuffs form rectangular to square columns. In general, these are tensional joints produced by cooling, but the mechanism for producing this widely occuring, 4-sided pattern in welded tuffs is not clear.

A study by Spengler et al (1979) of joint occurrence and distribution in drillhole UE25a-1 indicates that, in general, the densely welded ash flows are highly fractured, whereas bedded tuffs and nonwelded to moderately welded ash flows are less fractured. Fracturing in the densely welded zones is likely to be under-represented because of the frequent occurrence of badly broken intervals where accurate measurements of joint planes could not be obtained and because the holes were drilled subparallel to the main joint systems.

Figure 2.6 shows the distribution of joint inclinations (percent of joints in each 10 degree increment) for the five major stratigraphic units. Inclinations are expressed in degrees of dip as measured from the horizontal. As displayed, joints within the Tiva Canyon indicate a nearly random orientation ranging from 0 to 90 degrees. The absence of a preferred inclination more than likely indicates masking of high-angle cooling joints by lower angle planes of weakness resulting from removal of overburden from prestressed rock.

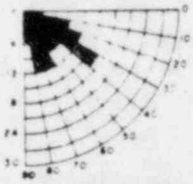
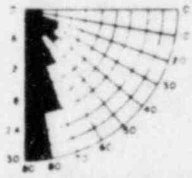
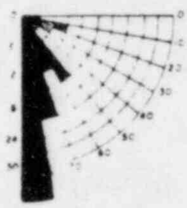
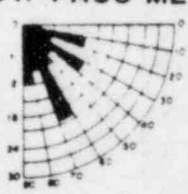
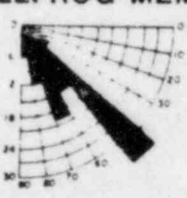
In contrast to the Tiva Canyon, joint development in both the Topopah Spring and the underlying tuffaceous beds of Calico Hills shows a conspicuous preferred inclination in the 80 to 90 degree range. In the Topopah Spring Member, the near-vertical trend of joints is believed to represent columnar joints generated in response to tensional forces active during cooling of the flow. It should also be noted here that fault planes, occurring within the same intervals, show coincident dips. Additional information, such as joint trends from oriented core samples, is needed to better understand this interrelationship and the mode of joint development.

Joints are relatively uncommon in the nonwelded parts of ash flows except where intervals are silicified. Most of the jointing in the tuffaceous beds of Calico Hills occurs near the top of the unit. These joints may represent propagation of pre-existing planes of weakness in the overlying Topopah Spring, possibly caused by differential compaction or regional stresses.

Jointing in the Prow Pass Member shows a trend similar to that found in the Tiva Canyon Member, but joints in the underlying moderately welded Bullfrog Member exhibit a pronounced dip inclined between 40 and 50 degrees. Based upon the abundance of faults with indeterminate persistance having similar inclinations the joint trend is probably related to tectonic processes.

Careful examination of joint faces revealed that 79 percent were partially coated and (or) stained with secondary minerals. Of the remaining joint faces examined, 18 percent were open with no coating and 3 percent were closed with no apparent coating. In decreasing order of abundance, the types of joint fillings are as follows: silica (37 percent), manganese and (or) iron oxides (17 percent), calcite (13 percent), and manganese oxide and silica (12 percent). The pressure-temperature conditions of the joint staining or coating minerals are not known at this time. Of the secondary minerals mentioned, cristobalite, feldspar, and clinoptilolite indicate deuteric alterations. Due to the stratified occurrence of zeolites in the nonwelded portions of the tuffs, it is more likely the clinoptilolite reflects hydrothermal

INCLINATIONS OF JOINTS WITHIN STRATIGRAPHIC UNITS Figure 2.6

INTERVAL FEET	INTERVAL METERS	PERCENT OF JOINTS PER 10° INCREMENT	NUMBER OF JOINTS MEASURED	PERCENT OF TOTAL JOINTS	AVERAGE NUMBER OF JOINTS PER 10-FOOT INTERVAL
54.0-270.0	16.5-82.3	TIVA CANYON MEMBER 	159	17.3	7.4
270.0-1,363.9	82.3-415.7	TOPOPAH SPRING MEMBER 	494	53.7	4.5
1,363.9-1,835.7	415.7-559.5	TUFFACEOUS BEDS OF CALICO HILLS 	46	5.0	.98
1,835.7-2,333.2	559.5-711.1	PROW PASS MEMBER 	181	19.7	3.6
2,333.2-2,500.6	711.1-762.2	BULLFROG MEMBER 	40	4.4	2.4

PERCENT OF FRACTURES

After Spengler et al, 1979

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alteration. However, silica, montmorillonite kaolinite, calcium carbonate, manganese oxide and iron oxide are nondiagnostic as to temperature - pressure conditions. Given sufficient efforts, the pressure - temperature conditions could probably be defined by O_{16}/O_{18} ratios.

Within the Tiva Canyon Member, over 50 percent of the fracture planes were stained with manganese and (or) iron oxides (Figure 2.7). Silica and (or) manganese oxide accounted for over 58 percent of the joint fillings within the Topopah Spring Member. Many siliceous coatings in the unit displayed a distinctive white chalky appearance. X-ray examination indicated the material principally consisted of quartz (40 percent), cristobalite (20 percent), and feldspar (20 percent). In addition to these major components, traces (5 percent) of montmorillonite, clinoptilolite, and kaolinite and less than 10 percent amorphous ash were also detected (Spengler et al, 1979). Both members of the Paintbrush Tuff were the only two stratigraphic units where noticeable amounts of calcite fracture fillings were observed. The deepest joint coated with calcite was reported at a depth of 378.7 m (1242.4 feet), although a few fragments of broken core with calcite coatings were recognized at a depth of 610.9 m (2004.3 feet), which is 141.0 m (462.7 feet) below the present water level. Three samples of calcite from depths of 87.2, 282.7, and 610.9 m (286, 927.5, and 2004.3 feet), were submitted for dating by the uranium-series method. Analyses of all samples resulted in ages greater than 400,000 years (Spengler et al, 1979).

Joints coated with silica accounted for 61 percent of the fractures examined in the tuffaceous beds of Calico Hills (30 percent had no coating). In the Prow Pass all types of fracture filling were observed except calcite. In contrast, only 23 percent of joints in the underlying Bullfrog Member were coated (silica and manganese and (or) iron oxide).

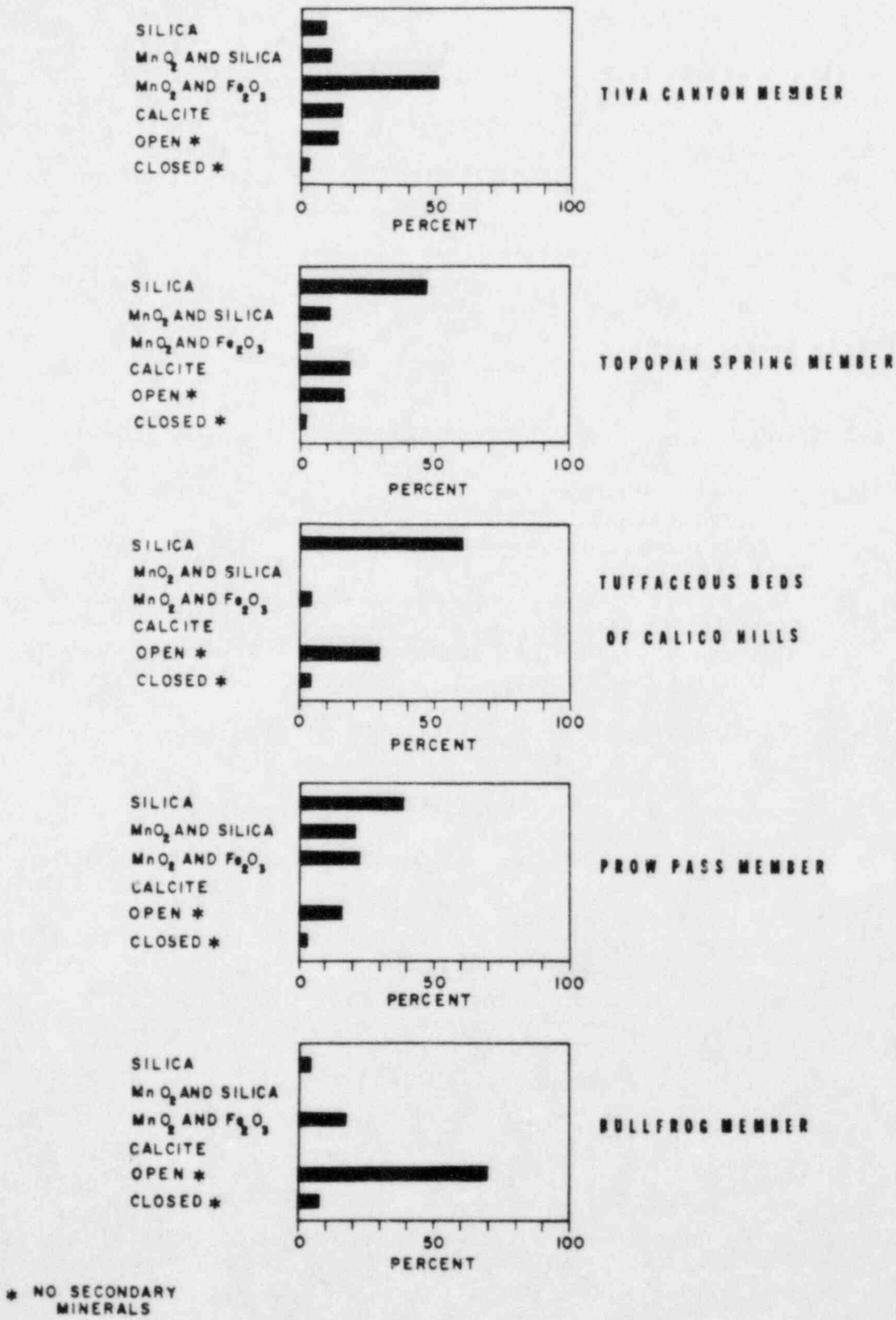
The attitude and spacing of the discontinuities in the tuffs of the Yucca Mountain sequence (Figure 2.5) are considered to be critical characteristics because of their impact on stability and the hydrologic properties of the rocks. The importance of infillings has not been determined in this study, however it may be postulated that thermal effects could increase the aperture of some joints while other joints may be closed by thermal expansion.

2.3.5.3 Folding

There is no record in the literature of folding of the Yucca Mountain beds. Some fault blocks are locally tilted. Folding is regarded as being of no significance in the design and construction of a repository.

TYPE AND PERCENT OF JOINT FILLINGS WITHIN STRATIGRAPHIC UNITS

Figure 2.7



After Spengler, et al, 1979

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2.3.5.4 Faulting

Yucca Mountain is composed of northward-trending and eastward-tilted structural blocks. North of an east-west hinge line located at 36° 52' latitude (Figure 2.4) there is dense north-south normal faulting. creating north to northeast trending structural blocks that are broken into smaller blocks by randomly oriented secondary faulting. This is postulated to be the result of subsidence and resurgence within the Claim Canyon caldera during eruption of the Paintbrush Tuff (Doyle et al, 1981). South of the east-west hinge line, major faulting is less abundant and displacements are of smaller magnitude. Steeply dipping, north-south normal faults delineate a system of horsts and grabens along the eastern flank of Yucca mountain.

The area being studied by DOE for potential repository development is situated along the east-west hinge line and is bounded by Tertiary faults. These faults are steeply dipping, and it is believed that repository construction activity within the block would avoid intersecting the faults at depths of less than 4000 feet (Doyle et al, 1981).

Based upon very limited data, no evidence of Quaternary faulting has been observed in the southwest quadrant of the NTS but it has been reported in the northeast and southeast quadrants. The major north-south faulting bounding the study area has been dated at 11.3 million years before present (Doyle et al, 1981).

Five fault zones were recognized in hole UE25a-1 by Spengler et al (1979). Evidence for faulting in this hole was based on brecciated core; abrupt changes in the dip of pumice layers, zones of granulation, and striations and slickensides on fracture surfaces. Due to the absence of any thin, well-defined marker beds, the magnitude of displacements within fault zones could not be established. The five fault zones are summarized in Table 2.1.

Two faults were encountered in drillhole USW-G1, both within the Tram Member. The first, located at a depth of 1074 m (3522 feet), is 2 cm thick. The second fault is situated at the base of the member at 1085.3 m (3558.2 feet). The fault corresponds with a 0.24 m (0.8 feet) thick layer of "swelling" green clay.

Faulting is likely to have a severe effect on the near-field and far-field characteristics of a repository site. At the present time, little is known about the width and nature of the fault zones other than that mentioned above in hole USW-G1. It is important to ascertain the width, composition, texture, and the continuity of individual shears within a fault zone as it may have a direct influence upon groundwater migration routes. Although it has been shown that the potential repository sites currently being studied at NTS have avoided the worst zones of faulting, the role of faulting in design has not yet been considered in detail. The fact that two of the few holes drilled to date have intersected faults indicates that they may be more widespread than initially supposed. Faulting is considered to be a characteristic of critical significance for design.

TABLE 2.1
Fault Zones in Drillhole UE25a-1

Fault Number	Interval; m	(ft)	Member
F1	(20.4-329)	67-100.4	Tiva Canyon & Topopah Spring
F2	(410-426)	125-130	Topopah Spring
F3	(665-725)	202.8-221	Topopah Spring
F4	(1226-1365)	374-416	Topopah Spring
F5	(2422-2500)	739.7-765.5	Bullfrog

2.4 DESIGN AND CONSTRUCTION

2.4.1 Generic Stratigraphic/Structural Characteristics Affecting Design and Construction

The stratigraphic and structural characteristics are of importance for design and construction reasons, insofar as they represent the framework upon which the mechanical, thermal and hydrological parameters depend. Thus, although these characteristics will not be determined by any in situ test and, hence, are rightly termed factors rather than parameters in the terms of this report, techniques need to be specified by which these factors can be described and their influence on the measurable parameters assessed. These factors must be addressed in the consideration of the integrity of the repository.

The matrix shown on Table 2.2 relates the geological characteristics to five key issues as defined in the introduction. Geological characteristics of critical and major significance have importance to design and construction in the following ways:

- Structural stability of the openings (tunnels, caverns, shafts) due to lithology, nature/orientation of the discontinuities and faults, and the stratigraphic sequence
- Deformation of the openings due to lithology and stratigraphic sequence
- Inflow to the excavations resulting from the lithology/mineralogy, stratigraphic sequence and faulting/jointing
- Material response to thermal changes due to the mineroloay
- Geochemical stability related to the mineralogy of the tuff and the alteration products within the tuff, i.e., zeolites and clays

TABLE 2.2

EVALUATION OF STRATIGRAPHIC/STRUCTURAL CHARACTERISTICS IN TERMS OF THEIR INFLUENCE ON KEY ISSUES

KEY ISSUES	CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Lithology/Mineralogy	beg (Major)	beg (Major)	aeg (Critical)	adg (Critical)	aeg (Critical)
Stratigraphic Sequence	beg (Major)	beg (Major)	aeg (Critical)	adg (Critical)	aeg (Critical)
Faulting/Jointing	adh (Critical)	ceh (Minor)	adh (Critical)	adh (Critical)	adh (Critical)
Alteration	cfg (Insignificant)	cfg (Insignificant)	beg (Major)	beg (Major)	adg (Critical)

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions of the levels of influence.

ATTRIBUTES

- availability of design and construction techniques which allow for conservative assumptions for the value of the characteristic:

  a) reasonable techniques are not available (i.e. high cost impact)
  b) some techniques are available, but at moderate cost impact
  c) reasonable techniques are available (i.e., little cost impact)

- uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:

  d) model has low uncertainty (i.e., is very representative) and high sensitivity to characteristic
  e) model has moderate uncertainty and moderate sensitivity
  f) model has high uncertainty or low sensitivity

- cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values:

  g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
  h) uncertainty can be reduced, but only during in situ testing
  i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization).

- Radionuclide migration dependent on the hydraulic conductivity which is closely related to the presence of faults, discontinuities and the geochemical stability of the tuffs.

2.4.2 Mitigating Design and Construction Strategies

The impact of adverse characteristics of the site may be reduced by appropriate design and construction strategies. Mitigating measures for adverse stratigraphic/structural characteristics which should be considered are:

- Siting the repository in a region of relative horizontal and vertical continuity
- Controlling the heat generated by the repository waste so that favorable cation sorption characteristics of zeolite are retained
- Siting repository away from sodium montmorillonite zones.

Other mitigating measures to control the mechanical, thermal and hydrological response of the site to the repository will be presented in Sections 4 through 6.

2.5 SITE SPECIFIC STUDY

2.5.1 General

The critical characteristics described from a generic point of view in the foregoing sections are considered specifically for the two repository horizons within the Yucca Mountain sequence, the Bullfrog Member and the Tram Member of the Crater Flat Tuff Formation (Figure 2.5).

As previously mentioned, the Yucca Mountain region is underlain by a tuff sequence which may locally exceed 3000 m in thickness. These Members are two of several horizons that have been selected as candidate repository horizons by the Department of Energy. The Bullfrog and Tram Members are subunits of the Crater Flat tuff, which overlies a flow breccia. The Crater Flat tuff is overlain by the tuffaceous beds of Calico Hills. The five exploratory holes that have been drilled within or immediately adjacent to the Yucca Mountain block (holes UE25a-1 and b-1, USW-G1, USW-H1, and USW-G2) and are used to broadly describe Yucca Mountain from the generic point of view, are the same holes used to describe in detail the repository horizons. Hole UE25a-1 bottomed within the Bullfrog Member after having penetrated 51 m (167 feet) of the unit. Holes USW-G1 and USW-H1 penetrated 142 and 125 m (466 and 410 feet) of the Bullfrog Member and 280 m (918 feet) and 284 m (932 feet) of the Tram Member respectively (Figure 2.5). Hole USW-G2 encountered 88 m (289 feet) of the Bullfrog Member and 152 m (499 feet) of the Tram Member.

Because there is insufficient data to describe separately the two members, they are treated together for the site specific study except where there are necessary distinctions to be made.

2.5.2 Bullfrog and Tram Members

2.5.2.1 Stratigraphy

Based on very limited data, the strata in Yucca Mountain appear to be gently dipping. Reported dips range from 5 and 7 degrees between holes USW-G1 and USW-H1 (DOE, August 1981). The Bullfrog and Tram Members appear to thin to the north toward USW-G2 from holes USW-G1, USW-H1, and UE25a-1 with dips ranging between 3 and 6 degrees (Figure 2.4). The Bullfrog Member thins from 142 m (465.8 feet) thick in G1 to 88.1 m (289 feet) thick in G2 and the Tram member thins from 280 m (918 feet) in G1 to 152 (499 feet) thick in G2. Apparently the upper lithic rich portion of the Tram Member is missing in hole USW-G2 (Fenix and Scisson, personal communication). This portion of the Tram Member may have been removed by faulting or, alternatively, may not have been deposited in this region of Yucca Mountain. The source caldera of the Tram Member is considered to lie in the Bare Mountain-Crater Flat region to the west-southwest of Yucca Mountain (Fenix and Scisson, personal communication). If such is the case, then drill holes USW-G1 and USW-H1 are located closer to the source area than USW-G2 which is 2.4 km (1.5 mi) north of USW-G1. Available data are insufficient to accurately evaluate stratigraphic continuity at Yucca Mountain.

2.5.2.2 Lithology, Mineralogy

As stated previously, the Bullfrog Member was encountered in holes USW-G1, USW-G2, USW-H1, and UE25a-1, although hole UE25a-1 did not penetrate the entire section of this unit. The following discussion of the Bullfrog and Tram Members lithology and mineralogy is based on the lithologic log of corehole USW-G1 supplied to us by Fenix and Scisson.

The upper 44 m (144.9 feet) of the Bullfrog Member in drillhole USW-G1 consists of nonwelded, devitrified ash-flow tuff which is locally argillic from 665 m (2,179 feet) to 707 m (2,317.4 feet). This nonwelded tuff is separated from an underlying partially welded vapor phase zone by a 0.15 m (0.5 foot) thick, moderately indurated, bedded and reworked tuff. The partially welded zone beneath the reworked tuff is 39 m (129 feet) thick and exhibits vapor phase crystalization. Underlying the partially welded zone, is a 31 m (100 feet) thick zone of moderately to densely welded, devitrified tuff exhibiting some vapor phase crystalization in the upper 6 m (20 feet). Beneath the moderately to densely welded zone, is a 17 m (55 feet) thick moderately to partially welded, devitrified tuff. The base of this unit is reported to dip 10 degrees relative to the core axis. The basal portion of the Bullfrog Member is characterized by a 11.5 m (37.8 feet) thick bedded and reworked tuff with beds containing from 5 to 80 percent pumice which is commonly zeolitized. A light red to moderate-reddish brown, thin bedded, highly silicified unit occurs at the base of the bedded interval. Phenocryst content ranges between 10 and 25 percent and typically consist of plagioclase, quartz, sanidine, biotite, and hornblende.

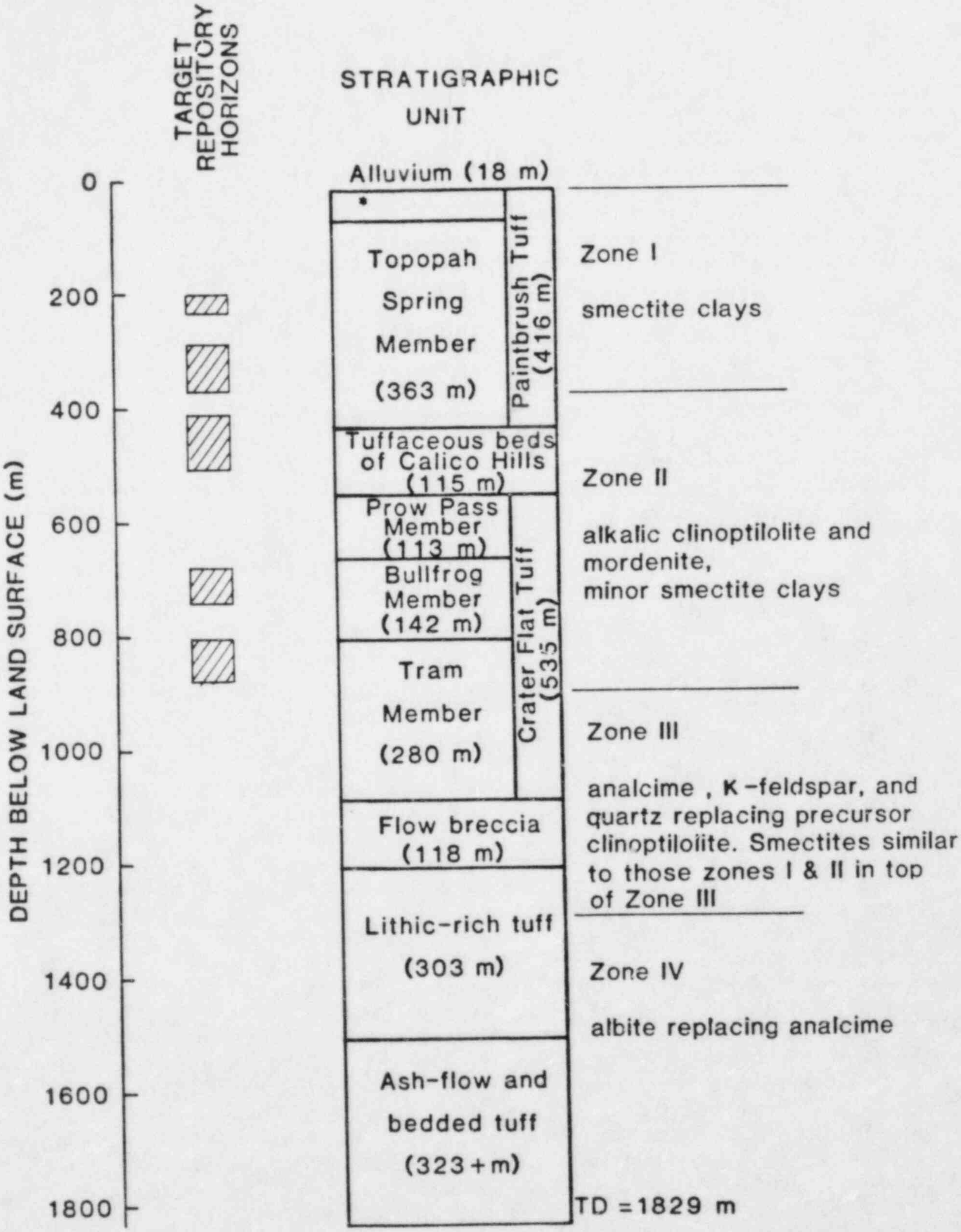
The Tram Member is partially to moderately welded from the top of the unit of 805 m (2639.4 feet) to a depth of 951.9 m (3121 feet). A 22.6 m (74 feet) thick lithic-rich zone, which is located between 931.2 m (3053 feet) and 953.7 m (3126.9 feet) contains 3 to 5 percent lithic fragments. Lithic fragments commonly range from 1 cm to 5 cm in diameter. The lithic rich zone contains localized intervals (approximately 0.3 m thick) containing as much as 50 percent lithics. The lithic rich zone is apparently missing 2.4 km (1.5 miles) to the north in drillhole USW-G2 (Fenix and Scission, personal communication).

Below the lithic-rich zone, the tuff ranges from nonwelded to partially welded. The upper 135 m (444 feet) of the unit is devitrified. The lower portion of the Tram Member extending from 940 m (3083 feet) to the base of the member at 1085 m (3558 feet) is argillic and zeolitized. The basal portion of the Tram Member is composed of a 11 m (36 feet) thick moderately indurated, bedded, reworked tuff and tuffaceous sandstone. The lower 0.24 m (0.8 foot) of the bedded and reworked tuff is altered to a grayish-yellow-green swelling clay. Phenocryst content ranges from 10 to 25 percent and phenocrysts consist of plagioclase, quartz, sanidine, hornblende, biotite, and possibly pyroxene. A zone of finely disseminated sulfides in the matrix as well as lithic fragments is located between 982 m (3218 feet) and 1074 m (3522 feet); the sulfide content increases downward.

The presence of zeolites and clays in some tuff units has some importance because it can result in highly favorable mineralogy from the standpoint of inhibiting radionuclide migration. Zeolite and clay alteration zones have been recognized in the stratigraphic section penetrated by drillhole USW-G1 (DOE, August 1981) and these are presented in Figure 2.8. Zone I, the upper tuff stratigraphy in the drillhole down to 395 m, contains the alteration assemblage Na-K montmorillonite clays, opal, chalcedony, and authigenic cristobalite. Zone II, which extends from 395 to 955 m below the surface, contains the assemblage alkalic clinoptilolite and mordenite as zeolite phases, minor clays, which again are Na-K montmorillonites with less than 10 percent illite and quartz predominating over cristobalite. The top of Zone III is placed at about the 955 m level; the zone shows pervasive development of analcime, K-feldspar, and quartz replacing precursor clinoptilolite. Na-K dioctahedral montmorillonite similar to those in Zones I and II are common in the top of Zone III. These montmorillonites are interstratified with less than 15 percent illite, and preliminary data indicate no clear trend of increasing interstratification with depth (DOE, August 1981). Zone IV represents the appearance of authigenic albite in the core and could possibly have intersected at 1340 m depth. Below 1550 m, authigenic albite and K-feldspar become the dominant secondary minerals in the nonwelded as well as welded units. The site specific repository horizons being considered both lie within Zone II as shown in Figure 2.8.

ZEOLITE AND CLAY ALTERATION ZONES IN DRILL HOLE USW-G1

Figure 2.8



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The temperatures of formation estimated from zeolite zone boundary characteristics are different from those implied by the degree of interstratification in the montmorillonites. Zeolite temperatures were based on zeolite phase relationships; particularly the clinoptiloite-analcime-albite reaction series which is very temperature sensitive. For clays, the amount of illite interstratified with the smectite clays was used to estimate the temperature of formation, as the amount of interstratified illite is a function of the paleogeotherm (personal communication, D. Vanimin, Los Alamos National Laboratories). Thus, zeolite and clays were formed at separate times through different processes. The implications of this, if any, are not clear at this time from the standpoint of mechanical or geochemical response.

Section 2.3.3 has considered alteration in tuff from a general standpoint. It is apparent from Figure 2.8 that clinoptilolite is the principal zeolite phase to be expected in the repository horizons with lesser mordinite, montmorillonite clays, illite and quartz. The sorptive properties of these altered minerals must be traded against their adverse properties produced by thermal change.

Although the profile of alteration distribution with depth has been well described for drillhole USW-G1, data available to this study was insufficient to gain an understanding of the lateral distribution of alteration products with regard to the repository horizons.

2.5.2.3 Structure

a. Discontinuities

Jointing affects the repository design primarily in the area of rock support, excavation stabilization, and permeability within and surrounding the repository horizon. The degree and frequency of joints and fractures are poorly known repository design parameters at Yucca Mountain. Until additional data become available, joint and fracture characteristics of tuffs can be discussed only in a general way with respect to the Bullfrog and Tram Members. The available data on fractures and joints near the target repository horizons are within the Bullfrog Member penetrated by hole UE25a-1. Densely welded tuffs are generally highly fractured and bedded tuffs and non-welded to moderately welded ash flows are less fractured (see Section 2.3.5). Fracturing in the densely welded zones is likely to be under-represented because of the frequent occurrence of badly broken intervals where accurate measurements of joint planes can not be made (Spengler et al, 1979). Forty joints were measured within the Bullfrog Member between 711.1 and 762.2 m (Figure 2.6). Joints within the Bullfrog Member exhibit a pronounced dip of 40 to 50 degrees from the horizontal. A second preferred dip is between 60 and 70 degrees to the horizontal. The average number of joints per 10-foot interval of core is 2.4. Circulation losses occurred repeatedly during coring of the highly fractured intervals, suggesting that many fractures are open and interconnected. Seventy percent of the joints within the Bullfrog Member measured by Spengler et al (1979) are open (Figure 2.7). He further suggests, based on similar shear fracture inclinations, that these joint trends are probably related to tectonic processes.

Because all the drilling was carried out vertically, subparallel to some of the joint systems, these discontinuities are not considered to be representative of the Bullfrog repository horizon as a whole.

b. Faulting

The structural setting is as described in Section 2.3.5.4. The incidence of fault zones identified within the core is described in the same section; only one of the faults described was within the potential repository sequence. No evidence of Quaternary faulting has been observed in the area. The major north-south faulting bounding the study area has been dated at 11.3 million years before present (Doyle et al, 1981).

Shear planes in four of the five fault zones indicate coincident dips with preferred orientations of joints within their respective stratigraphic units, except in the lower half of fault zone (F5) in the Bullfrog Member where steeper dips (70 to 80 degrees) were measured.

In fault zone F5, clay gouge was commonly recognized along shear fractures. Only limited data are available concerning the existence of faults in holes G1 and G2. However, two faults are present in the lower portion of the Tram Member in hole G1. One fault zone (2 cm thick) is located at the base of a nonwelded to partially welded tuff unit at a depth of 1074.2 m (3522 feet). The second fault, of unknown thickness, is located at the base of the Tram Member. The lithologic log of G1 indicates the lower 0.24 m (0.8 feet) of the member is altered to a grayish-yellow-green expansive clay.

These data are useful but cannot be considered as a comprehensive investigation of the Bullfrog and Tram horizons even at the site specific level.

2.5.3 Design and Construction Aspects of Repositories in the Bullfrog and Tram Members

There is no reason to indicate that the stratigraphic/structural characteristics identified in the generic study as critical to design and construction in tuff at Yucca Mountain (Table 2.2) would not also be critical in the two potential repository horizons in the Bullfrog and

Tram Members. These characteristics would include stratigraphic sequence, lithology and mineralogy, alteration, and faulting/jointing. However, to a large extent the justification for this statement is absent because information, on which the characteristics are assessed, is still being collected.

3. TECTONIC ACTIVITY

3.1 GENERAL

Tectonic activity refers to the large-scale disruption of the earth's crust as evidenced by seismicity, volcanism, faulting/folding and uplift/downwarp. Many of these processes are confined to well-delineated zones within the crust as the result of lithospheric plate movements. However, even outside the major zones, tectonic activity is present in varying degrees and must be considered as a group of potential disruptive processes which could have effects on the design and construction of a nuclear waste repository.

Although tectonic activity is considered primarily during the site selection stage of site characterization, it also has importance for design and construction. Particular aspects treated here are seismicity, potential for further crustal instability, volcanism and potentially active faulting.

Because tectonic aspects relate primarily to areas rather than specific features, and the site specific repository horizons are coincident with the study area at Yucca Mountain, no distinction is made between the generic study and the site specific study for tectonic characteristics.

The key issues of design and construction are significantly affected by the four tectonic characteristics in the following ways:

- Constructability
  - seismicity
  - faulting
- Thermal Response
  - volcanism
- Mechanical Response
  - seismicity
  - crustal instability
  - volcanism
  - faulting
- Hydrological Response
  - seismicity
  - crustal instability
  - faulting
- Geochemical Response
  - volcanism
  - faulting

The following sections critically examine the tectonic characteristics to assess their relative importance to these key issues in tuff. A matrix diagram is presented after these sections summarizing the assessment.

3.2 SEISMICITY

3.2.1 Background

Yucca Mountain is on the Western border of the Nevada Test Site about 1/3 of the distance from the southern to the northern boundary. The NTS is near the southern boundary of the state of Nevada about 1/3 of the distance from the eastern to the western state boundary. The NTS is in the Basin and Range geological province but is close to the Sierra Nevada batholith where faulting is apparently influenced by Pacific Plate movements to the east. The seismicity of eastern Nevada, including the NTS, is relatively low. Maximum magnitudes are in the M=5 range. In adjacent western Nevada and California, seismicity is higher and maximum magnitudes have been historically recorded in the M=7 range. Nuclear blast tests at NTS, which release energy on the order of magnitude 6.5, disrupt the local stress field causing aftershock sequences. These man-made perturbations have resulted in differences of opinion concerning the seismic hazard at NTS. Pretesting seismicity at NTS, however, closely matches posttesting seismicity in a zone 40 to 80 miles from NTS. This strongly suggests that natural seismicity at the NTS is very similar to that of eastern Nevada in general.

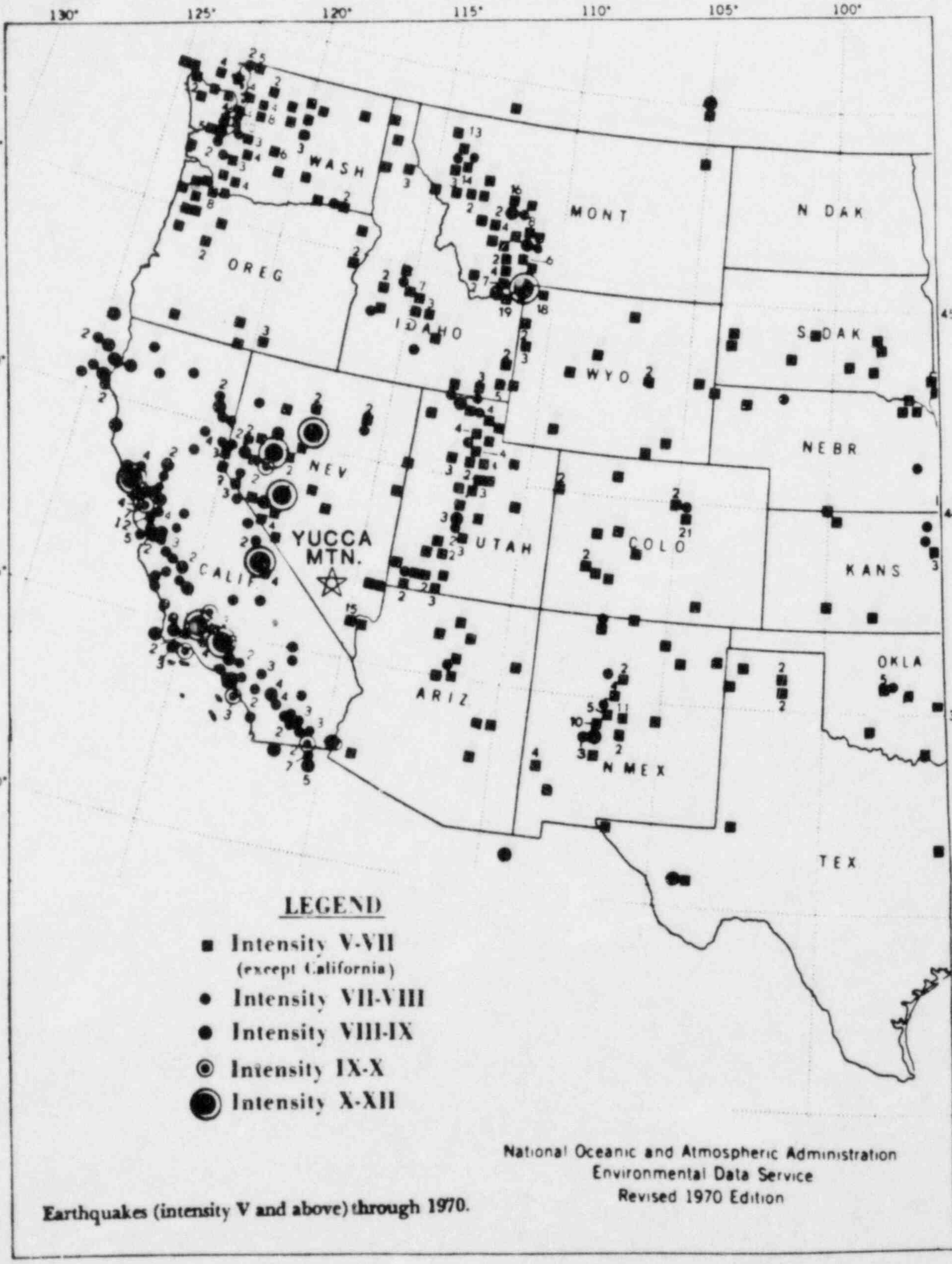
Volcanic activity and tectonic activity, which produced Basin and Range geomorphic features, were most active in the Tertiary geologic period from about 3.5 million to 2 million years before present (Albers, 1964). Coffman and Von Hake (1973) list 25 earthquakes which were felt and which occurred in eastern Nevada. The highest intensity of these was MMI=VII in 1901 but was felt over a very small area which suggests this intensity estimate may be high. The historic record began approximately at the turn of the century.

3.2.2 Seismic Sources

Sesmicity of the western United States, from Coffman and Von Hake (1973), is illustrated in Figure 3.1. This figure shows relative seismicity throughout the area including the Yucca Mountain repository site. West of Yucca Mountain lies the 118° seismic zone of Slemmons which contains earthquakes in the M=7+ range. This is depicted in more detail in Figure 3.2 which also includes many microearthquakes recorded by the University of Nevada seismic network. This zone is about 100 miles from Yucca Mountain and shaking from sources in this area would be attenuated to nondamaging levels at Yucca Mountain (as can be shown using the attenuation curves of Schnabel and Seed, 1973).

A plot of all earthquakes in the National Earthquake Information System (NEIS) computer tape for the area about the NTS is in Figure 3.3.

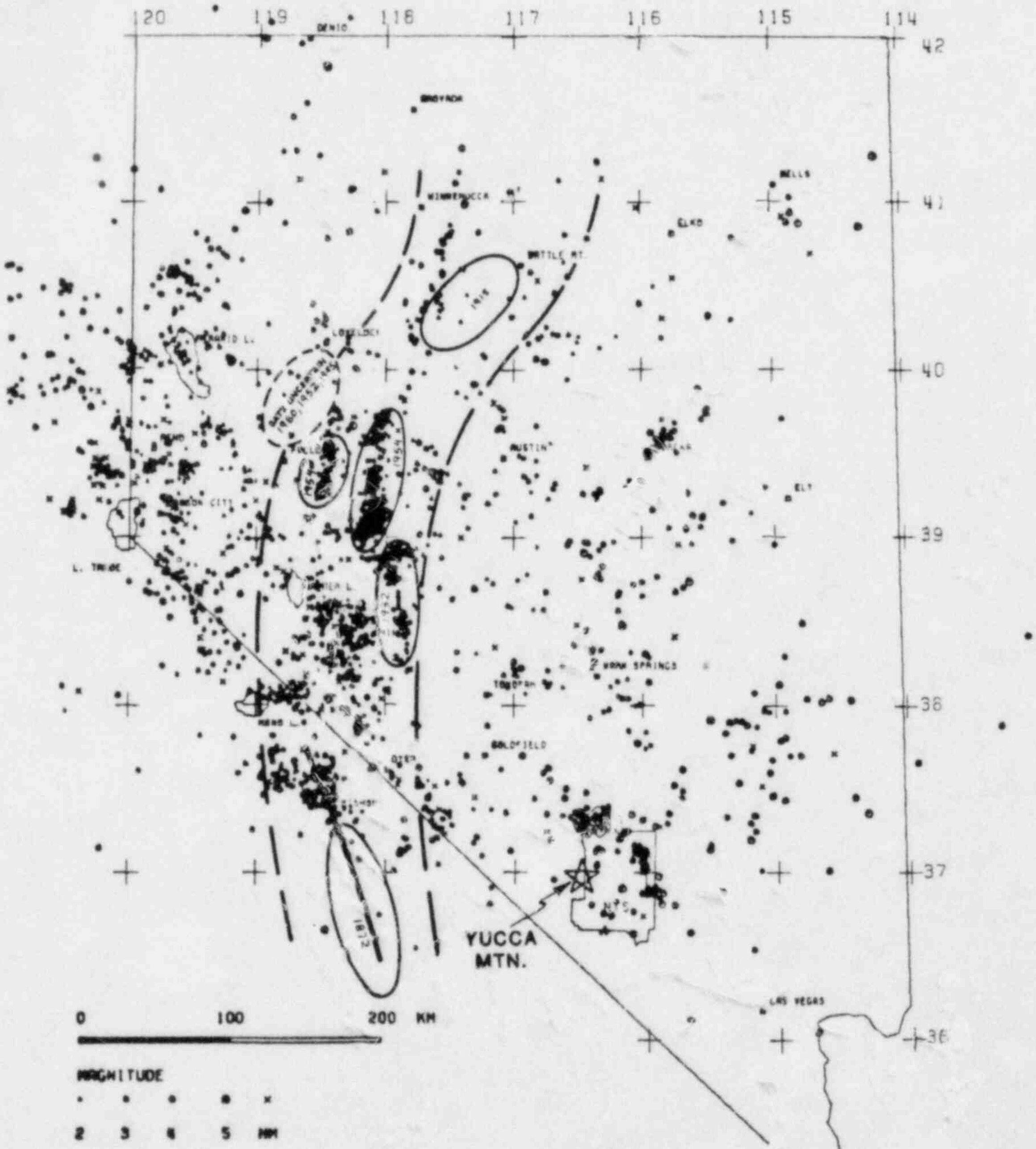
SEISMICITY OF THE WESTERN UNITED STATES Figure 3.1



After Coffman and Van Hake, 1973

THE 118° SEISMIC ZONE AND 1970 - 1978 MICROEARTHQUAKES

Figure 3.2



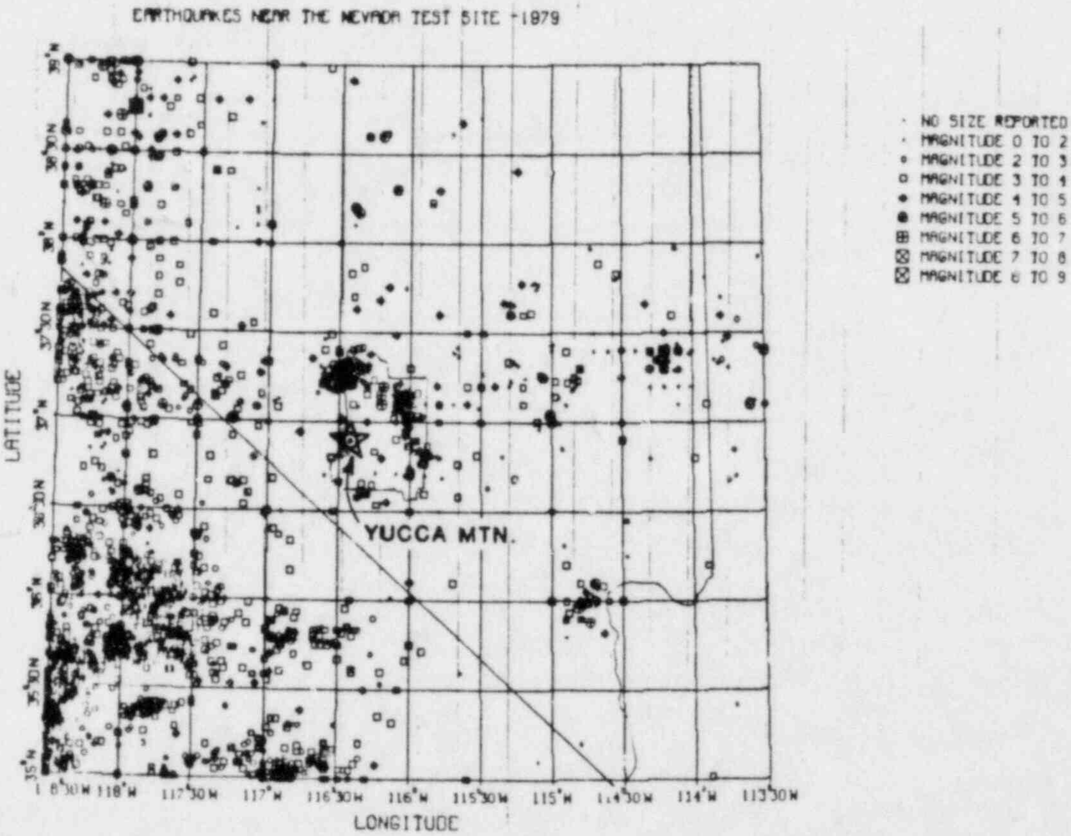
APPROXIMATE BOUNDARIES OF NEVADA SEISMIC ZONE

1970-1978 EPICENTERS FROM FINDLEY 1980 (U. of Nevada Data File)
ELLIPTICAL OUTLINES OF AREAS AFFECTED BY LARGER HISTORIC EARTHQUAKES FROM RYALL 1977
LINEAMENTS FROM SLEMMONS 1967

Project No. 83-116 Reviewed Date 12-81

NEIS EARTHQUAKE DATA TAPE PLOT

Figure 3.3



Project No. 8/3-1162C Reviewed ______ Date 12-81

Events on this figure include aftershocks of nuclear blast testing. Particularly noticeable are the blast aftershock clusters at Pahute Mesa (N.W. Corner of NTS) and Yucca Flat (NE and N. Center of NTS).

A conservative estimate of seismic hazard for NTS was made by Rogers et al (1977). Seismicity was considered to be uniform over a 400 mile radius from NTS, taking in California San Andreas activity. Faults which nuclear weapons testing had caused to move were considered capable of generating damaging level earthquakes. The seismicity level at NTS is questioned because few seismographs were in the area prior to nuclear blast testing and aftershocks which obviously accompanied large test blasts were observed in the subsequent records.

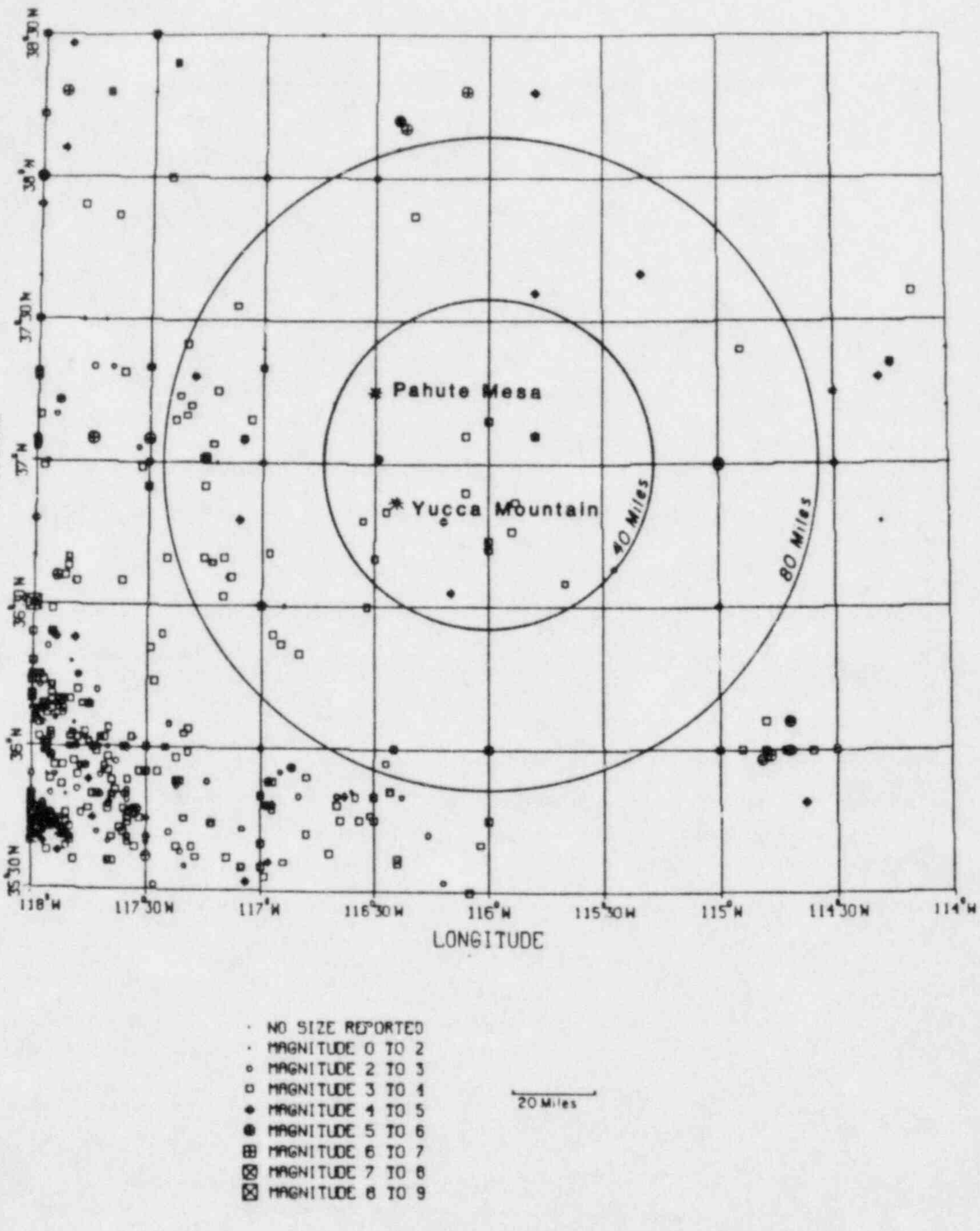
Seismicity data within 80 miles of NTS is examined in the following paragraphs to assist in resolving the issue of level of seismicity at NTS. Seismic events (excluding known explosions) are plotted in Figure 3.4 (events through 1960) and Figure 3.5 (events after 1960). According to Rogers et al (1977), nuclear weapons testing began in 1960 when the shift to underground testing occurred following the 1958 moratorium. Atmospheric tests, and perhaps other tests, were conducted starting in about 1951 (Corchary and Dinwiddie, 1973). NEIS and other catalogues examined, however, do not identify pre-1960 tests. Only three events within 4 miles of NTS are reported in the Rogers et al (1976) catalogue from 1951-1960. They are of magnitudes 4, 4.3 and 4.4. The NEIS data tape lists seven events in this time interval but no magnitudes are given. Their relationship with nuclear tests, if any, is unknown from literature available for review at this time.

A recurrence curve is developed from seismic events through 1960 within 80 miles of NTS, Figure 3.6. A recurrence curve for a 40 to 80 mile annular area about NTS for 1961 on is also on Figure 3.6. The two recurrence curves (both normalized to a 20,000 square mile area to permit comparison) are very similar. The latter curve has a slightly steeper slope, perhaps suggesting that underground nuclear testing may be inducing some aftershock activity at greater than 40 miles from 117°W, 37°N. A third recurrence curve for the 40 mile radius circle about NTS from 1961 on shows a striking increase in seismic activity (over an order of magnitude) compared to the other two recurrence curves. This activity clearly is associated with nuclear weapons testing.

The 80 mile radius was chosen because it is representative of historical seismicity in eastern Nevada and is specific to the NTS area. It does not include California seismicity, which is much higher than that of eastern Nevada, nor that of 118° zone of Slemmons (1967). All larger historic earthquakes in Nevada have occurred in this zone. It also excludes Wasatch front activity in Utah which is higher than for eastern Nevada. No large earthquakes, with magnitudes of greater than 5, are listed within the 80 mile radius about NTS by NEIS or by Rogers et al (1977).

EARTHQUAKES NEAR THE NEVADA TEST SITE THROUGH 1960

Figure 3.4



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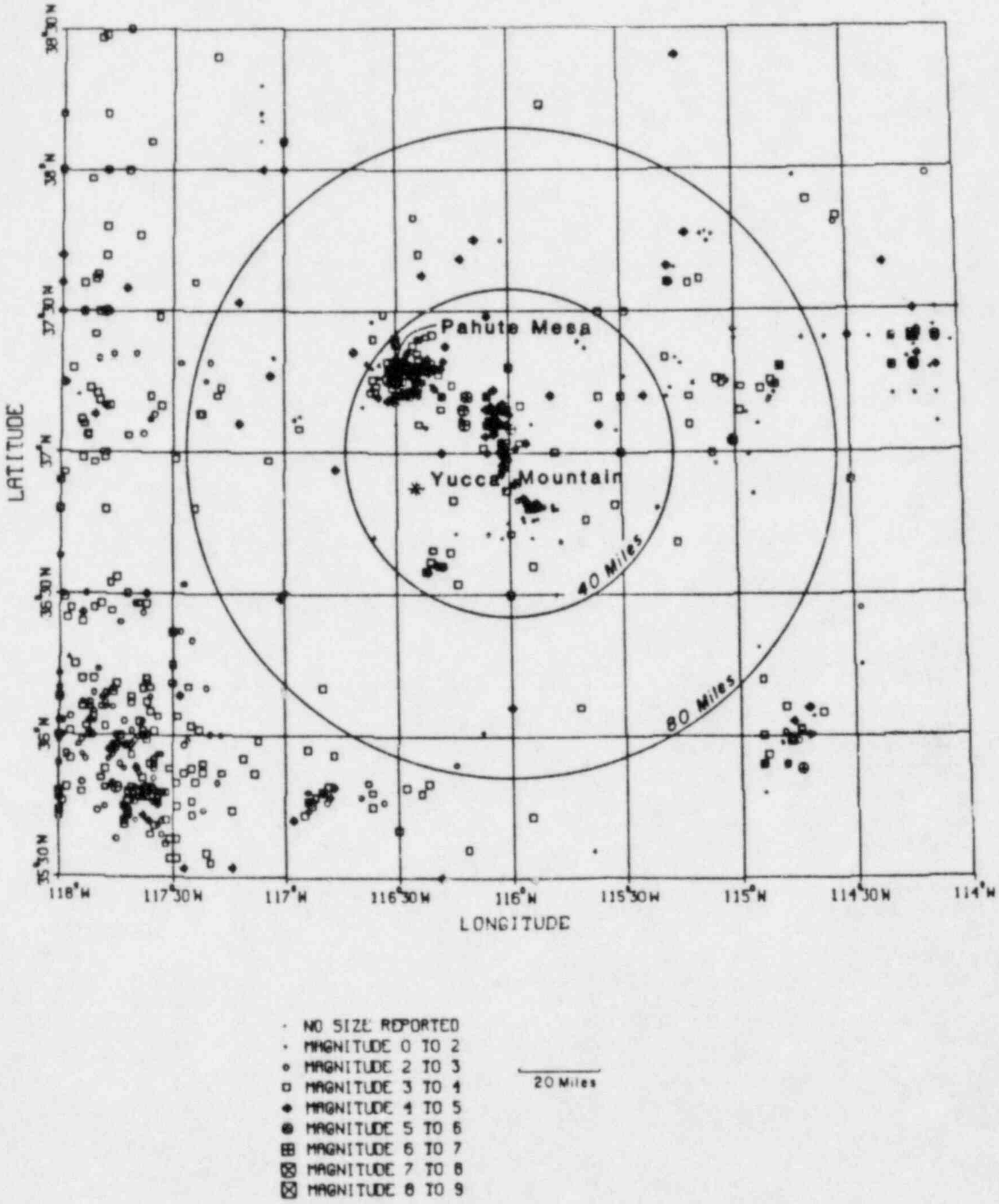
EARTHQUAKES NEAR THE NEVADA TEST SITE 1961 - 1979

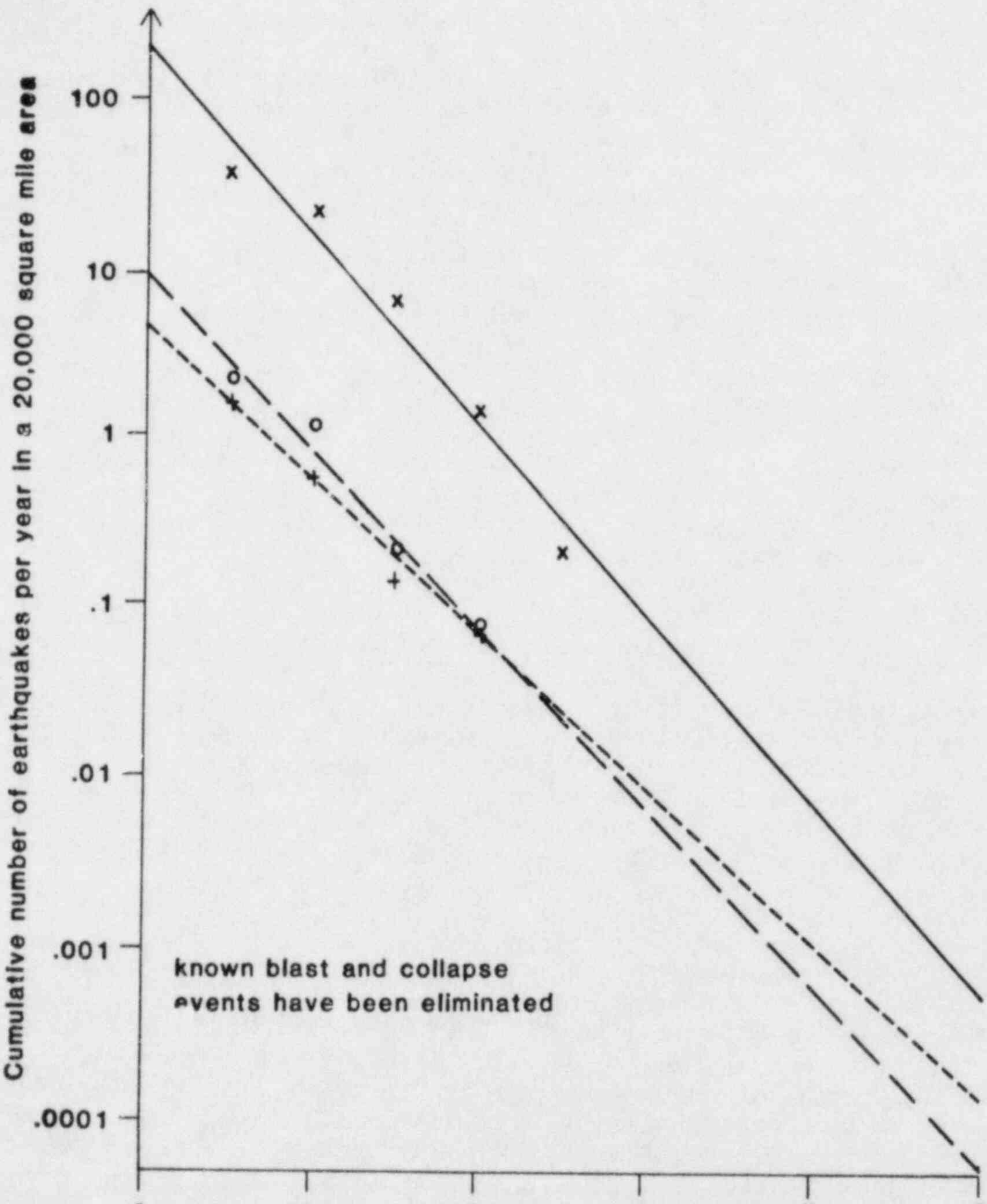
Figure 3.5



Project No. 313-1162C Reviewed ____ Date 12-10-81

CUMULATIVE NUMBER OF EARTHQUAKES AS A FUNCTION OF MAGNITUDE FOR NTS, BASED ON NEIS DATA

Figure 3.6



LEGEND

x ——— 1961 on, 40 mile radius circle

o — — 1961 on, 40 to 80 mile annulus

+ ----- through 1960, 80 mile radius circle

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Historical seismicity therefore indicates that a recurrence curve developed on pre-1960 data or for all data to a radius of 80 miles exclusive of the area affected by blasts, is conservative. The conservatism, in the perspective of historical seismicity, comes from the likelihood that some pre-1960 data may be influenced by testing beginning in 1951 and that later testing may have an effect on seismicity in the 40 to 80 mile annular area.

King and Rogers (1981) describe a 48 station seismic network being operated around NTS. A six station network was installed in Yucca Mountain in early 1981 with plans for an 18 station digital array. During its approximately six months of operation, no earthquakes or microearthquakes have been recorded with epicenters at Yucca Mountain.

In conclusion, damaging level earthquakes are generally few and infrequent in the NTS area of Yucca Mountain, however, because of the long term over which a high level nuclear waste repository should operate effectively, seismic effects must be taken into account in design and long-term performance assessment. The maximum level of shaking possible should be estimated based on historic seismicity, known active faults, and from research underway to better understand the sources of large, older historic earthquakes. It is concluded that seismicity should be considered a critical factor for evaluating mechanical response, a major factor for constructability and a minor factor in evaluating hydrological response.

3.2.3 Application of Seismic Information to Repository Design

Consideration of the seismicity is necessary to demonstrate that the integrity of surface structures, shafts, hydrologic seals and waste package installations would not be affected by seismic events. Design safeguards will be necessary to ensure that acceptable factors of safety against structural failure are achieved. In addition, it must be proven that the proposed repository would have a low risk of being disrupted by capable faulting.

There are four general approaches necessary:

- Dynamic finite element analysis of the excavation. This requires source to site modeling to obtain travelling wave displacements and accelerations. Results provide stress, strain and possible failure points within the excavation. Knowledge of in situ stresses will be required to construct the finite element model together with dynamic material properties of affected rocks.

- Probability studies of seismic shaking to set or affirm the level of shaking anticipated. It is necessary to select a distance from the site that a randomly occurring earthquake should be allowed to occur for design purposes.

- Probability of potential new faulting which might affect the repository

- Conventional seismic analysis of plant, equipment and buildings during the operational stage of the repository.

Algermission and Perkins (1975) and the ATC (1978) developed design acceleration maps of the U.S., Figure 3.7a and 3.7b. The former is based on a 475-year return period which is equivalent to 10 percent probability of exceedance in 50 years. The latter map modifies the former primarily in that some recent appearing faulting in Nevada, as well as in California, is used to modify the otherwise statistical results. Both maps suggest about 0.1g for surface structures in the Yucca Mountain area. Rogers et al (1977), by making a number of very conservative assumptions, imply in a preliminary assessment that a peak acceleration of 3 g might be appropriate for long time periods. Assumptions of the type made, however, will result in estimates of extremely high accelerations almost anywhere in the U.S. Justification for this approach requires that the site be in the near field of an M=7+ earthquake. The basis for this is Ryall's (1977) contention that the high level of seismic activity in his Ventura-Winsmucca zone (Slemmons' 118° zone) could migrate throughout Nevada. This topic is discussed later in this section.

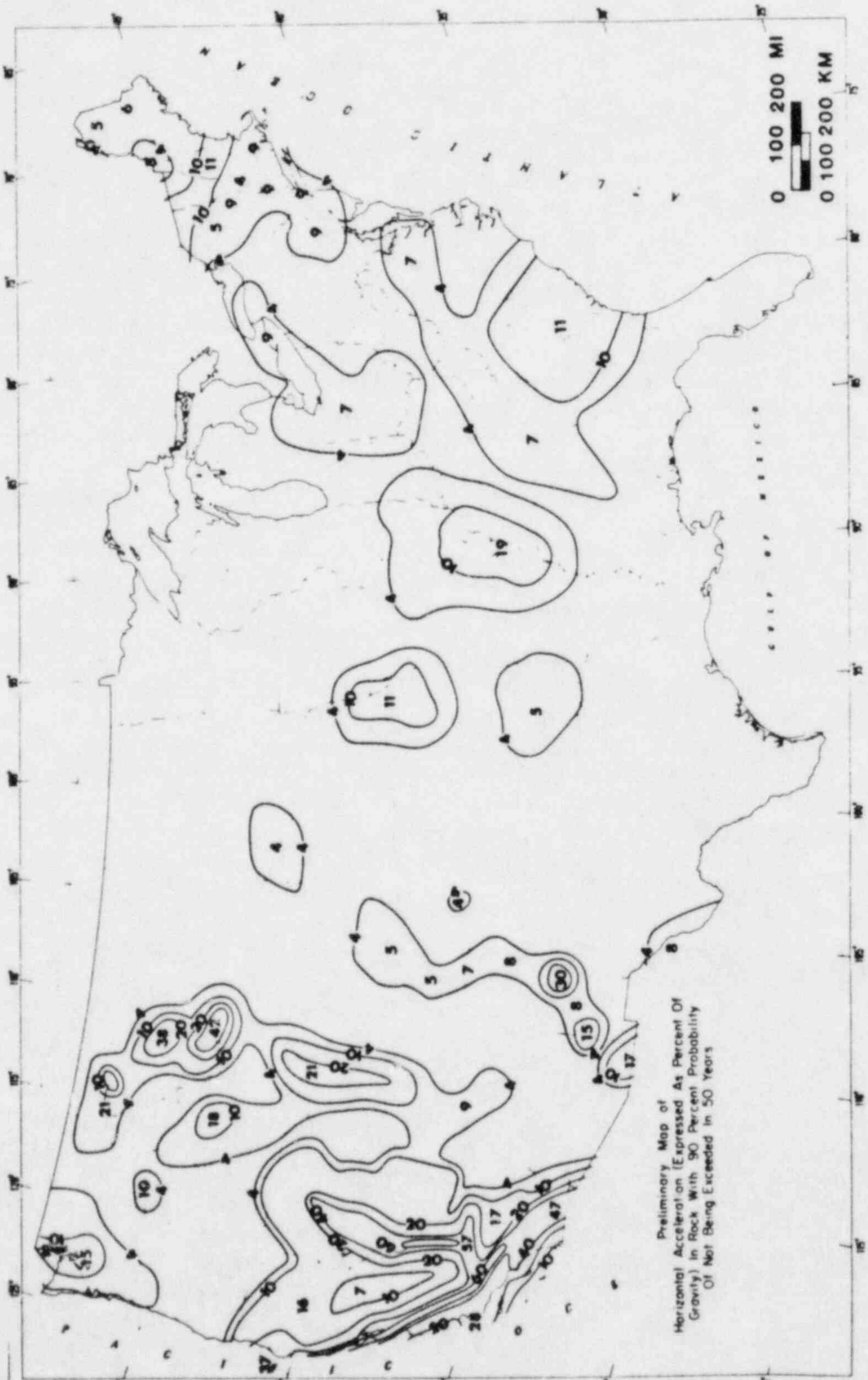
Relative to other areas in the U.S., Yucca Mountain appears to have a low level of seismicity. Probabilistic design accelerations would be limited by maximum magnitudes assigned to faults or seismic zones and a reasonable recurrence relationship.

Earthquake shaking theoretically decreases with depth away from the earth's free surface. This has been substantiated qualitatively by observations in mines e.g., Stevens (1977) and Dowding and Rogers (1978). In a few cases there is quantitative evidence, for example, the Pacific Gas and Electric Company report of strong motions recorded at their Humbolt nuclear power plant in 1975. Consequently the design acceleration at depths of thousands of feet in tuff will be less than on the surface for the same earthquake return period. Theoretical reductions are possible which would result in the acceleration at depth being half that at the surface. Analyses to provide spectra at depth are very site specific. Because a longer period of performance may be required at depth than for surface facilities, an analysis to determine the relative level of shaking at depth may be economically desirable.

Recent eyewitness accounts of the 1980 (M=7.9) earthquake in China (Evert Hoek, personal communication) tell of the massive surface destruction in which nearly one million people (by some accounts) are said to have perished, and the almost total lack of damage in the underground coal mines close by. This is a further demonstration of the substantially lower accelerations which develop at depth below the free surface during shaking, particularly in areas of low velocity surficial sediments.

DESIGN ACCELERATION MAP

Figure 3.7 a



After Algermissen and Perkins, 1975

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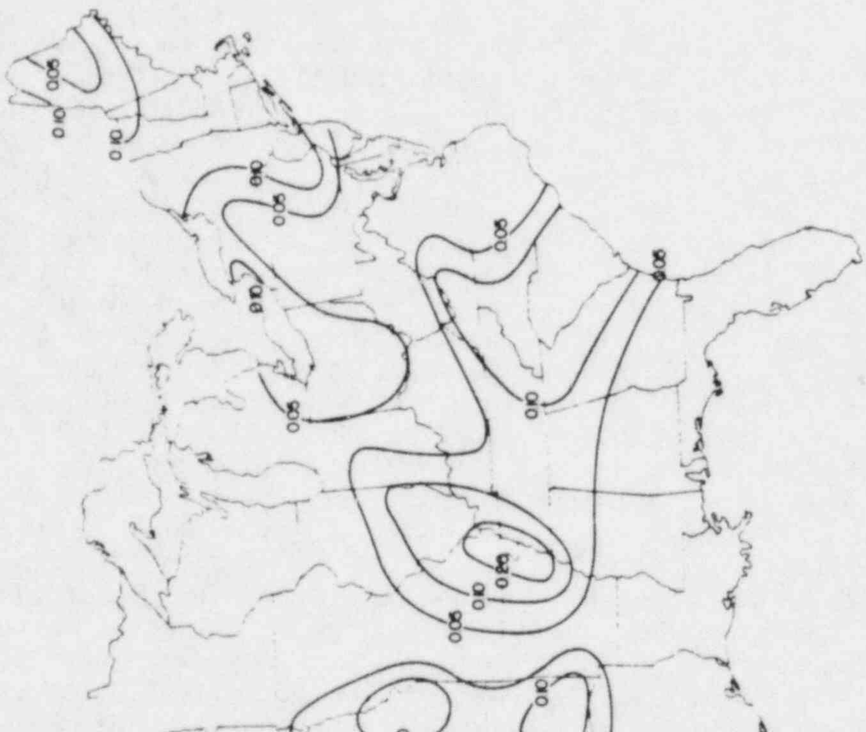
EFFECTIVE ACCELERATION MAP

Figure 3.7 b



NOTE: THE NUMBERS ON THE CONTOURS ARE VALUES OF EPA IN UNITS OF ACCELERATION OF GRAVITY.

After ATC, 1978

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3.3 CRUSTAL INSTABILITY

Current efforts to identify recent uplift or subsidence in the NTS area have not been completed. Hoover (1981) reported progress in attempts to date uplift by depths of erosional features along the edges of bluffs at NTS.

The question of seismic and tectonic stability was raised by Ryall et al (1974) and Ryall (1977). He has attempted the application of the theory developed by Fedotov (1968) for the Kurile-Kamchatka area to Nevada. Fedotov presented data in support of a concept that a buildup in seismicity occurred 15 to 20 years before a major earthquake in a given part of the Kurile-Kamchatka region. Following the major earthquakes, seismic activity diminished until it reached a very low level. Thus, an essentially aseismic period or "gap" continued for some time until the cycle resumes with an increase in seismicity followed by another major shock. Ryall et al (1974) conclude, based on the results of Slemmons (1967), that, over the last 11,000 years, faulting has occurred over the entire northern part of Nevada, and that where faulting appears to be barely "prehistoric" with fresh continuous scarps to 15 feet in height, current seismic activity is almost completely lacking. This, he suggests, implies a return period or cycle several centuries long. He points out that the epicentral areas of older large earthquakes in Nevada no longer have a high level of seismicity. The more recent a large earthquake, the more highly active the area surrounding the epicenter. He concludes that the seismic cycle in Nevada must be on the order of thousands of years compared to the 140 years found by Fedotov for the Kurile-Kamchatka area. He further suggests, ". . .that current seismicity of the region is probably typical of the average level of activity at times in the recent geologic past; however, the distribution of Late Quaternary faulting in the region indicates the location of this activity probably changes from time to time." He concludes that the appearance of small earthquakes in western Nevada and eastern California suggests that this region has a high potential for earthquakes in the future. This conclusion appears to be based at least as much on perceived alignments of epicenters as upon the level of seismic activity in analogy with Fedotov's cycles. NTS is located near the southeast margin of Ryall's zone of consideration.

Articles by Koizumi et al (1973), Gumper and Scholz (1971) and Scholz et al (1971) suggest that a downgoing slab was once active beneath Nevada. Basin and Range topography resulted from the melting, rising and spreading of slab material after activity ceased. Even this process has nearly abated as evidenced by lack of recent volcanism. Hence, the setting of Fedotov's seismic cycles does not appear analogous to present day Nevada.

In conclusion, crustal instability has been assessed as being a major factor for evaluating mechanical response and a minor factor in evaluating hydrological response.

3.4 VOLCANISM

Both basalt dikes and volcanoes are present in the NTS area. Considerable attention has been given to dating both types of events. Most are older than 4 million years before present. A lava flow in the wall of Ubehebe Crater in Northern Death Valley is 1.1 million years old, the youngest data mentioned in DOE (June, 1981). Doyle et al (1981) mention a 300,000 year date for a small cinder cone in Crater Flat, 23 miles southwest of Yucca Mountain. Younger basalts have increased amounts of trace minerals beginning at about 4 to 5 million years before present indicating a maturation of the volcanic process with increased differentiation of magma at that time. DOE (June 1981) and DOE (August 1981) concluded that no evidence had been found which would disqualify the Yucca Mountain site. Research into potential volcanic hazards and possible disruptions of the repository by basalt magma intrusions, however, continues.

Volcanism would have an impact on the in situ temperature field over the long-term and hence the thermal, mechanical and geochemical response. Volcanism is not considered to be a critical characteristic of the NTS area, however it is considered to have a major importance in an SCR from the standpoint of thermal, mechanical and geochemical response.

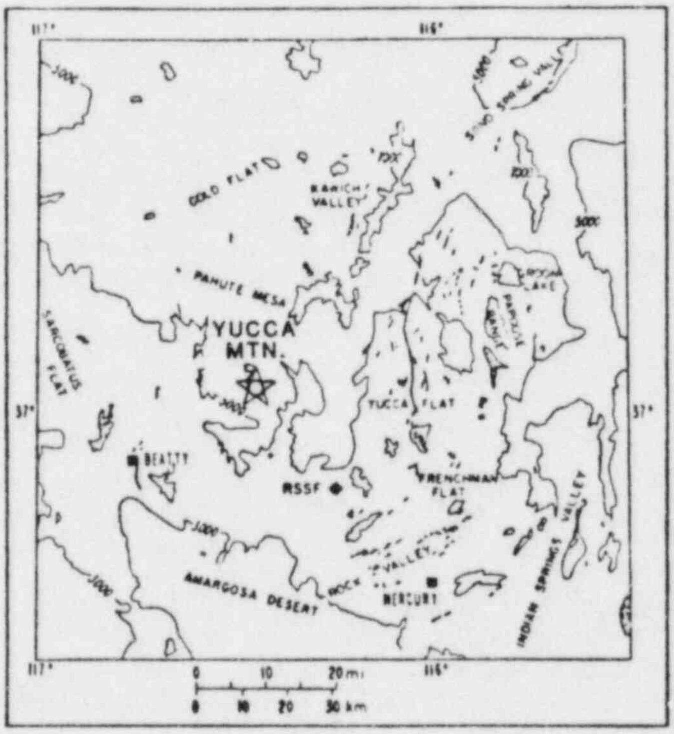
3.5 FAULTING

Doyle et al (1981) state that no evidence of Quaternary faulting has been found on Yucca Mountain. Work on what appears to be relatively recent faulting at NTS is on-going. Evidence for Holocene Movement of about one foot for a Bare Mountain fault zone southeast of Yucca Mountain is given by Hoover (1981). Rogers et al (1977) cite Carr (1974) and others regarding possible active faulting. Rogers' et al (1977) map as modified from Carr (1974) is reproduced as Figure 3.8. Their map of historic surface breaks (including those induced by nuclear testing) is in Figure 3.9. Table 3.1 lists faults which Rogers et al (1977) considered to be active.

Slemmons (1967) summarized Pliocene and Quaternary faulting throughout Nevada. His maps are reproduced in Figure 3.10. Although historic faulting is largely confined to the 118° seismic zone, short segments of Quaternary and Pliocene faulting are indicated in the eastern part of NTS as well as what appears to be the Bare Mountain fault southeast of Yucca Mountain. The Las Vegas shear zone is one of the more obvious features in the NTS area, however there is no evidence for Recent movement and no clearly associated microseismicity.

QUATERNARY FAULTS AND FRACTURES IN THE NTS REGION AND THEIR RELATION TO REGIONAL TOPOGRAPHY

Figure 3.8



After Rogers et al, 1977

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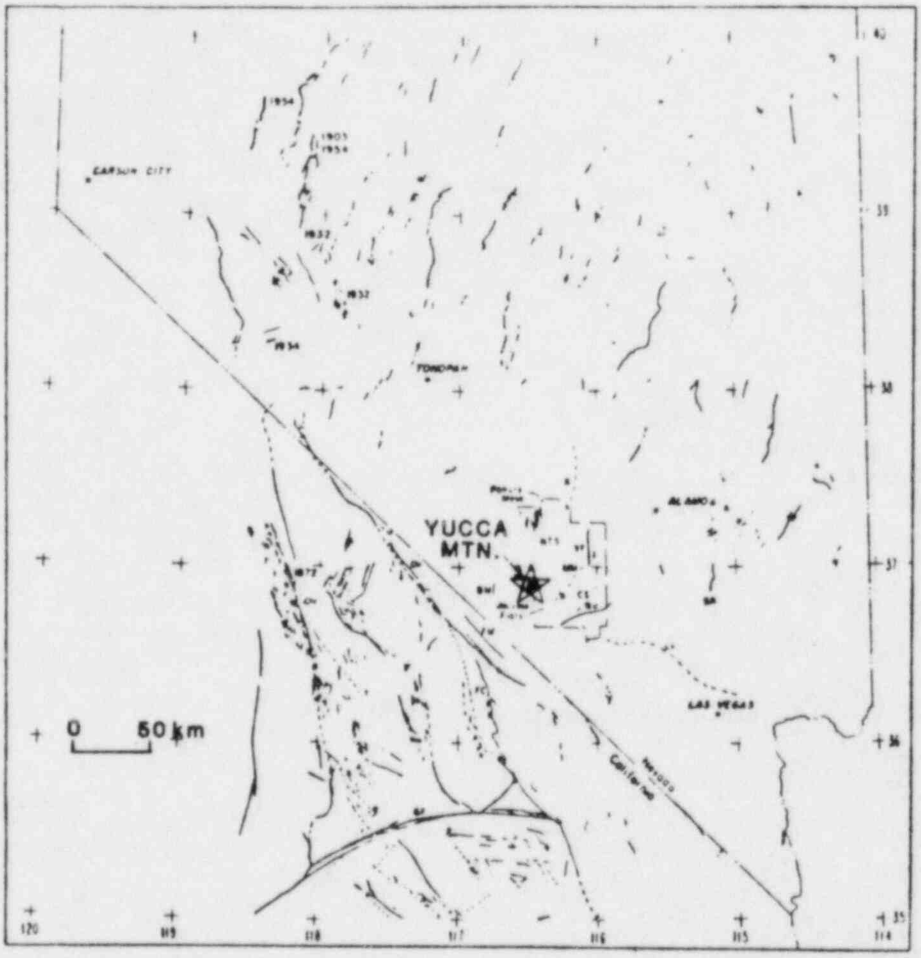
HISTORIC SURFACE BREAKS , QUATERNARY AND UPPER CENOZOIC FAULTS

Figure 3.9



LEGEND
- HISTORIC SURFACE FAULTS
- QUATERNARY FAULTS
- UPPER CENOZOIC FAULTS

After Rogers et al, 1977

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TABLE 3.1

ACTIVE FAULTS AND FAULT ZONES WHICH MAY REASONABLY BE CONSIDERED EARTHQUAKE SOURCE ZONES

Name	Symbol	Shortest Distance to RSSF (km)	Length (km)	Magnitude	Schnabel and Seed Mean Value Peak Accelerations at (g)	Stress Drop Modified Schnabel and Seed Mean Value Peak Accelerations at (g)
Mine Mountain	MM	1.7	29	6.9	0.7	1.0
Cane Spring*	CS	12	24	6.7	0.4	0.6
Rock Valley*	RV	14	36	7.2	0.4	0.6
Mercury Valley	MV	21	4	4.7	<0.01	<0.01
Yucca*	YF	25	25	6.8	0.2	0.3
Bare Mountain	BM	43	8	5.5	0.04	
Funeral Mountains	FM	55	38	7.2	0.08	
Death Valley*	DV	60	200+	8.5	0.2	
Furnace Creek*	FC	70	200+	8.5	0.2	
Sheep Range	SR	96	±20	6.5	0.03	
Alamo Area	[illegible]	105	32	7.0	0.03	
Garlock Zone	GF	140	200+	8.5	0.06	
Owens Valley*	OV	145	150	8.5	0.06	

* These faults have had historic ruptures, Holocene ruptures, or historic seismic activity.

RSSF retrievable surface storage facility.

After Rogers et al, 1977

PLIOCENE AND QUATERNARY CRUSTAL MOVEMENTS Figure 3.10

b) Summary of all faulting in Slemmons 1967 study

a) 118° zone contains surface faulting from historic earthquakes

After Slemmons, 1967

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Work on potentially active faulting at NTS continues, and some firm evidence for Holocene movement has been observed. For other faults, recent movement appears to have been induced by test blasts, Active faults are not known at Yucca Mountain but the evaluation of active and potentially active nearby faults, for seismic effects will clearly be an issue to be resolved.

Because active faults can significantly affect the mechanical response of the repository, faulting must be considered as a critical characteristic. Similarly, it should be considered as a major characteristic with regard to constructability and hydrological and geochemical response.

3.6 DESIGN AND CONSTRUCTION

3.6.1 Generic Tectonic Characteristics Affecting Design and Construction

Table 3.2 gives an evaluation of the tectonic characteristics in relation to design and construction of the repository. From this it can be seen that seismicity and potentially active faulting are considered critical for one key issue, namely mechanical response. This key issue is primarily related to the stability of and deformation around underground openings, both from a short-term operational point of view and, more importantly, for long-term containment.

3.6.2 Mitigating Design and Construction Strategies

The impact of adverse characteristics of the site may be reduced by appropriate design and construction strategies. Mitigating measures for adverse tectonic characteristics which should be considered are:

- Selecting tunnel lining and support systems to maintain the mechanical integrity of the repository
- Selecting seals, plugs and grouting methods to maintain the hydrological integrity of the repository.

TABLE 3.2

EVALUATION OF TECTONIC CHARACTERISTICS IN TERMS OF THEIR INFLUENCE ON KEY ISSJES

KEY ISSUES	CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Seismicity	bfg (Major)	(Insignificant or not relevant)	adi (Critical)	cei (Minor)	(Insignificant or not relevant)
Crustal Instability	cfg (Insignificant or not relevant)	(Insignificant or not relevant)	bdi (Major)	bei (Minor)	(Insignificant or not relevant)
Volcanism (Continuing)	cfg (Insignificant or not relevant)	beg (Major)	beg (Major)	cfg (Insignificant or not relevant)	beg (Major)
Faulting	beg (Major)	(Insignificant or not relevant)	adg (Critical)	beg (Major)	beg (Major)

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions of the level of influence.

ATTRIBUTES

- o availability of design and construction techniques which allow for conservative assumptions for the value of the characteristic:
  - a) reasonable techniques are not available (i.e. high cost impact)
  - b) some techniques are available, but at moderate cost impact
  - c) reasonable techniques are available (i.e., little cost impact)
- o uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:
  - d) model has low uncertainty (i.e., is very representative) and high sensitivity to characteristic
  - e) model has moderate uncertainty and moderate sensitivity
  - f) model has high uncertainty or low sensitivity
- o cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values:
  - g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
  - h) uncertainty can be reduced, but only during in situ testing
  - i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization).

4. MECHANICAL CHARACTERISTICS

4.1 GENERAL

This section deals with the mechanical characteristics of the tuff formations encountered in the Yucca Mountain rock sequence described in Section 2 and the specific aspects of the two fully saturated members upon which the site specific study is focused, the Bullfrog member and the Tram member.

It is only through an adequate knowledge of the mechanical characteristics of the rock mass, and an understanding of its behavior, that its response to excavation of a repository can be satisfactorily assessed for design and construction purposes. The mechanical behavior of a rock mass is dependent not only on the properties of the intact rock material (i.e., the basic substance comprising a cohesive assemblage of minerals), but also on the characteristics of the structural discontinuities such as joints, faults, bedding, and foliation which intersect the rock. The intact rock and discontinuities together comprise the rock mass. In addition, the rock mass is subjected to a number of processes, such as groundwater activity, weathering, and thermal effects arising from the operation of the repository. The mechanical behavior of the rock mass is also dependent on the in situ stress field.

In general, the mechanical properties of tuff material (i.e., intact rock) are determined by performing laboratory tests on small samples which contain few irregularities or discontinuities. The results of these tests, while giving reasonable estimates of the mechanical properties of the rock material, usually differ from those obtained by either larger scale laboratory tests or in situ testing. Tests on samples large enough to represent the entire rock mass, including the discontinuities, result in values more representative of the true mechanical properties of the rock mass. The most reliable tests, therefore, are generally those conducted in situ. Often, an additional advantage of in situ testing is that it greatly reduces the effects of sample disturbance which results from the handling required to obtain and prepare a laboratory specimen for testing. The minimization of these uncertainties results in values of mechanical properties which have a higher degree of reliability.

Unlike previous Golder Associates' reports (Golder Associates 1979a, 1979c), the present study addresses jointly the rock material and the rock mass for each mechanical property considered. The reason for this is three-fold. Firstly, it is the mechanical properties of the rock mass which are most important for the ultimate objective of specific site characterization, and this necessitates an evaluation of rock material properties only as a first approximation. Secondly, as discussed above, the degree of representativeness of the test results for the rock mass characterization increases with specimen scale, i.e., for the same fundamental property, the passage from "rock material" measurement to "rock mass" measurement occurs progressively rather than at an arbitrary point. Thirdly, although a great deal of information has been examined for the present study, it is not felt that this is sufficient to warrant the development of separate characterizations for tuff material and tuff mass at this time.

The reader is referred to a previous parametric study by Golder Associates (1979b) for definitions, theoretical aspects, and general testing techniques related to the mechanical characteristics discussed in this section.

4.2 DEFORMATIONAL PATTERNS

With regard to the behavior of the rock material under a given state of stress and a given mode of application, there are two basic patterns. The first pattern, linear elastic behavior, implies linearity between the applied stress and resulting strain. Although this condition is seldom met by actual rock materials, departure from such behavior is, in many cases, only slight. In a practical approximation, this theory may be applied only when other factors, such as temperature, remain constant. However, all materials will exhibit, at different stress levels, a point at which this linear relationship clearly breaks down, when the resulting strain begins to increase at a much greater rate than the applied stress. This limiting point, referred to as the elastic limit, denotes the onset of the second deformational pattern, which is generally termed plastic behavior. Within the plastic stage, the stress achieves or approaches a peak value at which fracturing or large strains occur; this stress level is referred to as the strength. Once the rock material enters the plastic stage, other factors will usually assume a controlling role. The particular case when, under a constant state of stresses, the material will continue to strain as a function of time, is referred to as time-dependent or creep behavior. A further complication is introduced in the case of some rocks when temperature has marked effects on the deformational behavior and/or when alteration occurs with time changing the nature of the rock.

This passage from elastic to plastic behavior, and the particular stress conditions under which it occurs, are critically important in the evaluation of nuclear waste repository sites for which a high degree of structural integrity is necessary. In fact, this dual behavior gives rise to two fundamental sets of problems:

- The very short-term (i.e., instantaneous and during construction) behavior of the repository excavation, where the deformational pattern is essentially independent of time and may be characterized, in a first approximation, through elastic theory, provided that the distribution and characteristics of the discontinuities are such that they do not exert structural control and that factors such as temperature remain constant. In this context, the development of instability leading to discrete failures must be investigated.

- The post-construction behavior of the repository excavation, where factors such as time and temperature assume a critical role in deformation. Time-dependent deformational processes are of a complex nature and may ultimately lead to creep rupture. Increasing temperature may lead to a general degradation of mechanical properties and increased thermal stresses, as well as alteration.

With respect to the very short-term behavior of the repository excavation, provided that a wide choice is available for a particular site, it is considered that tuff may be characterized approximately by visco-elastic theory and some of the corresponding parameters discussed in the following sections. In this context, it must be borne in mind that a plastic zone of limited extent may be formed around the openings.

The post-construction behavior of the repository, however, poses far more complicated problems than the comparatively simple short-term "mining" problems. This is compounded by the fact that there is insufficient experimental data on the behavior of such excavations in tuff over long periods of time. Depending on the creep behavior, deformations of pillars, floors and roofs can ultimately lead to complete closure. Obviously, this type of behavior in a repository would greatly affect its containment ability and waste package retrievability. Alteration of tuff, either existing altered zones or future alteration due to increased temperature and groundwater movement, often results in less competent materials with significant swelling potential. Clearly, this type of behavior would affect the structural integrity of the excavations, as swelling materials will exert high stresses when confined.

In different ways, both deformational patterns (i.e., elastic and plastic) are affected by a number of other factors, such as in situ and excavation-induced stresses, repository excavation shape and layout, temperature and, possibly, radiation exposure. In assessing these types of behavior, the ultimate objective remains one of ensuring that the repository excavations retain the degree of structural integrity necessary for satisfactory performance.

The problems associated with design of repository excavations for long-term performance are further complicated by the fact that "failure" of the excavation will be measured not only in terms of collapse or closure, but in terms of loss of containment of radionuclides. Therefore, the integration of rock deformation and hydrogeologic mass transport models is an essential step in the performance evaluation process.

4.3 TUFF

4.3.1 General

The typical, although by no means exclusive, way in which the mechanical characteristics of tuffs vary is best illustrated by the general characteristics of a cooling unit, as described previously in Section 2.2.1. A cooling unit is a tuff deposit that cooled as a single unit after formation. It has a core of welded material, typically exhibiting columnar jointing and lack of bedding. The base of this welded zone has a particularly high density. As the distance to the core increases, the degree of welding decreases, which results in the welded core being surrounded by zones of decreasing density, strength, and thermal conductivity, among other properties. The porosity of the deposit prior to alteration is probably the best indicator of most mechanical and thermal properties of tuff. The process of welding reduces the porosity, so that densely welded tuffs have low porosity; high porosity is only found in nonwelded tuffs.

In general, the mechanical properties of the Yucca Mountain tuffs, as determined by testing, are expected to be anisotropic and scale dependent, and depend on both sample variables and test variables, as follows:

- Sample Variables:
  - porosity
  - mineralogy
  - alteration
  - presence of discontinuities
  - water content

- Test Variables:
  - confining pressure
  - magnitude of stress difference
  - strain rate
  - temperature.

The possible influence of alteration warrants a special mention. From the geologic information availabl≥, it is expected that the process of alteration will lead to a general deterioration in the mechanical properties of Yucca Mountain tuffs, as well as the formation of materials with significant swell potential. The following two typical modes of alteration illustrate this possibility:

- Devitrification will produce bentonite, which has a high content of expansive clays (montmorillonite, see Section 2.3). These expansive clays will exhibit swelling upon wetting and shrinking upon drying, which would produce poorer mechanical properties and high stresses.

- Zeolites are more abundant than clays and, as alteration of zeolites through a mineralogic phase progresses, the quality of the mechanical properties is expected to diminish.

These possibilities of existing altered zones or future alteration (due to increased temperatures and groundwater movement with time), together with the lack of specific information on the effects of alteration upon the mechanical properties of Yucca Mountain tuffs, make it strongly advisable to investigate these processes in future testing work to obtain an adequate characterization of repository sites.

The mechanical properties to be discussed in the following sections are as listed below:

- Strength
- Elastic/deformation moduli
- Creep deformation
- Discontinuities
- Density
- Moisture content
- In situ stresses.

4.3.2 Strength

During repository excavation and subsequent thermal loading, limited zones of rock mass could typically fail (i.e., its strength will be exceeded), especially around waste packages and around shafts and tunnels. This failed (or disturbed) zone may affect the stability of the opening or, due to its increased fracturing, may reduce the capability of the repository to contain radionuclides.

The various definitions associated with the concept of strength are as discussed in Section 4.2 and in the previous parametric study (see Golder Associates, 1979b).

One of the most comprehensive studies to date on the strength properties of Yucca Mountain tuffs is that carried out by Sandia National Laboratories (SNL) (1980) and reported in Olsson and Jones (1980). In a testing program conducted on Yucca Mountain tuff samples from Borehole UE25a-1 and also on the Grouse Canyon welded tuff in G-tunnel (outside the generic study area), the effects of the following variables upon strength were studied:

- Sample Variables:
  - porosity (of intact rock)
  - water content
  - artificial joints

- Test Variables
  - confining pressure
  - temperature
  - strain rate.

The results of these tests are presented in Table 4.1, which shows for each confining pressure and temperature the resulting maximum stress difference (at failure), Young's modulus, Poisson's ratio, and calculated porosity. These tests were carried out at a strain rate of $10^{-4}\ s^{-1}$. The Mohr-Coulomb failure parameters calculated from the test results are shown on Table 4.2.

The effects of the degree of welding (indicated by porosity) and increasing confining pressure upon compressive strength are demonstrated by Figure 4.1 for unconfined and confined compression tests on air-dried samples at a strain rate of $10^{-5}\ s^{-1}$. Clearly, the strength of intact tuff is strongly related to porosity.

With regard to the influence of water upon strength, Figure 4.2 shows the typical effects of degree of saturation and strain rate on maximum compressive stress. Although this information is based on testing of G-tunnel samples, it is thought to be of general validity for tuff. It is not yet clear what the chemical and physical processes of weakening by water are, but it has been suggested by some authors that they are mostly of a chemical nature.

With regard to the effects of temperature upon strength, Olsson and Jones (1980) have reported, from testing work performed on Yucca Mountain and Grouse Canyon tuffs, that a strength decrease of as much as 30 percent may occur as the temperature is raised from room temperature to 200°C (see Table 4.1). Similar work has been described in the DOE Quarterly Report of December, 1980, on tuff strength testing at N.T.S. A preliminary short-term test simulating thermal runaway was performed, utilizing specimens of six different tuffs with varying degrees of welding. The samples were exposed to a temperature of 400°C at ambient pressure for 16 hours, and strength was determined indirectly by point load tests. The results are shown in Figure 4.3. It may be seen that the densely welded Bullfrog tuff exhibits the greatest strength reduction with temperature, although of course the information is too limited to determine trends.

TABLE 4.1

MECHANICAL PROPERTIES OF TUFF FROM HOLE UE25a-1

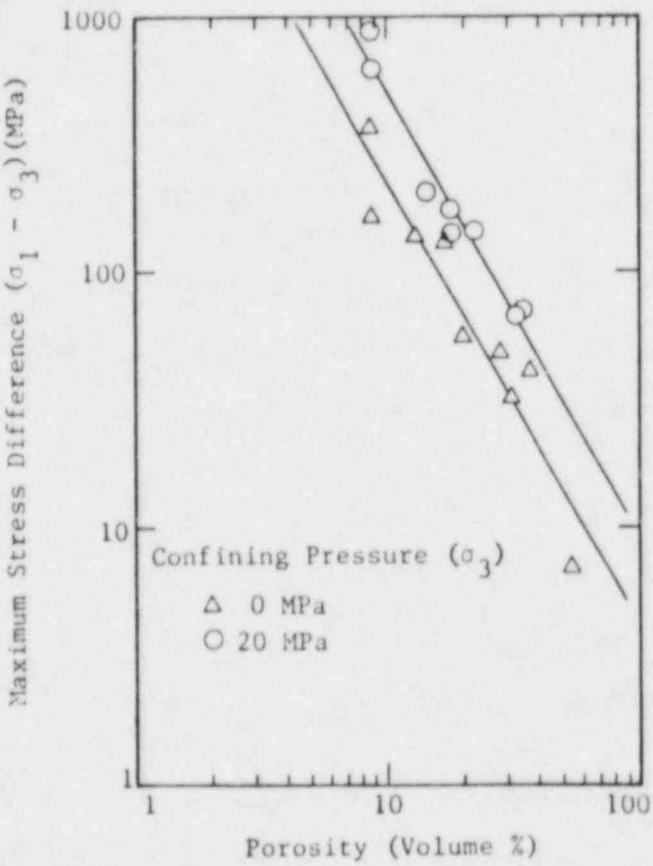
Unit	Specimen Number	Confining Pressure (MPa)	Temperature (°C)	Max. Stress Difference (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Calculated Porosity (%)
Tiva Canyon	87.6	0	RT	364	57.5	0.31	8.8
	87.6	10	RT	396	43.9	0.30	8.8
	87.6	20	RT	875	58.3	0.22	8.8
	185	20.7	200	105	----	----	26.7
	212.7	0	RT	7.03	0.41	0.28	54.0
Topopah Springs	723	0	RT	138	40.4	0.22	12.9
	739	20.7	200	133	23.9	0.15	11.3
	1250	0	RT	166	61.8	0.30	8.8 (est.)
	1250	10	RT	412	73.0	0.23	8.8 (est.)
	1250	20	RT	618	59.9	0.21	8.8 (est.)
Calico Hills	1490	0	RT	47.7	12.3	0.14	28.1
	1605	20.0	RT	26.1	7.99	0.22	29.5
	1634	20.7	RT	67.5	8.50	0.27	32.2 (est.)
	1662	20.0	RT	70.3	9.57	0.25	34.9
	1692	0	RT	40.8	14.0	0.20	36.6
Prow Pass	1948	100.0	RT	299	22.0	0.20	19.1
	1968	20.0	RT	176	27.0	0.20	18.0
	1985	20.7	RT	207	31.0	0.25	14.5
	2014	0	RT	130	47.9	0.30	16.7
	2039	0	RT	32.2	7.84	0.18	31 (est.)
Bullfrog	2401	50.0	RT	174	18.7	0.19	21.9
	2421	20.0	RT	145	19.2	0.23	22 (est.)
	2452	0	RT	54	6.37	0.05	20.3
	2491	20.7	RT	140	22.1	0.28	17.7

RT = room temperature

After Olsson & Jones, Nov. 1980

COMPRESSIVE STRENGTH OF TUFF AS A FUNCTION OF POROSITY AND CONFINING PRESSURE

Figure 4 1

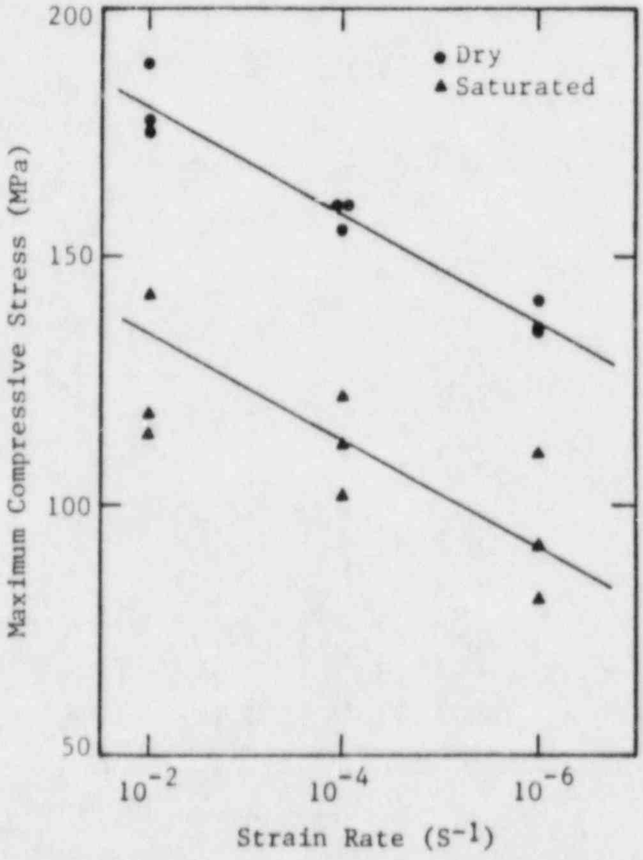


After Sandia National Laboratories, 1980

Project No 83-1162C Reviewed ICV Date 12-81

MAXIMUM COMPRESSIVE STRESS OF WELDED TUFFS AS A FUNCTION OF STRAIN RATE AND WATER CONTENT

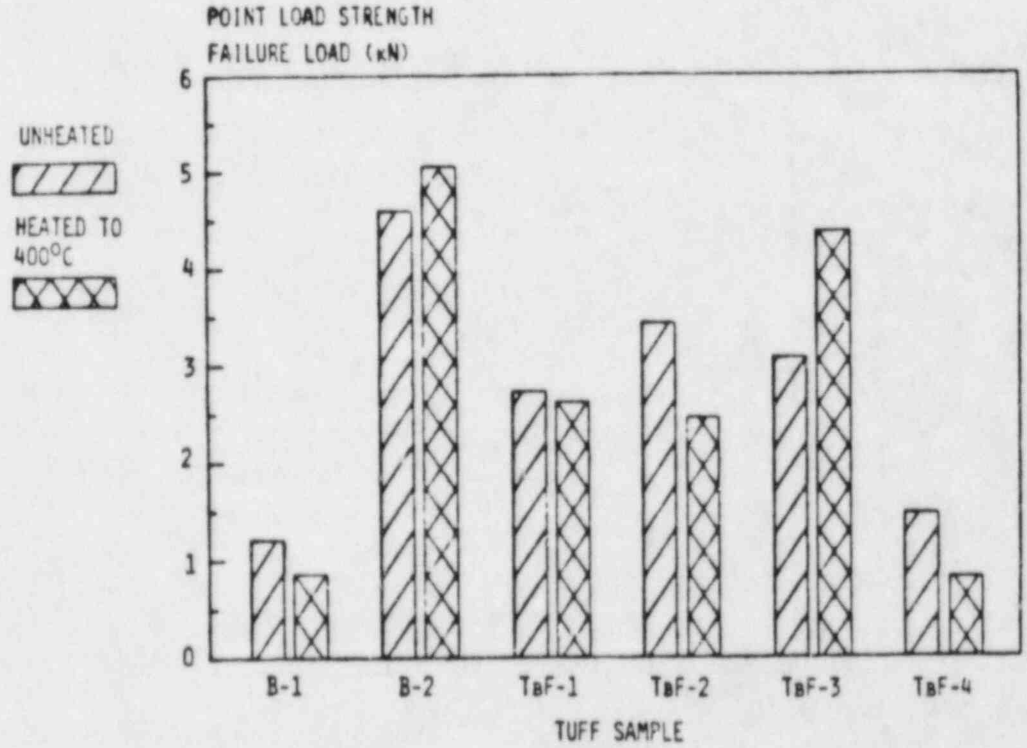
Figure 4.2



After Sandia National Laboratories, 1980

FAILURE LOADS OF TUFF BEFORE AND AFTER HEATING TREATMENT

Figure 4.3



B-1: nonwelded tuff of the Bandelier formation, Los Alamos, New Mexico
B-2: welded Bandelier tuff
TBF-1: nonwelded tuff from Bullfrog formation, type locality at Lathrop Wells, Nevada
TBF-2: partially welded Bullfrog tuff
TBF-3: partially welded Bullfrog tuff
TBF-4: densely welded Bullfrog tuff.

After D.O.E. Quarterly Report, Dec. 1980

Sandia National Laboratories (1980) have also reported investigations on the shear strength of jointed tuff by carrying out tests on artificial (sawed) joints. In such studies, partially welded tuff from Yucca Mountain tested at a displacement rate of approximately 10^{-5} m/s yielded an average value for the basic friction angle (Ø) of 30.5 degrees. This information is presented only as a general guideline, as Ø may depend strongly on the normal stress across the joint, in many practical cases, even in the absence of "real" (as opposed to apparent) cohesion. Further work showed that the frictional strength increases as the displacement rate decreases (see Figure 4.4). This has been attributed by some investigators to time-dependent growth of asperity contacts by creep.

In summary, the strength of tuff is mainly a function of:

- Degree of welding (porosity)
- Temperature
- Confining pressure
- Loading rate
- Discontinuities
- Saturation.

The design of the repository, especially the shape of underground openings and their support, should take into account the strength of the tuff in order to provide stable openings and reduce the disturbed (or fractured) zone of rock around those openings as much as possible. Due to the demonstrated dependence of strength on both stress levels and temperature, the anticipated thermal loadings and in situ stresses should be incorporated in this evaluation.

Strength will not have a critical influence on the key issues in design and construction. However, it will have a major influence on constructability and mechanical response, and a minor influence on hydrological and geochemical response.

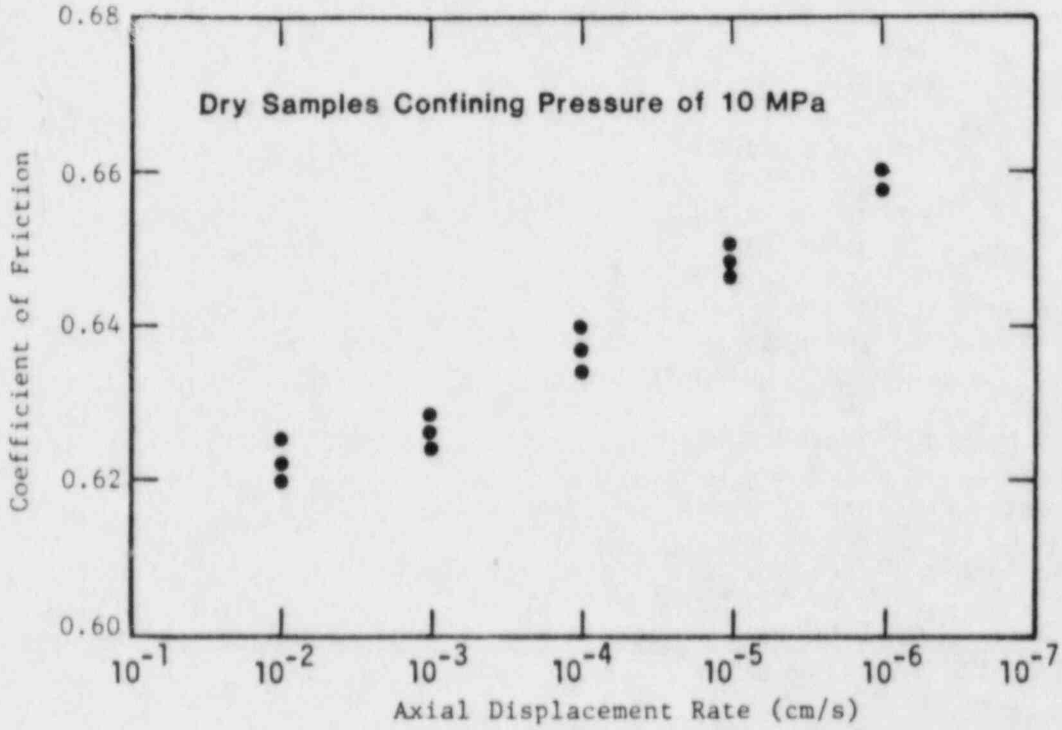
4.3.3 Elastic/Deformation Moduli

Although linear elastic theory is not appropriate for predicting the long-term deformational behavior of a repository excavation, it does provide a first approximation to the short-term deformation response of tuff to the elevated rock temperatures and the state of in situ and induced stresses existing in the vicinity of a waste canister and along the access shafts and tunnels.

Generally, five elastic constants are defined; the modulus of elasticity (Young's modulus) E, Poisson's ratio υ, the bulk modulus K, the modulus of rigidity G, and Lame's constant λ. Only two of these are independent for an isotropic material. The two most commonly determined are Young's modulus and Poisson's ratio.

COEFFICIENT OF FRICTION FOR AN ARTIFICIAL JOINT IN TUFF AS A FUNCTION OF THE DISPLACEMENT RATE

Figure 4.4



After Sandia National Laboratories, 1980

Project No. Reviewed Date

TABLE 4.2

MOHR-COULOMB FAILURE PARAMETERS FOR YUCCA MOUNTAIN TUFF

Geologic Unit	Cohesion C (MPa)	Friction Angle ϕ	Average Porosity (%)
Tiva Canyon*	28.1	68°	8.8
Topopah Springs	17.5	67°	9.4
Calico Hills	12.3	25°	33
Prow Pass	32.2	37°	17
Bullfrog	12.1	43°	20

*Parameters are for the densely welded upper part of this member.

(after Olsson and Jones, 1980)

The basic definitions of Young's modulus and modulus of deformation, as well as Poisson's ratio, are discussed in Golder Associates (1979b). Young's modulus is an important property of intact rock, which can often be idealized as an elastic, isotropic medium (at stress levels significantly below its strength). However, as discontinuities are progressively incorporated in the medium under consideration, nonelastic rock mass conditions are approached. In this case, the corresponding property is referred to as modulus of deformation, which is lower than Young's modulus.

The only significant and available information on modulus data for Yucca Mountain tuffs is that included in Table 4.1. As all these tests were carried out on small core samples from Hole UE25a-1, the resulting modulus may be more properly referred to as Young's modulus. However, the wide scatter of results, ranging from 6.37 to 47.90 GPa (923.9 to 6947.4 ksi), suggests that, despite the small specimen size, discontinuities may have a significant influence. Varying degrees of welding, as shown by the calculated porosity values, may also partly explain the scatter. Poisson's ratio is also shown for each case.

Based on Table 4.1, Olsson and Jones (1980) have plotted Young's modulus as a function of porosity for various confining pressures (see Figure 4.5). These results show that Young's modulus decreases as porosity increases, although the variations in confining pressures may also influence the results to some extent.

Sandia National Laboratories (1980) performed a series of independent measurements of linear axial and transverse strains under hydrostatic loading, which permitted the detection of anisotropy in Young's modulus. Figure 4.6 shows the measure of elastic anisotropy versus percent porosity for welded and nonwelded tuff. The welded tuff is stiffest in the direction perpendicular to bedding, whereas the nonwelded tuff is stiffest in the direction parallel to bedding.

No information has been obtained to date on the modulus of deformation of Yucca Mountain tuffs. This will only become available once larger scale load/deformation tests are carried out in situ, which will provide more representative information on the short-term deformational behavior of the tuff rock mass.

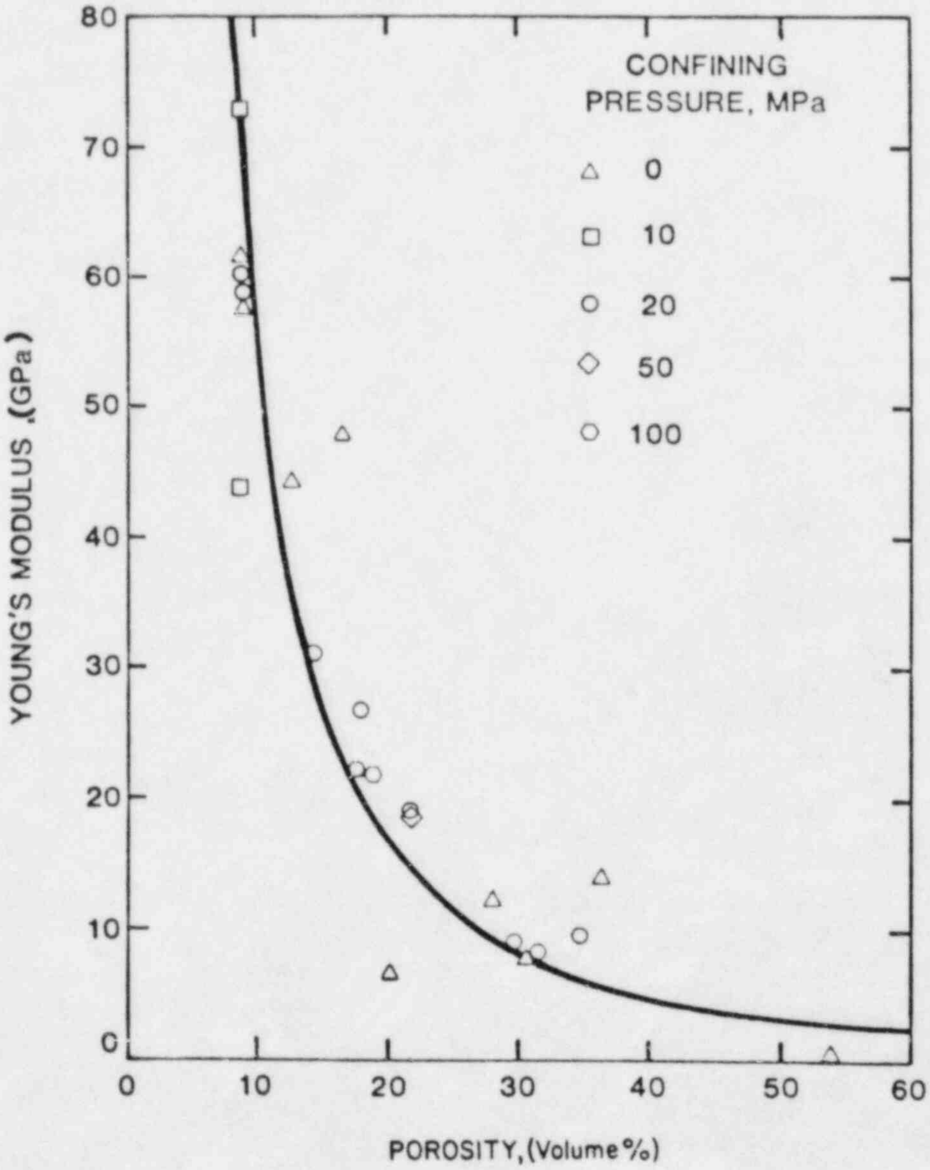
Thus, in the light of the information currently available, the elastic/deformation moduli of tuff exhibit anisotropy, and are predominantly functions of:

- Porosity (related to degree of welding)
- Discontinuities
- Scale
- Temperature and stress level (this is anticipated, although no specific information is yet available).

The design of the repository should account for the short-term response of the tuff surrounding the waste canisters to prevent the chance of

YOUNG'S MODULUS OF TUFF AS A FUNCTION OF POROSITY FOR VARIOUS CONFINING PRESSURES

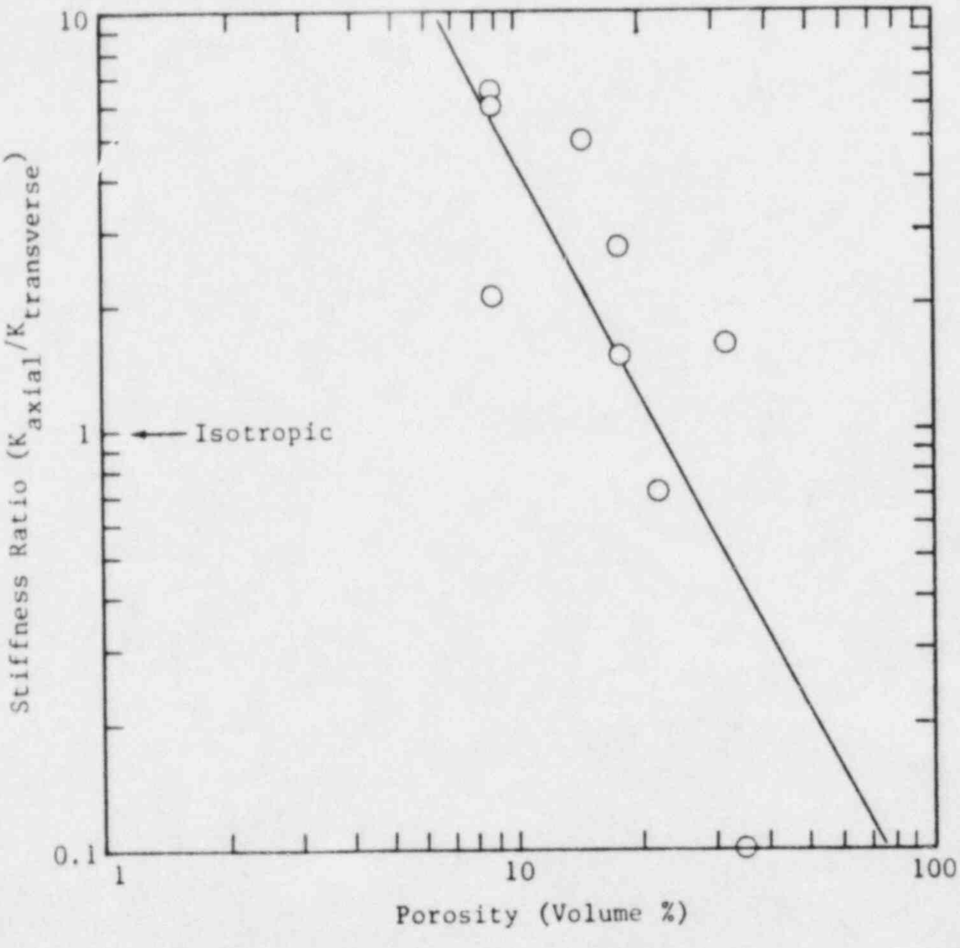
Figure 4.5



After Olsson & Jones, Nov., 1980

ANISOTROPY OF THE ELASTIC MODULI OF TUFF AS A FUNCTION OF POROSITY

Figure 4.6



After Sandia National Laboratories, 1980

Project No 813-1162 c Reviewed KJ Date 12-81 localized failure or abnormal pressures on the canisters, and it must also account for the overall deformation of all underground openings (shafts, tunnels, etc.). The evaluation of such response must incorporate anticipated thermal conditions.

The elastic/deformation moduli of tuff will not have a critical influence on any of the key issues in design and construction. However, they will have a major influence on the mechanical response and a minor influence on the hydrological response.

4.3.4 Creep Deformation

On the basis of limited information available for this study, the deformational pattern of tuff appears to have a plastic component. As discussed previously in Section 4.2, for rocks which undergo substantial time-dependent deformation under given stress conditions, this plastic behavior may be critically important to the physical integrity of underground excavations, especially post-construction.

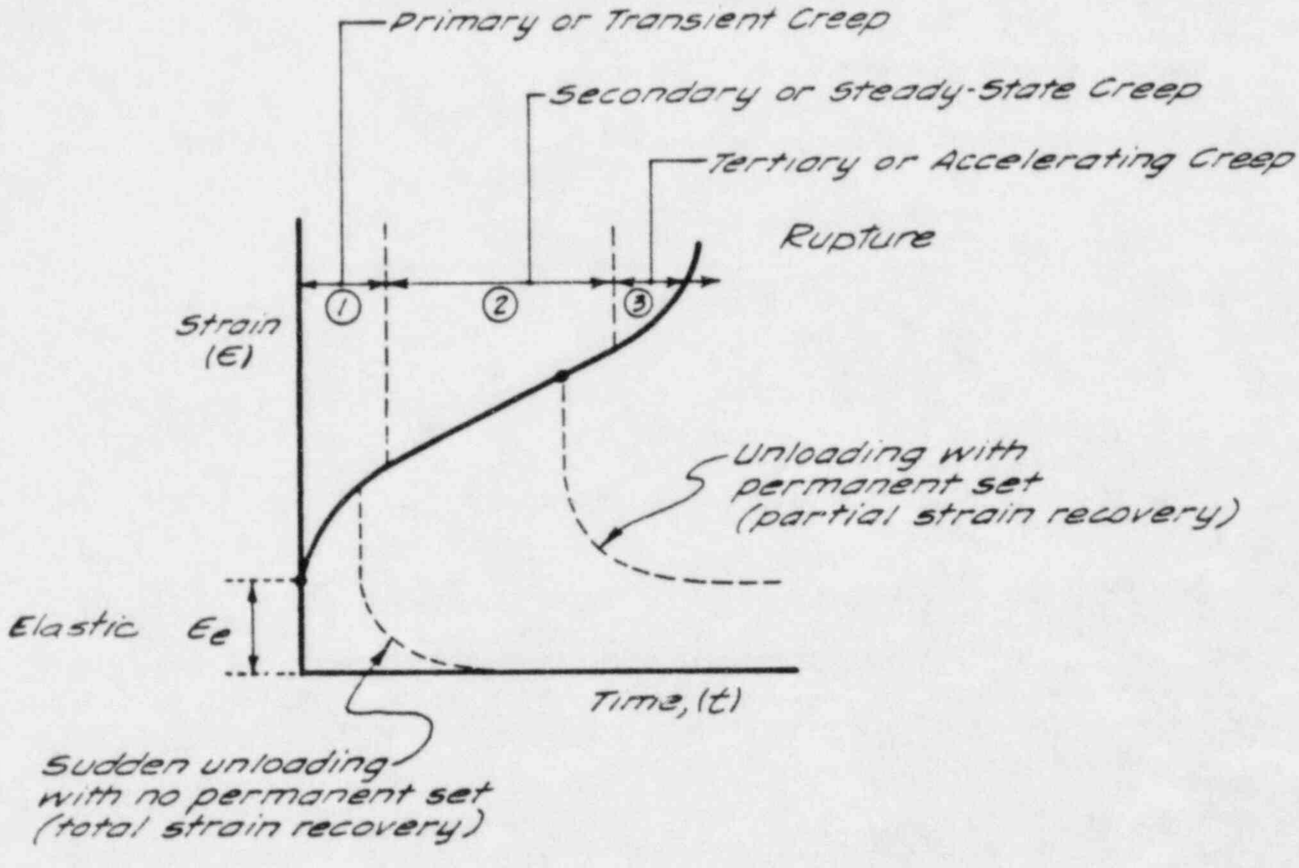
The term "creep" is customarily used to denote time-dependent effects which are observed to some extent in all rock materials, and certainly in tuff formations. The ultimate goals in the study of creep phenomena are. first, to find laws by which post-construction behavior of underground excavations can be predicted (particularly in terms of strain and strain rate), and second, to arrive at the formulation of creep "failure" criteria that may be incorporated in stability analyses for final design. In addition to time-dependence, other critical parameters, such as the state of applied stresses and temperature, strongly influence the deformational pattern.

Creep deformation can be divided into three stages, as shown in Figure 4.7. The first stage is transient creep, when on unloading the sample will recover all the induced strain with time. The second stage is a steady state creep, when on unloading there is only partial strain recovery. The third stage is characterized by accelerating creep, which leads to failure.

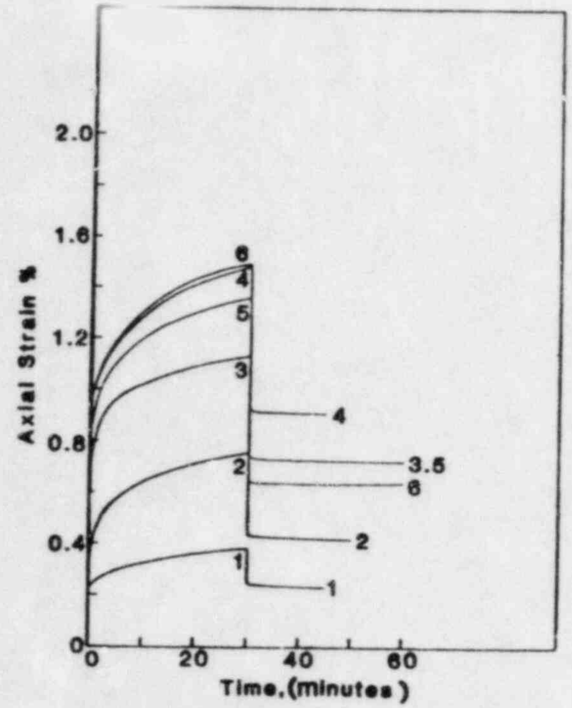
Butters et al (1980) report a series of drained and undrained triaxial creep tests on tuff specimens, at confining pressures of 0.25 kbar (25 MPa), 0.5 kbar (50 MPa), and 1.0 kbar (100 MPa). A constant axial stress was maintained and was set at percentages of failure loads defined by previous triaxial tests. After maintaining a constant stress difference for about 30 minutes, the axial loads were rapidly removed and the specimen recovery was monitored for another 30 minutes. The same procedures were then repeated for higher loads, as illustrated by the multiple curves in Figure 4.8a and 4.8b. All test specimens had progressed to the secondary creep stage by the end of 30 minutes; this is indicated by the approximately constant slope of the strain/time curves and the permanent set or incomplete strain recovery after removal of axial stresses. Other specimens (not shown on the figures) entered the tertiary creep stage. These tests showed that drained specimens

IDEALIZED CREEP CURVE AND STRAIN RECOVERY FOR A ROCK MATERIAL

Figure 4.7

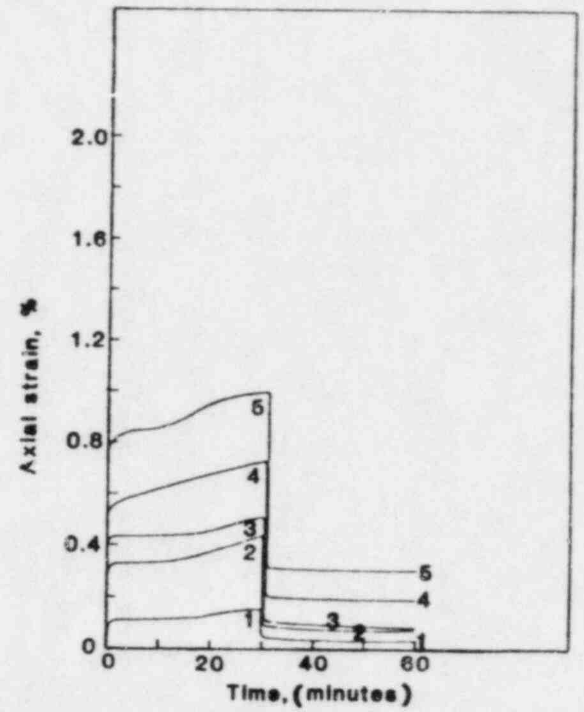


Project No. 813-1162C Reviewed KJ Date 12-81



Sample 1 produced curves 1, 2 and 4, and sample 2 produced curves 3.5 and 6.

a) Drained at 0.5 kilobars confining pressure



Sample 1 produced curves 1-5

b) Undrained at 0.25 kilobars confining pressure

After Butters et al, 1980

CREEP TESTS ON TUFF

Figure 4.8

creep more than undrained specimens. There was also a preliminary indication that, for a given stress difference, specimens tested at higher confining pressures exhibited more creep than those tested at lower confining pressures. However, these early indications require confirmation and an examination of other possible causes of "apparent" creep, such as consolidation.

To summarize, the creep deformation of tuff is predominantly a function of:

- Stress difference
- Time
- Temperature (this is anticipated, although no specific information is yet available).

In general, the repository design should consider the long-term deformation due to creep and must:

- Size pillars to reduce loading to account for thermal effect and required repository lifetime
- Provide room designs to keep room closures within allowable limits
- Design support structures and shaft linings in response to the plastic nature of the tuff
- Provide waste package spacing such that tuff temperature is held within allowable limits.

Creep behavior will not have a critical influence on any of the key issues in design and construction. However, it will have a major influence on the mechanical response and a minor influence on the hydrological and geochemical response.

4.3.5 Discontinuities

The presence of discontinuities within the rock mass markedly affects the mechanical properties (especially strength and deformation modulus), as well as the hydraulic properties (especially hydraulic conductivity) of the rock mass.

The term discontinuity is used in this study to denote any natural or induced fracture, separation plane or weakness plane defining the interface between different rock types in the rock mass. Typical discontinuities in a tuff rock mass are bedding planes, joints and fractures, shear planes or zones, and faults (see Section 2).

It has been pointed out previously that tuffs are highly variable in their structural characteristics, ranging between massive to well bedded. When interbedded with more competent volcanic rocks, tuffs will often exhibit shearing due to the concentration of movement within the weaker beds. A typical tuff cooling unit may have a densely welded zone, which exhibits a lack of bedding and predominantly columnar jointing. The more closely spaced joints are usually found in the zone of most intense welding. Vertical jointing is the most common occurrence (see Section 2.3.5), but other attitudes also exist, particularly low-angle stress-relief jointing.

The discontinuity surveys carried out to date at Yucca Mountain are described in Section 2. Such structures have a marked influence on the mechanical, as well as hydraulic, properties of the tuff, but insufficient information is currently known about them for their particular importance to be ascertained. Clearly, once determined, the effects of discontinuities should be incorporated in repository design.

The nature and distribution of discontinuities in tuff will have a critical influence on the design and construction key issues of mechanical, hydrological, and geochemical response, a major influence on constructability, and a minor influence on the thermal response.

4.3.6 Density

Apart from basic characterization purposes, the importance of density lies in the response of the repository rock mass to the high rock temperature generated by heat transfer from the waste canisters. The characteristics of the resulting plastic behavior of the rock mass, the extent to which this progresses, and the consequent degree of mobility of the waste canisters, as determined by buoyant forces, will all depend on the tuff rock mass density.

Typical bulk and grain density values for Yucca Mountain tuff material have been reported by Sandia National Laboratories (1980), as determined in samples from Hole UE25a-1. This information is included in Table 4.3, together with the corresponding calculated and measured porosity, water content by weight, and degree of saturation. Similar data have been provided by Butters et al (1980) during investigations on the mechanical properties of various tuffs at the Nevada Test Site.

Under anticipated temperature conditions, the density of the surrounding tuff medium relative to that of the waste canisters will partly determine whether or not these will be able to move and migrate beyond the near-field. Depending on the required degree of structural integrity of the repository excavation, the above knowledge will permit design provisions or modifications to be made (such as changing excavation dimensions which would alter temperature profile distributions) to reduce undesirable behavior. Construction techniques could also be adjusted to suit these conditions.

The density of tuff will not have a critical or even major influence on any of the key issues in design and construction. However, it will have a minor influence on thermal response.

TABLE 4.3

AVAILABLE BULK PROPERTIES DATA

Sample Location Depth (Ft)	Bulk Density (g/cm)	Grain Density (g/cm)	Porosity Calculated	Porosity Measured	Saturation
Hole Ue25a-1					
166	2.40	2.52	7.5	--	--
186	2.12	2.48	24.5	--	--
212	1.66	2.30	49.3	--	--
723	2.33	2.56	12.9	12.8	0.80
1290	2.33	2.40	3.7	--	--
1490	1.99	2.42	28.1	29.1	0.86
1544	1.95	2.43	34.0	--	--
1555	1.94	2.46	32.6	28.0	0.89
1561	1.95	2.48	33.5	30.3	0.91
1605	1.93	2.37	20.5	28.9	0.90
1662	1.87	2.38	34.9	34.1	0.91
1861					
1949	2.32	2.63	18.4	18.6	0.95
1968	2.28	2.61	18.0	20.9	0.76
1978	2.34	2.62	16.9	17.0	0.95
1981	2.36	2.63	16.0	--	--
1985	2.36	2.62	14.5	15.8	0.83
2402	2.28	2.61	19.2	20.7	0.98
2423	2.23	2.62	23.6	23.7	0.98
2432	2.33	2.64	18.2	18.1	0.96
2453	2.23	2.61	20.3	24.2	0.78
2492	2.30	2.60	17.7	20.8	0.90
2494	2.34	2.64	18.2	--	--
G-Tunnel					
Ev6#3-115	2.36	2.58	14.6	--	--
Ev6#1-181	1.69	2.20	42.8	--	--
Ev#11-35	1.96	2.50	35.6	--	--
Well J-13					
JA-6	2.37	2.52	8.1	--	--
JA-13	2.41	2.64	12.3	--	--
JA-22	2.00	2.45	29.9	--	--
JA-29	2.23	2.62	20.3	--	--

After Lappin, 1980

4.3.7 Moisture Content

The general effects of water on tuffs are very poorly known. Indeed, Sandia National Laboratories (1980) conclude that this is a major unresolved issue in current research. Studies so far indicate that water can have a major effect on mechanical properties.

As stated by Olsson and Jones (1980), water can affect the mechanical properties of rock through both chemical and mechanical processes. The mechanical effects arise through coupling of diffusion and deformation, which may cause nonequilibrium pore pressure. Rock which is compressing will have a pore pressure higher than the hydrostatic head, and the reverse is true if the rock is dilating. As a result, strength will be affected in accordance with the principle of effective stress. Chemical effects are related to surface chemical activity and dislocation mobility in minerals, which further reduce strength.

In general, there are two main sources of water in tuffs, namely pore water (groundwater) and mineralogical water, such as that contained in inclusions like zeolites, hydrated glass and clay. Depending on local conditions, each source is capable of contributing considerable quantities.

Typical values of water content by weight are included in Table 4.3, but it must be borne in mind that these refer to small-scale samples under laboratory conditions and may not be representative of specific tuff formations. Also, sampling disturbance and handling may significantly alter the water content, which would further decrease the representativeness of laboratory values.

A limited number of initial experiments with thermomechanical models has suggested that welded tuff may easily dry in a mine environment, while water may migrate from the surrounding rock medium into the hole containing a waste canister. The repository design should take this into account.

Moisture content is not expected to have a critical influence on any of the key issues in design and construction. However, it will have a major influence on hydrological and geochemical response and a minor influence on the thermal response.

4.3.8 In Situ Stresses

The significance of in situ stresses on the performance of a repository excavation is primarily related to the stability of the excavations. Also known as virgin stresses, geostatic stresses, lithostatic stresses and field stresses, the in situ stresses constitute the stress state in the rock mass prior to any excavation. The behavior of a repository will be affected both by the in situ stresses and the stresses induced during excavation.

Theoretical predictions of in situ stresses are not generally accurate and field measurements are required to generate the six tensor components which fully define the stress state. It is usual to record the in situ stresses in an orthogonal system with one axis vertical. The components would then be three normal stresses (x, y and z), and three shear stresses (xy, yz and zx). Alternatively, the stress state may be defined by the orientation and magnitude of the principal stress system, whereby the orientation of orthogonal axes is chosen so that there are no shear stresses.

In situ stresses arise from a combination of:

- Gravitational stresses, due to the weight of overlying material
- Stresses due to orogenic effects (mountain building)
- Stresses resulting from regional uplift and erosion of superincumbent material
- Stresses due to thermal and chemical effects, such as swelling.

In situ stresses may vary locally in the vicinity of a proposed excavation, especially in the proximity of any major discontinuity. For example, there may be a major variation in stress due to a fault.

Unfortunately, there is no information presently available on in situ stresses in the Yucca Mountain tuff units. There is no evidence to support or reject the hydrostatic in situ stress assumption widely accepted for other media, such as domal salt. However, on a largely conjectural basis, anisotropic stress conditions may be expected to exist in typical tuff formations, which could be related to the marked Young's modulus anisotropy resulting from varying degrees of welding, as discussed in Section 4.3.3 of this report. It is noted with interest the observation by Hooker (1981) that underground stress determinations at the nearby Climax stock and at several sites in Ranier Mesa demonstrate that the horizontal compressive stresses are strongly bi-axial, at least 4-to-1.

With regard to work presently planned for the future, the DOE's Quarterly Report (June, 1981) mentioned the scheduling of three overcoring holes to measure the in situ state of stress in the Nevada Test Site area. The holes are to be drilled such that stresses are measured parallel and perpendicular to the welded tuff unit. The measuring device will be the USBM 3-component borehole gauge for fractured rock.

The design of the waste repository should take into account in situ stresses so as to prevent the creation of excessive differential stresses around any excavation; in particular, the excavation shape and layout must be chosen so as to minimize unfavorable stress concentrations. An adequate knowledge of the in situ and induced stresses around a repository excavation is indispensable in assessing both the short- and long-term deformational response of the rock mass. In particular, any long-term creep deformation studies carried out by either rheological theory or empirical dependence laws could be rendered meaningless, unless parameters such as in situ and excavation-induced stresses and temperature are realistically portrayed.

The in situ stress field in tuff is not expected to critically influence any of the key issues in design and construction. However, it will have a major influence on mechanical, hydrological, and geochemical response, and a minor influence on constructability and thermal response.

4.4 DESIGN AND CONSTRUCTION

4.4.1 Generic Mechanical Characteristics Affecting Design and Construction

Many of the mechanical characteristics are of at least major importance for design and construction because the structural stability and deformation of the underground excavations are dependent on them. In addition, the response of the rock mass to the changed conditions of stress, temperature and groundwater flow will determine its suitability for long-term waste containment. Although each of the groups of mechanical, thermal and hydrologic characteristics are considered separately in this report, it must be stressed that, for repository design purposes, the interaction of these factors must also be taken into account. Table 4.4 identifies the relative priorities of the mechanical characteristics for the key issues in design and construction.

4.4.2 Mitigating Design and Construction Strategies

The impact of adverse characteristics of the site may be reduced by appropriate design and construction strategies. Mitigating measures which should be considered for adverse mechanical characteristics are:

- Selecting support methods, tunnel lining, and room sizes to reduce both short-term elastic deformation and long-term creep displacements

- Choosing the shape of underground openings to provide mechanical stability

- Choosing the excavation method to reduce the disturbed zone

- Selecting the repository geometry and waste package spacing to control the temperature loading

- Designing a cooling ventilation system to control temperatures within the repository.

TABLE 4.4

EVALUATION OF MECHANICAL CHARACTERISTICS IN TERMS OF THEIR INFLUENCE ON KEY ISSUES

KEY ISSUES	CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Rock Mass Strength	beh (Major)	cfh	bdh (Major)	ceh (Minor)	ceh (Minor)
Deformation Moduli	cfh	cfh	bdh (Major)	ceh (Minor)	cfh
Creep/Plasticity	cfh	cfh	beh (Major)	ceh (Minor)	ceh (Minor)
Discontinuities	beg (Major)	ceg (Minor)	bdg (Critical)	bdg (Critical)	bdg (Critical)
Density	cfg	ceg (Minor)	cfg	cfg	cfg
Moisture Content	cfg	ceg (Minor)	cfg	beg (Major)	beg (Major)
In Situ Stress	bfh (Minor)	ceh (Minor)	bdh (Major)	beh (Major)	beh (Major)

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions of the level of influence.

ATTRIBUTES

- availability of design and construction techniques which allow for conservative assumptions for the value of the characteristic:

  a) reasonable techniques are not available (i.e. high cost impact)
  b) some techniques are available, but at moderate cost impact
  c) reasonable techniques are available (i.e., little cost impact)

- uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:

  d) model has low uncertainty (i.e., is very representative) and high sensitivity to characteristic
  e) model has moderate uncertainty and moderate sensitivity
  f) model has high uncertainty or low sensitivity

- cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values:

  g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
  h) uncertainty can be reduced, but only during in situ testing
  i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization).

4.5 SITE SPECIFIC ASPECTS

The two horizons which have been given preliminary attention for potential repository locations within the Yucca Mountain tuffs are the Bullfrog Member and the Tram Member. According to DOE's Quarterly Report of March, 1981, the welded zone of interest in the Bullfrog Member extends from a depth of 2340 to 2547 ft (713 to 776 m), as determined in drillhole USW-G1. The second welded zone, the Tram Member, extends approximately between depths of 2780 and 3080 feet (848 to 921 m), also determined by the same borehole. The higher priority mechanical characteristics identified in Table 4.4 will now be discussed, where possible, for each site.

4.5.1 Bullfrog Member

Only a very limited amount of information on the mechanical characteristics of the Bullfrog Member tuff is presently available. In Table 4.1, taken from Olsson and Jones (1980), are some typical values of maximum stress difference, Young's modulus, Poisson's ratio, and calculated porosity for a few specimens from the Bullfrog Member tested at room temperature and several confining pressures.

A general comparison is possible between the mechanical properties for the specific horizon of interest, and those of the other tuff units in Yucca Mountain. It is interesting to note that the values of maximum stress difference for the Bullfrog Member are not by any means the highest in Table 4.1 as a whole, and that the Young's modulus values corresponding to the same Bullfrog unit fall within the middle to low range of this table. Such observations may be explained by the fact that the porosity values associated with Bullfrog specimens are relatively high, i.e., these specimens do not come from the most densely welded tuff in Yucca Mountain.

With respect to intact rock strength, Table 4.2 presents typical values of cohesion and friction angle, associated with their respective porosities, for most of the tuff units found in Yucca Mountain. The Bullfrog values indicate a relatively high porosity, and strength parameters belonging in the middle to lower range for the five geologic units reported.

Although the above remarks appear to confirm the general dependence of mechanical characteristics on porosity as stated earlier, it must be stated that the information currently available is insufficient to draw conclusions on the specific mechanical characteristics of the Bullfrog Member.

4.5.2 Tram Member

No specific information is yet available on the mechanical characteristics of this tuff formation. However, due to the similarities in geological characteristics and degree of welding between the Upper Tram

Member and the Bullfrog Member, it seems reasonable to expect, on a purely conjectural basis, that the Upper Tram formation will exhibit similar mechanical properties to those of the Bullfrog Member. The Lower Tram formation, on the other hand, appears to be largely non-welded; consequently, its mechanical characteristics are expected to be markedly different from those of the Bullfrog Member. Furthermore, if the general relationship already established in the generic study between mechanical characteristics and degree of welding is applied to these formations, the Lower Tram member may be expected to have mechanical characteristics of a much poorer quality than those of the Bullfrog member.

5. THERMAL CHARACTERISTICS

5.1 INTRODUCTION

The role of the thermal properties of tuff in the evaluation of repository response is discussed in this section at three fundamental levels:

- Thermal analysis
- Stress/deformation analyis
- Fracture analysis.

A simplified chart of input/output interactions of these different levels is shown in Figure 5.1, which will now be used to indicate the general interdependence between thermal and mechanical properties, and the analysis of response at the three levels in both the near-field and far-field.

The thermal analysis (conductive or convective flow) of the temperature distribution, which is the first component requires knowledge of:

- Repository geometry
- Thermal loading function (describing the heat transfer between the waste and the surrounding tuff medium)
- Thermal characteristics (i.e., conductivity and specific heat)
- In situ temperatures (i.e., prior to repository).

The output of this analysis is the temperature field.

The second component, the stress/deformation analysis, requires the following input information:

- Repository geometry
- Mechanical characteristics, as discussed in Section 4 (some may be temperature and fracture dependent)
- Temperature field (from the thermal analysis)
- Thermomechanical characteristics (i.e., the coefficient of linear expansion)
- Initial stress/deformation conditions.

The output of this analysis is the stress/deformation response.

The fracture analysis requires the input of:

- Stress/deformation response (from the stress/deformation analysis)
- Fracture criteria (which specify conditions for fracture initiation and propagation).

The output of this analysis is the fracture response, which in turn provides the fracture conditions input for the second component in the analysis, i.e., stress/deformation analysis.

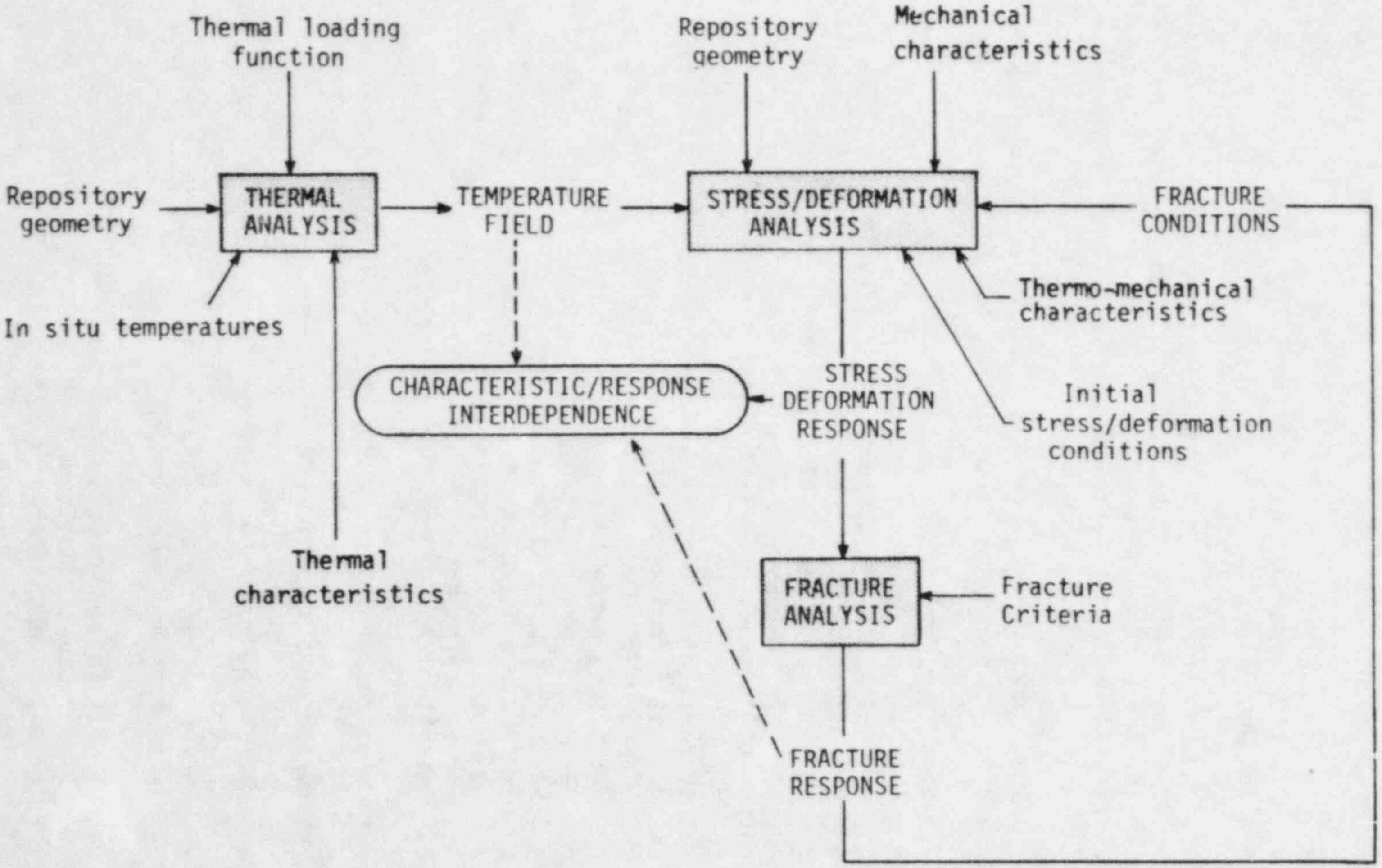


Figure 5.1

ROLE OF THERMAL CHARACTERISTICS IN THE EVALUATION OF REPOSITORY RESPONSE

As indicated in Figure 5.1, characteristic/response interdependence may exist between these three analytical components. This may require the response of any stage of the analysis to be calculated by an interactive iterative process.

5.2 GENERIC STUDY - YUCCA MOUNTAIN

In this section, the limited information available on the thermal properties of Yucca Mountain tuffs is presented, bearing in mind their role in the evaluation of repository response as discussed in Section 5.1. The Yucca Mountain tuffs are particularly appropriate for a generic study as they contain a wide range of tuff phases. However, because of the lack of sufficient data, only certain aspects of the characteristics introduced in Section 5.1 can be discussed here. These characteristics are:

- Temperature
- Thermal conductivity
- Specific heat
- Thermal expansion.

5.2.1 Temperature

The temperature distribution in and around the repository will depend upon the in situ temperatures, the distribution and heat generation of each of the high level waste packages and the thermal properties of the medium. The convective effects of ventilation (prior to backfilling) and fluids circulating under thermal, hydraulic, or chemical gradients (after backfilling) may also have a significant impact. Heat balance may be significantly altered by phase changes such as water to steam or mineralogical changes within the rock.

The analytical steps in the determination of the resulting temperature distributions have been briefly mentioned in Section 5.1; a detailed treatment of them falls outside the scope of this study. The process of alteration and the general deterioration of mechanical characteristics with increasing temperature has already been discussed in the course of Section 4.

From the viewpoint of initial site characterization, the determination of the in situ (i.e., prior to repository) temperature field is important, but no information of this type on Yucca Mountain tuffs was available for this study.

The design must account for the thermal characteristics of the repository, as discussed in Section 5.1, by adjusting the waste package spacing to keep the thermal load below critical levels, both during the operational life (ventilated) and after decomissioning (unventilated) of the repository. Critical thermal loads are those causing rock temperatures which endanger the structural integrity and performance of the repository and, hence, impact radionuclide containment.

As summarized in Table 5.1, in situ temperatures (pre-excavation) at Yucca Mountain are expected to have a major influence on the design and construction key issue of thermal response. It will also have a major influence on the mechanical, hydrological, and geochemical response, and a minor influence on constructability.

5.2.2 Thermal Conductivity

The thermal conductivity, K, is the ratio between the heat flow per unit area and the thermal gradient (temperature change per unit length), i.e.:

$$K\,(MLT^{-3}Te^{-1}) = \frac{\frac{Q}{At}\,(MT^{-3})}{\frac{\Delta Te}{L}\,(Te\,L^{-1})}$$

This parameter governs the response of a medium to steady state heating. Figure 5.2, taken from Sandia National Laboratories (1980), summarizes the available data on the thermal conductivity of many of the phases occurring in silicic tuffs. This shows that there is some limited information for silicic glasses and zeolites, and also for feldspars, quartz, and cristobalite, but not for mixed layer clays or montmorillonites. From this basic data, Sandia National Laboratories proceeds to analyze numerous trends of "zero-porosity" matrix conductivity, as a result of chemical reactions. In addition, the thermal conductivities of twelve tuffs varying widely in mineralogy and porosity have been analyzed. Extrapolated conductivities at zero percent porosity were then studied as a function of grain density. It was concluded that measured conductivity of silicate rocks, such as tuff, falls below theoretical values.

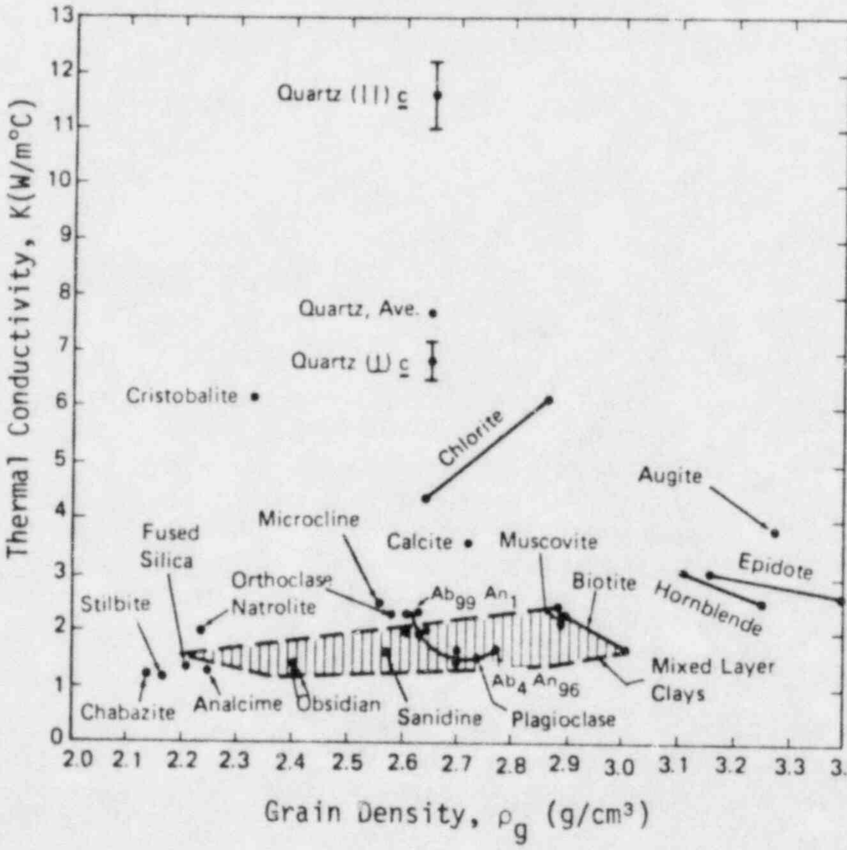
For feasibility studies in tuff, the relationships derived by Sandia National Laboratories appear capable of predicting the natural state conductivity of analyzed samples (some of which are from Yucca Mountain) to within 15 percent, when combined with porosity and saturation data in a geometric-means formulation.

Because waste emplacement may result in rock temperatures in excess of 100°C, there is also the need to predict the thermal conductivities of fully dehydrated tuffs. However, the derivation of predictive models in this case has encountered difficulties related to the selection of a realistic thermal conductivity parameter for air.

In general, the thermal conductivity of tuff is dependent on the grain size, orientation, and composition of the mineral particles, and on the size, orientation, and moisture content of the pores. It may be anisotropic and also a function of temperature, stress level, and scale.

THERMAL CONDUCTIVITY AS A FUNCTION OF DENSITY FOR PHASES OCCURRING IN SILICIC TUFFS

Figure 5.2



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As summarized in Table 5.1, the thermal conductivity of tuff will not have a critical influence on any key issue of design and construction. However, it will have a major influence on thermal response.

5.2.3 Heat Capacity

The mass heat capacity of a material is defined as the heat required to warm a unit mass of the material through one degree. The thermal capacity of a tuff sample is equal to the product of its mass and its mass heat capacity. The mass heat capacity Cm, and the thermal conductivity, K, define the thermal diffusivity, κ, as follows:

$$\kappa = \frac{K}{\rho C_m} \; (L^2 T^{-1})$$

where ρ is the material density. The thermal diffusivity governs the response of a system to transient heating.

No significant laboratory studies of mass heat capacity have been reported to date for Yucca Mountain tuffs. Sandia National Laboratories (1980) report a limited number of measurements on dehydrated samples, which show mass heat capacity of silicates in devitrified and glassy tuffs at about 100°C to be 0.20 Cal/g°C. For modeling studies, specific heats, Cm, have been estimated from the following relationship:

$$Cm\ (Cal/g°C) = 0.2\ (1 - P) + PS$$

where P is the porosity, and S is the saturation of the material. For these studies the mass heat capacity of liquid water was assumed to be constant at 1 Cal/g°C, while that of air was assumed negligible. It is thought that increasing temperature, and even slight bonding of water within zeolites and expandable clays typically present in tuffs, may cause actual values to depart from the above estimate. Because these studies were carried out on small samples under laboratory conditions, they are more representative of intact tuff characteristics than rock mass characteristics.

The heat capacity of tuff is not expected to have a critical influence on any key issue in design and construction. However, it will have a major influence on thermal response and a minor influence on geochemical response.

5.2.4 Thermal Expansion

Thermal expansion is a measure of the unrestricted change in size exhibited by a material in response to change in temperature. It may be anisotropic, and a function of temperature, stress level, and scale. The various forms of thermal coefficients commonly used to describe this change are linear expansion or linear strain per degree, and cubical expansion or volumetric strain per degree (usually assumed as three times the coefficient of linear expansion).

In much the same way as temperatures resulting from waste emplacement depend strongly on the thermal conductivity of rock, so the stresses induced by waste emplacement depend on the thermal expansion of the surrounding rock mass, when such expansion is restrained in a relatively confined environment. These thermal stresses will also depend on the parameters describing the stress-strain response of the rock mass and the timing of the backfill.

Figure 5.3, taken from Sandia National Laboratories (1980), summarizes a large number of linear expansion coefficients (i.e., linear strain per degree Celsius) between ambient temperature and 200°C as a function of porosity for Yucca Mountain tuff samples. It is interesting to note that the linear expansion coefficients for devitrified and quartz-bearing tuffs ranging from 8 to 27 percent porosity are all very similar. This suggests that the thermal expansion of the tuff matrices is largely insensitive to both mineralogy and porosity. For these samples, the average linear expansion coefficient between ambient temperature and 100°C is $(6.9 \pm 1.5) \times 10^{-6}\ °C^{-1}$, while that between 100°C and 200°C is $(11.3 \pm 2.6) \times 10^{-6}\ °C^{-1}$. However, in other cases, the situation is much more complicated as mineralogical effects may exercise a strong control on expansion behavior. This is very important, for example, in samples containing swelling clays, which are particularly abundant in many nonwelded tuffs.

The thermal expansion of tuff is not expected to have a critical influence on any key issue in design and construction. However, it will have a major influence on mechanical response and a minor influence on thermal response.

5.3 DESIGN AND CONSTRUCTION

5.3.1 Generic Thermal Characteristics Affecting Design and Construction

Table 5.1 summarizes the significance of thermal characteristics for design and construction of a repository in Yucca Mountain tuffs. In situ temperature, thermal conductivity and heat capacity are of major importance in the characterization of heat flow around the repository following the emplacement of high level waste. In situ temperatures and thermal expansion are of major importance for the determination of thermally induced stresses. In situ temperature will also have a major influence on the hydrological and geochemical response.

5.3.2 Mitigating Design and Construction Strategies

The impact of adverse characteristics of the site may be reduced by appropriate design and construction strategies. Mitigating measures which should be considered for adverse thermal characteristics are:

AVERAGE LINEAR EXPANSION COEFFICIENT OF TUFFS BETWEEN AMBIENT TEMPERATURE AND 200° C AS A FUNCTION OF POROSITY

Figure 5.3

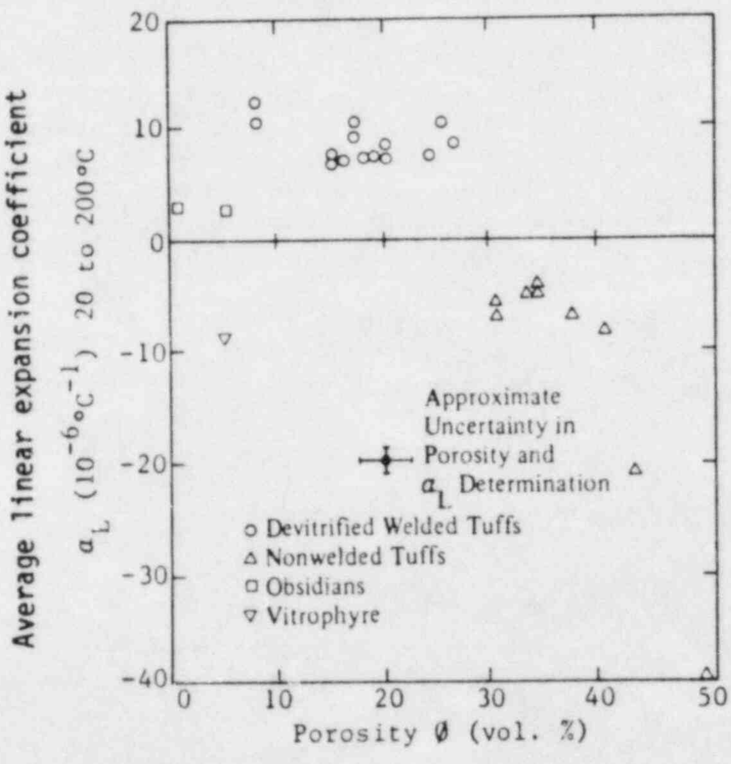

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TABLE 5.1

EVALUATION OF THERMAL CHARACTERISTICS IN TERMS OF THEIR INFLUENCE ON KEY ISSUES

KEY ISSUES	CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
In Situ Temperature	ceg	beg	beg	beg	beg
	Minor	Major	Major	Major	Major
Thermal Conductivity	cfh	bdh	cfh	cfh	cfh
		Major			
Heat Capacity	cfh	bdh	cfh	cfh	bfh
		Major			Minor
Thermal Expansion	cfh	bfh	bdh	cfh	cfh
		Minor	Major		

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions of the levels of influence.

ATTRIBUTES

- availability of design and construction techniques which allow for conservative assumptions for the value of the characteristic:

  a) reasonable techniques are not available (i.e. high cost impact)
  b) some techniques are available, but at moderate cost impact
  c) reasonable techniques are available (i.e., little cost impact)

- uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:

  d) model has low uncertainty (i.e., is very representative) and high sensitivity to characteristic
  e) model has moderate uncertainty and moderate sensitivity
  f) model has high uncertainty or low sensitivity

- cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values:

  g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
  h) uncertainty can be reduced, but only during in situ testing
  i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization).

- Choosing a repository geometry and waste package spacing to control the temperature loading

- Designing a cooling/ventilation system to control temperatures within the repository.

5.4 SITE SPECIFIC STUDY

A significant lack of specific information has prevented any meaningful assessment of the thermal characteristics of the two site specific horizons of interest in Yucca Mountain: the Bullfrog Member and the Tram Member. The limited data gathered to date are reported below (the effects of temperature upon the mechanical characteristics of the Bullfrog and Tram Members have been preliminarily discussed in Section 4.5).

5.4.1 Bullfrog Member

Sandia National Laboratories (1980) state that measured natural state and fully dehydrated thermal conductivities on samples of the partially welded Bullfrog tuff range from 2.19 to 2.65 W/m°C and 1.36 to 1.74 W/m°C, respectively, for an average porosity of 23 percent.

The DOE Quarterly Reports on Nevada Nuclear Waste Storage Investigations of March and June 1981 state that measurements of thermal conductivity parallel and perpendicular to bedding, made for partially welded, fully dehydrated samples from the Grouse Canyon Member, indicate the absence of any significant matrix thermal anisotropy. To assess the possible general validity of this result, limited additional measurements are planned in the Bullfrog Member and other nonwelded tuffs. If confirmation of such results is obtained, this would indicate that any appreciable in situ thermal anisotropy would result largely from the presence of joints and/or fluid flow.

With respect to thermal coefficients of linear expansion, a few expansion measurements under confining pressure have been reported by Sandia National Laboratories (1980). The results for Bullfrog tuff oven-dried samples agree reasonably well with free expansion measurements carried out at ambient pressure. At a confining pressure of 10.3 MPa (1494 psi), the average linear expansion coefficient obtained between ambient temperature and 200°C was calculated to be 6.1×10^{-6} °C-1 as compared with 8.9×10^{-6} °C^{-1} for unconfined conditions. Cooper and Simmons (1977) have postulated that this difference may be partly due to the closing of microcracks under pressure. Further work is needed to understand these variations.

5.4.2 Tram Member

No specific information is available on thermal properties of this geologic unit. For the Upper Tram Member, which has similar geology and degree of welding to the Bullfrog formation, the thermal properties may also be expected to be similar. The Lower Tram Member, which is essentially a nonwelded unit, may be expected to exhibit thermal properties which differ from those of the Bullfrog formation; however, this can not be confirmed in the absence of site specific information.

6. HYDROLOGIC CHARACTERISTICS

6.1 GENERAL

Hydrologic considerations for repository design include:

- Groundwater inflow into the excavations
- Sealing the access shaft to prevent vertical groundwater migration
- Resaturation of the backfill
- Assessment of the controlled release of nuclides into the groundwater flow system from the aspects of both containment and isolation.

Since an access shaft is required from land surface to the repository excavation as part of the test facility, hydrologic properties of geologic strata overlying and surrounding the tuff repository horizon need to be evaluated.

Consideration of the key design and construction issues identified in Section 1 along with the hydrologic characteristics shows that they may be related in the following way:

- Constructability
  - hydraulic conductivity
  - hydraulic gradient
  - total porosity
  - specific storage

- Thermal response
  - hydraulic conductivity
  - hydraulic gradient
  - total porosity
  - specific storage

- Mechanical response
  - hydraulic conductivity
  - hydraulic gradient
  - total porosity
  - specific storage

- Hydrological response
  - hydraulic conductivity
  - hydraulic gradient
  - total porosity
  - specific storage

- Geochemical response
  - hydraulic conductivity
  - hydraulic gradient
  - total and efective porosity
  - specific storage
  - dispersivity
  - adsorption
  - pore fluid composition.

The following sections describe the hydrologic characteristics and assess their importance for the design and construction issues with particular reference to the generic area at Yucca Mountain. A matrix diagram is presented at the end of these sections ranking the characteristics in terms of relative significance for design and identifying the significant characteristics as a guide to SCR assessment.

The second half of this hydrologic section assesses the two potential repository horizons below the water table at Yucca Mountain according to the ranking developed within the generic study.

6.2 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is a proportionality constant relating the Darcy velocity of a fluid (volume flux rate) to the hydraulic gradient as defined by Darcy's law:

$$q_i = -K_i \frac{\partial h}{\partial x_i}$$

where:
- x_i = 1, 2, 3 refers to the principal directions of hydraulic conductivity
- q_i = Darcy velocity in the i direction (LT^{-1})
- K_i = principal hydraulic conductivity in the i direction (LT^{-1})
- $\frac{\partial h}{\partial x_i}$ = hydraulic gradient in the i direction; rate of change in hydraulic head with distance (dimensionless)

Hydraulic head can be expressed as:

$$h = z + \frac{p}{\rho g}$$

where:
- h = hydraulic head at some point in the flow regime (L)
- z = elevation above an arbitrary datum (L)
- p = pore pressure ($ML^{-1} T^{-2}$)
- g = acceleration of gravity (LT^{-2})
- ρ = density of pore fluid (ML^{-3})

  Note: pore fluid density is affected by temperature.

The above equation indicates that hydraulic conductivity is a directional property of the porous medium. In layered sedimentary rocks, the principal directions of hydraulic conductivity are usually perpendicular and parallel to bedding with the former less than or equal to the latter. In fractured media, the directional relationships are much more arbitrary with higher hydraulic conductivities in the preferred directions of fracturing.

Hydraulic conductivity is a measure of the ability of a porous medium to transmit fluid of a particular density and viscosity. It is often convenient to separate the fluid properties from the porous medium properties as follows:

$$K = \frac{k \rho g}{\mu}$$

where
- K = hydraulic conductivity (LT^{-1})
- k = intrinsic permeability (L^2)
- ρ = fluid density (ML^{-3})
- g = gravitational acceleration (LT^{-2})
- μ = fluid dynamic viscosity ($ML^{-1}\,T^{-1}$)

Fluid density (ρ) and viscosity (μ) are sensitive to temperature and the composition of pore fluids. Intrinsic permeability (k) is approximately constant and considered a characteristic property of the medium.

The hydraulic conductivity of a formation represents flow between individual grains (interstitial or matrix hydraulic conductivity) and flow through fractures or other secondary openings in the rock (fracture hydraulic conductivity). Hydraulic conductivity values based on laboratory core samples do not generally reflect fracture permeability and therefore, usually represent a lower bound value. Hydraulic conductivity data based on field tests, such as full-scale pumping tests, more adequately reflect the in situ hydraulic conductivity of a rock mass.

Hydraulic conductivity is of great importance to repository design and construction. It directly or indirectly affects many design and construction issues including:

- Shaft inflow and the design of control measures
- Repository inflow and the design of control measures
- Post-decommissioning groundwater inflow to the repository
- Performance of shaft and borehole seals
- Local flow field in the immediate region of the waste package and the repository
- Velocity and direction of nuclide transport from the repository to the accessible environment.

Since groundwater velocity is proportional to hydraulic conductivity, the design of backfills and other engineered barriers must consider the hydraulic conductivity of the natural and man-made materials through which contaminated groundwater will flow.

Volcanic tuffs, as described in the type generic area of Yucca Mountain (see Section 2), exhibit large variations in lithology, mineralogy, degree of welding, and fracture density (DOE, August 1981). Therefore, hydraulic conductivity is likely to range over many orders of magnitude. Figure 6.1 is a diagrammatic representation of an individual tuff cooling unit which represents a single episode of deposition and is zoned according to the degree of welding. The upper and lower parts are generally nonwelded and contain little fracturing. These zones grade inward to a more densely welded central zone which typically has primary cooling joints and secondary stress related joints.

In situ hydraulic conductivity in the nonwelded zones is mainly controlled by the matrix hydraulic conductivity. An irregular rubble zone is common along the base of some flows, but since the rock fragments are completely surrounded by matrix material, these zones do not result in appreciable permeability. Open cavities of various origins can constitute up to 10 percent of the total rock volume, but they are generally unconnected and have not been shown to affect the hydraulic conductivity of the rock mass.

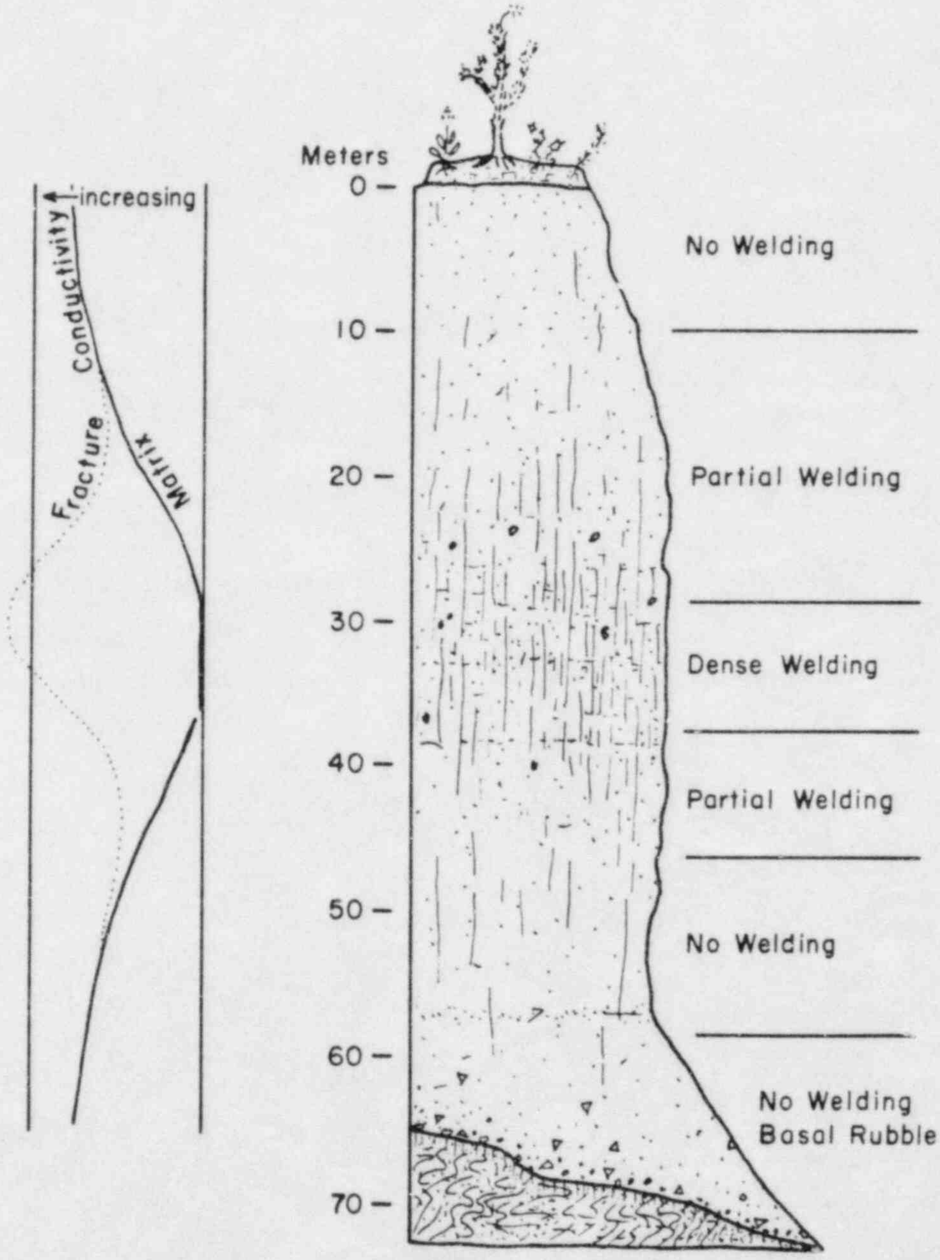
Within the partially and densely welded zones, hydraulic conductivity is controlled exclusively by joints and fractures. Primary cooling joints develop normal to the temperature isotherms soon after emplacement of the tuff. Observations of tuff outcrops and core samples (Winograd, 1971, and observations by Golder Associates personnel) indicate that the cooling joints tend to form perpendicular to bedding (Figure 6.2). For tuffs at the Nevada Test Site, spacing ranges from a centimeter to several meters and the joints tend to be more closely spaced in the zones of dense welding (Winograd and Thordarson, 1975). Horizontal partings are common in many tuff outcrops and have been observed to a lesser extent in core samples. They are thought to represent stress relief jointing due to removal of superincumbent load and are generally not likely to be open at depth. Jointing results in welded zones that are anisotropic with respect to hydraulic conductivity. Since the jointing has a preferred vertical orientation (in shallow dipping strata) the vertical hydraulic conductivity (Kv) tends to be greater than the horizontal hydraulic conductivity (Kh).

Permeability characteristics of welded tuff core samples at the Nevada Test Site have been described by Winograd and Thordarson (1975). Laboratory analysis indicates matrix hydraulic conductivities that vary inversely with the degree of welding (Figure 6.1), ranging from 10^{-4} cm/s in nonwelded zones to 10^{-10} cm/s in zones that are densely welded. In unfractured nonwelded tuff, the matrix hydraulic conductivity of core samples is probably similar to the in situ hydraulic conductivity, but such a relationship is not valid in the welded zones where hydraulic conductivity is controlled by fracturing.

Observations of underground workings in saturated zeolitic tuff of the Indian Trails Formation were made by Thordarson (1965). Although this tuff unit is not saturated below Yucca Mountain, the descriptions of fracturing and groundwater inflows provide useful comparative

DIAGRAMMATIC REPRESENTATION OF A TUFF COOLING UNIT SHOWING VARIATIONS IN MATRIX AND FRACTURE HYDRAULIC CONDUCTIVITY

Figure 6.1



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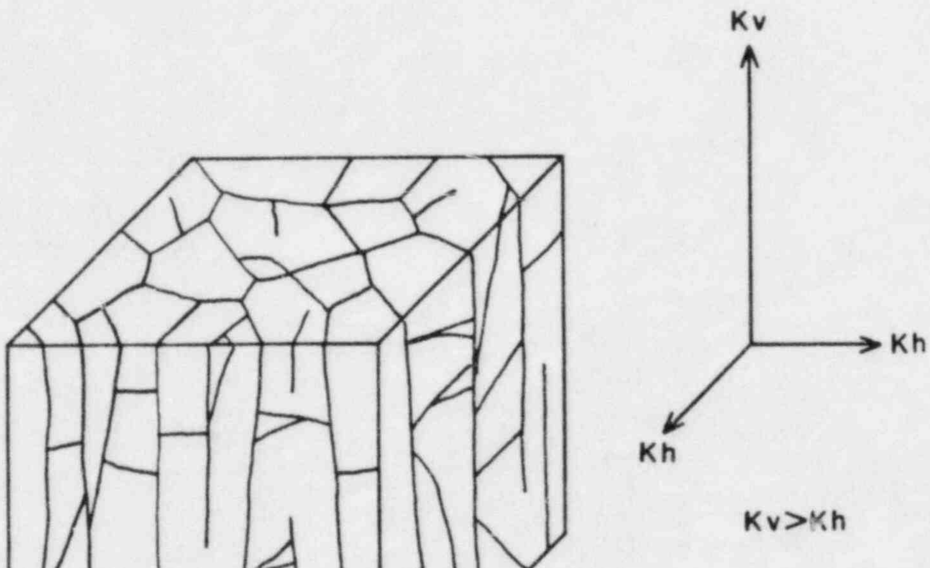
VERTICAL COLUMNAR JOINTING AND PRINCIPAL DIRECTIONS OF HYDRAULIC CONDUCTIVITY IN DENSELY WELDED ZONES

Figure 6.2



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qualitative information on the in situ nature of tuff hydraulic conductivity. The workings contained more than five miles of tunnels and shafts, some of which were constructed in a perched groundwater zone below Rainier Mesa. Most joints had near vertical attitudes and were generally closed. Open joints, however, had widely variable apertures and could be nearly closed at one location and open as much as 5 cm just a few meters away. Only a small percentage of the joints were water bearing. About 50 to 60 percent of tunnel inflows resulted from faults or breccia zones and 40 to 50 percent was attributed to fractures. The initial discharge of water from most fractures was less than 1.3 l/s but the discharge from one fault zone was about 13 l/s. The discharge from all fractures decreased rapidly with time and, within a few days, was a small fraction of the initial flow rate. Water-bearing joints tended to be poorly connected and tunneling often intersected saturated joints a hundred meters away from joints which had been dewatered several days earlier. Five thousand joints were mapped at the U12e tunnel complex by McKeown and Dickey (1961). Joint densities reached a maximum of one per meter of tunnel, but many sections of tunnel up to 10 m long were unjointed.

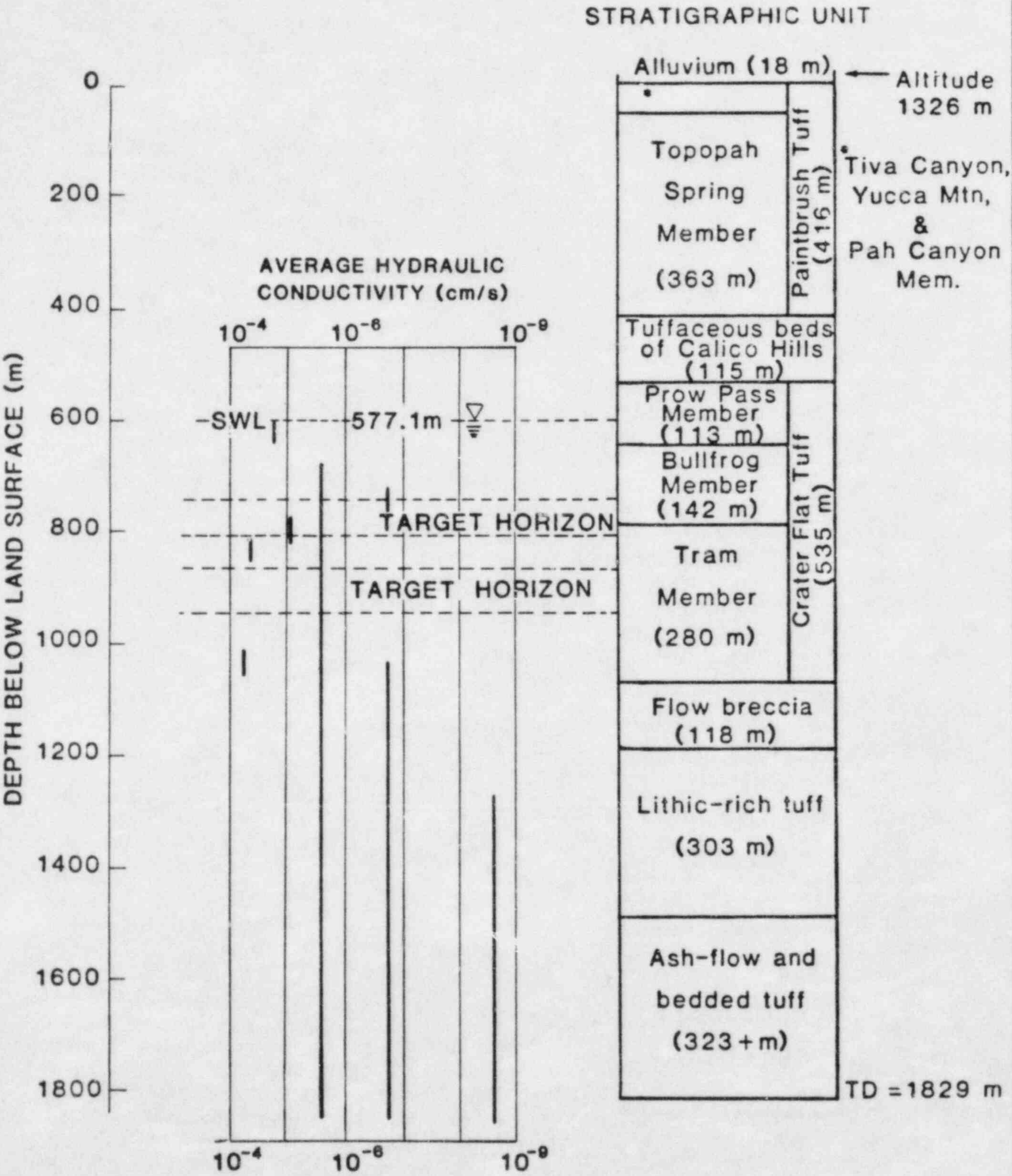
Wier (in Winograd and Thordarson, 1975), documented groundwater inflows in two deep test chambers in tuffaceous rocks beneath Pahute Mesa. In a chamber 300 m below the regional water table, he observed that most of the water seemed to be entering through that part of the chamber containing the most fractures. However, all the chamber walls were damp to wet which suggested that some water was also moving through the rock matrix, rather than entirely through the joint or fracture system. The total flow rate into this chamber was estimated at less than 0.25 l/s. In a deeper chamber 600 m below the water table, groundwater flowed only from microfractures on one side of the room at a rate of about 0.06 l/s and the remainder of the chamber walls were dry (i.e., seepage rate less than evaporation rate). Wier noted that the yield from the microfractures tended to decrease with time.

Single borehole packer tests were conducted by the U.S. Geological Survey in two boreholes at Yucca Mountain (Figure 6.3). Measured hydraulic conductivities ranged from 10^{-3} to 10^{-10} cm/s and the hydraulic conductivity tended to decrease with depth (DOE, August 1981). However, fracture densities and rock lithologies suggest that in situ hydraulic conductivity is quite variable within individual cooling units.

The U.S. Geological Survey tests were subject to a variety of errors and the values presented in Figure 6.3 are considered somewhat misleading. Leakage past the packers and "short circuiting" through the formation were known to have occurred in some of the tests which would have resulted in an overestimation of hydraulic conductivity. On the other hand, drilling fluids may not have been completely removed from the formation during well development, resulting in an artificial reduction in permeability near the borehole that would cause underestimation of the in situ hydraulic conductivity. In addition, packer testing was carried out over large stratigraphic intervals, thus masking thin

RESULTS OF PACKER TESTS IN BOREHOLE USW-G1, YUCCA MOUNTAIN STUDY AREA

Figure 6.3a



Vertical lines represent packed off intervals. Borehole diameter: 10.2 cm (4 in)
Drilling fluid: polymer mud

After DOE, August 1981

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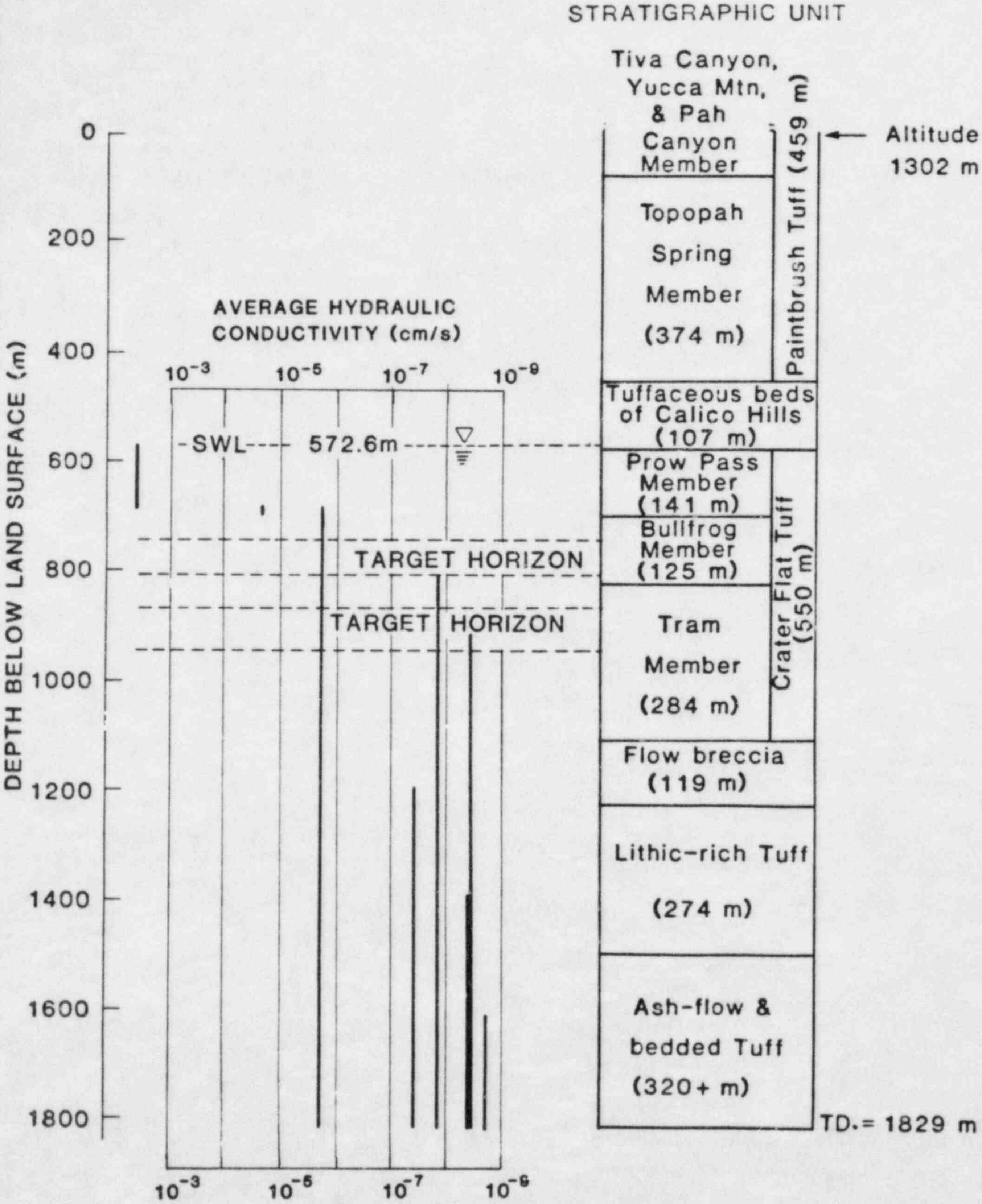
RESULTS OF PACKER TESTS IN BOREHOLE USW-H1, YUCCA MOUNTAIN STUDY AREA

Figure 6.3b



Vertical lines represent packed off intervals. Borehole diameter: 20.3 cm (8 in)
Drilling fluid: foam

After DOE, August 1981

Project No. 813-1162 Reviewed ___ Date 12-81 horizons of high hydraulic conductivity. While permeability tests in vertical boreholes may be an effective measure of horizontal hydraulic conductivity, such tests are relatively insensitive to vertical hydraulic conductivity. As previously stated, fracture attitudes in welded tuff suggest that vertical hydraulic conductivity is greater than that in the horizontal direction. As comparatively few vertical joints would have been intersected by a vertical hole, it is likely that the in situ vertical hydraulic conductivity of the welded zones is greater than the values given in Figure 6.3. As a result of uncertainties associated with these tests, the information must be currently treated with caution for repository design.

Hydraulic conductivity is considered a critical design characteristic with regard to the following key issues:

- Hydrological response - repository inflow rates are directly proportional to hydraulic conductivity
- Geochemical response - groundwater flow velocity is directly proportional to hydraulic conductivity.

Hydraulic conductivity is considered a major design characteristic with regard to:

- Constructability - hydraulic conductivity is important in designing shaft seals, tunnel linings, backfills, and other types of engineered barriers.

Hydraulic conductivity is considered a minor design characteristic with regard to:

- Thermal response - hydraulic conductivity has an effect on the rate of thermal convection.

6.3 HYDRAULIC GRADIENT

Hydraulic gradient is the rate of change in hydraulic head with distance. In the absence of other gradients (i.e., temperature and chemical) it causes fluid flow according to Darcy's law. Hydraulic gradient will probably be the major force causing fluid flow within tuff flow systems, although temperature gradients may be significant near the repository after decommissioning. Hydraulic gradients in natural groundwater systems can be complex, exhibiting three-dimensional variability that generally reflects the natural variations in hydraulic conductivity of the geologic media.

Hydraulic gradients are of major importance in design because they affect the following design considerations:

- The rate of groundwater inflow into the shaft and repository excavation during construction and operation
- The rate of inflow into the repository after decommissioning

- The velocity of groundwater carrying nuclides from the repository to the accessible environment.

In groundwater flow systems, hydraulic gradients are estimated by extrapolating the spatial distribution of hydraulic head from point measurements in piezometers. A piezometer data base does not exist at Yucca Mountain and therefore, the three-dimensional distribution of hydraulic head is unknown.

If vertical gradients are small, the horizontal gradient can be estimated from the slope of the piezometric surface, which represents a horizontal distribution of hydraulic head. In Figure 6.4, water level measurements from 14 wells completed in tuff have been used to construct a piezometric contour map in the area surrounding Yucca Mountain. Due to a lack of data, the contours in the northern part of the map are inferred. The map suggests a groundwater sink east of Yucca Mountain. No spring discharges have been documented in this area and, therefore, the map might suggest downward vertical flow along a local geologic structure in the vicinity of Forty Mile Canyon. It must be pointed out, however, that water-level measurements in wells represent an average hydraulic head along the uncased portion of the borehole. If vertical gradients are significant, the water level will be affected by the depth interval of the uncased portion. Because of this uncertainty, the piezometric contour map in Figure 6.4 is considered to be speculative.

Little data exists with regard to vertical hydraulic gradients in the tuff sequence below Yucca Mountain. During the drilling of two deep boreholes by the U.S. Geological Survey the vertical gradient was estimated by monitoring water levels during drilling. Although the measurements are not accurate, the data suggest a decrease in hydraulic head with depth which would indicate downward vertical flow (DOE, August 1981). In northern Yucca Flat, to the northeast of Yucca Mountain, the piezometric head in the tuff aquitard is as much as 40 m higher than that of the underlying carbonate aquifer (Winograd and Thordarson, 1975).

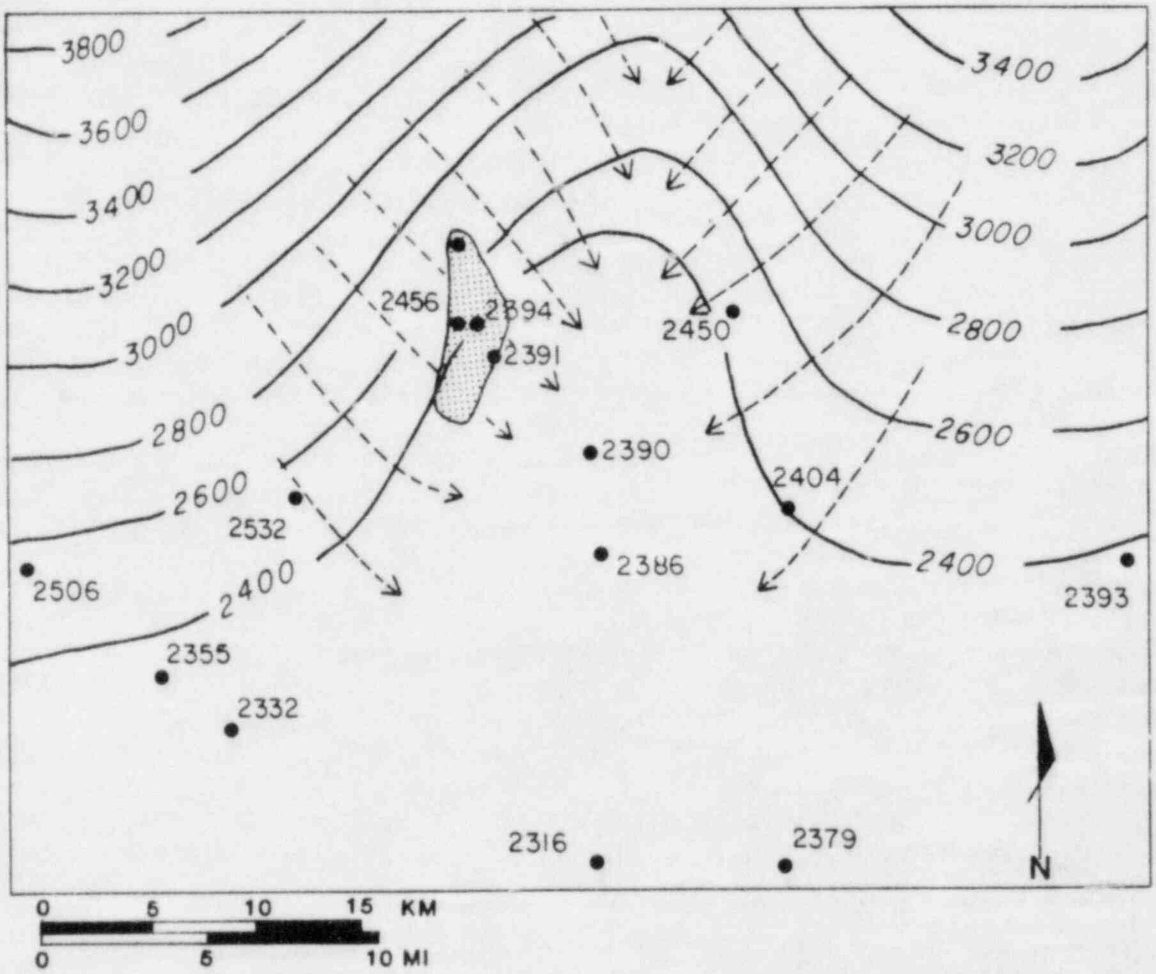
Winograd and Thordarson (1975) describe a laterally extensive carbonate aquifer (at depth below the tuff section) which, according to their interpretation, controls the regional movement of groundwater at the Nevada Test Site. Horizontal hydraulic gradients in this unit range from 0.06 to 1.1 m/km in a general southerly direction. Yucca Mountain boreholes drilled to a maximum depth of 1829 m did not intercept the carbonate formation and, therefore, its relationship to the site hydrology is unknown.

Hydraulic gradient is considered a critical design characteristic with regard to the following key issues:

- Hydrologic response - natural and man-induced hydraulic gradients will affect the pore pressure response of the rock mass

WATER-LEVEL ELEVATIONS IN THE VICINITY OF YUCCA MOUNTAIN

Figure 6.4



EXPLANATION:

- ● Water-Level Elevation in Observation Well (ft.)
- — Water-Level Elevation Contour (ft.)
- --→ Inferred Horizontal Flow Direction

Shaded area represents Yucca Mountain Block

NOTE: Water-level elevation represents average hydraulic head in open portion of boreholes terminating in various tuff units.

After DOE, August 1981

- Geochemical response - the velocity and direction of groundwater flow is controlled by the existing and induced hydraulic gradient.

Hydraulic gradient is considered a major design characteristic with regard to the following key issues:

- Constructability - hydraulic gradient has a major impact on the design of engineered barriers
- Mechanical response - hydraulic gradient is related to the change in pore pressure with distance. It therefore controls effective stress in the rock mass.

Hydraulic gradient is a minor design characteristic with regard to:

- Thermal response - hydraulic gradient will have some effect on the rate and direction of thermal convection.

6.4 POROSITY

Total porosity is the ratio of the volume of void space in the rock to the total volume. Primary porosity is formed when the material is deposited and consolidated. Secondary porosity forms after consolidation and is due to such features as joints, fractures, and dissolution cavities.

The term effective porosity is often defined as the ratio of void space through which fluid moves (interconnected voids) to the total volume and is, by definition, less than or equal to the total porosity. In terms of solute transport, it is defined as the porosity value which, when divided into the Darcy velocity, gives the true average flow velocity of the fluid the porous medium. The two definitions above are not necessarily equivalent, particularly in fractured media where a large proportion of the fluid can be carried by a very small proportion of the voids.

Effective porosities have not been measured in welded and nonwelded tuff. Total porosities vary inversely with the degree of welding, ranging from 50 percent in nonwelded zones to 5 percent in the central densely welded zones (Winograd and Thordarson, 1975). In nonwelded tuff, groundwater flow is primarily through the rock matrix and, therefore, effective porosity may be similar to total porosity. In densely welded tuff, where flow is controlled by fractures, effective porosity in likely to be much less than the total porosity.

For zeolitic nonwelded tuff, the total porosity is affected by temperature, as mineral assemblages break down and new ones are formed. Porosity of the zeolitic Calico Hills tuff increased by 20 percent upon heating from 25 to 80 degrees Celsius. In samples of Topopah Springs tuff, porosity increased 20 percent from 25 to 80 degrees and then decreased 25 percent from 80 to 180 degrees Celsius (DOE, August 1981).

Porosity is considered a major design characteristic with regard to the following key issues:

- Thermal response - total porosity of a saturated medium affects the in situ thermal conductivity
- Mechanical response - total porosity of a saturated media affects the in situ compressibility
- Hydrologic response - the time required to saturate the repository backfill will be directly related to its total porosity
- Geochemical response - the velocity of groundwater flow is inversely proportional to effective porosity. The ion exchange capacity of a media is inversely related to total porosity.

6.5 SPECIFIC STORAGE

The specific storage is the volume of fluid taken into or released from storage in a unit volume of porous medium per unit change in hydraulic head under saturated conditions. It is related to the compressibility of the rock matrix and the pore fluid. For porous media with high permeability the relationship can be expressed as (Domenico and Mifflin, 1965):

$$S_s = \rho g (n\beta + a)$$

where
- S_s = specific storage (L^{-1})
- β = compressibility of pore fluid ($LT^2 M^{-1}$)
- ρ = density of pore fluid (ML^{-3})
- g = acceleration of gravity (LT^{-2})
- a = compressibility of porous media matrix ($LT^2 M^{-1}$)
- n = total porosity (dimensionless)

The applicability of this equation to media with very low hydraulic conductivity is uncertain.

Specific storage is significant only when transient pressure response in the host rocks is considered, such as during depressurization (excavation) and repressurization (post-decommissioning). In nonwelded zeolitic tuff to partially welded tuff, specific storage may range from 10^{-5} to 10^{-7} cm^{-1}. In jointed densely welded tuff, values of 10^{-7} to 10^{-8} cm^{-1} may be considered realistic (values estimated after Walton, 1970).

Specific storage is considered a major design characteristic with regard to:

- Hydrologic response - specific storage affects the transient pore pressure response of the rock mass and will influence groundwater inflows from permeable formations into the access shaft.

6.6 DISPERSIVITY

Dispersion describes the spreading of a solute when introduced into a flow field and includes both mechanical dispersion and molecular diffusion. Mechanical dispersion results from the movement of fluid particles along statistically random paths through the porous medium while molecular diffusion results from physiochemical properties of the fluid and the surrounding rock. Molecular diffusion is normally neglected in natural groundwater systems and has not been measured in in situ tests (Reddell and Sunada, 1970).

Dispersivity (the measure of dispersion) is a length property of the medium which is largely dependent on the scale of the flow region under investigation. Values can range from 10^{-2} cm for laboratory tests to 10^{4} cm for regional systems (Cherry et al, 1975). At the microscopic (laboratory) scale, it is consequence of the tortuosity of the medium pore space while at the macroscopic (field) scale, it is primarily due to the divergence of flow paths resulting from heterogeneities in aquifer properties, particularly hydraulic conductivity. Dispersivity varies with direction and is described using both a lateral dispersion coefficient (perpendicular to flow direction) and a longitudinal dispersion coefficient (in the direction of flow).

A physical consequence of dispersion theory is that the leading front of a nonreactive contaminant plume travels faster than the average pore fluid velocity. Therefore, the calculation of travel time based on average fluid velocities may overestimate the time required for a nonreactive contaminant to first appear. In regional systems, the error may be severe. In situ measurements from a test facility may only be valid for near-field considerations.

Dispersion pertains primarily to the extent and rate of spread of a contaminant plume and will affect the migration of nuclides from the repository horizon to the more adsorptive (zeolitic) strata above and below. Consideration of dispersion may therefore aid in choosing a repository horizon and in designing engineered barriers to optimize the adsorptive capabilities of the zeolitic zones. No in situ dispersivity measurements have been performed in the tuffaceous rocks below Yucca Mountain.

Since dispersivity is a scale-dependent parameter, in situ measurements will only be relevant for the scale of the test. For example, dispersivity values measured in a multiple borehole tracer test are not valid for the waste package or regional scales. This places a severe limitation on the usefulness of measured dispersivity values. In most cases, repository performance can be evaluated by assuming conservative dispersivity values based on a limited number of in situ tests and/or generic information. Therefore, it is a minor design characteristic with regard to the geochemical response of the repository site.

6.7 ADSORPTION

The degree to which radionuclides are retarded depends on the solute species, the geochemical character of the rock, and the chemical composition of the pore fluid. Retardation of a specific ion is strongly dependent on the concentration of other ions in solution and on the adsorption history of the medium. Therefore, parameters which describe retardation may not be meaningful unless all geochemical characteristics of the system are specified. For a mixture of reactive contaminants, each species will travel according to its retardation properties and after a given time, the contaminant plume will segregate into different zones, each advancing at its own rate. If the adsorption reactions of a particular ion are nonreversible, the contaminant is permanently immobilized by the medium. Unfortunately, many nuclides have reversible adsorption reactions and, thus, a change in the geochemical environment (i.e., decrease in dissolved solute concentration) may cause the contaminant to be remobilized by the groundwater flow system.

Adsorption of nuclides by the geologic medium is a major concern in designing the backfill and other engineered barriers. Since the adsorption capacity of a medium varies with the nuclide species, an optimal backfill material should adsorb nuclides which are not strongly retarded by the host rocks. Therefore an assessment of the in situ adsorption properties is required.

The amount of contaminant adsorbed by a porous medium is commonly a function of the dissolved solute concentration. For low to moderate concentrations, the following relationship generally holds (Freeze and Cherry, 1979):

$$S = Kd\ C^b$$

where:

S = mass of adsorbed solute per unit bulk dry mass of the medium (dimensionless)

C = solute concentration; mass of solute per unit volume of fluid (ML^{-3})

Kd and b are experimentally determined coefficients which depend on the contaminant species and the geochemical character of the system. For many contaminants, b is close to unity. Therefore, the above equation may be approximated by:

$$S = Kd\ C$$

which describes a linear adsorption isotherm. Kd is known as the equilibrium distribution coefficient of the solute species and is defined as the mass of adsorbed solute per unit dry mass of the medium divided by the mass of dissolved solute per unit volume of fluid. It has dimensions of ($L^3\ M^{-1}$) and is normally expressed in (ml/g).

In situ adsorption tests are probably not feasible for all relevant nuclides, since this would require the introduction of potentially harmful contaminants into the natural environment. However, it may be advisable to perform a limited number of in situ tests so that the validity of other methods can be assessed.

Distribution coefficients are normally measured in the laboratory by batch or column tests. In batch tests, a contaminant solution of known initial concentration is mixed with powdered rock. When chemical equilibrium is achieved, the change in dissolved solute concentration is used to calculate the amount of solute adsorbed by the rock particles. Column experiments are similar except the solution is recirculated through a column of crushed rock until the disolved solute concentration ceases to change. Column tests give distribution coefficients which are lower and probably more realistic than the less expensive batch tests. In many tests, the reaction rates are very slow so that equilibrium conditions cannot be verified at the end of the test. In this case, the ratio S/C (called the sorption ratio) is similar to Kd but does not imply equilibrium conditions. Measured sorption ratios are less than or equal to the equilibrium distribution coefficient.

Batch tests have demonstrated that zeolitic tuff in the Yucca Mountain sequence is much more sorptive than devitrified tuff for many important cations. In tests at Los Alamos Scientific Laboratory, tuffs high in zeolitic minerals had sorption ratios of 10^3 to 10^4 ml/g for strontium, cesium, borium, cerium, europium, americium, and plutonium. For devitrified tuffs the sorption ratios ranged from 10^2 to 10^3 ml/g (DOE, August 1981). Preliminary results of column tests (Vine et al, 1980) showed that sorption ratios for strontium, cesium, and borium were similar to, although lower than, those values obtained by batch methods.

Based solely upon mineralogical considerations, an ideal repository horizon within the tuff section at Yucca Mountain would be a densely welded zone surrounded by zeolitic zones. The zeolitic zones would need to be a sufficient distance from the repository horizon so that thermal loading would not produce temperatures in excess of 125°C.

Some anions of iodine, technetium, and uranium have low sorption ratios and are not strongly absorbed by zeolitic or devitrified tuff (DOE, August 1981). Since zeolitic tuff has a large cation exchange capacity, it may be advisable to design a backfill with a large anion exchange capacity, provided it meets other engineering criteria.

Adsorption is considered a critical design characteristic with regard to:

- Geochemical response - radionuclide adsorption directly controls the retardation properties of the rock mass and engineered barriers.

6.8 COMPOSITION OF PORE FLUIDS

The salinity of groundwater is a primary consideration relating to hydrochemistry. It is normally expressed as total dissolved solids (TDS) and is given in units of milligrams/liter (mg/l) which is approximately equivalent to parts per million (ppm) for low salinities.

The final classification of water, however, should be based on the concentrations of major ions. The trilinear diagram (Piper, 1944) is designed to permit chemical compositions of many samples to be represented graphically (Figure 6.5). Since ionic concentrations are expressed as percentages of total milliequivalents, waters with different total concentrations can have identical representations on the diagram. A mixture of two different waters will plot on a straight line joining the points that describe the two water types.

Groundwater chemistry is important to repository design in that adsorption properties of the medium are directly affected by the chemical composition of pore fluids. Laboratory sorption ratios may not be meaningful unless the geochemical characteristics of the real system (including pore fluid composition) can be reproduced experimentally. Furthermore, the long-term integrity of the waste package and backfill is directly related to the near field hydrochemistry.

Winograd and Thordarson (1975) discuss the factors that affect groundwater chemistry at the Nevada Test Site. They include:

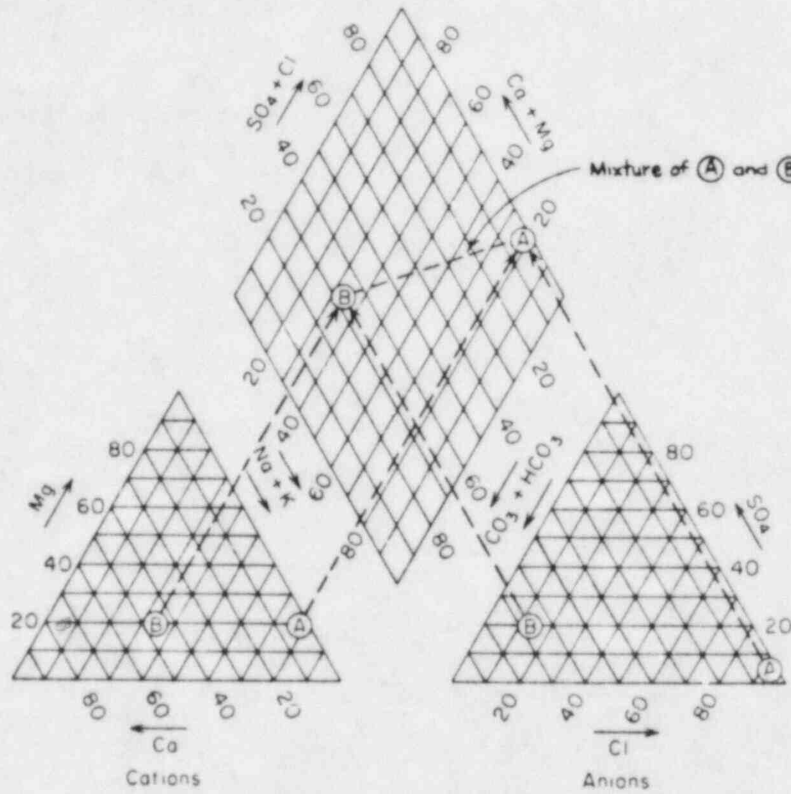
- Chemical characteristics of ground water as it enters the zone of saturation
- Adsorption-desorption capacity of the rocks
- Solubility of rock minerals
- Porosity and permeability
- Groundwater velocity and flow paths
- Geochemical conditions (i.e., temperature, pressure, Eh, pH)
- Mixtures of waters from different sources.

At the Nevada Test Site, fresh sodium-potassium bicarbonate type water is characteristic of groundwaters that have moved only through rhyolitic tuff, lava-flow terrain, or valley-fill deposits rich in volcanic detritus. Groundwaters which have moved only through the lower carbonate aquifer are a calcium-magnesium bicarbonate type. In Figure 6.6, the chemical analyses of groundwater from the Yucca Mountain tuffs are compared with the nearby hydrochemical facies described by Winograd and Thordarson (1975).

The hydrochemical data indicate that the sodium-potassium bicarbonate type groundwaters of the Yucca Mountain tuffs have not mixed appreciably with waters of the lower carbonate aquifer. This is consistent with preliminary measurements of vertical hydraulic gradients which suggest downward flow at Yucca Mountain.

TRILINEAR DIAGRAM

Figure 6.5



Percentage epm (milliequivalents)

NOTE: $\text{epm} = \dfrac{\text{moles of solute x valence}}{10^6 \text{ g of solution}}$

After Freeze and Cherry, 1979

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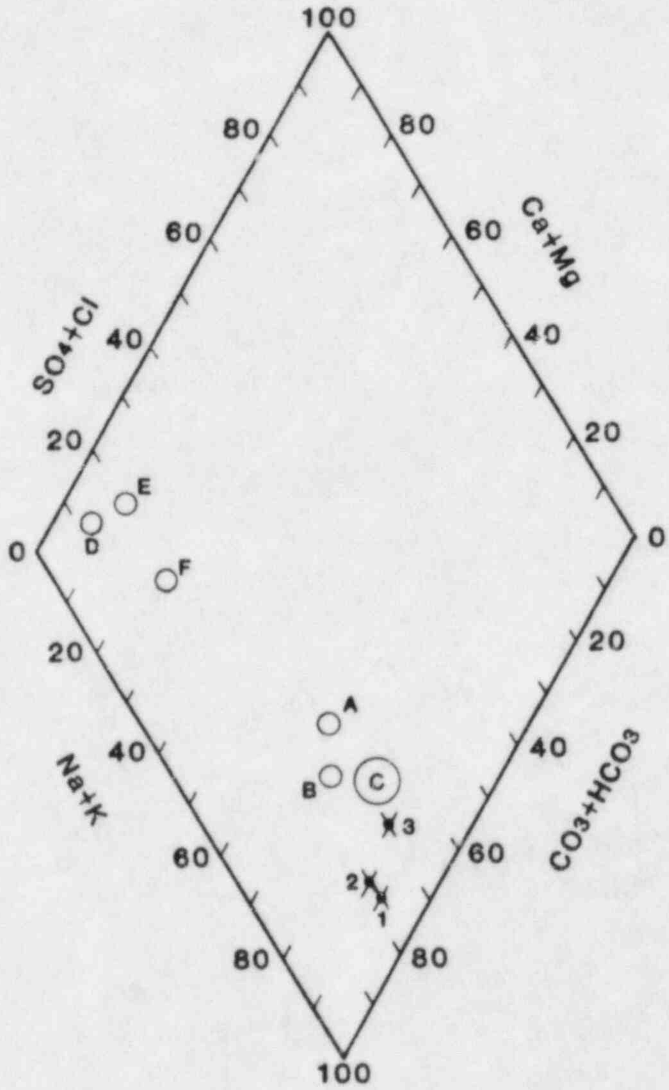
CHEMICAL ANALYSIS OF GROUNDWATER IN THE VICINITY OF YUCCA MOUNTAIN

Figure 6.6



HYDROCHEMICAL FACIES (Winograd And Thordarson, 1975)

Sodium-Potassium Bicarbonate Facies (volcanic tuffs)

A. Hills west of Yucca and Frenchman Flats (9 samples)
B. Jackass Flats (3 samples)
C. Oasis Valley (17 samples)

Calcium-Magnesium Bicarbonate Facies (carbonate aquifer)

D. Northwest Las Vegas Valley, southern Three Lakes Valley, southern Indian Springs Valley (10 samples)
E. Pahrump Valley (26 samples)
F. Pahranagat Valley (3 samples)

YUCCA MOUNTAIN TUFFS (DOE, August 1981)

1. Borehole H1; Prow Pass and Bullfrog Members (TDS = 176 mg/l)
2. Borehole H1; Bullfrog to older ash flow and bedded tuffs (TDS = 188 mg/l)
3. Borehole VH1; depth interval 336 - 762m (TDS = 277 mg/l)

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Pore fluid composition is considered a major design characteristic with regard to:

- Geochemical response - the chemical composition of pore fluid has major effect on the adsorption properties of the rock mass and engineered barriers.

6.9 DESIGN AND CONSTRUCTION

6.9.1 Generic Hydrologic Characteristics Affecting Design and Construction

All of the hydrologic characteristics bear some relevance to repository design, but some are considered more important than others. In Table 6.1, the relative importance of hydrologic characteristics is assessed for each of the design and construction issues. Table 6.1 also shows the criteria used in this assessment.

The following hydrologic characteristics are considered critical for repository design:

- Hydraulic conductivity: Since the velocity of groundwater flow is a critical concern, reliable in situ measurements must be performed at the repository horizon and in all geologic formations penetrated by the access shaft. Measurements below the repository horizon may also be desirable.

- Hydraulic gradient: Natural and man-induced hydraulic gradients will control the velocity and direction of groundwater flow. Therefore, point measurements of hydraulic head are required so that these gradients can be determined in three dimensions. Measurements should be performed in all saturated geologic formations from land surface down to the repository horizon. Measurements below the repository horizon may also be desirable.

- Adsorption: Reliable sorption coefficients must be determined for the important radionuclides and for each geologic material of interest (i.e., zeolitic tuff and devitrified tuff). Some in situ adsorption tests should be performed so that the validity of laboratory tests can be assessed.

The following hydrologic characteristics are of major importance to repository design.

- Porosity: Total porosity is particularly important at the repository horizon where it affects the thermal, mechanical, and hydrological response of the rock mass. Effective porosity is very important in assessing the effects of contaminant release and therefore, in situ values should be obtained for the repository horizon and adjacent geologic formations (i.e., zeolitic zones).

TABLE 6.1

EVALUATION OF HYDROLOGIC CHARACTERISTICS IN TERMS OF THEIR INFLUENCE ON KEY ISSUES

KEY ISSUES	CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Hydraulic Conductivity	beh (Major)	ceh (Minor)	cfh (Insignificant)	adh (Critical)	adh (Critical)
Hydraulic Gradient	beg (Major)	ceg (Minor)	beg (Major)	bdg (Critical)	adg (Critical)
Porosity	cfg (Insignificant)	beg (Major)	beg (Major)	beg (Major)	beh (Major)
Specific Storage	cfh (Insignificant)	cfh (Insignificant)	cfh (Insignificant)	beh (Major)	cfh (Insignificant)
Dispersivity					bei (Minor)
Adsorption					adg (Critical)
Pore Fluid Composition					beg (Major)

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions of the level of influence.

ATTRIBUTES

- availability of design and construction techniques which allow for conservative assumptions for the value of the characteristic:

  a) reasonable techniques are not available (i.e. high cost impact)
  b) some techniques are available, but at moderate cost impact
  c) reasonable techniques are available (i.e., little cost impact)

- uncertainty in the representation of the real world by the performance prediction model, and sensitivity of that model to characteristic value:

  d) model has low uncertainty (i.e., is very representative) and high sensitivity to characteristic
  e) model has moderate uncertainty and moderate sensitivity
  f) model has high uncertainty or low sensitivity

- cost effectiveness and scheduling limitations in potentially reducing the uncertainty in the assessment of characteristic values:

  g) uncertainty can be significantly reduced in a cost-effective and timely manner (i.e., prior to NRC review of an SCR)
  h) uncertainty can be reduced, but only during in situ testing
  i) uncertainty cannot be significantly reduced in a cost-effective or timely manner (i.e., prior to NRC review for construction authorization)

- Specific storage: Since specific storage affects inflow rates, in situ measurements should be performed at the repository horizon and in all geologic formations penetrated by the access shaft.

- Pore fluid composition: Groundwater hydrochemistry has a significant impact on the adsorption properties of the rock mass and engineered barriers. Measurements should be performed at the repository horizon and in adjacent geologic formations (i.e., zeolitic zones).

The following hydrologic characteristic is of minor importance to repository design:

- Dispersivity: Since dispersivity is scale dependent, in situ tests would have to be performed at scales that are most relevant to repository design. These scales may range from the waste canister dimensions to the thickness of tuff cooling units. It may not be economically feasible to perform a large number of in situ tests at different scales.

6.9.2 Mitigating Design and Construction Strategies

The impact of adverse characteristics of the site may be reduced by appropriate design and construction strategies. Mitigating measures to consider for adverse hydrological characteristics include:

- Selecting excavation methods to reduce the disturbed zone around underground openings
- Controlling inflows by seals, plugs, grouting and pumping
- Limiting extraneous boreholes and excavations
- Controlling the hydraulic gradient by drainage
- Choosing suitable stratigraphic formations for the repository horizons.

6.10 SITE SPECIFIC STUDY

The hydrologic characteristics identified in the generic report are applied to potential repository horizons at at approximate depths of 710 to 780 m in the Bullfrog Member and 850 to 920 m in the Tram Member. In situ hydrologic properties exhibit spatial variability in natural geologic deposits and it is difficult to predict the hydrologic conditions at a particular location unless detailed site specific data is available. In many cases, this site specific data base is lacking and, therefore, local or regional descriptions of similar geologic materials must be relied upon. A regional understanding of tuff hydrology is also useful in evaluating the reliability of existing site specific data. As stated above, far-field hydrologic data will also be necessary for the full assessment of a repository at any location.

6.10.1 Hydrologic Framework

Winograd and Thordarson (1975) give a thorough description of the regional hydrogeology for an area which includes Yucca Mountain. With regard to groundwater movement, they have delineated the following regional hydrogeologic units (in descending order):

- Tuff aquitard
- Lower carbonate aquifer
- Lower clastic aquitard.

The Bullfrog and Tram Members of the Crater Flat Tuff represent cooling units within the tuff aquitard.

According to their interpretation, lateral regional flow is controlled by fracture hydraulic conductivity in the lower carbonate aquifer and by its structural juxtaposition with the lower clastic aquitard. Presumably, flow in the tuff aquitard has a significant vertical component, which can locally recharge the carbonate aquifer. Hydrogeologic and hydrochemical data suggest that an area of at least 11,600 square km (including 10 intermontane valleys) is hydraulically integrated into one groundwater basin by movement of groundwater through the widespread carbonate aquifer. The direction of interbasin movement below Yucca Mountain is expected to the south-to- southwest. Discharge from this basin (a minimum of about 21 million cubic m annually) occurs along a fault-controlled spring line at Ash Meadows (southwest of Yucca Mountain).

6.10.2 Existing Site Specific Data

Hydrologic aspects, even on the site specific scale, must consider both the far-field as well as the near-field hydrologic systems. Therefore the properties of hydrologic units above and below the repository horizon must be assessed. The generic study in this section describes the existing data on the Bullfrog and Tram Members as well as other tuff units at Yucca Mountain. Therefore, for information on hydrologic characteristics at the site specific scale, the reader is referred to the data already presented in the generic report.

6.10.3 Design and Construction Aspects

A major limitation on the application of hydrologic characteristics to the specific repository horizons being considered at Yucca Mountain is the limited availability of site specific hydrologic data. In situ measurements, of limited reliability, have been performed in a few boreholes only. Due to this sparse data base, hydrologic characterization of Yucca Mountain on the site specific scale is still in the preliminary stages. As further testing is performed, the results may be checked against Table 6.1 to ensure that adequate data on design and construction characteristics are being obtained.

Shaft and repository inflows are important design and construction aspects of a repository. Since the phreatic surface is near the top of the Prow Pass Member, in situ measurements of horizontal/vertical hydraulic conductivity and specific storage in the Prow Pass, Bullfrog, and Tram units need to be performed. Values of these parameters can also be used to estimate resaturation time after decommissioning.

To determine the characteristics of nuclide transport, in situ measurements must be performed for total porosity, effective porosity, dispersivity, sorption ratios, and the composition of pore fluids as well as hydraulic conductivity and hydraulic gradient. At some time after decommissioning, hydraulic gradients will return more or less to their initial (preconstruction) condition. Therefore, hydraulic gradients prior to construction can be used to estimate flow paths and velocities after decommissioning, when nuclides may be released into the prevailing flow system. As there currently is insufficient data at Yucca Mountain to characterize the hydraulic head distribution in three dimensions, potential nuclide transport paths cannot be determined.

If the lower carbonate aquifer is present below the tuff section, it may have a strong influence on the site specific hydrology. Efforts must be made to verify the presence (or absence) of this unit and assess its impact on the groundwater flow regime of the area.

7. SUMMARY AND SCR REVIEW RECOMMENDATIONS

This study has identified a complete list of characteristics which could have an impact on repository design and construction in tuff. These characteristics have been separated into five main groups, namely:

- Stratigraphic/structural
- Tectonic
- Mechanical
- Thermal
- Hydrologic.

This study has examined the influence of each of the identified characteristics on five key issues related to repository design and construction in tuff. Previous reporting by others has indicated that these key issues can be delineated as follows:

- Constructability: This includes issues related to short-term safety during construction and operation, and the irreversible effects of construction on the long-term containment capability of a repository. In addition, construction of the repository will influence the design and performance of engineered barriers (such as room plugs and backfill, as well as major shaft seals).

- Thermal Response: The existing temperature field and the associated thermal properties of the rock in which the repository is to be excavated must be assessed so that the effects of waste generated heat can be predicted with time.

- Mechanical Response: Potential instability and deformations induced by excavation and thermal effects must be adequately predicted such that construction/operational safety and waste package retrievability is maintained. However, most importantly, the mechanical effects (such as opening of higher permeability pathways to the biosphere, etc.) must be adequately predicted so that the long-term containment of a repository will be progressively assured with greater certainty at each successive step in repository development.

- Hydrological Response: A potentially effective barrier to the escape of radionuclides from a repository is the resaturation or recharge time after a repository is closed. This is important since no escape can occur until the media through which radionuclides may pass are saturated and hydraulic gradients exist to drive the radionuclides from their source (waste package) to the accessible biosphere. Most of the hydrological issues are therefore long-term, but must be addressed at the time of the SCR with the understanding that they will be progressively refined during subsequent construction and operational phases. Of minor importance would be an assessment of the quantity of inflow of groundwater into the repository during the construction and operational phases since, if this was indeed a sustained quantity, it would imply high hydraulic conductivity which in turn would indicate that the repository would be unlikely to meet performance critiera.

- Geochemical Response: Geochemical characteristics of the engineered barriers and the rock units through which radionuclides may pass after the repository is resaturated must be addressed. This issue is perhaps the most difficult to address in an SCR since little is understood about adsorption, dispersion, retardation, etc., as well as the extent and effect of existing or potential alteration of geologic materials. Also, the plans in an SCR for in situ tests that may be carried out are the subject of considerable debate in the technical community. The coupling of all reponses, (i.e., thermal, mechanical, hydrological, and geochemical) into a mass transport performance model is the ultimate tool for assessing the SCR.

Three categories of attributes of characteristics have been identified and utilized to evaluate the level of influence of each characteristic on each key issue; these categories are:

- Availability of design and construction techniques which allow for a conservative assumption of the value of the characteristic (i.e., cost impact of a conservative assumption)

- Uncertainty in the representation of the real world by the performance prediction model (i.e., "goodness" of model, regardless of the uncertainty in the characteristics used as input), and the sensitivity of that model to characteristic values

- Cost effectiveness and scheduling limitations (i.e., availability prior to SCR or construction authorization review) in potentially reducing the uncertainty in the assessment of characteristic values.

Combinations of attributes in each of the three categories have been subjectively determined for each characteristic, as it relates to each key issue. This subjective evaluation, as discussed in Section 1.3.4, represents the cumulative practical experience and judgement of Golder Associates personnel associated with this task in the design and construction of underground openings, the modeling of the physical processes involved, and the difficulty in assessing characteristics used in those models. Although subjective, this evaluation has been clearly exposed in this report.

A ranking system has been developed which determines the level of influence a characteristic has on a given key issue based on the combination of attributes evaluated for that characteristic. The four levels of influence (in decreasing order of significance) are: critical, major, minor, and insignificant. Again, this ranking system is subjective, based on the experience and judgement of the Golder Associates personnel associated with this task, but is clearly defined.

The results of this process applied to tuff are summarized in Table 7.1. It is recommended that those characteristics which have the most significant influence on the key issues (i.e., designated as critical) have the highest priority in NRC's review of DOE submitted SCR(s) for site(s) in tuff. Similarly, those designated as major, minor, and insignificant should have decreasing priority in NRC's SCR review. This prioritization of characteristics will allow for a focused, adequate review by NRC and, although subjective, the process by which it has been achieved is exposed and trackable.

As is indicated in Sections 2 through 6, there are a number of areas in which sufficient data on the tuff formation are not currently available to address the key issues. Of particular concern are:

- The lack of information on
  - stratigraphic continuity and thickness of the horizons over the Yucca Mountain site
  - vertical faults and discontinuities
  - in situ stresses, temperatures, heat capacities and vertical hydraulic conductivities over the site
  - the three-dimensional distribution of hydraulic head
  - the mechanical and thermal properties of the Lower Tram formation

- The effects of increased temperature or groundwater movement on the mechanical properties of the Yucca Mountain tuffs

- The reaction of sodium montmorillonite to heating and drying

- The presence or absence of the lower carbonate aquifer postulated by Winograd and Thordarson (1975) beneath the tuff section.

To some extent, the impact of the currently perceived adverse characteristics of tuff can be decreased by appropriate design and construction strategies. Mitigating measures which should be considered include:

- Optimizing repository orientation and geometry
- Selecting optimum excavation methods
- Selecting tunnel lining and support systems
- Varying the waste package emplacement design
- Varying the room spacing and design
- Choosing suitable stratigraphic formations for the repository horizon, to include possibly widely separated multiple levels
- Selecting appropriate engineered barriers
- Designing a suitable ventilation/cooling system

TABLE 7.1

RECOMMENDED PRIORITIES IN THE REVIEW BY NRC OF AN SCR IN TUFF

CRITICAL CHARACTERISTICS FOR REVIEW

	CHARACTERISTICS	KEY ISSUES WHICH IMPACT ON DESIGN AND CONSTRUCTION: CONSTRUCTABILITY	THERMAL RESPONSE	MECHANICAL RESPONSE	HYDROLOGICAL RESPONSE	GEOCHEMICAL RESPONSE
Stratigraphic/Structural	Lithology/Mineralogy	Major	Major	Critical	Critical	Critical
	Stratigraphic Sequence	Major	Major	Critical	Critical	Critical
	Faulting/Jointing	Critical	Minor	Critical	Critical	Critical
	Alteration			Major	Major	Critical
Tectonic	Seismicity	Major		Critical	Minor	
	Crustal Instability			Major	Minor	
	Volcanism (Continuing)		Major	Major		Major
	Faulting	Major		Critical	Major	Major
Mechanical	Rock Mass Strength	Major		Major	Minor	Minor
	Deformation Moduli			Major	Minor	
	Creep/Plasticity			Major	Minor	Minor
	Discontinuities	Major	Minor	Critical	Critical	Critical
	Density		Minor			
	Moisture Content		Minor		Major	Major
	In Situ Stresses	Minor	Minor	Major	Major	Major
Thermal	In Situ Temperature	Minor	Major	Major	Major	Major
	Thermal Conductivity		Major			
	Heat Capacity		Major			Minor
	Thermal Expansion		Minor	Major		
Hydrologic	Hydraulic Conductivity	Major	Minor		Critical	Critical
	Hydraulic Gradient	Major	Minor	Major	Critical	Critical
	Porosity		Major	Major	Major	Major
	Specific Storage				Major	
	Dispersivity					Minor
	Adsorption					Critical
	Pore Fluid Composition					Major

KEY:*

- Critical
- Major
- Minor
- Insignificant or not relevant

*See Section 1.3.5 and Table 1.1 for definitions

- Controlling inflows by seals, plugs, grouting and pumping
- Limiting extraneous boreholes and excavations
- Controlling hydraulic gradients by drainage.

Specific mitigating strategies can be selected using information from the in situ testing and monitoring program.

We have determined that site suitability is sensitive to the following two points:

- There appears to potentially be a great deal of lateral and vertical variability in individual ash flows (i.e., tuff members), as indicated by the wide range in porosity values measured on small intact core samples. Because the mechanical and hydrologic characteristics especially have been found to be highly correlated with porosity, it would be expected that there will be large variability over relatively short distances in these characteristics. Hence, measurements of these characteristics in situ will be scale and location specific (i.e., applicable only to the location of the test and the scale or volume which is affected) and difficult to extrapolate to either other locations or other scales. The resulting uncertainty in the determination of characteristics will be transmitted through performance assessment models to produce potentially large uncertainty in the prediction of performance. Clearly, this variability within tuff members must be assessed. Thus, the uncertainty in predicted performance has built in a substantial uncertainty due to natural variability as well as the uncertainty due to models, testing etc.

- Generically, tuff has relatively poor mechanical characteristics, especially for higher porosities. This includes relatively low strength and potentially swelling materials and is due, in part, to the presence of disseminated montmorillonite. As temperature has a generally adverse effect on mechanical characteristics, as well as causing alteration of tuff (which has an additional adverse effect on mechanical characteristics), thermal loadings may have to be relatively low in order to ensure satisfactory mechanical (and thus hydrologic and geochemical) response. Low thermal loadings require increased waste package spacing, and thus increased lateral extent of the repository for a given waste package inventory. The necessity for reduced thermal loading will have a significant cost impact and, therefore, must be addressed.

8. GLOSSARY

Characteristic: Aspect of ground or environment describing repository site, and being either quantitative (parameter) or qualitative (factor)

Characterization: Assessment of a set of characteristics by testing or measurement

Factor: Nonquantitative characteristic

Key Issue: Influence on design and construction which may affect the ability of the repository to meet the criteria established for safe performance

Parameter: Quantitative characteristic

Scale: Volumetric aspects of repository, as follows (in size order):
- waste package (very near field)
- room (near field)
- repository (3 sq mi underground)
- site (10 sq mi) (far field)
- location (30 sq mi)
- area (1000 sq mi)
- basin
- region (multi state)
- nation (U.S.)

Stage: Distinct period of time during repository life, as follows (in chronological order):
- site selection
- detailed site characterization (followed by submittal of SCR)
- in situ testing
- repository construction (preceded by construction authorization permit)
- repository operation (preceded by operating license)
- waste retrieval (if required)
- decommissioning (preceded by license to decommission)
- post-decommissioning

Variable: Engineering aspect of design or construction which can be altered by the engineer (e.g., size, shape, and orientation of underground openings)

9. REFERENCES

J.P. Albers, "Tertiary and Quaternary Rock", Mineral and Water Resources of Nevada, Bulletin 65 of the Nevada Bureau of Mines, MacKay School of Mines, Reno, 1964. Available from public technical libraries.

S.T. Algermissen and D.M. Perkins, "A Probabalistic Estimate of Maximum Acceleration in Rock in the Contiguous United States", USGS Open-File Report 76-416, 1975. Available from USGS.

Applied Technology Council, (ATC) "Tentative Provisions for the Development of Seismic Regulations for Buildings", National Science Foundation - National Bureau of Standards, Washington D.C., 1978. Available from public technical libraries.

S.W. Butters, J.M. Gronseth, and J.F. Patterson, "Material Properties of Nevada Test Site Tuff and Grout," Terra Tek, Inc. Report DNA 5379F, May, 1980. Available from Terra Tek, Inc.

W.J. Carr, "Summary of Tectonic and Structural Evidence from Stress Orientation at the Nevada Test Site", USGS Open-File Report 74-176, 1974. Available from USGS.

J.A. Cherry, R.W. Gilliam, J.F. Pickens, "Contaminant Hydrology; Part 1, Physical Processes," J. Geoscience Canada, 2:76-8:, 1975. Available from public technical libraries.

J.L. Coffmann and C. Von Hake, "Earthquake History of the United States", U.S. Department of Commerce Publication 41-1 Revised Edition (through 1970), 1973. Available from public technical libraries.

J.L. Coffmann, "Earthquake History of the United States 1971-76 Supplement," U.S. Department of Commerce Publication 41-1, 1979. Available from public technical libraries.

H.W. Cooper and G. Simmons, "The Effects of Cracks on Thermal Expansion of Rocks," Earth Plan Sci Lett, 36:404-412, 1977. Available from public technical libraries.

G.D Corchary and G.A. Dinwiddie, "Field Trip to the Nevada Test Site," Guidebook prepared by the U.S. Geological Survey, Open-File Report 76-313, 1973. Available from USGS.

Department of Energy, Quarterly Report on Nevada Nuclear Waste Storage Investigations, NVO-196-15, June 1980. Available from NTIS.

Department of Energy, Quarterly Report on Nevada Nuclear Waste Storage Investigations, NVO-196-20, December 1980. Available from NTIS.

Department of Energy, Quarterly Report on Nevada Nuclear Waste Storage Investigations, NVO-196-21, March 1981.

Department of Energy, Quarterly Report on Nevada Nuclear Waste Storage Investigations, DE81029877, June 1981. Available from NTIS.

Department of Energy, "Peer Review on Nevada Nuclear Waste Storage Investigations," Nevada Operations Office, Las Vegas, August 1981a. This document is not publicly available because it contains proprietary information.

Department of Energy, Notes from Peer Review on Nevada Nuclear Waste Storage Investigations, August 1981b.

P.A. Domenico and M.D. Mifflin, "Water from Low-Permeability Sediments and Land Subsidence," Water Resources Research, 1: 563-576, 1965. Available from public technical libraries.

C.B. Dowding and A. Rogers, "Damage to Rock Tunnels from Earthquake Shaking," Journal of the Geotechnical Engineering Division of the American Society of Civil Engineers, GT2, pp. 175-191, February 1978. Available from public technical libraries.

F.L. Doyle, J.R. Pittiglio, L. Clayton, L. Lehman, P. Prestholt and R.J. Wright, Survey of Investigations for a High Level Waste Repository at Nevada Test Site; U.S. Nuclear Regulatory Commission, Division of Waste Management, May 1981.

D.E. Dunn, L.J. LaFountain, and R.E. Jackson, "Porosity Dependence and Mechanism of Brittle Fracture of Sandstone," J. Geophys. Res., 78:2403-2417, 1973. Available from public technical libraries.

S.A. Fedotov, "On the Seismic Cycle, Possibility of Collective Seismic Regionalization and Long Term Seismic Forecasting", in Seismic Regionalization of the USSR, Nauka, Moscow, p. 120, 1968. Available from public technical libraries.

R.A. Freeze and J.A. Cherry, Groundwater, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1979. Available from public technical libraries.

Golder Associates, "Geologic, Stratigraphic, Thermal and Mechanical Factors which Influence Repository Design in the Bedded Salt Environment," UCRL-15203, for Lawrence Livermore Laboratory, December 1979a. Available from NTIS.

Golder Associates, "Derivation of Parameters Necessary for the Evaluation of Performance of Sites for Deep Geological Repositories," UCRL-15166 (V. 2), for Lawrence Livermore Laboratory, 1979b. Available from NTIS.

Golder Associates, "Geologic, Structural, Thermal and Mechanical Factors which Influence Repository Design in Granitic and Basaltic Rocks," for Lawrence Livermore Laboratory, 1979c. Available from Lawrence Livermore Laboratory.

R.E. Grim and N. Guven, "Bentonites, Geology, Mineralogy, Properties and Uses," Developments in Sedimentology, 24, 1978. Available from public technical libraries.

F.J. Gumper and C. Scholz, "Microseismicity and Tectonics of the Nevada Seismic Zone," Bulletin of the Seismological Society of America, 61(5): 1413, 1971. Available from public technical libraries.

U. Hooker, U.S. Bureau of Mines, quoted in U.S. NRC letter to U.S. DOE, dated December 9, 1981, and numbered WMHT: 3103. Comment #6 following NNWSI Peer Review of August 1981.

D. Hoover, "Oral Progress Report" to the DOE Peer Review Group at the August 1981 NWTS Annual Review Meeting at Las Vegas, Nevada, 1981.

D.W. Hyndman, Petrology of Igneous and Metamorphic Rocks, McGraw-Hill Book Company, 1972. Available from public technical libraries.

K.W. King and A.M. Rogers, "The Nevada Nuclear Waste Storage Investigation Earthquake Monitoring Net" presented at conference on DOE ground motion and seismic programs on, around, and beyond the NTS, November 4 and 5, 1981, Albuquerque, N.M., 1981.

C.J. Koizumi, A. Ryall and K.F. Priestly, "Evidence for a High Velocity Lithospheric Plate Under Northern Nevada," Bulletin of the Seismological Society of America, 63: 2135, 1973. Available from public technical libraries.

A.R. Lappin, "Thermal Conductivity of Silicic Tuffs: I. Predictive Formalism and Comparison with Preliminary Experimental Results," SAND 80-0679, Sandia National Laboratories, in preparation.

A.R. Lappin, "Preliminary Thermal Expansion Screening Data for Tuffs," SAND 78-1147, Sandia National Laboratories, March 1980. Available from Sandia Library.

F.A. McKeown and D.D. Dickey, "Interim report on geologic investigations of the UI2e tunnel system, Nevada Test Site, Nye County, Nevada", USGS 61-93, Open-File Report, 1961. Available from USGS.

W.W. Moorehouse, The Study of Rocks in Thin Section, Harper & Row, 1959. Available from public technical libraries.

W.A. Olsson and A.K. Jones. "Rock Mechanics Properties of Volcanic Tuff from the Nevada Test Site," SAND 80-1453, Sandia National Laboratories, November 1980. Available from Sandia Library.

Pacific Gas and Electric Company, "The 1975 Humbolt Earthquake," Report to the U.S. Nuclear Regulatory Commission, 1975. Available from NRC.

A.M. Piper, "A Graphic Procedure in the Geochemical Interpretation of Water Analysis," Trans. Amer. Geophys. Union, 25: 914-923, 1944. Available from public technical libraries.

D. Racine, A. O'Donnell, J. Burmetti, P. Klouda, M. Marshall, E. Tobin, I. Megyesi and R. Wagner, "A Seismicity Study of the Southwest Regions of the United States 1 December 1961 to 1 January 1964," Report AL-79-5 and Supplement (1980) from the Alexandria Laboratories of Teledyne Geotech to the U.S. Army Corps of Engineers, South Pacific Division and the NRC, 1979.

V.L. Ratigan, "Preliminary Analysis of the Potential for Thermally-Induced Rock Fracture Around High-Level Waste Containers," Technical Memorandum Report RSI-0045, prepared by RE/SPEC, Inc., for Union Carbide Corporation and Oak Ridge National Laboratory, 1976. Available from Oak Ridge National Laboratory.

D.L. Reddell and D.K. Sunada, "Numerical Simulation of Dispersion in Groundwater Aquifers," Hydrol. Paper 41, Colorado State University, Fort Collins, Colorado, 1970. Available from Colorado State University.

C.F. Richter, Elementary Seismology, Freeman and Sons, N.Y., 1958. Available from public technical libraries.

C.J. Robinove, R.H. Langford and J.W. Brookhart, "Saline Water Resources of North Dakota," USGS Water-Supply Paper 1428, 1958. Available from public technical libraries.

A.M. Rogers, D.M. Perkins and F.A. McKeown, "A Catalogue of Seismicity within 400 km of the Nevada Test Site," USGS Open-File Report No. 76-832, October, 1976. Available from USGS.

A.M. Rogers, D.M. Perkins and F.A. McKeown, "A Preliminary Assessment of the Seismic Hazard of the Nevada Test Site Regions," Bulletin of the Seismological Society of America, 67 (6): 1587-1606, 1977. Available from public technical libraries.

C.S. Ross and R.L. Smith, "Ash Flow Tuffs: Their Origin, Geologic Relation and Identification," USGS Professional Paper 366, 1960. Available from public technical libraries.

A. Ryall, D. Slemmons and L. Gedney, "Seismicity, Tectonism and Surface Faulting in the Western United States During Historic Time," Bulletin of the Seismological Society of America, 56(5): 1105, 1966. Available from public technical libraries.

A. Ryall, W.U. Savage and C.J. Koizumi, "Seismic Potential in the Western Nevada - Eastern California Region," Proceedings of the 5th World Conference on Earthquake Engineering, Rome, 2, 1974. Available from public technical libraries.

A. Ryall, "Earthquake Hazard in the Nevada Region," Bulletin of the Seismological Society of America, 67 (2): 517, 1977. Available from public technical libraries.

Sandia National Laboratories, Evaluation of Tuff as a Medium for a Nuclear Waste Repository: Interim Status Report on the Properties of Tuff, SAND 80-1464, 1980. Available from Sandia Library.

P.B. Schnabel and H.B. Seed, "Acceleration in Rock for Earthquakes in the Western United States," Bulletin of the Seismological Society of America, 63 (2), 1973. Available from public technical libraries.

C. Scholz, M. Barazangi and M.L. Sbar, "Late Cenozoic Evaluation of the Great Basin, Western United States as an Ensialic Interarc Basin," Geological Society of America Bulletin, 82: 2979, 1976. Available from public technical libraries.

A.O. Shepard and H.C. Starkey, "Effect of Cation Exchange on the Thermal Behavior of Heulandite and Clioptilolite," USGS Professional Paper 475D, 1964. Available from USGS.

D.B. Slemmons, "Pliocene and Quaternary Crustal Movements of the Basin and Range Province, USA," Journal of Geoscience, Osaka University, 10, Art. 1-11, Osaka University, Osaka, Japan, 1967. Available from public technical libraries.

R.W. Spengler, D.C Muller and R.B. Livermore, "Preliminary Report on the Geology and Geophysics of Drill Hole UE25a-1, Yucca Mountain, Nevada Test Site," USGS Open-File Report 79-1244, 1979. Available from USGS.

P.R. Stevens, "A Review of the Effects of Earthquakes on Underground Mines," USGS Open-File Report 77-313, 1977. Available from USGS.

M.L. Sykes, G.H. Heiken, and J.R. Smyth, "Mineralogy and Petrology of Tuff Units from the UE25a-1 Drill Site, Yucca Mountain, Nevada," Informal Report LA-8139-MS, Los Alamos Scientific Laboratory, Nov. 1979. Available from NTIS.

M.L. Sykes and J.R. Smyth, "Evaluation of Tuff as a Medium for a Nuclear Waste Repository: Interim Status Report on the Properties of Tuff," Johnstone and Wolfsberg, Editors, SAND80-1464, Sandia National Laboratories, 1980. Available from Sandia Library.

W. Thordarson, "Perched Groundwater in Zeolitized-bedded Tuff, Rainier Mesa and Vicinity, Nevada Test Site," USGS 66-130, Open-File Report, 1965. Available from USGS.

E.N. Vine, R.D. Aguilar, B.P. Bayhurst, W.R. Daniels, S.J. DeVilliers, B.R. Erdal, F.O. Lawrence, S. Maestas, P.Q. Oliver, J.L. Thompson, and K. Wolfsberg, "Sorption-desorption Studies on Tuff; II. A Continuation of Studies with Samples from Jackass Flats, Nevada and Initial Studies with Samples from Yucca Mountain, Nevada," Information Report LA-8110-MS, Los Alamos Scientific Laboratory, Jan. 1980. Available from NTIS.

W.C. Walton, Groundwater Resource Evaluation, McGraw-Hill Book Company, New York, 1970. Available from public technical libraries.

R. Weisinger, L.S. Costin, and T.J. Lutz. "K_{Ic} and J-Resistance-Curve Measurements on Nevada Tuff," Exper. Mech. 20(2):68-72, 1980. Available from public technical libraries.

H. Williams, F.J. Turner, and C.M. Gilbert, Petrography, An Introduction to the Study of Rocks in Thin Sections, W.H. Freeman and Company, 1954. Available from public technical libraries.

I.J. Winograd and W. Thordarson, "Hydrogeologic and Hydrochemical Framework, South-Central Great Basin, Nevada-California, with special reference to the Nevada Test Site," USGS Professional Paper 712-C, p. 126, 1975. Available from USGS.

I.J. Winograd, "Hydrogeology of Ash Flow Tuff: A Preliminary Statement," Water Resources Research, 7(4): 994-1006, 1971. Available from public technical libraries.

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14. ABSTRACT (200 words or less)

The purpose of the complete project is to provide NRC with technical assistance to enable the focused, adequate review by NRC of the aspects related to design and construction of an underground test facility and final geologic repository as presented by the Department of Energy (DOE). The study presented in this report covers the identification of characteristics which influence design and construction of a geologic repository in tuff at the Nevada Test Site (NTS). This report has identified five key issues, i.e., constructibility, thermal response, mechanical response, hydrological response, and geochemical response. This report involves both short-term (up to closure) and long-term (post closure) effects. The characteristics of tuff and its environment are described under the headings of stratigraphic/structual tectonic, mechanical, thermal and hydrologic. Characteristics are separated into parameters (quantified and measured) and factors (qualitative). The characteristics are then subjectively ranked by their influence on the key issues. This ranking took into account availability and suitability of conservative design/construction techniques, uncertainty in model and the model sensitivity to characteristics.

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