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YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT
STUDY PLAN APPROVAL FORM

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LABORATORY THERMAL EXPANSION TESTING

Site Characterization Plan
Study 8.3.1.15.1.2

Performance Assessment Applications Department
Sandia National Laboratories

ABSTRACT

Licensing of a nuclear-waste repository by the Nuclear Regulatory Commission requires, among other things, demonstration of the long-term usability of the underground portion of the repository. Such a demonstration involves analysis of the thermomechanical response of the rock to the presence of heat-producing waste. An important parameter in the determination of the thermomechanical response is the coefficient of thermal expansion. This document describes (1) the rationale for obtaining thermal-expansion data; (2) the determination of specific requirements for the data (e.g., number of samples, experiment conditions); and (3) specific plans for experiments to obtain data on the coefficient of linear thermal expansion.

This Study Plan was prepared under WBS 1.2.3.2.7.1.2.

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1.0 INTRODUCTION

This Study Plan describes the experiments planned to obtain the data on thermal expansion required by repository design and performance assessment in support of the license-application process. The data base will contribute to estimation of the thermal expansion of the rock mass, which in turn will be used in analyses of thermal stress and strain in and around a repository. The estimated thermal expansion of the rock mass will be compared and, if appropriate, combined with information on thermal expansion obtained directly from in situ measurements. The in situ experiments for which in situ thermal expansion, thermal stresses, or both will be measured are summarized in Table 1.0–1.

Table 1.0–1
Summary of In Situ Experiments Obtaining Information Related to Data for the Thermal Expansion and Associated Thermal Stresses in the Rock Mass.

Study Plan	Experiment
8.3.1.15.1.6	Heater Experiment in Unit TSw1 Canister-Scale Heater Experiment Yucca Mountain Heated Block Thermal-Stress Measurements Heated-Room Experiments
8.3.4.2.4.4	Engineered-Barrier-System Field Tests

1.1 Objectives of Laboratory Thermal-Expansion Study

The experiments discussed in the Laboratory Thermal-Expansion Study are intended to provide all of the data on thermal expansion required by repository design and performance assessment that can be obtained in a laboratory setting (specific data requirements are discussed in Section 2.2). Included in the Study Plan are experiments designed to obtain laboratory data for the coefficient of thermal expansion as a function of temperature. The primary emphasis is to examine the variability of thermal-expansion behavior as a function of rock type and spatial location. Other factors that will be examined are the possible effects of fractures or lithophysal cavities on thermal expansion and the presence or absence of thermal-expansion anisotropy in the welded, devitrified portion of the Topopah Spring Member of the Paintbrush Tuff. Estimates of rock-mass thermal expansion will be made based on the data obtained in the laboratory and information on fracture abundance, orientation, and aperture, lithophysal-cavity abundance, and mineralogy of the rock mass.

1.1.1 Use of Results of Laboratory Thermal-Expansion Study

The principal information requirements for resolving preclosure issues related to repository design (addressing nonradiological health and safety as well as the feasibility of waste retrieval) center on the question of adequate support for the underground openings. The design of these openings and the supports to keep them open must take into consideration the rock-mass characteristics, the pre-existing in situ stress state, the redistribution of stresses due to the excavation of the opening, the changing temperature field, and the geometry of the openings and their spatial relationship with each other. Experiments to be conducted for the Laboratory Thermal-Expansion Study will contribute primarily to calculation of stresses and strains that are attributable to changes in temperature around a repository. Additional discussion of this topic is provided in Section 8.3.2.4 of the Site Characterization Plan (SCP) (DOE, 1988).

For performance assessment, data on the thermal-expansion behavior may contribute indirectly to resolution of post-closure issues by allowing calculation of thermally induced stresses and strains and the resulting changes in fracture apertures, fracture density, or both. These changes could affect ground-water travel time as well as assessment of the post-closure disturbed zone.

Experiments for the Laboratory Thermal-Expansion Study will be conducted on samples taken from thermal/mechanical units (a brief discussion of these units is provided in Section 2.2) that are expected to be within the zone of material in which elevated temperatures will occur as a result of the presence of a repository in the lower portion of the Topopah Spring Member of the Paintbrush Tuff. At present, the units of interest include all material from the ground surface (except for recent unconsolidated sediments) down to the vicinity of the static water level. For units that occur at deeper levels, coefficients of thermal expansion for tuffs of similar lithology will be assumed when these deeper units are included in an analysis.

1.2 Rationale and Justification for Information to be Obtained

1.2.1 Resolution of Performance and Design Issues

Performance allocation was used by the Yucca Mountain Site Characterization Project (YMP) to establish appropriate issue-resolution strategies (the issues to be resolved are presented in Section 8.2.1 of the SCP). A general discussion of the performance-allocation approach is provided in Section 8.1 of the SCP. Issue-resolution strategies for each Site Program are provided in Section 8.3.1 of the SCP.

Section 6.4 and 8.3 of the SCP provide detailed discussions of the approach that will be used in the design of the underground openings. This approach emphasizes the need to ensure that openings associated with the underground facility will remain usable throughout the retrieval period (Section 6.4.8 of the SCP).

The ability to predict the magnitudes of stress and displacement is fundamental to the ability to ensure the retrievability of waste for up to 50 years after emplacement begins and to demonstrate that an underground facility can be constructed in welded tuff using reasonably available technology.

The design, construction, and operation of the underground facility must comply with applicable health and safety standards (e.g., 30 CFR 57) and the underground openings must remain usable for the operational period of the facility. The initial design of the facility will be based on empirical design guidelines as well as the result of mechanical, thermal, and thermomechanical analyses. These analyses will be refined as the input data base, the design, or both evolve, and will not only allow estimation of the rock-mass response to repository-induced loads but also will allow assessment of the performance of the repository relative to the standards mentioned above. The ground-control-strategy concept (Hoek and Brown, 1980) initially establishes limiting values on the amounts of displacement and induced stress that cannot be exceeded during construction and operation for the proposed design of the underground openings. This design approach then uses Tunnel Index methods (Barton et al., 1974; Bieniawski, 1976) to establish the initial requirements for the ground-support system. These methods then are supplemented with an in situ monitoring system to assess the performance of the support system selected.

The preceding paragraphs outline the approach to be used in repository design. The site parameters that must be obtained to design the repository and to develop the repository operating procedures to assure the nonradiological safety of the worker are summarized in Information Need 4.4.1, "Site and Performance Assessment Information Needed for Design," (Section 8.3.2.5.1 of the SCP), which includes the data needs of Issues 2.4 (Waste Retrievability), 4.2 (Nonradiological Health and Safety), and 4.4 (Preclosure Design and Technical Feasibility). A similar set of parameters is identified in Information Need 1.11.1, "Site Characterization Information Needed for Design," (Section 8.3.2.2.1 of the SCP) as necessary for analysis of the thermal and thermomechanical response of the tuffs after closure of the repository. Data for the coefficient of thermal expansion are required by both of these Information Needs.

Issue 1.6 (Ground-Water Travel Time, Section 8.3.5.12 of the SCP) addresses ground-water travel time. In order to perform the necessary calculations, the boundary of the disturbed zone must be estimated [see Langkopf (1988) for definition and discussion of the disturbed zone]. This estimation requires an estimate of the location of selected isotherms surrounding a repository, and of the effect of temperature changes on the properties of the rock mass. One of the properties of interest is the coefficient of thermal expansion.

Issue 1.10 (Waste Package Characteristics, Post-closure), Section 8.3.4.2 of the SCP) addresses, among other topics, the stability of waste-emplacement boreholes. As described for the stability of underground openings in general, predictions of borehole stability also require calculation of thermally induced stresses, which in turn requires data on thermal-expansion behavior.

Issue 1.12 (Seal Characteristics, Section 8.3.3.2 of the SCP) addresses the sealing of underground openings to enhance the isolation of radionuclides from the accessible environment. The process of designing seals for the openings requires an estimation of the stress state to which the seals will be subjected during the period of required integrity.

As is evident from the preceding paragraphs, estimation of the stresses to be expected in the vicinity of the repository is necessary in order to resolve some performance and design issues. Part of the stresses will be thermally induced; in a fully constrained, isotropic, linearly elastic medium, these stresses (σ) are calculated using the following equations:

one-dimensional: $$\sigma = E\alpha\Delta T \quad (1.1\text{–}1)$$

two-dimensional: $$\sigma = \frac{E\alpha\Delta T}{1-\upsilon} \quad (1.1\text{–}2)$$

or

three-dimensional: $$\sigma = \frac{E\alpha\Delta T}{1-2\upsilon} \quad (1.1\text{–}3)$$

where E is Young's modulus, α is the coefficient of linear thermal expansion, ΔT is the temperature difference, and ν is Poisson's ratio (Timoshenko and Goodier, 1970). Data for E and ν will be obtained for Study 8.3.1.15.1.3, "Laboratory Determination of the Mechanical Properties of Intact Rock," and as a result of several in situ tests. Figure 1.2–1 shows the relationships between studies that will obtain information related to thermal stress. Although some of the material in the vicinity of a repository will not be fully constrained, the rock mass is expected to be sufficiently constrained that significant thermally induced stresses may occur. Clearly, determination of the thermal-expansion behavior is essential to an assessment of the contribution of thermally induced stresses to the overall stress state in the vicinity of a repository.

1.2.2 Regulatory Requirements

This study will provide some of the information required to assess compliance with several key regulations outlined in 10 CFR Part 60 (NRC, 1986) ("Disposal of High-Level Radioactive Wastes in Geologic Repositories; Licensing Procedures"). These regulations form the basis for the requirements outlined in

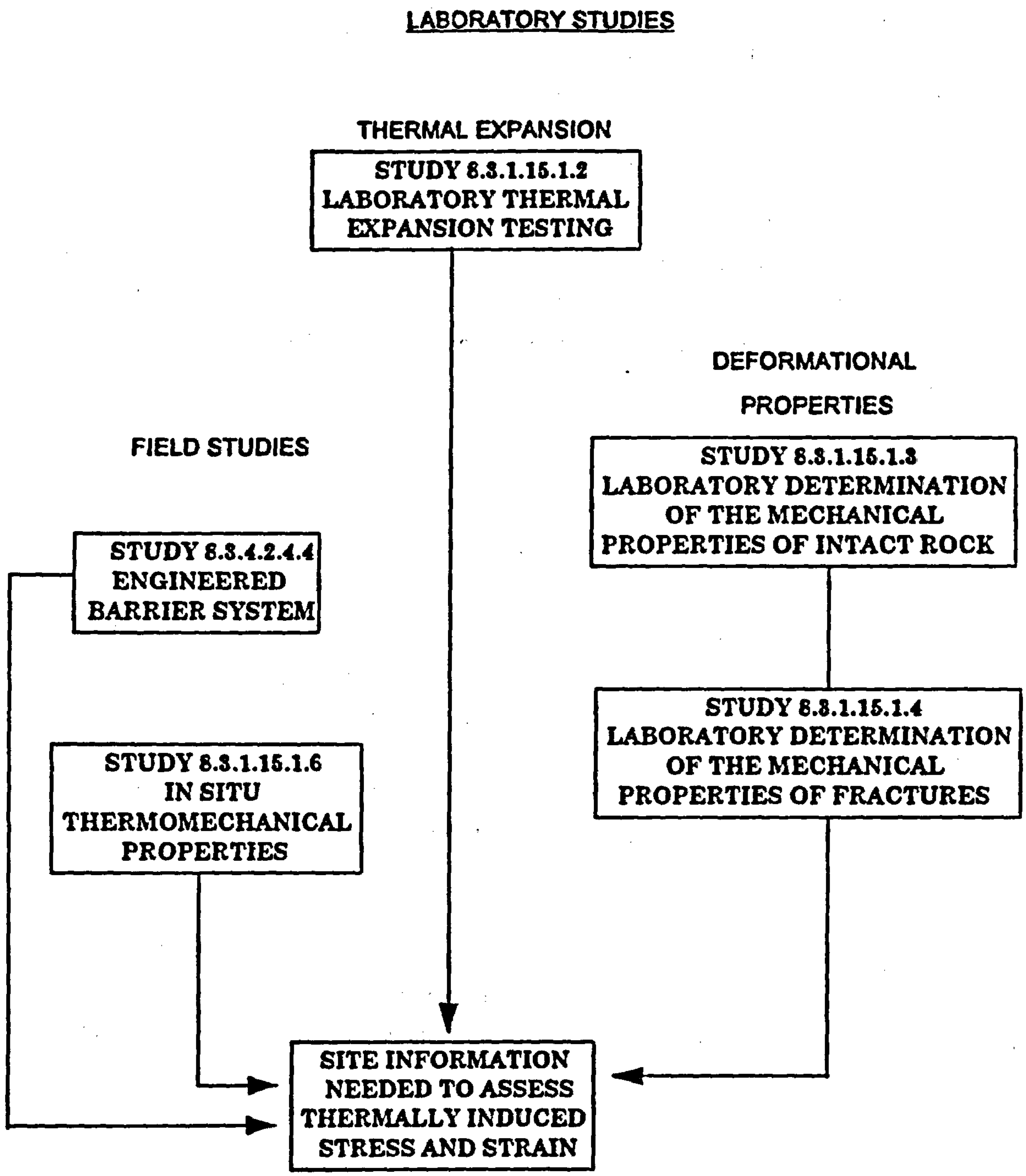


Figure 1.2-1. Relationships Between Studies Providing Information on Thermal Stress.

10 CFR Part 960 (DOE, 1984). Performance objectives as stated in 10 CFR Part 60 require demonstration that: (1) waste retrieval shall be feasible starting at any time up to 50 years after waste emplacement begins [60.111(b)]; and (2) the overall system performance of the geologic repository shall be such as to ensure that releases of radioactive material to the accessible environment conform to applicable Environmental Protection Agency requirements (60.112).

Experiments conducted for the Laboratory Thermal-Expansion Study will provide data that will be used to calculate stresses and displacements caused by changes in temperature induced by the presence of heat-producing waste. The estimated values of these stresses and displacements will be used in the evaluation of retrievability by affecting the design of the ventilation and ground-support systems that will ensure that most openings remain usable.

The Nuclear Regulatory Commission (NRC) describes as one potentially adverse condition the presence of geomechanical properties that do not permit the design of underground openings that will remain stable through permanent closure [10 CFR 60.122(c)(21)]. 10 CFR 60.133(e)(1) and 60.133(e)(2) specify that openings in the underground facility shall be designed for safe operations, to maintain the option of retrievability of the waste, and to reduce the amount of deleterious rock movement or fracturing of overlying or surrounding rock. Potentially adverse conditions outlined in 10 CFR Part 960.5-2-9 (rock characteristics) include in situ characteristics that could necessitate extensive maintenance during repository operation and closure and in situ conditions that require engineering measures beyond reasonably available technology during the construction of the underground facility. Thermally induced stresses and displacements must be estimated in order to ascertain the expected need for maintenance of openings or the viability of reasonably available technology.

A Safety Analysis Report (SAR), which must be prepared for submittal with the License Application, will contain a description and assessment of the proposed geologic repository operations area that might influence design and performance. This report will document the geoengineering properties and conditions, including thermally induced stresses and displacements.

2.0 RATIONALE FOR LABORATORY THERMAL-EXPANSION STUDY

Experiments are planned to determine the coefficient of thermal expansion in the laboratory and to use the resulting data to estimate the thermal-expansion behavior of the rock mass for the relevant thermal/mechanical units within the boundary of the underground facilities. These rock-mass properties then will serve as primary input to thermomechanical calculations performed in support of repository-design and performance-assessment activities.

2.1 Rationale and Justification for Laboratory Thermal-Expansion Experiments

Analytical models and numerical methods that will be used to determine thermally induced stresses and displacements resulting from temperature changes induced by waste emplacement require as input coefficients of thermal expansion. The performance-allocation process resulted in the definition of both preferred limits for thermal-expansion coefficients and confidence in those limits. Thermal-expansion data gathered in the small number of in situ experiments (Table 1.0–1) are unlikely to have narrow confidence intervals even for the thermal/mechanical units (TSw1 and TSw2) in which such experiments will be performed. In addition, the in situ experiments will be unable to provide data either to examine spatial variability within the relevant thermal/mechanical units (because the number of experiments will be insufficient) or to provide rock-mass thermal-expansion coefficients for units in which no in situ experiments are to be conducted.

As a result of these limitations for the in situ experiments, a program of laboratory experiments is necessary as a first step in obtaining rock-mass thermal-expansion data. The laboratory program can be designed to provide both the number of samples and the proper distribution of sampling localities to enable the limitations mentioned previously to be overcome. In addition, laboratory experiments will examine thermal-expansion behavior under controlled conditions, thus permitting the effects of parameters (e.g., saturation level) to be studied.

An initial assumption is made that the coefficient of thermal expansion for the rock mass is the same as that measured in the laboratory. Qualitative comparison of the expected expansion behavior of fractured material with the behavior of unfractured (but otherwise identical) material suggests that the coefficient of thermal expansion of the rock mass cannot be greater than that of the intact rock. The possibility exists that fractures could reduce thermal expansion by absorbing some of the thermally induced deformation. This reduction in overall expansion would reduce thermal strains and stresses for a given temperature change or temperature gradient. Thermal expansion measurements on several samples from new core holes will be made to examine the effects of natural fractures on thermal-expansion behavior (Section 2.2.2.1); in addition, the validity of the assumption will be tested by comparing the results from in situ tests in the Exploratory Studies Facility (ESF) with laboratory data. If the in situ thermal-expansion behavior differs from that seen in the laboratory, a method suitable to extrapolate the laboratory data to the in situ scale will be developed.

2.2 Rationale for the Number, Location, and Alternatives for Laboratory Thermal-Expansion Experiments

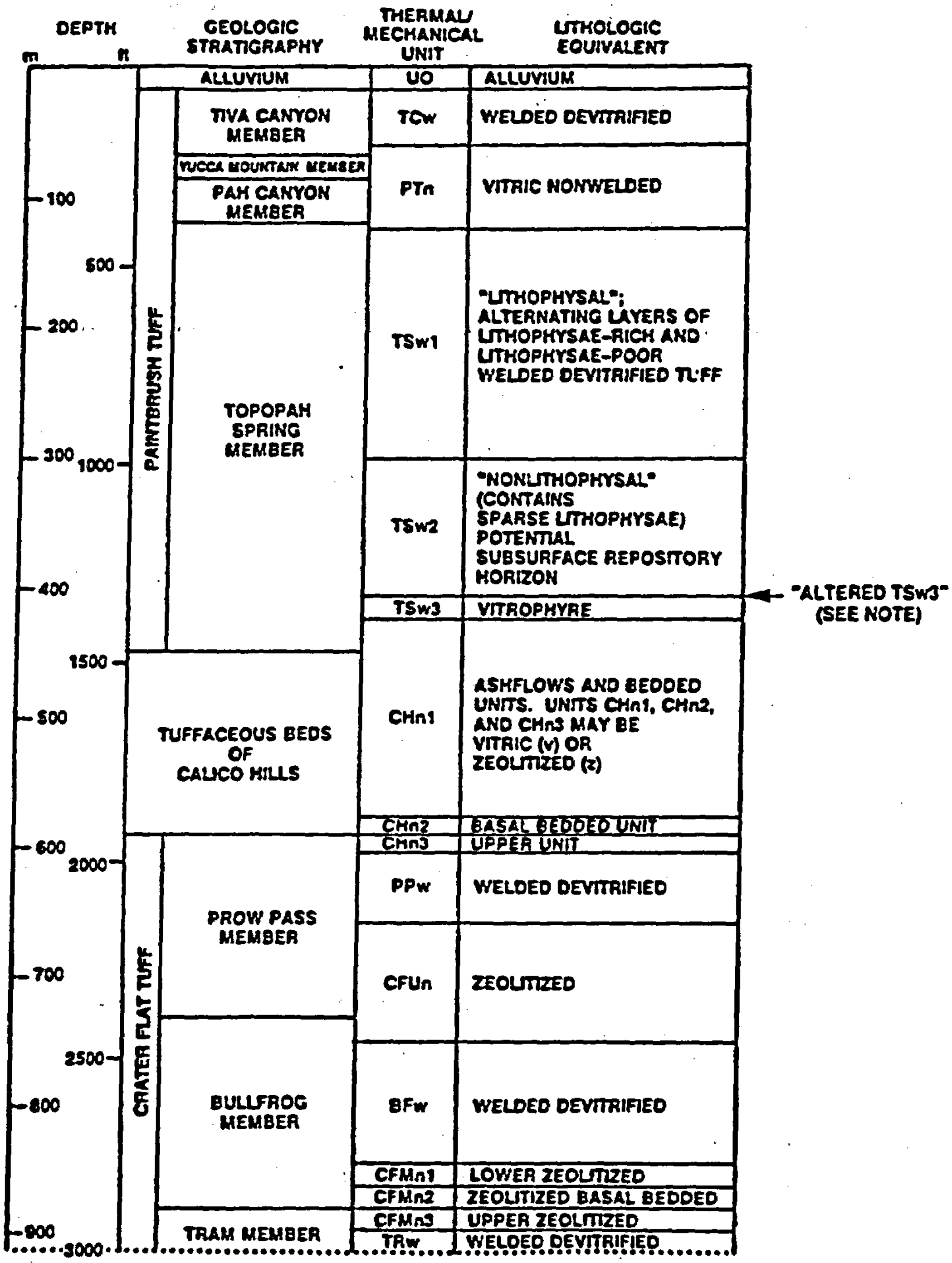
Preliminary data for thermal-expansion behavior and for other thermal and mechanical properties have been obtained for various tuffaceous units at Yucca Mountain. These data have permitted definition of a thermal/mechanical stratigraphy, in which units are distinguishable based on differences in one or more of the thermal and mechanical properties. A comparison of these units with the formal stratigraphic units is provided in Figure 2.2–1.

Because the thermal/mechanical units have been defined based on differences in thermal properties, mechanical properties, or both, each of the units is assumed to be independent in terms of sampling. Thus, the performance-allocation process has resulted in data requirements for each pertinent thermal/mechanical unit separately.

The existing version of the thermal/mechanical stratigraphy does not include material found between units TSw2 and TSw3, which is characteristic of neither unit. This material is extremely variable in lithology (usually rich in clay and zeolite) and in thickness [usually less than 10 ft (3 m)]; the variable lithology is the reason the material has not been treated as a thermal/mechanical unit. A brief discussion of the material is provided by Nimick and Schwartz (1987).

The following sections discuss the number (Section 2.2.1) and the location (Section 2.2.2) of experiments planned to characterize thermal-expansion behavior of the tuffs at Yucca Mountain. Section 2.2.3 discusses additional thermal-expansion experiments planned to examine, in a scoping fashion, the effects of sample size, and saturation level on thermal-expansion behavior.

In order to formulate the plans discussed in these sections, preliminary assumptions were made about the spatial variability of thermal expansion. Existing data are insufficient to analyze large-scale horizontal variability (e.g., between existing core holes) or vertical variability within each thermal/mechanical unit at any given core hole location. Thus, it has been assumed that little is known about the spatial variability of thermal-expansion behavior. Section 2.2.1 addresses the number of experiments and Section 2.2.2 discusses sampling locations. Taken together, these sections present the plans to assess the issue of spatial variability.



NOTE: Altered TSw3 is not included; it is a zone of variable lithology and thickness (see text).

Figure 2.2-1. Comparison of Thermal/Mechanical and Formal Stratigraphies, Including General Lithologic Descriptions and Representative Thicknesses for the Yucca Mountain Area (DOE, 1993).

Given this lack of information, existing data have been used to provide information with which to estimate number of samples (Section 2.2.1) which, if there is spatial variability between core holes (i.e., horizontally), would be sufficient to satisfy the data requests of performance assessment and repository design at any single sampling location. In addition, if variability is random and uncorrelated both horizontally and vertically, present sampling plans will provide data that are more than sufficient to satisfy data requirements.

2.2.1 Number of Samples

A preliminary estimate of the necessary number of samples for the thermal-expansion experiments can be obtained using information provided by repository design and performance assessment through the performance-allocation process. A compilation of the data requirements from a number of design and performance-assessment issues is provided in Table 2.2–1. Before beginning the detailed discussion of estimating the number of samples, it should be noted that the identification of the data requirements and associated qualitative confidence levels has been done with little or no support in the form of sensitivity analyses. Often, the specification of tolerance limits and confidence levels has been made based solely on the expert judgment of repository design personnel. As additional analyses are performed, it is possible that some aspects of the repository design will prove to have a different sensitivity to thermal expansion than has been assumed to date. Whenever analyses do indicate changed sensitivity relative to that assumed for the preliminary estimates given in the SCP, the estimated numbers of samples required for experiments will be reevaluated appropriately.

The repository-design and performance-assessment activities express the data requirements in the following form:

> We want a proportion, (γ), of the data population to fall within the limits $\overline{X} \pm K\overline{X}$ with a (1-α) level of confidence.

(Note that this requirement is a request for statistical tolerance limits within which the proportion (γ) is expected to occur, not for a confidence interval around $\overline{X}$.) Ideally, the design requirements specify values for γ and α (which expresses the degree of conservatism in the design), and K (a constant for specific combinations of γ, α) from which the sample size, n, can be estimated for a given population distribution of the data.

Insufficient thermal-expansion data are available to determine the population distribution. Although it is preferable to determine sample sizes based on an approach that makes no assumptions about the

Table 2.2-1

Summary of Data Requirements for Thermal Expansion from Repository-Design and Performance-Assessment Activities

SCP Issue	Thermal/Mechanical Unit	Required Interval	Required Confidence Level
1.6	Not specified	Not specified	Not specified
1.11	TSw2 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	High
	TSw1 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Medium
	TSw3 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Medium
	CHn1 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Medium
	TCw (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Low
	PTn (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Low
	CHn2 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Low
1.12	TSw2 (Rock Mass)	Not Specified	Medium
	CHn1 (Rock Mass)	Not Specified	Medium
4.4	TSw2 Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Medium
	TSw2 (Rock Mass)	$\overline{X} \pm 0.15\overline{X}$	Medium

underlying population distribution, the sample sizes obtained using distribution-free tolerance limits are impractical when scheduling and budgeting also are considered. Therefore, a normal population distribution is assumed for calculating initial sample sizes.

For this study, the method of Bowker and Lieberman (1972) that is based on an assumed normal distribution is used to design the initial sampling program. In this method,

"...statistical tolerance limits for a normal distribution are given by $[L = \overline{X} - KS, U = \overline{X} + KS]$ and have the property that the probability is equal to a preassigned value that the interval includes at least a specified proportion $1 - \alpha$ of the distribution."

(Bowker and Lieberman, 1972, p. 310)

This definition of statistical tolerance limits can be used to estimate the value of n required to obtain tolerance limits of predefined size if values for $\overline{X}$, S, γ, and α are established. Since repository-design and performance-assessment activities do not establish numerical values for α and γ, values must be assigned.

As shown in Table 2.2-1, one of three qualitative levels of confidence has been associated with each data request — high, medium, or low. In general, the closer the thermal/mechanical unit is to the repository horizon, the greater the level of confidence required for the data from that unit. For this study, the following numerical values of α (the level of significance) have been assigned to each of the qualitative confidence levels:

Qualitative Confidence Level	α
High	0.05
Medium	0.10
Low	0.25

The qualitative levels of confidence were assigned by different individuals, all of whom have different problems to address. Thus, the values of α given above may be more restrictive than is necessary for some applications. However, the values have been selected in an attempt to satisfy even the most stringent of the qualitative requirements.

Values for γ have been assigned based on the assumption that the proportion of the population (γ) required to lie within the statistical tolerance limits (defined as $B\overline{X}$) is the same as the confidence interval (1-α):

Qualitative Confidence Level	γ
High	0.95
Medium	0.90
Low	0.75

Thus, the higher the level of confidence required in the data, the higher the proportion of the data population that must lie within the tolerance limits.

A preliminary estimate of the number of samples required for thermal-expansion testing (Table 2.2-2) can be determined by using existing data for $\overline{X}$ and S, and calculating K by equating KS and the specified value for $B\overline{X}$ from a repository-design or performance-assessment issue (Table 2.2-1). For many of the entries in Table 2.2-1, no existing data are available with which to calculate $\overline{X}$ and S, so that a preliminary number of required samples cannot be estimated. For other entries, the data requirements from repository design and performance assessment may be unrealistic given the high variability of existing data (equating KS and $B\overline{X}$ yielded a value of K that is not realizable no matter how many samples are tested). In both cases, an alternative approach is necessary that, although arbitrary, will allow a preliminary sampling strategy to be formulated.

The alternative approach selected involves finding the number of samples required at each confidence level that will provide the same statistical tolerance limits [i.e., the same (arbitrary) value of K]. Some of the data requirements in Table 2.2-1 demand narrower tolerances than others. The initial sampling estimates that are discussed below are based on narrower tolerances (i.e., the greater number of samples). Two-sided statistical tolerance limits are used in the estimation.

The number of samples (n) are 3 [$\gamma = (1-\alpha) = 0.75$ (low confidence)], 11 [$\gamma = (1-\alpha) = 0.90$ (medium confidence)], and 34 [$\gamma = (1-\alpha) = 0.95$ (high confidence)], for a value of $K = 2.5$. These three values have been rounded to 5, 10, and 35 for this study. (For the more rigorous confidence levels, the rounding does not change the value of K except in the third significant digit. For the lowest sample number, rounding will result in an increased amount of data.)

The initial estimates of number of samples are summarized in Table 2.2-2. Suppose that the requirements stated above resulted in n samples for a given thermal/mechanical unit (based on existing data and the assumption that all data are for random, uncorrelated samples). These n samples, taken from numerous core holes and scattered vertical locations within the unit, would be sufficient in the absence of spatial variability. However, thermal-expansion behavior may be dependent on spatial location. Thus, rather than selecting n samples for the entire area (or volume) to be characterized, n samples will be taken from each selected (horizontal) sampling location, and will be distributed vertically in a manner that any systematic vertical variability should be detectable. Additional details on the locations for sampling are provided in Section 2.2.2.

Table 2.2-2

Initial Estimates of Numbers of Samples[a] Required for Site Characterization of Thermal-Expansion Behavior

Unit	Number of Samples	No Existing Data	Existing Data Highly Variable
TCw	5	x	
PTn	5	x	
TSw1	10		x
TSw2	35		x
Altered TSw3	10[b]	x	
TSw3	10	x	
CHn1v	10		x
CHn1z	10		x
CHn2v	5	x	
CHn2z	5	x	

[a] These numbers of samples pertain to each core hole to be sampled. Six new core holes are planned for testing.
[b] This number of samples will be tested if sufficient material is available.

It is emphasized that the numbers given in Table 2.2-2 are those with which the initial sampling program will be designed. Once the site-characterization testing begins, the resulting data will be examined periodically to assess whether the assumption of normality is justified. If the data do not represent a sample from a normal distribution, the actual distribution will be evaluated, a new sample size will be estimated based on data requirements, and this sample size will be compared to the number of samples already tested. If additional tests are required, more samples will be tested to provide the necessary data.

2.2.2 Sampling Locations

Samples will be taken from the following locations: (1) existing core holes from which samples have been obtained previously for thermal-expansion measurements; (2) main accesses of the ESF; (3) main drifts to be excavated within Unit TSw2 of the ESF; and (4) new core holes proposed as part of the surface-based exploration program described in Sections 8.3.1.4.1 and 8.3.1.4.3.1.1 of the SCP.

A discussion of the number of samples required for site characterization is provided in Section 2.2.1. The discussion does not address the possibility that the thermal-expansion behavior of one or more of the units may vary as a function of spatial location, either horizontally within the boundary of the underground facilities or vertically within the unit. Given the number of cases in which no thermal-expansion data are available at the present time, it is assumed that little is known about the spatial variability of the thermal-expansion behavior before site characterization begins. Thus, the number of samples discussed in Section 2.2.1 applies for each sampling location employed in site characterization. Additional detail is given in the following subsections.

Not all of the relevant thermal/mechanical units will be penetrated by the subsurface excavations that will provide access to material for sampling. New core holes are planned to extend to depths 200 ft (61 m) below the static ground-water level, so that most of the thermal/mechanical units of interest should be sampled in each core hole.

2.2.2.1 Sampling in New Core Holes

Although a quantity of data on the coefficient of thermal expansion has already been obtained for sample from existing core holes, only one of the existing core holes (USW G-4) (Spengler and Chornack, 1984) is located within the main area for site characterization. Thus, data from additional locations are necessary in order to examine the spatial variability of thermal expansion within the boundary of the underground facilities as well as to ascertain whether the existing data are representative of the tuffs within the area. In order to coordinate with core holes planned for other YMP activities, six of the core holes suggested as part of a systematic drilling program (SCP Section 8.3.1.4.3.1.1) are anticipated to be used for sampling for the Thermal-Expansion Study. Data from these holes should enable an adequate analysis of the lateral variability of thermal-expansion behavior to be made.

It is possible that areas outside the boundary of the underground facilities will be evaluated as potential extensions of the main area. If this evaluation includes new core holes, the sampling program discussed in this section would be applied to one or more of these additional holes.

As stated earlier, each thermal/mechanical unit will be considered as an independent entity in terms of sampling. In each core hole, the thermal/mechanical units each will be divided into *n* potential sampling intervals, where *n* is the number of samples given in the summary at the end of Section 2.2.1. In each of these intervals, a sample will be selected from a location as close to the center of the interval as possible. [Preliminary analysis has shown that the average Kriging variance (a common criterion for optimizing a sampling strategy) will be lower using this sampling strategy rather than a fully random strategy.]

An attempt will be made to avoid any bias in sampling to the extent practicable. Thus, rather than selecting the material that appears to be the best candidate for a sample, the only criterion applied will be that a sample be of sufficient size to meet any size requirements imposed by the experiment. If a fragment or piece of core of sufficient size is not available within any given interval, the number of samples estimated as necessary for a given unit may not be achievable. Adjustments to the sampling program may be necessary so that the statistical basis of the program will be maintained while still acquiring as close to *n* samples as possible. The nature of these adjustments will depend on the situation. For example, if suitable samples cannot be obtained from some of the predefined intervals, redundant samples could be selected from one or more of the remainder of the sampling intervals to ensure that sufficient measurements could be made. (The fact that a fragment or piece of core was not available in a given interval may be useful information in the analysis of spatial variability of thermal-expansion data or of the material on which the data were gathered. Thus, such information will be retained for use after sampling has been completed.)

The thermal-expansion behavior of Unit TSw2 potentially is a function of orientation (i.e., may be anisotropic). The presence or absence of anisotropy in the coefficient of thermal expansion will be examined using a subset of 10 of the 35 samples to be collected from Unit TSw2 in each core hole.

It is anticipated that fractures will not cause a difference between the coefficient of thermal expansion of Unit TSw2 measured in the laboratory and the coefficient of thermal expansion of the rock mass; however, no data exist with which to evaluate this assumption. Although rock-mass values will be obtained during in situ experiments, the effects of fractures may not be separable from the influence of other parameters such as boundary effects. Therefore, two samples per new core hole containing natural fractures are planned to examine the effects of fractures on laboratory-determined thermal-expansion behavior. Additional samples will be obtained from the main test level if initial experiment results indicate that more data are required. All tests on fractured samples will include a small stress (≤7 MPa) normal to the fracture in order to simulate in situ conditions.

2.2.2.2 Sampling in the ESF Main Accesses

Samples from the ESF main accesses will be obtained in several ways. First, samples will be taken from core obtained from the multiple point borehole extensometer (MPBX) holes that are planned as part of the access-convergence test (Study 8.3.1.15.1.5, Excavation Investigations). Six samples will be taken from each of the access-convergence stations within the main accesses. A minimum of three access-convergence stations is planned for study.

The second sampling location will be the upper Demonstration Breakout Room (DBR), to be located within the lithophysae-rich portion of Unit TSw1. Three evenly-spaced samples will be taken from each of the MPBX holes from the upper DBR; ten holes are planned as part of Study 8.3.1.15.1.5.

If core from MPBX holes is insufficient in either quality or quantity to provide samples for all thermal-expansion tests, additional samples will be obtained from horizontal boreholes located in the ESF main accesses.

2.2.2.3 Sampling in the ESF Main Drifts

The sampling strategy in the main drifts to be excavated at the main test level in the ESF will be similar to that employed for the main accesses (i.e., samples will be taken from core obtained from MPBX holes or horizontal boreholes located in the ESF main drifts). In this case, the MPBX holes will be cored for Study 8.3.1.15.1.8 (In Situ Design Verification.) Current plans are that three evenly-spaced samples will be obtained from each hole. By the time core is available from these MPBX holes, additional data on thermal expansion may be available with which to define in a more rigorous fashion the optimum number of samples.

2.2.2.4 Additional Sampling

2.2.2.4.1 Additional Sampling for Bulk Properties

The three preceding subsections describe the sampling strategy for thermal expansion; a similar strategy will be followed for sampling for other thermal and mechanical properties. In each case, the random selection of samples will allow relatively accurate estimates to be made of the statistical distribution of the population of each property. However, the small-scale spatial correlation of the data will be unknown because, in general, samples will be no closer than 1 ft (0.3 m) to each other, and in the thicker units may be much farther apart.

In order to ascertain whether small-scale spatial correlation is significant for thermal and mechanical properties, measurements of bulk properties (matrix porosity and density) will be made. The description of sampling plans for these measurements is contained in Study Plan 8.3.1.15.1.1. Correlations have been established between porosity and several of the thermal and mechanical properties [e.g., heat capacity, compressive strength, Young's modulus (Nimick and Schwartz, 1987)]. Although thermal-expansion behavior is expected to be independent of porosity (Lappin, 1980), a positive correlation may exist between grain density and the coefficient of thermal expansion because of the dependence of both parameters on mineralogy. In order to ascertain whether small-scale variability of thermal-expansion behavior can be estimated from the bulk-property data, the mineralogy of the closely spaced bulk property samples will be determined. In addition, the density, porosity, and mineralogy of the thermal-expansion samples will be obtained to examine correlations between properties. (Description of the methods to be used for collection of density and porosity data is provided in Study 8.3.1.15.1.1, Laboratory Thermal Properties, and for mineralogic data in Study 8.3.1.3.2.1, Mineralogy, Petrology, and Chemistry of Transport Pathways.)

2.2.2.4.2 Additional Sampling in Support of In Situ Experiments

As mentioned earlier, rock-mass thermal-expansion behavior also will be observed as part of several in situ experiments to be conducted in the ESF (Table 1.0–1). Laboratory values for the coefficient of thermal expansion are required to aid in the interpretation of the results of the experiments. The laboratory values will be determined for samples taken from the vicinity of the relevant in situ experiments. These samples are not considered as part of the systematic sampling program described earlier, nor is the number of these supporting measurements governed by the estimates made for the systematic sampling. Instead, the number and location of these samples will be determined by the Principal Investigator (PI) for an in situ experiment in consultation with the PI for laboratory determination of the coefficient of thermal expansion. The results of these thermal-expansion tests, however, will be incorporated into this study.

2.2.2.4.3 Additional Sampling of Anomalous Material

The possibility exists that, during the excavation of the main accesses or associated underground openings, material may be encountered that cannot be considered to be representative of the thermal/mechanical unit in which it is located. An example of such material would be fault gouge. If such material is encountered, appropriate repository-design and performance-assessment personnel will determine whether data on the thermal-expansion behavior of the material are necessary to their work. If so, samples will be collected under constraints imposed by the data requirements (e.g., confidence level, tolerance limit) for the unit in which the material is located.

2.2.3 Effects of Test Parameters on Thermal Expansion

Several parameters selected by an experimenter before measuring thermal-expansion behavior have the potential to affect the observed behavior. These include confining pressure, sample size, and the saturation level of the samples. The existing state of knowledge does not allow conclusions to be drawn concerning the importance of any of these parameters. As a result, scoping studies to establish baseline test conditions will be performed to assess whether any important effects on thermal expansion would occur. These studies will not include tests at all combinations of conditions, but instead are designed to examine potential effects of each condition separately. The ranges of each parameter are given below.

Confining Pressure:	ambient (0.1 MPa)
Sample Size:	2.54 to 10.2 cm (length), 0.6 to 2.54 cm (diameter)
Saturation Level:	0.0 to 1.0

Confining pressure is not anticipated to have a significant effect on the thermal-expansion behavior of the rock mass. However, should rock-mass analyses indicate that confining pressure is an important parameter, thermal-expansion measurements will be conducted at different confining pressures.

To incorporate some of the potential variability between samples, five samples will be tested at each set of conditions for each material of interest. Each of the four major lithologies (welded devitrified; welded vitric; nonwelded vitric; nonwelded zeolitic) will be examined. Thus, the scoping studies are planned to include measurements on 60 samples.

One additional concern must be addressed by a scoping study — the potential effects of sample irradiation on the thermal-expansion behavior of Unit TSw2. Twenty samples will be used to examine the effect. First, the thermal expansion of all 20 samples will be measured, then ten of the samples will be subjected to a radiation dose (of approximately the peak rate estimated at the surface of the waste package) and all 20 samples will be tested again.

If the scoping studies indicate that one or more of the parameters discussed above have a significant effect on the thermal-expansion behavior of tuffs, the sampling and testing program described in Sections 2.2.1 and 2.2.2 will be modified to include characterization of the parameter effects. Details of such modification cannot be specified until the results of the scoping studies are available.

2.2.4 Summary of Sampling Plans

There are three sampling groups for this study. First are samples for the scoping studies. These samples will be obtained from existing core or, if no core is available, from outcrop material. The second group of samples will come from the new core holes; the numbers and locations for samples in this group are given in Table 2.2-2 and described in Section 2.2.2.1. In addition, samples from each of the core holes will be obtained to study the potential effects of fractures on the thermal-expansion behavior of Unit TSw2. The third group of samples will be obtained from the ESF. This group includes samples from the main accesses, the upper DBR and the main drifts. In addition, samples will be obtained to support in situ testing.

A summary of the sampling plan is provided in Table 2.2-3.

Table 2.2-3
Summary of Sampling Plans

Portion of Study	Location(s)	Unit(s)	Estimated Number of Samples	Section
Scoping Activities	Existing Core or Outcrop	•TCw, TSw1, TSw2	10 (size effects)	2.2.3
			5 (saturation effects	2.2.3
		•TSw2	20 (radiation effects)	2.2.3
		•TSw3	10 (size effects	2.2.3
			5 (saturation effects	2.2.3
		•PTn, CHn1v, CHn2v.	10 (size effects)	2.2.3
			5 (saturation effects)	
		•CHn1z, CHn2z	10 (saturation effects)	2.2.3
			5 (saturation effects)	
Spatial Variability and Site Characterization	New Core Holes	•TCw	30 (5 per hole)	2.2.2.1
		•PTn	30 (5 per hole)	2.2.2.1
		•TSw1	60 (10 per hole)	2.2.2.1
		•TSw2	210 (35 per hole; includes 10 per hole for anisotropy) 12 fractured (2 per hole)	2.2.2.1
		•Altered TSw3	60 (10 per hole)	2.2.2.1
		•TSw3	60 (10 per hole)	2.2.2.1
		•CHn1v	60 (10 per hole)	2.2.2.1
		•CHn1z	60 (10 per hole)	2.2.2.1
		•CHn2v	30 (5 per hole)	2.2.2.1
		•CHn2z	30 (5 per hole)	2.2.2.1
	Main Accesses	•TSw1	12 (access-convergence)	2.2.2.2
			30 (upper DBR)	2.2.2.2
		•TSw2	6 (access-convergence)	2.2.2.2
	Main Drifts	•TSw2	105	2.2.2.3
In Situ Test Support	Main Test Level	•TSw2	25	2.2.2.4.2

*This number of samples will be tested if sufficient material is available.

2.2.5 Measurement Techniques and Alternatives for Laboratory Thermal-Expansion Experiments

The following subsections briefly discuss the planned approach for obtaining the thermal-expansion data and the alternatives to the approach. A brief summary of the actual experimental technique also is provided.

In addition to the techniques described in the remainder of Section 2.2.5, some mineralogic, petrologic, and petrographic characterization of samples will be performed. This characterization is intended to provide data that can be used to interpret experiment results as well as to examine potential correlations between the thermal-expansion behavior and sample characteristics that might be useful in inferring coefficients of thermal expansion from the results of mineralogic and petrologic studies performed by other project participants. If correlations are found between mineral percentages and coefficients of thermal expansion, data to be gathered during characterization of the mineralogy of the host rock and of possible transport pathways will be used to enhance the spatial coverage over which thermal-expansion behavior has been determined.

The characteristics of the propagation of seismic waves in rocks are a function of the degree to which a rock is fractured. Thus, comparison of such characteristics measured on samples before and after thermal-expansion measurements may provide useful information about microcracking caused by the thermal cycling. A resonant-bar technique that determines seismic attenuation is probably best for determination of seismic characteristics of the small thermal-expansion samples. Scoping measurements will be performed on a set of samples before site-characterization data are collected to ascertain whether the measurements will help in interpretation and analysis of thermal-expansion data. If the information is useful, measurements will become a part of the standard measurements made on thermal-expansion samples.

2.2.5.1 Preferred Technique for Determination of Thermal-Expansion Behavior

A number of experimental methods are available for measuring thermal expansion. Of the various choices (see Section 2.2.3.3.1 for brief descriptions of alternative methods), the preferred method is that which uses a tube-type dilatometer. Valentich (1981) describes this technique and the different types of dilatometers in some detail. The following paragraph briefly summarizes the technique.

The dilatometer has a tube and rod made of vitreous silica. A sample is placed in series with the rod inside the tube, with a linear variable differential transformer (LVDT) mounted at the open end of the tube to measure displacements. (A dual pushrod technique can also be used; in this case, displacement of the sample plus one rod is compared to the displacement of a second, longer rod.) The assembly is inserted in the center of a cylindrical furnace and heated at a rate of ≤3°C/min. The temperature of the sample is monitored with a thermocouple; the temperature and associated displacement are recorded continuously for the duration of a test.

The displacement of the sample is obtained from the total displacement by subtracting the displacement of the silica rod and the displacements of any other portions of the apparatus. This correction is determined by calibrating the apparatus with a sample of pure copper (or other standard material, with a coefficient of linear thermal expansion closer to that of tuff samples, from the National Institute of Standards and Technology). The standard sample is machined to the same size as the rock samples to be measured later, and a thermal-expansion test is performed using the standard with all test conditions kept the same as those to be used with the rocks. The ideal expansion values for the standard are subtracted from the measured expansions to obtain the system correction.

The dilatometer method of determining thermal expansion is the method used in a number of standard test methods published by the American Society of Testing and Materials (ASTM), including ASTM B-95, C-372, C-824, C-832, and E-228. Other national organizations, including the U.S. Bureau of Mines (Lewis and Tandanand, 1974) and ONWI (Shuri et al., 1981), suggest the use of dilatometers as well. Van Buskirk et al. (1985) adapted this method for use under conditions in which confining pressure and pore pressure can be varied independently.

Thermal-expansion data collected previously (Lappin and Nimick, 1985; Nimick and Schwartz, 1987) strongly suggest that initially saturated tuff samples contract when exposed to laboratory air of low relative humidity (<50 percent) at ambient temperature. This behavior has been observed both in welded, devitrified tuffs and in zeolitized tuffs. Such contractions are not representative of expected behavior at low temperatures in situ, where the relative humidity should be high. Thus, laboratory thermal expansion measurements will need to be made in a controlled atmosphere (e.g., air with high relative humidity); dilatometers with this capability are available commercially.

If necessary, samples for thermal-expansion experiments will be machined to the size appropriate to the dilatometer selected for testing. The sample size anticipated for the majority of testing is 2.54. cm (1.0 in.) in diameter and 5.08 cm (2.0 in.) in length, pending the results of the scoping study on the effects of sample size on thermal-expansion behavior. The sample will be saturated before experiments are started. The samples will be heated at a controlled rate of ≤1°C/min, and the atmosphere surrounding the sample during testing will be controlled to minimize sample dehydration at temperatures below the nominal boiling temperature of 100°C. When this temperature is exceeded, temperature will be held constant until the sample length stabilizes, then heating will be restarted. Heating will continue until the maximum temperature planned for the experiment is reached, then the sample will be cooled at a controlled rate of ≤1°C/min. The maximum temperature will vary, depending on the thermal/mechanical unit, as required by repository design and summarized in Table 2.2-4.

Table 2.2-4

Heating and Cooling Rates and Maximum Temperatures to be Attained During Thermal-Expansion Experiments

Thermal/Mechanical Unit	Heating and Cooling Rates (°C/min)	Maximum Temperature (°C)
TCw	≤ 1	100
PTn	≤ 1	100
TSw1	≤ 1	275
TSw2	≤ 1	300
Altered TSw3	≤ 1	275
TSw3	≤ 1	275
CHn1v	≤ 1	275
CHn2v	≤ 1	100
CHn1z	≤ 1	275
CHn2z	≤ 1	100

The devitrified tuffs comprising Units TSw1 and TSw2 contain the three silica polymorphs quartz, cristobalite, and tridymite. The latter two of these polymorphs undergo polymorphic transformations at temperatures below 275°C. In order to accurately characterize the temperatures at which these transformations begin and end, and their effect on the thermal-expansion behavior of the two units, heating rates for experiments on samples from the two units may be significantly less than rates used for experiments on samples from other units. The exact values of heating rates will be determined during development of technical procedures for the thermal-expansion experiments.

Displacement data as a function of temperature will be acquired in a digital form. Subsequent analysis of the data can take several forms. Average thermal-expansion coefficients can be calculated for temperature ranges of interest (this is the way existing data for Yucca Mountain tuffs have been reported in the past). Polynomial functions of temperature can be used to fit the data, and the slope of a given function at any selected temperature can be used as the thermal-expansion coefficient for that temperature. Finally, secants can be calculated from 25°C to the temperature of interest to obtain the expected displacement as temperature increases from ambient conditions.

Each of the approaches is useful in some circumstances. The approach that probably will be used most commonly is the calculation of average thermal-expansion coefficients for temperature ranges, where the ranges will be defined by visual inspection of the displacement-temperature graphs. Other interpretations of the data will be provided if requested.

As mentioned in Section 2.2.2.4.1, the bulk properties (bulk density, grain density, and porosity) and mineralogy of thermal-expansion samples will be determined to allow interpretation of thermal-expansion behavior. If correlations can be found between thermal-expansion coefficients and one or more of these other properties, additional information about the spatial variability of thermal-expansion behavior can be deduced using information that is to be gathered for other studies [e.g., Study 8.3.1.15.1.1 (Laboratory Thermal Properties) and Study 8.3.1.3.2.1 (Mineralogy, Petrology, and Chemistry of Transport Pathways)].

2.2.5.2 Alternatives for Experimental Determination of Thermal Expansion

Many methods of measuring thermal expansion have been proposed in the published literature. Hidnert and Souder (1950) and Krishnan et al. (1979) provide two of the numerous overviews of this topic. A brief synopsis of the survey of techniques is given below.

1. Precision micrometric method: the distance between fine wires hanging from the ends of a sample is measured with two micrometer microscopes. Hidnert and Souder (1950) stated that this technique was the most precise known at the time of their survey. The technique is not suitable for making many routine measurements because of the precision required in fabrication and operation of the apparatus.

2. Interference method: displacement of a sample held between two fused-quartz plates causes displacement of optical interference fringes past a reference mark. This method is suitable for very small samples with irregular shapes. A number of adaptations of this method are in use; Fizeau's interferometric technique would be the best alternative to the dilatometer method selected as the preferred method for this study. ASTM E-289 describes an interferometric method.

3. Autographic optical-lever method: the displacements of a sample and of a standard material (Chromel), both of which are in contact with a mirror, cause the mirror to rotate. A spot of light is focused on the mirror, and the movement of the spot is recorded by photographic media.

4. Liquid micrometer method: an adaptation of the dilatometer method, this method measures displacements of a sample by transmitting the movement via a fused silica rod to a hydraulic device filled with colored water. The movement of the meniscus magnifies the displacement of the sample by approximately two thousand times. This method would require assembly of a unique apparatus rather than the purchase of readily available equipment.

5. Capacitance method: displacement of the sample moves the plate of a small capacitor. Changes in the capacitance of the circuit cause changes in the current that can be used to calculate length changes in the sample. The equipment for this technique is difficult to fabricate, as is the specimen.

6. Density method: the volume thermal expansion can be determined by weighing a sample in a liquid of known density at different temperatures, and the linear thermal expansion can be calculated from the coefficient of volume thermal expansion. This method is not convenient to use over a wide range of temperatures.

7. Differential transformer method: displacement of the sample moves one coil relative to a larger concentric coil, causing a net mutual inductance change. This technique cannot be used for materials that are slightly magnetic, is less sensitive at higher temperatures, and the equipment is difficult to fabricate.

8. Strain gauge method: strain gauges can be mounted directly on the sample to determine displacements in more than one direction, allowing an assessment of anisotropy as well as volumetric expansion. The two potential problems with this method are the size of the gauges relative to sample heterogeneities and evaluation of thermal effects on the gauges and the material used to bond the gauges to the samples.

2.3 Constraints on Laboratory Thermal-Expansion Study

2.3.1 Potential Impact on the Site

The potential impact on the site of the coring of new core holes will be addressed when the various proposals for drilling and coring from the surface are evaluated. The proposals are summarized in Section 8.3.1.4 of the SCP. The potential impacts related to the construction of the ESF on the site are discussed in Section 8.4 of the SCP. No additional impacts on the site are expected as a result of the experiments to be conducted for this study. No additional coring or excavation presently is anticipated to be required beyond that already planned for other studies.

2.3.2 Repository Simulation

The ultimate goal of this study is to characterize the thermal-expansion behavior of the rocks in the vicinity of the underground facilities. As such, data gathered for the study will be analyzed and synthesized (incorporating relevant information obtained from the in situ tests to be conducted for Study 8.3.1.15.1.6, In Situ Thermomechanical Properties) to provide property values appropriate to the scale and indicated variability of the in situ rock mass. Thus, within the limitations imposed by the assumptions involved in extrapolating the measured data to the in situ conditions and to the areas from which no samples were obtained, the results of the study will have accounted for the scales (spatial dimensions) and the environmental conditions expected to be experienced by the rock surrounding a repository.

2.3.3 Required Accuracy and Precision of Thermal Expansion Coefficients

The accuracy and precision required for use of the data are built into the data requirements expressed by repository-design and performance-assessment personnel through the performance-allocation process. In the summary of Table 2.2–1, the ranges in thermal-expansion coefficients all are ±15 percent of the mean values for the coefficients. As discussed in Section 3.2.2, accuracies of better than ±3 percent are achievable using the dilatometric technique. Thus, all constraints imposed by required accuracies and precisions will be accounted for by satisfaction of the data requirements and are included in the estimation of the numbers of samples required to obtain the data (Section 2.2.1).

The preceding paragraph discusses measured values for thermal-expansion coefficients. In addition, possible correlations between the thermal-expansion coefficients and mineralogy or grain density are to be studied. If such correlations exist, extrapolated thermal-expansion coefficients can be obtained. The accuracy of such extrapolated values cannot be estimated now, but will be evaluated at such time as extrapolations are made.

2.3.4 Limits and Capabilities of Analytical Methods

No analytical models or numerical methods will be used either for designing experiments or for interpreting the thermal-expansion data to be obtained for this study. No comparison will be made between measured data and composite coefficients of thermal expansion derived from data for individual minerals because the requisite data (e.g., coefficients of thermal expansion, elastic moduli) are not available for several volumetrically significant phases in the tuffs. Thus, analytical models and numerical methods impose no constraints on this study.

2.3.5 Time Required Versus Time Available

This study is designed to provide current information on the thermal-expansion behavior whenever such information is requested, and to provide in a timely manner written summaries of thermal-expansion data for use in analyses supporting major deliverables such as the Draft Environmental Impact Statement or the License Application. Thus, if core is available on a timely basis, time will not be a constraint on the study.

As described in Section 2.2.3, several scoping activities must be performed early in the testing program for this study. The general result of each of these activities (i.e., does a given test parameter have a significant effect on thermal-expansion behavior) should be available as early in the site-characterization process as possible. This constraint is necessary in case the plans for routine thermal-expansion measurements need to be amended to optimize the test parameters. It is anticipated that the results of the scoping activities can be obtained before any site-characterization data for thermal expansion are gathered, so that the activities will not constrain the study.

2.3.6 Statistical Relevance of Data

The strategy for sampling and testing of the thermal/mechanical units that is discussed in Section 2.1 is based on satisfying the data requirements of repository design and performance assessment using statistical considerations. As such, the results of the Laboratory Thermal-Expansion Study will be directly relevant in the applications for which they are required. Should site characterization be unable to provide data within the requested constraints, the data base for coefficients of thermal expansion should still be sufficient to provide a statistical basis for any reevaluation of the design or performance-assessment goals.

Part of the basis for planning this study is the existing definition of the thermal/mechanical units. At intervals during data collection, statistical evaluation of thermal-expansion data will be performed to evaluate whether the unit divisions are reasonable and defensible. If they are, no changes will be made. If a need for definition of new unit boundaries is indicated, the redefinition will be performed and sampling plans for any remaining core holes will be amended as necessary. (Because the present thermal/mechanical stratigraphy is defined primarily on the basis of mineralogic differences, changes to the stratigraphy based on thermal-expansion data are considered to be unlikely.)

The existing thermal/mechanical stratigraphy is assumed to apply for all thermal and mechanical properties. Similar periodic evaluations will be performed for laboratory thermal properties (Study 8.3.1.15.1.1) and laboratory mechanical properties of intact rock (Study 8.3.1.15.1.3). Should one or more of these evaluations suggest that a redefined stratigraphy would be appropriate, a new set of units can be defined for the relevant property or properties. Thus, multiple stratigraphies may result; all would be independent, so that the different studies would not be mutually constraining. (Again, the probability of needing to redefine the thermal/mechanical stratigraphy is considered to be low.)

2.3.7 Scale of Phenomena

If the laboratory values of thermal expansion coefficients cannot be used directly for the rock mass (based on comparison with data from in situ experiments) relationships between coefficients for the laboratory and rock mass will be developed. The nature of such relationships will depend on the results of the comparison of in situ and laboratory data. The ultimate product will be thermal expansion coefficients for the rock mass that are appropriate for modeling the repository at all relevant scales.

2.3.8 Interrelationships With Other Studies

The experiments planned in the Laboratory Thermal Expansion Study will contribute to a data base that will serve as one of the primary inputs for calculations involving thermal stresses. Data from several other studies (Table 1.0–1) will provide measurements of in situ thermal-expansion behavior that can be used to evaluate the validity of the method used to extrapolate laboratory-determined coefficients of thermal expansion to the rock mass.

If correlations can be developed between the coefficients of thermal expansion and one or more of the parameters bulk density, grain density, porosity, and mineralogy, then information from two other studies can be used to contribute to the interpretation of the spatial variability of thermal-expansion behavior. These two studies are Study 8.3.1.15.1.1 (Laboratory Thermal Properties) and 8.3.1.3.2.1 (Mineralogy, Petrology, and Chemistry of Transport Pathways).

2.3.9 Interrelationships With ESF Construction Activities

A large number of samples for determination of thermal-expansion behavior will be taken from core obtained from the MPBX holes planned as part of activities for other studies. The construction schedule for the ESF will determine when the MPBX holes can be placed in the main accesses and drifts, and thus, will constrain the availability of samples for thermal-expansion testing.

3.0 DESCRIPTION OF LABORATORY THERMAL-EXPANSION EXPERIMENTS

The Laboratory Thermal Expansion Study Plan is intended to provide some of the data necessary to perform calculations of thermal stresses and displacements for a repository at Yucca Mountain. Experiments will be performed at testing laboratories that (1) have been determined to possess the technical expertise necessary to obtain quality data for the thermal expansion of the tuffs and (2) are able to satisfy all Sandia National Laboratories YMP quality-assurance requirements. The experimental methods that will be used or from which a method will be selected are discussed in Section 2.2.5.

3.1 EXPERIMENT UNCERTAINTY

The uncertainty of determinations of properties is best specified using two quantities: precision and accuracy (also known as bias) (Eisenhart, 1963). Accuracy is defined as the deviation of a determination of a property from the "true" value for the property. In theory, the accuracy is unknowable because the "true" value cannot be determined. In the remainder of this document, accuracy will be used to describe the difference between the mean of the measured values of a property for a standard material and the accepted mean value for that property.

In addition to accuracy, precision must be determined. Precision is the reproducibility of successive determinations of a property. Eisenhart (1963) suggest that a useful index of the precision of a series of measurements made on the same sample is the calculated value of the standard deviation or of the variance. For the work conducted for this study, the standard deviation will be used.

Properties may be determined for standard materials (i.e., materials for which "true" values have been estimated with a degree of accuracy which is assumed to be high) and for rock samples. The accuracy of property determinations for the rock samples will be estimated by replicate determinations of a property for one or more standard material and comparison of the mean value of the results with the accepted "true" value of the property for the standard(s). Statements about accuracy will include an estimate of the accuracy (the difference between the accepted "true" value and the mean value of the replicate measurements) and the precision (the standard deviation of the replicate measurements).

The precision of property determinations for rock samples also will be estimated by performing replicate measurements on individual rock samples. Because thermal-expansion experiments may induce permanent changes in the rock samples, these replicate measurements may not provide reliable estimates of precision. The usefulness of replicate measurements on rock samples will be evaluated during development of relevant technical procedures. If precision can be determined by means of measurements on rock samples, it will be determined for each thermal/mechanical unit separately. The initial estimates of precision will be made using five replicate property determinations from each thermal/mechanical unit . These precisions will be indicative of values of multi-operator, single-location measurements (see ASTM E-177 for definitions of these and related terms), so that they will be described as "repeatability" rather than "reproducibility."

The precision with which measurements have been made using standard materials is discussed in Section 3.2.2.

3.2 Experiments

3.2.1 Quality Assurance Requirements and Technical Procedures

All work will be performed in accordance with the Sandia National Laboratories YMP quality assurance requirements. The experiments will be governed by SNL Quality Assurance Grading Report (QAGR) No. 1.2.3.2.7.1.2 which specifies applicable QA criteria.

Appropriate planning documents and Technical Procedures (TPs) (Table 3.2-1) will be prepared for each experiment. The planning documents and TPs will be issued prior to initiation of thermal-expansion data collection activities.

3.2.2 Accuracy and Precision

Previous determinations by SNL of thermal-expansion behavior of tuffs for the Yucca Mountain Site Characterization Project included calibration checks using a platinum sample. The coefficient of thermal expansion of this standard material was required to be within ±2.5 percent of the "true" value before thermal-expansion experiments on rock samples were performed. Valentich (1981) suggests that accuracies of three percent or better are achievable using tube-type dilatometers. This suggested value of accuracy is consistent with ASTM C-372, which goes on to state that accuracies of 0.5 percent are achievable. (Note that although ASTM C-824 is one standard test method that uses the dilatometric technique, this method should not be used for development of technical procedures if accuracies of better than five percent are desired.)

The precision (reproducibility) of SNL determinations of the thermal expansion of platinum is ≤4.5 percent except for the temperature interval of 25 to 50°C, in which precision is approximately 12 percent. (This high value results from starting the measurements at 25°C rather than beginning at some lower temperature (e.g., 15 to 20°C) before measuring the expansion for 25 to 50°C. Much lower values of precision

Table 3.2-1

Technical Procedures[a] for Determination of Coefficients of Thermal Expansion

TP-059	Procedure for laboratory sample petrology determination (completed)
TP-062	Laboratory procedures for mineralogic analysis by X-ray powder diffraction Part 1: Data gathering (completed)
TP-064	Procedures for vacuum saturation of geologic core samples (completed)
TP-065	Procedure for drying geologic core samples to constant weight (completed)
TP-102	Laboratory procedure for mineralogic analysis by X-ray powder diffraction Part 2: Data analysis (completed)
TP-143	Seismic attenuation measured by the resonant-bar technique
TP-203[b]	Measurement of Thermal Expansion of Geologic Samples using a Push Rod Dilatometer (completed)

[a] Technical procedures for this work will be standard procedures and will incorporate relevant portions of nationally recognized procedures.
[b] More than one TP may be developed for thermal expansion measurements, depending on the need for equipment modifications to perform the parameter-effects testing discussed in Section 2.2.3 and the tests on fractured samples discussed in Section 2.2.2.1.

for the 25 to 50°C range should be achievable if the tests are run differently in the future.)

ASTM C-832 provides data on precision that gives a repeatability of ±0.152 to 0.520 percent and a reproducibility of ±0.191 to 0.735 percent for refractory bricks. These precisions may not apply to the rock samples because rock is not a homogeneous material and permanent changes may be introduced during the thermal-expansion experiments. Thus the values for platinum and refractories probably are minimum values to be expected during future testing.

3.2.3 Range of Expected Results

The range of expected values for the coefficients of thermal expansion of the thermal/mechanical units is given in Table 3.2-2. The ranges have been calculated as $\overline{X} \pm 3S$, where $\overline{X}$ and S are based on existing data. (For "no data" entries, most expected values should lie within the range of values provided in

Table 3.2-2

Ranges in Expected Values of Coefficients of Thermal Expansion

	Range (10^{-6}/°C)					
	25-50°C	50-100°C	100-500°C	150-200°C	200-250°C	250-275°C
TCw	4.3-13.3[a]	5.0-11.0[a]	NA[b]	NA[b]	NA[b]	NA[b]
PTn	4.9 to 16.7[c]	1.1-4.0[c]	NA[b]	NA[b]	NA[b]	NA[b]
TSw1	4.3-13.3	5.0-11.0	5.3-8.3	9.7[d]	No data	No data
TSw2	4.3-13.3	5.0-11.0	5.3-8.3	9.7[d]	No data	No data
Altered TSw3	No data	No data	No data	No data	No data	No data
TSw3	13.3[d]	10.6[d]	8.0[d]	No data	No data	No data
CHn1v	-4.9 to 16.7	1.1-4.0	-1.1[d]	No data	No data	No data
CHn1z	3.3-15.9	0.9-17.7	-40.0-8.6	No data	No data	No data
CHn2v	No data	No data	NA[b]	NA[b]	NA[b]	NA[b]
CHn2z	No data	No data	NA[b]	NA[b]	NA[b]	NA[b]

[a] Values assumed to be the same as those for Units TSw1 and TSw2.
[b] Not applicable.
[c] Values assumed to be the same as those for Unit CHn1v.
[d] Previous data obtained on a single sample; no standard deviation available.

the table. The exceptions are the entries for Units TSw1 and TSw2 at temperatures 200°C; coefficients of thermal expansion for these two units at these temperatures may be as large as 50 x 10^{-6}/°C.) The temperature intervals in the table were chosen for convenience; presentation of future data will use a format as discussed in Section 2.2.5.1.

The negative values in Table 3.2-2 are real, in the sense that some samples have been observed to contract in the temperature ranges containing the negative values. The contractions are interpreted to be drying phenomena rather than true negative expansion caused by heating. In moist conditions, none of the tuff samples will contract during heating.

Another aspect of Table 3.2-2 is the apparent temperature dependence of the coefficients of thermal expansion. The nonlinearities in temperature-displacement curves that can be inferred from the temperature dependence are not an artifact of testing. In addition to a mild temperature dependence of the coefficients of thermal expansion (and elastic properties) of the constituent minerals, some of the minerals undergo significant transformations when heated in the temperature ranges in the table. Examples of this are silica (SiO_2) polymorphic inversions (tridymite and cristobalite), which cause larger coefficients at temperatures above 150°C, and dehydration of zeolites, which causes large contractions whenever the temperature exceeds the boiling temperature for the water in the pores of the sample.

3.2.4 Equipment and Design Requirements

The equipment required to perform measurements of thermal-expansion behavior is composed of one or more dilatometers, a length-measuring device, and a vacuum chamber suitable for vacuum saturation of the samples. Additional discussion of equipment and test design is provided in Section 2.2.5.1.

3.2.5 Analyses of Measurements

Data obtained during thermal-expansion measurements, as well as supporting information such as mineralogy and density, will be reported in a series of data reports. The data in these reports then will be analyzed using several statistical techniques. The general sequence of steps will be as follows:

1. Examine the spatial correlation (as a function of depth, of distance from the point of origin, or of location within a unit) using geostatistical techniques and analyses thereof.

2. Examine the nature of the statistical distribution of data gathered at a specific location (i.e., core hole, lateral drift, etc.) for each unit.

3. Calculate appropriate statistical parameters for the data from each location for each unit, or of subgroups of data identified at a single location within each unit.

4. To the extent possible, use analysis-of-variance techniques to evaluate the variability between locations for each unit.

5. When appropriate, perform correlation analysis of properties with each other and with spatial location for each unit.

6. Report the results of these analyses in one or more analysis reports.

Implicit in the listing above is the validity of the current definition of the thermal/mechanical units. At several times during the data-gathering process, data from adjacent units will be examined and compared to evaluate whether the division into thermal/mechanical units is accurate, justifiable, or both. Information gathered for other studies, especially Study 8.3.1.15.1.1 (Laboratory Thermal Properties) and Study 8.3.1.15.1.3 (Laboratory Determination of Mechanical Properties of Intact Rock), also will be used in these evaluations.

The analyses outlined above will be performed on the data resulting from laboratory experiments. If the in situ thermal-expansion behavior differs from that seen in the laboratory, a method suitable to extrapolate the laboratory data to the in situ scale will be developed.

3.2.6 Representativeness of Results

On the basis of the statistical considerations included in the sampling strategy (discussed in Section 2.2) and on the plans for analyses of the resulting data, experimental results for the coefficients of thermal expansion are expected to be as representative of the site as necessary for the requirements of repository design and performance assessment.

3.2.7 Performance Goals and Confidence Levels

The performance goals and confidence levels established by repository design and performance assessment have been included in the design of a sampling strategy. As such, there is a reasonable assurance that some of the goals will be achieved with the required confidence. The variability of existing data in some of the thermal/mechanical units suggests that a certain number of the performance goals may not be achievable as established. Should this appear to be the case as data are obtained, consultations will be held with the appropriate Project personnel to reevaluate the performance goals, the confidence levels, or both.

4.0 APPLICATION OF RESULTS

Sections 1.1.1, 1.2.1, and 1.2.2 of this document discuss the manner in which results from the laboratory thermal-expansion experiments are to be applied for resolution of regulatory requirements and the Information Needs and Investigations identified by the performance-allocation process. The data from this study will be used to address or help to resolve the Issues and Investigations identified by the Yucca Mountain Site Characterization Project that are listed in Table 4.0–1. Data obtained in the laboratory for the coefficients of thermal expansion will be used as estimates of coefficients of thermal expansion for the rock mass. The

Table 4.0–1

Issues and Investigations Addressed During the Laboratory Thermal-Expansion Study

Issue	Investigation	SCP Section
1.6	Ground-water travel time	8.3.5.12
1.11[a]	Configuration of underground facilities (post-closure)	8.3.2.2
1.12	Seal characteristics	8.3.3.2
2.4	Waste Retrieval Option (data requirements subsumed in Issue 4.4)	8.3.5.2
4.2	Nonradilogical Health and Safety (data subsumed in Issue 4.4)	8.3.2.4
4.4[b]	Preclosure design and technical feasibility	8.3.2.5

[a] Includes data requirements from Issue 1.10.

data for the rock mass then will be compared to values obtained during in situ experiments and an evaluation of the most realistic rock-mass thermal-expansion behavior will be made. The relevant coefficients of thermal expansion then will be used as input to calculations of thermal stresses and displacements that are a part of the evaluation of stability, operability, and flexibility of the underground-facility design (Issues 1.11, 2.4, 4.2, and 4.4). In addition, the thermal-expansion data will contribute to the definition of the disturbed zone (Issue 1.6) and to determination of requirements for sealing of underground openings (Issue 1.12).

4.1 Resolution of Site Programs

Results of the Laboratory Thermal-Expansion Study will provide data to aid in resolving Site Program 8.3.1.15 (Thermal and Mechanical Rock Properties Program). The contribution of the study will be both direct (by determination of coefficients of thermal expansion) and indirect (by contributing to the results of a number of in situ experiments).

4.2 Resolution of Performance and Design Issues

This study will contribute to the resolution of performance and design Issues by providing data on coefficients of thermal expansion that will be used as input to thermomechanical calculations. These calculations will in turn aid in resolving those Issues that require such calculations (e.g., 1.6, 1.11, 1.12, and 4.4).

5.0 SCHEDULE AND MILESTONES

5.1 Duration and Interrelationship of Laboratory Thermal-Expansion Study Experiments

The work for this study can be divided into three major parts — preliminary scoping studies using existing core or outcrop samples, followed by site-characterization testing in two stages, first using samples from new core holes and then using samples from the ESF. It is anticipated that plans for sampling of each thermal/mechanical unit would be developed prior to the time that coring of the new holes begins. Sampling then would begin as soon as core from the first selected interval was available for sampling. Sample preparation time is expected to be minimal relative to the time required for the actual experiments. Sampling and experiments would continue until all preselected sampling intervals had been sampled.

For sampling in the main accesses and drifts, the sequence will be very similar to that described for the new core holes.

5.2 Scheduling Relative to Other Studies

This study interfaces with other studies in one area. Coefficients of thermal expansion will be determined in the laboratory in support of a number of in situ experiments (described in Study Plans 8.3.1.15.1.6, In Situ Thermomechanical Properties, and 8.3.4.2.4.4, Engineered Barrier System Field Tests). Interpretation and analysis of these in situ experiments will depend in part on the laboratory data. Samples in support of the in situ experiments will be obtained during experiment set-up in the ESF, and laboratory data should be available before each relevant in situ experiment is completed.

This study exerts no presently identifiable constraints on other YMP studies.

5.3 Schedule and Milestones

The exact schedule for obtaining samples and conducting experiments is dependent upon the scheduling of new core holes, the construction schedule for the ESF, and the level of funding.

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C–824: Linear Thermal Expansion of Vitreous Glass Enamels and Glass Color Frits by the Dilatometer Method.
C–832: Measuring the Thermal Expansion and Creep of Refractories Under Load.
E–177: Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material (1971; reapproved 1980)
E–228: Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer.
E–289: Linear Thermal Expansion of Rigid Solids with Interferometry.

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SP 8.3.1.15.1.2, R1

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