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Critical Parameters for a High-Level Waste Repository
Volume 1: Basalt

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ABSTRACT

This report addresses critical parameters specific to a repository in basalt, using the Columbia River Basalt Group as the principal example. For the purposes of this report, a parameter is considered to be a physical property whose value helps determine the characteristics or behavior of a repository system. Parameters which are defined as critical are those essential to evaluate and/or monitor leakage of radionuclides from the repository and to evaluate the need for retrieval. The parameters are considered with respect to the disciplines of geomechanics, geology, hydrology, and geochemistry and are rank ordered in terms of importance. The specific role of each parameter, specific factors affecting the measurement of each parameter, and the interrelationships between the parameters are considered in detail.

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NOMENCLATURE

List of Abbreviations

AE	acoustic emission
BWIP	Basalt Waste Isolation Project
HLW	high-level waste
LBL	Lawrence Berkeley Laboratory
LLNL	Lawrence Livermore National Laboratory
NSTF	Near Surface Test Facility (at BWIP)
ppm	parts per million
RHO	Rockwell Hanford Operations
SCR	site characterization report

EXECUTIVE SUMMARY

As a task in the evaluation of geotechnical, environmental, and radiation field measurement systems for nuclear waste isolation, geomechanical, geological, hydrological, and geochemical parameters critical to emplacement of radioactive waste in basalt have been identified. For purposes of this report, a parameter is considered to be a physical property whose value helps determine the characteristics or behavior of a repository system. The parameters have been chiefly addressed using the geologic setting of the Columbia River Basalt flows as they occur on the Hanford Reservation, Washington; however, certain generalities have been derived.

Of strongest consideration were measurements that focused ultimately on the contamination by radionuclides of an aquifer that could be accessible to the biosphere. In this respect, direct assumptions were not made concerning probable radionuclide pathways. Rather, measurements were considered that would be used to evaluate essentially all potential pathways between the repository, aquifers, and ultimately the surface.

In this assessment, a parameter is considered to be "critical" if a mistake in its measurement, or the inability to measure it, could lead to the wrong conclusions of the adequacy of a repository. The phase of development of a repository is important in considering the criticality of a parameter. A parameter is critical only during the phase or phases when it must be measured or monitored. Once a parameter has been determined and is considered to be nonvarying, it is no longer considered critical for measurement or monitoring purposes.

The relative importance of critical parameters for basalt was determined for each phase of repository activity: site characterization, construction, operation (including retrievability), and closure and decommissioning. Figure 1 lists parameters and shows their time sequence during repository phases. These phases are not necessarily distinct time periods, but may overlap each other. For example, operations may start in one underground location well before construction is completed in another sector of the repository.

The relative ranking of closely spaced (in importance) parameters is only approximate and can change significantly depending on site-specific considerations and increased understanding of each parameter's importance. Even though the rank ordering is somewhat subjective and can change with future information, the magnitude of each change will probably not be great. The exact priority of the parameters is considered less important than having the critical parameters clearly defined.

Priorities were assigned to critical parameters for each phase as indicated in Fig. 1, and are tabulated and described in detail by discipline (geomechanics, geology, hydrology, geochemistry) in the body of the text. Of greatest concern in the site characterization phase is establishment of an understanding of the geologic setting, especially the depth, thickness,

orientation, and lateral continuity of hydrostratigraphic units encompassing and bounding the repository. An understanding of the hydrologic characteristics of these hydrostratigraphic units is also of principal concern during the site characterization phase, with monitoring of these parameters continuing into subsequent phases. Measurement of geochemical parameters: groundwater composition, water age, and sorptive capability of fracture-lining minerals, is also of high priority in the site characterization phase. Canister corrosion tests are started during the site characterization phase and long-term observations conducted throughout the entire repository sequence. Naturally occurring radionuclide concentrations in the repository rock and groundwater are also important to measure during site characterization. Characterization of the fracture, thermal, and mechanical properties of the rock mass is also of high priority during site characterization. Measurement of geomechanical properties is of even greater importance during the site construction phase, emphasizing the deformation experienced during construction of underground openings and the effect of the openings on the hydrological regime in the near field of the repository. Highest-priority critical parameters during the site operation phase include those concerned with response of the rock mass and hydrologic system to the thermal effects from the introduction of the radioactive waste. Critical parameters requiring measurement and long-term monitoring systems, installed during operations and extending into (and in some cases beyond) the closure and decommissioning phase of the repository, include as high priority those concerned with radionuclide leakage and the effectiveness of backfill and sealing systems.

Several geologic parameters, such as faulting, folding, and erosion rate, are not directly measurable by instrumentation systems, but may be determined indirectly by surface and/or subsurface geophysical techniques. Similarly, not all hydrological parameters are directly measurable, but rely on interpretation of measurements of specific hydrological properties of the rock mass.

In several cases, parameters will be measured initially in test facilities that begin operation during the site characterization phase. The most important tests will monitor the performance of canisters, backfill, and seals, and the hydro-thermo-mechanical response of the rock mass to the introduction of the waste. These measurements and long-term monitoring will subsequently be extended to the actual repository locations as canisters are emplaced and as the full-scale sealing systems are established.

The critical parameters and their priorities for basalt that have been established in this report may be similar to those for other candidate repository rock types, especially tuffaceous and crystalline rock. Variations from the conclusions for basalt will become clear as the other rock types are addressed in detail.

1.0 INTRODUCTION

This report covers an important identification phase for our current project whose objective is to consider the adequacy and reliability of the different measurement techniques and instruments which may be used by the DOE in the national high-level nuclear waste (HLW) disposal program. The repository phases of concern in the HLW program include site characterization, site construction, site operation, and closure and decommissioning. The measurements considered include all those which are used to characterize the site and/or to monitor the site performance and which will be used in the prediction of site performance adequacy for safe, long-term disposal of nuclear waste.

An important phase of the analysis of these measurements is an understanding of what must be measured and the special needs, if any, of determining those parameter values. Numerous analyses have been performed in this regard, but have not resulted in a consensus regarding which parameters are critical, nor an estimate of the relative importance of the different parameters. Any consideration of the adequacy of an overall parameter measurement approach must take into account these factors to assure that proper consideration be given to those parameters which are most critical. One reason that such a consensus does not presently exist is that media-specific and site-specific characteristics must be considered. In this report, we have developed the critical parameter information for basalt, and have considered site-specific information which allows us to address these parameters using the Columbia River Basalt as an example.

Relatively few assumptions have been made regarding the specific pathways for release of radionuclides. For the purposes of this study, we considered the possibility of contamination of a subsurface aquifer, which may eventually be accessible to the biosphere, to be of primary concern. Considerations pertinent to this concern include:

- canister failure due to corrosion and/or stress field encountered during storage,
- leaching of radionuclides from the waste form,
- radionuclide escape through backfill material, and
- radionuclide escape through the fractured basalt.

We have also assumed that the repository will be located in a basalt horizon in the saturated zone below the water table.

We have not considered in detail, release of radionuclides that might accompany volcanic or seismic events, inadvertent human intrusion, or extensive surface erosion. Such possible release scenarios are largely determined on the basis of noninstrumented evaluations (e.g., evidence of past volcanic or seismic activity or the presence of valuable mineral resources). With regard to contamination of accessible aquifers, no direct assumptions were made concerning probable pathways. Rather, we considered measurements which will likely be used to evaluate essentially all potential paths of

communication between the repository and subsurface aquifers or ground surface. However, it is recognized that the basalt flows may be limited in thickness, with high permeability strata above and below the repository horizon, and that the fractured nature of basalt flows can lead to increased vertical connectivity between horizontal aquifers as a result of repository emplacement and operation.

In this study, we have not assumed nor proposed a particular methodology of site characterization or assessment. Instead, we have examined all of the physical properties and processes which may have bearing on the ability of a site to isolate radioactive waste and have chosen those which seem to be most significant, regardless of their compatibility with any specified assessment methodology.

Our definition of a critical parameter also needs to be considered. We consider a parameter to be critical if its mismeasurement could lead to incorrect conclusions regarding repository adequacy. The concept of mismeasurement in this case includes the inability to make a measurement. When the latter condition occurs, it is necessary to either measure additional alternative parameters which would result in reaching the correct conclusion concerning repository adequacy, or else a means must be found for evaluating the parameter in question. Often, these alternative parameters may not involve instrumentation but, rather, interpretation. In terms of prioritization, a parameter is considered to be less critical if, by not measuring it, the likelihood of drawing the wrong conclusion concerning repository adequacy is not increased. Hence, it can be concluded that a parameter is considered critical only during those repository phases when it must be measured or otherwise determined or monitored. Though knowledge of a parameter's values may be critical during repository phases following its determination, once the parameter has been determined and can also be considered as nonvarying, it is no longer considered critical for measurement or monitoring purposes.

In considering the likely values and ranges of these parameters for purposes of instrumentation applicability, we have relied on experimental observations where reported. In many cases, such information is not available. In these cases, we have made our best estimate based on related media information and/or expert opinion.

2.0 CRITICAL PARAMETERS FOR BASALT

In developing the lists of critical parameters for basalt, consideration was given to the relative importance of those parameters in specific discipline areas: geomechanics, geology, hydrology, and geochemistry. The relative importance of the parameters was considered for each phase of repository activity: site characterization, site construction, site operation (including retrievability), and site closure and decommissioning.

The time frames of interest for the different parameters are illustrated in Fig. 1. This chart, which contains both instrumented and noninstrumented parameters, follows the need to measure a specific parameter through the repository phases under consideration. Though federal regulations do not presently require measurements after repository closure, it seems prudent to assume that it will be highly likely that certain measurements will continue to be made. These measurements are listed under the "Closure and Decommissioning Phase" of Fig. 1 and in Tables 4 and 8. However, we assume that no measurements will be made that require physical penetration into the repository after closure. Future instrumentation technology may allow continued in situ repository monitoring using, yet undefined, remote sensing or isolated communications techniques.

Characterization, construction, operation, and closure and decommissioning are not necessarily distinct time periods, but may overlap each other. For example, site characterization activities may continue completely through the construction phase of the repository, and operation may start in one underground location well before the total completion of construction in another location of the same repository.

Figure 1 shows the priority of parameter importance in parentheses for each phase. Dashed time-line segments, such as for water inflow rate and initial in situ stress, indicate reduced levels of importance of a given parameter in certain repository phases. Such parameters will have been determined during previous phases, and there is little likelihood of change during the phases indicated by dashed lines. However, a low level of monitoring of these parameters should be continued during the dash-lined phases in the event that the unlikely change should occur and the parameter again becomes one of primary importance.

Based on the time-line considerations and on the parameter requirements in each discipline area, composite listings of the parameter needs for each repository phase were developed. The authors, who have expertise in each of these discipline areas, singly or as a group, considered the relative importance of parameters on a qualitative scale for each repository phase in basalt. The relative rankings of these parameters for generic basalt are shown in Tables 1 through 4. The relative ranking of parameters within any single numerically designated priority level in these tables is not necessarily listed in any subpriority order. Within numerically designated levels, parameters are considered to have equal priorities.

It should be noted that the relative ranking of closely spaced (in importance) parameters is only approximate and could change significantly, depending on site-specific considerations and increased understanding of parameter importance. In addition, a different group of experts may develop a slightly different relative ranking, and these factors are recognized. However, the relative importance of parameters near the top of each table will likely continue to be greater than those near the bottom of each table, irrespective of site-specific considerations or different expert interpretation.

PARAMETER AND DISCIPLINE[a]	REPOSITORY PHASE AND PRIORITY LEVELS[b] SITE CHARACTERIZATION	CONSTRUCTION	OPERATIONS (Including Retrievability)	CLOSURE AND DECOMMISSIONING
Hydrostratigraphic Unit Depth, Thickness, Orientation & Continuity* (H)	(1)			
Water Inflow Rate (H)	(1)	(1)	(2)	- - -
Groundwater Discharge and Recharge Locations & Rates (H)	(1)	(4)	(17)	(5)
Permeability (H)	(1)	(1)	(6)	
Hydraulic Head (H)	(1)	(3)	(14)	(10)
Fluid Velocity (H)	(1)	(1)	(6)	
Effective Porosity (H)	(1)	(1)		
Geologic Variables (Lithologic Parameters, etc.)** (G)	(1)	(1)	(9)	
Fracture Properties (Including Hydrologic Properties) (M&H)	(2)	(1)	(4)	
Temperature (M)	(3)	(3)	(3)	(8)
Initial In Situ Stress (M)	(4)	(2)	- - -	
In Situ Stress Changes (M)	(4)	(1)	(8)	
Displacement & Deformation (M)	(4)	(1)	(4)	
Rock Modulus and Poisson's Ratio (M)	(4)	(2)	(5)	
Expansivity (M)	(4)			
Rock Strength (M)	(4)	(2)		
Induced Fractures (M)	(4)	(1)	(1)	
Groundwater Chemistry (C)	(5)	(3)	(7)	
Solubility of Radionuclide Species of Interest (C)	(5)			
Sorptive Capacity of Fracture Lining Material (C)	(5)			
Age of Water (C)	(5)			
Tectonic Factors (Faults & Folding)** (G)	(6)	(1)		
Tectonic Factors (Seismicity) (G)	(6)	(1)	(16)	(6)
Thermal Conductivity, Heat Capacity & Diffusivity (M)	(7)	- - -	- - -	
Canister Corrosion Rate (C)	(8)	- - -	(10)	(4)
Seal and Backfill Permeability (H)	(8)	- - -	(12)	(3)
Seal and Backfill Leakage (C)	(8)	- - -	(12)	(2)
Decrepitation and Spalling (M)	(8)	- - -	(13)	
Crustal Deformation Including Uplift (G)	(9)	(4)	(16)	(7)
Erosion Rate** (G)	(9)	(4)	(18)	(9)
Existing Underground Workings* (G)	(10)			
Water, Mineral & Petroleum Resources* (G)	(10)			
Potential Igneous Activity* (G)	(11)			
Naturally Occurring Radionuclides (G)	(12)			
Radionuclide Leakage (C)	- - -	- - -	(15)	(1)
Canister Movement (M)	- - -	- - -	(11)	

(a) Disciplines are given by: (M) = Geomechanics; (G) = Geology; (H) = Hydrology; (C) = Geochemistry.

(b) Priority level for each parameter is given in parentheses for each repository phase.

* Not dependent on instrumentation.

** Not directly dependent on instrumentation, but may use some geophysical techniques.

\- - Dashed lines indicate parameters of secondary importance for measurement and/or monitoring purposes during these phases.

Fig. 1. Critical parameter time line.

Table 1. Prioritized critical parameters for site characterization.

PRIORITY LEVEL	CRITICAL PARAMETERS
1.	Hydrostratigraphic unit depth, thickness, orientation, and continuity
	Water inflow rate
	Groundwater discharge and recharge locations and rates
	Permeability
	Hydraulic head
	Fluid velocity
	Effective porosity
	Geologic variables, lateral and vertical variations in - lithology - mineralogy - stratigraphy - bedding
2.	Fracture properties (including hydrologic properties of fractures) - spacing - orientation - aperture - continuity - connectivity
3.	Temperature
4.	Initial _in situ_ stress
	In situ stress changes
	Displacement and deformation
	Rock modulus and Poisson's ratio
	Expansivity
	Rock strength
	Induced fractures (and excavation damage)
5.	Groundwater chemistry - composition - pH - Eh
	Solubility of radionuclide species of interest
	Sorptive capacity of fracture lining material
	Age of water
6.	Tectonic factors - faulting - folding - seismicity
7.	Thermal conductivity
	Heat capacity
	Thermal diffusivity
8.	Canister corrosion rate (tests) - moisture and temperature at canister surface
	Seal and backfill permeability (tests)
	Seal and backfill leakage (tests)
	Decrepitation and spalling (tests)
9.	Crustal deformation including uplift
	Erosion rate
10.	Existing underground workings
	Water, mineral, and petroleum resources
11.	Potential igneous activity
12.	Naturally occurring radionuclides

Table 2. Prioritized critical parameters for site construction.

PRIORITY LEVEL	CRITICAL PARAMETERS
1.	Fracture properties (including hydrologic properties of fractures) - spacing - orientation - aperture - continuity - connectivity
	Displacement and deformation
	In situ stress changes
	Induced fractures (and excavation damage)
	Water inflow rate
	Permeability
	Fluid velocity
	Effective porosity
	Tectonic factors - faulting - folding - seismicity
	Geologic variables, lateral and vertical variations in - lithology - mineralogy - stratigraphy - bedding
2.	Rock strength
	Rock modulus and Poisson's ratio
	Initial *in situ* stress
3.	Hydraulic head
	Temperature
	Groundwater chemistry - composition - pH - Eh
4.	Crustal deformation including uplift
	Groundwater discharge and recharge locations and rates (changes)
	Erosion rate

Table 3. Prioritized critical parameters for site operation.

PRIORITY LEVEL	CRITICAL PARAMETERS
1.	Induced fractures
2.	Water inflow rate
3.	Temperature
4.	Displacement and deformation Fracture properties (including hydrologic properties of fractures) - aperture - continuity - connectivity
5.	Rock modulus and Poisson's ratio
6.	Permeability Fluid velocity
7.	Groundwater chemistry - composition - pH - Eh
8.	_In situ_ stress changes
9.	Geologic variables (changes in mineralogy due to heating)
10.	Canister corrosion rate - moisture and temperature at canister surface
11.	Canister movement
12.	Seal and backfill permeability Seal and backfill leakage
13.	Decrepitation and spalling
14.	Hydraulic head
15.	Radionuclide leakage
16.	Tectonic factors - seismicity Crustal deformation including uplift
17.	Groundwater discharge and recharge locations and rates (changes)
18.	Erosion rate

Table 4. Prioritized critical parameters for site closure.

PRIORITY LEVEL	CRITICAL PARAMETERS
1.	Radionuclide leakage
2.	Seal and backfill leakage
3.	Seal and backfill permeability
4.	Canister corrosion rate (simulation in test facility) - moisture and temperature at canister surface
5.	Groundwater discharge and recharge locations and rates (changes)
6.	Tectonic factors - seismicity
7.	Crustal deformation including uplift
8.	Temperature
9.	Erosion rate
10.	Hydraulic head

In terms of the analysis of the different measurement techniques and instruments for the listed parameters, it is useful to separate the parameters listed in Tables 1 through 4 into specific disciplines (i.e., geomechanical, geological, hydrological, and geochemical). In addition, Tables 1 through 4 contain both instrumented and noninstrumented parameters. We have included the noninstrumented parameters for completeness because these need to be known to establish repository adequacy. In Tables 5 through 8 the critical parameters are listed by repository phase and discipline area, and a differentiation is made between the instrumented and noninstrumented parameters. Within a given phase and discipline area, the relative parameter importance is rank ordered, however, this rank ordering is subject to the caveats discussed in the preceding paragraph and should be used only for general guidance. Considerations which may affect the relative parameter importance within a given discipline area or repository phase are discussed in Section 3 on Detailed Critical Parameter Considerations.

Table 5. Prioritized critical parameters by discipline for site characterization.

GEOMECHANICAL PARAMETERS	GEOLOGICAL PARAMETERS	HYDROLOGICAL PARAMETERS	GEOCHEMICAL PARAMETERS
Instrumented Fracture properties - spacing - orientation - aperture - continuity - connectivity Temperature Initial in situ stress In situ stress changes Displacement and deformation Rock modulus and Poisson's ratio Expansivity Rock strength Induced fractures (and excavation damage) Thermal conductivity Heat capacity Thermal diffusivity Decrepitation and spalling (tests)	Instrumented Tectonic factors - seismicity Crustal deformation including uplift Naturally occurring radionuclides Noninstrumented Geologic variables, lateral and vertical variations in - lithology - mineralogy - stratigraphy - bedding Tectonic factors - faulting - folding Erosion rate Existing underground workings Water, mineral, and petroleum resources Potential igneous activity	Instrumented Water inflow rate Groundwater discharge and recharge locations and rates Permeability Hydraulic head Fluid velocity Effective porosity Hydraulic properties of fractures Seal and backfill permeability (tests) Noninstrumented Hydrostratigraphic unit depth, thickness, orientation, and continuity	Instrumented Groundwater chemistry - composition - pH - Eh Solubility of radionuclide species of interest Sorptive capacity of fracture lining material Age of water Canister corrosion rate (tests) - moisture and temperature at canister surface Seal and backfill leakage (tests)

Table 6. Prioritized critical parameters by discipline for site construction.

GEOMECHANICAL PARAMETERS	GEOLOGICAL PARAMETERS	HYDROLOGICAL PARAMETERS	GEOCHEMICAL PARAMETERS
<u>Instrumented</u>	<u>Instrumented</u>	<u>Instrumented</u>	<u>Instrumented</u>
Fracture properties - spacing - orientation - aperture - continuity - connectivity Displacement and deformation *In situ* stress changes Induced fractures (and excavation damage) Rock strength Rock modulus and Poisson's ratio Initial *in situ* stress Temperature	Tectonic factors - seismicity Crustal deformation including uplift <u>Noninstrumented</u> Tectonic factors - faulting - folding Geologic variables, lateral and vertical variations in - lithology - mineralogy - stratigraphy - bedding Erosion rate	Hydraulic properties of fractures Water inflow rate Permeability Fluid velocity Effective porosity Hydraulic head Groundwater discharge and recharge locations and rates (changes)	Groundwater chemistry - composition - pH - Eh

Table 7. Prioritized critical parameters by discipline for site operation.

GEOMECHANICAL PARAMETERS	GEOLOGICAL PARAMETERS	HYDROLOGICAL PARAMETERS	GEOCHEMICAL PARAMETERS
<u>Instrumented</u>	<u>Instrumented</u>	<u>Instrumented</u>	<u>Instrumented</u>
Induced fractures	Tectonic factors - seismicity	Water inflow rate	Groundwater chemistry - composition - pH - Eh
Temperature	Crustal deformation including uplift	Hydraulic properties of fracture	
Displacement and deformation		Permeability	Canister corrosion rate - moisture and temperature at canister surface
Fracture properties - aperture - continuity - connectivity	<u>Noninstrumented</u>	Fluid velocity	
Rock modulus and Poisson's ratio	Geologic variables (changes in mineralogy due to heating)	Seal and backfill permeability	Seal and backfill leakage
	Erosion rate	Hydraulic head	Radionuclide leakage
<u>In situ</u> stress changes		Groundwater discharge and recharge locations and rates (changes)	
Canister movement			
Decrepitation and spalling			

Table 8. Prioritized critical parameters by discipline for site closure.

GEOMECHANICAL PARAMETERS	GEOLOGICAL PARAMETERS	HYDROLOGICAL PARAMETERS	GEOCHEMICAL PARAMETERS
Instrumented	Instrumented	Instrumented	Instrumented
Temperature	Tectonic factors - seismicity	Seal and backfill permeability	Radionuclide leakage
	Crustal deformation including uplift	Groundwater discharge and recharge locations and rates (changes)	Seal and backfill leakage
		Hydraulic head	Canister corrosion rate (Simulate in test facility) - moisture and temperature at canister surface
	Noninstrumented		
	Erosion rate		

3.0 DETAILED CRITICAL PARAMETER CONSIDERATIONS

Consideration of the adequacy of a measurement technique or instrument for a given parameter or group of parameters depends on detailed knowledge of the measurement problems and environment, the parameter range of interest, and the accuracy with which it must be determined. Such considerations are obviously media specific and site specific. In considering the parameters identified in Section 2, the parameter's role during each repository phase and its interaction with other parameters are addressed where appropriate. A number of other questions and factors are also considered as follows:

1. Normal parameter range.
2. Is this parameter site sensitive?
3. Expected parameter variations during normal site operation.
4. Parameter values that may signal trouble (where sufficient information is available).
5. What may happen if this parameter is not measured?
6. Measurement conditions and potential problems.

While each consideration indicated above may not apply to each parameter, they were considered useful and were used as guides in the following discussions. Due to the relative variations in parameter priorities between the different repository phases, no attempt was made to discuss each parameter in priority order. Rather, the parameter and specific consideration regarding that parameter are treated by discipline. Due to the extensive data base acquired for the Hanford Basalt Waste Isolation Project (BWIP), specific examples of parameters measured or extrapolated for that project are used for discussion where appropriate. Note that closely related parameters are usually discussed jointly due to their interdependence or similarity.

3.1 GEOMECHANICAL PARAMETERS

Geomechanical parameters discussed in the following sections include those parameters that directly interrelate stresses, physical responses, thermal characteristics, and thermomechanical properties within the repository media. All are considered to be parameters generally requiring instrumentation for measurement or monitoring.

3.1.1 Displacement and Deformation

The rock mass around a repository will deform as a result of the disturbances caused by the construction of the repository and by waste emplacement. Measurements of strain and closure* will be performed during the site characterization phase as part of in situ tests where constitutive laws for the rock mass will be quantified. These measurements will be performed to

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*The ratio of change in length to initial length is known as strain. Closure is defined as the amount of inward deformation of an underground opening, though the deformation may not always be inward.

monitor rock behavior during the construction and operation phases to verify the adequacy of the repository design, to validate the predictive models used, and to monitor the stability of the repository.

Rock displacement and deformation are closely related to rock stability and to the capability to retrieve the waste. Excessive rock displacement or deformation may affect the waste package. They may also affect the movement of water through rock by causing the opening or closing of fractures. The rock deformations measured around a repository will be a complex function of the in situ mechanical and thermomechanical properties of the rock mass (including discontinuities), the state of stress, and the temperature of the rock. Deformations in the rock mass will also depend on: coefficients of thermal expansion, creep laws, and the moduli of deformation.

In fractured basalt, most of the measured displacement will occur along fractures because they are the most deformable elements of the rock mass system. Consequently, measured displacements are related to various fracture characteristics (e.g., orientation, roughness and waviness, fracture frequency, filling minerals and their moisture contents). The measured displacements and deformations will also be a function of the orientation of the underground workings relative to the major principal stress axes.

3.1.1.1 Normal Parameter Range. Measurements of total displacement and deformation are expected to be of the order of millimeters over the distance of a few meters under normal repository conditions.

3.1.1.2 Are These Parameters Site Sensitive? Deformations and displacements are directly related to the in situ mechanical properties of the rock mass, which are site sensitive, thus, these parameters are also site sensitive.

3.1.1.3 Expected Parameter Variations During Normal Site Operation. Displacements and deformations will be complex functions of multiple variables. Thus, the expected parameter variations are difficult to predict precisely with the limited information presently available.

3.1.1.4 Parameter Values That May Signal Trouble. In the long-term, accelerating displacement or deformation rates occurring after periods of relatively constant changes will be indicative of areas of potential instability. Displacements and deformations greater than normal parameter range may be indicative of mechanical instability. In addition, even small changes can change the permeability of the rock.

3.1.1.5 What May Happen If These Parameters Are Not Measured? Absolute displacements and deformations and their rates are two very important diagnostic responses of rock behavior. In concept, these parameters are easy to measure in situ and with proper attention can be measured accurately and reliably. Displacement and deformation measurements integrate the effect of inhomogeneous mechanical properties of the in situ rock which cause variability in local measurements of the state of stress. Without measurements of deformation, constitutive laws relating stress and strain

cannot be quantified; thus, models used to predict repository behavior cannot be validated.

Verification of the repository design cannot be performed without displacement and deformation measurements. Potential areas of instability will not be adequately monitored because excessive displacements or deformations indicative of unstable rock zones will not be adequately monitored. The waste packages may suffer undetectable damage if rock displacement or deformation near the waste package is excessive and is not measured.

Rock deformation can be back calculated from measurements of stress changes and of modulus of deformation. This approach is not commonly used because it may provide unreliable results in rock masses which are substantially inelastic (e.g., fractured basalt).

3.1.1.6 Measurement Conditions and Potential Instrumentation Problems. Displacements and deformations measured in basalt will probably occur along fractures because they tend to be the most deformable element in the rock mass. Consequently, measurements of displacements and deformations are likely to vary throughout the area of the repository because of the variable nature of the fracture network. Relatively large displacement may be measured in areas of the rock with larger fracture density. Zones of increased fracturing may also be flow paths for water inflow. Water may affect the durability and reliability of the measurement instruments. It may also be difficult to anchor measurement instruments in fractured regions of rock.

3.1.2 Fracture Properties and Induced Fractures

Fractures are the weakest, most deformable, and most permeable elements of the rock mass system. However, they may be completely filled or lined with minerals which will adsorb radionuclides. Rock deformation, mechanical stability, and groundwater flow will be strongly controlled by the fracture network. Recent experiments have indicated, for example, that groundwater flow can be controlled by two or three single, discrete fractures (Wilson et al. 1982; C. R. Wilson, Lawrence Berkeley Laboratory, Berkeley, California, personal communication, 1983). In a repository scenario, the characterization investigations should be sufficiently detailed to detect the fractures that control the mechanical and hydrologic response of the rock mass. The anisotropy and inhomogeneity of various rock properties are also greatly influenced by fracture systems.

New fractures may be induced by repository construction or heating resulting from waste emplacement. Rock bursts (sudden release of strain energy related to high-stress concentrations around openings) can cause new fractures. Thermal degradation and slabbing may occur in the hottest zones of rock. Massive (unfractured) rock may be susceptible to fracturing if surrounded by deformable fractured rock, because stress concentration may develop in the massive rock.

Various fracture characteristics affect rock behavior. Important among these are: the abundance of fractures (absolute spacing, fracture density), their geometrical and statistical characteristics (orientation, length, aperture), surface roughness and waviness, and connectivity of fractures.

A number of important rock properties and parameters are affected by the presence of fractures in the rock mass. Rock deformation and rock modulus of deformation are affected by fracture roughness, orientation, persistence, spacing, and aperture as well as by the character of the filling materials. Rock mass strength is influenced by the previously listed characteristics and by water pressure distributions within the fractures. Rock permeability is governed by fracture density, aperture, filling materials, continuity, and connectivity. The state of stress around underground openings can also be affected by fractures.

3.1.2.1 Normal Parameter Range. Lengths of natural fractures, in hard rock like basalt, range from a few centimeters to a few tens of meters, and fractures are spaced a few centimeters to perhaps a meter or two apart. They may be unfilled or have locally varying amounts of clay minerals, zeolites, calcite, or silica polymorphs. Rockwell Hanford Operations (RHO, 1982, Vol. 1, Chap. 3), for example, reports that the great majority of fractures in drill core from Grande Ronde Basalt of the Columbia River Basalt Group have apertures of less than 0.5 mm filled with multiple generations of secondary minerals. The abundance of all these fractures is less than 0.4 volume percent with the volume of unfilled fractures ranging from 0.025 to 0.059 volume percent. However, hydrologic testing of these fracture zones is required to assess their hydraulic conductivity.

3.1.2.2 Is This Parameter Site Sensitive? Fractures are, by nature, spatially variable even within a given rock unit. Consequently, all fracture characteristics are highly site specific. The orientations of fractures in basalt may vary within a flow depending on their location, ranging from mostly vertical in the colonnade, to fan-shaped or horizontal in the entablature, to random in brecciated zones.

3.1.2.3 Expected Parameter Variation During Normal Site Operation. Fracture aperture will change as the rock mass deforms in response to the repository environment. This can significantly influence hydrologic parameters due to the square dependence of permeability on fracture aperture (see Section 3.3.2, Hydrologic Properties of Fractures). The composition and water content of minerals filling the fractures will also change as rock temperature changes. New fractures may be created, and rock burst can even occur, where the rock mass is mechanically unstable or experiences large stress changes.

3.1.2.4 Parameter Values That May Signal Trouble. Fractured zones showing evidence of water inflow can be expected to be potential flow paths for radionuclide release. Of particular concern are any near-vertical fractures which may connect the repository horizon with aquifers above or below it. Steeply dipping fractures trending parallel to or at an acute angle to repository openings can cause roof instability. Unstable rock may exist in

areas where the spacing between fractures is smaller than the width of the tunnel rooms and where the fractures combine to form unstable blocks or wedges. Near horizontal fractures may also affect roof stability depending on fracture spacing, continuity, orientation with respect to stress directions, and proximity to stress concentrations. Acoustic emission and microseismic measuring techniques should be used to monitor for induced fracturing and potential rock burst conditions.

3.1.2.5 What May Happen If This Parameter Is Not Measured? Repository performance can only be predicted with a low level of confidence if fracture characteristics are not known. Results of in situ tests designed to investigate the mechanical and hydrological properties of rocks cannot be correctly interpreted without fracture measurements, because fractures will affect these results. Areas of potential instability are unlikely to be adequately monitored because they will be unidentifiable without fracture information. Radionuclides may escape unpredictably through fracture flow paths which have not been detected. New fractures caused by the construction or operation of the repository can cause new flow paths which will change the hydrological response of the rock mass. Unexpected releases of radionuclides may occur and their magnitude, discharge locations, and flow rates will be unknown if the characteristics of these fractures are unknown.

Without adequate information on fracture characteristics, retrievability cannot be guaranteed because failure of the underground workings, including rock burst, could occur unpredictably. Fracture information is required to properly place instruments that will monitor rock behavior. Excessive deformation, which can occur along fractures, and induced fracturing can affect the integrity of waste packages and the waste form.

3.1.2.6 Measurement Conditions and Potential Instrumentation Problems. The characteristics of the fracture network are likely to vary both laterally and vertically. Fracture orientation and density, for example, should be expected to be spatially variable. Such instruments as borehole stress meters, borehole deformation gauges, and extensometer anchors should be located in intact rock sections (i.e., not at fractures); as a result their effectiveness can be questionable in a highly fractured medium such as basalt.

Of critical importance are those fractures which interconnect with other fractures to create lateral or vertical flow paths connecting the repository horizon with the highly permeable flow top breccias or other permeable interflow and intraflow units. Since it is necessary to minimize the number of penetrations between repository drifts, and overlying and underlying aquifers, fracture mapping using vertically inclined borehole cores will also be held to a minimum. It is important, therefore, to further develop remote sensing and indirect methods to characterize rock properties from repository drifts. Such methods can include seismic, microseismic, and ultrasonic techniques, acoustic emission measurements, as well as electrical and electromagnetic measurement techniques. Hydrologic tests can also provide valuable fracture information (see Section 3.3.2, Hydrologic Properties of Fractures).

3.1.3 Initial In Situ Stresses and Stress Changes

The rock mass surrounding an HLW repository will contain stress components due to the weight of overlying materials, confinement, and tectonic processes. The initial stress state of the rock will be disturbed by repository construction and by thermal loading from waste emplacement. Consequently, the virgin state of stress in the rock and stress changes due to repository construction and operation are of concern. The magnitude and orientation of stresses around underground workings are directly related to rock behavior and need to be known to predict stability and deformation of structures in the rock. Knowledge of initial stresses is necessary to properly design subsurface repository workings (e.g., their slope, size, and orientation), and stress changes also affect the stability and deformations of the repository tunnels and emplacement boreholes.

During the site characterization stages, measurements of initial stresses will provide baseline information with which to assess potential for rock failure and rock bursts, and provide information needed to properly design and construct the underground facilities of the repository. Measurements of stress changes performed during in situ tests help to provide an understanding of the phenomenological response of the rock and provide information required to quantify constitutive laws which describe rock mass response to thermal, hydraulic, and mechanical perturbations.

Beyond the site characterization stage, measurements of stress changes used in conjunction with measurements of displacement and deformation will serve to monitor rock mass behavior. These measurements are also needed to validate models and verify the adequacy of the repository design. Measurements of initial stresses should be performed during construction in any newly excavated areas where a different state of stress is suspected to exist as a result of differences in geologic conditions.

The usefulness of stress measurements is directly related to the confidence with which they can be used. Stress information is meaningless unless it is used in conjunction with other geotechnical parameters such as rock mass strength and rock modulus of deformation. Therefore, the accuracy with which rock mass strength and modulus of deformation are measured will partially control the usefulness of stress measurements. The relative importance of stress measurements is roughly equal to that of rock mass strength and modulus of deformation measurements.

The state of stress not only affects the geomechanical behavior of a rock mass, but also the movement of groundwater. Stresses cause fractures to deform and change their aperture. Thus, the permeability of the fractures can change with changes in stress. (See Sections 3.3.1 and 3.3.2 on Permeability, and Hydrologic Properties of Fractures, respectively.)

The state of stress in the host rock of a repository will be a complex function of several variables: the depth of the repository, regional

stresses, geologic structures and discontinuities, variations in surface or basement rock topography, thermal loading, and the underground openings present. The state of stress will also be a function of the in situ mechanical properties of the rock mass. A spatially variable state of stress can be expected in basalt flows because their in situ mechanical properties are likely to be inhomogeneous.

The state of stress or changes in the state of stress can be back calculated from measurements of deformation (or strain), if accurate moduli of rock deformation are used. Geophysical parameters, such as the propagation velocity of seismic waves, cross-hole ultrasonics, and acoustic emission, may prove to be reliable indicators of changes of stress (Paulsson et al., 1980).

3.1.3.1 Normal Parameter Range. At the depths at which the repositories will be constructed, a reasonable assumption is that the vertical normal stress is directly proportional to the weight of the overlying rock (0.027 MPa/meter of depth, Goodman, 1980). The ratio of vertical to average horizontal stresses typically ranges from 0.5 to 2.0 at a depth of 1 kilometer (Brown and Hoek, 1978).

The orientation and magnitude of the principal stresses will be controlled by site-specific conditions, such as the regional stresses and the geological structures present, as well as by man's activities (e.g., repository construction and operation). For example, at Hanford candidate sites the axis of maximum horizontal stress is expected to be perpendicular to the axis of the syncline in which the repository will be constructed. The ratio of maximum horizontal to vertical stresses is expected to be somewhat greater than 2 (RHO, 1982, Vol. 2, Chap. 10).

3.1.3.2 Is This Parameter Site Sensitive? Many of the factors affecting the state of stress are geological conditions which are site specific (e.g., regional stresses, fracture characteristics). Thus, measurements of the initial state of stress will be site specific. Changes in stress, caused by man's activities, will also be site specific because they are controlled by the inhomogeneity of the mechanical properties of basalt flows.

3.1.3.3 Expected Parameter Variation During Normal Site Operation. Quantitative values are unknown at present; however, stress changes will be created by repository excavation and thermal loading.

3.1.3.4 Parameter Values That May Signal Trouble. At repository depths, initial stresses can be high enough to trigger rock failure. Changes in the initial state of stress caused by construction and waste emplacement can also cause rock instability and failure. Goodman (1980) indicates that rock failure can be expected to occur whenever the major principal stress is more than about 25 percent of the unconfined compressive strength of the rock.

3.1.3.5 What May Happen If This Parameter Is Not Measured? Initial stresses must be known to adequately design a repository and to evaluate its short-term stability. Inadequate repository design may result in excessive deformation

of emplacement tunnels and boreholes, damage to waste packages, or instability of roofs and walls of the excavations. Changes in stress created during in situ testing are needed to establish the phenomenological response of rock. Stress measurements are also used to quantify the constitutive laws that predict rock behavior. If stress changes are not monitored during in situ tests, constitutive laws needed to predict repository behavior cannot be quantified. Furthermore, predictive model validation and repository design verification cannot be accomplished without state of stress information. Knowledge of in situ stress and stress changes is important during the site construction and operations phases because of their influence on induced fracturing and potential rock burst.

3.1.3.6 Measurement Conditions and Potential Instrumentation Problems. The state of stress in a basaltic rock mass will vary because in situ mechanical properties of basalt are variable. Consequently, measurements of stress should be made at numerous locations throughout the repository to adequately characterize the state of stress. However, even precise stress measurements obtained in an inhomogeneous geologic environment will be difficult to relate directly to repository performance. Considerable judgment will be required to interpret and apply the results.

3.1.4 Rock Strength

Rock strength parameters describe the failure behavior of rock (where failure is defined as that load at which the rock ceases to perform satisfactorily). Important rock strength parameters are: compressive strength (maximum compressive load per unit area immediately before failure), tensile strength (maximum tensile load per unit area immediately before failure), and shear strength (maximum deviatoric load per unit area immediately before failure). In jointed rock masses, the shear strength of fractures will likely control the overall strength of the rock mass. Fracture shear strength is described by the peak and residual angles of joint friction, the cohesion, and the stiffness of the joint.

Rock strength parameters are used in conjunction with state of stress information to design the repository and to predict the stability of the rock mass. Rock strength varies with rock porosity, temperature, and confining stress. Various fracture characteristics strongly affect rock strength (i.e., fracture density, fracture roughness and waviness, fracture orientation, filling materials, and their moisture content). The shear strength of fractures is related to the displacements which occur along the fracture plane, because roughness of the fracture surfaces can cause joint dilatancy during displacement. This phenomenon alters the state of stress acting on the fractures and their resistance to failure. Because fracture characteristics are spatially variable and anisotropic, rock strength parameters are spatially variable and anisotropic.

3.1.4.1 Normal Parameter Range. The following range of rock strength parameters for basalt were obtained from Lama and Vutukuri (1978).

compressive strength	57-344 MPa
tensile strength	3-18 MPa

Goodman (1980) indicates that a representative value for the shear strength of intact (unfractured) basalt is:

cohesion = 66.2 MPa, with an angle of internal friction = 31°

He reports that friction angles for fractures typically range from 21 to 40°, with 30° appearing to be a reasonable average value. The angle of friction can be much lower when filling materials such as clay gouge, mica, talc, chlorite, or other sheet silicate minerals coat the sliding surface.

A limited number of laboratory rock property measurements have been conducted on core from Hanford site basalts, primarily from the Umtanum and Cohassett flows of the Grande Ronde Basalt and the Pomona Member of the Saddle Mountains Basalt (RHO, 1982, Vol. 1, Chap. 4). A summary of rock strength parameter ranges obtained from these measurements is given below for the entablature and colonnade rock:

Brazilian tensile strength	11.9 ± 6.9 to 19.4 ± 3.8 MPa
uniaxial compression strength	212 ± 106 to 356 ± 42 MPa
cohesion (inherent shear strength)	45 to 59 MPa
angle of internal friction	44 to 53°

Coefficients of friction of joints for Umtanum entablature samples tested in triaxial compression ranged from 0.169 to 3.185 over confining stresses of 6.9 to 34.5 MPa and temperatures of 20 to 500°C.

3.1.4.2 Is This Parameter Site Specific? The strong influence of fractures on rock strength parameters and the inhomogeneous nature of fracture systems make rock strength parameters very site specific.

3.1.4.3 Expected Parameter Variations During Normal Site Operation. Unknown.

3.1.4.4 Parameter Values That May Signal Trouble. Goodman (1980) has indicated that whenever the major stress in a region is more than about 25 percent of the unconfined compressive strength of the rock, rock failure can be expected. This "rule of thumb" is useful as an estimate of instability if the rock is relatively unfractured and at ambient temperature. Lower rock strength will result when the rock is heated and/or fractured.

3.1.4.5 What May Happen If This Parameter Is Not Measured? When rock strength parameters are unavailable, the potential for rock mass instability cannot be evaluated. Thus, unexpected failure of the underground workings may hurt or kill people, and make it difficult or impossible to retrieve the waste. Furthermore, new fractures created may be potential leakage pathways that can adversely affect waste isolation.

3.1.4.6 Measurement Conditions and Potential Instrumentation Problems. The process of formation of basaltic rock gives rise to geological heterogeneity which can be excessive. Changes in fracture characteristics and in the thicknesses of the interflow and intraflow units surrounding the repository result in changes in the in situ mechanical and hydrological properties of the rock mass. Since rock strength is strongly dependent on the fractures present, significant variations in rock strength can be expected to occur at various localities throughout the repository. Fractures will also cause rock strength parameters to be anisotropic. Rock strength parameters should be measured at numerous locations to account for spatial variability and anisotropy.

Also, rock strength parameters used to design the repository workings and to predict repository behavior should be measured in situ. The volume of rock tested should encompass from a few to several cubic meters of rock which contain the geological heterogeneities expected to affect rock strength. Even doing that, it will be difficult to obtain rock strength measurements representative of the total repository rock mass.

3.1.5 Rock Modulus and Poisson's Ratio

Rock deformation moduli (including Poisson's ratio) and viscoelastic constants describe the deformation behavior of rock under mechanical or thermomechanical stress. They are generally used to describe rock behavior at two scales: 1) a macroscopic scale describing the behavior of small rock specimens (i.e., a hundred cubic centimeters, or larger) which are typically intact, but may contain one joint; and 2) a megascopic scale describing the in situ behavior of larger rock masses containing several joints and involving a few to several cubic meters of rock.

On the macroscopic scale, deformation moduli of intact rock, over the short term, may deviate only slightly from the behavior of elastic materials. For that reason, parameters defined by the theories of elasticity are used in first-order calculations and as a fundamental part of the information in more complex modeling algorithms to compute behavior in stressed rock masses. In fact, a thorough understanding of the elastic characteristics of the rock will be essential to adequately model stresses and deformations in and around a repository in basalt. Modulus of elasticity (Young's modulus) and Poisson's ratio are the two most widely used and accepted fundamental parameters for the characterization of elastic materials in the range defined by Hooke's law (i.e., where deformation is directly proportional to applied stress). Modulus of elasticity (E) is defined as the ratio of stress (σ) to deformation (strain, ε) for uniaxial stress (i.e., $E = \sigma/\varepsilon$); and Poisson's ratio (ν) is defined as the negative ratio of lateral deformation (ε_2) to axial deformation (ε_1) for an axial stress (σ_1) or applied load (i.e., $\nu = -\varepsilon_2/\varepsilon_1$). Lame's constant ($\lambda$), modulus of rigidity or shear modulus (G), and bulk modulus or incompressibility (K) are other parameters defined by the theories of elasticity, and are related to Young's modulus and Poisson's ratio by the following expressions (Jaeger and Cook, 1979):

$$\lambda = \frac{E\nu}{(1 + \nu)(1 - 2\nu)} , \qquad G = \frac{E}{2(1 + \nu)} , \text{ and } \qquad K = \frac{E}{3(1 - 2\nu)}$$

These parameters are frequently used in three-dimensional analysis relating principal stresses and strains.

A material's behavior is called elastic if the strain returns to zero after a loading and unloading cycle. The relation between stress and strain need not be linearly proportional, nor does it need to follow the same path during unloading as during loading. Consequently, values of moduli representing slopes along a stress/strain curve, called tangent moduli, or values representing linear stress/strain lines drawn between the origin and individual points on the curve, called secant moduli, are sometimes used to more accurately represent moduli values of a material than the linearly proportional relation between stress and strain represented by Young's modulus. Whether a modulus is determined during loading or during unloading can also be significant. The actual behavior of certain rocks, such as intact basalt, will generally be nonlinear during loading and unloading, and may not completely return to zero deformation after unloading. However, their behavior can still be reasonably approximated, within certain loading limits, by assuming elastic characteristics.

On the megascopic scale, the deformational behavior of a rock mass to stress is influenced by discontinuities (e.g., fractures, faults, filling material, etc.), and by inhomogeneity and anisotropy. This is particularly true with basalt because: 1) rock characteristics vary through the vertical structure of a flow, 2) colonnade formations generally have preferred orientations, and 3) the rock can be highly fractured. The term "modulus of deformation" (or deformation modulus), as opposed to modulus of elasticity (Young's modulus), is used in this report when discussing the stress/strain behavior of larger rock masses which do not closely follow elastic theory as a whole body, and/or have highly nonlinear stress/strain characteristics. Typically, deformation moduli and Poisson's ratio values increase, trending toward values for intact rock, as fractures close due to increased confining stress. An understanding of elastic properties of the intact rock, along with the deformation moduli and values of Poisson's ratio for larger masses, gives insight to the behavior of discontinuities within the rock; a knowledge that is critical to understanding the hydrology within a rock mass (see Section 3.3.2, Hydrologic Properties of Fractures).

Creep deformation is one of the most important rock mechanics parameters in the assessment of long-term repository behavior. Viscoelastic constants describe the time-dependent deformation of rocks. These parameters can be empirically derived or can consist of linear rheological laws based on rheology models. Viscoelastic constants typically used are: (1) dynamic viscosity (expresses proportionality between shear stress and shear strain rate, which can be divided into two quantities--the rate of delayed elasticity and the rate of viscous flow), and (2) a measure of distortion consisting of the elastic shear modulus and the amount of delayed elasticity (Goodman, 1980).

Even though fractures and other characteristics prevent rock from behaving elastically, Young's modulus and Poisson's ratio will provide valuable information useful to evaluating short-term stability of underground openings during the site characterization and construction phases. In situ measurements should be made during the site characterization phase to determine deformation moduli of larger rock masses, more representative of the rock that will be encountered during the repository construction and operation phases. Expected environmental conditions should be simulated as closely as practical. Because of the heterogeneity of basalt, Young's modulus, Poisson's ratio, and limited volume deformation modulus should be included in the suite of parameter measurements that will progress into newly opened repository rock volumes during the construction phase. In situ stress and deformation measurements made as rock volumes relax during repository construction can also be useful parameters in determining deformation moduli.

It is likely that the elastic properties and deformation moduli of the near-field repository rock will change with time due to the elevated temperatures from the waste emplacement, and/or such other factors as dehydration, hydration, chemical changes, and stress changes. A thorough understanding of the hydrology through the repository system following closure will require a knowledge of the behavior of these properties and moduli as a function of time and environment. It is, therefore, recommended that they be remeasured within the repository system from time to time during the operations phase, along with the measurement of other parameters critical to repository hydrology (e.g., permeability, fracture properties, in situ stress changes, deformations and displacements, etc.). The long-term repository behavior evaluations should also include creep laws which describe time-dependent deformations of the rock mass.

Numerous parameters interact with modulus of deformation and Poisson's ratio in rock. For example, modulus of deformation and Poisson's ratio relate stress to rock deformation, which causes change in fracture apertures and rock permeability. This, in turn, influences the movement of groundwater through fractures. Rock moduli of deformation also affect the distribution of stresses surrounding repository openings (e.g., high-stress concentrations may develop in the stiffer sections of the rock). Rock deformation moduli, including Poisson's ratio, are affected by various rock characteristics and environmental factors. Fracture characteristics such as fracture frequency, aperture, and moisture content of filling materials affect deformation moduli. On the scale of a mined repository, fracture characteristics are likely to be inhomogeneous. Therefore, deformation moduli can exhibit spatial variability throughout the repository. Furthermore, deformation behavior is likely to be anisotropic because fractures are anisotropic. Other factors influencing rock modulus of deformation and Poisson's ratio include porosity, temperature, coefficient of thermal expansion, and the confining stresses acting on the rock.

Measurements of stress and deformation are used to obtain the deformation moduli. Consequently, the accuracy of deformation moduli is controlled by the accuracies with which stresses and deformations are measured. Measurements of

deformations used in conjunction with deformation moduli are used to back calculate the stresses acting in the rock.

3.1.5.1 Normal Parameter Range. The following values for Basalt were obtained from Vutukuri et al. (1974).

Young's modulus: 23-100 GPa
Poisson's ratio: 0.13-0.37

Deformation modulus of 67.8 GPa and Poisson's ratio of 0.26 were used by Rockwell Hanford Operations in their conceptual design of a nuclear waste repository in basalt. These values were based on laboratory measurements selected from a literature survey (Agapito et al., 1977) done prior to the BWIP laboratory testing program (RHO, 1982, Vol. 1, Chap. 4). BWIP laboratory tests on intact samples of core from the Hanford site Umtanum flow, the Cohassett flow, and the Pomona Member of the Saddle Mountain Basalt gave static measurement values for the entablature and colonnade zones that covered the following ranges:

Young's modulus: 47.8 ± 20.8 to 85.6 ± 9.4 GPa
Poisson's ratio: 0.24 ± 0.06 to 0.27 ± 0.03

Parameter values obtained for intact core from the entablature zones and from the colonnade zones of the respective flows were similar. Young's modulus of 24.5 ± 19.4 GPa and Poisson's ratio of 0.247 ± 0.05 were obtained by laboratory static tests on intact core from the Umtanum interflow zones. Dynamic measurements, on the same core that was used for the static tests, resulted in similar values for elastic modulus as the respective static tests (RHO, 1982, Vol. 1, Chap. 4).

Goodman jack tests within the entablature zone of the Pomona flow at BWIP's Near Surface Test Facility (NSTF) generally yielded significantly lower values of modulus than any other tests even though care was taken to make the measurements within intact rock sections of boreholes. Even considering only those measurements where jacking pressure was greater than 20.7 GPa, thus exceeding the initial lower modulus range characteristic of this type of test, moduli ranged from 3.65 to 60.6 GPa with the average moduli ranging from 6.9 ± 0.69 GPa, for shallow measurements in vertical boreholes, to 18.75 ± 1.87 GPa in deeper horizontal boreholes (RHO, 1982, Vol. 1, Chap. 4). These modulus values should probably be considered as questionable at this point due to a number of variables during the Goodman jacking tests that could have influenced the results.

A single-slot flat jack test conducted in the Pomona entablature produced rock-mass deformation modulus values ranging from 34 to 48 GPa for a direction parallel to the basalt columns (RHO, 1982, Vol. 1, Chap. [illegible]). These measurements were made at three temperatures ranging from [illegible] to 100°C with flat jacks applying stress over a 2 m by 2 m area in the [illegible]est portion of a 3.5 m slot. The number of tests was not sufficient to arrive at any conclusive relations between temperature and modulus of deformation; however,

the moduli measured, from test to test and within each test, gave consistent results for the one specific rock volume and direction.

3.1.5.2 Is This Parameter Site Sensitive? Rock deformation moduli (including Poisson's ratio) are dependent on chemical composition, water content, confining stress, and stress history; and, therefore, are site sensitive. Moreover, due to the heterogenous and anisotropic nature of basalt, deformation moduli can vary within any specific basalt flow, and within the zones (entablature, colonnade, and interflow). Recognizable differences exist between physical and mechanical properties of the same zone of different flows (e.g., Pomona entablature versus Umtanum entablature) (RHO, 1982, Vol. 1, Chap. 4).

3.1.5.3 Expected Parameter Variations During Normal Site Operation. There may be variations in deformation moduli as a function of temperature as the rock is heated by thermal loading from the nuclear waste. There may also be variations with time due to heating, geochemical changes, fracture aperture changes, and dehydration or hydration. For these reasons, sample measurements of rock modulus and Poisson's ratio should be continued until repository closure.

3.1.5.4 Parameter Values That May Signal Trouble. Values for rock deformation moduli that may signal trouble are not known at present.

3.1.5.5 What May Happen If This Parameter Is Not Measured? Deformation moduli serve as input to the repository design and, in conjunction with creep laws, are used to predict rock behavior surrounding the repository and emplacement boreholes. If deformation moduli were unavailable, a faulty repository design could result in excessive deformation of the tunnels and emplacement holes. Excessive deformation can make retrievability difficult or impossible by causing instability of the repository tunnels or causing damage to the waste packages by excessive closure of the emplacement holes. Excessive deformation may cause backfilled boreholes to close, thereby binding canisters, extruding them from boreholes, or compressing waste packages and damaging them. Excessive deformation may also affect the transportation systems (e.g., rails) used to handle the waste packages.

Displacement measurements used in conjunction with deformation moduli provide an integrated measurement of the stresses acting on the rock. Rock modulus and Poisson's ratio are necessary to translate rock deformation measurements into stress within the rock mass. Even the use of rigid inclusion stress meters requires some knowledge of these parameters for stress determination in hard rock such as basalt. The importance of determining deformation moduli by large-scale in situ testing, along with laboratory and borehole measurements, must also be emphasized. Without large-scale measurements, deformation moduli that integrate discontinuity characteristics cannot be determined; and "it is the network of discontinuities encompassing the intact rock matrix that controls the rock-mass response, not the rock fabric itself" (RHO, 1982, Vol. 1, Chap. 4).

3.1.5.6 Measurement Conditions and Potential Instrumentation Problems. Rock deformation moduli can be affected by layering and by fractures, by changes in the state of stress, and temperature of the rock. Tests in which deformation moduli are established should be performed under the same range of conditions (i.e., temperature, stress, fracture characteristics, bedding planes) operating on the rock mass throughout the life of the repository. Rock deformation moduli will be spatially variable throughout the area of the repository because of the variability in local geologic conditions, and may change with time due to heating, geochemical changes, dehydration, or hydration.

3.1.6 Temperature

Temperature plays a role, either directly or indirectly, with nearly every measured repository parameter at one time or another. The most direct role of temperature is as a parameter in itself to monitor response to thermal loading and natural heating and cooling conditions in repository and test facility environments. Temperature measurements will be required at canisters, and in backfill, rock mass, air, and water to monitor responses to thermal loading from: nuclear waste; site characterization test emplacements; equipment (mining, drilling, lighting systems); ventilation, cooling, and heating systems; rock ambient conditions; and water flow, evaporation, and condensation.

Temperature is also a critical parameter in all thermal and thermomechanical response measurements. Thermal characteristics of repository rock media and engineered barrier materials should be measured under laboratory conditions with confirmatory measurements made in situ to account for variables not easily predicted or simulated in laboratory tests. These thermal characteristics include:

- Thermal conductivity
- Heat capacity
- Thermal diffusivity (thermal conductivity divided by heat capacity)

Their accurate determination requires accurate temperature measurements, and is important in modeling temperatures in repository media to ultimately determine thermomechanical response of the system.

Thermal expansivity, or coefficient of thermal expansion, can be considered the principal thermomechanical response parameter. Thermal expansion provides the driving force influencing the other thermomechanical responses in the repository system. As with the thermal characteristics listed above, coefficients of thermal expansion should be determined by laboratory measurements and during in situ tests, and are dependent on accurate temperature measurements. Other measurements that are directly influenced by temperature and thermal expansivity include:

- Initial stress
- Stress changes

- Strain
- Deformation and displacement
- Permeability
- Fracture aperture changes
- Induced fracturing such as that monitored by microseismic and acoustic emission techniques
- Rock porosity
- Rock decrepitation and spalling
- Uplift

Certain rock property critical parameters are also a function of temperature, and in some cases are a function of the amount of time at elevated temperatures and, consequently, must be remeasured from time to time. These properties include:

- Modulus of deformation
- Poisson's ratio
- Rock strength

Modulus of deformation and Poisson's ratio are particularly important in modeling repository thermomechanical response and must be known over the full operating temperature range.

Temperature also plays a role in hydrological measurements. For example, fluid viscosity and vaporization are functions of temperature. During large-scale rock mass permeability tests (also referred to as macropermeability or ventilation experiments), evaporation and humidity levels are monitored and controlled by monitoring and controlling temperature levels.

In geochemical measurements, temperature influences corrosion rate, dissolution rate, and sorption, as well as the fundamental parameters, pH, and Eh.

Temperature measurements can also signal sudden changes in local repository or test facility conditions. In this respect temperature changes can be used to detect cooling (or heating) from water inflow or sudden changes in water and moisture patterns. Rock decrepitation around heat sources can also be quickly detected by sudden changes in temperature patterns.

One of the more indirect, but important roles of temperature measurements, is in making thermal corrections to data obtained from other instrumentation. At elevated temperatures, like those in repositories or repository test facilities, it is not unusual for instrument thermal corrections to exceed output signals. Instruments requiring thermal corrections can include:

- Extensometers for deformation measurements in rock and openings. (Corrections are required for rod or wire thermal expansion, and transducer temperature variations.)
- Borehole strain gauges

- Stressmeters
- Fracture aperture monitors
- Geophysical tools
- Hydrology pressure gauges
- Water flow meters
- Geochemical instrumentation

Temperature is included in all four of the repository phases of the critical parameter lists. Its priority level is determined by the necessity for its direct measurement and monitoring, as well as its role as a parameter for thermomechanical response measurements. Though temperature is critical to other parameter measurements (e.g., determining water viscosity for permeability measurements, influence on geochemical measurements, instrument temperature corrections, etc.), these less direct influences are not part of the consideration for its priority level placement.

During the site characterization phase, temperature measurements will play a role in all the parameter measurements covered in the preceding part of this section. Tests requiring temperature measurements will simulate or exceed temperatures expected in the actual operating repository. In the site construction phase, the principal need for temperature monitoring will be for human comfort and safety. Temperature will also be monitored during construction as an indirect parameter in assessing the response of the rock mass to construction and its potential effects on future repository integrity. Typically, temperatures during construction will not greatly exceed rock ambient temperatures. During the site operation phase, temperature measurements will play a direct role in monitoring the repository response to thermal loading from high-level nuclear waste. Habitable areas will continue to be monitored for human comfort and safety. During the closure phase, temperature measurements will have a less significant role. Near-field temperature measurements may well be totally discontinued to facilitate repository sealing. Temperature measurements may be continued by remote sensing, along with measurements in surface experiments simulating repository conditions.

3.1.6.1 Normal Parameter Ranges. The maximum allowable basalt temperature in a repository has been established as 500°C. However, other considerations will probably dictate that actual basalt temperatures be kept below 300°C. For example, if high-level waste is stored in a vitrified glass form, the glass is thermodynamically unstable and can eventually devitrify to a crystal form, resulting in a highly soluble waste form (RHO, 1982, Vol. 2, Chap. 11). To reduce this effect, the vitrified waste should not greatly exceed 300°C. Another consideration is that bentonite backfill materials will irreversibly lose water at temperatures above 300°C.

The ambient temperature in the rock at potential basalt sites will likely exceed 20°C due to geothermal heating. However, there should be no need to cool any repository volume below approximately 20°C. The normal temperature range will, therefore, probably be from 20 to 300°C with the possibility that the maximum may be pushed up as high as 500°C. The highest temperatures will most likely be reached during site characterization experiments.

Examples of temperature ranges that may be encountered are given by Rockwell Hanford Operations (RHO, 1982, Vol. 2, Chap. 11) for two basalt flows in the Columbia River Basalt Group assuming a waste canister storage density compatible with the basalt. Initial rock mass temperature in the Umtanum Horizon is expected to be 57-58°C; and in the alternate repository candidate basalt Cohasset flow, the expected temperature is 51°C. Work areas may be cooled to as low as 20°C for habitation. Recent calculations, reported by Rockwell Hanford Operations, "show that the spent fuel waste package center line temperature will rise to a maximum of approximately 270°C four years after waste emplacement, while the emplacement hole surface will reach approximat ly 220°C six years after emplacement." A conservative temperature range in either of the candidate Hanford basalt flows is estimated to be from 20°C at the surface of the underground workings to a maximum of 300°C. However, temperatures in a test facility for further site characterization may exceed the 300°C operating maximum.

3.1.6.2 Is This Parameter Site Sensitive? Temperature will be dependent on thermal conductivity, heat capacity, initial ambient temperatures, and hydrological conditions; all of which can vary from one basalt site to another. However, engineering considerations such as waste packing density, canister thermal output, backfill emplacement, and cooling will probably override the inherent site sensitivities.

3.1.6.3 Expected Parameter Variations During Normal Site Operation. Canister temperatures will peak sometime within the first ten years of waste emplacement, depending on the waste material and its cooling period prior to emplacement (RHO, 1982, Vol. 2, Chap. 11). The maximum average temperature in a repository occurs at its center. Wang et al. (1981) report that, for both spent fuel and reprocessed waste, this temperature reaches a maximum after a period of less than 100 years and thereafter decays very slowly over a period of many thousands of years. The temperature gradient near the ground surface at the epicenter above the repository will reach its maximum in basalt after several thousand years, depending on waste form and repository depth.

3.1.6.4 Parameter Values That May Signal Trouble. Any measured temperature value that does not fall within a predicted range at any point in the repository may signal trouble. A few examples are:

- Excessive canister temperatures. (Maximum temperature is dependent on the waste form, but in the case of borosilicate glass, maximum acceptable temperature will probably be about 300°C.)
- Excessive backfill temperatures. (Temperatures above 300°C can result in irreversible loss of water from bentonite, or dehydration of crushed basalt in backfill.)
- Unpredicted temperatures in rep‥itory basalt or fluids. (Low or high temperatures can be indicative of excessive water flow such as may occur if communication is established between underlying and/or overlying aquifers. Lower temperatures can result from water cooling or loss of heat due to vaporization, and higher temperatures from heat transfer by liquid, vapor, or condensation.)

- Excessive temperature in habitable locations. (Temperatures above established values can indicate dangerous cooling and ventilation system failures.)

Sudden changes in temperature, even though they may be small, may also signal trouble. These changes can be indicative of such phenomena as:

- Sudden changes in water flow (such as might result from fracture opening or closure, or from a change in hydraulic pressure elsewhere in the repository).
- Rock decrepitation or spalling which can be particularly significant around waste canisters before backfilling. Decrepitated or spalled rock can act as a thermal insulator causing a rise in canister temperature.
- Cooling and ventilation system failure.

3.1.6.5 What May Happen If This Parameter Is Not Measured? Temperature is truly one of the critical parameters in repository measurements. Without knowledge of this parameter, thermal characteristics, and thermomechanical response parameters are meaningless. Most hydrological and geochemical measurements in a repository environment are temperature dependent. Nearly all *in situ* instrumentation also requires temperature correction.

3.1.6.6 Measurement Conditions and Potential Instrumentation Problems. With respect to temperature (and other) measurements, the two most significant conditions that may cause some problems are the relatively high ambient rock temperature and high potential hydraulic pressure. For example, hydraulic pressure in the Umtanum Horizon of the Columbia River Basalt Group can be up to 1600 psi, and ambient temperature about 57-58°C (RHO, 1982, Vol. 2, Chap. 6 and 11). Either of these conditions can make instrument installation difficult. Care must be taken to avoid possibilities of water intrusion into transducer, cables, and other components that may be exposed to the high water pressures. Sensors can also be forced from their intended positions by hydraulic pressures in backfilled locations unless proper precautions are taken. The high ambient temperature may require special cooling or design considerations for some instrumentation support electronics (e.g., thermocouple temperature references, signal amplifier, etc.).

3.1.7 Expansivity

Expansivity as a repository critical parameter includes such characteristics as coefficients of thermal expansion, expansion due to changes in confining pressure, and expansion due to hydration of clays (e.g., bentonite) used in backfill mixtures. This section of the report concentrates on the role of thermal expansion in repository measurements. Expansion due to changes in confining pressure is covered under the topic of Rock Modulus and Poisson's Ratio in Section 3.1.5. Expansion due to hydration of clay and rock backfill mixtures, their sealing capabilities, and any stresses resulting from their expansion, should be thoroughly studied during the site characterization phase and will be dependent on site-specific engineering configurations and requirements. Hydration of clay and backfill mixtures are considered under Geochemical Parameters in Section 3.4.

The coefficient of thermal expansion describes the amount of dimensional change experienced by a material as a result of change in temperature. In basalt, as with other rock types, this can be affected by anisotropic characteristics, heterogeneity of the rock throughout the repository, and discontinuities within any specific rock volume. Confining pressure will also influence thermal expansion of the basalt. In this sense, there is an interaction between coefficient of thermal expansion and such other parameters as modulus of deformation, Poisson's ratio, and porosity.

The coefficient of thermal expansion is considered one of the basic thermal properties of a material. Thermal expansion can also be considered as the basic thermomechanical response that provides the driving force coupling temperature change to other thermomechanical response parameters. In a repository environment, these other parameters can include:

- Initial stress
- Stress changes
- Strain
- Deformation and displacement
- Permeability
- Fracture aperture changes
- Induced fracturing and fracture growth
- Rock porosity
- Rock decrepitation and spalling
- Uplift

Coefficients of thermal expansion will be used in testing, modeling, and analysis throughout the life of the repository. However, since values and characteristics for this parameter should be completely determined by laboratory and <u>in situ</u> measurements during the site characterization phase, it is listed as a critical parameter during that phase only.

3.1.7.1 Normal Parameter Range. The normal range of thermal expansion coefficients for basalt, from a 1977 literature review (RHO, 1982, Vol. 1, Chap. 4), is:

$$2.9 \text{ to } 11.8 \times 10^{-6} \, {}^\circ K^{-1}$$

Since 1977, additional thermal properties tests have been conducted on basalt from a variety of flows and horizons within the Hanford site (RHO, 1982, Vol. 1, Chap. 4). Thermal expansion coefficients from these tests are given in Table 9.

Table 9. Thermal expansion coefficients for Hanford basalts.

BASALT FLOW	THERMAL EXPANSION COEFFICIENT 10^{-6}°K^{-1}	
	RANGE	MEAN
Umtanum Flow	6.21 to 10.77	8.81 ± 1.78
Cohassett Flow	5.78 to 6.56	6.17 ± 0.55
Pomona Member of Saddle Mountains Basalt	5.0 to 8.5	5.52 ± 0.56

The coefficients of thermal expansion were found to be constant over the investigated temperature ranges of 20 to 300°C. Tests to determine these parameter values were made on small, intact laboratory specimens under ambient confining pressures. In situ confining pressures may significantly lower thermal expansion.

3.1.7.2 Is This Parameter Site Sensitive? Because of the heterogeneity of basalt within any flow and from one flow to another, coefficients of thermal expansion are spatially variable and site sensitive.

3.1.7.3 Expected Parameter Variations During Normal Site Operation. Once completely defined by in situ tests as a function of confining pressure in the repository environment, this parameter will likely have no significant variations during the remainder of the site operation.

3.1.7.4 Parameter Values That May Signal Trouble. Not known at present.

3.1.7.5 What May Happen If This Parameter Is Not Measured? Determination of this parameter is critical to early modeling of the thermomechanical and hydrological response of the repository system. Direct measurements of other thermomechanical responses (stress and strain changes, deformations and displacements, permeability, fracture aperture changes, porosity, uplift, etc.), along with temperature, should be used to confirm calculated responses from thermal expansion coefficients. Measurements of these types are, conversely, used in determining the coefficients of thermal expansion. This parameter must be determined, either directly or indirectly, to adequately model the thermomechanical responses of the repository system.

3.1.7.6 Measurement Conditions and Potential Instrumentation Problems. The biggest problem in measuring the coefficients of thermal expansion within a basalt horizon may result from the anisotropic and heterogeneous rock characteristics. Large differences between vertical and horizontal confining pressures may also affect the directional characteristics of this parameter. It may be necessary to make a large number of multiple-axis in situ measurements over a significant volume of the candidate flow to obtain representative parameter values. Another problem will be in obtaining representative thermal expansion coefficients for the strata above and below the candidate basalt stratum with minimum penetration into overlying and underlying aquifer regions.

3.1.8 Thermal Conductivity, Heat Capacity, and Diffusivity

Any two of the three parameters, thermal conductivity, heat capacity, or thermal diffusivity, are critical in determining the rate of heat transfer from high-level nuclear waste material and the heat storage capacity of the media surrounding the waste canisters. These properties ultimately influence the waste, canister, backfill, and rock temperatures; and, consequently, influence the thermomechanical response of the repository system.

Thermal conductivity, heat capacity, and thermal diffusivity are interrelated as shown in the following expression:

$$D = \frac{k}{cd}$$

Where: D = thermal diffusivity
k = thermal conductivity
c = specific heat
d = density
cd = heat capacity

Thermal conductivity (k) represents the time rate of heat transfer through a unit thickness, across a unit area for a unit temperature gradient. The specific heat (c) of a substance is the heat per unit mass per degree change in temperature, and heat capacity (cd) is the heat per unit volume per degree change in temperature.

It is assumed that the engineered materials (waste form, canisters, backfill, etc.) can be designed to meet their specific heat transfer needs. The critical parameters when considering measurement requirements are the thermal conductivity, heat capacity, and thermal diffusivity of the rock together with its groundwater. These parameters will be influenced by fracture density and aperture, water content of the rock and other hydrological conditions that can vary throughout the repository rock volume; and, consequently, may be difficult to simulate by small-scale laboratory experiments. It will probably be necessary to perform a number of scattered in situ heated rock tests, each with the capacity to heat rock volumes of the order of tens of cubic meters, to adequately encompass the variables. Heated rock experiments to determine these parameters in situ are relatively simple

in concept. Basically they require a well-controlled heat source (e.g., an electric heating unit) positioned in the rock and an array of temperature sensors located in the rock volume surrounding the heat source at varying distances from it.

Thermal properties will be used in modeling and data analysis throughout the life of the repository. However, since these properties, under defined conditions, should be completely determined by laboratory and in situ measurements during the site characterization phase, they are considered critical parameters of primary importance only during that phase. If conditions in the repository rock should vary in a manner not predicted during site characterization (e.g., due to extensive hydration, dehydration, or decrepitation), it may become necessary to make verification measurements of the thermal properties during the construction or operating phases.

3.1.8.1 Normal Parameter Range. The normal parameter ranges of thermal properties for basalt given in Table 10 are from a 1977 literature search (RHO, 1982, Vol. 1, Chap. 4) combined with actual measurements made in Hanford basalt.

Table 10. Normal thermal property ranges for basalt.

Property	Range
Diffusivity (m^2/s)	4.00 to 9.00 x 10^{-7}
Thermal Conductivity (W/m·K)	1.10 to 4.28
Specific heat (J/g·K)	0.75 to 1.25
Density (g/cm^3)	2.7 to 3.1

Thermal properties for Umtanum and Cohassett basalt flows, two of the possible horizons for candidate repository sites at Hanford, have been determined from the few available core samples (RHO, 1982, Vol. 1, Chap. 4) and are given in Table 11. Measurements have been on small, intact laboratory specimens at laboratory ambient confining pressure conditions. Actual in situ properties may be influenced by confining pressure, water content, anisotropy, heterogeneity, and discontinuities. Actual representative in situ values must be obtained during site characterization tests.

Table 11. Thermal properties of Hanford site basalts.

Property	Umtanum Flow Range	Umtanum Flow Mean	Cohassett Flow Range	Cohassett Flow Mean
Thermal Diffusivity (m^2/s) x 10^{-7}	4.0 to 9.0	5.22	--	7.18 @ 50°C
Thermal Conductivity (W/m·K)	1.25 to 2.50	2.16	1.34 to 1.86	1.60 @ 60°C
Specific Heat (J/g·K)	0.820 to 1.160	0.930	0.791 to 0.937	0.762
Density (g/cm^3)	2.71 to 2.98	--	2.81 to 2.93	--

Thermal diffusivity was found to be constant over the investigated temperature range of 20 to 300°C. However, thermal conductivity and specific heat of the Hanford basalts increased linearly with increasing temperature.

3.1.8.2 Are These Parameters Site Sensitive? Because of the heterogenous nature of basalt, thermal properties can vary from one site to another, between basalt flows, and within any single flow.

3.1.8.3 Expected Parameter Variations During Normal Site Operation. Thermal properties can be influenced by changes in rock fracture characteristics and water content of the rock during normal site operation. However, parameter variations due to these phenomena should be thoroughly determined during the site characterization phase. The most dramatic variation in thermal properties would probably be associated with rock decrepitation or spalling. This would be most significant around waste canisters not protected by backfill where decrepitated and spalled rock can act as a thermal insulation resulting in a waste form temperature rise. This phenomenon should also be simulated and modeled during site characterization.

3.1.8.4 Parameter Values That May Signal Trouble. Changes in thermal conductivity and rock heat capacity can signal trouble such as rock decrepitation, spalling, or excessive dehydration. However, these parameters will probably only be monitored indirectly during site operation by monitoring temperature at critical locations within the repository. Monitoring systems

incorporating established temperature maximums, determined by the repository system design, should provide adequate indication to signal any trouble resulting from unexpected changes in thermal properties.

3.1.8.5 What May Happen If These Parameters Are Not Measured? Thermal properties of the basalt are critical in determining the rate of heat transfer from the nuclear waste. Without representative values, waste, canister, backfill, rock, air, and water temperatures within the repository system cannot be adequately modeled. Representative thermal properties of strata above and below the repository basalt flow must also be determined to completely model repository long-term temperature response and, consequently, long-term thermomechanical response. This modeling is particularly important to ensuring that nuclear waste forms will not exceed certain maximum temperatures that will influence radioactive release rates.

3.1.8.6 Measurement Conditions and Potential Instrumentation Problems. Anisotropic and heterogeneous characteristics, along with variations in water content of the rock and other hydrological conditions, may require a number of in situ measurements to obtain representative values for thermal properties in the repository and surrounding media. Laboratory tests can help in determining these properties; however, it will be nearly impossible to simulate all in situ conditions in the laboratory. Consequently, relatively large-scale tests, covering tens of cubic meters of rock volume, will be required at in situ test facilities. Though simple in concept, these tests require the emplacement of relatively large well-controlled heaters (in the order of a few kilowatts), and a sufficient number of instrumentation boreholes surrounding the heater to adequately monitor temperature distribution within the rock.

3.1.9 Decrepitation and Spalling

The critical concern with rock decrepitation and spalling is their effect on the thermal properties in the very near field regions surrounding HLW canisters. Under certain conditions, decrepitation and spalling can decrease the overall heat transfer properties near the canisters resulting in increased canister temperatures.

The following scenario illustrates the potential problem. The emplacement of HLW canisters into boreholes provides heat sources which will cause thermally induced stress changes in the rock immediately surrounding the canisters. These stress changes, combined with the initial in situ stresses, will cause decrepitation fracturing in the borehole walls where rock strength is exceeded. This, in turn, can result in the spalling of small pieces of rock from the borehole walls into open volumes surrounding the canisters. Spalling will be a particular concern where boreholes are not backfilled following canister emplacement. Decrepitation fractures, which may open as the stress field moves outward with thermal propagation through the rock, and voids between fragments of spalled rock can provide dead air spaces under dry conditions, acting as a thermal insulation. The added thermal insulation will cause an increase in canister temperature which can result in further

decrepitation and spalling. The net result is a regenerative feedback, sometimes referred to as "thermal runaway," that continues until decrepitation and spalling cease, or until some other phenomenon occurs, such as water inflow, to stop the temperature increase. Thermal runaway, should it occur, can conceivably cause waste forms to exceed their maximum design temperatures.

Decrepitation and spalling can also affect water inflow around the canisters. Increased water inflow will most likely decrease canister temperatures, however, it may increase the potential for canister (or liner) corrosion and radionuclide release, depending on flow rate and water chemistry.

The preceding paragraphs have briefly described the interaction between rock decrepitation and the following other critical parameters:

- Thermal expansion
- Initial in situ stress
- Stress changes
- Rock strength
- Induced fractures
- Thermal conductivity and diffusivity
- Temperature
- Water inflow
- Canister corrosion rate
- Radionuclide release

A number of other critical parameters can also interact with rock decrepitation and spalling. For example, permeability and porosity can be influenced by decrepitation. Water inflow rates in decrepitated rock will be influenced by hydraulic head. Rock modulus, Poisson's ratio, and fracture properties can also be affected by rock decrepitation. Rock mineralogy can influence strength and, consequently, the susceptibility for decrepitation.

During the site characterization phase, experiments should be conducted to determine the susceptibility of site specific basalt to decrepitation and spalling. Laboratory tests can be made on stressed and heated samples, but in situ heated rock tests using canister sized heaters in underground repository test facilities will better simulate actual repository conditions. Measurements should also be made on actual or simulated decrepitated and spalled rock to determine potential worst case thermal properties. Since rock susceptibility to decrepitation and spalling may be dependent on the amount of time at elevated temperatures, experiments during site characterization should be extended over the maximum period that the site characterization phase will allow.

Rock decrepitation and spalling will continue to be a critical parameter during the repository operations phase unless experiments during the site characterization phase show conclusively that decrepitation and spalling will not occur, or show that, if they do occur, canister temperatures will not exceed a maximum safe design value. Backfilling of canister storage holes can

also reduce the necessity to monitor for decrepitation or spalling. There are numerous methods to monitor for decrepitation and spalling, from direct observations using borescopes, to emplacing complex sensor systems to monitor for rock fragments in boreholes, but probably the simplest and most direct method is to monitor canister surface temperatures for sudden transients using simple temperature sensors (e.g., thermocouples). Acoustic emission (AE) monitoring can also give valuable data indicating possible rock decrepitation.

3.1.9.1 Normal Parameter Range. Repository designs and maximum temperatures should be such that under normal operating conditions there will be negligible or no rock decrepitation or spalling.

3.1.9.2 Is this Parameter Site Sensitive? The susceptibility of rock to decrepitation and spalling, and the resulting thermal properties are dependent on hydrologic characteristics, rock mineralogy, in situ stress, rock strength, and rock thermal properties, any or all of which can vary from site to site or even within a particular repository horizon. Therefore, this parameter is site sensitive.

3.1.9.3 Expected Parameter Variations During Normal Site Operations. Changes in the susceptibility of basalt to decrepitation and spalling following long periods of exposure to high temperatures have not yet been determined. There is little tabulated data on decrepitation or spalling in basalt and the possible effects on canister temperatures. However, there is some information on this subject from experiences encountered during heated rock experiments in granite. Large-scale decrepitation and spalling occurred around a five kilowatt electrically heated HLW canister simulation after peripheral heaters were turned on during the Stripa, Sweden experiments. Canister temperatures increased 31.5°C from 396°C in a period of less than 30 hours following the initial spalling. Prior to that, temperatures had been increasing steadily at about 1°C per six hour period. The first six hour period following initial spalling showed a temperature increase of approximately 16°C (Chan et al., 1980, Appendix D microfiche; E. P. Binnall, Stripa Experiment Field Notes, February 7, 1979).

3.1.9.4 Parameter Values That May Signal Trouble. A sudden increase in canister temperature can indicate large-scale rock spalling around a canister, or unexpected high canister temperatures may be a result of slower rock decrepitation. Sudden increases in water i[illegible]v, probably accompanied by a sudden decrease of canister temperature, ca[illegible]o indicate rock decrepitation and/or more extensive induced fracturing.

Heavy spalling can make it difficult to backfill around canisters, and difficult to remove canisters if they should need to be retrieved.

3.1.9.5 What May Happen If This Parameter Is Not Measured? The susceptibility of site specific basalt to decrepitation and spalling, and the thermal properties of the decrepitated and spalled basalt are among the important parameters that must be considered in the repository, canister, and waste form design to ensure that thermal runaway will not occur, and that the

waste form and other materials will not exceed design temperatures, or be exposed to excessive water flow.

3.1.9.6 Measurement Conditions and Potential Problems. The nonhomogeneous characteristics of basalt may make it difficult to determine characteristic and worst case susceptibility to decrepitation and spalling without a significant number of tests throughout the repository during the site characterization phase. The same equipment and locations used to determine *in situ* thermal conductivity, heat capacity, and diffusivity (Section 3.1.8) can also serve to test for decrepitation and spalling susceptibility by increasing heater temperatures and/or extending the test periods.

Any monitoring for decrepitation and spalling near waste canisters during the operations phase will require precautions typically established for work in the vicinity of radioactive material.

3.1.10 Canister Movement

Canister movement in storage boreholes can be caused by forces acting directly on canisters or by forces transmitted through backfill material. Driving forces can originate from a number of sources including:

- Hydrostatic pressure
- Steam
- Expansion of clay in backfill mixtures due to hydration
- Rock deformation
- Rock failure

Massive rock failure can cause canister movement in open boreholes, however, it is more likely that canisters will be exposed to driving forces that can cause significant movement after the volumes around the canisters become tightly sealed with hydrated backfill. Most of the backfill mixtures under consideration contain dehydrated clay that expands and improves sealing characteristics when wetted (e.g., bentonite).

Assuming a tightly sealed backfill scenario, hydraulic and steam pressure are the two most likely candidates capable of creating driving forces with sufficient volumes to cause significant canister movements. Water intrusion into a storage borehole, vertical or horizontal, with backfill surrounding the canisters can initiate a series of events that can ultimately cause movement of a single canister or a string of canisters. First, water inflow, say at a single fracture intersecting the borehole, can cause expansion of clay in the backfill, enhancing the seal around the canisters. With a tight enough seal, hydrostatic pressure can create a pressure gradient across the borehole, or, more likely, down the length of the borehole. Expansion of the clay itself can also act as a pressure source. However, the pressure source with the largest volumetric capacity will probably be steam generated from water heated by the high-level waste canisters; that is, until water inflow causes pressure that exceeds the vapor pressure of the heated water. If vapor pressure is exceeded, hydraulic pressure, which can ultimately reach the hydrostatic

pressure at the repository depth, will dominate as the pressure source. The magnitude of the pressure gradient will depend on the ability of pressures to equilibrate through and around the backfill material, the amount of backfill compression and extrusion that takes place, and the extent of pressure relief paths (either intrinsic to the rock structure or designed into the repository system). Pressure relief paths, however, can also be potential paths for radionuclide escape. Canister movement will occur when the forces across the pressure gradient exceed the forces holding the canister or canisters in place.

To illustrate the potential problem, assume that a fracture opens in the wall of a backfilled, horizontal storage borehole so that one end of a 0.457 m (18 in.) diameter canister, midway in a string of end-to-end canisters, becomes subjected to water inflow. Also assume that pressure equilibrates very slowly through the backfill along the borehole length resulting in the full pressure gradient appearing along the canister string such that the opposing pressure on the canister string remains close to one atmosphere; and assume that the canister surface is at its maximum temperature of 300°C. Since the vapor pressure of water at 300°C is 8.59 MPa (1246 psi) (Handbook of Chemistry and Physics, 1972), steam can be generated with pressures up to 8.59 MPa (1246 psi). This translates into a potential driving force of up to 1.41×10^6 N (0.317×10^6 lbs.) on the cross-sectional area at one end of the canister string.

If hydrostatic pressure at the canister depth is greater than the vapor pressure of the heated water, water inflow can continue in liquid state until pressure behind the canister end reaches hydrostatic pressure, assuming that nothing happens to relieve the pressure buildup. As examples of possible pressure amplitudes, hydrostatic pressures in basalt flows at the Hanford BWIP site have been measured at 9.3 MPa (1350 psi) in the Cohassett flow and 11.1 MPa (1610 psi) in the Umtanum flow (RHO, 1982, Vol. 2, Chap. 6). These translate into driving forces equivalent to 1.53×10^6 N (0.343×10^6 lbs.) and 1.82×10^6 N (0.410×10^6 lbs.), respectively, on the pressure exposed end area of the canister string in the example. Canister movement is one mechanism by which these very large driving forces may be relieved.

Rock deformation (thermomechanical, etc.) and rock failure, particularly in boreholes tightly sealed by rehydrated backfill, can create driving forces on canisters considerably greater than potential forces from water inflow. However, even though rock deformation can cause extremely high pressures, the volumetric displacement should be insufficient to cause any significant canister movement. Pressures created by massive rock failures can approach lithostatic pressures or pressures equivalent to maximum horizontal stress fields, which are two to three times greater than lithostatic pressures in some of the Columbia River Basalt Group flows (RHO, 1982, Vol. 2, Chap. 10). Even though a massive rock failure can cause significant canister movement, the design of the repository should be such that the probability of this type of failure in and around a canister borehole will be extremely low. In a basalt repository located well below the water table, it will probably be considerably more difficult to guard against water inflow.

Canister movement can interact with the following other critical parameters:

- Water inflow rate
- Permeability
- Hydraulic head
- Effective porosity
- Fracture properties
- In situ stress and stress changes
- Displacement and deformation
- Rock modulus and Poisson's ratio
- Thermal expansion
- Induced fractures
- Thermal conductivity, heat capacity, and diffusivity
- Rock strength
- Seal and backfill leakage
- Decrepitation and spalling
- Radionuclide release

Most of the ways by which these interactions can occur are apparent from the preceding discussions in this section.

Monitoring and measurement of canister movement is considered critical only during the site operations phase when radioactive canisters are in place. The most likely time for canister movement will be during the period after hydration of backfill around the canister, and before pressures have adequate time to equilibrate throughout the backfill volume. Knowledge of canister movement will become particularly important if retrieval should become necessary. This is also true if it should become necessary to open a closed repository or repository section for canister retrieval during the closure phase. Opening a repository section after pressures have equilibrated can cause large force imbalances that, in turn, can cause significant movements of backfill material and canisters. Even though small movements can relieve hydraulic forces, reducing pressure of super-heated water can cause it to flash into steam providing high-volume force potentials, still at significant pressures, capable of causing very large movements of backfill and canisters. Even taking that into consideration, with present technology the potential benefits do not appear to outweigh the possible problems that may result from attempts to directly monitor for canister movement following initiation of the closure phase.

In situ testing, using heated canister simulations for other critical parameter measurements during the site characterization phase, should provide data on the sensitivity of canisters to movement from pressure gradient buildup. However, canister movement is not considered a critical parameter in itself during the site characterization phase.

3.1.10.1 Normal Parameter Range. The repository and canister storage design should be such that significant canister movement will not take place under normal operating conditions.

3.1.10.2 Is this Parameter Site Sensitive? The possible forces that can act on canisters to cause their movement are dependent on permeability, hydrostatic pressure, lithostatic pressure, in situ stress, fracture properties, and rock strength, all of which can vary from one site to another. Therefore, the potential for canister movement is site (and design) sensitive.

3.1.10.3 Expected Parameter Variations During Normal Site Operation. Forces acting on canisters that may cause their movement will vary as repository conditions vary with time. For example, fractures may open changing water inflow rates behind backfilled canisters as thermomechanical stresses move outward through the rock. However, quantitative estimates of expected variations in the probability for significant canister movements are not available at this time.

3.1.10.4 Parameter Values That May Signal Trouble. Canister movements that may signal trouble will probably be in the order of centimeters or greater; at least large enough to make retrieval difficult if it should become necessary, or large enough to move a canister from a protected and shielded location in its storage borehole.

3.1.10.5 What May Happen If This Parameter Is Not Measured? Canister movement may become so great before corrective action can be taken that retrieval becomes difficult, or engineered barrier protection from radioactive release becomes significantly reduced.

3.1.10.6 Measurement Conditions and Potential Problems. The most difficult problem may be in the installation of instrumentation to monitor for canister movement without compromising the backfill seal. Direct measurement instrumentation may need to be in close proximity to radioactive material making it difficult to check or service the instrumentation.

3.2 GEOLOGICAL PARAMETERS

Geological parameters fall into two categories: those that can be measured directly and those that have no instrumentation for their direct measurement but require application of one or more geophysical techniques for their characterization and continued monitoring.

The former category, described first in this section, includes direct, or nearly direct measurement of crustal deformation, naturally occurring radionuclides, and seismicity. The latter category, described subsequently, includes lithology, faulting, folding, erosion rate, igneous activity, and the presence of existing underground workings, water, mineral, and petroleum resources. With the exception of the resources (whose presence would be discerned by a literature search), these parameters are indirectly measurable by a combination of geophysical techniques, employing surface, borehole, and airborne surveys. For example, the depth, lateral extent, and thickness of lithologic units might be discerned by high-resolution active-seismic surveys

and to a lesser degree by electrical and/or electromagnetic measurements. These types of measurements would be employed extensively in surveys conducted during the site characterization phase, in conjunction with measurements in widely spaced drill holes and analyses of samples from these holes. After a shaft has been sunk and significant excavation for the initial test facility started, direct observation of most geologic parameters will be afforded by the underground workings. Horizontal, continuously cored holes, drilled from these workings would then provide sets of core samples for geological observations as well as material for preliminary laboratory measurements of physical and hydrological properties of the candidate repository host rock. The horizontal holes might also provide locations for specific active seismic and/or electromagnetic geophysical measurements.

3.2.1 Crustal Deformation

Long-term crustal deformation, including uplift, subsidence, and crustal lengthening or shortening, can perturb groundwater flow paths and surface mass wasting processes, conceivably either improving or diminishing the ability of a site to inhibit migration of radionuclides. A localized uplift may occur in response to the thermal regime introduced by the presence of the radioactive waste. To assess these effects at a site, long-term monitoring of crustal deformation is required. Such monitoring depends on establishment of geodetic measurement networks spanning the site region. The networks include leveling transects for vertical control and length-measurement segments to detect horizontal components of crustal movement. The networks should be established early enough in the site characterization phase to provide a set of baseline data, against which results of subsequent surveys will be compared. The extent of the networks should be broad enough to include points outside the site region that can serve as fixed benchmarks. For basis of discussion, the tectonic setting of the Columbia River basalt is used as a specific example in the following sections.

3.2.1.1 Normal Parameter Range. Because of the extent of knowledge of crustal deformation of the Columbia River Plateau, this information is used to illustrate the range of this parameter. Westward tilting of the Columbia River plateau region prior to the extrusion of the Miocene basalts is evident from the broad lateral extent of the flows. Subsequent crustal shortening in the Pasco Basin area in response to north-south oriented tectonic forces is evident from the presence of east-west anticlinal ridges. Observations of basalt flow thicknesses, controlled to some extent by the preflow topography, combined with radiometrically determined ages of the flows, indicate that long-term uplift rates averaged 40 mm per million years. Trilateration surveys indicate that crustal shortening is still progressing at rates estimated at 0.04 mm per km per year in a northeasterly direction and 0.02 mm per km per year in a northwesterly direction (these data are provisional because of the short time base since installation of the survey network). These present-day strain rates agree reasonably well with the overall direction and rate of strain determined from geological observations.

3.2.1.2 Is This Parameter Site Sensitive? Given the above provisional crustal deformation rates, a site in the Pasco Basin with dimensions of a few kilometers should experience north-south compression of a few hundredths of a millimeter per year. Of course, crustal deformation magnitudes and rates may differ considerable in other basaltic provinces and in other parts of the Columbia River Plateau.

3.2.1.3 Rationale for Continued Measurements. Vertical- and horizontal-control geodetic surveys over established networks are required periodically throughout the site-operating phases, closure, and beyond. Localized uplift, in response to the thermal effects from the waste, can only be assessed by precise vertical control based on long-term observations.

3.2.1.4 Expected Parameter Variations During Normal Site Operation. The short time base of geodetic measurements does not provide an indication of the variations that might occur in crustal strain rates. However, geologic evidence indicates that 10 to 14 million years ago the basalt flows were folded slowly enough to permit their ductile deformation, rather than their being largely offset by faulting. More recently, flows have been offset along faults in the Pasco Basin; the most recent activity, tabulated in the Site Characterization Report (RHO, 1982, Vol. 1, Chap. 3), was 13,000 years ago. That measurable crustal deformation may accompany present-day seismic events can only be confirmed by repeated occupation of geodetic networks.

3.2.2 Naturally Occurring Radionuclides

The gamma radiation environment upon which the effects of the introduction of radioactive waste will be superimposed depends on the abundances of the naturally occurring elements, uranium, thorium, and potassium. A survey of the location and abundance of these elements in the rock matrix, fracture-filling minerals, and groundwater establishes the natural environmental radioactivity baseline, and also aids in the determination of the age and origin of groundwater, thus assisting in evaluation of the hydrologic suitability of a candidate site. A knowledge of radioelement location and abundance will also help to determine the likely path of radionuclide transport into and through the hydrologic system of the rock mass encompassing the repository.

The distribution and abundance of U and Th in the rock matrix and fracture-filling minerals provide indications of the mobility of these elements in and away from a repository environment. For example, differences observed between concentrations of U and Th in the rock matrix and in fracture- and vug-filling minerals indicate the ability of these minerals to adsorb radioelements from water circulating through these openings. An investigation of the state of secular equilibrium in the U and Th decay series in fracture-filling minerals reveals the varying mobility of members of the series and would help to determine the age of deposition of components of the mineral assemblage. Monitoring of the U-series daughter, ^{222}Rn, in the atmosphere of the underground workings is necessary to establish the initial environmental baseline and to detect subsequent increases that might result

from water inflows, rock deformation, and heating of the rock (Nelson et al., 1980).

A knowledge of contents of uranium isotopes in the groundwater can be used to estimate the age of the water, an important parameter in assessing the degree of isolation of the hydrologic system encompassing the repository. Corroborative age information may be obtained from measurements of the He contents of the water, combined with contents of U and Th in the rock. Age dating of groundwater is discussed in Section 3.4.2, Age of Water.

The contents of radioelements in the rock are readily determined by laboratory gamma spectrometry, substantiated by delayed neutron and/or neutron activation analyses. With appropriate calibrations provided by laboratory analyses, it has been demonstrated that reliable concentration values can be obtained by measurements in underground workings by a portable gamma spectrometer (Wollenberg et al., 1980). The gamma-ray exposure rates due to the presence of U, Th, and K in the rock can then be calculated by applying conversion factors, adjusted for the 4π geometry provided by the workings.

3.2.2.1 Normal Parameter Range. The distribution and abundance of U, Th, and K strongly depends on rock type, and basalt has relatively low concentrations compared to most igneous rocks. For example,

	U(ppm)	Th(ppm)	K(%)
Ranges in Columbia River basalt are:	0.2-2.1	1.1-6.6	0.3-1.6
Within basalts of the Pasco Basin, ranges are:	0.7-2.1	3.4-6.6	0.6-1.6.

Uranium contents of groundwater range from 1 to 10 μg/l in some springs and Saddle Mountains basalt waters, to less than 0.01 μg/l in water of the Grande Ronde and Wanapum basalts. $^{234}U/^{238}U$ activity ratios range from unity to over 3 in Pasco Basin Waters.

3.2.2.2 Expected Parameter Variations During Normal Site Operation. Variations detected in natural radionuclide contents of groundwater, as with other element content variations, would indicate changes in the hydrologic regime. Addition of chemical components of one aquifer system into another system would indicate hydrologic connection, perhaps along vertical fractures or along pathways caused by excavation and operation of the repository. For these reasons, chemical signatures of the aquifer systems present in a basalt sequence must be well established and periodically monitored.

3.2.2.3 Rationale for Measurements. Investigations of the distributions and abundances of naturally occurring radioelements in the rock and groundwater, besides furnishing the natural radioactivity baseline, also would help reveal the sorptive capabilities of fracture-filling minerals, the mobility of members of the U and Th decay series in the groundwater system, and would contribute to the determination of the age and origin of the water, important factors in the evaluation of site suitability.

3.2.3 Seismicity

The effect of local and regional seismicity on underground workings involves considerations similar to those for surface facilities: the magnitudes of the earthquakes, their epicentral distance from the repository, the regional geologic setting, and the nature of the materials encompassing the repository. These then influence the accelerations experienced at a given site and the duration of shaking, which in turn control the earthquake intensity at that site.

An assessment of earthquake damage to underground facilities by Pratt et al. (1978) suggests that, in general, the deeper the underground workings, the less their response to a given earthquake, compared to surface conditions. This is largely attributed to attenuation of the high frequency ground motions with depth below the ground surface. Vertically oriented workings, shafts, and wells are less prone to damage than are horizontal workings. The primary concern then, aside from the obvious one of not locating the site astride an active fault, is shaking which might disrupt support facilities on the surface and might damage the shafts. However, surface structures are very short-lived compared to the repository. The effects of earthquakes on these structures are of principal concern during the periods of repository operations and retrievability rather than during the period of long-term isolation.

3.2.3.1 Normal Parameter Range. As stated previously (3.2.1.1) information specific to the Columbia River Plateau is used to illustrate the range of this parameter in a basaltic province. Earthquake magnitudes in the Columbia River Plateau range to 6 (the Milton-Freewater earthquake of 1936 had a magnitude of 5.75 to 6.1) and Modified Mercalli intensities range to VII. Two earthquakes of magnitude greater than 5 occurred in 1981 in the Cascade Range north of Mt. St. Helens. Closer to the Hanford Reservation, an earthquake of epicentral intensity VI occurred near the town of Corfu in 1918.

In the Pasco Basin region, the largest earthquakes (magnitudes of 4.5) have occurred in the Saddle Mountains and Frenchman Hills, 30 to 50 km north of the reference repository location. An area near Coyote Rapids, about 10 km north of the reference repository location, has experienced earthquake swarm activity, with a maximum magnitude of 3.8.

The design for the Washington Public Power Supply Unit 2 on the Hanford Reservation considered a maximum Modified Mercalli intensity of VIII, incorporating a ground acceleration of 0.25G.

3.2.3.2 Is This Parameter Site Sensitive? Repository sites in the basalt of the Columbia River plateau would probably respond similarly to earthquakes of given magnitude and epicentral distance, irrespective of their location in the plateau. The responses of sites in other basaltic provinces could differ considerably, depending on their tectonic settings.

3.2.3.3 Expected Parameter Variations During Normal Site Operation. Over the span of repository operations, seismicity in the Columbia plateau region can be expected to vary from low magnitude events, often associated with swarms, to a few single events of magnitude 5 to 6. Associated Modified Mercalli intensities would vary accordingly, from less than I to VIII, depending of course on epicentral distance and magnitude. The frequency of occurrence of events ranges from ~1 of magnitude ~4 every 10 years, to 10 to 100 events of magnitude 1 to 2 annually.

3.2.3.4 Rationale for Continued Measurements. Seismic monitoring networks should continue to be operated to detect significant variations from the zonations, recurrence rates, focal mechanisms, and magnitudes observed to date. On the basis of these observations and depending on the stage of operations, design of surface and underground waste handling facilities could be confirmed or modified.

3.2.4 Lithologic Parameters

A principal concern in evaluating a repository site in basalt is the homogeneity of the candidate horizon over a lateral extent sufficient to encompass the repository and its buffer zone. In basalt, the "horizon" may comprise just the entablature zone of a specific flow. Homogeneity implies that the candidate horizon has a vertical extent sufficient to contain the repository excavations. (Hydrostratigraphic homogeneity is discussed in Section 3.3.7). Lateral homogeneity must not only apply to the gross thickness and structural integrity of a candidate rock unit, but also to its lithologic uniformity. This in turn implies that the rock's chemical and mineralogical composition are relatively uniform over a given area. Compositional uniformity can best be assessed by visual observation and recording of drill core and the rock exposures afforded by the walls, roof, and floor of the underground workings.

It is pointed out in Sections 3.1.2 and 3.3.2 that careful visual observation and recording of fracture spacing, orientation, and aperture are necessary to properly characterize the physical as well as hydrologic behavior of the candidate rock mass to predict its response to excavation, the introduction of radioactive waste, and the ability of the rock mass to ultimately contain the waste. In this same sense, careful observation and recording of the mineralogy of material that fills the fractures must also be undertaken. Such observations would commence with the initial excavation at the bottom of the first shaft, and would continue through site operations as new vertical and horizontal openings were developed. Observations of the mineralogy and chemical composition of fracture-filling material would provide evidence of the nature of the hydrologic system that has been circulating in the basalt. Observations of fracture-filling material also disclose the presence and abundance of minerals that could adsorb radionuclides from the groundwater moving through the fracture system. This subject is discussed in Section 3.4.3, Sorptive Capacity of Fracture Lining Material.

3.2.5 Faulting

The presence and magnitude of most of the faults transecting the region encompassing a repository location would be detected in the early stages of site investigations by geologic mapping and geophysical surveys. Subsequent observations and drilling from underground workings might disclose smaller offsets not discernible from the surface. In the semiarid Columbia Plateau, many faults are discernible from examination of aerial photographs, and have been recorded in the course of regional geologic mapping. Fifty-three faults have been identified within the Pasco Basin region. Many of them are reverse or thrust faults with general WNW-ESE strikes. Their lengths range from less than 1 to over 40 km, and displacements from a few tens of meters to over 500 m. There are fewer normal faults in the region. They are considerably shorter in length, more steeply dipping, and strike more to the north-south than the thrust faults; vertical displacements range from less than 5 to over 80 m. Continued or renewed movement on these, or yet-to-be-discovered faults in the repository area, would be detected by reoccupation of the trilateration and/or leveling networks, discussed in Section 3.2.1 on Crustal Deformation.

3.2.6 Folding

As with faulting, major folds can be detected by surface mapping and geophysical surveys. In the Pasco Basin, the major WNW-ESE-trending folds are discernible from aerial photographs. More detailed expressions of folding have been disclosed from surface and borehole geophysical data, and folding is also indicated by the topography of the top of the basalt from drill hole intersections. Amplitudes of the larger folds of the Pasco Basin range from several hundred meters to over 1 km. The reference repository site occupies the trough of a relatively low-amplitude, asymmetric syncline, with a steep south limb. Smaller folds will most likely be encountered by the underground workings and, as with faults, should be documented in detail by careful geologic observation.

As indicated in the section on crustal deformation, crustal shortening is still progressing in the Pasco Basin region, so that existing folds and faults may become more accentuated with time. Reoccupation of the aforementioned leveling and trilateration networks to monitor crustal deformation would also serve to monitor any ongoing development of folds.

3.2.7 Erosion Rate

The principal concern here is incisement of the site by the effects of erosion. This could be caused by two factors: short-term single or repeated erosion of the site by catastrophic flooding; and erosive incision of the rock encompassing the repository in response to tectonic uplift. In the latter case, monitoring of uplift rates will indicate the propensity for erosion. However, a location in the trough of a syncline reduces the probability of uplift-caused incision of the basalt sequence encompassing a repository in the Pasco Basin to nil, given the tectonic regime in that region.

An assessment of the effects of catastrophic flooding due to the failure of an ice dam 13,000 years ago, on sediments overlying basalt of the Pasco Basin, indicates that the sediments were not incised more than several meters. Of the 175 to 200 m of sediments that overlie the basalt, only 50 m are flood deposits.

3.2.8 Existing Underground Workings

The presence of old man-caused underground workings in the repository site area can be established by review of well records and the mining and engineering literature of the region, supplemented by discussions with state geological survey personnel, and followed, if necessary, by detailed ground checks and geophysical surveys. Underground workings on the Columbia Plateau are essentially limited to water wells and engineering structures: railroad tunnels and water conduits for hydroelectric and irrigation systems. Natural cavities in the basalt are for the most part limited to vesicles and vugs, though the presence of larger-diameter tubes and caves cannot be completely ruled out. Salt and limestone terranes containing solution cavities and tuffaceous terrane with large lithophysae may require extensive geophysical surveys.

3.2.9 Water-Mineral-Petroleum Resources

An assessment of the potential water, mineral, and petroleum resources of a site region and their valuation requires an extensive literature search as well as communication with existing and potential operators in the region. Instrumentation would not be required in this activity.

3.2.10 Igneous Activity

The propensity of igneous activity to occur in a site region during the lifetime of a repository can best be assessed by investigating the recurrence rates of volcanic and intrusive episodes. Such rates may be determined from the historical record and from rock age dating. The age relationships and absolute ages of basalt flows in the Columbia River Plateau are well understood. The youngest flows, the Lower Monumental Member of the Saddle Mountains Basalt, were extruded about 6 million years ago, culminating a 10- to 11-million-year episode of extrusion. More recently, felsic and basaltic intrusives of probable Plio-Pleistocene age have intruded the basalt sequence at a few locations in the Columbia River Plateau and on its margins (Sheppard, 1967). These intrusives are relatively scarce, and an estimate of recurrence rates of igneous activity based on their ages would have little credence. Some felsic intrusives are associated with the early stages of Cascade volcanism (and may be contemporaneous with those in the Plateau), but their occurrences are confined to the present-day High Cascades zone, west of the Plateau.

3.3 HYDROLOGICAL PARAMETERS

The most likely mode of transportation of radionuclides to the accessible environment is through the groundwater system. The rate and path of transport are primarily governed by the distributions of permeability and hydraulic head throughout the host rocks. As both excavation and thermal loading are anticipated to change these parameters, their values in both the natural and altered state must be considered to accurately assess a candidate site. If, and only if, a site is thoroughly and accurately assessed will it be possible to reliably predict transport rates and times to the accessible environment (barring unforeseen disasters or short-circuiting of the natural groundwater path through boreholes or shafts). There are, however, many serious practical and conceptual difficulties associated with evaluating the critical hydrological parameters in basaltic rock.

The theory and methodology currently used to evaluate the hydrologic properties of candidate sites were originally developed for studying groundwater aquifers. Extension of classical groundwater theory and test methodology to deep basaltic rocks are complicated by four factors:

1. Testing of very low permeability rocks is difficult, time consuming, and expensive.
2. Evaluating rock permeability and porosity from test data is hindered by the lack of well established interpretive techniques for fractured rocks.
3. Interpretation of data obtained to determine permeability and hydraulic head is often complicated by nonisothermal conditions.
4. Prediction of the interaction between the thermomechanical response and the hydrologic parameters of the rock is subject to large uncertainty.

Ongoing research to improve testing, interpretive, and predictive techniques in deep basaltic rocks has resulted in the illumination of some of these difficulties. However, because of the time constraints placed on establishing a HLW repository, site characterization and construction will go hand in hand with much needed research.

Because of the great importance of accurate evaluation of the hydrologic parameters, much effort will be focused on measuring them during the site characterization phase. Periodic or continual measurement of some of the critical parameters will continue throughout the site construction, operation and closure phases to confirm measurements made during site characterization and to detect excavation or thermally induced changes. Continual integration of this data into the system and predictive models will minimize the likelihood of unforeseen problems.

3.3.1 Permeability

The permeability of a medium is a measure of its ability to transmit fluid. In general, it is a directional quantity and must be described by a tensor. Formulation of the fluid flow and chemical transport equations in terms of the permeability tensor is valid if one can define a suitable volume-

averaged permeability and make measurements which encompass a volume greater than the appropriate "representative elementary volume." If it is not possible to accurately describe the flow and transport characteristics in terms of the bulk permeability tensor and associated bulk volumes, it is necessary to treat the permeability on the basis of discrete flow paths or individual fractures. This will be discussed more in Section 3.3.2 on Hydrologic Properties of Fractures.

Insofar as the rate at which fluid will flow through a rock mass is proportional to the permeability, the rock permeability interacts with almost all of the critical hydrologic parameters: fluid velocity, rate and location of groundwater recharge and discharge, and water influx rate. Because each of these parameters is inferred from the permeability and the hydraulic head, errors in the calculated bulk permeability are directly transferred to these parameters. Since the permeability range for basalt is so large (greater than ten orders of magnitude) and it is difficult to make permeability measurements over large volumes, the potential uncertainty is great. The permeability of basalt is the result of fractures and microfractures in the rock matrix. Both the magnitude and directional properties of the permeability tensor are governed by the fracture characteristics: aperture, orientation, spacing, continuity, and connectivity (Snow, 1968).

In the groundwater literature, it is common to describe the fluid flow equations in terms of the hydraulic conductivity. The hydraulic conductivity (K) is related to the permeability (k) by

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

where ρ is the fluid density, g the acceleration due to gravity, and μ the fluid viscosity. Under nonisothermal conditions, the permeability (k) is the appropriate parameter to use because it is a function only of the rock properties. The hydraulic conductivity is strongly temperature dependent (it can change by over a factor of ten between 20 to 300°C for a constant rock permeability). Hence, to eliminate ambiguity about the true rock properties, the permeability itself must be considered the true critical parameter.

Both the fluid density (a function of water composition, temperature, and pressure) and the fluid viscosity (primarily a function of temperature) must be known to evaluate the rock permeability. When injection testing under nonisothermal conditions, the appropriate set of fluid parameters (i.e., those of the injected fluids or those of the <u>in situ</u> fluids) to which the measurements correspond must be determined (Benson and Bodvarsson, 1982; Benson, 1983).

3.3.1.1 <u>Normal Parameter Range</u>. Basalt permeability is extremely site specific and highly variable. Values of 10^{-9} to 10^{-20} m^2 have been reported in the literature (Brace, 1980; RHO, 1982, Vol. 1, Chap. 5). Measured horizontal permeabilities in the Hanford basalts range from 10^{-18} to 10^{-20} m^2 for flow interiors and from 10^{-10} to 10^{-18} m^2 for flow tops (RHO, 1982, Vol. 1, Chap. 5). There are no reported measured values for the vertical permeability.

3.3.1.2 Expected Parameter Variation During Normal Site Operation. Unknown. However, the potential variation is relatively large in the near-repository region because the permeability of an individual fracture is proportional to the square of its effective aperture (Snow, 1968; Tsang and Witherspoon, 1981). Fracture apertures in the near-repository region are expected to change as the result of excavation and thermomechanical loading of the rock.

3.3.1.3 Parameter Values That May Signify Trouble. The rate at which groundwater flows through a rock mass is governed by the fluid potential gradient and the permeability. Therefore, it is not possible to place meaningful limits on one without specifying the other. Constraints on the maximum tolerable permeabilities will be governed primarily by two factors, the largest tolerable water influx rate into the repository and the minimum allowable transit time to the accessible environment.

3.3.1.4 Role During Each Repository Phase. During the site characterization, in situ tests will be conducted to determine the horizontal and vertical permeability of the hydrostratigraphic units above, in, and below the repository horizon. Measurements will also be made throughout the groundwater basin to fully characterize all of the units that may potentially affect the ability of the site to isolate the HLW.

During site construction, in situ tests will be continued to verify the measurements previously obtained and to detect any excavation induced changes. Concurrently, permeability measurements of the backfill material and seals should be made in an underground test facility. During the site operation, permeability measurements should continue in order to ensure that new permeable conduits are not being formed as a result of thermal loading or excavation.

3.3.1.5 Measurement Conditions and Potential Instrumentation Problems. The permeability of a rock mass is inferred from measurement of the fluid flow rate when a known hydraulic gradient is imposed, or vice versa. There are four essential measurements needed to calculate the permeability: fluid pressure, volumetric flow rate, fluid temperature, and time. There is little difficulty associated with the measurement of the fluid temperature, time, or pressure. However, relatively warm temperatures in deep basalts, such as those found at Hanford, will require that the pressure transducers used for the in situ tests be suitable for use at elevated temperatures. Such transducers are available but at a higher cost than conventional transducers (Lamers, 1979). Flow rate measurements at very low rates may present some difficulties and require novel measurement techniques (i.e., air humidity). However, the lack of appropriate testing and interpretive techniques create far greater uncertainty in the permeability measurements than do instrument related difficulties.

3.3.2 Hydrologic Properties of Fractures

Fractures usually act as the major groundwater conduits in basaltic rocks. They also provide the bulk of the pore volume. Their important hydrologic parameters include: aperture, spacing, orientation, continuity, connectivity, and the composition and degree of filling material. In general, the larger the aperture, the closer the spacing, and the greater the connectivity and continuity: the greater the permeability. It has been shown that the magnitude of the fracture permeability is proportional to the square of the effective aperture (Snow, 1968). The directional properties of the bulk permeability are governed by the interplay between the fracture parameters. Accurate quantification of the relationship between the hydrologic parameters and fracture parameters is not yet possible, and research in this area is still in its infancy. Therefore, fractured rock is usually treated hydrologically in terms of an equivalent porous medium. The applicability of this approach has been investigated by Long, 1983.

Because both the permeability and porosity are directly related to the fracture properties, the fracture parameters have a critical role in the location and rate of natural recharge and discharge, water influx rate, fluid velocity, and hydrodynamic dispersion. The fracture parameters will also play a major role in the thermomechanical response of the system. The potential impact of the thermomechanical response on the hydrologic parameters in the near repository region is great because of the square-dependence of permeability on fracture aperture.

3.3.2.1 Normal Parameter Range. This parameter is highly site specific. See Sections 3.1.2.1 and 3.1.2.2 under Fracture Properties and Induced Fracturing.

3.3.2.2 Expected Parameter Variation During Normal Site Operation. Expected parameter variations are uncertain. See Section 3.1.2.3 under Fracture Properties and Induced Fracturing.

3.3.2.3 Parameter Values That May Signify Trouble. Specific values of the fracture parameters cannot be given. In many instances, the larger the aperture and the closer the spacing, the greater the potential for rapid fluid migration to the accessible environment. Excessive numbers of fractures with a vertical orientation may indicate large vertical permeabilities.

3.3.2.4 Role During Each Repository Phase. During site characterization, the fracture parameters will be characterized geologically, mechanically, and hydrologically. Characterization for the purpose of hydrological evaluation will be discussed here. In situ injection, pumping, and tracer tests will be conducted to determine fracture permeabilities and bulk porosity (fracture/bulk volume). Visual observation and geophysical techniques will also be used to describe the spacing, length, interconnection, and orientation of fractures in cores, boreholes, outcrops, and underground exposures. Data verification will continue throughout the site construction and site operations phases. Microseismic methods will be used to detect the creation of new fractures or movement along existing fractures caused by excavation and/or thermal

loading. Microseismic monitoring should continue throughout the closure and decommissioning phase.

3.3.2.5 Measurement Conditions and Potential Instrumentation Problems. Characterization of the hydrologic properties of fractures has been attempted by two approaches: measurement of permeability by relatively conventional flow tests (see Section 3.3.1.5 on Permeability), and measurement of permeability and porosity (fracture volume) with tracer tests. Computed fracture apertures from the two techniques have been observed to vary significantly. Additional research is required before interpretive techniques and test procedures will be adequate to characterize and predict the hydrologic behavior of naturally fractured rock.

3.3.3 Hydraulic Head

The hydraulic head (s) is defined as the potential energy per unit weight of fluid. Mathematically this is expressed

$$s = z + \int_{P_o}^{P} \frac{dP}{\gamma}$$

where z is the elevation above a chosen datum at which the measurement is made, γ is the specific weight of the fluid, and P is the fluid pressure. The fluid pressure, the elevation at which the pressure was measured, and the specific weight of the fluid as a function of depth must be measured to correctly determine the hydraulic head. It is particularly important to recognize that the specific weight cannot be treated as a constant in systems where the temperature or fluid chemistry changes with depth or location. Under steady flow conditions, the rate at which fluid flows by a cross-sectional area is proportional to the gradient of the hydraulic head.

3.3.3.1 Normal Parameter Range. Hydraulic head is site specific. Hydraulic heads in candidate horizons at Hanford of 110 to 140 m above sea level are reported (RHO, 1982, Vol. 1, Chap. 5).

3.3.3.2 Expected Parameter Variation During Normal Site Operation. The largest change in hydraulic head will take place in the immediate vicinity of the underground openings. Initially, the fluid pressure component at the drift face will be reduced by an amount equivalent to the depth of the opening. This state will persist until the repository is closed and refills with water. The head will also change in response to thermal loading and the resultant thermal expansion of the rock and pore fluid. The degree to which this will occur depends on the rock temperature, permeability, and porosity. The hydraulic head may also change in response to climatic change or changes in the groundwater usage pattern.

3.3.3.3 Role During Each Repository Phase. During site characterization hydraulic heads will be measured throughout the entire groundwater basin in

order to define the flow system. Hydraulic head measurements are also essential for conducting flow tests (permeability and porosity measurements), and for determining the impact of excavation on the near-repository rock. Measurements will continue throughout the site construction phase to monitor the impact of excavation and verify the previous permeability and porosity measurements. The hydraulic heads in the far field will also be monitored to detect changes that might affect the ability of the repository to isolate the HLW. During the site operation phase, hydraulic head will be measured to detect changes in the fluid flow pattern caused by thermal loading and excavation. Monitoring will continue in the far field throughout the closure and decommissioning phase in order to detect changes in the hydraulic head that would alter the shortest predicted path to the accessible environment (e.g., due to climatic changes, induced vertical fractures, and/or buoyancy flow).

3.3.3.4 Measurement Conditions and Potential Instrumentation Problems. Five measurements are required to calculate the hydraulic head: fluid pressure, barometric pressure, elevation, and fluid chemistry and temperature. In deep basalts, such as the Umtanum flow at Hanford, pressures in excess of 1500 psi will be measured. Because the pore fluid temperatures may exceed the operating limit of some conventional transducers, appropriate instruments must be chosen. Such instruments are available but at a somewhat greater cost (Lamers, 1979). Accurate measurement of the fluid pressure also requires that the interval in the borehole in which the measurement is being made is completely isolated from the surrounding intervals. In addition, in low permeability rocks, it may take a long time before the pressure in the borehole is equilibrated with that in the surrounding formation. The elevation may be determined from the measured depth to the transducer if the appropriate correction is made for the borehole inclination. If the measurements are to be made with permanently installed instruments, the long-term reliability and temperature sensitivity of the pressure and temperature transducers and the packers or seals will be a major concern (Rogue and Binnall, 1983).

3.3.4 Effective Porosity

The effective porosity is defined as the total connected pore volume per unit bulk volume of rock. In fractured basalts the connected pore volume is created by interconnected vesicles and the fracture volume itself. For a given hydraulic head gradient and permeability, the average interstitial velocity is inversely proportional to the effective porosity. Effective porosity depends on the fracture aperture, spacing, continuity, and connectivity.

3.3.4.1 Normal Parameter Range. Effective porosity is highly variable and site specific. At Hanford, for example, effective porosities range from 5 percent in the flow tops to less than 1 percent in the flow interiors (RHO, 1982, Vol. 1, Chap. 5).

3.3.4.2 Expected Parameter Variation During Normal Site Operation. The range of variation in the near-repository rock is uncertain. Essentially no change is anticipated in the far field.

3.3.4.3 Parameter Values That May Signify Trouble. Uncertain.

3.3.4.4 Role During Each Repository Phase. During site characterization, in situ tests will be conducted to determine the effective porosity of the hydrostratigraphic units above, in, and below the repository horizon. Measurements will be made throughout the groundwater basin in order to determine the groundwater velocity distribution. During site construction, measurements will be made to verify previous results and to determine any changes in effective porosity due to the site construction processes. By the site operation and closure phases, measurements intended solely to determine the effective porosity will have ceased.

3.3.4.5 Measurement Conditions and Potential Instrumentation Problems. Effective porosity is usually inferred from the results of chemical tracer tests. Due to the very slow groundwater velocities in low-permeability rocks, it is difficult to measure the effective porosity over statistically meaningful volumes. Interpretive techniques also need to be refined in order to remove the uncertainty resulting from the lack of a well defined flow path between the injection and sampling points (Apps et al, 1979). Refinement and/or development of borehole logging techniques for determining effective porosity of the near-bore rock is needed.

3.3.5 Fluid Velocity

The fluid velocity is defined as the true particle velocity in the fractures and the rock openings. Ultimately, it is the fluid and particle velocity that will govern the release of radionuclides to the accessible environment. The average interstitial velocity is calculated by dividing the fluid flux by the effective porosity. The distribution of the true velocities around the average velocities is reflected in the hydrodynamic dispersion coefficient. Historically, the field of hydrology was concerned with fluid fluxes rather than fluid velocities; therefore, effective porosities were only of concern in fluid reserve calculations, subsidence, and transient flow problems. Additional research is required to fully understand the chemical transport properties which are governed by the relationship between the fluid flux, fluid velocity, and effective porosity.

3.3.5.1 Normal Parameter Range. Fluid velocity is highly variable. Fluid velocities in basalt range from tens of meters per hour to a fraction of a meter per year (Horne, 1982; RHO, 1982, Vol. 2, Chap. 12). Predicted horizontal velocities at Hanford range from 0.3 to 19 m/yr in the flowtops and interbeds. Predicted vertical velocities in flow interiors range from 9.5×10^{-5} to 0.05 m/yr (RHO, 1982, Vol. 2, Chap. 12).

3.3.5.2 Parameter Variation During Normal Site Operation. Uncertain. Fluid velocities may be greatly increased in the near-repository region by

excavation, thermal loading, and induced fracturing. See discussions on Permeability, Hydraulic Head, Effective Porosity, and Fracture Properties and Induced Fractures (Sections 3.3.1, 3.3.3, 3.3.4, and 3.1.2, respectively).

3.3.5.3 Parameter Values That May Signify Trouble. Since the fluid particle will transverse numerous hydrostratigraphic units in traveling to the accessible environment, maximum velocities must be specified for each of the units. Detailed numerical simulation is required to determine maximum velocities.

3.3.5.4 Role During Each Repository Phase. During the site characterization, in situ measurements of the fluid velocity will be attempted. Effective porosities, permeability, and hydraulic head measurements will also be made; from which the fluid velocity can be estimated. Measurements will be made throughout the groundwater basin. During the site construction and site operation phases, measurements will continue in the near-repository region to verify previous data and to assess the impact of thermal loading and excavation. Measurements with the sole intention of defining fluid velocities will have ceased by the closure and decommissioning phase.

3.3.5.5 Measurement Conditions and Potential Instrumentation Problems. Direct measurement of the in situ fluid velocity is usually performed by observing the travel time of chemical tracers through the rock mass. Two techniques are commonly used: single borehole dilution methods and multiple borehole methods. Both methods have difficulties with choosing suitable chemical tracers (Apps et al., 1979). Multiple well tests are usually conducted with an artificially induced head; therefore, they do not measure the fluid velocity under the natural conditions of the system. In low-permeability formations, fluid velocities are very slow. Large-scale experiments that cover a statistically significant volume are impractical. Usually, fluid velocities are inferred from calculated fluid fluxes and effective porosities.

3.3.6 Water Influx Rate

The water influx rate is the rate at which water enters the excavated opening and boreholes. It is this parameter that governs when the prevailing hydraulic head gradient will change from being toward the repository to away from it. Water influx rate is directly proportional to the permeability of the fractures and the hydraulic gradient in the near-repository rock.

3.3.6.1 Normal Parameter Range. Water influx rate is highly site specific. A value for the expected range at Hanford is not available.

3.3.6.2 Parameter Variation During Normal Site Operation. Unknown.

3.3.6.3 Parameter Values That May Signify Trouble. Unknown. However, large increases in the water influx rate may signify development of new permeable pathways in the near-repository rock.

3.3.6.4 Role During Each Repository Phase. Water influx into the excavated openings will be monitored throughout the site characterization, site construction, and site operation phases primarily for environmental considerations (ventilation and mine safety). It is also measured in "bulk permeability experiments" in which the permeability of a large volume of rock is sampled (Wilson et al., 1981). Water influx rate will also be a useful indicator of changes in the hydraulic head and permeability resulting from thermal loading and excavation during the site operation and closure.

3.3.6.5 Measurement Conditions and Potential Instrumentation Problems. The technique used to measure the water influx is rate dependent. If the rate is large enough to require that water be pumped from the repository, conventional flow meters can be used. For low water influx rates the usual procedure is to collect the fluid in containers and/or measure the moisture content of the air leaving the ventilation system (Witherspoon et al., 1980). In general, low flow rates are difficult to measure accurately on a continuous basis with the instrumentation available today, especially in a repository setting. Water influx occurs over a large area, rendering both fluid collection and rate measurement difficult.

3.3.7 Hydrostratigraphic Unit

A hydrostratigraphic unit is defined as a rock unit or group of rock units which behave in a hydrologically uniform manner. Within a hydrostratigraphic unit, the directional permeability, porosity, and compressibility are the same. Depending on the scale appropriate to the problem, a hydrostratigraphic unit may encompass several basalt flows, a single flow, an entablature, an interbed, or a single fracture. Close to the underground repository, very detailed definition of the hydrostratigraphic units is required, perhaps on the scale of a single fracture. In the far field, definition of hydrostratigraphic units encompassing several flows may be sufficient. Accurate determination of the hydrostratigraphic units throughout the groundwater system is required to locate the permeable pathways along which radionuclides may travel to an accessible environment. Numerical modeling of the system also requires adequate definition of the hydrostratigraphic units.

Hydrostratigraphic units are determined by correlating lithologic, hydrologic, and perhaps geomechanical data between boreholes or excavations. Correlatable rock units with the same hydrologic properties can be defined as a hydrostratigraphic unit. Care must be taken to spatially define all the physical parameters in a given unit. For instance, inference of the permeability distribution, based on correlatable lithologic units, may result in gross errors because the permeability can vary by several orders of magnitude within the same rock unit. Conventional borehole logging, drill cutting inspection, petrologic analysis of cores and chips, geochemical analysis of pore fluids, and hydrologic tests are required to define the hydrostratigraphic units. (Section 3.2.4, Lithologic Parameters, also discusses these subjects.) Temporal changes in groundwater chemistry within a given hydrostratigraphic unit may indicate new hydrologic communication

between hydrostratigraphic units resulting from repository associated activities and operations.

3.3.8 Seal and Backfill Permeability

Permeability of backfill material immediately surrounding waste canisters will be one of the critical factors in controlling radionuclide containment if the canister is breached and waste form leached by groundwater. If not sufficiently impermeable, seals and backfill materials in shafts and boreholes may provide the shortest path to the accessible environment. In situ and laboratory tests will be conducted to determine the effect of heating and chemical interaction on the permeability of the materials. (Refer to Section 3.3.1 on Permeability for a discussion of measuring the in situ permeability of low permeability materials.) Laboratory tests will be conducted with the standard equipment used to measure permeability at high temperatures and pressures. If backfill and seal permeability is very low, both in situ and laboratory measurements will be difficult.

3.3.9 Rate and Location of Groundwater Recharge and Discharge

The total quantity of water which will come in contact with the repository is governed by the amount of fluid that is recharged to the system from local and distant sources. The rate and location of discharge govern the shortest path to the accessible environment, the potential concentration of contaminants, and rate at which they will be delivered to the accessible environment. Both the rate and location of discharge may be altered from their original state in response to thermal loading, excavation, and changes in climate and groundwater usage patterns. The rate of recharge (discharge) is specific to each of the hydrostratigraphic units and, in general, is greatest in the most permeable units. The rate and location of recharge (discharge) is inferred from the location of surface outcrops of the individual units, hydraulic heads, groundwater usage, permeabilities, and distribution of chemical species in the groundwater (see Section 3.4.1 for a detailed discussion of groundwater geochemistry). In general, recharge has both vertical and horizontal components. Accurate measurement of both the directional permeability and hydraulic head are required to determine rate and location of recharge. (Refer to Sections 3.3.1 and 3.3.3 for a detailed discussion of these parameters.)

3.4 GEOCHEMICAL PARAMETERS

There are several important chemical issues related to the isolation of high-level waste in basalt:

1. The rate at which rehydration of the backfill proceeds, and its effect on the pressure, temperature, and porosity of the backfill.
2. The rate at which the canister corrodes.
3. Once the canister has been breached by corrosion, the rate at which radionuclides are leached from the waste
4. The rate of radionuclide migration throu[illegible]e backfill.

5. Once past the backfill material, the extent to which radionuclide migration is retarded by chemical interaction with the rock.

In large measure, addressing these concerns requires fundamental scientific knowledge (e.g., the solubility of actinide oxides) or the results of applied research (e.g., the rate of corrosion under given conditions). These are scientific issues, and not directly issues of instrumentation. Such scientific issues will be discussed here only insofar as necessary to define critical parameters and the corresponding measurement and instrumentation needs. Solubility and corrosion rate are themselves functions of temperature, oxidation potential (Eh), pH, and groundwater composition. These are parameters which must be measured meaningfully to apply the results of basic and applied research to predicting repository performance, and this is where instrumentation comes in. Changes in groundwater chemistry due to radiolysis are considered under the topic of Canister Corrosion Rate (Section 3.4.5).

Some chemical parameters are determined by laboratory procedures that require routine instruments only, but the procedures are intricate, and require correct methods and proper execution to yield good results. We include discussion of some such techniques in this review.

It is certain that during the periods of site characterization, repository construction, and operation and retrievability, in situ studies of the repository environment, canister corrosion, etc., will be conducted. In preparing this review, we have attempted to anticipate what these studies might involve, and what the associated instrumentation needs might be.

Report NUREG/CR-3062, "Status of Geochemical Problems Relating to the Burial of High-Level Radioactive Waste, 1982" (Apps et. al., 1983) was used as a source of information about general geochemical issues related to nuclear waste isolation.

3.4.1 Groundwater Chemistry

The groundwater chemistry breaks down into a number of subparameters. Eh, or oxidation-reduction potential, and pH are primary in determining the solubility of many transition metal radionuclides. The higher oxidation states of metals are more soluble. The hydroxides of most metals are insoluble such that at lower pH (lower hydroxide ion concentration) the hydroxides will be more soluble.

Eh has the dimension of volts and can be either measured directly or calculated indirectly. Direct measurement is unreliable due to electrode overvoltages or nonequilibrium conditions in the system measured. This last is particularly important in a system as vast as a repository. Eh is usually calculated by putting concentration values of redox couples, usually ferrous-ferric or sulfur-sulfate, into the Nernst equation, e.g.,

$$E = \frac{RT}{F} \ln \frac{[Fe^{II}]}{[Fe^{III}]}$$

where: E is the potential in volts
R is the gas constant
T is the absolute temperature
F is the Faraday constant

However, because the voltage is dependent on the ratio of concentration, by itself Eh tells nothing about the quantity of radionuclides the rock formation can be expected to reduce. To do this, the rock must be analyzed for the concentration of each member of the redox couple of interest. There are several redox couples commonly used to determine Eh. These are Fe^{II}-Fe^{III}, S-$S^{\circ IV}$, S^{II}-S° and Mn^{II}-Mn^{IV}.

Although it might seem that exposure to atmospheric oxygen during sampling will perturb the ratios of redox couples in rocks, this can be avoided by making powdered samples from bulk ones in anoxic conditions. Based on crystal geometries of minerals in the repository formation, a calculation of the surface concentration of the reducing species can be made. This datum can then be used to estimate the reductive capacity of fracture surfaces in the far field where oxygen will not have penetrated.

Important secondary parameters are the concentrations of ions which complex with the transition metals among the waste radionuclides. Carbonate, sulfate, chloride, and fluoride ions complex with metal ions, increasing metal solubility. Certain organic compounds which may be introduced into a repository by human activity also complex with metal ions, with the same effect.

The effect of trace components of groundwater, those with concentrations on the order of less than one part per million, is not important. An exception is aluminum which, because it is a trivalent ion with high-charge density, is a powerful inducer of colloid flocculation. Mole for mole, it is expected to have a flocculating effect 100 times stronger than that of divalent ions such as calcium and 10,000 times stronger than monovalent ions such as sodium. One ppm of aluminum will have the same flocculating power as 852 ppm of sodium. The concentration of aluminum in groundwater can influence the migration of radiocolloids which may form.

In the future, it will be important to monitor radionuclides and their decay products which leak from the repository into groundwater. Since some of these elements are occasionally found in groundwater, analyses for background concentration must be made (see Section 3.2.2, Naturally Occurring Radionuclides). The important naturally occurring radionuclides are uranium, thorium, and radium. Some naturally stable elements with radioactive isotopes occurring in waste are cesium, iodine, lead, selenium, tin, and palladium.

Groundwater chemistry must be determined during the site characterization phase, and monitored during site construction and operations phases to determine if human activity has induced any changes. This includes the effects of radiolysis on groundwater chemistry.

3.4.1.1 Interaction with Other Parameters. The nongeochemical parameter that has the greatest effect on groundwater chemistry is temperature. The solubility of most solid materials increases with higher temperature. Over the post-closure history of a repository, changes in temperature will have significant effect on groundwater chemistry. Scenarios are conceivable in which these chemical changes would affect the hydrologic properties of the formation. Hot water flowing through rock pores or fractures may dissolve enough material to increase their dimensions and significantly increase water flow rate through the rock. As the water cools, material may be precipitated in pores or fractures in amounts sufficient to decrease flow rates. These two scenarios could occur sequentially in different sections of the rock formation. Dissolution of rock may also alter its mechanical properties.

Study of groundwater chemistry should be coordinated with hydrology studies. The chemical composition of groundwater often provides important clues to the history of this water, its flow path, and time of travel.

Calcium combines with fluoride, carbonate, or sulfate to form insoluble compounds. A high concentration of calcium necessarily means a low concentration of the others. In the case of calcium carbonate, magnesium and pH are also important factors.

A consideration to keep in mind is that groundwater chemistry will be altered as groundwater dissolves materials from the repository. Groundwater migrating back out of the repository will be different from when it entered. The major changes will come about due to ion exchange with backfill materials, which cannot be defined at this time. After the backfill material is completely loaded, leaking dissolved radionuclides will alter the chemistry. Some of the radionuclides will complex with groundwater anions.

3.4.1.2 Normal Parameter Range. The range of pH of groundwaters is from 3.0 to 9.5. The range of Eh is from -0.4 volts (reducing) to +0.7 volts (oxidizing) (Bass Becking et al., 1960). The range of concentration of chloride in groundwater is usually a few tens of parts per million but can be as high as a few tens of thousands of ppm in some brines. The range of sulfate or magnesium is usually up to several tens of ppm but can be a few hundred ppm in limestone areas. The concentration of calcium is usually several tens of ppm. The concentration of fluoride is usually less than one ppm but can be up to a few tens of ppm (White et al., 1963). The range of anthropogenic organic chemicals cannot be assessed a priori.

3.4.1.3 Is This Parameter Site Sensitive? The concentration of dissolved materials in groundwater is very much dependent on the composition of the rock through which it traveled. This parameter is site sensitive.

3.4.1.4 Expected Parameter Variations During Normal Site Operation. Except for Eh and anthropogenic organics, these subparameters should not vary during normal site operation. Eh will necessarily increase as the repository rock is exposed to oxygen from air in the tunnels. The concentration of anthropogenic

organics may vary depending on the nature and extent of spills of such materials and the thoroughness of cleanup operations. Variations due to increased temperatures have been discussed in Section 3.4.1.1, Interaction with Other Parameters.

3.4.1.5 Parameter Values That May Signal Trouble. The interaction of these subparameters is complex, but several computer codes exist which can predict the solubilities of various metals, given the groundwater composition.

3.4.1.6 What May Happen If This Parameter Is Not Measured? Without knowledge of the groundwater chemistry, the solubilities of radionuclides cannot be accurately predicted.

3.4.2 Age of Water

The age of water is an indicator of the travel time through rock upstream from the site. If the upstream and downstream formations are of similar permeability, a prediction of the release rate of radionuclides can be made. This is done by comparing the ratios of the radioisotopes tritium, ^{14}C, and ^{36}Cl, produced by cosmic ray interaction with atmosphere, to their decay products or stable counterparts. However, calibration is difficult due to various isotope fractionation processes, including differential evaporation, precipitation, ion exchange, and sorption. In practice, only upper limits of water age can be established.

Other age-dating techniques compare the ratio of ^{238}U to its daughter ^{234}U or measure the concentration of helium. In both techniques it is necessary to know the concentrations of the isotopes of interest in the rock formation through which the water travels and to have some idea of the rate at which they enter the water. These also require careful calibration (Andrews et al., 1982). The ^{32}Si method of dating waters requires samples with volumes of a cubic meter and should, therefore, be considered not practical (Fritz and Fontes, 1980, p. 127). Ages derived by different methods are often not in good agreement. Where there is such disagreement, prudence dictates that the younger age be accepted.

The age of water should be determined during the site characterization phase.

3.4.2.1 Interaction With Other Parameters. The age of water can serve as means of confirming groundwater discharge and recharge rates. It is influenced by such hydrologic parameters as water inflow rate, permeability, and hydraulic head.

Important questions to be answered in any isotope dating method are whether the rock or water containing the dating isotopes have been a closed system since the isotope ratio was originally established, or if the amount of either isotope which may have diffused into or out of the rock or water is known. As an example with the the ^{40}K isotope dating method ^{40}Ar is less reliable than ^{40}Ca because argon is more likely to diffuse out of the matrix

in which it is produced. ^{40}Ca is not useful if there is a high concentration of nonradiogenic calcium in the matrix. ^{40}K dating is used for the dating of alteration minerals and not water.

The diffusion problem also applies to attempts to date with He. Not only may helium in some cases diffuse out of a matrix, giving an age lower than actual, but it may also diffuse into a matrix and give an age greater than actual. Accumulation of radiogenic gases is useful as a dating method only if the rock has been a closed system, which for noble gases is often not the case. Work on age dating by isotopes cannot be done in isolation from studies of other critical parameters. Efforts to determine ages from isotope ratios must be integrated with other studies.

Determining the age of water flowing through a formation is not the same problem as determining the age of the formation. Rubidium and strontium isotope ratios are used to date rock, but to use them to date water assumes that they are equally soluble in water under all conditions which they travel. Even if this could be shown, the data indicated would be the age of the formation rather than the age of the water. Methods most applicable to the dating of water are based on the decay of a particular fixed quantity of an isotope which has entered the water at a distant point in space and time, as the start of percolation of meteoric waters containing either tritium, ^{14}C, or ^{36}Cl.

Isotopes can be used whose quantities are fixed by entry into the water system at a fixed point in space. In the case of uranium and thorium daughters used to date water, the water must have left the area in which these daughters diffused into the water, or newly produced daughters will confound the ratios. Again, it is important that isotope dating studies be correlated with structural studies. It is important to determine the degree to which the system being dated has remained closed. The validity of any method of isotope dating depends strongly on lithological and mineralogical parameters.

3.4.2.2 Normal Parameter Range. The age of groundwater can be measured up to 100 years with tritium dating and up to 25,000 years using ^{14}C dating techniques. The $^{238}U/^{234}U$ dating technique can measure the age of water up to 100,000 years. ^{36}Cl can be used to date waters to 1,000,000 years.

3.4.2.3 Is This Parameter Site Sensitive? Rock formations vary in permeability, hydraulic head, and extent. Thus, this parameter is site sensitive. Also, fractionation of isotopes due to various mechanisms in the hydrologic cycle requires calibration for waters of each hydrostratigraphic unit at a site. The $^{238}U/^{234}U$ technique is sensitive to uranium content of groundwater and the extent of rock-water interface. In all cases calibration must be done for each hydrostratigraphic unit of the site since water of different units and ages sometimes mix. The ^{14}C method is sensitive to the presence of carbonate minerals since ^{14}C may exchange with ^{12}C and produce spuriously greater age.

3.4.2.4 Expected Parameter Variations During Normal Site Operation. This is unknown, but the potential for variation in the direction of younger water is large in the near-repository region because of changes in permeability induced by human activities. Further, human activities may alter the flow patterns leading to mixing of waters from different hydrostratigraphic units and, thus, difficulty in accurately determining their ages.

3.4.2.5 Parameter Values That May Signal Trouble. While groundwater discharge rates upstream from the repository, as indicated by water age, may not have a direct effect on downstream flow, young age may indicate trouble when upstream and downstream rock formations are compared. One of the age-dating isotopes, tritium, has been introduced into the environment by atmospheric nuclear weapons tests at levels initially up to one hundred times greater than those produced by natural processes. This provides a clear signal of very young waters. In any case, the presence of tritium, with its eighteen year half-life, signifies very young water, between twenty and forty years since its precipitation and consequent rapid flow rates.

3.4.2.6 What May Happen If This Parameter Is Not Measured? If water age is not determined, other means of measuring groundwater flow rates exist, but age dating of the water will increase the degree of confidence that can be placed in them.

3.4.3 Sorptive Capacity of Fracture Lining Material

Different materials lining the fractures of rock around the repository site may sorb different radionuclides to varying degrees. The effect is to retard the release of radionuclides to the biosphere in varying degrees. Depending on values of sorptive capacity of fracture lining material and of backfill material, it is possible that the backfill will have the dominant effect on retardation of radionuclide leakage. Sorptive capacity of fracture lining materials should be measured during the site characterization phase.

3.4.3.1 Interaction With Other Parameters. These parameters will interact with groundwater chemistry. Temperature, complexing ions, pH, and Eh all affect the thermodynamics and kinetics of sorption.

3.4.3.2 Normal Parameter Range. A measure of sorptive capacities of minerals is the distribution coefficient, called K_d, R^d, or D in the literature. It is influenced by the particular combination of radionuclide sorbing mineral and type and concentration of groundwater solutes. Expressed as the ratio of material sorbed per gram of mineral to material remaining per milliliter of solution, K_ds range from 0 to 70,000. A K_d of 0 means that no material is sorbed while a K_d of 1000 means that over 99.9 percent has been sorbed. "The complexity of these interactions and sheer numbers of parameters and constituents which are important, necessitates the use of computers" (Serne and Relyea, 1982). Several computer codes have been developed which can be used or adapted to make predictions of sorption behavior. These include WATEQ, developed by the U.S. Geologic Survey (Ball et al., 1979) and EQ3/EQ6 developed at LLNL (Wolery, 1979).

3.4.3.3 Is This Parameter Site Sensitive? Since fracture lining material can be expected to vary with different rock formations and their histories, this parameter is site sensitive.

3.4.3.4 Expected Parameter Variations During Normal Site Operation. Until radionuclides migrate beyond the backfill, this parameter will not change so that, in a narrow sense, it will not vary during normal occupation of the site. As radionuclides are released from the site, they will be sorbed onto fracture lining materials, using up that capacity. Those radionuclides which are upstream will migrate further before they encounter unloaded material. Due to temperature increase after the emplacement of high level waste it is expected the sorptive capacity, per se, will not change but the kinetics of sorption reactions will, so that sorption occurs more slowly. Dissolved radionuclides will migrate further into cooler sections of the formation before being sorbed.

3.4.3.5 Parameter Values That May Signal Trouble. Again, the complexity of this question makes it impossible to give a quantitative answer at this time. Researchers are working on the problem. Sorptive capacity of fracture lining material is only one element in the calculation of the retarding effects of the rock formation. While high values of sorptive capacity are desirable, it is possible for greater fracture surface area or low rate of groundwater flow to compensate for low sorption values. A mineral with $K_d < 1$ will leave more radionuclide in solution than it absorbs.

3.4.3.6 What May Happen If This Parameter Is Not Measured? If this parameter is not measured, accurate prediction of the migration rate of radionuclides in the far field will not be possible.

3.4.4 Solubility of Radionuclides of Interest

Radionuclide solubilities have been studied in the laboratory and are well characterized. Baes and Mesmer, 1976, provides a discussion, element by element, of radionuclide solubilities. Solubilities vary depending on temperature, and the groundwater chemistry parameters: pH, Eh, and anion concentrations. There are three broad categories of radionuclides, based on their positions on the periodic table. The first category is iodine and cesium, which will be soluble under all natural conditions, but in the case of iodine may be precipitated by properly chosen additions to backfill material. The second category is the alkaline earth, in nuclear waste represented mainly by barium, strontium, and radium. These will all be precipitated by carbonates and sulfates present in groundwater or minerals; precipitation is influenced by pH. The third category is the transition metals, lanthanides, and actinides which have several oxidation states. Each state has a different solubility with the more oxidized states being more soluble. Although the near field may be expected to have a relatively high Eh due to exposure to air, far-field conditions are expected to be such as to precipitate these radionuclides. In the case of plutonium, the reduction reaction is expected to take place on mineral surfaces so that, even though

the solution Eh can be oxidizing, the mineral may nonetheless precipitate it. Radionuclide solubility can be determined by calculation rather than in situ measurement.*

Another means of transportation of some radionuclides is by colloidal suspension. Many actinides and a few transition metals form hydroxide colloids under the appropriate conditions. Colloidal particles must be smaller than the fractures in rocks to pass through them. Colloidal particles may be aggregated into larger ones by the process of flocculation. Here the critical variables are particle size and surface charge. Particle size is a function of pH and radionuclide concentration. Flocculation is dependent on pH, ion types, and their concentration in groundwater. Flocculation can be determined by consulting literature and calculation, rather than in situ measurement.

3.4.4.1 Interaction with Other Parameters. Solubility of radionuclides is so strongly affected by groundwater chemistry and its aforementioned subparameters, that it can be said to be determined by them. Groundwater anions can greatly increase the solubility of many radionuclides due to complexation. Each of the many complexes which can form from these radionuclides and even just one type of anion is considered a separate species for the purpose of determining equilibrium solubility. The interaction is complex. Solubility is also affected by temperature, most solubilities varying directly with this parameter.

3.4.4.2 Normal Parameter Range. This is an extremely intricate issue which must be answered for each radionuclide with reference to all groundwater constituents and in some cases (e.g., iodine) with other radionuclides. In principle, they can be predicted (given these data) using computer programs such as WATEQ (Ball et al., 1979) and EQ3/EQ6 (Wolery, 1979).

3.4.4.3 Is This Parameter Site Sensitive? Since radionuclide solubility is strongly affected by the groundwater chemistry, which is site sensitive, it is also site sensitive.

3.4.4.4 Expected Parameter Variations During Normal Site Operation. The most important influence on the solubility of certain radionuclides which can occur during normal site occupation is the spill of anthropogenic organics in the repository. The sources of such materials most likely in a repository are decontaminating agents, drilling muds, rust removers, and detergents. Since this depends on the nature and extent of such spills and thoroughness of cleanup, it presently is not possible to quantify this. Knowing the amount of such materials remaining in the repository after closure will be necessary to predict the effect on radionuclide solubility. Therefore, analyses of all such materials should be done and a record of their use, spills, and cleanup

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*Most solubility studies have been done at 25°C. It is important to confirm predictions of solubilities by laboratory studies at temperatures expected in a repository.

should be kept. After cleanup, and certainly before closure of the repository, accumulated water should be analyzed for these organics.

Radionuclide solubility will also vary, as previously discussed, due to temperature variations during the site operation and closure phases.

3.4.4.5 Parameter Values That May Signal Trouble. While the solubilities of most radionuclides are dependent on the chemistry of the groundwater, the solubilities of iodine, and particularly cesium, are less so. These radionuclides, especially the latter, will have high solubilities under any conditions. Therefore, a record of the cesium loading of the waste should be kept. Iodine forms insoluble or slightly soluble salts with some of the transition metals, which will be among the other radionuclides present in the waste, so that its concentration in the waste must be compared with the concentration of the other radionuclides.

3.4.4.6 What May Happen If This Parameter Is Not Measured? Without the capability of measuring this parameter the transport of radionuclides cannot be predicted. The solubilities of radionuclides, with respect to each other and common groundwater constituents, are presently being investigated for the temperature and pressure ranges expected in repository environments. A number of computer codes are being tested and databases are being established that will lead to calculations of the expected concentrations of radionuclides if the concentrations of groundwater constituents and supply of radionuclides are known.

3.4.5 Canister Corrosion Rate

The rate of canister corrosion is a critical parameter and should be measured in situ using test canisters during the periods of site characterization and repository operation, and, after closure, in a simulated environment. Moisture and temperature at the canister surface are the major determinants of corrosion rate, and themselves are critical parameters because of this. The groundwater components cloride and magnesium have been shown to enhance the corrosion of steel, so that their concentrations are also critical parameters.

Canister integrity for 300 to 1,000 years has been considered. Maintaining canister integrity for this long or longer will ensure that only a relatively small quantity of long-lived radionuclides will remain when the canister finally is breached.

The length of time that canister integrity is maintained is important even above and beyond this. The rate of waste form devitrification (if it is a glass) and leaching depend strongly on temperature. Devitrification can begin as soon as the waste form has solidified and sufficiently heated, and the processes of leaching will begin when the canister is breached and water reaches the waste. The leaching rate will vary directly with temperature. Repository temperature itself is a function of time since the emplacement of waste. With canisters intended to last through the period of maximum

temperature, when they breach temperature will be declining monotonically. All other things being equal, the rate of leaching will decline slowly with time. Since exposed surface area of the waste form may increase with time, leaching rate as a function of time is a complex problem.

During the period of repository construction and operation, the repository will be filled with atmospheric air, and all materials in it will be exposed to abundant free oxygen. The pores in the backfill will be filled with air when it is emplaced, and some atmospheric oxygen probably will penetrate into the rock surrounding the repository. In all cases, the presence of oxygen will effectively increase Eh (oxidation potential), and oxygen in the backfill will accelerate canister corrosion.

Due to the intense gamma radiation of high-level wastes, several significant radiolytic reactions may occur. Where air and water are available, the radiolytic synthesis of nitric acid from nitrogen and oxygen is expected. Where water is present, the formation of hydrogen gas is expected. Nitric acid will corrode the steel canister and hydrogen may cause hydrogen embrittlement of the steel. The rates of formation of nitric acid or hydrogen, and the total amounts formed, depend on the level of radiation and the fugacities of oxygen or water in irradiated spaces.

The fugacity* of oxygen in the backfill is a critical subparameter. It is presumed that the oxygen in the repository will rapidly be removed by reaction with the crushed basalt in the backfill after the repository is sealed. This needs to be confirmed by measuring the oxygen fugacity near test canisters, employing suitable in situ instrumentation.

Hydrogen fugacity is a critical, dependent subparameter. Hydrogen embrittlement of some candidate canister materials is possible. Hydrogen in the repository atmosphere will make it a reducing environment and tend to retard corrosion of the canister. Which of these two effects is dominant depends on engineering decisions about waste loading and backfill moisture (Stahl and Miller, 1983).

The initial water fugacity of the repository may depend on engineering decisions regarding backfill material and its water content. Water fugacity also influences backfill behavior. Some of the candidate backfill materials swell as they absorb water. It is conceivable that, in a confined space, the swelling could lead to pressure which causes the collapse of canisters or the rupture of seals. Relatively simple design features can eliminate this problem. The behavior of backfill material with respect to water fugacity should be the subject of pilot studies.

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*Fugacity is measure of the chemical potential of a substance, expressed in units of pressure. In an ideal gas mixture, the fugacity of a gas is equal to its partial pressure. Fugacity is well defined, even if a vapor phase is not present.

When moisture penetrates the backfill and contacts the canister, corrosion will begin. After the canister has been breached, the water in the backfill will contact the waste form and leach radionuclides from it. Thus, rehydration of the backfill will strongly influence the processes of canister corrosion and waste form leaching. The fugacity of water or moisture profile in the backfill around at least some canisters must be monitored. Presumably, this will be done with some test canisters emplaced early during the periods of repository operation.

3.4.5.1 Interaction With Other Parameters. Canister corrosion is a variable dependent on five other variables: temperature, the fugacities of oxygen and water, groundwater flow rate, and groundwater chemistry. Corrosion of steel is essentially the oxidation of iron, so that the activity of oxygen has a strong influence. This reaction is mediated and catalyzed by liquid water. In addition, chloride ions attack many stainless steels and the oxidation product by complexing with iron ions. Oxygen is used up by the corrosion reaction so that the rate at which oxygen is supplied to the canister surface is also important in determining the rate of corrosion. The oxygen supply rate is a function of oxygen fugacity and groundwater flow rate. Interaction of canister corrosion with temperature and groundwater chemistry are discussed in Sections 3.1.6 and 3.4.1, respectively.

3.4.5.2 Normal Parameter Range. The current "design canister" assumed by DOE for planning purposes would be made of carbon steel and have walls about 6 cm thick (RHO, 1982, Vol. 2, Chap. 11). The average rate of corrosion under repository conditions would probably only be about 1 cm/1,000 years = 10 micrometers/year. Therefore, canister corrosion must be measured, in situ, in the range 2 to 60 micrometers/year. The upper value of oxygen fugacity to be measured will be 0.21 bar (atmospheric). The lower value should be the lowest that can be attained, and certainly lower than 0.01 bar.

There are two aspects to measuring water fugacity. It is necessary to detect the presence of liquid water. The presence of liquid water defines the maximum fugacity of water that can exist at the given temperature and pressure. Lower values of water fugacity also must be monitored within the backfill. The minimum value of water fugacity at any given temperature will be that of the nominally dry backfill material. This may be one- or two-tenths the fugacity of liquid water. Values of water fugacity between these values must be measured in situ. These values will vary with temperature and pressure.

Saturation ratio is equivalent to water fugacity. This is fugacity divided by that of pure liquid water at the given temperature and pressure. The range of saturation ratio that needs to be determined will be about 0.1 to 1.0 at any temperature and pressure.

3.4.5.3 Is This Parameter Site Sensitive? Canister corrosion will be dependent on the amount of groundwater infiltration and the groundwater composition. Thus, it is site sensitive.

3.4.5.4 Expected Parameter Variations During Normal Site Operation. The determining subparameter, water fugacity, may be affected by changes in rock permeability due to repository development. Some areas may experience a decline as water is channeled to other areas which experience an increase. Oxygen fugacity will be 0.21 bar as long as the workings are open to the atmosphere, but will be reduced in areas where backfill has been emplaced or purging with an inert atmosphere has occurred. With respect to factors affecting corrosion rate, groundwater chemistry is not expected to vary greatly.

3.4.5.5 Parameter Values That May Signal Trouble. Rate of corrosion is dependent on, among other factors, the metal used for the canister. This issue is best resolved by lab studies with candidate alloys under conditions expected at candidate sites.

3.4.5.6 What May Happen If This Parameter Is Not Measured? If rate of corrosion is not measured, nor attempts made to calculate it, it will be impossible to predict when radionuclides begin leaching from the waste form. This is a step in the process of leakage from waste form to biosphere, which is important for shorter-lived radionuclides.

3.4.6 Radionuclide Leakage Rate

The rate of radionuclide leakage from the canister is the second step in the release process. The value of this parameter can be calculated when the value of other parameters becomes available.

Radionuclide leakage through the repository formation, or rather its delay, is the rationale for the effort of nuclear waste storage. Monitoring leakage will provide the proof for all previous measurements, designs, and calculations. It can be done directly during site operations and after closure by taking water samples from monitoring wells bored at significant locations in the repository formation and analyzing the samples for radionuclides. This data combined with that from hydrologic studies will allow future generations to calculate the direction and velocity of the plume of radionuclides leaking from the repository and estimate when radionuclides will reach the biosphere.

This parameter is a function of many others. Calculable influences include the exposed surface area of the waste form, radionuclide inventory, radionuclide solubility, temperature, water fugacity, and groundwater flow rates, all at the time of canister breaching and afterwards. Incalculable influences are the geometry of corrosion of the canister, its variation among canisters, and its variation over time.

The rate of radionuclide leaching from the canister affects the rate of loading of the backfill.

There are two issues to be considered here. The first is the rate of travel of the front of the plume of leaking radionuclides. Determining this

will give the time scale necessary for decision and action. The second is the steady state concentration of radionuclides in the plume. This gives a measure of the potential hazard when the plume reaches the biosphere.

3.4.6.1 Interaction With Other Parameters. Radionuclide leakage rate from the canister will be a function of groundwater flow rate and groundwater chemistry. It is the input term for backfill and seal leakage rates.

Radionuclide leakage through the formation takes as input the seal leakage output term. It is influenced by groundwater flow rates, backfill and seal leakage rates, groundwater chemistry, radionuclide solubility, sorptivity of fracture lining material, and fracture permeability.

3.4.6.2 Normal Parameter Range. An important parameter which influences leaching rate is the exposed surface area of the waste form, which depends on engineering decisions not yet made, namely the waste form itself. Laboratory simulation is the best means of studying leach rate.

The normal range of radionuclide leakage rate from the formation is influenced by many other parameters, some of which are based on engineering decisions not yet made. It is not possible to give a range at this time.

3.4.6.3 Is This Parameter Site Sensitive? The site-dependent variables affecting leach rates from the canister are groundwater chemistry and flow rate, which are site sensitive.

Site dependent variables affecting radionuclide leakage through the repository formation include groundwater flow rate, groundwater chemistry, fracture permeability and fracture lining material sorptive capacity. Radionuclide leakage through the formation is thus site sensitive.

3.4.6.4 Expected Parameter Variations During Normal Site Operation. Although the intent of repository design is to prevent leakage before closure, it is possible that corrosion of early placed canisters will be severe enough that leakage begins during normal operations. This problem can be obviated by laboratory and pilot studies of canister corrosion.

Radionuclide leakage through the repository formation will be influenced by the heating of the formation as thermal energy from the waste diffuses into it. At higher temperature the radionuclides will be more soluble and the kinetics of sorption will be less favorable. Thus, radionuclides can be expected to travel farther in the formation before they are sorbed. Any computer model of radionuclide migration through the formation must take into account the rise in temperature.

3.4.6.5 Parameter Values That May Signal Trouble. The value of leakage rate from the canister is the supply term for backfill leakage calculations. Leakage rates should be determined by computer modeling and physical simulation. Simulations using exposed waste in pilot facilities can be used to determine modeling parameters.

Radionuclides leaking through a rock formation must travel distances on the order of 10 kilometers and should take at least 10,000 years to do so. This comes to a rate of 1.0 meters per year as a rough estimate of the maximum tolerable rate for the front of any plume of radionuclides migrating through the formation. Maximum permissible concentrations of radionuclides in water in the biosphere are established by government regulation and may change in the future.

3.4.6.6 What May Happen If This Parameter Is Not Measured? If radionuclide leakage from the canister cannot be determined, a critical source term is unavailable for calculation of radionuclide supply to mechanisms further along the escape path. It is important to any modeling study.

If the rate of radionuclide leakage through the repository formation is not measured, then prediction of the date at which radionuclides reach the biosphere will be dependent on computer modeling. A thorough understanding of potential radionuclide leakage rates must include computer models using worst-case parameter values measured during testing. While computer modeling can, in principle, produce accurate results, it is susceptible to systematic errors due to human oversight. Monitoring of radionuclide migration can serve to confirm such predictions and provide warning if they are incorrect.

3.4.7 Seal and Backfill Leakage

There are many configurations of seals and backfills which may be considered. Models of various combinations of physical layout can be used to determine overall leakage. Data on leakage through seal and backfill can be obtained from laboratory and pilot studies during the site characterization phase. Actually, measurements of leakage out of the repository may be done with monitoring wells drilled at selected points in the far field during the operations and closure phases. Water samples taken from these wells would be analyzed for the various expected radionuclides. Since the site is expected to be operated for fifty years, leakage from sections filled earlier in the operation is an important consideration, not only as a pilot model for overall leakage, but from consideration for the health and safety of repository personnel. Before emplacement of seals and closure, backfill leakage can be monitored by taking samples and by using remote radiation detectors.

Although leakage through the backfill can be modeled with a pilot study, in situ measurements are also possible. Placement of tracers and detectors in the backfill will make it possible to monitor groundwater flow even before release of radionuclides from breached canisters.

3.4.7.1 Interaction with Other Parameters. Backfill leakage rate is a function of groundwater flow rate, radionuclide leakage rate from the canister, and groundwater chemistry, backfill chemistry, backfill mechanical properties, and temperature. Seal leakage rate is a function of groundwater flow rate, properties of seal material, and backfill leakage rate.

3.4.7.2 Normal Parameter Range. Backfill and seal leakage are the functions of other parameters which will be fixed by engineering decisions and should be determined by modeling.

3.4.7.3 Is This Parameter Site Sensitive? Backfill and seal leakage rates are a function of groundwater flow rate and groundwater chemistry which are site dependent.

3.4.7.4 Expected Parameter Variations During Normal Site Operation. Leakage rates are not determinable at this time. This parameter is critical after site closure. Seal and backfill materials should be tested in laboratory and *in situ* situations for a variety of thermal conditions, groundwater chemistries, and flow rates.

3.4.7.5 Parameter Values That May Signal Trouble. Values for backfill and seal leakage rates will be fixed by engineering decisions not yet made and are necessary inputs for rock formation leakage calculations. Therefore, they should be determined by computer modeling and physical simulation during the design process.

3.4.7.6 What May Happen If This Parameter Is Not Measured? If this parameter cannot be determined, a critical rate in the overall repository flow pattern is unavailable for calculation of radionuclide supply to mechanisms further along the flow path. It is, therefore, important to any modeling study.

4.0 CONCLUSION

Identification of critical parameters and assignment of priorities to them show that certain parameters are prominent in specific phases of a repository's evolution. During the site characterization phase, a definition of the geologic setting, groundwater flow paths, hydrologic characteristics for the site and rock, water composition and age, and sorptive capacity of fracture-lining material are of high priority, as are characterization of fractures and mechanical and thermal properties of the rock mass. Measurement of geomechanical properties and the effect of underground openings on the hydrologic regime are of prime importance during the site construction phase, while high-priority parameters during site operations are those concerned with the response of the rock mass and hydrologic system to the thermal effects from the introduction of the radioactive waste. Parameters associated with radionuclide leakage and the effectiveness of backfill and sealing systems require measurement and long-term monitoring systems installed during operations and extending into, and in some cases beyond, the closure phase of the repository.

In several cases, parameters will initially be measured and systems to measure them will be tested and refined in test facilities which are installed during the site characterization phase. These measurements will subsequently be extended to the actual repository locations as canisters are emplaced and as the full-scale sealing systems are established.

Geomechanical parameters discussed in the report include those critical parameters that directly interrelate stresses, physical responses, thermal characteristics, and thermomechanical properties within the repository system. All the critical parameters in this particular category require instrumentation for measurement and monitoring. Moreover, many of these instruments must be capable of reliable operation over long periods under harsh conditions including a corrosive, high-temperature, high-pressure environment.

Geological parameters fall into two categories: those that can be measured directly and those that have no instrumentation for their direct measurement but require application of one or more geophysical techniques for their characterization and continued monitoring. The former category includes direct, or nearly direct, measurement of crustal deformation, naturally occurring radionuclides, and seismicity. The latter category includes lithology, faulting, folding, erosion rate, igneous activity, the presence of existing underground workings, water, mineral, and petroleum resources. With the exception of the resources, these parameters are indirectly measurable by a combination of geophysical techniques, employing surface, borehole, and airborne surveys.

The hydrologic parameters that are critical to the successful isolation of HLW in a basalt repository are probably the same ones that would be chosen for most igneous rock types, although the rank ordering may be different. In that sense, the anticipated measurement difficulties are not unique to basalt. However, there are several hydrologic considerations that are unique to evaluation of basalt. These result from the fact that the rock permeability and porosity result largely from fractures and interflow zones. Evaluation of the hydrologic and transport properties of fractured rock has only recently received a great deal of attention. As such, test methodology and interpretive techniques are still in an experimental stage. Therefore, site assessment and development of techniques to evaluate the critical parameters will proceed hand-in-hand. A second aspect of characterizing the hydrologic properties of fractured rock results from the intrinsic nature of the permeability and porosity of basalt. Unlike many rock properties such as thermal conductivity and heat capacity, the permeability can vary by many orders of magnitude. For instance, some of the most permeable groundwater aquifers are known to occur in fractured basalts. Therefore, the potential variation in the permeability is extremely large and must be evaluated throughout the entire groundwater system of importance to the isolation of the HLW. It is not sufficient to infer the rock permeability by assuming that it is a homogeneous property of a given lithologic unit (or flow). This also has implications on the measurement techniques that are applicable to evaluating the permeability and porosity of basalt. First, only in situ measurement of permeability can give reliable estimates of these parameters and second, the measurement apparatus and techniques depend on the absolute value of these parameters. All of the above must be taken into consideration to properly evaluate the permeability and porosity of basalt. Because these parameters are so critical to the ability of the medium to isolate the HLW, it is a formidable task to evaluate them. Consideration must also be given to the

fact that the permeability, porosity, and hydraulic head of the system will change in response to excavation and thermal loading. The magnitude of the changes is uncertain and, therefore, values of these parameters must be monitored throughout critical periods. In situ test facilities will greatly increase the ability to foresee such problems and allow remedial action to be taken immediately.

Critical geochemical parameters may be divided into those which are direct indicators of radionuclide containment and those which can be used to predict containment where direct observation is not feasible. In the first category are the concentrations of radionuclides in water samples obtained from monitoring wells. The second category is further divided into measurements of conditions which influence containment and computer modeling or pilot studies. Influential conditions to be measured include groundwater constituents and pH, and mineral redox and sorptive capacities. Parameters to be studied by computer modeling or pilot operations, using the influential parameters as input or experimental conditions, include canister corrosion, radionuclide leakage, and performance of backfill and seals. The solubility of radionuclides with respect to each other and common groundwater constituents are presently being investigated for the temperature and pressure ranges expected in repository environments. Age of water serves to confirm hydrologic parameters which may be determined by other means. Since they are the input to predicted parameters, the influential parameters must be measured first. Background levels of radionuclides must be measured before any waste is emplaced.

The critical parameters and their priorities for basalt that have been established in this report are similar, in several cases, to those for tuffaceous and crystalline rock. Variations from the findings for basalt will become clear as the other rock types are addressed in detail.

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This report addresses critical parameters specific to a repository in basalt, using the Columbia River Basalt Group as the principal example. For the purposes of this report, a parameter is considered to be a physical property whose value helps determine the characteristics or behavior of a repository system. Parameters which are defined as critical are those essential to evaluate and/or monitor leakage of radionuclides from the repository and to evaluate the need for retrieval. The parameters are considered with respect to the disciplines of geomechanics, geology, hydrology, and geochemistry and are rank ordered in terms of importance. The specific role of each parameter, specific factors affecting the measurement of each parameter, and the interrelationships between the parameters are considered in detail.

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