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In Situ Test Programs Related to Design and Construction of High-Level Nuclear Waste (HLW) Deep Geologic Repositories

Main Report
Final Report (Task 2) - June 1981-November 1982

Prepared by W. Roberds, F. Bauhof, L. Gonano, E. Wildanger, W. Dershowitz,
F. Marinelli, K. Jones, C. Weldon, B. Nebbitt,
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Golder Associates

Prepared for
U.S. Nuclear Regulatory
Commission

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REPORTS IN SERIES

Report Number	Issuance Date	Contract Task	Title
NUREG/CR-2613	3/12/82	1	Identification of Characteristics which Influence Repository Design - Tuff
NUREG/CR-3065 Vols. 1 & 2	3/83	1	Identification of Characteristics Which Influence Repository Design - Domal Salt
(draft)	2/82	2	In Situ Test Programs Related to Design and Construction of High Level Nuclear Waste (HLW) Deep Geologic Repositories
NUREG/CR-2854	7/9/82	3	Evaluation of Alternative Shaft Sinking Techniques for High Level Nuclear Waste (HLW) Deep Geologic Repositories
NUREG/CR-2959	10/12/82	4	Relationship of an In Situ Test Facility to a Deep Geologic Repository for High Level Nuclear Waste
(in preparation)		5	Evaluation of Engineering Aspects of Backfill Placement for High Level Nuclear Waste (HLW) Deep Geologic Repositories

ABSTRACT

This report represents the results of Task 2, "In Situ Test Programs Related to Design and Construction of High Level Nuclear Waste (HLW) Deep Geologic Repositories," of U.S. Nuclear Regulatory Commission (NRC) Contract NRC-02-81-037, "Technical Assistance for Repository Design." The purpose of the complete project is to provide the NRC with technical assistance to enable the focused, adequate review by NRC of aspects related to design and construction of an in situ test facility and final geologic repository, as presented in U.S. Department of Energy (DOE) Site Characterization Reports (SCR) and License Application (LA).

The Task 2 results include the general recommendation of available tests which should be considered in designing media/site specific in situ test programs. Tests will be conducted within an in situ test facility, consisting of an exploratory shaft and an underground test facility at the prospective repository horizon. Plans for these programs are expected to be presented in the initial SCR and the complete results presented in the LA. The media and sites considered include (1) basalt at Hanford, Washington; (2) tuff at Yucca Mountain, Nevada Test Site; (3) domal salt at specific Gulf Coast sites; (4) bedded salt at an unspecified site; (5) granite at an unspecified site.

A licensing perspective is outlined and a defensible rationale developed and utilized for the test selection process. This rationale essentially consists of:

- Establishing the information needs for construction authorization
- Assessing the relevant capabilities of available tests
- Matching the capabilities of specific tests to the perceived information needs.

The information needs at any time consist of the additional information (if any) needed in order to predict satisfactory repository system performance with the required level of confidence, and thus are a function of:

- The significance of the repository engineered components and site characteristics to system performance
- The currently available information, which may be supplemented with time
- The acceptable level of confidence in satisfactory performance for each licensing step.

Determination of the acceptable levels of confidence and the significance of repository system components is outside the scope of this report. Suitable assumptions have thus been made regarding the development of information needs for construction authorization by the time of initial SCR submittals.

Tests which are available and respond to the perceived media/site specific information needs, either by simulation or assessment of site characteristics, are identified and their capabilities assessed. Specific in situ tests are investigated and described in detail. Research and development which might be effective in improving test capabilities have been recommended.

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

This report represents the results of Task 2, "In Situ Test Programs Related to Design and Construction of High Level Nuclear Waste (HLW) Deep Geologic Repositories," of U.S. Nuclear Regulatory Commission (NRC) Contract NRC-02-81-037, "Technical Assistance for Repository Design."

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

- To enable the focused, adequate review by NRC of aspects related to design and construction of an in situ test facility and final geologic repository, as presented in U.S. Department of Energy (DOE) Site Characterization Reports (SCR)
- To ascertain that the DOE site characterization will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a License Application (LA).

This report presents a licensing perspective, describes a methodology for designing an in situ test program and recommends a tentative test program together with test details which should be considered between initial SCR submittal and LA. The in situ tests, tentatively recommended to be conducted within an in situ test facility, have been compiled with reference to the currently perceived specific information needs of five media/sites: (1) basalt at Hanford, Washington; (2) tuff at Yucca Mountain, Nevada Test Site; (3) domal salt at specific Gulf Coast sites; (4) bedded salt at an unspecified site; (5) granite at an unspecified site.

ES.2 PERSPECTIVE

Any deep geologic repository for the permanent disposal of high level waste (HLW) must be designed to achieve certain performance objectives, which can be summarized as:

- Short term construction and operation objective (through decommissioning, about 100 years) of minimizing hazards jeopardizing the safety of the public and personnel during repository construction and operation (including possibly retrieval and decommissioning activities).
- Long term waste containment and isolation objective (post-decommissioning, from about 100 to 10,000's years) of minimizing radionuclide flux (rate/unit area) to accessible environment and thus minimizing hazards jeopardizing public safety after decommissioning. This objective dictates maintaining a waste retrieval capability for a specified period after waste emplacement

and prior to decommissioning, thereby providing the opportunity for verifying a sufficiently high probability of satisfactory long-term performance and also providing a contingency plan for demonstrated non-verification.

Performance criteria define and, where possible, quantify performance objectives. These criteria can be given either deterministically (i.e., an absolute numerical limit) or probabilistically (i.e., an acceptable level of confidence that a numerical limit will not be exceeded by the particular repository performance indicator). Where the criteria are given deterministically, a determination must still be made, although implicitly rather than explicitly, of the level of confidence in not exceeding the deterministic limit.

The performance of the repository will be a function of both the engineered components of the repository and the inherent characteristics of the site in which it is located. In many cases, the response of the combined system is a result of an interaction of both engineered components and site characteristics. Thus, performance objectives, criteria and assessment can be related to the integrated system of engineered components and site characteristics. This concept forms the basis for the methdology of establishing the information needs and the associated in situ testing requirements presented here.

There are two primary ways of maximizing the level of confidence that the performance criteria will be achieved and that the actual performance of the repository system will be satisfactory:

- Selecting a suitable repository site

- Appropriately designing, constructing, and operating the repository.

Several questions are apparent:

- How can a suitable site for a repository be selected so as to maximize the level of confidence in satisfactory performance?

- Once a site has been selected, how can the repository be designed and constructed so as to maximize the level of confidence in satisfactory performance?

- How can a high level of confidence in satisfactory performance be demonstrated at each step in repository development?

These three questions are critical to the licensing process, and define the development of a repository. There is a need to assess, at various discrete stages during development, the level of confidence in satisfying each designated performance criterion, based on the available data on engineered components and site characteristics and the uncertainty of this data. If that confidence level is found to be acceptably high, the appropriate authorization or license amendment necessary to initiate the next phase of repository development is granted. However, if the level of confidence in compliance is found to be unacceptably low, then one of two approaches can be taken by the applicant:

(1) If the level of confidence can be increased by additional cost effective characterization or design modification, then that characterization or modification may be performed and the application updated.

(2) If the level of confidence cannot be cost effectively increased by further characterization or design modification, then repository development should be stopped at this site.

The discrete points in repository development are (see Figure ES-1):

(1) Site characterization report (SCR) submittals, primarily DOE decision points for which NRC only offers opinions
(2) License application (LA)
(3) Updated application for license to operate (emplace waste)
(4) License amendment to decommission.

The acceptable level of confidence in satisfactory performance for each step can be established by considering the consequences of not satisfying the performance criteria at that particular stage, as well as the risks for other alternatives in HLW disposal. These acceptable levels will increase with repository development. As presently perceived, it should be highly probable at LA that ultimate repository system performance will be satisfactory in order to provide reasonable assurance that the repository will be fully licensable, prior to extensive development and major expenditure of funds.

Acceptable levels of confidence may be established either:

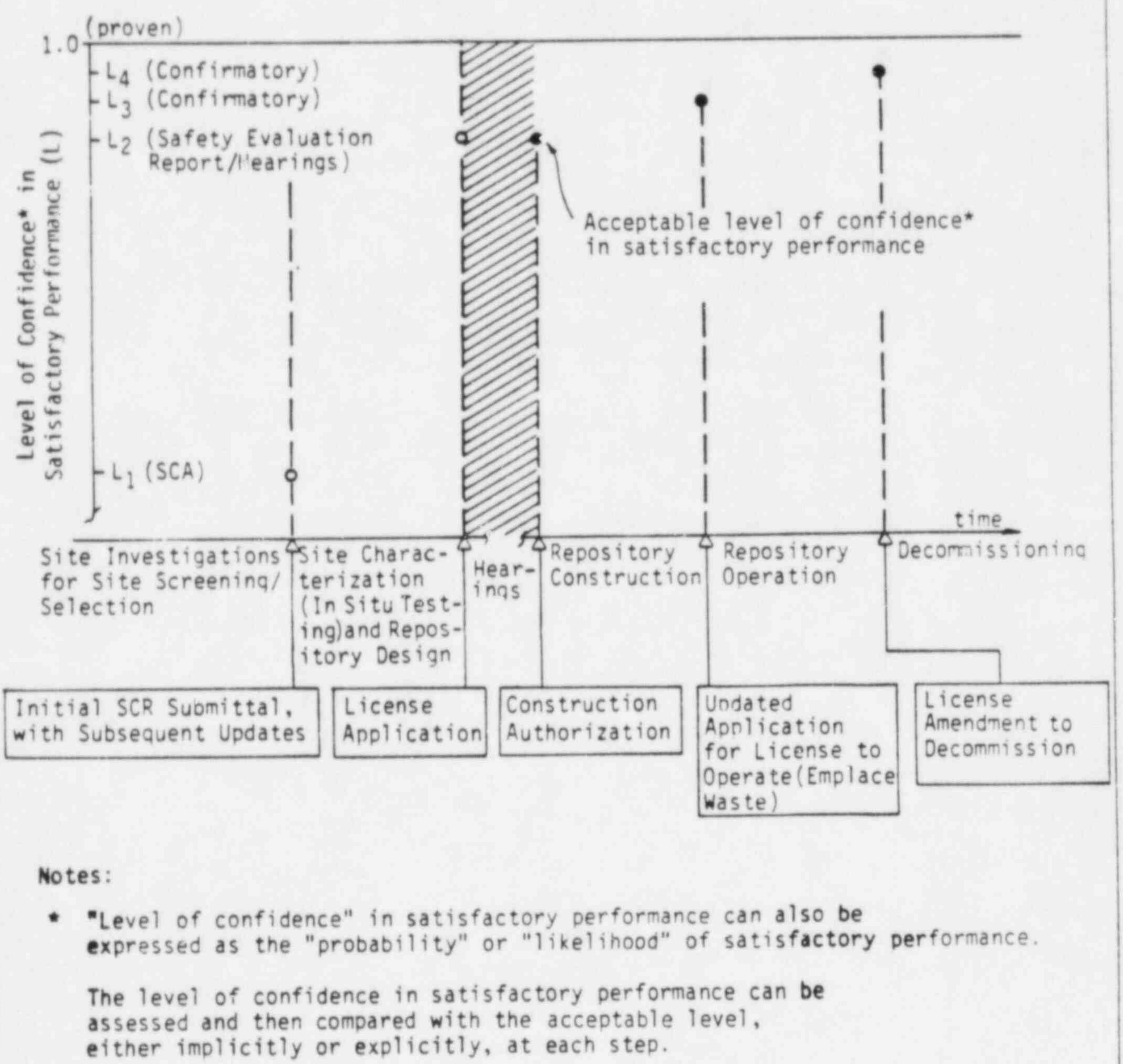
- Implicitly, through progressive technical discussions between the regulator and applicant

- Explicitly, through rigorous decision-making utilizing quantitative risk assessment methodology.

Although recognizing the difficulties in performing quantitative risk assessments and subsequently defending the results in the decision-making process (especially within the institutional framework), Golder Associates considers it important to be attempting to utilize uncertainty and probability assessments of the important parameters affecting repository performance. These assessments should be used as a guidance tool during the site characterization phase. While these probability approaches are being established, the current approach of assessing acceptability implicitly through technical discussions needs to be continued.

ACCEPTABLE LEVEL OF CONFIDENCE IN SATISFACTORY PERFORMANCE

Figure ES-1



Notes:

* "Level of confidence" in satisfactory performance can also be expressed as the "probability" or "likelihood" of satisfactory performance.

The level of confidence in satisfactory performance can be assessed and then compared with the acceptable level, either implicitly or explicitly, at each step.

It is anticipated that certain testing/monitoring methods will need to be utilized in order to demonstrate an acceptable level of confidence in satisfactory performance at each step of repository development. This perspective of the licensing process can be summarized, as follows:

- For site screening/selection, as summarized in the initial SCR submittal, site investigation will focus generally on large-scale features and consists of surface, borehole and laboratory testing. This generally rough assessment of characteristics will allow for comparison between sites and for the demonstration of an acceptable level of confidence in satisfactory performance based on a conceptual repository design.

- For a detailed repository design, as summarized in a license application (LA), site characterization will focus on features adjacent to planned shafts and the repository horizon, as well as on large-scale features. This site characterization will consist primarily of the construction and operation of an in situ test facility. In addition to the improved assessment of site characteristics provided by in situ testing and by monitoring of the in situ test facility, certain aspects of key issues may be adequately resolved by prototype simulation (and extrapolation of results) and predictive models may be partially verified. The construction and operation of this in situ test facility may thus provide information for the detailed repository design and for the demonstration of an acceptable level of confidence in satisfactory performance with that design.

- In an updated application for license to operate (emplace waste), the assessment of site characteristics will be further refined as more areas underground are exposed and as the performance of the repository is monitored. This monitoring may also provide information for modifications in design (if required), additional verification of predictive models, updating of performance predictions, and for the demonstration of an acceptable level of confidence in satisfactory performance.

- Finally, in a license amendment to decommission, the assessment of site characteristics will be further refined by monitoring repository performance. This monitoring may also provide information for additional verification of predictive models and updating of performance predictions. A final assessment of the level of confidence in satisfactory long-term performance will be made, and a determination made by the NRC as to whether this confidence level is sufficiently high. If it is determined that the confidence level is too low, modifications to the repository or retrieval of the waste will be required.

ES.3 APPROACH

A defensible rationale has been developed and utilized to tentatively select available tests to be included in the media/site specific in situ test programs. This rationale essentially consists of:

- Establishing the information needs for construction authorization at each site
- Assessing the capabilities of available tests to meet the specific information needs
- Matching the capabilities of specific tests to the perceived information needs.

The information needs existing at any time result from the unacceptable uncertainties in the prediction of repository system performance. Information needs are determined as follows:

- Identify the existing information and assess the associated level of confidence in satisfactory repository system performance
- Compare the assessed level of confidence with the acceptable level, either implicitly or explicitly
- Determine what additional information is needed to raise the level of confidence in satisfactory performance to the acceptable level, by:
  - establishing the relationship between each component of the repository system and system performance (i.e., sensitivity)
  - identifying where the existing information regarding significant components of the system is insufficient and can be readily supplemented.

The information needs at any time are thus a function of:

- The significance of repository engineered components and site characteristics to system performance
- The currently available information, which may be supplemented with time
- The acceptable level of confidence in satisfactory performance for each licensing step.

The significance of the repository system components to system performance and the acceptable levels of confidence have not been determined and are outside the scope of this report. Qualitative assessments of acceptable levels of confidence and of the significance of system components, as well as assumptions regarding the information developed by the time of the initial SCR submittal, have thus been made for the purpose of establishing information needs for construction authorization.

The selection of tests to satisfy the perceived information needs involves the prior determination of the relevant capabilities of candidate tests, and the integrated compilation of a program of tests that collectively best respond to the information needs. In the selection of these tests, only presently available tests and potential advancements to the state-of-the-art within current concepts and technologies are considered. With future development, the test capabilities may be improved.

These tests satisfy the information needs either by:

- Simulating various aspects of the repository (e.g., construction techniques) for extrapolation of results
- Assessing identified media/site specific characteristics (e.g., hydraulic conductivity) to be used in numerical modeling
- Verifying predictive numerical models.

It is expected that the in situ test program will evolve with time somewhat independently for each media/site considered as the perceived information needs and test capabilities develop. It is even possible that the information needs for construction authorization might be satisfied prior to the initial SCR submittal, precluding the need for most (if not all) in situ testing. The in situ test program must also be flexible enough to take into account new information which becomes available during its performance, as presented in SCR updates. The complete design and specifications for any particular test cannot be accomplished a priori without detailed descriptions of each individual test location, as well as identification of specific information needs. Hence, the recommendations for the conduct of specific tests are of a scoping nature only.

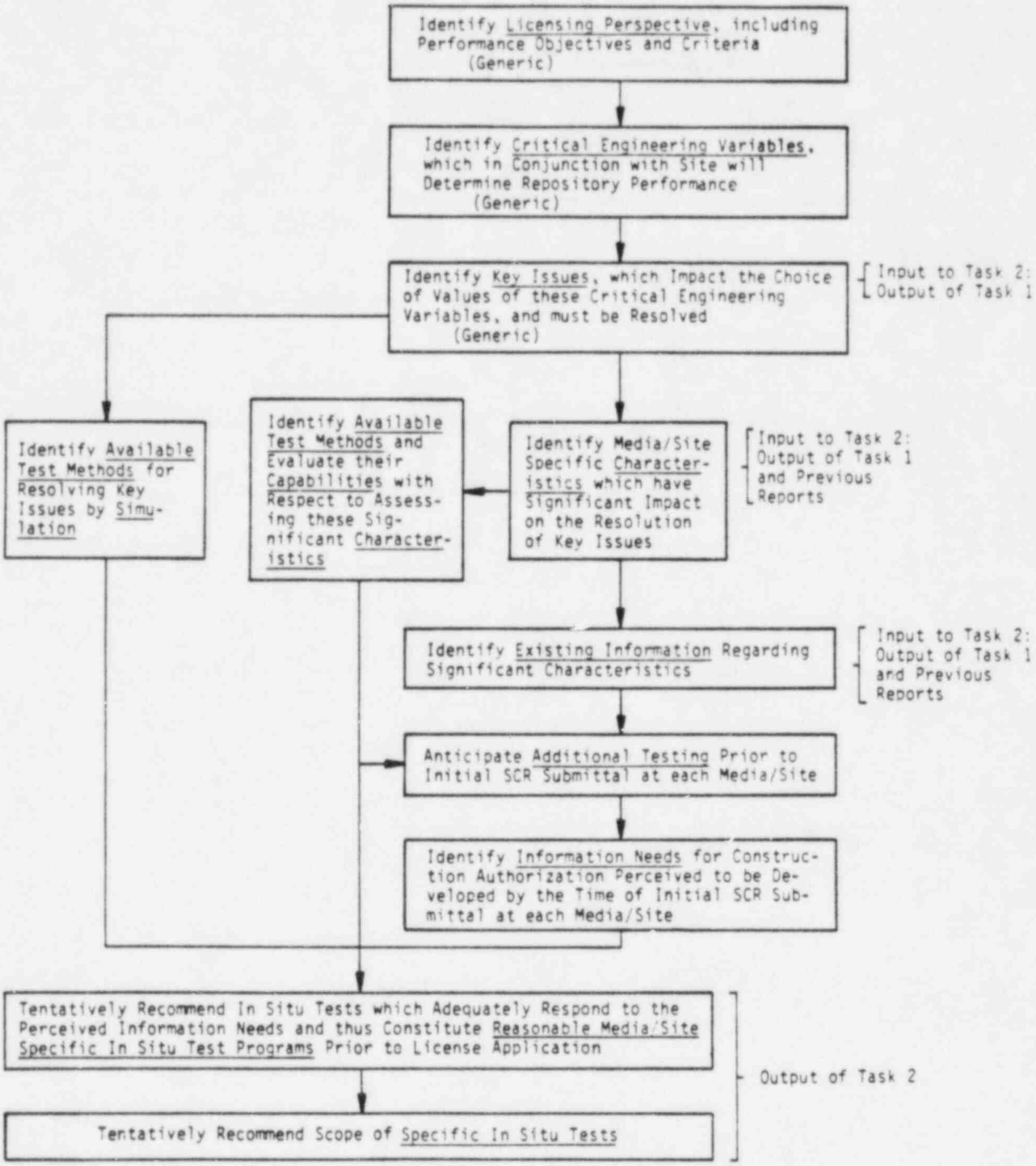
ES.4 STUDY ACTIVITIES

In the course of developing recommendations for in situ testing, the following activities have been undertaken (see Figure ES-2):

- The licensing perspective, including the various licensing steps, for repository development has been identified, based on the procedural rule of 10-CFR-60. At each step, the level of confidence in satisfactory repository system performance should be assessed, and a determination made of whether that level of confidence is sufficient to allow further development. The acceptable level of confidence at each step underlies the establishment of the information needs.

TASK 2 ACTIVITY FLOW CHART

Figure ES-2



Note: Media/site specific considerations have been made to the extent possible in each activity for basalt, tuff, domal salt, bedded salt, and granite.

Rev. ______ Dwg. No. AB13-1143 ______ Date Nov 92 ______ Eng DR

- Critical engineering variables, which in conjunction with the site will determine repository system performance, have been identified. This has been accomplished by first identifying the primary engineering variables of repository design and construction (e.g., shaft dimension, shape, etc.). The influence of these primary engineering variables on the level of confidence in satisfactory performance has been qualitatively assessed and those perceived to have a significant potential impact, in conjunction with a capability for change at reasonable cost, have been judged to be critical. These critical engineering variables should be investigated by in situ testing, as well as emphasized during NRC's review process.

- Key issues, relating to the performance criteria, have been previously identified in Task 1 of this project. These key issues impact the choice of values for the critical engineering variables and must be adequately resolved to demonstrate an acceptable level of confidence in satisfactory performance. These key issues, which must be addressed in both the SCR and the LA review, include:

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

    - Thermal Response. Can the temperature field be adequately predicted as a function of time and reliably incorporated into mechanical, hydrological and geochemical models?

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

    - Hydrologic Response. Can an adequate prediction be made regarding the resaturation time of the repository (post-closure) and of the long-term groundwater flow through the repository?

    - Geochemical Response. Can an adequate prediction be made of the extent and effect of geochemical alteration of the engineered barriers and the rock? Can the quantity and rate of migration of specific radionuclides over the long-term be adequately predicted?

    Information needs are thus related to the resolution of these key issues.

- Characteristics which have a significant impact on the resolution of the key issues have been identified (see Table ES-1). Each of the characteristics has subsequently been evaluated for each media/site

SIGNIFICANT CHARACTERISTICS

Table ES-1

CHARACTERISTICS	KEY ISSUES				
	Constructability	Thermal Response	Mechanical Response	Hydrologic Response	Geochemical Response
GEOLOGIC SETTING					
Stratigraphic/structural*	●	●	●	●	●
Tectonic	○	●	●	●	○
In situ stress field	○	○	●	○	○
In situ hydraulic head field	●	○	○	●	○
In situ temperature field	●	●	○	○	○
RESPONSE					
(MECHANICAL)					
Strength	●		●	○	○
Deformation	○		●	○	
Creep/fusing	○		●	○	○
(THERMAL)					
Thermal conductivity		●	○		
Heat capacity		●	○		
Linear thermal expansion		●	●		
(HYDROLOGIC)					
Hydraulic conductivity				●	○
Effective porosity				●	●
Specific storage				●	
(GEOCHEMICAL)					
Dispersivity					●
Adsorption/retardation					●
Alteration/solubility	○	○	○	●	●

* includes the physcial and chemical characteristics of each rock mass unit (including pore fluid composition).

● characteristic significantly impacts resolution of key issues.

○ characteristic impacts resolution of key issues, but to a lesser degree in terms of its influence on satisfying each of the performance criteria. This evaluation has taken into account the following general attributes of each characteristic:

- availability of cost-effective design and construction techniques which allow for a conservative assumption of the value of the characteristic
- uncertainty in the representation of the phenomenological laws of nature by the performance prediction model
- sensitivity of the performance prediction model to the value of the characteristic
- cost effectiveness and scheduling limitations of measures to reduce the uncertainty in the assessment of the value of the characteristic.

From this evaluation, a tentative determination has been made regarding the maximum acceptable level of uncertainty in the assessment of each of the characteristics. However, until the licensing perspective (Figure ES-1) has been clarified and the sensitivity of system performance to all the system components determined, these maximum acceptable levels of uncertainty for each characteristic can be considered as qualitative indicators only.

- The current assessment of the significant characteristics for each media/site has been based on previous work by Golder Associates, performed either as part of this project or in previous projects. These assessments have been presented in terms of a best estimate and an indication of the level of uncertainty in that value.

- Test methods (including surface, borehole, laboratory, and in situ tests) which are available to assess the significant characteristics have been identified. Existing repository-related in situ testing programs have been summarized to assist in the identification of available in situ tests. The inclusion of other tests has been based on experience.

  The capabilities of each of the available test methods regarding its determination of the significant characteristics have been assessed. This assessment has been based partly on the test's representation of those environmental conditions which affect the characteristic. The assessment has also included the factor of test scale, i.e., whether a representative volume of rock mass is tested. The importance of index testing in the assessment of characteristics and their variability throughout the zone of influence has been recognized.

- Those in situ tests which can be used to resolve the key issues by simulation have been identified. These tests, as well as the in situ test facility itself, simulate various construction/ operation aspects of the repository, so that their results can be used to directly predict expected repository performance.

- The testing which will precede in situ testing has been anticipated. The information obtained by this testing at sites where it is now incomplete will supplement the existing information, and the present assessment of significant characteristics may change prior to initial SCR submittal.

- The information needs for construction authorization, which are perceived to exist at the time of initial SCR submittal, have been identified, based on the current media/site specific assessment of significant characteristics, anticipated future site investigation, and the licensing perspective.

- Media/site-specific in situ test programs have been tentatively recommended (see Table ES-2). These programs consist of available in situ test methods which best respond to the information needs, either by simulation or by adequate assessment of the significant characteristics. Where no one appropriate method exists, a combination of independent methods which adequately responds to the perceived information needs has been identified.

  An example in situ test facility which can accommodate these programs has been developed under Task 4 of this project.

- Scoping recommendations have been made regarding specific in situ tests. These tests have been investigated in detail, and a description, an evaluation, and a recommendation regarding methodology and utilization of results have been presented for each.

- Potentially effective research and development of in situ testing techniques have been identified and recommended. Currently available in situ tests may present difficulties in fulfilling perceived information needs, especially in assessing characteristics for the additional effects of radiation, temperature, and long term behavior. These recommendations are primarily concerned with advancements within available concepts and technologies and not with the development of new or hybrid tests.

To the extent possible, consideration has been given in each of the above activities to aspects which are perceived to be unique to each of the media and sites under consideration, i.e., basalt, tuff, domal salt, bedded salt, and granite.

ES.5 SUMMARY AND CONCLUSIONS

Golder Associates believes that this report presents defensible recommendations regarding those tests which should be specifically considered in a reasonable in situ test program conducted within an in situ test facility prior to construction authorization at any site. These tests

REASONABLE IN SITU TEST PROGRAMS

Table ES-2
1 of 3

IN SITU TEST METHOD (Appendix, Section):	CHARACTERISTICS ASSESSED BY TEST: (see Table ES-1)									ASPECTS SIMULATED BY TEST:		MINIMUM NUMBER OF TESTS PERFORMED IN:		MEDIA/SITE FOR WHICH TEST IS RECOMMENDED:				
	Geologic Setting																	
	Stratigraphic/ Structural (1a)	Tectonics	In Situ Stress Field (1b)	In Situ Hydraulic Head Field (1b)	In Situ Temperature Field(1b)	Mechanical Characteristics (2)	Thermal Characteristics (2)	Hydrologic Characteristics (2)	Geochemical Characteristics (2)	Constructability	Repository Performance	Exploratory Shaft	Underground Test Facility	Basalt (3)	Tuff (4)	Domal Salt (5)	Bedded Salt (6)	Granite (7)
Plate Test (9) (A.1)						●						-	a	●	●			●
Block Test (A.2)						●	●	●	●			-	2	●	●	●	●	●
Chamber Test (A.3)								●	●		●	-	1	●	●			●
Mine-By Test (A.4)						●				●	●	-	1	●	●	●	●	●
Heater Test (Large Scale) (A.5)							●		●	●	●	-	1	●	●	●	●	●
Heater Test (Small Scale) (A.5)							●					a	a	●	●	●	●	●
Tracer Test (A.6)				●				●	●			a	a	●	●			●
Multiple Borehole Permeability Test (10) (A.7)								●				a	a	●	●			●
Overcoring (A.8)			●									b	b	●	●	●	●	●
Flatjack Test (A.9)			●			●						a	a	●	●	●	●	●
Acoustic Emission Monitoring (A.10)		●				●				●	●	c	c	●	●	●	●	●
Exposure Mapping (A.11)	●							●	●	●		c	c	●	●	●	●	●

Rev.
Dwg. No. 18:3-1163 Date 12-82 Eng BR

REASONABLE IN SITU TEST PROGRAMS

Table ES-2
2 of 3

IN SITU TEST METHOD (Appendix, Section):	CHARACTERISTICS ASSESSED BY TEST: (see Table ES-1)									ASPECTS SIMULATED BY TEST:		MINIMUM NUMBER OF TESTS PERFORMED IN:		MEDIA/SITE FOR WHICH TEST IS RECOMMENDED:				
	Geologic Setting																	
	Stratigraphic/ Structural (1a)	Tectonics	In Situ Stress Field (1b)	In Situ Hydraulic Head Field (1b)	In Situ Temperature Field (1b)	Mechanical Characteristics (2)	Thermal Characteristics (2)	Hydrologic Characteristics (2)	Geochemical Characteristics (2)	Constructability	Repository Performance	Exploratory Shaft	Underground Test Facility	Basalt (3)	Tuff (4)	Domal Salt (5)	Bedded Salt (6)	Granite (7)
Exploratory Excavations (11)	●									●	●	*	*	●	●	●	●	●
Coreholes (12)	●									●		b	b	●	●	●	●	●
Rock Mass Sampling (13b)	●					●	●	●	●			b	b	●	●	●	●	●
Groundwater Sampling (13a)									●			b	b	●	●	●	●	●
Permeability Test (Single Borehole) (10)								●				b	b	●	●	●	●	●
Hydro-fracturing (17)			●									a	b	●	●	●	●	●
Laboratory Tests (14)	●					●	●	●	●	●		b	b	●	●	●	●	●
Index Tests on Exposures (15)						●				●		b	b	●	●	●	●	●
Geophysic/Seismic (X-hole, Exposure-borehole)	●					●				●		b	b	●	●	●	●	●
Seismic Monitoring		●									●	c	c	●	●	●	●	●
Monitor Temperature in Rock Mass and Excavations (16)					●		●			●	●	c	c	●	●	●	●	●
Monitor Displacements in Rock Mass and Excavations (16)						●	●			●	●	c	c	●	●	●	●	●
Monitor Pore Pressures in Rock Mass (16)				●				●			●	c	c	●	●	●	●	●
Monitor Drainage into Excavation (16)								●		●	●	c	c	●	●	●	●	●
Monitor Alteration/ Solutioning of Exposures									●		●	c	c	●	●	●	●	●
Construction Monitoring										●	●	c	c	●	●	●	●	●
Operation Monitoring											●	c	c	●	●	●	●	●

Rev. ____ Dwg. No. ABW-462 Date 12-82 Eng BR

REASONABLE IN SITU TEST PROGRAMS

Table ES-2

3 of 3

Notes:

a = several (≤ 10)
b = numerous (> 10)
c = continual
✱ = Exploratory shaft and underground test facility are exploratory excavations.

(1) a) The stratigrapnv/structure includes the physical and chemical characteristics of each rock mass unit (including poor fluid composition).

b) The in situ (i.e., pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(2) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These reponse characteristics can be assessed either:

- Directly by testing a large scale sample which contains a significant number of discontinuities
- Indirectly by separately assessing the response characteristics of the intact rock, discontinuities, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(3) Basalt at Hanford, Washington (8)
(4) Tuff at Yucca Mountain, Nevada (8)
(5) Domal Salt at Gulf Coast Sites (8)
(6) Bedded Salt at unspecified site (8)
(7) Granite at unspecified site (8)

(8) Significance of characteristics for in situ testing, as they relate to design, for each media/site was subjectively evaluated using a specific process.

(9) Plate test is very similar to two other tests:

- Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation.
- Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(10) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test.

(11) Exploratory excavations include the exploratory shaft and underground test facility.

(12) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(13) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.

b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(14) Laboratory tests are performed on rock mass or groundwater samples

(15) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer on rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(16) Monitoring performance implies associated analysis to assess characteristic.

(17) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

adequately respond to the information needs for construction authorization which are perceived to exist at the time of initial SCR submittal, and hence assist in resolving the key issues related to short- and long-term performance criteria. The defensibility of these recommendations relies on Golder Associates' current perception of the information needs, which in turn are based on their licensing perspective and assessment of currently available information.

Although some of the judgements made in the selection of these in situ tests are necessarily subjective and the licensing perspective may not be universally shared, the rationale is clearly outlined so that specific areas of technical disagreement can be readily identified and these disagreements (if any) resolved. It must be emphasized, however, that the media/site specific in situ test programs will be a function of both the information needs and test capabilities at the time of initial SCR submittal. It is expected that the in situ test program will evolve with time somewhat independently for each media/site considered as these information needs and test capabilities develop. In addition, the program and the design of specific tests must be flexible enough to take into account new information which becomes available during program performance, as presented in SCR updates.

Golder Associates thus recommends that the NRC should, accordingly, identify the information needs for each site and then focus on (1) the plans of the in situ test program in their review of an SCR and (2) the results of this program, and the appropriate incorporation of these results in design and performance assessment, in their review of a LA.

TABLE OF CONTENTS

Table of Contents continued.

Table of Contents continued.

Table of Contents continued.

LIST OF FIGURES

List of Figures continued.

List of Figures continued.

LIST OF TABLES

List of Tables continued.

PREFACE - LICENSING PERSPECTIVE

P.1 INTRODUCTION

It is the intent of this report to specifically address the requirements of in situ test programs for the development of deep geologic repositories for the permanent disposal of high level nuclear waste (HLW), so that the U.S. Nuclear Regulatory Commission (NRC) can adequately review U.S. Department of Energy (DOE) programs. In order to identify these requirements, it is first necessary to establish a perspective from which this will be accomplished. Too often, the perspective is not clear and disagreements regarding the conclusions are then often not easily resolved. In order to alleviate this problem, the perspective from which Golder Associates views repository development, and in situ testing in particular, is discussed in this Preface. The requirements of in situ test programs can then be identified and discussed on a logical basis.

The following topics are addressed within this Preface:

- Overview of high level nuclear waste program (Section P.2)
- Site selection (Section P.3)
- Repository design (Section P.4)
- Demonstrability (Section P.5)

P.2 OVERVIEW OF HIGH LEVEL NUCLEAR WASTE ISOLATION PROGRAM

High level nuclear waste (HLW) presently exists and in relatively large volumes. This waste is toxic, with its toxicity lasting for thousands of years. This toxicity may lead to adverse health effects and thus HLW must be isolated from the accessible environment during the period of its toxicity.

Compared to other forms of permanent disposal of HLW, a deep geologic repository appears to be optimum in terms of:

- Isolation (health effects)
- Feasibility
- Timeliness
- Cost-effectiveness
- Permanence, requiring no perpetual maintenance
- Public concensus and acceptability.

A federal-level approach is presently being taken to HLW disposal in a deep geologic repository, with provisions for the concurrence of the states involved. The U.S. Department of Energy (DOE) is expected to design, construct, and operate any HLW disposal facility. The U.S. Environmental Protection Agency (EPA) is the federal agency which is expected to establish the ultimate performance criteria that any facility must satisfy. These ultimate performance criteria are presently embodied in the draft rule 40-CFR-191. The U.S. Nuclear Regulatory Commission (NRC) is the federal agency which is expected to regulate HLW disposal, i.e., ensure that the DOE facility will achieve certain performance objectives related to public safety. In this regulatory role, the NRC has produced the draft rule 10-CFR-60 to help ensure DOE's compliance with the EPA criteria, as well as other performance objectives.

The performance objectives, specifically related to public safety, which deep geologic repositories for permanent disposal of HLW must achieve can be summarized as:

- Short term construction and operation objective (through decommissioning, about 100 years) of minimizing hazards jeopardizing the safety of the public and personnel during repository construction and operation (including possibly retrieval and decommissioning activities).

- Long term waste containment and isolation objective (post-decommissioning, from about 100 to 10,000's years) of minimizing radionuclide flux (rate/unit area) to accessible environment and thus minimizing hazards jeopardizing public safety after decommissioning. This objective dictates maintaining a waste retrieval capability for a specified period after waste emplacement and prior to decommissioning, thereby providing the opportunity for verifying a sufficiently high probability of satisfactory long-term performance and also providing a contingency plan for demonstrated non-verification.

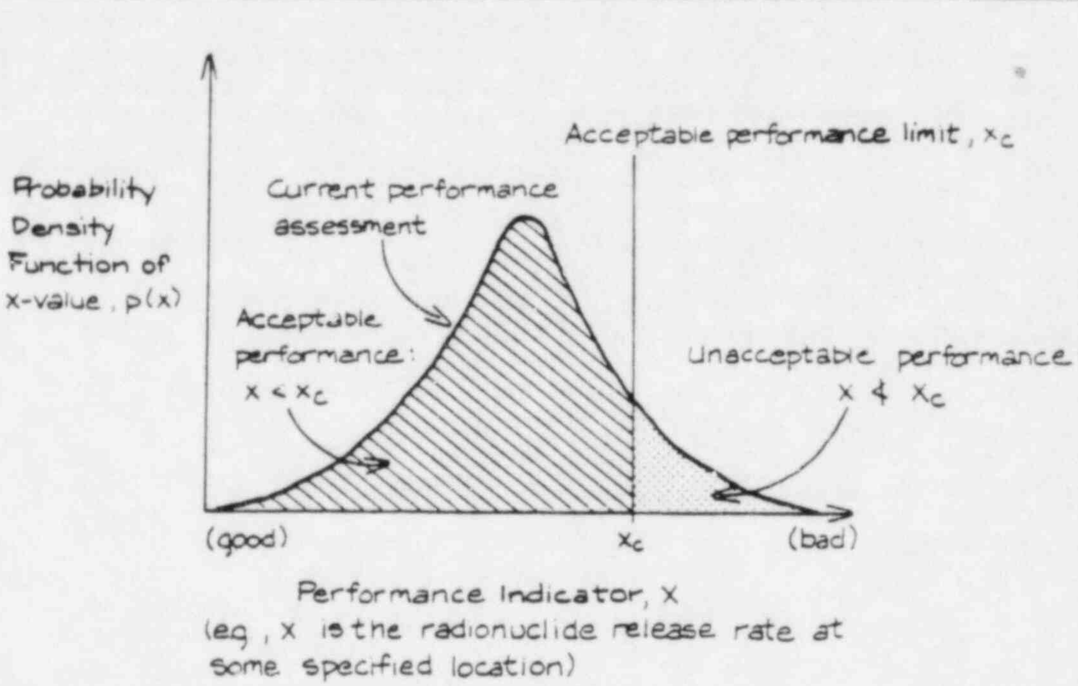
Performance criteria must be established in order to define and, where possible, quantify the performance objectives. These critiera, such as the NRC criteria (10-CFR-60), which incorporate the EPA criteria (40-CFR-191), or other interim criteria established by the DOE or its contractor, can be given either as (see Figure P-1):

1) Deterministic, in which an absolute numerical limit (Xc) is specified for each quantitative performance indicator (X), so that (if small X is good) X must be less than Xc for compliance

2) Probabilistic, in which an acceptable level of confidence (Lc) is specified for not exceeding the numerical limit (Xc) by the actual value of the quantitative performance indicator (X), so that the probability or likelihood of (X<Xc), or P(X<Xc), must be greater than Lc for compliance.

DEFINITIONS OF "COMPLIANCE WITH PERFORMANCE CRITERIA"

Figure P-1



- Performance criteria can be specified as either:
  - (1) Absolute numerical limit, x_c, so that $x < x_c$
  - (2) Acceptable level of confidence, L_C, in satisfactory performance (i.e., $x < x_c$), so that probability of $(x < x_c)$ is greater than L_c.

- Level of confidence in satisfactory performance, i.e., probability of not exceeding the performance limit, x_c:

  Probability of $(x < x_c)$ or $P(x < x_c) = \int_{[\text{good bound}]}^{[x_c]} p(x)\,dx$ = shaded area

  (e.g., the probability of the radionuclide release rate being less than some limit x_c might be 0.8 or 80%.)

- Level of confidence in unsatisfactory performance, i.e., probability of exceeding the performance limit, x_c:

  Probability of $(x \nless x_c)$ or $P(x \nless x_c) = \int_{[x_c]}^{[\text{bad bound}]} p(x)\,dx$ = dotted area

  (e.g., the probability of the radionuclide release rate being greater than some limit x_c might be 0.2 or 20%.)

- Summation of probabilities of satisfactory and unsatisfactory performance must equal 1.0 or 100%, i.e.:

  $p(x < x_c) + p(x \nless x_c) = 1.0$

  (e.g., 0.8 + 0.2 = 1.0)

Where the criteria are given deterministically, a determination must still be made, although implicitly rather than explicitly, of the level of confidence in not exceeding the deterministic limit. Hence, it is Golder Associates' opinion that a probabilistic approach, which quantifies and explicitly incorporates the uncertainties in performance prediction, should be taken where possible.

In either case, for both technical and political reasons, it will be necessary to maximize the level of confidence (i.e., increase the probability or likelihood) that the actual performance will be satisfactory. There are two primary ways of maximizing this level of confidence:

- Selecting a suitable repository site
- Appropriately designing, constructing and operating the repository.

Three questions are apparent:

1) How can a suitable site for a repository be selected so as to maximize the level of confidence in satisfactory performance?

2) Once a site has been selected, how can the repository be designed and constructed at that site so as to maximize the level of confidence in satisfactory performance?

3) How can an acceptably high level of confidence in satisfactory performance, i.e., compliance with the performance criteria, be demonstrated at each step in repository development?

Each of these questions is addressed in the following three sections.

P.3 SITE SELECTON

The first question, related to site selection, which needs to be addressed, is:

How can a suitable site for a repository be selected so as to maximize the level of confidence in satisfactory performance?

Repository site screening and selection requires the assessment of certain nonquantitative factors and quantitative parameters, which describe the site and its properties. These site characteristics can then be evaluated with respect to a particular set of site suitability criteria, which are based on how those characteristics are expected to affect repository system performance. In addition, these site characteristics can be input into performance models, which assess the probability of satisfactory performance. Both approaches could be used to compare sites. However, Golder Associates believes that the selection of an optimum site requires that several of the top ranking sites be compared against specific performance criteria. Furthermore, the use of performance models in the ranking process will significantly enhance the demonstrability of the selection process.

Site investigation for site screening and selection focuses primarily on large-scale features and does not generally require low uncertainty in the assessment of the characteristics. At this stage it thus consists of tests conducted from the surface, within limited boreholes, and in the laboratory on samples obtained from the site (e.g., core from boreholes), as well as prior information. As a result, the assessment of characteristics may have widely varying levels of uncertainty at this stage. It is possible that the assessment of certain characteristics at this stage could have low uncertainty and thus require no further information at subsequent stages.

P.4 REPOSITORY DESIGN

The second question, related to repository design, which needs to be addressed, is:

How can the repository be designed and constructed at the selected site so as to maximize the level of confidence in satisfactory performance?

Design and construction of a repository at the selected site will consist of selecting values for the engineering variables of each repository component, so as to optimize both the predicted performance and cost. Generally, once the site has been selected, the level of confidence in satisfactory performance will be maximized by a combination of (see Figure P-2):

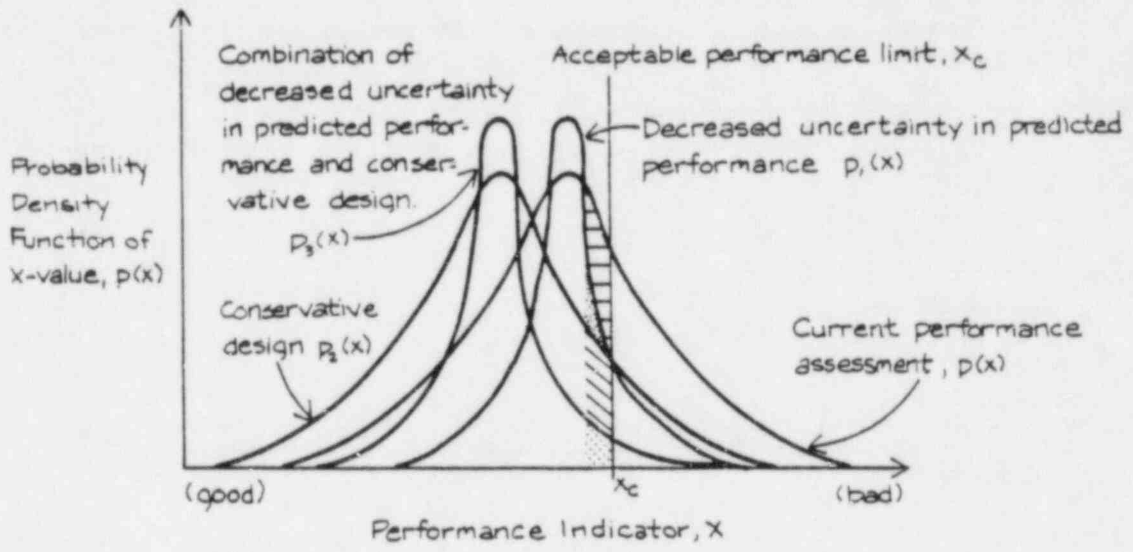
- conservative design (increased margin of predicted performance over performance limits)
- decreased uncertainty in predicted performance (by decreasing uncertainty in predictive model and input, and by careful construction).

Both of these can be achieved, but only at increasing cost.

In order to optimize repository design and construction in terms of predicted performance and cost, it will be necessary to focus on those engineering variables which have a potentially significant impact on compliance with performance criteria at reasonable cost, and in addition can truly be varied (i.e., are not predetermined and set). An example of such an engineering variable is the excavation and associated support method, which may have a significant impact on performance. This is because such variables will affect the transport properties of a potentially important pathway for radionuclide escape. Once those significant engineering variables have been identified, key issues can be identified. Some of these key issues can be resolved by extrapolation of the results of prototype simulation (e.g., construction

MAXIMIZING THE LEVEL OF CONFIDENCE IN SATISFACTORY PERFORMANCE

Figure P-2



Level of confidence in satisfactory performance (see Figure P-1) increases with conservative design and/or decreased uncertainty in predicted performance, i.e.:

$$\int_{[\text{good bound}]}^{[x_c]} p(x)\,dx \;\le\; \left\{ \begin{array}{c} \text{(decreased uncertainty in predicted performance)} \\ \displaystyle\int_{[\text{good bound}]}^{[x_c]} p_1(x)\,dx \\ \text{or} \\ \displaystyle\int_{[\text{good bound}]}^{[x_c]} p_2(x)\,dx \\ \text{(conservative design)} \end{array} \right\} \;<\; \int_{[\text{good bound}]}^{[x_c]} p_3(x)\,dx$$

(Combination of decreased uncertainty in predicted performance and conservative design) of trial sections), whereas others require the assessment of specific site characteristics for input to predictive numerical models. Both approaches will be essential to the resolution of the key issues.

Significant characteristics of the site, i.e., those which resolve key issues affecting the choice of values of significant engineering variables, must generally be assessed with considerably greater certainty than for site screening/selection. However, if the uncertainty is already sufficiently low, then no additional effort may be required. Hence, site characterization should generally update the assessment of site characteristics for site screening/selection, especially by tests conducted in an in situ test facility. In addition to assessing site characteristics, this in situ test facility can serve as a simulation of the repository, and thereby resolve key issues.

In situ tests to be conducted in this facility are expected to reduce the uncertainty in the assessment of the significant characteristics. This reduction in uncertainty will be provided primarily by directly testing a representative volume of rock mass which is large enough to contain a significant number of discontinuities. Tests on a representative volume do not require scale-effect corrections in the determination of quasi-continuum rock mass characteristics, whereas smaller scale tests (e.g., borehole, laboratory, or small-scale in situ tests) assess either the intact rock or the discontinuity characteristics, and not the composite rock mass characteristics. Due to their generally high cost and long duration, however, the results of large-scale in situ tests must be used to develop and verify site-specific correlations with the results of tests which are less expensive and of short duration. Once reliable correlations have been determined, these simpler tests can be used with increased confidence in assessing the significant characteristics throughout the repository.

P.5 DEMONSTRABILITY

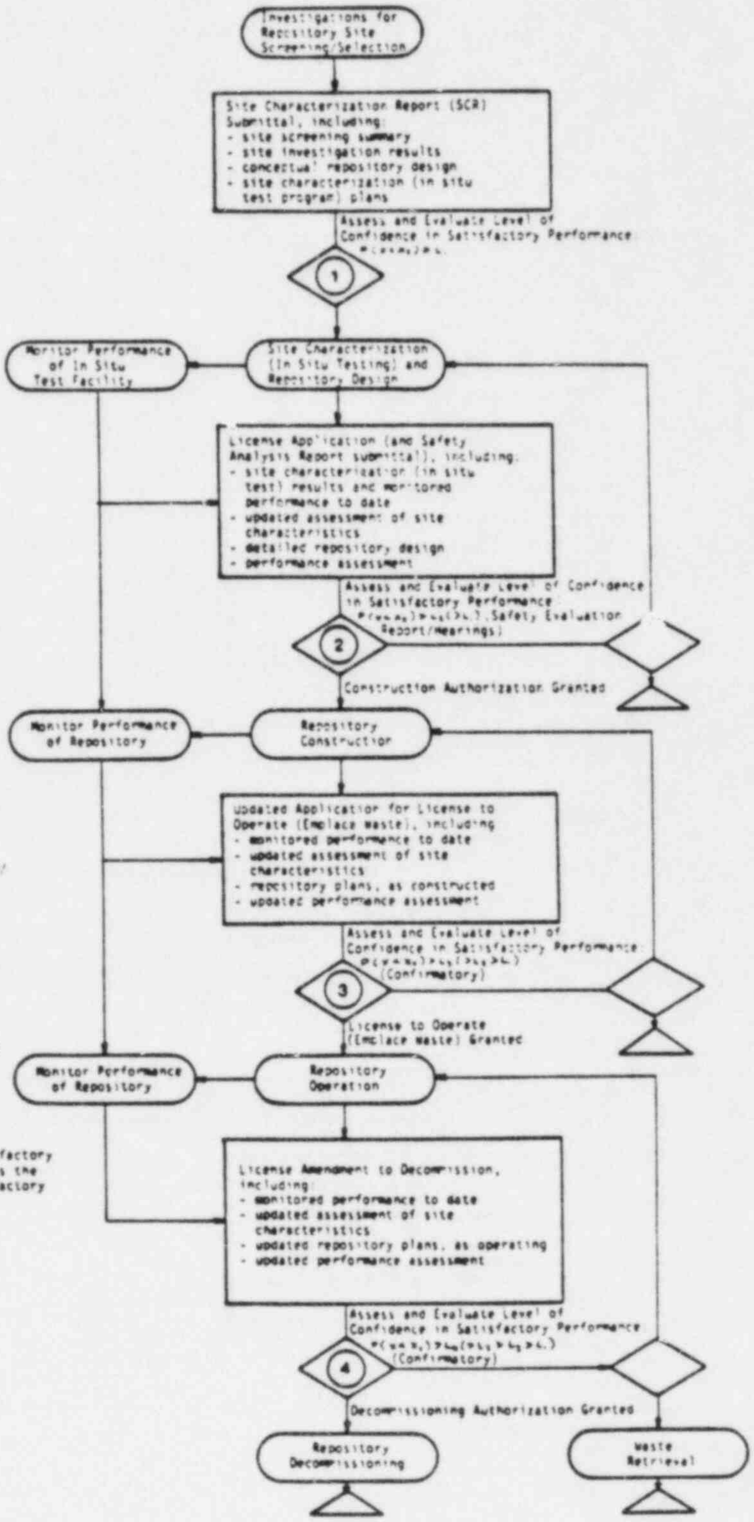
The third question, related to demonstrability, which must be addressed, is:

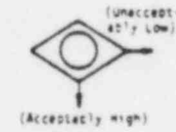
How can an acceptably high level of confidence in satisfactory performance, i.e., compliance with the performance criteria, be demonstrated at each step in repository development?

This question essentially defines repository development (see Figure P-3). The NRC must assess the level of confidence in satisfactory performance at various discrete decision points in repository development, especially at LA. If the confidence level is found to be acceptably high, the appropriate authorization or license amendment necessary to initiate the next phase of repository development is granted. However, if the level of confidence in compliance is found to be unacceptably low, then one of two approaches can be taken by the applicant:

REPOSITORY DEVELOPMENT

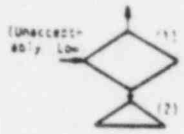
Figure P-3





Discrete decision point at which the level of confidence in satisfactory performance $P(x < x_c)$ should be assessed and then the acceptability of that level evaluated, i.e., is $P(x < x_c) > L$ where L is the acceptable level. This can be done either implicitly or explicitly.

If the level of confidence in satisfactory performance is acceptably high, then authorization/license required to initiate next phase of repository development is granted.



If the level of confidence in satisfactory performance is unacceptably low, then either: (1) additional cost effective testing or design modifications are performed to increase the level of confidence in satisfactory performance to acceptable levels and the application is updated.

(2) repository development is stopped.

NOTE: "Level of confidence" in satisfactory performance can also be expressed as the "probability" or "likelihood" of satisfactory performance.

Rev. A813-1163 10-82 BR
Dwg. No. A13-1163E Date 5-82 Eng. BR

(1) If the level of confidence can be increased by additional cost effective characterization or design modification, then that characterization or modification may be performed and the application updated

(2) If the level of confidence cannot be cost effectively increased by further characterization or design modification, then repository development should be stopped at this site.

The discrete points in repository development are:

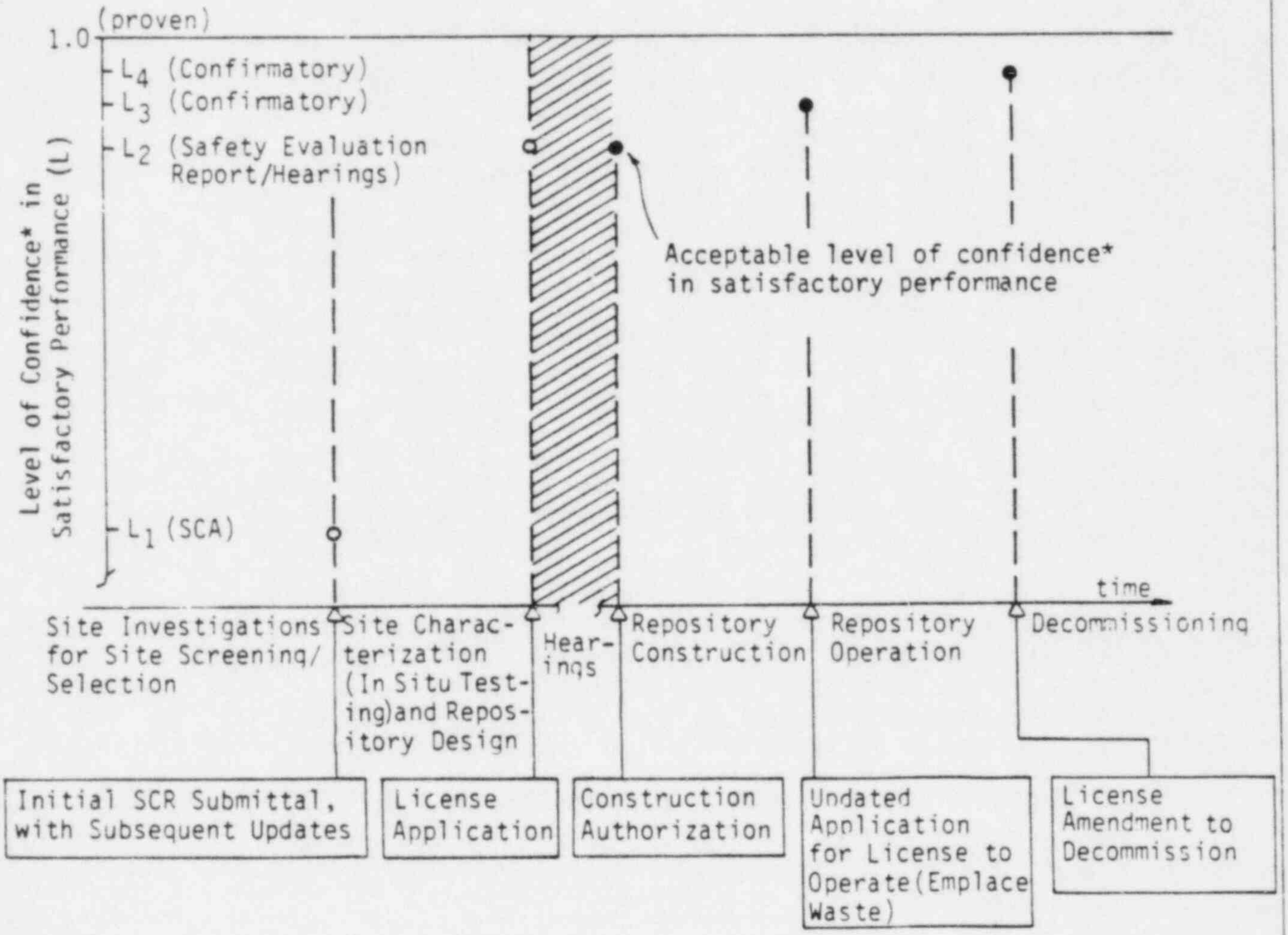
(1) Site characterization report (SCR) submittals, primarily DOE decision points for which NRC offers only opinions
(2) License application (LA)
(3) Updated application for license to operate (emplace waste)
(4) License amendment to decommission.

The acceptable level of confidence in satisfactory performance, especially compliance with the ultimate (long-term) criteria, will increase with repository development, i.e., from initial SCR submittal to decommissioning (see Figure P-4). It is presently perceived that the acceptable level of confidence should be high at LA in order to provide reasonable assurance that the repository will be fully licensable, prior to extensive development and major expenditure of funds. If this were not a concern, then the acceptable level of confidence in satisfactory performance could be lower at LA, and the information gained after LA relied upon to improve the level of confidence sufficiently for decommissioning.

The assessment of the level of confidence in satisfactory performance, relative to the acceptable level, at each decision point will affect subsequent repository development activities (Figure P-3) and will determine the nature and extent of subsequent in situ testing and construction and operation monitoring. For example, if the level of confidence in satisfactory performance was high enough at the initial SCR submittal, due possibly to conservative and reliable engineered components and/or predictable geology/geohydrology, in situ testing prior to LA might not be necessary. Conversely (see Figure P-5), if the level of confidence in satisfactory performance at the time of the initial SCR submittal was perceived to be insufficent for granting construction authorization, in situ testing would be necessary to sufficiently improve the level of confidence in satisfactory performance. An exploratory shaft supplemented by surface tests might improve the level of confidence in satisfactory performance, but still not enough for granting a construction authorization. An underground test facility would thus be necessary, prior to LA, in order to sufficiently improve the level of confidence in satisfactory performance. The results of tests after LA, as well as construction and operation monitoring, could then sufficiently improve the level of confidence in satisfactory performance for subsequent licensing steps.

ACCEPTABLE LEVEL OF CONFIDENCE IN SATISFACTORY PERFORMANCE

Figure P-4



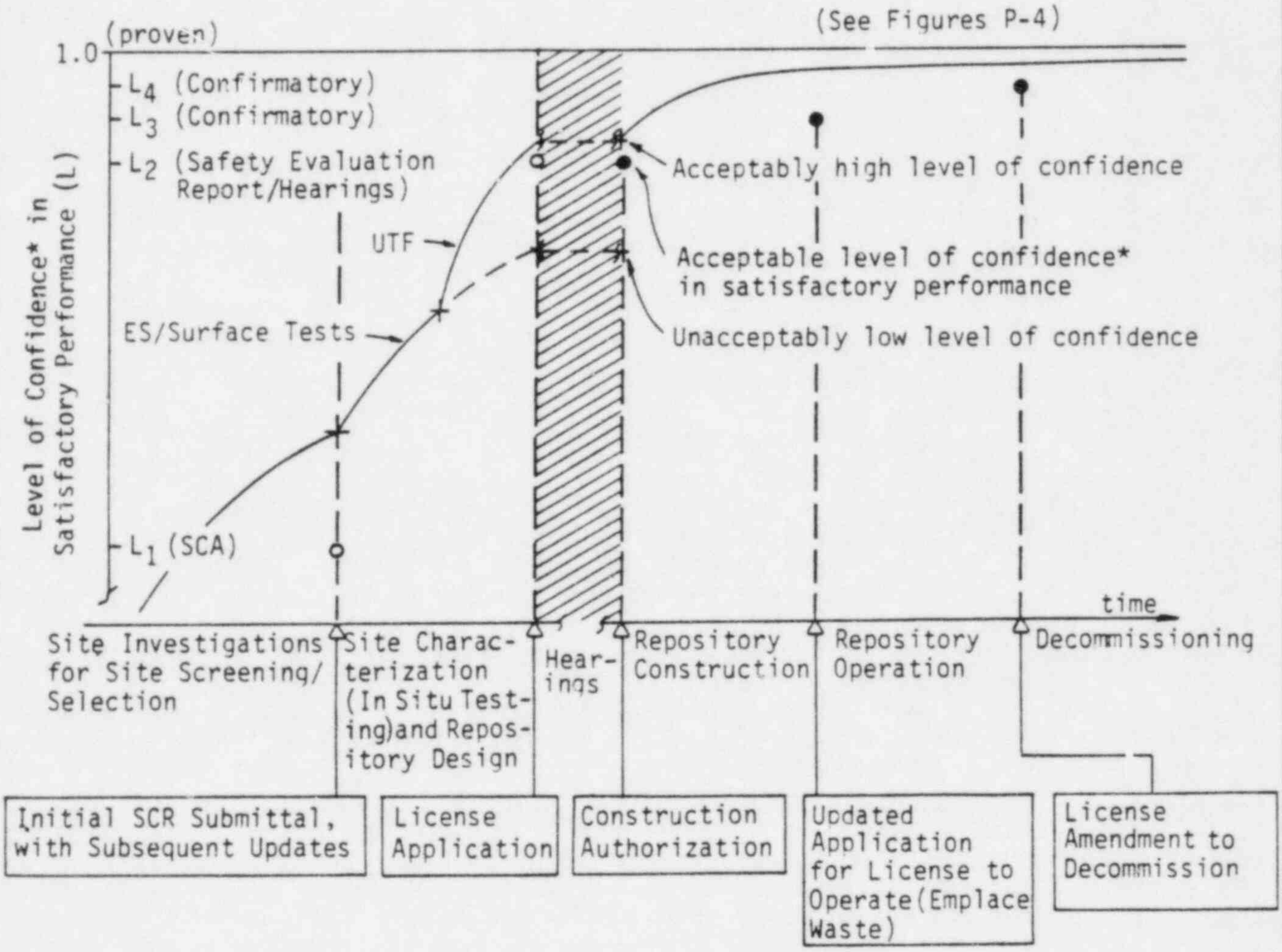
Notes:

* "Level of confidence" in satisfactory performance can also be expressed as the "probability" or "likelihood" of satisfactory performance.

The level of confidence in satisfactory performance can be assessed and then compared with the acceptable level, either implicitly or explicitly, at each step.

ASSESSMENT OF LEVEL OF CONFIDENCE IN SATISFACTORY PERFORMANCE (EXAMPLE)

Figure P-5



Notes:

* "Level of confidence" in satisfactory performance can also be expressed as the "probability" or "likelihood" of satisfactory performance.

The level of confidence in satisfactory performance can be assessed and then compared with the acceptable level, either implicitly or explicitly, at each step.

Rev. ____ Dwg No. A823-063 Date 10-82 Eng BR

Acceptable levels of confidence may be established either:

- Implicitly, through progressive technical discussion between the regulator and applicant

- Explicitly, through rigorous decision-making utilizing quantitative risk assessment methodology (e.g., Roberds, 1981). Such a risk assessment includes explicit consideration of the consequences of not satisfying the performance objectives/criteria, as well as the risks in other alternatives for HLW disposal.

Although recognizing the difficulties in performing quantitative risk assessments and subsequently defending the results in the decision-making process (especially within the institutional framework), Golder Associates considers it important to be attempting to utilize uncertainty and probability assessments of the important parameters affecting repository performance. These assessments should be used as a guidance tool during the site characterization phase. While these probabilistic approaches are being established, the current approach of assessing acceptability implicitly through technical discussions needs to be continued.

The required demonstration of compliance with the performance criteria can be provided at any step in repository development by:

- Prediction (with inherent uncertainties) of future performance, based on numerical modeling or extrapolation of physical simulation

- Verification of past performance, based on monitoring performance.

Monitoring of repository system performance will not be possible, however, until later stages of repository development and, even then, complete verification of compliance with long-term performance criteria for waste isolation will not be possible. Hence, to demonstrate compliance with performance criteria, either numerical models, which rely on site characteristic assessments and the proposed repository design, or physical simulations must be utilized to predict repository performance, with some associated uncertainty.

The uncertainty in predicted performance must generally be decreased with each successive licensing step in order to demonstrate compliance. This can be accomplished by:

- Decreasing the uncertainty in the assessment of significant site characteristics

  This can be accomplished by continually updating the assessment, e.g., by additional site investigation, by in situ testing, by construction as more areas are exposed, and by performance monitoring.

- Decreasing the uncertainty in predictive numerical models

  This can be accomplished by comparing predicted large-scale in situ test results with the actual results and by comparing predicted performance of the in situ test facility or repository with the results of performance monitoring.

- Improving the correlation between simulation tests and the prototype

  The uncertainty in the extrapolation of results from a test case to the prototype will be a function of the degree of similarity between the two. Thus, as this similarity is increased (i.e., by making the test case as similar as possible to the prototype in terms of site characteristics, test conditions, and design/construction), the correlation will be improved and the uncertainty reduced.

- Updating performance predictions

  The uncertainty in performance prediction increases with the time of projection. Performance monitoring allows for some previous predictions to be adjusted to agree with the actual performance at the time of measurement, and thus progressively eliminate measured errors and effectively reduce the projection time of subsequent projections. However, due to the relatively short operating period, this updating will be only marginally effective in reducing the uncertainty in predicting very long term performance.

P.6 SUMMARY

It is anticipated that certain testing/monitoring methods will need to be utilized in order to demonstrate an acceptably high level of confidence in satisfactory performance at each step of repository development (Figures P-3 and P-4). This perspective of the licensing process can be summarized as follows:

- For site screening/selection, as summarized in the initial SCR submittal, site investigation will focus generally on large-scale features and consists of surface, borehole and laboratory testing. This generally rough assessment of characteristics will allow for comparison between potential sites and for the possible demonstration of an acceptably high level of confidence in satisfactory performance based on a conceptual repository design.

- For a detailed repository design, as summarized in a license application (LA) for construction authorization, site characterization will focus on features adjacent to planned shafts and the repository horizon, as well as on large-scale features. This site characterization effort will consist primarily of the construction and operation of an in situ test facility. In addition to the improved assessment of site characteristics provided by in situ testing and by monitoring of the in situ test facility, certain aspects of key issues may be adequately resolved by prototype simulation and predictive numerical models may be partially verified. The construction and operation of this in situ test facility may thus provide information for the detailed repository design and for the possible demonstration of an acceptably high level of confidence in satisfactory performance with that design.

- In an updated application for license to operate (emplace waste) subsequent to construction, the assessment of site characteristics will be further refined as more areas underground are exposed and as the performance of the repository is monitored. Additional verification of predictive numerical models and updating of performance predictions may be provided by monitoring. This monitoring may also provide information for modifications in design (if required) and for the possible demonstration of an acceptably high level of confidence in satisfactory performance by the constructed repository.

- Finally, in a license amendment to decommission, the assessment of site characteristics will be further refined by monitoring repository performance. Monitoring may also provide additional verification of predictive numerical models and updating of performance predictions. A final assessment of the level of confidence in satisfactory long-term performance will then be made, and a determination made by the NRC as to whether this likelihood is high enough. If it is determined that the likelihood is too low, modifications to the repository or retrieval of the waste will be required.

Hence, the assessment of site characteristics is a continual process, from site screening/selection to decommissioning, of reducing uncertainty in the assessment of those characteristics which have a significant impact on compliance with the performance criteria. Similarly, the verification of predictive numerical models is also a continual process, and consists of reducing their uncertainty.

1.0 INTRODUCTION

1.1 INTRODUCTION

This report represents the results of Task 2, "In Situ Test Programs Related to Design and Construction of High Level Nuclear Waste (HLW) Deep Geologic Repositories," of U.S. Nuclear Regulatory Commission (NRC) Contract NRC-02-81-037, "Technical Assistance for Repository Design."

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

- To enable the focused, adequate review by NRC of aspects related to design and construction of an in situ test facility* and final geologic repository, as presented in U.S. Department of Energy (DOE) Site Characterization Reports (SCR)
- To ascertain that the DOE site characterization will provide, as far as possible, all the information necessary to permit a review to be conducted by NRC of a License Application (LA).

This report presents and utilizes a defensible rationale to tentatively identify those in situ tests (if any) which constitute reasonable media/site specific in situ test programs for adequately responding to the perceived information needs for construction authorization. These information needs are related to the additional information needed after initial SCR submittal (and site investigation) to adequately resolve the key issues of repository system performance for construction authorization at each site. It is expected that the in situ test program will evolve with time somewhat independently for each media/site considered as the perceived information needs and test capabilities develop. The program and design of specific tests must thus be flexible enough to take into account new information which becomes available during program performance, as presented in SCR updates. In addition, scoping recommendations have been made regarding (1) how specific in situ tests should be conducted, (2) research and development which may effectively improve the capabilities of the test program, and (3) the utilization of the Task 2 results by the NRC in their licensing review process.

It has been assumed that the in situ test program will be conducted within an in situ test facility, consisting of an exploratory shaft, extending from the surface to the prospective repository horizon possibly with test stations at various depths, and an underground test facility, consisting of appropriate tunnels and test rooms at that horizon. Plans for the program are expected to be presented in the initial SCR submittal and complete results presented in the LA.

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*Specific terms utilized are defined in attached Glossary.

1.2 APPROACH

This study, within the context of the current licensing perspective (see Figure 1.1), involves the development of general recommendations for in situ testing, with variations for each of the specific media and sites under consideration. The media and sites specifically considered in this study include (see Table 1.1):

- Basalt at Hanford Reservation, Washington
- Tuff at Yucca Mountain, Nevada Test Site, Nevada
- Domal salt at Richton or Cypress Creek, Mississippi, or Vacherie, Louisiana
- Bedded salt at unspecified site (generic)
- Granite at unspecified site (generic).

The descriptions of domal salt and tuff media/sites were the subjects of Task 1 of this project (Golder Associates, 1982a and b, respectively) and the basalt, granite, and bedded salt media/sites were the subjects of other and earlier work (especially Golder Associates 1979a and c, and 1981).

This study is limited to consideration of tests conducted within an in situ test facility in the time frame between the initial SCR submittal and LA (i.e., site characterization). Testing preceding initial SCR submittal (i.e., site investigation during site screening/selection) is outside the scope of work and thus has not been evaluated; SCR requirements are given in the "Standard Format and Content of Site Characterization Reports for High-Level Waste Geologic Repositories" (NRC, 1981). Testing or monitoring subsequent to LA (i.e., during repository construction/operation) is also outside the scope of work.

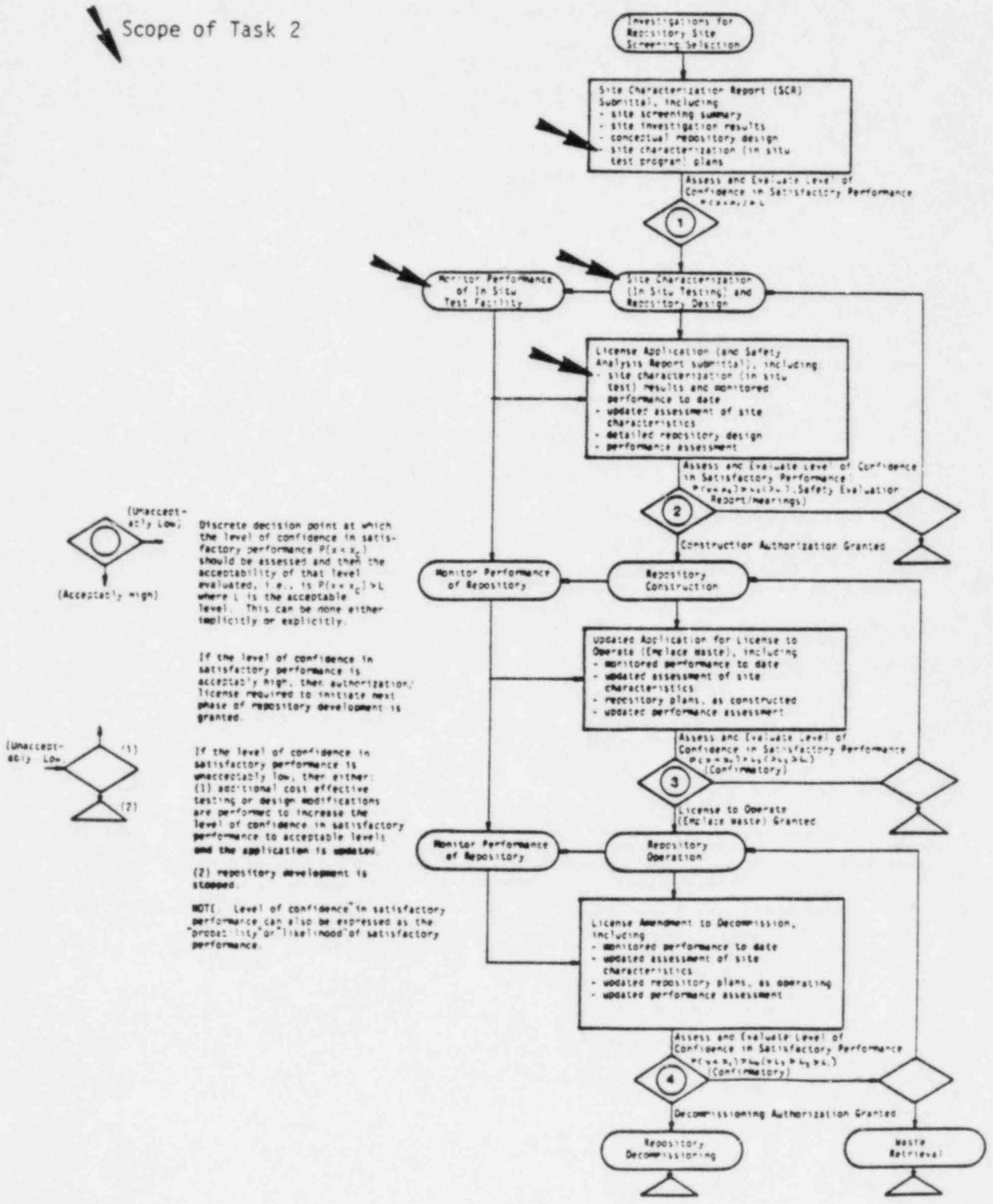
A defensible rationale has been developed and utilized to tentatively select available tests to be included in the media/site specific in situ test programs. This rationale essentially consists of:

- Establishing the information needs for construction authorization at each site
- Assessing the capabilities of available tests to meet the specific information needs
- Matching the capabilities of specific tests to the perceived information needs at each site.

The information needs at any time result from the uncertainties in the prediction of repository system performance, and consist of the additional information needed in order to predict satisfactory performance with the required level of confidence. Information needs are determined as follows:

IN SITU TEST PROGRAM WITHIN REPOSITORY DEVELOPMENT

Figure 1.1



Discrete decision point at which the level of confidence in satisfactory performance $P(x < x_c)$ should be assessed and then the acceptability of that level evaluated, i.e., is $P(x < x_c) > L$ where L is the acceptable level. This can be done either implicitly or explicitly.

If the level of confidence in satisfactory performance is acceptably high, then authorization/license required to initiate next phase of repository development is granted.

If the level of confidence in satisfactory performance is unacceptably low, then either: (1) additional cost effective testing or design modifications are performed to increase the level of confidence in satisfactory performance to acceptable levels and the application is updated.

(2) repository development is stopped.

NOTE: "Level of confidence" in satisfactory performance can also be expressed as the "probability" or "likelihood" of satisfactory performance.

Rev. ABB3-1163 10-82 3R

Dwg. No. A13-1163C Date 5-82 Eng. JR

PRESENT STATUS OF DOE'S REPOSITORY SITE SCREENING/SELECTION PROGRAM

Table 1.1

- Basalt at Hanford Reservation, Washington

  Basalt Waste Isolation Project (BWIP), DOE prime contractor - Rockwell:

  The prospective repository horizon is in basalt flow (presumably the Umtanum, which is about 80 feet thick and 3800 feet deep) in Cold Creek Syncline at Hanford Reservation, Washington; SCR submittal is expected in late 1982, exploratory shaft is expected to be initiated in 1983.

- Tuff at Yucca Mountain, Nevada Test Site, Nevada

  Nevada Nuclear Waste Storage Investigations (NNWSI), DOE prime contractor - Sandia:

  The prospective repository horizon is in tuff (possibly the Bullfrog formation, which is about 400 feet thick and 2100 feet deep, but 3 other formations are being studied to similar levels) under Yucca Mountain at Nevada Test Site (NTS), Nevada; SCR submittal is expected in 1983, exploratory shaft is expected to be initiated in 1983.

- Domal Salt at Richton or Cypress Creek, Mississippi, or Vacherie, Louisiana

  Gulf Coast Domal Salt Investigation, DOE prime contractor - ONWI*:

  A choice between Vacherie Dome in Louisiana, Richton Dome and Cypress Creek Dome in Mississippi is expected to be made in 1983 ; a subsequent choice between the selected dome and the selected salt basin is expected to be made in 1983 for exploratory shaft initiation.

- Bedded Salt at unspecified site (generic)

  Bedded Salt Investigation, DOE prime contractor - ONWI*:

  A choice between the Paradox Basin in Southeastern Utah and the Permian Basin in Northwest Texas is expected to be made in 1983; a subsequent choice between the selected basin and the selected salt dome is expected to be made in 1983 for exploratory shaft initiation.

- Granite at unspecified site (generic)

  Granite Investigation, DOE prime contractor - ONWI*:

  The investigation and site selection process for a suitable site in granite is expected to begin throughout the eastern portion of the U.S. in 1982; SCR submittals for as many as three selected sites are expected in about 1986.

* ONWI - Office of Nuclear Waste Isolation is managed for DOE by Battelle-Columbus

Note: This perceived status is as of November 1982, and is subject to update and revision.

- Identify the existing information and assess the associated level of confidence in satisfactory repository system performance

- Compare the assessed level of confidence with the acceptable level, either implicitly or explicitly

- Determine what additional information is needed to raise the level of confidence in satisfactory performance to the acceptable level, by:

  - establishing the relationship between each component of the repository system and system performance (i.e., sensitivity)

  - identifying where the existing information regarding significant components of the system is insufficient and can be readily supplemented (i.e., where the existing uncertainty is large, but can be effectively reduced).

The information needs at any time are thus a function of:

- The significance of each component of the repository system (including site characteristics) with respect to system performance

- The currently available information, which in conjunction with the repository design determines the level of confidence in satisfactory repository system performance

- The acceptable level of confidence in satisfactory repository system performance for each licensing step.

Regarding the above, performance assessment (including sensitivity studies) is outside the scope, so that the significance of repository system components cannot be quantitatively evaluated and the level of confidence in satisfactory performance cannot be assessed. Also, the existing information is not constant, but continually being supplemented and updated. Determination of the acceptable level of confidence in satisfactory performance at each step is a part of the licensing perspective, and is outside the scope. Thus, for this study, tentative information needs must be established based on Golder Associates' premises, perceptions, and interpretations of available information.

The capabilities of available tests, with respect to responding to the information needs, must be assessed. These tests satisfy the information needs either by:

- Appropriately simulating various aspects of the actual repository (e.g., construction techniques) for extrapolation of results

- Adequately assessing identified media/site specific characteristics (e.g., hydraulic conductivity) to be used in numerical modeling

- Sufficiently verifying predictive numerical models.

However, the development of new or hybrid tests (i.e., incorporating new concepts or combining available concepts) is outside the scope, so that only presently available tests and potential advancements to the state-of-the-art (i.e., expanding available concepts or improving technology) are considered. Areas are also pointed out where research and development might improve either individual test capabilities or the combined capabilities of a test program in better responding to the perceived information needs. Hence, test capabilities may improve with time.

From a comprehensive list of available tests and associated capabilities, appropriate in situ tests can be identified which adequately respond to the perceived information needs for construction authorization at each media/site considered. These tests must then be integrated into a reasonable in situ test program. An in situ test facility, which can accommodate such reasonable in situ test programs, can then be developed.

The actual media/site specific in situ test program will be a function of the information needs and test capabilities at that time. Hence, it is expected that the test program will evolve with time somewhat independently for each media/site considered as the perceived information needs and test capabilities develop. It is even possible that the information needs for construction authorization might be satisfied prior to the initial SCR submittal, precluding the need for most (if not all) in situ testing. The program must thus be flexible enough to take into account new information which becomes available during its performance, as presented in SCR updates. Also, the complete design and specifications for any particular test cannot be accomplished a priori without detailed descriptions of each individual test location, as well as identification of specific information needs. Hence, the recommendations for the conduct of specific tests are of a scoping nature only.

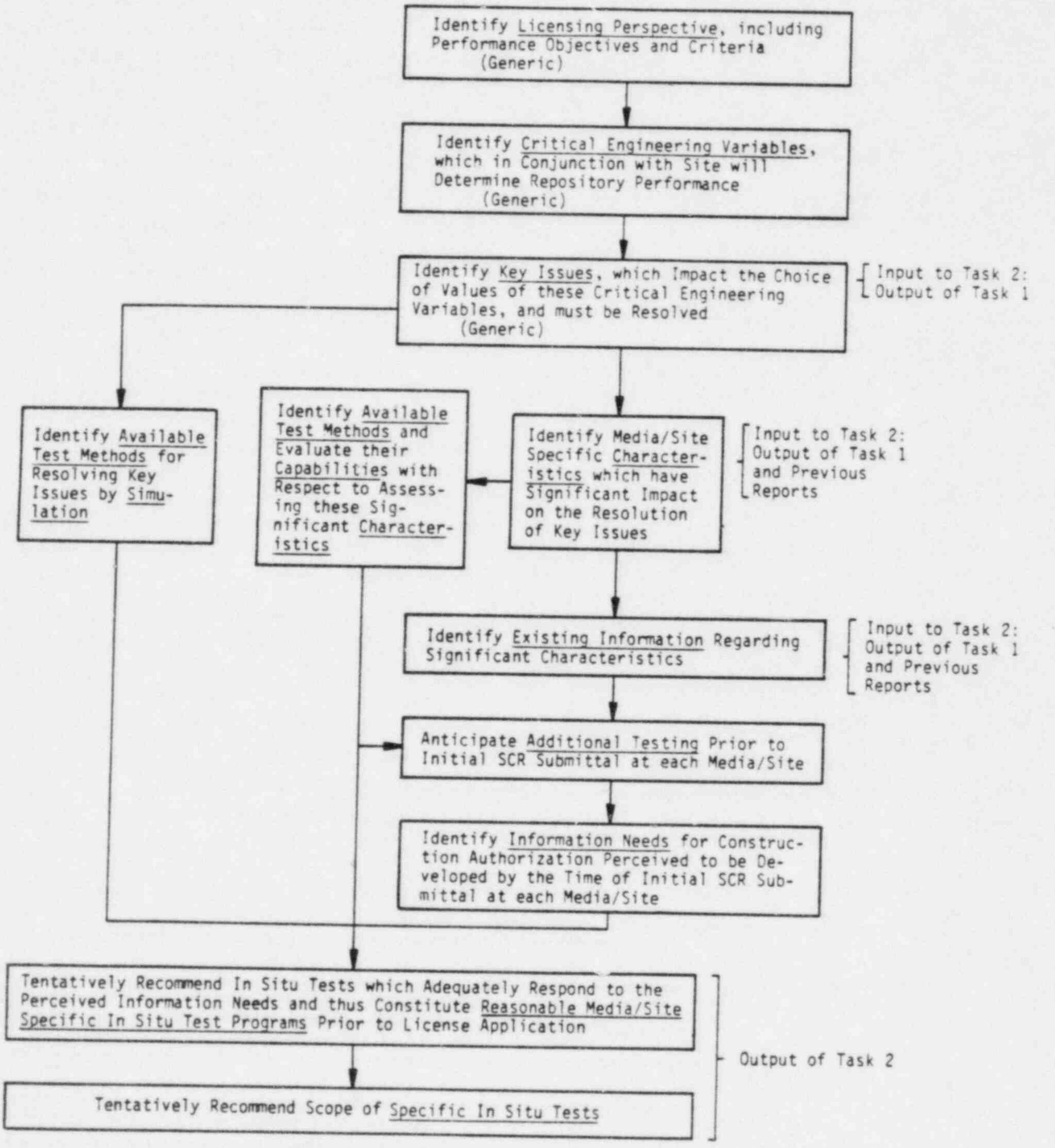
1.3 STUDY ACTIVITIES

The following activities have been undertaken in the course of developing recommendations for in situ testing (see Figure 1.2):

- A licensing perspective has been established (see Preface). The various licensing steps in repository development have been identified, based on the procedural rule of 10-CFR-60. At each step, the level of confidence in future satisfactory repository system performance should be assessed, and a determination made of whether that level of confidence is sufficiently high to allow further development (Figure 1.1). These steps are:

TASK 2 ACTIVITY FLOW CHART

Figure 1.2



Note: Media/site specific considerations have been made to the extent possible in each activity for basalt, tuff, domal salt, bedded salt, and granite.

Rev. ______ Dwg. No. AB/3-11(3) Date Nov 82 Eng BR

(1) SCR submittals
(2) License application (LA)
(3) Updated application for license to operate (emplace waste)
(4) License amendment to decommission.

The acceptable level of confidence at each step underlies the establishment of the information needs.

- Critical engineering variables, which in conjunction with the site characteristics will determine repository system performance, have been identified (see Chapter 2, Section 2.1). This has been accomplished by first identifying the primary engineering variables of repository design and construction (e.g., shaft dimension, shape, etc.). The impact of these primary engineering variables on the level of confidence in satisfactory performance has been qualitatively assessed and those perceived to have a significant potential impact, in conjunction with a capability for change at reasonable cost, have been considered to be critical. These critical engineering variables should be investigated by in situ testing, as well as emphasized during NRC's review process.

- Key issues, essentially related to compliance with the various aspects of the short-term construction/operation and the long-term waste containment/isolation performance critiera, have been identified (see Chapter 2, Section 2.2). These key issues impact the choice of values for the critical engineering variables and must be adequately resolved to demonstrate an acceptably high level of confidence in satisfactory performance. Hence, these key issues must be addressed in both the SCR and the LA review. Information needs are related to the adequate resolution of these key issues.

  These key issues can typically be resolved either by extrapolating the results of appropriate prototype simulation or by adequately assessing specific site characteristics and then incorporating them in sufficiently verified numerical models.

- Characteristics of a site which are perceived to have a significant impact on the resolution of the key issues have been identified (see Chapter 3). The assessment of each characteristic entails some uncertainty, due to natural variability as well as due to the quality of the data base on which the interpretaton is based. The sources of uncertainty in this assessment have been identified. In addition, response characteristics may be anisotropic, scale-dependent, time-dependent, and a function of present and past environmental conditions (i.e., stress level, pore pressure, temperature, radiation dose). Ignoring the effect of these conditions results in greater uncertainty. Hence, the relationship of each of the significant characteristics to these environmental conditions has been qualitatively determined, based on experience.

Each of the characteristics has subsequently been evaluated in terms of its influence on satisfying the performance criteria. This evaluation has taken into account the following attributes of each characteristic:

- availability of cost-effective design and construction techniques which allow for a conservative assumption of the value of the characteristic
- uncertainty in the representation of the phenomenological laws of nature by the performance prediction model
- sensitivity of the performance prediction model to the value of the characteristic
- cost effectiveness and scheduling limitations of measures to reduce the uncertainty in the assessment of the characteristic.

From this evaluation, a qualitative determination has been made regarding the maximum acceptable level of uncertainty in the assessment of each of the characteristics. However, these levels are not independent of the magnitude of characteristic values (individually or combined), the sensitivity of performance to all the system components, or the acceptable level of confidence in satisfactory repository system performance.

- The present assessment of the value of significant characteristics at each media/site being considered, based on available information, has been summarized (see Chapter 3, Section 3.5 and Appendix B of Volume II). For tuff and domal salt sites, this has been based primarily on the results of Task 1 of this project (Golder Associates, 1982a and b). For basalt, bedded salt and granite sites, this has been based on earlier work (Golder Associates, 1979a, b, and c), complementary work (Golder Associates, 1981 and 1982c), work by others, and past experience. These assessments have been presented in terms of a best estimate and an indication of the level of uncertainty in that value.

- Test methods which are available to assess the significant characteristics have been identified (see Chapter 4). This has been accomplished by first listing all of the common test methods, including surface tests, borehole tests, laboratory tests, and in situ tests, available for assessing each characteristic (see Section 4.2). Existing repository-related in situ testing programs have been summarized to assist in the identification of available in situ tests (see Section 4.1 and Appendix C of Volume II).

  The capabilities of each of the available test methods regarding its determination of the significant characteristics has been assessed (see Section 4.3). This assessment has been based partly on the test method's incorporation of those environmental conditions which affect the characteristic, as well as whether a representative volume of rock mass is tested. These test capabilities are not independent of either the magnitude of the characteristic value or media.

- Those in situ tests which can be used to resolve the key issues by simulation have been identified (see Chapter 4, Section 4.4). These in situ tests, as well as the in situ test facility itself, simulate various construction/ operation aspects of the repository, so that their results can be extrapolated to directly predict repository performance.

- The testing which will precede in situ testing has been anticipated (see Chapter 5, Section 5.1.1). The information obtained by this testing at sites where it is now incomplete will supplement the existing information, and the present assessments of significant characteristics may change prior to the initial SCR submittal and subsequent initiation of in situ testing.

- The information needs for construction authorization, which are perceived to exist at the time of the initial SCR submittal, have been identified (see Section 3.5.2). This has been accomplished by identifying the existing media/site specific assessment of significant characteristics and the anticipated additional site investigation, and comparing that level of information expected at initial SCR submittal with what is perceived to be required for construction authorization.

- Tentative media/site-specific in situ test programs have been recommended (see Chapter 5). These programs consist of available in situ test methods which best respond to the perceived information needs for each of the media/sites, either by simulation or by adequate assessment of the significant characteristics. Where no one appropriate method exists, a combination of independent methods which adequately responds to the perceived information needs has been identified.

  It is expected, however, that these tentative programs will evolve, even during their performance, as information needs and even test capabilities develop.

  An example in situ test facility which can accommodate these programs has been developed under Task 4 of this project (see Section 5.3).

- Scoping recommendations have been made regarding specific in situ tests (see Appendix A of Volume II). These tests have been investigated in detail, and a description, an evaluation, and a recommendation regarding methodology and utilization of results have been presented for each. However, it is expected that the design of each test will evolve as the information needs are defined, more information regarding the site becomes available, and testing technology improves.

- Potentially effective research and development of in situ testing techniques have been identified and recommended (see Chapter 6). These recommendations are primarily concerned with advancements to the state-of-the-art (i.e., expanding available concepts or improving technology), although the development of new or hybrid tests (i.e., incorporating new concepts or combining available concepts) and program integration have been addressed.

2.0 KEY ISSUES FOR REPOSITORY DESIGN AND CONSTRUCTION

2.1 CRITICAL REPOSITORY DESIGN AND CONSTRUCTION ENGINEERING VARIABLES

The repository must be designed, constructed, and operated so as to demonstrably satisfy established performance criteria (see Preface - Licensing Perspective). The repository system consists of engineered components and the geologic site, which has certain characteristics. It is the integration of engineered components and site characteristics which will determine the level of confidence in satisfactory performance.

The primary engineered components of the repository, which must be designed and constructed so as to optimize predicted performance and cost, are:

- Surface facilities

- Underground facilities, including engineered barriers
  (large-scale)
  - shafts
  - tunnels/caverns

  (small-scale)
  - waste packages.

Surface facilities are outside the scope of this report, and only underground facilities, not including engineered barriers, have been considered. The waste package itself is also outside the scope of this report, but the waste package emplacement hole has been considered.

Once the conceptual repository design has been completed (as presented in the SCR), only certain aspects in the design and construction of each repository component can be varied to achieve optimization. Those engineering variables which are perceived to have a significant and cost effective impact on the level of confidence in satisfactory performance have been termed "critical." These critical engineering variables (see Table 2.1) should be focused on, for in situ testing, design, performance assessment, and NRC review. These variables have been assumed to be essentially media/site independent.

2.2 KEY ISSUES WHICH IMPACT THE CHOICE OF THE VALUES OF CRITICAL ENGINEERING VARIABLES

The key issues which will affect the choice of the value of each critical engineering variable (Table 2.1), and hence the level of confidence in satisfactory performance, can be separated into those related to:

- Purpose of each repository component, as defined by the repository conceptual design

Rev. 10-82
Dwg. No. 813-11638 Date 1-82 Eng. BR
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Table 2.1

CRITICAL REPOSITORY DESIGN AND CONSTRUCTION ENGINEERING VARIABLES

	CRITICAL ENGINEERING VARIABLES		
	(Large scale)		(Small scale)
REPOSITORY STAGE	SHAFTS	TUNNELS/CAVERNS	WASTE PACKAGE EMPLACEMENT HOLES
Pre-construction (Design)	number location (spacing) orientation depth size (x-section) shape (x-section)	depth number location (spacing) orientation length size (x-section) shape (x-section)	location orientation spacing hole diameter hole depth
Construction*	excavation method support method/ requirements liner requirements	excavation method support method/ requirements liner requirements (if any)	
	dewatering ventilation hoisting	dewatering ventilation transport	
Operation*			hole drilling hole lining waste package emplacement hole backfill/plug waste package corrosion protection waste package retrieval
Post-Operation (Decommissioning)	backfill plugging	backfill sealing	

(Excluding surface facilities and waste package)

* Construction and operation are sequential for any panel, but they are concurrent for the total repository.

- Engineering variable interrelationships (if any)
- Site characteristics.

The purpose of the repository component is defined by the repository conceptual design, and includes the following key issues:

- Usage (type) definition, e.g.-
  - conveyance of men, equipment, muck from mining, or waste packages
  - provision of ventilation, utilities, or dewatering
  - storage of equipment, muck, or waste packages
  - operating life
- Capacity requirements, e.g.-
  - dimensions of equipment
  - conveyance capacity
  - ventilation capacity
- Isolation requirements, e.g., separation of mining and waste storage operations
- Layout requirements or interrelationships between components, e.g., repository level conceptual layout affecting shaft location.

Key issues which are related to site characteristics include the following:

- Constructability. Can the facility be constructed in a timely and safe fashion, and so that it will not jeopardize the long-term waste containment/isolation capability of the facility? Both the unavoidable creation of a disturbed zone of rock around underground openings and the construction of engineered barriers will have an effect on the response of the repository.
- Thermal Response. Can the temperature field be adequately predicted as a function of time to use as input to the mechanical, hydrological and geochemical models?
- Mechanical Response. Can the stability and deformation of underground openings (including waste package emplacement holes) be adequately predicted for the periods of short-term construction/operation and long-term waste containment/isolation?
- Hydrologic Response. Can an adequate prediction be made regarding the resaturation time of the repository (post-closure) and of the groundwater flow through the repository over the long term, including the potential impact of shafts? Of lesser importance is the question of the amount of inflow into the repository during operation, i.e., over the short term.
- Geochemical Response. Can an adequate prediction be made of the nature and extent of geochemical alteration of the engineered

barriers and the rock? Can the quantity and rate of migration of specific radionuclides over the long term be adequately predicted?

The above key issues are essentially related to predicting the short-term construction/operation performance and the long-term waste containment/isolation performance. Generally, they are a function of both the constructed repository and the site characteristics. The site characteristics include those of the rock mass around underground openings which have been disturbed by excavation, as well as those of the undisturbed rock mass. The constructed repository will also include engineered barriers (e.g., backfill, seals, and plugs). The interface between the barriers and the rock mass must also be considered.

The various key issues affecting the choice of the value of each identified engineering variable for shafts, tunnels/caverns, and waste package emplacement holes (Table 2.1) have been identified (see Tables 2.2, 2.3, and 2.4, respectively). These key issues are considered to be essentially media independent.

The key issues must be resolved in order to:

- Design and construct a repository (i.e., choose values for the critical engineering variables) for any of the media/sites being considered
- Demonstrate an acceptably high level of confidence in satisfactory performance for that repository design and site.

These key issues can be resolved either by:

- Adequately assessing certain media/site specific characteristics, which are used as input in predictive numerical modeling, and sufficiently verifying these models.
- Appropriately simulating various aspects of the repository, in order to extrapolate the results.

These two approaches will be discussed separately. Information needs, to which in situ test programs must respond, are related to the adequate resolution of these key issues.

KEY ISSUES AFFECTING CHOICE OF VALUES OF CRITICAL SHAFT ENGINEERING VARIABLES

Table 2.2

CRITICAL SHAFT ENGINEERING VARIABLE (See Table 2.1)

		PRE-CONSTRUCTION						CONSTRUCTION			CONSTRUCTION /OPERATION			POST-OPERATION	
	KEY ISSUE	Number	Location	Orientation	Depth	Size (X-Section)	Shape (X-Section)	Excavation Method	Support Method/Requirements	Liner Requirements	Dewatering Requirements	Ventilation Requirements	Hoisting Requirements	Backfill	Plugging
PURPOSE OF SHAFTS	Usage	●	●	●		●	●	●	●	●	●	●	●	●	●
	Capacity Requirements	●				●					●	●	●		
	Isolation Requirements	●	●								●	●	●	●	●
	Layout Requirements	●	●	●	●						●	●	●	●	●
VARIABLE INTERRELATIONSHIP	Number	X	●			●					●	●		●	●
	Location	●	X								●	●		●	●
	Orientation		●	X		●	●	●	●		●	●		●	●
	Depth			●	X			●			●	●			
	Size (X-Section)	●				X	●	●	●	●	●	●		●	●
	Shape (X-Section)	●				●	X	●	●	●				●	●
	Excavation Method		●	●		●	●	X	●	●	●	●		●	●
	Support Method/Requirements					●	●	●	X	●	●	●		●	●
	Liner Requirements					●	●		●	X	●			●	●
	Dewatering Requirements									●	X				
	Ventilation Requirements	●	●	●		●						X			
	Hoisting Requirements	●	●	●		●							X		
	Backfill					●	●	●	●	●	●	●		X	●
	Plugging					●	●	●	●	●	●	●		●	X
SITE CHARACTERISTIC RELATED	Constructability	●	●	●				●				●		●	●
	Thermal Response								●			●		●	●
	Mechanical Response		●	●		●	●	●	●					●	●
	Hydrologic Response					●		●	●	●	●			●	●
	Geochemical Response								●	●				●	●

● Issue affects choice of engineering variables

X Issue of variable interrelationship does not exist (identical)

Rev. 10-82

Dwg. No. RCS-11638 AMT 012 Date 1-82 Eng. BR

Rev. 10-82
Dwg. No. 212-4638 Art 0-3 Date 1-82 Eng. BR

KEY ISSUES AFFECTING CHOISE OF VALUES OF CRITICAL TUNNEL/CAVERN ENGINEERING VARIABLES

Table 2.3

CRITICAL TUNNEL/CAVERN ENGINEERING VARIABLE (See Table 2.1)

		PRE-CONSTRUCTION							CONSTRUCTION			CONSTRUCTION /OPERATION			POST-OPERATION	
	KEY ISSUE	Depth	Number	Location (Spacing)	Orientation	Length	Size (X-Section)	Shape (X-Section)	Excavation Method	Support Method/Requirements	Liner Requirements	Dewatering Requirements	Ventilation Requirements	Transport Requirements	Backfill	Sealing
PURPOSE OF TUNNEL/CAVERNS	Usage		●	●	●		●	●	●	●	●	●	●	●	●	●
	Capacity Requirements		●			●	●							●		
	Isolation Requirements	●	●	●		●						●	●	●	●	●
	Layout Requirements	●	●	●	●	●						●	●	●	●	●
VARIABLE INTERRELATIONSHIP	Depth	X							●			●	●			
	Number		X	●		●						●	●	●	●	●
	Location (Spacing)		●	X								●	●	●	●	●
	Orientation			●	X			●	●	●		●		●		
	Length		●			X						●	●	●		
	Size (X-Section)						X	●	●	●	●	●	●	●	●	●
	Shape (X-Section)						●	X	●	●	●			●	●	●
	Excavation Method			●	●		●	●	X	●	●	●	●	●	●	●
	Support Method/Requirements						●	●	●	X	●	●		●	●	●
	Liner Requirements						●	●		●	X	●			●	●
	Dewatering Requirements								●		●	X				
	Ventilation Requirements		●	●		●			●				X			
	Transport Requirements		●	●	●	●	●	●						X		
	Backfill						●	●				●	●		X	●
	Sealing						●	●				●	●		●	X
SITE CHARACTERISTIC RELATED	Constructability		●	●	●		●	●	●						●	●
	Thermal Response									●			●		●	●
	Mechanical Response			●	●		●	●	●	●					●	●
	Hydrologic Response				●		●		●	●	●	●			●	●
	Geochemical Response									●	●				●	●

● Issue affects choice of engineering variables

X Issue of variable interrelationship does not exist (identical)

KEY ISSUES AFFECTING CHOISE OF VALUES OF CRITICAL WASTE PACKAGE EMPLACEMENT HOLE ENGINEERING VARIABLES

Table 2.4

CRITICAL WASTE PACKAGE EMPLACEMENT HOLE ENGINEERING VARIABLE (See Table 2.1)

	KEY ISSUE	PRE-CONSTRUCTION					OPERATION					
		Location	Orientation	Spacing	Hole Diameter	Hole Depth	Hole Drilling	Hole Lining	Waste Package Emplacement	Hole Backfill/Plug	Waste Package Corrosion Protection	Waste Package Retrieval
PURPOSE OF WASTE PACKAGE EMPLACEMENT HOLES	Usage	●	●		●	●	●	●	●	●	●	●
	Capacity Requirements		●	●	●	●	●		●	●	●	●
	Isolation Requirements	●	●			●			●			●
	Layout Requirements	●	●	●			●		●	●		
VARIABLE INTERRELATIONSHIP	Location	X	●	●			●		●			
	Orientation	●	X	●		●	●		●	●		●
	Spacing	●	●	X								
	Hole Diameter				X		●	●		●		●
	Hole Depth	●	●			X	●	●	●	●		●
	Hole Drilling		●		●	●	X	●				
	Hole Lining				●		●	X	●	●	●	●
	Waste Package Emplacement		●			●		●	X	●		
	Hole Backfill/Plug				●	●		●	●	X	●	●
	Waste Package Corrosion Protection				●	●		●		●	X	●
	Waste Package Retrieval		●			●		●	●	●	●	X
SITE CHARACTERISTIC RELATED	Constructability				●	●	●					
	Thermal Response	●	●	●	●			●		●		●
	Mechanical Response	●	●		●	●		●		●		●
	Hydrologic Response									●		●
	Geochemical Response	●		●	●			●		●	●	●

● Issue affects choice of engineering variables

X Issue of variable interrelationship does not exist (identical)

Rev. 12-82
Dwg. No. 813 11634 Date 1-82 Eng. BR

3.0 SIGNIFICANT CHARACTERISTICS WHICH IMPACT THE RESOLUTION OF KEY ISSUES

3.1 SITE CHARACTERISTICS

Certain characteristics of a site must be assessed in order to adequately resolve the key issues (see Table 3.1). These characteristics (see Glossary) can be summarized as those which describe the:

- Geologic setting of the site
- Response or behavior of the site

The geologic setting constitutes the geometry and boundary/ field conditions of the site, as well as the "physical" characteristics of the materials.

The geometry consists of the present stratigraphy/ lithology and structure of rock mass units. Each rock mass unit is considered to be relatively homogeneous and consists of intact rock intersected by discontinuities, such as joints, shears, and fractures, with pore fluid (i.e., liquid and/or gas) contained in spaces within the rock mass. Boundaries of rock mass units can be defined by changes in lithology or structure, i.e., either large scale faults or changes in discontinuity patterns.

The boundary/field conditions include the pre-excavation:

- In situ stress field
- In situ hydraulic head field, which defines the direction and magnitude of hydraulic gradients
- In situ temperature field.

The "physical" characteristics which describe each rock mass unit include:

- Mineralogy, texture (including microcracking, bedding, schistosity), porosity, and density of the intact rock

- Spacing, orientation, persistence, roughness/planarity, aperture, and nature of infilling or surface materials of the discontinuities

- Content and composition of pore fluid.

Also, the potential changes in the boundary/field conditions and corresponding changes in structure (i.e., tectonics) or physical characteristics, which are unrelated to repository development, must be discussed as part of the geologic setting.

The "response" characteristics, i.e., those which describe the mechanical, thermal, hydrologic, and geochemical response to any loading, of the rock mass are strongly related to the physical

CHARACTERISTICS WHICH IMPACT THE RESOLUTION OF KEY ISSUES

Table 3.1

CHARACTERISTICS	KEY ISSUES Constructability	Thermal Response	Mechanical Response	Hydrologic Response	Geochemical Response
GEOLOGIC SETTING					
Stratigraphic/structural*	●	●	●	●	●
Tectonic	○	●	●	●	○
In situ stress field	○	○	●	○	○
In situ hydraulic head field	●	○	○	●	○
In situ temperature field	●	●	○	○	○
RESPONSE					
(MECHANICAL)					
Strength	●		●	○	○
Deformation	○		●	○	
Creep/fusing	○		●	○	○
(THERMAL)					
Thermal conductivity		●	○		
Heat capacity		●	○		
Linear thermal expansion		●	●		
(HYDROLOGIC)					
Hydraulic conductivity				●	○
Effective porosity				●	●
Specific storage				●	
(GEOCHEMICAL)					
Dispersivity					●
Adsorption/retardation					●
Alteration/solubility	○	○	○	●	●

* includes the physcial and chemical characteristics of each rock mass unit (including pore fluid composition).

● characteristic significantly impacts resolution of key issues.

○ characteristic impacts resolution of key issues, but to a lesser degree characteristics of each rock mass unit. It is generally assumed that the response characteristics (or their functions) are unique for each rock mass unit because the physical characteristics are relatively constant throughout that unit. However, each rock mass unit is only approximately homogeneous, so that there is some variability in physical characteristics throughout the unit and some resulting variability in response characteristics as measured from point to point within the unit.

Volumes which are relatively homogeneous with respect to hydrologic response characteristics are often termed "hydrologic units." Such hydrologic units consist of one or more rock mass units, and will not necessarily be homogeneous with respect to physical characteristics or other response characteristics. The characteristics of rock mass units will thus be discussed here.

Discontinuities, as separations in the intact rock matrix, tend to dominate the response of the rock mass. Hence, two different approaches have been developed to assess the response of a rock mass (i.e., consisting of intact rock, discontinuities, and pore fluid). The rock mass can be treated as either:

- A discontinuum, in which the discontinuities are represented discretely and explicitly
- A continuum, in which the discontinuities are implicitly represented as part of a quasi-continuum rock mass.

The explicit treatment of each discontinuity in a discontinuum-type analysis necessitates the following:

- Description of each discontinuity. This includes determining the location, orientation, and planarity, as well as the response characteristics of each discontinuity. These response characteristics will be related to the physical characteristics of the discontinuity, i.e., persistence, aperture, roughness, nature of infilling or surface materials.
- Description of the intact rock. This includes determining the response characteristics of the intact rock, which will be related to the physical characteristics of the intact rock, i.e., its mineralogy and texture (including microcracking, bedding, and schistosity).

However, it is logistically very difficult to assess and model each discontinuity explicitly on a large scale and perform numerical analyses.

The implicit treatment of all the discontinuities in a continuum-type analysis necessitates the description of the rock mass. This includes determining the response characteristics of the rock mass, as a composite of the intact rock and discontinuities. These response characteristics will thus be related to the physical characteristics of the rock mass (i.e., the spacing, orientation, and planarity of the discontinuities), as well as the response characteristics of both the intact rock and the discontinuities. It is relatively easy to perform continuum-type analyses.

3.2 VARIABLES WHICH AFFECT ASSESSMENT OF RESPONSE CHARACTERISTICS

3.2.1 Sensitivity

The response characteristics for any volume of material are often:

- Anisotropic (i.e., vary with orientation)
- Scale-dependent (i.e., vary with the scale of the sample)
- Time-dependent (i.e., vary over time)
- A function of the present and past environmental conditions, including
  - stress level (σij, in tensor notation)
  - pore pressure (u)
  - temperature (Te)
  - radiation dose (R)

Thus, the value of an anisotropic parameter (P_{kl}, in tensor notation) for a volume of material at any location can be generally expressed as:

$$(P_{kl}) = f(V, T, \sigma ij, u, T_e, R)$$

where

V = scale or volume of the sample
T = time of applicability

The sensitivity of the value of each response characteristic to each of the assessment variables can be investigated. For example, if the multivariable function "f" were reliably known, the sensitivity could be assessed by taking the partial derivative of "f" with respect to any assessment variable, e.g. (see Figure 3.1):

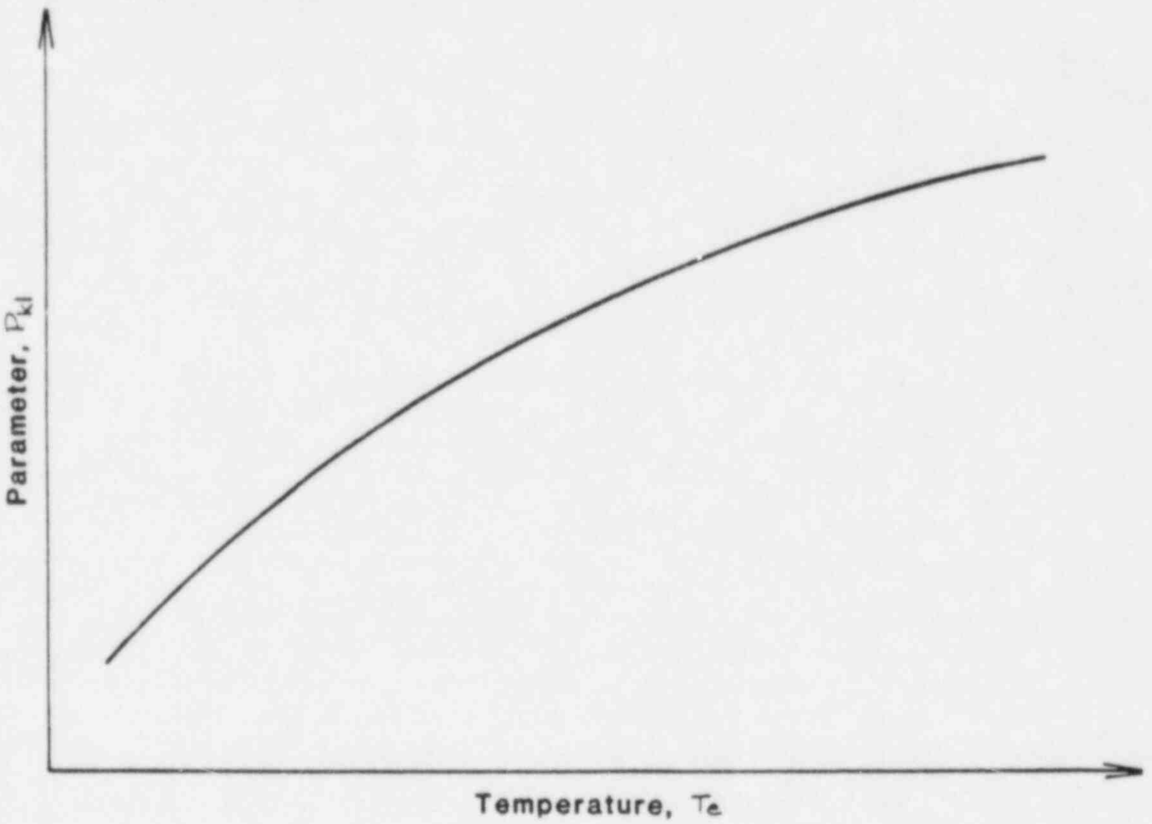
$$\frac{\delta (P_{kl})}{\delta Te} = \frac{\delta f(V, T, \sigma ij, u, Te, R)}{\delta Te}$$

The multivariable function "f" is not typically known, however, so that the sensitivity is often assessed by observing the change in P_{kl} with a change in one assessment variable, while maintaining the others constant. The observed sensitivity may change significantly, however, for another set of assessment variable values.

SENSITIVITY OF A RESPONSE CHARACTERISTIC TO AN ASSESSMENT VARIABLE (EXAMPLE)

Figure 3.1

Sensitivity of parameter to one assessment variable is for a given set of the other assessment variables (i.e., constant) and a given set of physical characteristics of the material.



Value of anisotropic parameter, P_{kl} (in tensor notation), is a function of various assessment variables:

$$(P_{kl}) = f(V, T, \sigma_{ij}, u, T_e, R)$$

where V = **scale or volume of sample**

T = **time of applicability**

σ_{ij} = **stress level (in tensor notation)**

u = **pore pressure**

T_e = **temperature**

R = **radiation dose**

— **Environmental conditions (past and present)** (σ_{ij}, u, T_e, R)

This multivariable function is unique for a given set of physical characteristics of the material.

Rev. ______ Dwg. No. 523-013 Art 007 ______ Date 1-82 10-82 ______ Eng. BL

The general sensitivity of each of the response characteristics to the assessment variables has been qualitatively assessed, based on experience (see Table 3.2). However, the relationship, and thus sensitivity, of response characteristics to the assessment variables have not been explicitly established and, also, are not independent of media in many cases. Hence, these sensitivities provide a qualitative indication only of which assessment variables can be expected to affect the characteristic values.

3.2.2 Representative Sample

It is assumed that, for a given set of physical characteristics, the multivariable function "f" is unique. Thus, in order to adequately assess this function, it is necessary to obtain and test a representative sample, i.e., the sample must have a set of physical characteristics which is very similar to that of the material. However, the material is relatively homogeneous only within a certain dimensional range (see Figure 3.2):

- Intact rock is relatively homogeneous between the scales of textural features (i.e., typically fractions of an inch) and discontinuity spacing (i.e., up to tens of feet). A representative sample of intact rock can often be obtained by coring. Thus, the response characteristics of intact rock are relatively easy to assess.

- Discontinuities are relatively homogeneous between the scales of roughness (i.e., typically inches to feet) and planarity (i.e., often many feet). Although the physical characteristics of discontinuities within a set vary widely, it is often assumed that discontinuities within a joint set have similar physical characteristics, so that one joint is considered to be representative of the set. However, it is difficult to assess large-scale physical characteristics such as planarity and persistence. A representative sample of a discontinuity is difficult to obtain, except exposed in underground openings. Thus, the response characteristics of discontinuities are relatively difficult to assess.

- The rock mass is relatively homogeneous between the scales of discontinuity spacing (i.e., typically inches up to tens of feet) and stratigraphic/structural features (i.e., often many tens of feet). At smaller scales, either the intact rock or the discontinuity is tested, and not the composite rock mass. Conversely, at very large scales, the rock mass is no longer homogeneous, as diverse rock mass units are included in the sample. At an intermediate scale, however, the volume is sufficient to contain a significant number of representative discontinuities. This "representative" volume of the rock mass is typically difficult to achieve and thus the quasi-continuum response characteristics of the rock mass are often relatively difficult to assess. They can be assessed in one of two ways, either:

SENSITIVITY OF RESPONSE CHARACTERISTICS TO ASSESSMENT VARIABLES

Table 3.2

ASSESSMENT VARIABLES

				ENVIRONMENTAL CONDITIONS (Past and Present)			
RESPONSE CHARACTERISTICS (see Table 3.1)	Anisotropic	Scale-Dependent	Time-Dependent	Stress Level	Pore Pressure	Temperature	Radiation Dose
MECHANICAL							
Strength	●	●	●	●	●	●	○
Deformation	●	●	●	●	●	●	○
Creep/fusing	○	○	●	●	○	●	○
THERMAL							
Thermal conductivity	●	●		●	○	●	
Heat capacity		○		○	○	●	
Linear thermal expansion	●	●	○	●	○	●	○
HYDROLOGIC							
Hydraulic conductivity	●	●		●	●	●	
Effective porosity	○	●		○	●	●	
Specific storage	○	●		○	●	●	
GEOCHEMICAL							
Dispersivity	●	●	○		○	●	●
Adsorption/retardation	●	●	○	○	○	●	●
Alteration/solubility		●	●	○	●	●	●

● response characteristic is typically sensitive to variable

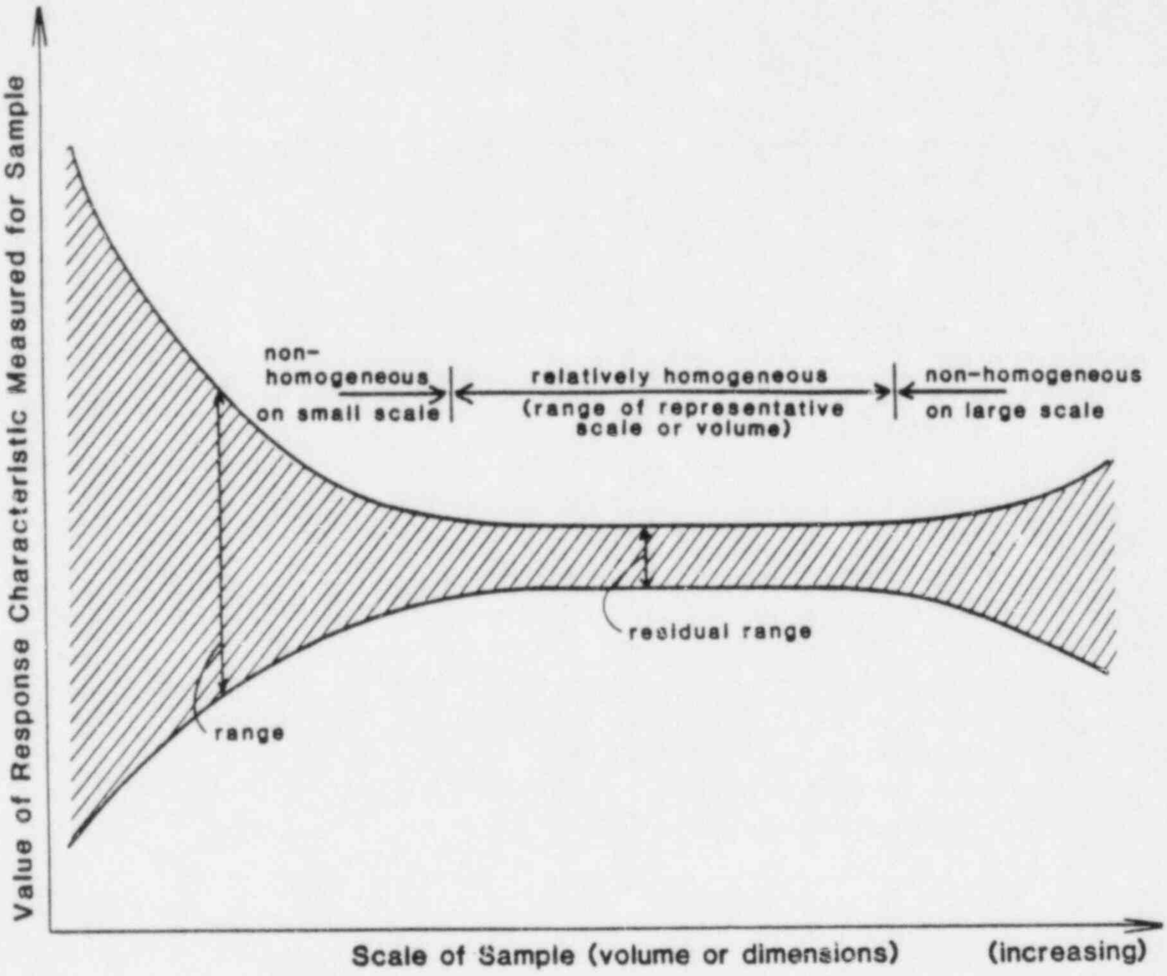
○ responce characteristic may be sensitive to variable, but probably at a low level (if at all)

Note: The sensitivity of response characteristics to the assessment variables have been qualitatively assessed, based on experience. However, these sensitivities are <u>qualitative indicators only</u>, as the relationship, and thus the sensitivity, of response characteristics to the assessment variables have not been explicitly established and, also, are not independent of media in many cases.

Rev. [illegible] Date [illegible] Eng [illegible]
Dwg. No. 813-11635 4AT016 Date 1-82 Eng BR

SCALE EFFECT ON MEASURED VALUES OF A RESPONSE CHARACTERISTIC

Figure 3.2



Note: Although there will be some residual variability, the mean value of the response characteristic can be confidently assessed if based on a representative volume.

Rev. 10-82
Dwg. No. 83-1534 A81008 Date 1-82 Eng BR

- a large-scale sample, which contains a significant number of representative discontinuities, can be tested and the quasi-continuum response characteristics directly assessed. However, it is logistically very difficult to obtain and test a sufficiently large sample (i.e., often with dimensions of many feet), except with large-scale in situ tests.

- the quasi-continuum response characteristics can be indirectly determined as a result of explicitly modeling (numerically) representative discontinuities within a simulated volume of rock mass. Although it is relatively difficult to assess the characteristics of the discontinuities, it is relatively easy to adequately assess the response characteristics of the intact rock and to assemble a model to develop quasi-continuum response characteristics for the rock mass. This indirect assessment may contain significant uncertainty in the derived response characteristics.

Each rock mass unit is approximately homogeneous, however, so that the physical characteristics of even appropriately sized samples will vary from sample to sample. The response characteristics measured for these samples will thus exhibit some natural variability within each rock mass unit.

Other problems in obtaining a representative sample include changes in the physical characteristics due to sampling and with time. For example, the aperture of discontinuities typically changes with sampling. This causes a significant change in the response characteristics (e.g., strength, hydraulic conductivity, etc.). As another example, the intact rock mineralogy may change as alteration occurs with time. Similarly, the pore fluid content/composition and the nature of discontinuity infilling/surface coating may change with time.

The physical characteristics of the disturbed rock mass which will exist immediately around any underground openings will be unknown until after construction and may be significantly different from the undisturbed rock mass. This is especially related to the overstressing which occurs during excavation, and which leads to additional microcracking of intact rock and creation of additional discontinuities. Also, this zone may be dewatered and exposed to conditions which will accelerate alteration. The differences in the physical characteristics, and thus the response characteristics, may be significant between the disturbed and undisturbed rock mass, and will be a function of the excavation procedure. Prior to construction, these differences can only be predicted, whereas after construction they can be observed.

3.3 UNCERTAINTY IN THE ASSESSMENT OF CHARACTERISTICS

The estimate of each response characteristic is based on the interpretation of all available information, i.e., the data base. In addition to the inherent uncertainty in the predicted value of each characteristic due to this interpretation, there will be some unknown natural variability throughout each rock mass unit. The level of uncertainty in the assessment of each characteristic will be related to:

- Range in physically possible values. Absolute upper and lower bounds on the value of each characteristic can be set by physical laws, e.g., shear strength, thermal conductivity, and hydraulic conductivity have lower bounds of zero. The larger the range between the upper and lower bounds, the larger the potential uncertainty is in the assessment of a given characteristic.

- Natural variability. There will exist some natural variability throughout each rock mass unit. This variability causes a residual uncertainty in the estimate of each characteristic, even for an ideal data base. The larger this variability, the larger the residual (or minimum possible) uncertainty.

- Quality of data base. The data base must contain sufficient information to draw conclusions regarding the mean value and natural variability of each significant characteristic. Thus, the data base must be sufficiently large, and the correlation between each data point and the actual value must be high. This correlation will be a function of random errors and/or systematic errors (or biases) in the determination of each data point. These errors, in turn, are a function of:

    - Representation of the material by the sample. The physical characteristics of the sample tested may be different than the rock mass unit of interest, e.g., due to scale problems, sampling disturbance, or a change in pore fluid. Also, the physical characteristics may change with time, e.g., as alteration or solution occurs. In the case of the potential disturbed zone, the physical characteristics are a function of the excavation procedure. Where a numerical model is used to represent the coupling of individual components of a rock mass unit, there will be additional uncertainty in the derived data point.

    - Representation of the environmental conditions by the test. The test may not establish the complete relationship between the response characteristic and all of the environmental conditions. For example, one of the environmental conditions (e.g., temperature) might be held constant as the others are varied. If the characteristic is sensitive to that variable, then there will be significant uncertainty in the resulting assessment.

    - Accuracy in individual test results. The results of each test will have some inherent uncertainty due to possible measurement errors/ biases and assumptions/interpretations in the analysis. With care, this uncertainty can often be significantly reduced.

> As the quality of the data base improves, e.g., incorporating appropriate data from carefully controlled in situ tests under operating conditions, the uncertainty in the assessment of a characteristic decreases.

Where the characteristic is quantifiable and thus the probability of values is continuously distributed, e.g., hydraulic conductivity, the uncertainty in the assessment can be expressed in terms of confidence levels, e.g., those bounding values for which there is a 90% chance that the actual value will lie between (see Figure 3.3). Higher uncertainty is reflected by larger ranges for a given confidence level (see Figure 3.4). Where the characteristic is non-quantifiable (or has integer values) and thus the probabilities are discretely distributed, e.g., the presence of faults, the uncertainty can be expressed in terms of probabilities for each possibility (or scenario) in a comprehensive, mutually exclusive set.

It must be emphasized that the probability distributions for each characteristic are assessed based on the interpretation of available information (i.e., the data base). This probability distribution is not equivalent to the statistical distribution of data contained within the data base, but should take into account all components of uncertainty.

3.4 PRESENT ASSESSMENT OF MEDIA/SITE SPECIFIC CHARACTERISTICS

3.4.1 Basis for Present Assessment

The values of significant characteristics have been roughly assessed, as discussed in previous sections, for each of the media/sites under consideration (see Appendix B of Volume II). This assessment has been based on readily available information. That is, a data base has been assembled for each media/site and subsequently interpreted. This present assessment of media/site specific characteristics consists of a best estimate and an indication of the present level of uncertainty in that value (e.g., 90% confidence levels). This uncertainty includes the natural variability of the characteristic.

Although this assessment is considered to be sufficient for the purposes of this study, i.e., illustrating the development of, and subsequent response to, information needs, it should not be construed as being sufficient for accurate performance assessment/licensing purposes. As additional information becomes available, this assessment will change.

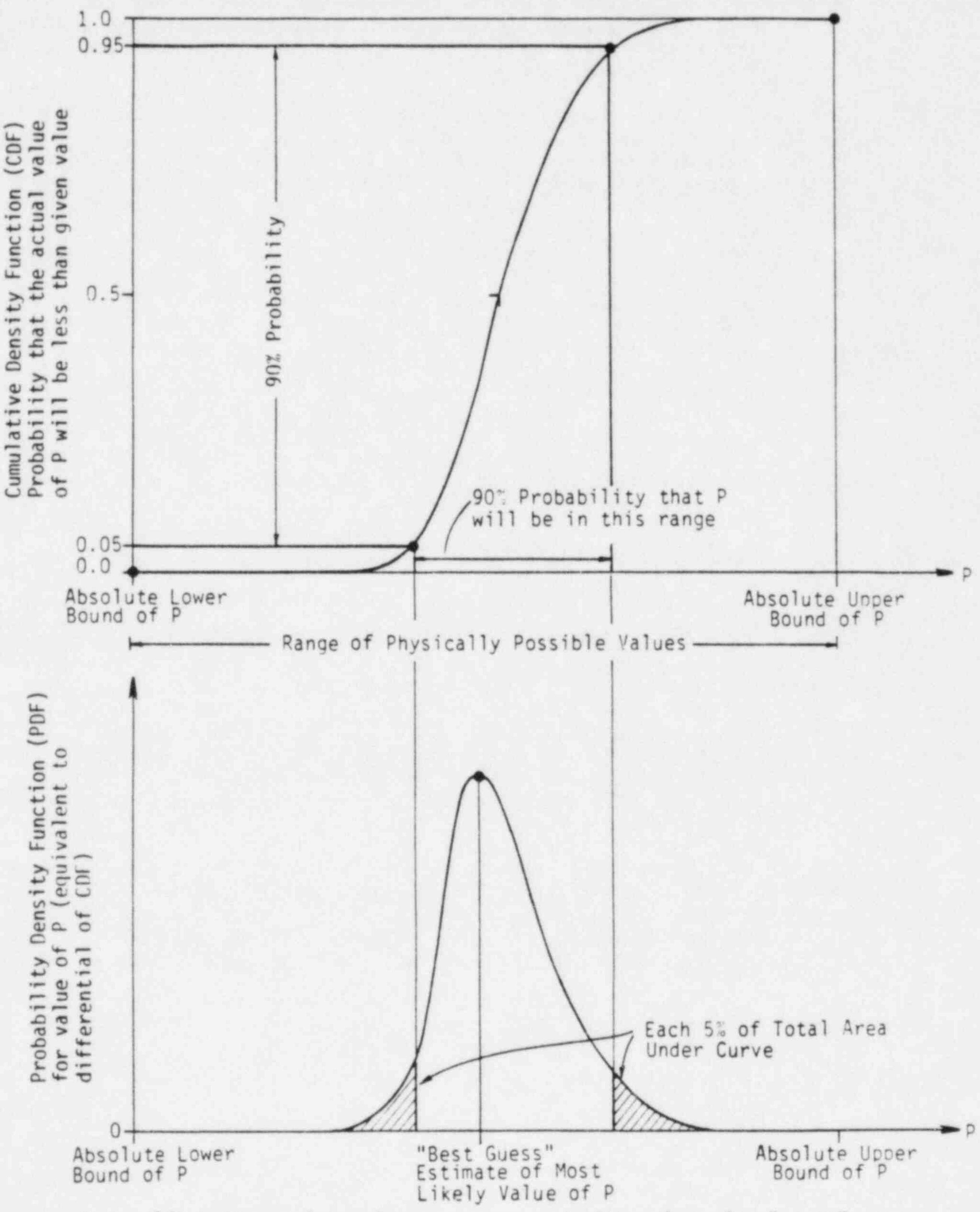
3.4.2 Present Media/Site Specific Assessments

3.4.2.1 Basalt

In accordance with the previously described basis (see Section 3.4.1), the present assessment of characteristics of the site in basalt at the Hanford Reservation in Washington has been accomplished (see Appendix B

PROBABILITY DISTRIBUTIONS FOR RESPONSE CHARACTERISTIC (EXAMPLE)

Figure 3.3

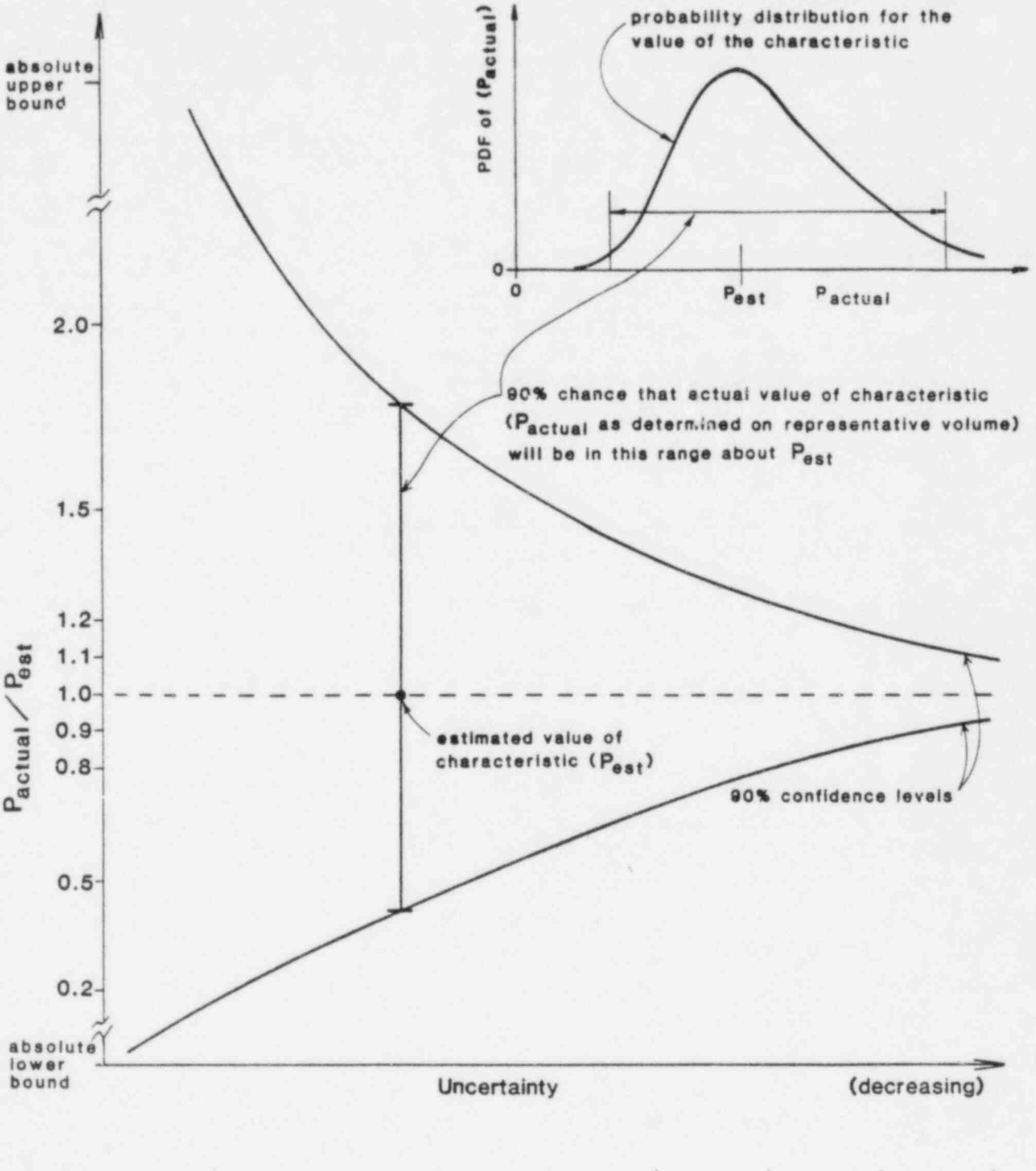


Note: Often the engineer is more concerned with values for "worst" case rather than for "best" case, so that more effort is expended in defining the tail distribution.

Rev. ____ Dwg No. 18/37/63 Date 10-82 Eng BR

UNCERTAINTY IN ESTIMATION OF VALUE OF CHARACTERISTIC

Figure 3.4



Rev. ______
Dwg. No. 513 11638 AML 229 Date 1-82 10-82 Eng ______

of Volume II, Table B-2). The distinctive features of the site include:

- Relatively complex geology (flow structures)
- Potential for tectonic activity
- High horizontal in situ stresses
- High in situ temperatures
- Proximity to a major water resource
- Highly fractured rock mass, especially vertical cooling joints; the intact rock is relatively strong, brittle, abrasive, impermeable, and thermally conductive, but the fractures dominate rock mass strength, stiffness, hydraulic conductivity, effective porosity and adsorption/retardation (similar to granite, see Section 3.4.2.5).

3.4.2.2 Tuff

In accordance with the previously described basis (see Section 3.4.1), the present assessment of characteristics of the site in tuff at Yucca Mountain at the Nevada Test Site has been accomplished (see Appendix B of Volume II, Table B-3). The distinctive features of the site include:

- Relatively complex geology (flow structures)
- Potential for tectonic activity
- Deep water table
- Very porous fractured rock mass; the rock mass is relatively weak and may have high hydraulic conductivity, although it may be highly adsorptive
- Susceptibility of rock to alteration, especially with elevated temperatures.

3.4.2.3 Domal Salt

In accordance with the previously described basis (see Section 3.4.1), the present assessment of characteristics of the potential sites in domal salt along the Gulf Coast has been accomplished (see Appendix B of Volume II, Table B-4). The distinctive features of these sites include:

- Relatively complex geology (folding)

- Possibly ongoing diapirism (dome building)

- Relatively weak and plastic rock mass, which exhibits creep and self-healing/fusing (minimal fracturing); mechanical characteristics degrade rapidly with increasing temperature

- Relatively impermeable rock mass, but the rock is soluble and the pore fluid is corrosive (similar to bedded salt, see Section 3.4.2.4).

3.4.2.4 Bedded Salt

In accordance with the previously described basis (see Section 3.4.1), the present assessment of characteristics at any potential site in bedded salt has been accomplished (see Appendix B of Volume II, Table B-5). The distinctive features of these sites include:

- Possible existence of continuous, porous interbeds

- Relatively weak and plastic rock mass, which exhibits creep and self-healing/fusing (minimal fracturing); mechanical characteristics degrade rapidly with increasing temperature

- Relatively impermeable rock mass, but the rock is soluble and the pore fluid is corrosive (similar to domal salt, see Section 3.4.2.3).

3.4.2.5 Granite

In accordance with the previously described basis (see Section 3.4.1), the present assessment of characteristics at any potential site in granite has been accomplished (see Appendix B of Volume II, Table B-6). The distincitve features of these sites include:

- Rock mass with widely spaced joints; the intact rock is relatively strong, brittle, abrasive, impermeable, and thermally conductive, but the fractures dominate rock mass strength, stiffness, hydraulic conductivity, effective porosity and adsorption/retardation (similar to basalt, see Section 3.4.2.1).

3.5 SIGNIFICANCE OF EACH CHARACTERISTIC

3.5.1 Process of Evaluation

The uncertainty in the assessment of each characteristic must be reduced to certain levels in order to resolve the issues and demonstrate an acceptably high level of confidence in satisfactory performance. However, the required level of confidence in the prediction of each characteristic will not necessarily be media/site independent, but may be a function of its expected value and the values of other significant characteristics. This is because repository performance is a function of many characteristics, and acceptable repository performance can be predicted with the required level of confidence by various combinations of characteristic values.

In order to establish the approximate required level of confidence in the prediction of each characteristic, the significance of each characteristic, in terms of its influence on the short-term construction/operation and long-term waste containment/isolation performance, must first be established. This evaluation should take into account the following general attributes of the characteristic:

- Availability of cost-effective design and construction techniques which allow for a conservative assumption of the value of the characteristic
- Uncertainty in the representation of the phenomenological laws of nature by the performance prediction model
- Sensitivity of the performance prediction model to the value of the characteristic
- Cost effectiveness and scheduling limitations of measures to reduce the uncertainty in the assessment of the value of the characteristic.

The process used in this evaluation of the significance of each characteristic regarding compliance with each of the two summary performance criteria (short-term construction/operation and long-term waste containment/isolation) was to ask the following three questions in sequence and respond based on experience (see Figure 3.5):

(1) Is this characteristic significant to the particular performance criteria?

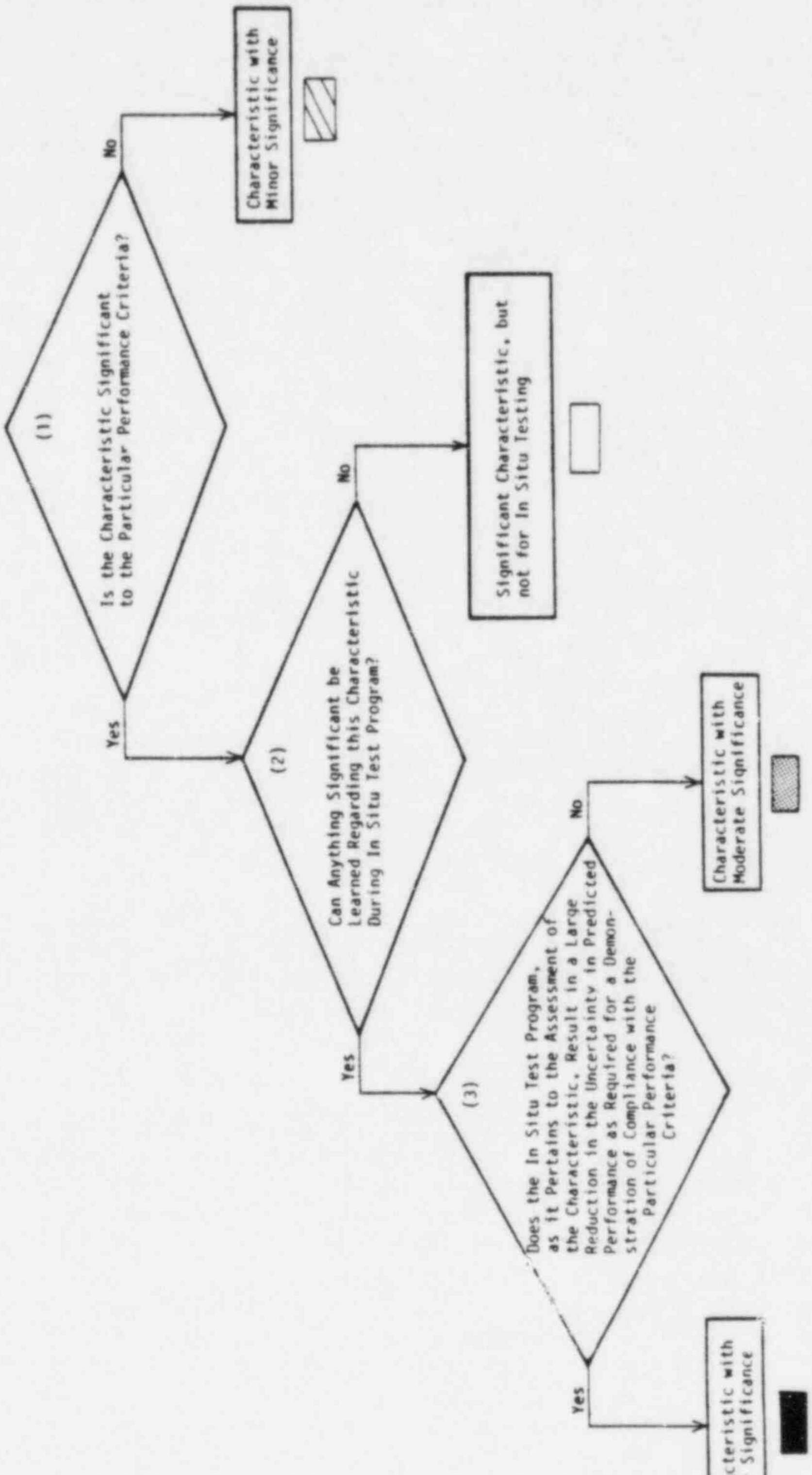
In other words, must the characteristic be assessed in order to design a critical engineering variable and/or demonstrate compliance with the performance criteria? If there is no significant relationship between the characteristic and the performance criteria, then the characteristic is determined to be of minor significance and should have the lowest priority for assessment and review. For example, such a lack of significance could be because either:

(a) a conservative assumption for the value of the characteristic can easily be designed around and thus has little cost impact

(b) the predictive model used in performance assessment and demonstration of compliance with performance criteria is not very representative of the real world and/or that model is relatively insensitive to the characteristic, so that a reduction in the uncertainty in the assessment of the characteristic does not result in a significantly improved performance assessment.

PROCESS OF EVALUATING SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN

Figure 3.5



Rev. 7813-1163B 8/3-1163 B 10-82 5-82 BR BR

Dwg. No. 8/3-1163B A125 006 Date 1-82 Eng. BR

If there is a significant relationship between the characteristic and the performance criteria, further evaluation is required.

(2) Can anything significant be learned regarding this characteristic during the in situ test program?

In other words, can the uncertainty in the assessment of the characteristic be potentially reduced in a cost-effective manner subsequent to the initial SCR submittal and prior to license application (LA)? If nothing realistic can be done, then the characteristic is determined to be significant, but not for in situ testing. For example, this might be because either:

(a) there is no test available to better assess the characteristic during the in situ test program

(b) there is low uncertainty in its present assessment.

If the uncertainty in the assessment can be realistically reduced, further evaluation is required.

(3) Does the in situ test program, as it pertains to the assessment of this characteristic, result in a large reduction in the uncertainty in predicted performance, as required for a demonstration of compliance with the performance criteria?

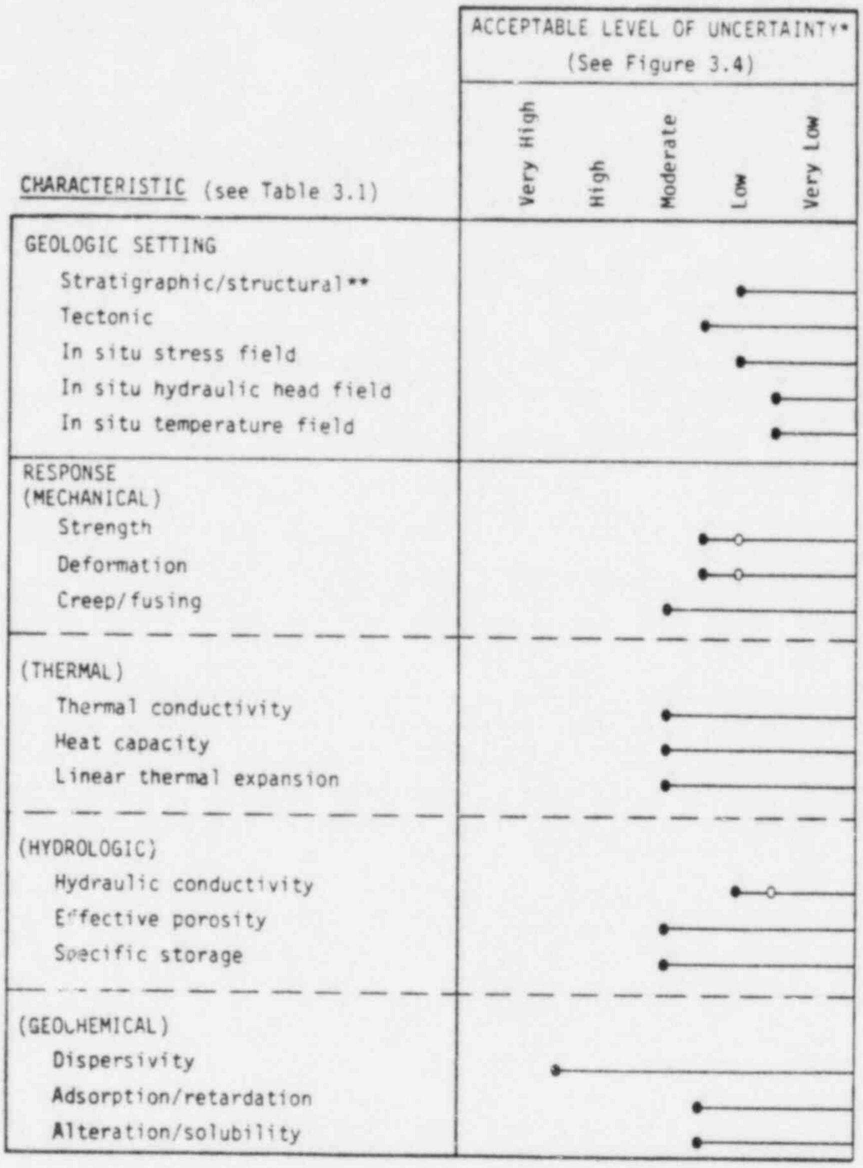
In other words, does the predictive model used in performance assessment and demonstration of compliance with the performance criteria adequately represent the real world and also is that model sensitive to the characteristic? If the model is very representative (i.e., has low uncertainty) and is also highly sensitive to the characteristic, so that the in situ test program results in a major improvement in the performance assessment, then that characteristic is determined to be of major significance. If the model is only moderately representative and/or only moderately sensitive to the characteristic, so that the in situ test program results in only a moderately better performance assessment, then that characteristic is determined to be of moderate significance.

Characteristics with major significance need to be assessed with relatively low uncertainty and should have highest priority for in situ testing. Characteristics with moderate significance can be assessed with greater uncertainty and should have next highest priority for in situ testing. Characteristics with minor significance can be assessed with relatively large uncertainty and should have low priority for in situ testing. Characteristics which are significant, but cannot be assessed during in situ testing must be assessed with relatively low uncertainty subsequent to repository construction.

The maximum acceptable level of uncertainty in the prediction of each characteristic which will sufficiently resolve the key issues (Table 3.1) has been subjectively assessed (see Table 3.3) based on experience

ACCEPTABLE LEVEL OF UNCERTAINTY IN THE ASSESSMENT OF EACH CHARACTERISTIC

Table 3.3



*Note: Acceptable levels of uncertainty have been subjectively assessed, based on experience and a particular licensing perspective, especially regarding the acceptable level of confidence in satisfactory performance (see Preface). However, these levels are qualitative indicators only, as the sensitivity of performance to all system components has not been explicitly determined. Also, the significance of these characteristics is not independent of magnitude of the characteristic value, of each other or of media.

● Maximum acceptable level of uncertainty for undisturbed rock mass characteristic (and disturbed, unless otherwise indicated)

○ Maximum acceptable level of uncertainty for disturbed (due to excavation) rock mass characteristic

**Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition).

Rev. ____ Dwg. No. A817-463 ____ Date Oct 82 ____ Eng. BR and a particular licensing perspective, especially regarding the acceptable level of confidence in satisfactory performance (see Preface). However, until the sensitivity of performance to all system components (including site characteristics) has been determined and the licensing perspective clarified, these maximum acceptable levels of uncertainty in the prediction of each characteristic can be considered as qualitative indicators only. Also, the significance of characteristics is not independent of the magnitude of the characteristic value, of each other or of the media.

The significance of the various characteristics, specifically as they relate to short- and long-term performance, has been determined utilizing the above procedure (Figure 3.5) for each of the media/sites under consideration. This assessment of significance is thus based on the present assessment of media/site specific characteristics (including magnitude and uncertainty) (see Section 3.4 and Appendix B of Volume II), and also the perceived reliability of models, general test capabilities, and sensitivity of performance to each characteristic.

3.5.2 Media/Site Specific Evaluations

3.5.2.1 Basalt

The significance of the characteristics, as they relate to the short- and long-term performance criteria, has been evaluated for the site in basalt at the Hanford Reservation in Washington (see Table 3.4). This evaluation has been based on the previously discussed procedure (see Section 3.5.1), the present assessment of characteristics (see Section 3.4.2.1 and Appendix B of Volume II, Table B-2), and experience.

3.5.2.2 Tuff

The significance of the characteristics, as they relate to the short- and long-term performance criteria, has been evaluated for the site in tuff at Yucca Mountain at the Nevada Test Site (see Table 3.5). This evaluation has been based on the previously discussed procedure (see Section 3.5.1), the present assessment of characteristics (see Section 3.4.2.2 and Appendix B of Volume II, Table B-3), and on experience.

3.5.2.3 Domal Salt

The significance of the characterisitcs, as they relate to the short- and long-term performance criteria, has been evaluated for the potential sites in domal salt along the Gulf Coast (see Table 3.6). This evaluation has been based on the previously discussed procedure (see Section 3.5.1), the present assessment of characteristics (see Section 3.4.2.3 and Appendix B of Volume II, Table B-4), and on experience.

SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN (BASALT - HANFORD, WASHINGTON)

Table 3.4

CHARACTERISTICS (see Table 3.1)	PERFORMANCE CRITERIA	
	SHORT-TERM (up to 100 years) CONSTRUCTION/OPERATION	LONG-TERM (100-10,000's Years) WASTE CONTAINMENT/ ISOLATION
GEOLOGIC SETTING		
Stratigraphic/structural*	■	■
Tectonic	□	□
In situ stress, hydraulic head and temperature fields	■	■
RESPONSE (MECHANICAL)		
Strength	▒	▒
Deformation	▒	▒
Creep	▨	▨
(THERMAL)		
Thermal conductivity	▒	▒
Heat capacity	▒	▒
Linear thermal expansion	▒	▒
(HYDROLOGIC)		
Hydraulic conductivity	■	▒
Effective porosity	▨	▒
Specific storage	▒	▒
(GEOCHEMICAL)		
Dispersivity	▨	□
Adsorption/retardation	▨	■
Alteration/solubility	▨	▨

*Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition)

■ Characteristic with major significance

▒ Characteristic with moderate significance

▨ Characteristic with minor significance

□ Characteristic is significant, but not during in situ testing

Note: Significance of characteristics was subjectively evaluated using the process illustrated in Figure 3.5 and discussed in Section 3.5.1.

SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN (TUFF - YUCCA MOUNTAIN, NEVADA)

Table 3.5

CHARACTERISTICS (see Table 3.1)	PERFORMANCE CRITERIA	
	SHORT-TERM (up to 100 years) CONSTRUCTION/OPERATION	LONG-TERM (100-10,000's Years) WASTE CONTAINMENT/ ISOLATION
GEOLOGIC SETTING		
Stratigraphic/structural*	■	■
Tectonic	□	□
In situ stress, hydraulic head and temperature fields	■	■
RESPONSE		
(MECHANICAL)		
Strength	■	▒
Deformation	▒	▒
Creep	▒	▒
(THERMAL)		
Thermal conductivity	▒	▒
Heat capacity	▒	▒
Linear thermal expansion	▒	▒
(HYDROLOGIC)		
Hydraulic conductivity	■	▒
Effective porosity	▨	▒
Specific storage	▒	▒
(GEOCHEMICAL)		
Dispersivity	▨	□
Adsorption/retardation	▨	■
Alteration	▒	■

*Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition)

■	Characteristic with major significance
▒	Characteristic with moderate significance
▨	Characteristic with minor significance
□	Characteristic is significant, but not during in situ testing

Note: Significance of characteristics was subjectively evaluated using the process illustrated in Figure 3.5 and discussed in Section 3.5.1.

Rev. 813-1163E Date 5-82 10-82 BR
Dwg. No. 813-1163B A&S 5-83 Date 5-82 Eng. DR

SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN (DOMAL SALT - GULF COAST SITES)

Table 3.6

CHARACTERISTICS (See Table 3.1)	PERFORMANCE CRITERIA SHORT-TERM (up to 100 years) CONSTRUCTION/OPERATION	 LONG-TERM (100-10,000's Years) WASTE CONTAINMENT/ ISOLATION
GEOLOGIC SETTING		
Stratigraphic/structural*	■	■
Tectonic	□	□
In situ stress, hydraulic head and temperature fields	▒	▒
RESPONSE (MECHANICAL)		
Strength	▒	▒
Deformation	▒	▒
Creep	■	■
(THERMAL)		
Thermal conductivity	▒	▒
Heat capacity	▒	▒
Linear thermal expansion	▒	▒
(HYDROLOGIC)		
Hydraulic conductivity	▒	▒
Effective porosity	▨	▒
Specific storage	▨	▨
(GEOCHEMICAL)		
Dispersivity	▨	□
Adsorption/retardation	▨	□
Solubility	□	□

*Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition)

■ Characteristic with major significance

▒ Characteristic with moderate significance

▨ Characteristic with minor significance

□ Characteristic is significant, but not during in situ testing

Note: Significance of characteristics was subjectively evaluated using the process illustrated in Figure 3.5 and discussed in Section 3.5.1.

Rev. 83-11638 10-82 5-82 BR

Dwg. No. 83-11638 AECS 0X9 Date 1-82 Eng. JR

3.5.2.4 Bedded Salt

The significance of the characteristics, as they relate to the short- and long-term performance criteria, has been evaluated for potential sites in bedded salt (see Table 3.7). This evaluation has been based on the previously discussed procedure (see Section 3.5.1), the present assessment of characteristics (see Section 3.4.2.4 and Appendix B of Volume II, Table B-5), and on experience.

3.5.2.5 Granite

The significance of the characteristics, as they relate to the short- and long-term performance criteria, has been evaluated for potential sites in granite (see Table 3.8). This evaluation has been based on the previously discussed procedure (see Section 3.5.1), the present assessment of characteristics (see Section 3.4.2.5 and Appendix B of Volume II, Table B-6), and on experience.

SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN (BEDDED SALT - UNSPECIFIED SITE)

Table 3.7

CHARACTERISTICS (see Table 3.1)	PERFORMANCE CRITERIA SHORT-TERM (up to 100 years) CONSTRUCTION/OPERATION	 LONG-TERM (100-10,000's Years) WASTE CONTAINMENT/ ISOLATION
GEOLOGIC SETTING		
Stratigraphic/structural*	▒	▒
Tectonic	☐	☐
In situ stress, hydraulic head and temperature fields	▒	▒
RESPONSE		
(MECHANICAL)		
Strength	▒	▒
Deformation	▒	▒
Creep/fusing	■	■
(THERMAL)		
Thermal conductivity	▒	▒
Heat capacity	▒	▒
Linear thermal expansion	▒	▒
(HYDROLOGIC)		
Hydraulic conductivity	▒	▒
Effective porosity	▨	▒
Specific storage	▨	▨
(GEOCHEMICAL)		
Dispersivity	▨	☐
Adsorption/retardation	▨	▒
Solubility	☐	☐

*Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition)

■	Characteristic with major significance
▒	Characteristic with moderate significance
▨	Characteristic with minor significance
☐	Characteristic is significant, but not during in situ testing

Note: Significance of characteristics was subjectively evaluated using the process illustrated in Figure 3.5 and discussed in Section 3.5.1.

Rev. 83-1036
Dwg. No. 83-4434 ACES 019
Date 1-82 5-82 10-82
Eng BR BR

SIGNIFICANCE OF CHARACTERISTICS FOR IN SITU TESTING AS THEY RELATE TO DESIGN (GRANITE - UNSPECIFIED SITE)

Table 3.8

CHARACTERISTICS (See Table 3.1)	PERFORMANCE CRITERIA SHORT-TERM (up to 100 years) CONSTRUCTION/OPERATION	LONG-TERM (100 to 10,000's Years) WASTE CONTAINMENT/ ISOLATION
GEOLOGIC SETTING		
Stratigraphic/structural*	■	■
Tectonic	□	□
In situ stress, hydraulic head and temperature fields	■	■
RESPONSE (MECHANICAL)		
Strength	▒	▒
Deformation	▒	▒
Creep	▨	▨
(THERMAL)		
Thermal conductivity	▒	▒
Heat capacity	▒	▒
Linear thermal expansion	▒	▒
(HYDROLOGIC)		
Hydraulic conductivity	■	▒
Effective porosity	▨	▒
Specific storage	▒	▒
(GEOCHEMICAL)		
Dispersivity	▨	□
Adsorption/retardation	▨	▒
Alteration/solubility	▨	▨

*Includes the physical and chemical characteristics of each rock mass unit (including pore fluid composition)

■ Characteristic with major significance

▒ Characteristic with moderate significance

▨ Characteristic with minor significance

□ Characteristic is significant, but not during in situ testing

Note: Significance of characteristics was subjectively evaluated using the process illustrated in Figure 3.5 and discussed in Section 3.5.1.

Rev. 813-1163E 10-82 5-82 BR
Dwg. No. 813-1163A 1EX3 8½ Date 1-82 Eng. BR

4.0 AVAILABLE TEST METHODS

4.1 EXISTING REPOSITORY-RELATED IN SITU TEST PROGRAMS

4.1.1 Significance of Existing Programs

The DOE site screening/selection program is progressing rapidly (Table 1.1). In situ test plans have been or will be developed by DOE (or their contractors) for responding to the perceived information needs not only in a generic sense, but specifically for each of the sites under consideration. In addition, test facilities have been developed or are planned for various media to assess specific test techniques and verify certain aspects of predictive models; however, these media specific test facilities have generally been limited in scope and not intended for site characterization purposes.

The existing site specific in situ test programs and media specific test facilities (see Table 4.1) have been identified (see Appendix C of Volume II) although they are subject to update and revision. The evaluation of these existing programs is not within the scope of this study. However, these programs serve as examples of what has been considered by others to be appropriate for responding to perceived information needs. These existing programs also identify some available test methods.

4.1.2 Existing Media Independent Programs

A generic in situ test program has been developed by DOE (DOE/NWTS, 1981), and summarized in "NWTS Program Strategy and Guidelines for the Development of Test Facilities at Candidate Repository Sites" (January 8, 1982).* This program is subject to update and revision, but presently consists of the following facilities (see Table 4.2):

- Exploratory shaft
    - Phase I to determine the suitability of the site for a test and evaluation facility (TEF),
    - Phase II for site characterization
- At-depth test facility (ADTF) for site characterization
- Test and evaluation facility (TEF) for operational procedures.

The TEF, and its associated activities, are outside the scope of work, and thus have not been considered further in this study.

A variety of tests (see Table 4.3) is expected to be performed within these facilities in order to satisfy the stated objectives; the actual tests are subject to update and revision.

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*F.E. Coffman, DOE-Washington D.C., personal communication to J.B. Martin, NRC-Washington D.C., January 28, 1982.

PRESENT STATUS OF SITE SPECIFIC IN SITU TEST PROGRAMS AND MEDIA SPECIFIC TEST FACILITIES

Table 4.1

MEDIA	SITE SPECIFIC IN SITU TEST PROGRAM PLAN	MEDIA SPECIFIC TEST FACILITIES
BASALT	Cold Creek Syncline at Hanford, Washington.	Near Surface Test Facility at Hanford, Washington.
TUFF	Yucca Mountain at Nevada Test Site.	G-Tunnel at Nevada Test Site.
DOMAL SALT	None.	Conceptual Experimental Test Facility in South Texas. Avery Island Mine in Louisiana. Asse Mine in West Germany.
BEDDED SALT	None. (Although Waste Isolation Project Plant-WIPP in Carlsbad, New Mexico is an example)	Conceptual Experimental Test Facility in West Texas. Carey Salt Mine in Hutchinson, Kansas. Project Salt Vault in Lyons, Kansas. WIPP in Carlsbad, New Mexico
GRANITE	None.	Stripa Mine in Sweden. Colorado School of Mines Experimental Mine in Colorado. Climax Stock at Nevada Test Site. UKAEA at Cornwall, England. Underground Research Laboratory for AECL in Manitoba, Canada.

Note: This status is as of November 1982, and is subject to update and revision.

Rev.
Dwg. No. A813-1163 Date 10-82 Eng. BR

NWTS OBJECTIVES OF IN SITU TEST FACILITIES

Table 4.2

Exploratory Shaft		At-Depth Test Facility (ADTF)	Test and Evaluation Facility (TEF)
Phase I	Phase II		
• Access to horizon for Phase II Testing • Allow decision on TEF site suitability	• Allow decision on site suitability for repository • Geotechnical design verification data for TEF (selected site only) • Provide information necessary to finalize SCR submittal to NRC	• Geotechnical design optimization and verification data for repository - sealing technology - thermal response - thermomechanical response - excavation methods - ground control - water control • Expanded verification of Reference Repository conditions	• Verification of waste handling, emplacement, and retrieval technology and procedures (not site-specific) • Data base for occupational exposure • Verification of ventilation system design • Verification of instrumentation and control system design • Evaluation of equipment performance • Develop scaling factors to full repository • Develop operational procedures for both routine and abnormal operations • Operator training and certification • Reduced uncertainty in design bases

Note: These objectives are subject to update and revision.

from "NWTS Program Strategy and Guidelines for the Development of Test Facilities at Candidate Repository Sites" (January 8, 1982) by F.E. Coffman, DOE-Washington, D.C., personal communication to J.B. Martin, NRC-Washington, D.C., January 28, 1982.

SUMMARY OF PRESENTLY PROPOSED NWTS IN SITU TEST PROGRAM

Table 4.3

- EXPLORATORY SHAFT - PHASE I
  - Coreholes (limited)
  - Exploratory excavation (limited)
  - Determine rock mass structure
  - Determine in situ stress field
  - Determine rock mass strength
  - Monitor drainage into excavation
  - Construction monitoring

- EXPLORATORY SHAFT - PHASE II
  - Coreholes
  - Exploratory excavation
  - Exposure mapping
  - Groundwater sampling
  - Determine rock mass structure
  - Determine in situ stress field
  - Determine rock mass deformation moduli/Poisson's ratio
  - Determine horizontal and vertical permeability of rock mass

- AT-DEPTH TEST FACILITY
  - Exploratory excavation
  - Exposure mapping
  - Seismic monitoring
  - Groundwater sampling
  - Mine-by test
  - Heater test
  - Determine geochemical interactions
  - Monitor drainage into excavation
  - Monitor construction and performance of excavations which simulate repository (including associated rock disturbance/ damage)
  - Borehole sealing test
  - Shaft sinking/sealing test
  - Backfill test

Note: This summary represents Golder Associates' perception of the current NWTS program, which is subject to update and revision.

The test and evaluation facility (TEF) is outside the scope of work, and has not been considered.

from "NWTS Program Strategy and Guidelines for the Development of Test Facilities at Candidate Repository Sites" (January 8, 1982) by F.E. Coffman, DOE-Washington, D.C., personal communication to J.B. Martin, NRC-Washington, D.C., January 28, 1982.

4.2 TEST METHODS AVAILABLE TO ASSESS SIGNIFICANT CHARACTERISTICS

There are typically a variety of test methods available for assessing the previously identified significant characteristics (see Chapter 3). These methods can be generally categorized as:

- Surface tests
- Borehole tests
- Laboratory tests
- In situ tests.

The test methods within each category which are generally available to assess each significant characteristic have been identified (see Table 4.4), based on experience as well as existing repository-related in situ test programs (see Section 4.1 and Appendix C of Volume II). This is a relatively comprehensive list of available tests; it should not be construed that all of these tests are being recommended. The selection of appropriate tests from this list will be a function of the perceived information needs and test capabilities.

It must be recognized that there are no surface or borehole tests available to assess the characteristics of the disturbed zone surrounding an underground opening, except those which are used for the undisturbed rock mass and whose results must be modified to estimate the disturbed zone's characteristics. Also, any laboratory or in situ tests used to assess the response characteristics of the disturbed zone should be performed on samples with physical characteristics similar to those which will exist in the repository. Hence, laboratory samples should be obtained from, and in situ tests performed in, underground openings which are excavated and supported using similar techniques as are contemplated for the repository.

4.3 COMPARISON OF CHARACTERISTIC ASSESSMENT BY SPECIFIC TEST METHODS

The various test methods available for assessing each significant characteristic (Table 4.4) do so with various limitations and levels of uncertainty. As previously discussed (see Section 3.3), the uncertainty in the assessment of each characteristic is due to (1) range in physically possible values, (2) natural variability and (3) quality of data base, which in turn is a function of the size of the data base and random/systematic errors in each datum; these errors are a function of (a) representation of the material by the sample, (b) representation of the environmental conditions by the test, and (c) accuracy in individual test results.

The level of uncertainty in the determination of each characteristic, due to quality of the data base, roughly varies with categories of test methods, generally decreasing as follows:

TEST METHODS AVAILABLE FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 4.4

1 of 4

CHARACTERISTIC (see Table 3.1)	AVAILABLE TEST METHOD (see notes() at end of Table)			
	SURFACE	BOREHOLE (from surface)	LABORATORY	IN SITU (from subsurface excavation)
(GEOLOGIC SETTING)				
Stratigraphic/ structural (includes the physical and chemical characteristics of each rock mass unit, including pore fluid composition)	o geologic mapping (1) o surface geophysics (2).	o cutting evaluation o coreholes (3) o geophysic/seismic (x-hole, surface-borehole) o groundwater sampling (5a) - gas detector.	o core logging o determination of rock sample mineralogy (thin section, x-ray diffraction) o determination of groundwater sample composition and age o hydrochemical analysis of rock sample.	o exploratory excavations (including exposure mapping) o coreholes (3, 4) o rock mass sampling (5b) o geophysic/seismic (x-hole, exposure-borehole) o exposure geophysics (radar scanning) o groundwater sampling (4,5a) - gas detector (4) - gas detector in mine.
Tectonic	o geologic mapping (1) o surface geophysics (2) o seismic monitoring - monitor surface displacements/ tilt - monitor electrical potential/current/ discharge.	o acoustic emission monitoring - monitor stress changes in rock mass - monitor displacements in rock mass - monitor temperatures in rock mass - monitor pore pressures in rock mass - monitor gas emission in rock mass - monitor electrical potential/ current/ discharge in rock mass.		o acoustic emission monitoring o seismic monitoring - monitor stress changes in rock mass (4) - monitor stress changes in supports - monitor displacements in rock mass (4) - monitor temperatures in rock mass (4) - monitor temperatures in excavation - monitor pore pressures in rock mass (4) - monitor drainage into excavation - monitor gas emission in rock mass (4) - monitor gas emission in excavation - monitor electrical potential current/discharge.
In situ stress field (stress tensor) (6)		o rock mass sampling (5b) o hydrofracturing (16) o borehole jacking o overcoring.	o core observation (stress relief, core discing).	o rock mass sampling (4, 5b) o hydrofracturing (4) o borehole jacking (4) o overcoring (4) o flat jack test o overcoring (exposure) (7) - monitor stress changes in rock mass (4, 7) - monitor displacements in rock mass (4, 7) - monitor displacements at exposure (7) - monitor stress changes and strains in supports
In situ hydraulic head field (pore pressure) (5)	o hydrologic mapping - climatic monitoring.	o monitor pore pressures - monitor borehole inflow - groundwater sampling (5a).	- determination of groundwater sample composition and age.	o monitor pore pressures in rock mass (4) - monitor borehole drainage (4) - monitor drainage into excavation (7) - groundwater sampling (5a).
In situ temperature field (temperature) (6)		o monitor temperatures.		o monitor temperatures in rock mass (4) - monitor temperature in excavation (7).
(MECHANICAL) Strength (8)		o rock mass sampling (5b) - borehole jacking (10a) - hydrofracturing.	o index tests on rock samples (9) o simple strength tests on rock sample (sliding test, Brazilian test, point load test, beam test, tensile strength test, fracture toughness test) (10a) o direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) o unconfined compression test on rock core (w/or w/o heat) (10a) o triaxial test on rock core (w/or w/o heat (10a,b).	o index tests on exposures (9) o rock mass sampling (5b) o shear jacking (10b, 11) o pillar test (w/or w/o heat) (12) o mine-by test o monitoring fracturing in rock mass around excavation (e.g., by acoustic emission monitoring) (7) - borehole jacking (4, 10a) - hydrofracturing (4) - plate test (13)

TEST METHODS AVAILABLE FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 4.4

2 of 4

CHARACTERISTIC (see Table 3.1)	AVAILABLE TEST METHOD (see notes() at end of Table)			
	SURFACE	BOREHOLE (from surface)	LABORATORY	IN SITU (from subsurface excavation)
Deformation (8)	o surface geophysics (2)	o rock mass sampling (5b) o borehole jacking (10a) o geophysic/seismic (x-hole, surface-borehole).	o index tests on rock sample (9) o unconfined compression test on rock core (w/or w/o heat) (10a) o triaxial test on rock core (w/or w/o heat) (10a,b) o true triaxial test on large rock sample (w/or w/o heat) (10a,b) o direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) o sonic velocity test on rock core (w/or w/o stress) (10a).	o index tests on exposures (9) o rock mass sampling (5b) o borehole jacking (4, 10a) o geophysic/seismic (x-hole, exposure-borehole) o exposure geophysics o flat jack test o plate test (13) o pillar test (w/or w/o heat) (12) o block test (w/or w/o heat) o chamber test w/displacement monitoring (w/or w/o heat) o shear jacking (10b,11) o mine-by test o monitor stress changes in rock mass as excavation occurs (4,7) o monitor displacements in rock mass as excavation occurs (4,7) o monitor displacements at exposure as excavation occurs(7) o monitor stress changes and strains in supports (7).
Creep (8)		o rock mass sampling (5b) - borehole jacking, long term (10a) - monitor deformation of hole after boring w/soft inclusion (7,10a) - monitor stress changes around hole after boring w/hard inclusion (7,10a).	o unconfined compression test on rock core, long term (w/or w/o heat) (10a) o triaxial test on rock core, long term (w/or w/o heat)(10a) o true triaxial test on large rock sample, long term (w/or w/o heat) (10a,b) o direct shear test on discontinuity sample, long term (w/or w/o heat) (10b,14) - core observation (monitor deformations as stress relieved by coring) (7, 10a).	o rock mass sampling (5b) o flat jack test, long term o plate test, long term (13) o pillar test, long term (w/or w/o heat) (12) o block test, long term (w/or w/o heat) o chamber test w/displacement monitoring, long term (w/or w/o heat) o mine-by test o monitor stress changes in rock mass after excavation (4,7) o monitor displacements in rock mass after excavation (4,7) o monitor displacements at exposure after excavation (4,7) o monitor stress changes and strains in supports (7) - borehole jacking, long term (4,10a) - monitor deformation of hole after boring w/soft inclusion (4,7,10a) - monitor stresses around hole after boring w/hard inclusion (4,7, 10a).
(THERMAL) Thermal conductivity (8) Heat capacity (8)		o rock mass sampling (5b) o thermal probe (single borehole small scale heater test) (10a) o heater test (x-hole small scale).	o heated rock sample (10a) o unconfined compression test on rock core w/heat (10a) o triaxial test on rock core w/heat (10a).	o rock mass sampling (5b) o thermal probe (single borehole small scale heater test) (4,10a) o heater test (x-hole small scale) (4) o heater test (large scale) o block test w/heat (w/or w/o stress) o pillar test w/heat (12) o chamber test w/heated water o monitor temperature in rock mass and excavation (w/ventilation/cooling) (7).
Linear thermal expansion(3)		o rock mass sampling (5b).	o heated rock sample (10a) o unconfined compression test on rock core w/heat (10a) o triaxial test on rock core w/heat (10a).	o rock mass sampling (5b) o heater test (large scale) o block test w/heat (w/or w/o stress) o pillar test w/heat (12) o chamber test w/heated water and w/displacement monitoring o monitor temperatures and displacements in rock mass and excavation (7).

TEST METHODS AVAILABLE FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 4.4

3 of 4

CHARACTERISTIC (see Table 3.1)	AVAILABLE TEST METHOD (see notes() at end of Table)			
	SURFACE	BOREHOLE (from surface)	LABORATORY	IN SITU (from subsurface excavation)
(HYDROLOGIC) Hydraulic conductivity (8) Effective porosity (8) Specific storage (8)		o rock mass sampling (5b) o geophysical well logging o permeability test (single borehole) (15) o multiple borehole permeability test (15) o monitor borehole inflow (7).	o index tests on rock sample (9) o axial permeability test on rock core (w/or w/o heat, stress) (10a,15) o radial permeability test on rock sample (w/or w/o heat, stress)(10a,b, 15).	o rock mass sampling (5b) o geophysical well logging (4) o permeability test (single borehole) (w/or w/o heated water) (4,15) o multiple borehole permeability test (w/or w/o heated water) (4,15) o block test w/multiple borehole permeability test (w/or w/o heat, stress) o chamber test (w/or w/o heated water) (15) o monitor drainage into excavation and pore pressure in rock mass (7) o monitor borehole drainage (4,7).
(GEOCHEMICAL) Dispersivity (8) Adsorption/ retardation (8)		o rock mass sampling (5b) o groundwater sampling (5a) o tracer test.	o determination of groundwater sample composition and age o tracer test on rock sample (w/or w/o heat, stress) (10a,b) o determination of rock sample mineralogy.	o rock mass sampling (5b) o groundwater sampling (4,5a) o tracer test (w/or w/o heated water) (4) o block test w/tracer test (w/ or w/o heat, stress) o chamber test w/tracer injection and monitoring (w/or w/o heated water).
Alteration/ solubility	o geologic mapping (1).	o rock mass sampling (5b) o groundwater sampling(5a) o monitor stability of borehole.	o determination of groundwater sample composition and age o core logging o determination of rock sample mineralogy o slaking or accelerated weathering test on rock sample (w/heat, stress) o solubility test on rock sample (w/or w/o heated water) o monitor alteration/ solutioning of rock sample.	o exposure mapping o rock mass sampling (5b) o groundwater sampling (4,5a) o heater test (large scale) o chamber test (w/or w/o heat) o monitor alteration/solutioning of exposures.

TEST METHODS AVAILABLE FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 4.4

4 of 4

Notes:
o Primary test method
\- Possible secondary test method

(1) Geologic mapping includes a geodetic survey and exposure mapping, as well as possibly aeropnotograpny (by airplane or satellite, black-and-white, color, or infrared).

(2) Surface geophysics include possibly gravity and magnetic surveys (land or air based), electrical survey, and seismic surveys (reflection and refraction).

(3) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(4) Tests are conducted in boreholes drilled from underground.

(5) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.
b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(6) The in situ (i.e,. pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(7) Monitoring performance implies associated analysis to assess characteristic.

(8) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These response characteristics can be assessed either:
- Directly by testing a large scale sample which contains a significant number of discontinuities
- Indirectly by separately assessing the response characteristics of the intact rock, discontinuitis, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(9) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer on rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(10) Tests assess the response characteristics of only the a) intact rock or b) discontinuity, and does not directly assess the response characteristics of the rock mass (see note 8).

(11) Shear jacking is very similar to torsion jacking. Because of these similarities, only shear jacking will be discussed, although torsion jacking might be a suitable alternative.

(12) Pillar test can consist of either:
- Jacking an isolated pillar or unconfined block to failure (i.e., essentially an unconfined plate test or an axially loaded unconfined block test)
- Reducing the dimensions of a pillar (and thus increasing stresses) until failure occurs.

(13) Plate test is very similar to two other tests:
- Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation
- Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(14) Direct shear test on discontinuity samples can be of various scales and is also very similar to torsional shear tests. Because of these similarities, only the direct shear test will be discussed, although torsional shear test might be a suitable alternative.

(15) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test. Multiple borehole permeability tests are often called "pump" tests.

(16) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

This is a relatively comprehensive list of test methods which are available for assessing site characteristics. It should not be construed that all of these available tests are being recommended.

(1) Estimate based on typical values for similar materials and conditions

(2) Interpretation of the results of surface tests

(3) Interpretation of the results of borehole or laboratory tests

(4) Interpretation of the results of in situ tests

(5) Interpretation of the monitored response of prototypes or prototype simulations.

The differences in uncertainty in the assessment of characteristics between the various test methods are due primarily to the quality of the data generated:

- Surface tests, although testing material with minimal sampling disturbance and under existing environmental conditions, generally have the following limitations:
  - characteristics assessed at the surface must be extrapolated to depth with significant uncertainty
  - characteristics of a volume of rock mass, which is often larger than the representative volume (i.e., nonhomogeneous), are often interpreted with poor resolution and no range in environmental conditions.
- Borehole tests, although testing the material in place, generally have the following limitations:
  - small-scale sample, so that either the intact rock or individual discontinuity, and not a representative volume of the rock mass, is tested
  - some disturbance of the sample tested occurs due to drilling (i.e., a change in physical characteristics)
  - only a very limited range of environmental conditions can be evaluated
  - poor control of test due to remoteness.
- Laboratory tests, although often allowing a full range in environmental conditions to be applied with good test control, generally have the following limitations:
  - small-scale sample, so that either the intact rock or possibly an individual discontinuity, and not a representative volume of rock mass, is tested

    - significant disturbance of the sample occurs due to drilling and change in environmental conditions, such as stress relief or dessication.

- In situ tests, although testing a representative volume of material in place, generally have the following limitations:
    - some minimal disturbance of the sample due to excavation and instrumentation installation
    - limited range of environmental conditions can be practically evaluated.

The assessment variables (see Section 3.2.1) which can be incorporated in each of the available test methods have been identified (see Table 4.5), based on standard test methodologies. Clearly, in order to adequately assess a characteristic, a test method must be able to incorporate those assessment variables which that characteristic is sensitive to (Table 3.2).

The potential minimum level of uncertainty in the assessment of each of the significant characteristics by the various available test methods has thus been subjectively evaluated (see Table 4.5), based solely on the resulting quality of the data:

(1) General sample representativeness
(2) Applied range in environmental conditions
(3) Typical test reliability.

Clearly, however, the sample representation and test reliability are not necessarily media/site independent. Also, the level of uncertainty is not independent of the absolute magnitude of the value measured, i.e., a test may be appropriate for a given range of values only and very inaccurate outside of that range. Other factors, i.e., the range in possible values, natural variability, and size of the data base, also impact the level of uncertainty. The subjective evaluation of the potential minimum level uncertainty in the assessment of each characteristic by various available test methods (Table 4.5) thus provides a qualitative indication only of individual test capabilities.

4.4 IN SITU TEST METHODS AVAILABLE WHICH SIMULATE THE REPOSITORY

As previously discussed, rather than resolving key issues by adequately assessing certain characteristics, in situ tests can be used to resolve key issues by appropriately simulating various aspects of the repository. The in situ test facility is itself a simulation of various construction and operation aspects of the repository. The uncertainty in the extrapolation of results from a test case (i.e., in situ test or test facility) to the prototype (i.e., repository) will be a function of the degree of similarity between the two. This correlation is improved, and the uncertainty thus reduced, by making the test case as similar as

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
1 of 9

	TEST METHOD (See Notes ( ) at end of Table)	TEST ASSESSMENT VARIABLES							CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
					RANGE IN ENVIRONMENTAL CONDITIONS									
		Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
(SURFACE TEST METHODS)	Hydrologic mapping	–	●	–	–	X	–	–	In situ hydraulic field	—	—			
	Geologic mapping (1)	–	●	–	–	–	–	–	Stratigraphic/structural	—	—			
		–	●	●	–	–	–	–	Tectonic	—				
	Surface geophysics (2)	–	●	–	–	–	–	–	Stratigraphic/structural	—	—			
		–	●	●	–	–	–	–	Tectonic	—				
		●	●	X	X	X	X	–	Deformation	—				
	Seismic monitoring	–	●	X	–	–	–	–	Tectonic	—				
(BOREHOLE TEST METHODS)	Cutting evaluation	–	X	–	–	–	–	–	Stratigraphic/structural	—	—			
	Coreholes (3)	–	●	–	–	–	–	–	Stratigraphic/structural	—	—	—		
	Rock mass sampling (5b) (see laboratory tests)	–	o	–	–	–	–	–	(Pore fluid composition)					
		o	o	–	o	–	–	–	In situ stress field					
		o	X	o	o	o	o	–	Strength					
		o	X	o	o	o	o	–	Deformation					
		–	–	o	o	–	o	–	Creep/fusing					
		o	o	–	o	–	o	–	Thermal conductivity					
		–	–	–	–	–	o	–	Heat capacity					
		o	o	–	o	–	o	–	Linear thermal expansion					
		o	X	–	o	o	o	–	Hydraulic conductivity					
		–	X	–	–	o	o	–	Effective porosity					
		–	X	–	–	o	o	–	Specific storage					
		o	X	–	–	–	o	o	Dispersivity					
		o	X	–	–	–	o	o	Adsorption/retardation					
		–	o	o	–	o	o	o	Alteration/solubility					
	Groundwater sampling (5a) (see laboratory tests)	–	●	–	–	–	–	–	(Pore fluid composition)					
		X	X	–	–	–	o	o	Dispersivity					
		X	X	–	–	–	o	o	Adsorption/retardation					
		–	o	X	–	X	o	o	Alteration/solubility					

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____ Dwg. No A182-1163 Date 10-82 Eng BR

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
2 of 9

		TEST ASSESSMENT VARIABLES							CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
					RANGE IN ENVIRONMENTAL CONDITIONS									
	TEST METHOD (See Notes ( ) at end of Table)	Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
(BOREHOLE TEST METHOD)	Geophysical well logging	X	X	—	X	X	X	—	Hydraulic conductivity	├┤				
		—	X	—	—	X	X	—	Effective porosity	├┤				
		—	X	—	—	X	X	—	Specific storage	├┤				
	Geophysic/seismic (x-hole, surface-borehole)	—	●	—	—	—	—	—	Stratigraphic/structural	├	┤			
		●	●	X	X	X	X	—	Deformation	├┤				
	Borehole jacking (10a)	X	X	—	●	—	—	—	In situ stress field	├	┤			
		X	X	o	●	X	X	—	Deformation	├	┤			
	Overcoring	o	X	—	●	—	—	—	In situ stress field	├	─	┤		
	Hydrofracturing (16)	X	o	—	●	—	—	—	In situ stress field	├	┤			
	Permeability test (single borehole) (15)	X	o	—	X	●	X	—	Hydraulic conductivity	├	┤			
		—	o	—	—	●	X	—	Effective porosity	├	┤			
		—	o	—	—	●	X	—	Specific storage	├	┤			
	Multiple borehole permeability test (15)	●	o	—	X	●	X	—	Hydraulic conductivity	├	─	┤		
		—	o	—	—	●	X	—	Effective porosity	├	─	┤		
		—	o	—	—	●	X	—	Specific storage	├	─	┤		
	Tracer test	●	o	—	—	—	X	●	Dispersivity	├	┤			
		●	o	—	—	—	X	●	Adsorption/retardation	├	┤			
	Thermal probe (single borehole small scale heater test) (10a)	X	●	—	X	—	●	—	Thermal conductivity	├┤				
		—	—	—	—	—	●	—	Heat capacity	├┤				
	Heater Test (x-hole small scale)	●	o	—	X	—	●	—	Thermal conductivity	├	┤			
		—	—	—	—	—	●	—	Heat capacity	├┤ ├	┤			
	Acoustic emission monitoring	—	●	X	—	—	—	—	Tectonic	├┤				
	Monitor pore pressure	—	●	—	—	●	—	—	In situ hydraulic field	├	─	┤		
	Monitor temperature	—	●	—	—	—	●	—	In situ temperature field	├	─	┤		
	Monitor borehole inflow (7)	X	o	—	X	X	X	—	Hydraulic conductivity	├	┤			
		—	o	—	—	X	X	—	Effective porosity	├	┤			
		—	o	—	—	X	X	—	Specific storage	├	┤			
	Monitor stability of borehole	—	●	●	—	X	X	X	Alteration/solubility	├	┤			

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____ Dwg. No. ____ Date ____ Eng. ____

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
3 of 9

	TEST METHOD (See Notes ( ) at end of Table)	TEST ASSESSMENT VARIABLES: Anisotropy	Scale (Rep. Volume)	Duration	RANGE IN ENVIRONMENTAL CONDITIONS: Stress Level	Pore Pressure	Temperature	Radiation Dose	CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**: Very High	High	Moderate	Low	Very Low
(LABORATORY TEST METHODS)	Core observation (stress relief, core discing)	X	X	–	o	–	–	–	In situ stress field	├──	─┤			
	Core logging	–	●	–	–	–	–	–	Stratigraphic/structural	├──	──	─┤		
		–	o	o	–	X	X	X	Alteration/solubility	├──	─┤			
	Determination of rock sample mineralogy (thin section, x-ray diffraction)	–	o	–	–	–	–	–	Stratigraphic/structural	├──	─┤			
		X	X	–	–	–	X	X	Dispersivity	├┤				
		X	X	–	–	–	X	X	Adsorption/retardation	├┤				
		–	o	o	–	X	X	X	Alteration/solubility	├┤				
	Hydrochemical analysis of rock sample	–	●	–	–	–	–	–	(Pore fluid composition)	├──	──	──	──	─┤
	Determination of ground-water sample composition and age	–	●	–	–	–	–	–	(Pore fluid composition)	├──	──	──	─┤	
		X	X	–	–	–	X	X	Dispersivity	├──	─┤			
		X	X	–	–	–	X	X	Adsorption/retardation	├──	──	──	──	─┤
		–	o	X	–	X	X	X	Alteration/solubility	├──	─┤			
	Index tests on rock sample (9)	o	X	X	X	X	X	–	Strength	├┤				
		o	X	X	X	X	X	–	Deformation	├┤				
		o	X	–	X	X	X	–	Hydraulic conductivity	├┤				
		–	X	–	–	X	X	–	Effective porosity	├┤				
		–	X	–	–	X	X	–	Specific storage	├┤				
	Sonic velocity on rock core (with or without stress) (10a)	o	X	X	o	X	X	–	Deformation	├┤				
	Simple strength tests on rock sample (10a)	o	X	X	X	X	X	–	Strength	├┤				
	Unconfined compression test on rock core (with or without heat) (10a)	o	X	o	X	X	o	–	Strength	├──	─┤			
		o	X	o	o	X	o	–	Deformation	├──	─┤			
	long term (with or without heat) (10a)	–	–	●	o	–	o	–	Creep/fusing	├──	─┤			
	with heat (10a)	o	o	–	o	–	●	–	Thermal conductivity	├──	──	─┤		
		–	–	–	–	–	●	–	Heat capacity	├──	──	─┤		
		o	o	–	o	–	●	–	Linear thermal expansion	├──	──	─┤		

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. Dwg. No. A82-1163 Date 10-82 Eng. [illegible]

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
4 of 9

		TEST ASSESSMENT VARIABLES								UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
					RANGE IN ENVIRONMENTAL CONDITIONS									
	TEST METHOD (See Notes ( ) at end of Table)	Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose	CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	Very High	High	Moderate	Low	Very Low
(LABORATORY TEST METHOD)	Triaxial test on rock core (with or without heat) (10a, b)	●	X	○	●	○	○	–	Strength	─	─	─┤		
		●	X	○	●	○	○	–	Deformation	─	─	─┤		
	long term (with or without heat (10a)	–	–	●	●	–	○	–	Creep/fusing	─	─	─┤		
	with heat (10a)	●	○	–	●	–	●	–	Thermal conductivity	─	─	─┤		
		–	–	–	–	–	●	–	Heat capacity	─	─	─┤		
		●	○	–	●	–	●	–	Linear thermal expansion	─	─	─┤		
	True triaxial test on large rock sample (with or without heat) (10a,b)	●	X	○	●	○	○	–	Deformation	─	─	─┤		
	long term (with or without heat) (10a)	–	–	●	●	–	○	–	Creep/fusing	─	─	─┤		
	Direct shear test on discontinuity sample (with or without heat) (10b, 14)	●	X	○	●	○	○	–	Strength	─	─┤			
		●	X	○	●	○	○	–	Deformation	─	─┤			
	long term (with or without heat) (10b, 14)	–	–	●	●	–	○	–	Creep/fusing	─┤				
	Heated rock sample (10a)	●	○	–	X	–	●	–	Thermal conductivity	─	─	─┤		
		–	–	–	–	–	●	–	Heat capacity	─	─	─┤		
		●	○	–	X	–	●	–	Linear thermal expansion	─	─	─┤		
	Axial permeability test on rock core (with or without heat, stress) (10a, 15)	○	X	–	●	●	○	–	Hydraulic conductivity	─	─┤			
		–	X	–	–	●	○	–	Effective porosity	─	─┤			
		–	X	–	–	●	○	–	Specific storage	─	─┤			
	Radial permeability test on rock sample (with or without heat, stress) (10a, b, 15)	●	X	–	○	●	○	–	Hydraulic conductivity	─	─┤			
		–	X	–	–	●	○	–	Effective porosity	─	─┤			
		–	X	–	–	●	○	–	Specific storage	─	─┤			
	Tracer test on rock sample (with or without heat, stress) (10a, b)	○	X	–	–	–	○	●	Dispersivity	─	─┤			
		○	X	–	–	–	○	●	Adsorption/retardation	─	─	─┤		
	Slaking or accelerated weathering test on rock sample (with heat, stress)	–	●	●	–	X	●	X	Alteration/solubility	─	─	─	─┤	
	Solubility test on rock sample (with or without heated water)	–	●	●	–	X	○	X	Alteration/solubility	─	─	─	─┤	

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____
Dwg. No. MLS-1463 Date 10-82 Eng. BR

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
5 of 9

	TEST METHOD (See Notes ( ) at end of Table)	TEST ASSESSMENT VARIABLES			RANGE IN ENVIRONMENTAL CONDITIONS				CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
		Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
	Monitor alteration/ solutioning of rock sample	—	●	●	—	X	X	X	Alteration/solubility	—	—	┤		
(IN SITU TEST METHODS)	Exploratory excavations	—	●	—	—	—	—	—	Stratigraphic/structural	—	—	—	┤	
	Exposure mapping	—	●	—	—	—	—	—	Stratigraphic/structural	—	—	—	┤	
		—	●	o	—	X	X	X	Alteration/solubility	—	—	┤		
	Index tests on exposure (9)	o	o	X	X	X	X	—	Strength	—	┤			
		o	o	X	X	X	X	—	Deformation	—	┤			
	Coreholes (3, 4)	—	●	—	—	—	—	—	Stratigraphic/structural	—	—	—	┤	
	Rock mass sampling (5b) (see laboratory tests)	—	o	—	—	—	—	—	Stratigraphic/structural					
		—	o	—	—	—	—	—	(Pore fluid composition)					
		o	o	—	o	—	—	—	In situ stress field					
		o	X	o	o	o	o	—	Strength					
		O	X	o	o	o	o	—	Deformation					
		—	—	o	o	—	o	—	Creep/fusing					
		o	o	—	o	—	o	—	Thermal conductivity					
		—	—	—	—	—	o	—	Heat capacity					
		o	o	—	o	—	o	—	Linear thermal expansion					
		o	X	—	o	o	o	—	Hydraulic conductivity					
		—	X	—	—	o	o	—	Effective porosity					
		—	X	—	—	o	o	—	Specific storage					
		o	X	—	—	—	o	o	Dispersivity					
		o	X	—	—	—	o	o	Adsorption/retardation					
		—	o	o	—	o	o	o	Alteration/solubility					
	Groundwater sampling (4, 5a) (see laboratory tests)	—	●	—	—	—	—	—	(Pore fluid composition)					
		X	X	—	—	—	o	o	Dispersivity					
		X	X	—	—	—	o	o	Adsorption/retardation					
		—	o	X	—	X	o	o	Alteration/solubility					
	Geophysical well logging (4)	X	X	—	X	X	X	—	Hydraulic conductivity	┤				
		—	X	—	—	X	X	—	Effective porosity	┤				
		—	X	—	—	X	X	—	Specific storage	┤				

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____ Dwg. No. ____ Date ____ Eng ____

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
6 of 9

	TEST METHOD (See Notes ( ) at end of Table)	TEST ASSESSMENT VARIABLES							CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
					RANGE IN ENVIRONMENTAL CONDITIONS									
		Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
(IN SITU TEST METHODS)	Geophysic/seismic (x-hole, exposure-borehole)	—	●	—	—	—	—	—	Stratigraphic/structural	├─	┤			
		●	●	X	X	X	X	—	Deformation	├┤				
	Exposure geophysics (radar screening)	—	●	—	—	—	—	—	Stratigraphic/structural	├┤				
		○	●	X	X	X	X	—	Deformation	├┤				
	Borehole jacking (4, 10a)	X	X	—	●	—	—	—	In situ stress field	├─	┤			
		X	X	○	●	X	X	—	Deformation	├─	┤			
	Overcoring (4)	○	X	—	●	—	—	—	In situ stress field	├─	─	─	┤	
	Hydrofracturing (4)	X	○	—	●	—	—	—	In situ stress field	├─	┤			
	Permeability test (single borehole with or without heated water) (4, 15)	X	○	—	X	●	○	—	Hydraulic conductivity	├─	┤			
		—	○	—	—	●	○	—	Effective porosity	├─	┤			
		—	○	—	—	●	○	—	Specific storage	├─	┤			
	Multiple borehole permeability test (with or without heated water) (4, 15)	●	○	—	X	●	○	—	Hydraulic conductivity	├─	─	┤		
		—	○	—	—	●	○	—	Effective porosity	├─	─	┤		
		—	○	—	—	●	○	—	Specific storage	├─	─	┤		
	Tracer test (with or without heated water) (4)	●	○	—	—	—	○	●	Dispersivity	├─	─	┤		
		●	○	—	—	—	○	●	Adsorption/retardation	├─	─	┤		
	Thermal probe (single borehole small scale heater test) (4, 10a)	X	○	—	X	—	●	—	Thermal conductivity	├┤				
		—	—	—	—	—	●	—	Heat Capacity	├┤				
	Heater test (x-hole small scale) (4)	●	●	—	X	—	●	—	Thermal conductivity	├─	┤			
		—	—	—	—	—	●	—	Heat capacity	├─	┤			
	Heater test (large scale)	●	●	—	X	—	●	—	Thermal conductivity	├─	─	┤		
		—	—	—	—	—	●	—	Heat capacity	├─	─	┤		
		●	●	—	X	—	●	—	Linear thermal expansion	├─	─	┤		
		—	●	○	—	X	●	X	Alteration/solubility	├─	┤			
	Overcoring (exposure) (7)	○	○	—	●	—	—	—	In situ stress field	├─	─	┤		
	Flatjack test	○	○	—	●	—	—	—	In situ stress field	├─	─	┤		
		●	○	○	●	X	X	—	Deformation	├─	┤			
	long term	—	—	●	●	—	X	—	Creep/fusing	├─	┤			
	Plate test (13)	●	○	○	●	X	X	—	Deformation	├─	─	─	┤	
	long term	—	—	●	●	—	X	—	Creep/fusing	├─	─	┤		
	Shear jacking (10b, 11)	●	○	○	●	X	X	—	Strength	├─	─	┤		
		●	○	○	●	X	X	—	Deformation	├─	─	┤		

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____ Dwg. No. AR3-[illegible]63 Date 10-82 Eng DR

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
7 of 9

		TEST ASSESSMENT VARIABLES												
					RANGE IN ENVIRONMENTAL CONDITIONS				CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
	TEST METHOD (See Notes ( ) at end of Table)	Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
(IN SITU TEST METHODS)	Block test (with or without heat)	●	○	○	●	X	○	–	Deformation	—	—	—		
	long term (with or without heat)	–	–	●	●	–	○	–	Creep/fusing	—	—	—		
	with heat (with or without stress)	●	○	–	○	–	●	–	Thermal conductivity	—	—	—	—	
		–	–	–	–	–	●	–	Heat capacity	—	—	—	—	
		●	○	–	○	–	●	–	Linear thermal expansion	—	—	—	—	
	with multiple bore-hole permeability test (with or without heat, stress)	●	○	–	○	●	○	–	Hydraulic conductivity	—	—	—		
		–	○	–	–	●	○	–	Effective porosity	—	—	—		
		–	○	–	–	●	○	–	Specific storage	—	—	—		
	with tracer test (with or without heat, stress)	●	○	–	–	–	○	●	Dispersivity	—	—	—		
		●	○	–	–	–	○	●	Adsorption/retardation	—	—	—		
	Pillar test (with or without heat) (12)	○	○	○	●	X	○	–	Strength	—	—	—		
		○	○	○	●	X	○	–	Deformation	—	—	—		
	long term (with or without heat (12)	–	–	●	●	–	○	–	Creep/fusing	—	—	—		
	with heat (12)	○	○	–	●	–	●	–	Thermal conductivity	—	—			
		–	–	–	–	–	●	–	Heat capacity	—	—			
		○	○	–	●	–	●	–	Linear thermal expansion	—	—			
	Mine-by test	●	●	●	X	X	X	–	Strength	—	—	—	—	
		●	●	●	X	X	X	–	Deformation	—	—	—	—	
		–	–	●	X	–	X	–	Creep/fusing	—	—	—	—	
	Chamber test (with or without heated water) (15)	●	●	–	X	●	○	–	Hydraulic conductivity	—	—	—	—	
		–	●	–	–	●	○	–	Effective porosity	—	—	—	—	
		–	●	–	–	●	○	–	Specific storage	—	—	—	—	
		–	●	○	–	●	○	X	Alteration/solubility	—	—	—		
	with deformation monitoring (with or without heated water)	●	●	○	X	●	○	–	Deformation	—	—	—	—	
	long term with deformation monitoring (with or without heated water)	–	–	●	X	–	○	–	Creep/fusing	—	—	—		
	with heated water	●	●	–	X	–	●	–	Thermal conductivity	—	—	—	—	
		–	–	–	–	–	●	–	Heat Capacity	—	—	—	—	
	with heated water and displacement monitoring	●	●	–	X	–	●	–	Linear thermal expansion	—	—	—		
	with tracer injection and monitoring (with or without heated water)	●	●	–	–	–	○	●	Dispersivity	—	—	—	—	
		●	●	–	–	–	○	●	Adsorption/retardation	—	—	—	—	

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____ Drg. No. ____ Date ____ Eng. ____

LIMITATIONS AND UNCERTAINTY IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS BY AVAILABLE TEST METHODS

Table 4.5
8 of 9

	TEST METHOD (See Notes ( ) at end of Table)	TEST ASSESSMENT VARIABLES			RANGE IN ENVIRONMENTAL CONDITIONS				CHARACTERISTICS ASSESSED BY TEST METHOD (see Table 4.4)	UNCERTAINTY IN ASSESSMENT OF CHARACTERISTIC**				
		Anisotropy	Scale (Rep. Volume)	Duration	Stress Level	Pore Pressure	Temperature	Radiation Dose		Very High	High	Moderate	Low	Very Low
(IN SITU TEST METHODS)	Acoustic emission monitoring	—	●	X	—	—	—	—	Tectonic	—				
	Seismic monitoring	—	●	X	—	—	—	—	Tectonic	—	—			
	Monitor pore pressures in rock mass (4)	—	●	—	—	●	—	—	In situ hydraulic field	—	—	—	—	
	and drainage into excavation (7)	●	●	—	X	X	X	—	Hydraulic conductivity	—	—	—		
		—	●	—	—	X	X	—	Effective porosity	—	—	—		
		—	●	—	—	X	X	—	Specific storage	—	—	—		
	Monitor temperatures in rock mass (4)	—	●	—	—	—	●	—	In situ temperature field	—	—	—	—	
	and excavation (with ventilation/cooling) (7)	●	●	—	X	—	X	—	Thermal conductivity	—	—	—		
		—	—	—	—	—	X	—	Heat capacity	—	—	—		
	and displacements in rock mass and excavation (7)	●	●	—	X	—	X	—	Linear thermal expansion	—	—	—		
	Monitor stress changes and/or displacements in rock mass and excavations (7)	●	●	●	X	X	X	—	Deformation	—	—	—	—	
		—	—	●	X	—	X	—	Creep/fusing	—	—	—	—	
	Monitor stress changes and strains in supports (7)	●	●	●	X	X	X	—	Deformation	—	—	—		
		—	—	●	X	—	X	—	Creep/fusing	—	—	—		
	Monitor fracturing in rock mass around excavation (e.g., by acoustic emission monitoring) (7)	●	●	●	X	X	X	—	Strength	—	—	—		
	Monitor alteration/solutioning of exposure	—	●	○	—	X	X	X	Alteration/solubility	—	—	—		
	Monitor borehole drainage (4,7)	○	○	—	X	X	X	—	Hydraulic conductivity	—	—			
		—	○	—	—	X	X	—	Effective porosity	—	—			
		—	○	—	—	X	X	—	Specific storage	—	—			

**Note: This is only a qualitative indication of uncertainty in the assessment of each characteristic, due only to quality of the data base which will be media/site specific and a function of the magnitude of the value measured (see Figure 3.4).

Rev. ____
Dwg. No. 1013 1163 Date 10-81 Eng JR

LIMITATIONS AND UNCERTAINTY
IN ASSESSMENT OF SIGNIFICANT CHARACTERISTICS
BY AVAILABLE TEST METHODS

Table 4.5
9 of 9

NOTES:

● Assessment variable is adequately incorporated in test method.

○ Assessment variable can be adequately incorporated in test method (optional).

− Assessment variable is not adequately incorporated in test method.

X Characteristic is relatively insensitive to assessment variable (see Table 3.2), and thus the assessment variable is not relevant.

(1) Geologic mapping includes a geodetic survey and exposure mapping, as well as possibly aerophotography (by airplane or satellite, black-and-white, color, or infrared).

(2) Surface geophysics include possibly gravity and magnetic surveys (land or air based), electrical survey, and seismic surveys (reflection and refraction).

(3) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(4) Tests are conducted in boreholes drilled from underground.

(5) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.
b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(6) The in situ (i.e,. pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(7) Monitoring performance implies associated analysis to assess characteristic.

(8) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These response characteristics can be assessed either:
- o Directly by testing a large scale sample which contains a significant number of discontinuities
- o Indirectly by separately assessing the response characteristics of the intact rock, discontinuitis, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(9) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer or rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(10) Tests assess the response characteristics of only the a) intact rock or b) discontinuity, and does not directly assess the response characteristics of the rock mass (see note 8).

(11) Shear jacking is very similar to torsion jacking. Because of these similarities, only shear jacking will be discussed, although torsion jacking might be a suitable alternative.

(12) Pillar test can consist of either:
- o Jacking an isolated pillar or unconfined block to failure (i.e., essentially an unconfined plate test or an axially loaded unconfined block test)
- o Reducing the dimensions of a pillar (and thus increasing stresses) until failure occurs.

(13) Plate test is very similar to two other tests:
- o Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation
- o Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(14) Direct shear test on discontinuity samples can be of various scales and is also very similar to torsional shear tests. Because of these similarities, only the direct shear test will be discussed, although torsional shear test might be a suitable alternative.

(15) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test. Multiple borehole permeability tests are often called "pump" tests.

(16) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

This is a relatively comprehensive list of test methods which are available for assessing site characteristics. It should not be construed that all of these available tests are being recommended.

possible to the prototype in terms of site characteristics, test conditions, and design/construction.

Available simulation test methods, which resolve key issues, have been identified (see Table 4.6). These tests attempt to duplicate a construction or operation method, which is being considered for repository development, and then observe and extrapolate the results to the repository.

The tests with appropriate capabilities can subsequently be selected from this relatively comprehensive list of available tests, in order to respond to the perceived information needs. For those key issues which have already been adequately resolved, or will be by other means, simulation tests may not be necessary. Only those key issues which need additional resolution need to be addressed. Hence, it should not be construed that all of these available tests (Table 4.6) are being recommended.

IN SITU TEST METHODS AVAILABLE TO RESOLVE THE KEY ISSUES BY SIMULATION

Table 4.6
1 of 2

KEY ISSUE	SIMULATION TEST METHOD
CONSTRUCTABILITY	• Shaft or tunnel test section* in which the excavation/support procedures are varied: - determine advance rates and cost for each procedure - monitor blast vibrations (if drill and blast) and acoustic emissions for each procedure - determine corresponding extent and nature of disturbed zone after excavation - monitor performance (i.e., stress, displacement, stability) of opening for each procedure - observe rate of weathering, alteration, or solutioning of exposure with time - determine effectiveness of ground and groundwater control procedures - determine characteristics of as-constructed disturbed zone.
	• Borehole, shaft, or tunnel test section in which the backfill/seal/plug materials and placement procedures are varied: - determine rate of placement and cost of engineered barrier - monitor performance of engineered barrier - observe rate of alteration, weathering, or solutioning with time - determine characteristics of as-placed engineered barrier and rock/barrier interface.
	• Grout injection tests.
	• Evaluate procedures for emplacing and retrieving waste packages.
	• Evaluate operating procedures (i.e., hoisting/transporting, ventilating, drainage/pumping) in shaft/tunnel test sections.*
THERMAL RESPONSE	• Monitor thermal response of tunnel test section (with or without test backfill/seals/plugs) due to emplaced (actual or simulated) waste packages.
MECHANICAL RESPONSE	• Monitor mechanical response (i.e., deformations) of shaft/tunnel test section* (with or without test backfill/seals/plugs) in which excavation/support procedures are varied.
	• Rock bolt pull out tests.
HYDROLOGIC RESPONSE	• Monitor hydrological response (i.e., pore pressures and flow) of shaft/tunnel test sections* (with or without test backfill/seals/plugs.)

IN SITU TEST METHODS AVAILABLE TO RESOLVE THE KEY ISSUES BY SIMULATION

Table 4.6
2 of 2

KEY ISSUE	IN SITU TEST METHOD
GEOCHEMICAL RESPONSE	• Observe exposures over long term after excavation of shaft/tunnel test sections.* • Monitor geochemical response (i.e., waste-rock interaction/corrosion/alteration and radionuclide migration) of tunnel test section (with or without test backfill/seals/plugs) due to emplaced waste packages.

* Notes: The entire in situ test facility constitutes shaft/tunnel test sections.

This is a relatively comprehensive list of in situ test methods which are available to resolve the key issues by simulation. It should not be construed that all of these available tests are recommended.

5.0 REASONABLE IN SITU TEST PROGRAMS

5.1 PROGRAM CONSIDERATIONS

5.1.1 Testing Which is Expected to Precede In Situ Test Program

Site investigation is expected to precede the in situ test program. This precedent testing, including surface tests and tests within a limited number of boreholes, as well as laboratory tests on samples obtained from those boreholes, has been anticipated (see Table 5.1). The results of actual site investigation will be presented in the Site Characterization Report (SCR), as delineated in "Standard Format and Content of Site Characterization Reports for High-Level Waste Geologic Repositories" (NRC, 1981).

The information needs, to which the in situ test program must respond, will develop as the present assessment of characteristics at each site changes with site investigation prior to initial SCR submittal. It is possible that some characteristics may be adequately assessed for construction authorization prior to initial SCR submittal. In most cases, however, in situ tests will be required to reduce the uncertainty in the assessment of significant characteristics to acceptable levels and adequately resolve the key issues.

5.1.2 In Situ Test Program Objectives

The in situ test program must adequately respond to the information needs for construction authorization which have developed by the time of initial SCR submittal at a given site. This is accomplished by utilizing appropriate tests which:

- Reduce the uncertainty in the assessment of significant characteristics to acceptable levels. The uncertainties are reduced by improving the quality of the data base. Large-scale in situ tests, including predicting/monitoring the performance of the in situ test facility itself, assess the characteristics of a representative volume of a rock mass unit which is large enough to contain a significant number of discontinuities. Tests on such a representative volume do not require scale-effect corrections in the determination of quasi-continuum rock mass characteristics, whereas smaller scale tests (e.g., borehole, laboratory, or small-scale in situ tests) assess either the intact rock or the discontinuity characteristics, and not the composite rock mass characteristics. Due to their generally high cost and long duration, however, the results of large-scale in situ tests should be used to develop and verify site-specific correlations with the results of tests which are less expensive and of short duration. Once reliable correlations have been determined, these simpler tests can be used with improved confidence to build a large quality data base. The magnitude and natural variability of characteristics can thus be assessed over a large area.

TESTING WHICH IS EXPECTED TO PRECEDE IN SITU TEST PROGRAM

Table 5.1

1 of 3

CHARACTERISTIC (see Table 3.1)	TEST METHOD (see notes() at end of Table)			(See Table 4.4)
	SURFACE	BOREHOLE (from surface)	LABORATORY	
(GEOLOGIC SETTING)				
Stratigraphic/ structural (includes the physical and chemical characteristics of each rock mass unit, including pore fluid composition)	● geologic mapping (1) ● surface geophysics (2)	● cutting evaluation ● coreholes (3) ● geophysic/seismic (x-hole, surface-borehole) ● groundwater sampling (5a)	● core logging ● determination of rock sample mineralogy (thin section, x-ray diffraction) ● determination of groundwater sample composition and age ● hydrochemical analysis of rock sample.	**(No** in situ tests are anticipated)
Tectonic	● geologic mapping (1) ● surface geophysics (2) ● seismic monitoring			
In situ stress field (stress tensor) (6)		● rock mass sampling (5b) ● hydrofracturing (16)	● core observation (stress relief, core discing).	
In situ hydraulic head field (pore pressure) (6)	● hydrologic mapping	● monitor pore pressures		
In situ temperature field (temperature) (6)		● monitor temperatures.		
(MECHANICAL) Strength (8)		● rock mass sampling (5b)	● index tests on rock samples (9) ● simple strength tests on rock sample (sliding test, Brazilian test, point load test, beam test, tensile strength test, fracture toughness test) (10a) ● direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) ● unconfined compression test on rock core (w/or w/o heat) (10a) ● triaxial test on rock core (w/or w/o heat (10a,b).	
Deformation (8)	● surface geophysics (2)	● rock mass sampling (5b)	● index tests on rock sample (9) ● unconfined compression test on rock core (w/or w/o heat) (10a) ● triaxial test on rock core (w/or w/o heat) (10a,b) ● direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) ● sonic velocity test on rock core (w/or w/o stress) (10a).	

Rev. ______
Dwg. No. A913-1163 Date Nov 82 Eng BR.

TESTING WHICH IS EXPECTED TO PRECDED IN SITU TEST PROGRAM

Table 5.1
2 of 3

CHARACTERISTIC (see Table 3.1)	TEST METHOD (see notes() at end of Table)			(See Table 4.4)
	SURFACE	BOREHOLE (from surface)	LABORATORY	
Creep (8)		• rock mass sampling (5b)	• unconfined compression test on rock core, long term (w/or w/o heat) (10a) • triaxial test on rock core, long term (w/or w/o heat)(10a)	(No in situ tests are anticipated)
(THERMAL) Thermal conductivity (8) Heat capacity (8)		• rock mass sampling (5b)	• heated rock sample (10a)	
Linear thermal expansion(3)		• rock mass sampling (5b).	• heated rock sample (10a)	
(HYDROLOGIC) Hydraulic conductivity (8) Effective porosity (8) Specific storage (8)		• rock mass sampling (5b) • geophysical well logging • permeability test (single borehole) (15)	• index tests on rock sample (9) • axial permeability test on rock core (w/or w/o heat, stress) (10a,15)	
(GEOCHEMICAL) Dispersivity (8). Adsorption/ retardation (8)		• rock mass sampling (5b) • groundwater sampling (5a)	• determination of groundwater sample composition and age • tracer test on rock sample (w/or w/o heat, stress) (10a,b) • determination of rock sample mineralogy.	
Alteration/ solubility	• geologic mapping (1).	• rock mass sampling (5b) • groundwater sampling(5a)	• determination of groundwater sample composition and age • core logging • determination of rock sample mineralogy • slaking or accelerated weathering test on rock sample (w/heat, stress) • solubility test on rock sample (w/or w/o heated water)	

TESTING WHICH IS EXPECTED TO PRECEDE IN SITU TEST PROGRAM

Table 5.1
3 of 3

NOTES:

• Test which is expected to precede in situ test program.

(1) Geologic mapping includes a geodetic survey and exposure mapping, as well as possibly aerophotography (by airplane or satellite, black-and-white, color, or infrared).

(2) Surface geophysics include possibly gravity and magnetic surveys (land or air based), electrical survey, and seismic surveys (reflection and refraction).

(3) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(4) Tests are conducted in boreholes drilled from underground.

(5) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.
b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(6) The in situ (i.e,. pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(7) Monitoring performance implies associated analysis to assess characteristic.

(8) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These response characteristics can be assessed either:
- o Directly by testing a large scale sample which contains a significant number of discontinuities
- o Indirectly by separately assessing the response characteristics of the intact rock, discontinuitis, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(9) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer or rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(10) Tests assess the response characteristics of only the a) intact rock or b) discontinuity, and does not directly assess the response characteristics of the rock mass (see note 8).

(11) Shear jacking is very similar to torsion jacking. Because of these similarities, only shear jacking will be discussed, although torsion jacking might be a suitable alternative.

(12) Pillar test can consist of either:
- o Jacking an isolated pillar or unconfined block to failure (i.e., essentially an unconfined plate test or an axially loaded unconfined block test)
- o Reducing the dimensions of a pillar (and thus increasing stresses) until failure occurs.

(13) Plate test is very similar to two other tests:
- o Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation
- o Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(14) Direct shear test on discontinuity samples can be of various scales and is also very similar to torsional shear tests. Because of these similarities, only the direct shear test will be discussed, although torsional shear test might be a suitable alternative.

(15) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test. Multiple borehole permeability tests are often called "pump" tests.

(16) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

- Partially verify predictive numerical models, by comparing the measured results of large-scale in situ tests with predictions. This includes comparing predicted performance of the in situ test facility with monitored performance.

- Simulate important aspects of the repository. By monitoring the performance of the in situ test facility, some of the data collected during construction and operation of this facility can be extrapolated to predict repository construction/operation performance. The validity of this extrapolation will be a direct function of how well the in situ test facility represents the repository, both in site characteristics and design/construction.

The in situ test program is assumed to consist of tests which are available (Tables 4.4 and 4.6), and are conducted within an in situ test facility in the time frame between initial SCR submittal and LA. This in situ test facility is assumed to consist of an exploratory shaft, extending from the surface to the prospective repository horizon possibly with test stations at various depths, and an underground test facility, consisting of appropriate tunnels and test rooms at that horizon.

The exploratory shaft should be constructed to:

- Allow description of the site below the surface (including the repository horizon) near the shaft

- Provide access to the repository horizon

- Provide information on shaft design and construction engineering variables

- Provide information on shaft operation (i.e., ventilation, hoisting, etc.) by monitoring

- Not adversely impact repository performance.

The underground test facility should be constructed, if the site has not been disqualified after construction of the exploratory shaft, to:

- Allow description of the repository horizon

- Provide information on tunnel design and construction engineering variables

- Provide information on tunnel operation (i.e., ventilation, transportation, etc.)

- Not adversely impact repository performance.

It is expected that plans for this in situ test program will be presented in the initial SCR submittal and that the complete results will be presented in a LA. Testing preceding the initial SCR submittal (Table 5.1) will affect the in situ test program, as the uncertainty in the assessment of some characteristics is reduced and the information needs correspondingly change. Similarly, testing or monitoring subsequent to LA (i.e., during repository construction/operation) may be required to further increase the level of confidence in satisfactory performance to acceptable levels. This subsequent testing has not been considered, however.

5.1.3 Tentative Media Independent In Situ Test Program

Tests which should generally be considered for inclusion in an in situ test program have been identified (see Table 5.2, in conjunction with Table 4.6). This selection has been based on the objectives of the in situ test program (see Section 5.1.2), especially based on:

- The perceived information needs for construction authorization which will typically exist when the initial SCR is submitted, which in turn depend on:
  - The maximum acceptable level of uncertainty in the assessment of the significant characteristics (see Section 3.5)
  - The present assessment of significant characteristics (see Section 3.4)
  - The tests which are expected to precede in situ testing (see Section 5.1.1)
- The assessed capabilities of each test in addressing these information needs, which in turn depend on:
  - The typical level of uncertainty in the assessment of each significant characteristic by available test methods (see Section 4.3)
  - In situ tests which are available to resolve the key issues by simulation (see Section 4.4)

Specific in situ test methods, which comprise this program and are especially unique and important, have been investigated in detail (see Appendix A of Volume II). These methods have been individually described and evaluated, and Golder Associates has made recommendations regarding test methodology, utilization of test results, and potential research/ development.

As previously discussed, however, neither the information needs for construction authorization nor the test capabilities at the time of initial SCR submittal can be firmly established at this time. Also, neither are independent of media or site. Thus, this tentative program (Tables 5.2 and 4.6) provides only a preliminary indication of an adequate in situ test program.

TENTATIVE IN SITU TEST PROGRAM FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 5.2
1 of 3

CHARACTERISTIC (see Table 3.1)	TEST METHOD (see note 1 at end of Table) (See Table 4.4)		
		LABORATORY	IN SITU (from subsurface excavation)
(GEOLOGIC SETTING)	(Refer to Table 5.1 for tests anticipated to be conducted from surface or in boreholes drilled from surface prior to in situ test program.)		
Stratigraphic/structural (includes the physical and chemical characteristics of each rock mass unit, including pore fluid composition)		• core logging • determination of rock sample mineralogy (thin section, x-ray diffraction) • determination of groundwater sample composition and age • hydrochemical analysis of rock sample.	• exploratory excavations (including exposure mapping) • coreholes (3, 4) • rock mass sampling (5b) • geophysic/seismic (x-hole, exposure-borehole)
Tectonic			• acoustic emission monitoring • seismic monitoring
In situ stress field (stress tensor) (6)			• hydrofracturing (4) • overcoring (4) • flat jack test
In situ hydraulic head field (pore pressure) (6)			• monitor pore pressures in rock mass (4)
In situ temperature field (temperature) (6)			• monitor temperatures in rock mass (4)
(MECHANICAL) Strength (8)		• index tests on rock samples (9) • simple strength tests on rock sample (sliding test, Brazilian test, point load test, beam test, tensile strength test, fracture toughness test) (10a) • direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) • unconfined compression test on rock core (w/or w/o heat) (10a) • triaxial test on rock core (w/or w/o heat (10a,b).	• index tests on exposures (9) • rock mass sampling (5b) • mine-by test • monitoring fracturing in rock mass around excavation (e.g., by acoustic emission monitoring) (7)
Deformation (8)		• index tests on rock sample (9) • unconfined compression test on rock core (w/or w/o heat) (10a) • triaxial test on rock core (w/or w/o heat) (10a,b) • true triaxial test on large rock sample (w/or w/o heat) (10a,b) • direct shear test on discontinuity sample (w/or w/o heat) (10b, 14) • sonic velocity test on rock core (w/or w/o stress) (10a).	• index tests on exposures (9) • rock mass sampling (5b) • geophysic/seismic (x-hole, exposure-borehole) • flat jack test • plate test (13) • block test (w/or w/o heat) • mine-by test • monitor displacements in rock mass as excavation occurs (4,7) • monitor displacements at exposure as excavation occurs (7)

Rev. Dwg. No. A813-1162 Date Nov 92 Eng. BR

TENTATIVE IN SITU TEST PROGRAM FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 5.2
2 of 3

CHARACTERISTIC (see Table 3.1)	TEST METHOD (see notes() at end of Table) (See Table 4.4)		
		LABORATORY	IN SITU (from subsurface excavation)
Creep (8)	(Refer to Table 5.1 for tests anticipated to be conducted from surface or in boreholes drilled from surface prior to in situ test program.)	• unconfined compression test on rock core, long term (w/or w/o heat) (10a) • triaxial test on rock core, long term (w/or w/o heat)(10a) • true triaxial test on large rock sample, long term (w/or w/o heat) (10a,b) • direct shear test on discontinuity sample, long term (w/or w/o heat) (10b,14)	• rock mass sampling (5b) • flat jack test, long term • plate test, long term (13) • block test, long term (w/or w/o heat) • mine-by test • monitor displacements in rock mass after excavation (4,7) • monitor displacements at exposure after excavation (4,
(THERMAL) Thermal conductivity (8) Heat capacity (8)		• heated rock sample (10a) • unconfined compression test on rock core w/heat (10a) • triaxial test on rock core w/heat (10a).	• rock mass sampling (5b) • heater test (x-hole small scale) (4) • heater test (large scale) • block test w/heat (w/or w/o stress) • monitor temperature in rock mass and excavation (w/ventilation cooling) (7).
Linear thermal expansion(3)		• heated rock sample (10a) • unconfined compression test on rock core w/heat (10a) • triaxial test on rock core w/heat (10a).	• rock mass sampling (5b) • heater test (large scale) • block test w/heat (w/or w/o stress) • monitor temperatures and displacements in rock mass and excavation (7).
(HYDROLOGIC) Hydraulic conductivity (8) Effective porosity (8) Specific storage (8)		• index tests on rock sample (9) • axial permeability test on rock core (w/or w/o heat, stress) (10a,15) • radial permeability test on rock sample (w/or w/o heat, stress)(10a,b, 15).	• rock mass sampling (5b) • permeability test (single borehole) (w/or w/o heated water) (4,15) • multiple borehole permeability test (w/or w/o heated water) (4,15) • block test w/multiple borehole permeability test (w/or w/o heat, stress) • chamber test (w/or w/o heated water) (15) • monitor drainage into excavation and pore pressure in rock mass (7)
(GEOCHEMICAL) Dispersivity (8) Adsorption/ retardation (8)		• determination of groundwater sample composition and age • tracer test on rock sample (w/or w/o heat, stress) (10a,b) • determination of rock sample mineralogy.	• rock mass sampling (5b) • groundwater samplinu (4,5a) • tracer test (w/or w/o heated water) (4) • block test w/tracer test (w/ or w/o heat, stress)
Alteration/ solubility		• determination of groundwater sample composition and age • core logging • determination of rock sample mineralogy • slaking or accelerated weathering test on rock sample (w/heat, stress) • solubility test on rock sample (w/or w/o heated water)	• exposure mapping • rock mass sampling (5b) • groundwater sampling (4,5a) • heater test (large scale) • chamber test (w/or w/o heat) • monitor alteration/solutioning of exposures.

Rev. ____ Dwg. No. A8(3)-1163 Date Nov 92 Eng. B.R.

TENTATIVE IN SITU TEST PROGRAM FOR ASSESSING SIGNIFICANT CHARACTERISTICS

Table 5.2
3 of 3

Notes:

- Test which should be specifically considered in a reasonable in situ test program. The actual selection of tests will be a function of the information needs for a specific site, as well as the test capabilities regarding those needs. Hence, it is not to be expected that all of the indicated tests will be required at each site.

(1) Geologic mapping includes a geodetic survey and exposure mapping, as well as possibly aerophotography (by airplane or satellite, black-and-white, color, or infrared).

(2) Surface geophysics include possibly gravity and magnetic surveys (land or air based), electrical survey, and seismic surveys (reflection and refraction).

(3) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(4) Tests are conducted in boreholes drilled from underground.

(5) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.
b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(6) The in situ (i.e,. pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(7) Monitoring performance implies associated analysis to assess characteristic.

(8) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These response characteristics can be assessed either:
- o Directly by testing a large scale sample which contains a significant number of discontinuities
- o Indirectly by separately assessing the response characteristics of the intact rock, discontinuitis, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(9) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer on rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(10) Tests assess the response characteristics of only the a) intact rock or b) discontinuity, and does not directly assess the response characteristics of the rock mass (see note 8).

(11) Shear jacking is very similar to torsion jacking. Because of these similarities, only shear jacking will be discussed, although torsion jacking might be a suitable alternative.

(12) Pillar test can consist of either:
- o Jacking an isolated pillar or unconfined block to failure (i.e., essentially an unconfined plate test or an axially loaded unconfined block test)
- o Reducing the dimensions of a pillar (and thus increasing stresses) until failure occurs.

(13) Plate test is very similar to two other tests:
- o Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation
- o Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(14) Direct shear test on discontinuity samples can be of various scales and is also very similar to torsional shear tests. Because of these similarities, only the direct shear test will be discussed, although torsional shear test might be a suitable alternative.

(15) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test. Multiple borehole permeability tests are often called "pump" tests.

(16) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

5.2 TENTATIVE MEDIA/SITE SPECIFIC IN SITU TEST PROGRAMS

Tests which should be specifically considered for inclusion in an in situ test program for each of the media/sites under consideration have been identified (see Table 5.3). These selections of tests are derived from the tentative in situ test program (see Section 5.1.3), taking into additional consideration:

- The present assessment of characteristics for each media/site (see Section 3.4.2 and Appendix B of Volume II)
- The significance of characteristics for each media/site (see Section 3.5.2)
- The applicability of each test to the media/site specific conditions (see Appendix A of Volume II).

The media and sites considered include (Table 1.1):

- Basalt at Hanford Reservation, Washington
- Tuff at Yucca Mountain, Nevada Test Site, Nevada
- Domal salt at Richton or Cypress Creek, Mississippi, or Vacherie, Louisiana
- Bedded salt at unspecified site (generic)
- Granite at unspecified site (generic).

Golder Associates believes that the tentative media/site specific in situ test programs (Table 5.3) offer the best available opportunity for adequately responding to the presently perceived information needs, and thus resolving the key issues related to repository design and construction, prior to LA.

However, the information needs may change between now and when the initial SCR is submitted, especially for granite and to a lesser extent domal salt, bedded salt, and tuff. This is due to the additional data which might be generated by surface, borehole and laboratory testing performed prior to initial SCR submittal, and thus preceding in situ testing, at these sites. This is also due to possible clarification of the licensing perspective. Similarly, the capabilities of specific tests will generally improve in the future and even new or hybrid tests, which have not been considered herein, may be developed having significantly different capabilities.

Due to the possible changes in both information needs and test capabilities, the reasonable media/site specific in situ test programs (Table 5.3) are preliminary in nature and will evolve with time. In situ test programs must thus incorporate some flexibility in order to easily adapt to these changes, as presented in SCR updates.

TENTATIVE MEDIA/SITE SPECIFIC IN SITU TEST PROGRAMS

Table 5.3
1 of 3

IN SITU TEST METHOD (Appendix, Section):	CHARACTERISTICS ASSESSED BY TEST: (see Table 5.2)									ASPECTS SIMULATED BY TEST: (see Table 4.6)		MINIMUM NUMBER OF TESTS PERFORMED IN:		MEDIA/SITE FOR WHICH TEST IS RECOMMENDED: (See Table 1.1)				
	Geologic Setting																	
	Stratigraphic/ Structural (1a)	Tectonics	In Situ Stress Field (1b)	In Situ Hydraulic Head Field (1b)	In Situ Temperature Field (1b)	Mechanical Characteristics (2)	Thermal Characteristics (2)	Hydrologic Characteristics (2)	Geochemical Characteristics (2)	Constructability	Repository Performance	Exploratory Shaft	Underground Test Facility	Basalt (3)	Tuff (4)	Domal Salt (5)	Bedded Salt (6)	Granite (7)
Plate Test (9) (A.1)						●						-	a	●	●			●
Block Test (A.2)						●	●	●	●			-	2	●	●	●	●	●
Chamber Test (A.3)								●	●		●	-	1	●	●			●
Mine-By Test (A.4)						●				●	●	-	1	●	●	●	●	●
Heater Test (Large Scale) (A.5)							●		●	●	●	-	1	●	●	●	●	●
Heater Test (Small Scale) (A.5)							●					a	a	●	●	●	●	●
Tracer Test (A.6)				●				●	●			a	a	●	●			●
Multiple Borehole Permeability Test (10) (A.7)								●				a	a	●	●			●
Overcoring (A.8)			●									b	b	●	●	●	●	●
Flatjack Test (A.9)			●			●						a	a	●	●	●	●	●
Acoustic Emission Monitoring (A.10)		●				●				●	●	c	c	●	●	●	●	●
Exposure Mapping (A.11)	●							●	●	●		c	c	●	●	●	●	●

Rev ___ Dwg No ABI-1163 Date 10 82 Eng [illegible]

TENTATIVE MEDIA/SITE SPECIFIC IN SITU TEST PROGRAMS

Table 5.3
2 of 3

IN SITU TEST METHOD (Appendix, Section):	CHARACTERISTICS ASSESSED BY TEST: (see Table 5.2)									ASPECTS SIMULATED BY TEST: (see Table 4.6		MINIMUM NUMBER OF TESTS PERFORMED IN:		MEDIA/SITE FOR WHICH TEST IS RECOMMENDED: (See Table 1.1)				
	Geologic Setting																	
	Stratigraphic/ Structural (1a)	Tectonics	In Situ Stress Field (1b)	In Situ Hydraulic Head Field (1b)	In Situ Temperature Field (1b)	Mechanical Characteristics (2)	Thermal Characteristics (2)	Hydrologic Characteristics (2)	Geochemical Characteristics (2)	Constructability	Repository Performance	Exploratory Shaft	Underground Test Facility	Basalt (3)	Tuff (4)	Domal Salt (5)	Bedded Salt (6)	Granite (7)
Exploratory Excavations (11)	●									●	●	*	*	●	●	●	●	●
Coreholes (12)	●									●		b	b	●	●	●	●	●
Rock Mass Sampling (13b)	●					●	●	●	●			b	b	●	●	●	●	●
Groundwater Sampling (13a)									●			b	b	●	●	●	●	●
Permeability Test (Single Borehole) (10)								●				b	b	●	●	●	●	●
Hydrofracturing (17)			●									a	b	●	●	●	●	●
Laboratory Tests (14)	●					●	●	●	●	●		b	b	●	●	●	●	●
Index Tests on Exposures (15)						●				●		b	b	●	●	●	●	●
Geophysic/Seismic (X-hole, Exposure-borehole)	●					●				●		b	b	●	●	●	●	●
Seismic Monitoring		●									●	c	c	●	●	●	●	●
Monitor Temperature in Rock Mass and Excavations (16)					●		●			●	●	c	c	●	●	●	●	●
Monitor Displacements in Rock Mass and Excavations (16)						●	●			●	●	c	c	●	●	●	●	●
Monitor Pore Pressures in Rock Mass (16)				●				●			●	c	c	●	●	●	●	●
Monitor Drainage into Excavation (16)								●		●	●	c	c	●	●	●	●	●
Monitor Alteration/ Solutioning of Exposures									●		●	c	c	●	●	●	●	●
Construction Monitoring										●	●	c	c	●	●	●	●	●
Operation Monitoring											●	c	c	●	●	●	●	●

Rev. ______
Dwg. No. AB13-uc3 Date 10-82 Eng BR

TENTATIVE MEDIA /SITE SPECIFIC IN SITU TEST PROGRAMS

Table 5.3

3 of 3

Notes:

a = several (≤ 10)
b = numerous (> 10)
c = continual
✱ = Exploratory shaft and underground test facility are exploratory excavations.

(1) a) The stratigraphy/structure includes the physical and chemical characteristics of each rock mass unit (including poor fluid composition).

b) The in situ (i.e., pre-excavation or virgin) stress, hydraulic, and temperature fields can be indirectly assessed or inferred from the stratigraphy/structure and tectonics (e.g., in situ stress field can be inferred from the geomorphology and tectonics of the site).

(2) The response characteristics refer to the rock mass, which consists of intact rock, discontinuities and pore fluid. These reponse characteristics can be assessed either:

- Directly by testing a large scale sample which contains a significant number of discontinuities
- Indirectly by separately assessing the response characteristics of the intact rock, discontinuities, and pore fluid, and then assembling by a model. Hence, the rock mass response characteristics can often be inferred from the stratigraphy/structure.

(3) Basalt at Hanford, Washington (See Section 3 and Appendix B of Volume II) (8)
(4) Tuff at Yucca Mountain, Nevada (See Section 3 and Appendix B of Volume II) (8)
(5) Domal Salt at Gulf Coact Sites (See Section 3 and Appendix B of Volume II) (8)
(6) Bedded Salt at unspecified site (See Section 3 and Appendix B of Volume II) (8)
(7) Granite at unspecified site (See Section 3 and Appendix B of Volume II) (8)

(8) Significance of characteristics for in situ testing, as they relate to design, for each media/site subjectively evaluated as shown in Figure 3.5.

(9) Plate test is very similar to two other tests:

- Cable jacking test, in which the reaction is provided by an anchor in the rock mass rather than the opposite wall of the excavation.
- Radial jacking, in which the entire circumference of the opening is jacked using, for example, several plate jack systems.

Because of these similarities, only the plate test will be discussed, although cable jacking or radial jacking might be suitable alternatives.

(10) Tests are constant head injection, constant head withdrawal, constant flow rate withdrawal, pulse injection, or gas injection permeability test.

(11) Exploratory excavations include the exploratory shaft and underground test facility.

(12) Coreholes include coring and core logging, as well as possibly borehole surveying, caliper logging, oriented coring, integral sampling, impression packer, borehole TV/camera, borehole radar, and geophysical well logging (electrical, acoustic, and nuclear).

(13) a) Groundwater sampling implies subsequent laboratory determination of groundwater composition and age.

b) Rock mass sampling, either coring or large block samples, implies subsequent laboratory tests.

(14) Laboratory tests are performed on rock mass or groundwater samples (See Table 5.2 for a complete listing).

(15) Index tests do not assess the characteristic directly, but by empirical correlations (e.g., use of a Schmidt hammer on rock core or on an exposure is an index test whose results can be roughly correlated with the modulus of deformation, based on experience). There are too many index tests, with varying reliability, to list.

(16) Monitoring performance implies associated analysis to assess characteristic.

(17) Hydrofracturing must be very carefully performed in order to control the extent of fractures which are generated.

5.3 EXAMPLE IN SITU TEST FACILITY FOR BASALT AT HANFORD, WASHINGTON

The configuration, schedule, and cost of a reasonable in situ test facility which can accommodate the tentative in situ test program has been developed in Task 4, "Relationship of an In Situ Test Facility to a Deep Geologic Repository for High Level Nuclear Waste" (Golder, 1982d), of this project. The development of the example in situ test facility has utilized the geologic setting, the existing exploratory shaft design, and the preconceptual repository design for the Basalt Waste Isolation Project (BWIP) at Hanford, Washington. BWIP was chosen as an example case because the repository program was the most advanced and more information was available, as compared to other media/sites.

The example configuration of a reasonable underground test facility for basalt (see Figure 5.1) has been primarily influenced by the following factors:

- Accommodate example in situ test program
- Construct certain test and access tunnels to repository dimensions and orientations to evaluate full scale opening response
- Spatially separate experiments to reduce test interaction
- Confirm the extent of the proposed repository host rock mass and evaluate the variability of characteristics in two orthogonal directions (long, near-horizontal boreholes can be added to extend this investigation)
- Provide sufficient working area, access and utilities for quality assurance and safety.

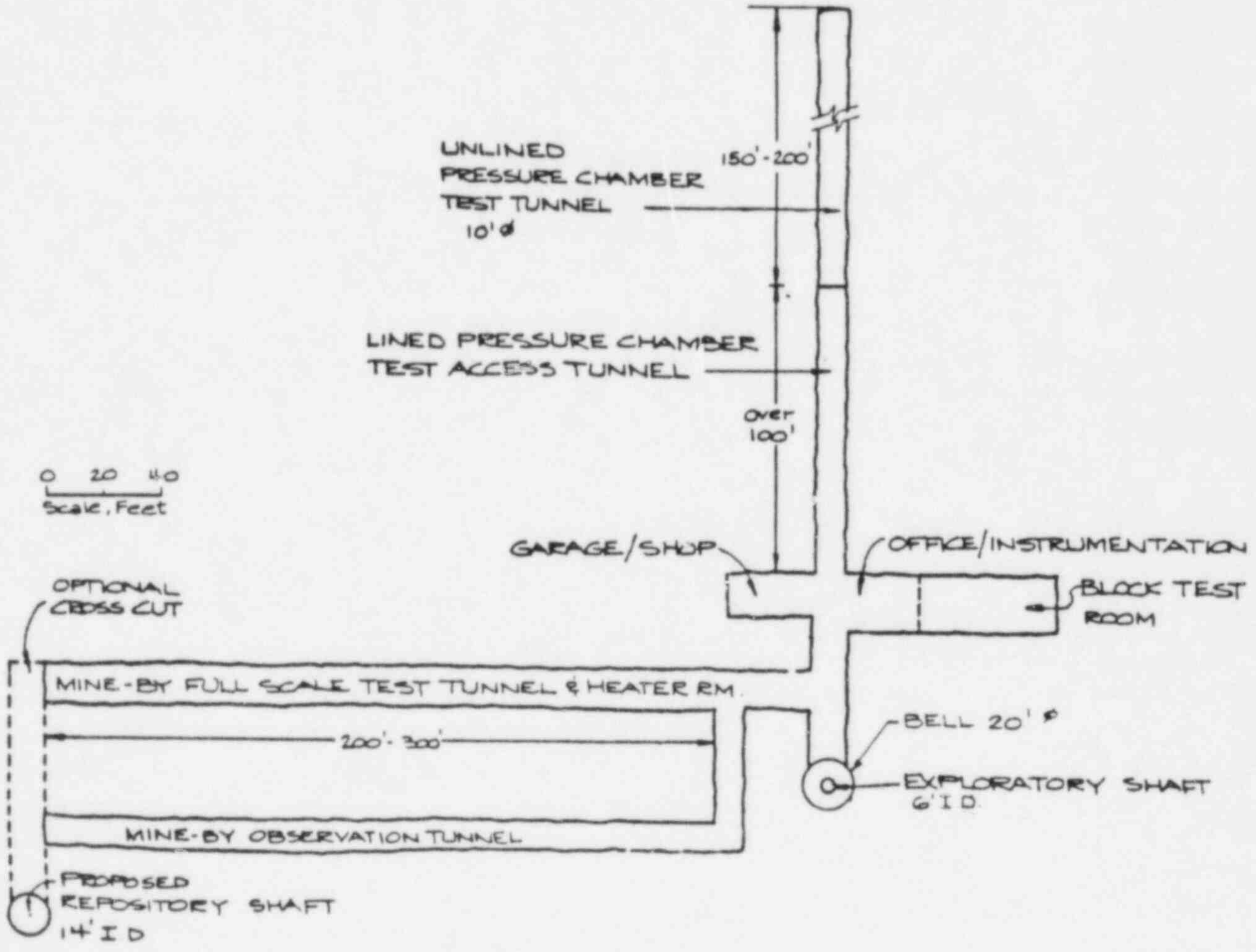
The schedule for the development of the example in situ test facility for basalt has been estimated to be about 66 months, from mobilization to completion of the test program; however, this could possibly be accelerated to about 47 months.

The cost of the example in situ test facility construction, in situ testing, and facility operation has been estimated to be about $60 million, of which $4 million and $19 million have been estimated for testing in the shaft and the underground facility, respectively.

The configuration, schedule and cost of an in situ test facility at other potential repository sites will probably vary from the example developed for basalt at Hanford, Washington. The test program, and corresponding configuration, schedule and costs of an example test facility, have been developed based on presently perceived information needs and test capabilities. Either of these may change with time, so that the in situ test program and facility may also change, and thus should be considered tentative and remain flexible.

EXAMPLE IN SITU TEST FACILITY CONFIGURATION FOR BASALT

Figure 5.1



Notes: 1) This example configuration has been developed to accommodate the example in situ test program for Basalt (see Table 5.3).

2) Repository tunnels not shown.
Mine-by observation tunnel above the test tunnel not shown.

(from Golder, 1982d)

6.0 RECOMMENDED IN SITU TESTING RESEARCH

6.1 INTRODUCTION

Although the tentative media/site specific in situ test programs (see Section 5.2), in conjunction with the recommendations regarding specific in situ tests (see Appendix A of Volume II), provide the best available means for resolving the key issues, there are some remaining limitations. In order to reduce or mitigate these remaining limitations, Golder Associates recommends that research be conducted in three broad areas:

(1) Existing tests
Recommended areas of specific research (especially in monitoring or measurement) in tests already selected (see Appendix A of Volume II).

(2) New or hybrid tests
Research and development of new or hybrid in situ tests which will improve the understanding of fundamental laws and assist in the development and verification of complex coupled predictive models. (An example would be the coupling of thermal effects with bulk modulus properties, as measured in a Plate Test.)

(3) Program integration
Of considerable importance to schedules and cost in construction of a geologic repository is to establish how many, how extensive, where, and when in situ tests should be performed during the process of repository development.

Each of these research topics is discussed in the following subsections. Also, research needs have been previously discussed by others for many areas of rock mechanics (e.g., National Research Council, 1981) and specifically for repository development (e.g., LBL, 1979).

6.2 POTENTIAL IMPROVEMENTS TO EXISTING IN SITU TESTS

6.2.1 Plate Test

The recommendations for research and development regarding the plate test (see Appendix A of Volume II, Section A.1) include:

- Development of improved modeling of the plate test for determination of various deformation parameters
- Development of improved correlations of plate test results with other simple tests

- Modification of the plate test to incorporate variables which affect the deformational characteristics, e.g.:
    - temperature
    - radiation
    - water saturation/pore pressure
    - confining stress
- Development of improved waterproofing of electrical instrumentation and improved corrosion resistance for all equipment
- Development of more sensitive, accurate, and stable electronic deformation monitoring instrumentation, especially for long-term creep tests
- Development of more sensitive, accurate, and stable application of boundary conditions, especially for long-term creep tests
- Development of more accurate determination of boundary conditions
- Elimination of MPBX anchor slippage and stress-induced flowage at the edge of the loaded area, especially in salt.

6.2.2 Block Test

The recommendations for research and development regarding the block test (see Appendix A of Volume II, Section A.2) include:

- Development of improved modeling (i.e., discontinuum) of the block test for determination of various thermal, thermomechanical and mechanical parameters
- Development of improved correlations of block test results with other in situ tests
- Development of improved waterproofing of electrical instrumentation and improved corrosion resistance for all equipment
- Development of more convenient, sensitive, accurate, and stable electronic or optical subsurface deformation/strain monitoring instrumentation, especially for long-term creep tests
- Development of improved joint permeability measurement methods and related analytical models
- Improvement in the methods of stress tensor determination for use in the block test heating phases.

6.2.3 Chamber Test

The recommendations for research and development regarding the chamber test (see Appendix A of Volume II, Section A.3) include:

- Investigation of flow in natural fractures. Statistical methods can possibly be developed to characterize the aperture, orientation, attitude, and persistence of fractures in geologic materials. Such efforts may result in the development of practical, discontinuum numerical models for flow in fractured media.
- Investigation of the relationship between the dimensions of fracturing and the size of a representative elementary volume (REV). This would allow a better assessment of the use of porous media models for describing flow in fractured media.
- Refinement of algorithms for automatic calibration of hydrologic parameters in groundwater models (inverse models)
- Modification of the chamber test to incorporate other variables which affect the hydrologic response of a rock mass:
    - stress environment
    - temperature
    - rock and fracture deformability
    - anisotropy
- Development of improved numerical modeling of the chamber test for determination of various hydrologic, thermal, and deformational parameters.

6.2.4 Mine-by Test

The recommendations for research and development regarding the mine-by test (see Appendix A of Volume II, Section A.4) include:

- Development of a borehole instrument that will provide continuous monitoring of both longitudinal and transverse deformations at 1 m intervals along the borehole
- Development of a borehole instrument that can monitor stress changes in three dimensions
- Development of improved modeling of the mine-by test for determination of various deformational parameters
- Further development of improved correlations of mine-by test results with other simple tests and empirical relations.

6.2.5 Heater Test

The recommendations for research and development regarding heater tests (see Appendix A of Volume II, Section A.5) include:

- Developments to improve sensitivity, reliability, and durability for all instruments which must operate for long periods at high temperatures and under adverse moisture conditions
- Development of numerical modeling techniques to predict rock mass thermomechanical response. An understanding must be achieved of coupled reactions, such as the effects of temperature and stress on the thermal and thermomechanical properties, and heat transfer by conduction and convection in an anisotropic, nonhomogeneous media.
- Development of correlations of the thermal and thermomechanical rock mass parameters derived from the heater tests with those derived from laboratory tests, as well as correlations with those derived from heated block tests.

6.2.6 Tracer Test

The recommendations for research and development regarding tracer tests (see Appendix A of Volume II, Section A.6) include:

- Investigation of solute transport in natural fractures. Statistical methods can possibly be developed to characterize the aperture, orientation, attitude, and continuity of fractures in geologic materials. Such efforts may result in the development of practical, discrete, numerical models of solute transport in fractured media.
- Investigation of the relationship between the dimensions of fracturing and the size of a representative elementary volume (REV). This would allow a better assessment of the use of porous media models for describing solute transport in fractured media.
- Modification of the tracer test methodology and analysis to incorporate other variables (such as temperature, rock and fracture deformability and anisotropy) which affect the hydrologic response of a rock mass
- Development of laboratory techniques for determination of the equilibrium distribution coefficient to verify calculated values from tracer tests
- Investigation to define the variance of a measured value and to determine the relationship of the value measured to the scale of testing.

6.2.7 Multiple Borehole Permeability Test

The recommendations for research and development regarding multiple borehole permeability tests (see Appendix A of Volume II, Section A.7) include:

- Investigation of flow in natural fractures. Statistical methods can possibly be developed to characterize the aperture, orientation, attitude, and persistence of fractures in geologic materials. Such efforts may result in the development of practical discontinuum numerical models for flow in fractured media.
- Investigation of the relationship between the dimensions of fracturing and the size of a representative elementary volume (REV). This would allow a better assessment of the use of porous media models for describing flow in fractured media.
- Refinement of algorithms for automatic calibration of hydrologic parameters in groundwater models (inverse models)
- Modification of the multiple borehole permeability test to incorporate other variables which affect the hydrologic reponse of a rock mass:
    - temperature
    - rock and fracture deformability
    - anisotropy
- Development of improved numerical modeling of the multiple borehole permeability test for determination of various hydrologic, thermal, and deformational parameters.

6.2.8 Overcoring

The recommendations for research and development regarding overcoring (see Appendix A of Volume II, Section A.8) include:

- Improvement of adhesives, i.e., maximizing reliability and strength and minimizing setting time and time-dependent characteristics, for the adverse conditions found in drilling.
- Improvement of present designs of installation devices to make them more convenient to use and more reliable
- Reduction in the cost of in situ measurements. These efforts should include reducing the cost of each measurement, reducing the number of unsuccessful measurements, and reducing the number of successful measurements necessary to establish a local stress field with confidence.

- Improvement of strain gauges and their accuracy. Specifically, some work needs to be performed on eliminating or reducing the effects of temperature, length of electrical cables, or other phenomena which adversely impact the reliability of strain readings. These improvements might easily be effected by manufacturers.
- Continued investigation into methods to improve data reduction and instrument calibration
- Continued improvement in the measurements of the in situ mechanical properties of the rock mass required in analysis
- Development of refined analysis methods for nonlinear or anisotropic rock
- Development of techniques to extend the depth to which in situ stress measurements can be made by overcoring techniques.

6.2.9 Flatjack Test

The recommendations for research and development regarding the flatjack test (see Appendix A of Volume II, Section A.9) include:

- Investigation, possibly coordinated with repository geotechnical investigations, into large scale flatjack testing
- Development of the flatjack test for use deeper in the rock mass
- Continued investigations into numerical and analog techniques for improved interpretation of flatjack measurements.

6.2.10 Acoustic Emission Monitoring

The recommendations for research and development regarding acoustic emission monitoring (see Appendix A of Volume II, Section A.10) include:

- Development of more sensitive seismometers to detect lower amplitude emissions
- Development of telemetry and fiber-optics systems to transmit signals more efficiently from remote seismometers to a central recording station
- Development of more sophisticated analysis techniques for event location and source parameter determination.

6.2.11 Exposure Mapping

The recommendations for research and development regarding exposure mapping (see Appendix A of Volume II, Section A.11) include:

- Development of a standard scratch hardness tester that would apply a constant force to the specimen. This would help eliminate operator variability. The tester would be similar to a pocket penetrometer used for soils, but would have a sharpened tip for scratching the specimen. A standard scratch hardness tester is already available for laboratory use.

- Development of a "full perimeter tunnel camera." This would be similar to a borehole camera, but would simultaneously photograph the crown, walls, and invert of a tunnel.

- Further development of computer methods for storing, analyzing, and plotting geologic information

- Further investigation of statistical analysis of discontinuity characteristics

6.3 DEVELOPMENT OF NEW OR HYBRID TESTS

Some of the available tests selected for resolving the key issues of repository development are aimed at establishing the relationship of a characteristic with the assessment variables. However, in many cases, only a certain range (which is often insufficient) in the assessment variables can be evaluated by any one test presently available. The extension of this range to cover the conditions expected during the repository life should be attempted. For example, the chamber test could be further complicated by the addition of a fluid at a variety of elevated temperatures. This would also enable a further clarification of the laws relating heat and fluid flow. Such research, with similar improvements in modeling of such tests, may be the only way in which model uncertainty in specific site performance evaluations can be adequately reduced. The minimum acceptable level of confidence in satisfactory performance will control whether or not such research is required for a particular site. Stated in another way, research should be carried out at a particular site only if there is a clear benefit in establishing or predicting performance. If justified, R&D may need to be accelerated in order to meet the constraining schedules of repository development.

It is not within the scope of this project to detail research needs under the general heading of improving fundamental knowledge. It is thus only important to establish the areas where, for specific sites, the current knowledge may be unacceptably low. These areas include:

(1) The interaction between heat and fluid transport in a fractured medium, which cannot be adequately characterized by porous flow behavior. This coupling of flow through fractures under a variety of heat loads has been studied in the laboratory, but very little work has been carried out in situ.

(2) The relationship between induced stress and fracture aperture/deformation, and the resulting effect on hydraulic conductivity. This is only partially understood from limited field and laboratory experiments.

(3) The transport of specific radionuclides. The effect of assessment variables (e.g., temperature), in conjunction with the material type and pore fluid composition, on adsorption/retardation of various radionuclides is not well understood. At present, the determination of the equilibrium distribution coefficient (K_d), which dominates repository performance assessment, is very uncertain.

6.4 INTEGRATION OF IN SITU TEST PROGRAM IN REPOSITORY DEVELOPMENT

The integration of the in situ test program in repository development, i.e., number, extent, location, and timing of in situ tests relative to the repository configuration and schedule, is a critical question which demands site specific consideration. This topic has been addressed under Task 4 of this project (Golder Associates, 1982d) (see Section 5.3). Exploration by means of subsurface development, i.e., a system of tunnels (or boreholes) and an access shaft, is a most important step in deciding on whether further investment should be made at a particular site. This decision must be based on the observed variability of the geological setting, as well as on the results of tests and hydrologic and mechanical response of the test facility due to excavation of subsurface openings. The possibility of modular development of the in situ test facility, as well as of the repository, with explicit intermediate decision points, requires further detailed investigation for each potential repository site.

7.0 SUMMARY AND CONCLUSIONS

The Task 2 results include the general recommendation of those tests which should be specifically considered in designing media/site specific in situ test programs. It has been assumed that these tests will be conducted within an in situ test facility, consisting of an exploratory shaft, extending from the surface to the prospective repository horizon possibly with test stations at various depths, and an underground test facility, consisting of appropriate tunnels and test rooms at that horizon. Plans for the program are expected to be presented in the initial SCR submittal and the complete results presented in the license application (LA). The media and sites considered include (1) basalt at Hanford, Washington; (2) tuff at Yucca Mountain, Nevada Test Site; (3) domal salt at specific Gulf Coast sites; (4) bedded salt at an unspecified site; (5) granite at an unspecified site.

A defensible rationale has been developed and utilized to tentatively select available tests to be included in the media/site specific in situ test programs. This rationale essentially consists of:

- Establishing the information needs for construction authorization developed by the time of initial SCR submittal at each site
- Assessing the relevant capabilities of available tests
- Matching the capabilities of specific tests to the perceived information needs at each site.

The information needs at any time result directly from the uncertainties in the prediction of repository system performance, and consist of the additional information needed to adequately demonstrate satisfactory performance. Information needs are determined as follows:

- Establish a licensing perspective, by:
    - developing repository system performance criteria to quantify performance objectives
    - identifying the steps during repository development at which compliance with the criteria must be demonstrated
    - establishing (either implicitly or explicitly) the acceptable level of confidence in satisfactory repository system performance at each step which constitutes adequate demonstration of compliance
- Identify the existing information and assess (either implicitly or explicitly) the associated level of confidence in satisfactory repository system performance
- Compare the assessed level of confidence with the acceptable level (either implicitly or explicitly)

- Determine what additional information, if any, is needed to raise the level of confidence to the acceptable level, by:
    - establishing the sensitivity of system performance to each component of the repository system
    - identifying where the existing information regarding significant components of the system is insufficient and can be efficiently supplemented (i.e., where the existing uncertainty is large, but can be effectively reduced).

The information needs at any time are thus a function of:

- The significance of each component of the repository system (including site characteristics) to system performance
- The existing information related to system performance
- The acceptable level of confidence in satisfactory repository system performance for each licensing step.

Performance assessment (including sensitivity studies) is outside the scope, so that the significance of repository system components has only been qualitatively evaluated and the level of confidence in satisfactory repository system performance, based on existing information, has not been assessed. The existing information for each media/site considered has been summarized herein; descriptions of tuff at NTS and domal salt at specific Gulf Coast sites were generated under Task 1 of this project, whereas descriptions of the other media/sites were derived from previous work. Also, the testing expected to precede in situ testing, and thus supplement the existing information, has been identified. The acceptable level of confidence in satisfactory performance, specifically for construction authorization, has not been explicitly established for each stage of repository development. This acceptable level has in the past, and may continue to be, established implicitly through progressive technical discussions between NRC and DOE (see Preface - Licensing Perspective). In the absence of a specified acceptable level, the information needs for construction authorization cannot be firmly established at this time. Hence, information needs for construction authorization which are perceived to develop by the time of initial SCR submittals at each media/site have been utilized to illustrate the rationale for test selection.

Tests which are available and respond to the specific information needs have been identified, and their capabilities assessed. Specific in situ tests, which might be included in an in situ test program and are especially important or unique, have been investigated in detail. Because design and specifications for each test require prior definition of information needs and a detailed description of each test location, recommendations regarding the conduct of each test and the utilization of test results are of a scoping nature only. Potential advancements to the state-of-the-art have been suggested, and areas pointed out where research and development might improve test capabilities in response to the perceived information needs.

From a comprehensive list of available tests and their relevant capabilities, in situ tests have been identified which adequately respond to the perceived information needs for construction authorization at each media/site considered (Table 5.3). These tests satisfy the information needs either by:

- Simulating various aspects of the repository for extrapolation of results
- Assessing identified media/site specific characteristics to be used in numerical modeling
- Verifying predictive numerical models.

An in situ test facility which can accommodate such reasonable in situ test programs has been developed for basalt at Hanford under Task 4 of this project and summarized here for illustration of program integration.

The actual selection of tests which should be included in a media/site specific in situ test program will be a function of the information needs and test capabilties at that time. Additional information can be expected to be obtained during ongoing or future site investigation prior to initial SCR submittal for some media/sites. Also, new or hybrid tests and modeling techniques, with improved capabilities, can be expected to be developed with time. Hence, it is expected that the in situ test program will evolve somewhat independently with time for each media/site considered as the perceived information needs and test capabilities develop. The program and the design of specific tests must be flexible enough to take into account new information which becomes available during program performance, as presented in SCR updates.

Golder Associates believes that this report presents defensible recommendations, based on currently available knowledge, regarding those in situ tests which should be specifically considered in designing a reasonable in situ test program conducted within an in situ test facility prior to construction authorization at any site. These tests adequately respond to the perceived information needs, and thus sufficiently resolve the key issues related to short-term construction/operation and long-term waste containment/isolation performance (as given in the current drafts of NRC's 10-CFR-60 and EPA's 40-CFR-191), for construction authorization at each media/site.

Although some of the assessments made within the rationale for the tentative selection of these in situ tests are necessarily subjective and the licensing perspective may not be universally shared, the rationale is clearly outlined so that specific areas of technical disagreement can be readily identified and these disagreements (if any) resolved.

Golder Associates thus recommends that the NRC should, accordingly, identify the information needs for each site and then focus on (1) the plans of the in situ test program in their review of an SCR and (2) the results of this program, and the appropriate incorporation of these results in design and performance assessment, in their review of a license application.

GLOSSARY

G.1 GENERAL TERMS

Advancements in State-of-the-Art:	Expanding available concepts or improving available technology.
Characteristic:	Aspect of ground or environment describing repository site, and being either quantitative ("parameter") or qualitative ("factor").
Characterize:	Describe the set of "characteristics," based on testing results or measurement.
Critical Engineering Variable:	"Engineering variable" which has a significant impact on the "level of confidence in satisfactory performance."
Engineering Variable:	Engineering aspect of repository design or construction which can be altered by the engineer (e.g., size, shape, and orientation of underground openings).
Environmental Conditions:	Those conditions which may affect the assessment of a "characteristic," including stress level, pore pressure, temperature and radiation dosage.
Factor:	Nonquantitative "characteristic."
Geologic Setting:	Description of the geometry and boundary/field conditions of the site, as well as the physical (nonresponse) characteristics of the materials. The geometry consists of the stratigraphy/lithology and structure of rock mass units. Boundary/field conditions include the pre-excavation in situ stress field, in situ hydraulic head field and in situ temperature field. The potential changes in the geometry or boundary/field conditions unrelated to repository development (i.e., tectonics) are also part of the geologic setting.
Hydrologic Unit:	Volumes which are relatively homogeneous with respect to hydrologic "response characteristics". Such hydrologic units consist of one or more "rock mass units," and will not necessarily be homogeneous with respect to physical characteristics or other "response characteristics."

(Note: all terms in quotation marks are defined separately herein.)

Information Needs: Additional information needed to improve the "level of confidence in satisfactory performance" to acceptable levels, i.e., sufficiently reduce the uncertainty in predicted repository system performance. The information needs at any time are thus a function of:

- The significance of components of the "repository system" (including site characteristics), with respect to system performance
- The existing information, which determines the "level of confidence in satisfactory performance"
- The "acceptable level of confidence in satisfactory performance".

The information needs can be responded to by:

- Appropriately simulating various aspects of the actual repository (e.g., construction techniques) for extrapolation of results
- Adequately assessing identified media/site specific "characteristics" (e.g., hydraulic conductivity) to be used in predictive numerical modeling
- Sufficiently verifying predictive numerical models.

In Situ Test Facility: Consists of an exploratory shaft (or drift), extending from the surface to the repository horizon possibly with test stations at various depths, and an underground test facility, consisting of appropriate tunnels and test rooms at that horizon. The plans for this facility will be presented in the initial SCR and the complete results presented in the license application.

In Situ Test Program: Consists of a suite of appropriate in situ tests conducted within an "in situ test facility" (after initial SCR submittal and prior to construction authorization) to adequately respond to the "information needs" and thus resolve "key issues," either by simulation or by assessing "significant characteristics" with acceptable uncertainty.

Key Issue: Question, essentially related to short-term construction/operation and long-term waste containment/isolation performance, which influences the design of "critical engineering variables" and which must be adequately resolved to demonstrate compliance with "repository performance criteria."

Level of Confidence in Satisfactory Performance: Probability that the repository system performance will comply with the "performance criteria". This probability is based on the "performance assessment."

Acceptable Level of Confidence in Satisfactory Performance: Required "level of confidence in satisfactory performance" which must be demonstrated at each "stage" for "repository development" to proceed. The acceptable "level of confidence in satisfactory performance" should increase during "repository development" from L_1 at the time of initial submittal of the Site Characterization Report, to L_2 at the time of construction authorization, to L_3 at the time of issuing the license to emplace waste, to L_4 at the time of decommissioning. Thus, $L_4>L_3>L_2>L_1$.

New or Hybrid Test: A test which incorporates new concepts or combines available concepts in a significant manner, as opposed to simply expanding avalable concepts or improving technology.

Parameter: Quantitative "characteristic."

Performance Assessment: The prediction of various aspects of performance, i.e., the determination, either explicitly or implicitly, of a probability distribution for a given performance indicator (X). For example, X might be the radionuclide release rate at some specific location.

Performance Criteria: Technical requirements or performance standards which quantify short-term construction/operation and long-term waste containment/isolation performance objectives. These criteria are given either:

- Deterministically, in which an absolute numerical limit (Xc) for each quantitative performance indicator (X) is specified, so that (if small X is good) X must be less than Xc for compliance.

- Probabilistically, in which an acceptable level of confidence (Lc) that the numerical limit (Xc) will not be exceeded by the actual value of the quantitative performance indicator (X) is specified, so that the probability of (X<Xc), o P(X<Xc), must be greater than Lc f compliance.

Repository Development: The process of proceeding through the various "stages" of repository life from site screenin selection to decommissioning.

Repository System: Consists of all components which contribute to performance, i.e., the site characteristics and engineered components.

Response Characteristics: "Parameters" which describe the response or behavior (i.e., mechanical, thermal, hydrologic and/or geochemical) of a volume of material. These "characteristics" are strongly related to the physical characteristics of the material, and also may be:

- Anisotropic (i.e., vary with orientation)
- Scale-dependent (i.e., vary with the scale)
- Time-dependent (i.e., vary over time)
- A function of the present and past environmental conditions, including
  - stress level
  - pore pressure
  - temperature
  - radiation dose.

Rock Mass Unit: Volume of rock which is relatively homogeneous with respect to its physical characteristics (i.e., intact rock, discontinuities, and pore fluid). Boundaries of rock mass units can be defined by changes in lithology, structure (i.e., large faults or changes in discontinuity patterns), or pore fluid. Due to this relative homogeneity, the "response characteristics" (or their functions) are relatively constant throughout each unit. However, each rock mass unit is only approximately homogeneous, that there is some variability in physical characteristics throughout the unit and some resulting variability in "response characteristics" as measured from point to point.

Scale: Dimensional aspects of a repository, as follows (in increasing size order):

- Waste package (very near field)
- Room (near field)
- Repository (3 sq mi underground)
- Site (10 sq mi) (far field)
- Location (30 sq mi)
- Area (1000 sq mi)
- Basin
- Region (multi-state)
- Nation (U.S.).

Significant Characteristic: "Characteristic" which has a significant impact on the resolution of "key issues," and thus influences design of "critical engineering variables." These "characteristics", in conjunction with the engineered components, will determine repository system performance.

Site Characterization: The program of exploration and research, both in the laboratory and in the field, undertaken to establish the "characteristics" of a particular site. Site characterization includes borings, surface excavations, excavation of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing at depth needed to determine the suitability of the site for a geologic repository, but does not include preliminary borings and geophysical testing needed to decide whether site characterization should be undertaken.

Site Investigation: The program of exploration, both in the laboratory and in the field (e.g., preliminary borings and geophysical testing) conducted during site screening and selection, prior to SCR submittal.

Stage: Distinct period of activity during repository life, as follows (in chronological order):

- Site screening
- Site selection
- Detailed site investigation (followed by initial submittal of SCR)
- In situ testing and repository design
- Repository construction (preceded by license application and construction authorization)
- Repository operation (preceded by updated license application and operating license)
- Waste retrieval (if required)
- Decommissioning (preceded by license amendment and decommissioning authorization)
- Post-decommissioning.

G.2 COMMON ROCK MASS RESPONSE CHARACTERISTICS

Various parameters (i.e., quantifiable response characteristics) are used to describe the mechanical, thermal, thermomechanical, hydrologic, and geochemical response of a rock mass. Each of the common response characteristics discussed in this report (see Table G-1) is briefly defined in the following sections. Other less common characteristics are defined as they are used in the report.

G.2.1 MECHANICAL

Young's Modulus

Young's modulus, or modulus of elasticity, E, is defined as the ratio of the change in stress to the corresponding strain increment (in uniaxial compression or tension), for linear elastic behavior of the material:

$$E = \frac{\Delta \sigma x}{\Delta \epsilon x} \quad (ML^{-1}\ T^{-2})$$

where

$\Delta \sigma x$ = stress change $(ML^{-1}\ T^{-2})$
$\Delta \epsilon x$ = strain change (dimensionless)

Young's modulus, in conjunction with one other elastic parameter (typically Poisson's ratio), describes the elastic behavior of an isotropic material.

Deformations within rock masses, however, typically consist of a combination of elastic and inelastic behavior, and may be nonlinear. The term "deformation modulus" (analogous to Young's modulus) is often used to describe the elastic/inelastic, as well as nonlinear, behavior of rock masses.

These moduli are often anisotropic and scale dependent. Their values often vary with stress history, stress level, strain rate, temperature and possibly radiation dosage.

Poisson's Ratio

Poisson's ratio, ν, is defined as the negative ratio of lateral strain to axial strain produced by an applied axial load, for elastic behavior of the material:

$$\nu = \frac{\Delta \epsilon_L}{\Delta \epsilon_A} \quad \text{(dimensionless)}$$

where

$\Delta \epsilon_L$ = lateral strain (dimensionless)
$\Delta \epsilon_A$ = axial strain (dimensionless)

Poisson's ratio, in conjunction with one other elastic parameter (typically Young's modulus), describes the elastic behavior of an

COMMON ROCK MASS RESPONSE CHARACTERISTICS

Table G-1
1 of 2

	RESPONSE CHARACTERISTIC	COMMON SYMBOL	DIMENSIONS	COMMON UNITS
Mechanical				
	Young's Modulus	E	$ML^{-1}T^{-2}$	psi, MPa
	Poisson's Ratio	ν	(dimensionless)	-
	Creep	-	T^{-1}	hr^{-1}
	Strength	-	$ML^{-1}T^{-2}$	psi, MPa
	Joint Normal Stiffness	K_n	$ML^{-2}T^{-2}$	MPa/mm
	Joint Shear Stiffness	K_s	$ML^{-2}T^{-2}$	MPa/mm
Thermal				
	Thermal Conductivity	K	$MLT^{-3}Te^{-1}$	Watt/meter ^oC
	Mass Heat Capacity	C_m	$L^2T^{-2}Te^{-1}$	Calorie/gm ^oC
	Volumetric Heat Capacity	C_v	$ML^{-1}T^{-2}Te^{-1}$	Calorie/cm^3 ^oC
	Specific Heat	C_p	(dimensionless)	-
	Thermal Diffusivity	κ	L^2T^{-1}	cm^2/sec
Thermo-Mechanical				
	Coefficient of Thermal Expansion:			
	linear	α	Te^{-1}	$^oF^{-1}$, $^oC^{-1}$
	volumetric	β	Te^{-1}	$^oF^{-1}$, $^oC^{-1}$
Hydrologic				
	Hydraulic Conductivity	K	LT^{-1}	fps, cm/sec
	Intrinsic Permeability	k	L^2	cm^2
	Specific Storage	S_s	L^{-1}	cm^{-1}
	Effective Porosity	n_e	(dimensionless)	-

COMMON ROCK MASS RESPONSE CHARACTERISTICS

Table G-1
2 of 2

	RESPONSE CHARACTERISTIC	COMMON SYMBOL	DIMENSIONS	COMMON UNITS
Geochemical				
	Dispersivity	a	L	cm
	Equilibrium Distribution Coefficient	K_d	L^3M^{-1}	ml/gm
	Sorption Ratio	R_d	L^3M^{-1}	ml/gm
	Retardation Factor	R	(dimensionless)	-

Key: M = mass
L = length
T = time
Te = temperature

isotropic material. Poisson's ratio is also often used to describe the typical elastic/inelastic, as well as non-linear, behavior of rock masses.

Poisson's ratio may be anisotropic and scale dependent. In addition, the value may vary with stress level, temperature, strain rate, and possibly radiation dosage.

Creep Parameters

Creep parameters express the viscous behavior of a material i.e., the strain which occurs with time at constant stress or the stress relaxation which occurs with time and no deformation. There is presently no well-accepted formulation for creep behavior in all media. However, the following characteristics are sometimes exhibited under constant stress conditions (see Figure G-1):

- Primary creep, in which initial creep strain occurs at a decreasing rate with time, and unloading produces complete strain recovery
- Secondary creep, in which the creep strain approaches a steady state (i.e., constant creep rate) and unloading does not result in complete strain recovery (i.e., permanent set); secondary creep is exhibited only at relatively high stress levels
- Tertiary creep, in which the creep strains become very large and the rate of strain increases to rupture; tertiary creep occurs only at stress levels approaching the strength of the material.

Creep behavior is often anisotropic and scale dependent. In addition, the behavior is often a function of stress level, temperature, and possibly radiation dosage.

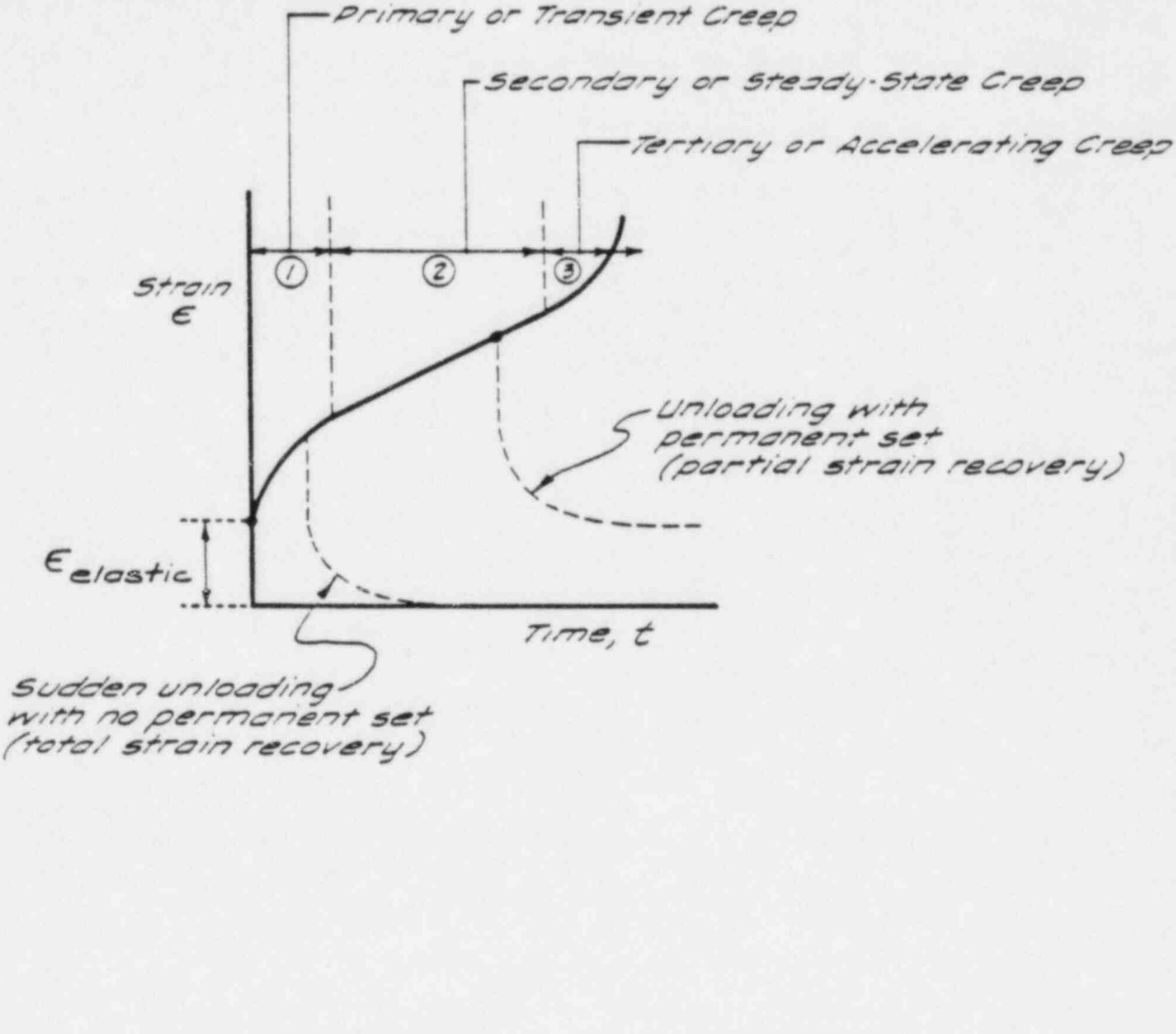
Strength

The strength of a material expresses the limiting state of stress ($ML^{-1} T^{-2}$) at which failure occurs. In this sense, failure consists of fracturing or sliding along existing discontinuities in brittle material, or of large deformations in ductile material. In brittle material, peak and residual strengths may be defined, where peak strength is the maximum stress state (at which failure occurs) and residual strength is the post-peak steady-state (i.e., frictional) stress state (see Figure G-2).

A strength criterion for a material can be defined as a unique combination of stress parameters which define the boundary (surface) between stable and unstable conditions. Strength is termed tensile strength, compressive strength, or shear strength depending on the loading and constraint conditions.

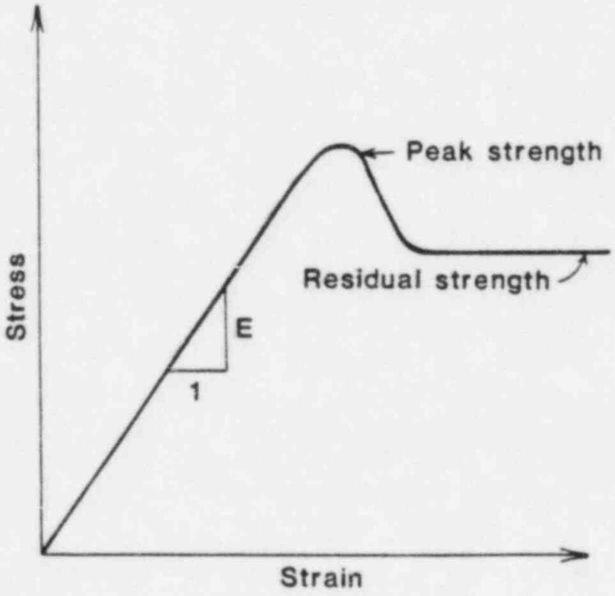
IDEALIZED CREEP CURVE AND STRAIN RECOVERY FOR A ROCK MATERIAL

Figure G-1



STRENGTH OF A BRITTLE MATERIAL

Figure G-2



Rev. ____
Dwg. No. 813-4638 A6002 Date 1-82 Eng. KW

Strength is often anisotropic and scale dependent, especially in discontinuous media. In addition, due to its partly frictional nature, strength is strongly a function of confining stress, as well as temperature, stress history, strain rate, pore pressure, and possibly radiation dosage.

Joint Normal Stiffness

The joint normal stiffness, K_n, is defined as the normal displacement across the joint caused by a unit change in stress normal to the joint. The joint normal stiffness is a function of the stress level, stress history, strain rate and temperature.

Joint Shear Stiffness

The joint shear stiffness, K_s, is defined as the relative shear displacement along the joint caused by a unit change in shear stress parallel to the joint. The joint shear stiffness is a function of the stress level, stress history, strain rate and temperature.

G.2.2 THERMAL

Thermal Conductivity

The coefficient of thermal conductivity, K, is defined as the rate of heat transferred by conduction per unit area normal to the direction of heat flow per unit thermal gradient in the direction of heat flow, under steady-state conditions:

$$K = \frac{Q}{At} \left(\frac{\delta T}{\delta x}\right)^{-1} \quad (MLT^{-3}\ Te^{-1})$$

where

Q = amount of heat energy ($ML^2\ T^{-2}$)
A = cross-sectional area normal to flow (L^2)
t = time of flow (T)
$\frac{\delta T}{\delta x}$ = thermal gradient, or change in temperature per unit length in the x-direction (TeL^{-1})

Thermal conductivity may be anisotropic and scale dependent. It may vary with temperature, state of stress, and pore fluid composition.

Mass Heat Capacity

The mass heat capacity, C_m, is defined as the amount of heat energy necessary to change the temperature of a unit mass of material by one degree:

$$C_m = \frac{Q}{m \Delta T} \quad (L^2\ T^{-2}\ Te^{-1})$$

$$= \frac{C_v}{\rho_d}$$

where

Q = amount of heat energy ($ML^2\ T^{-2}$)
m = mass of material (M)
ΔT = change in temperature (T_e)
δ_d = dry density of material (ML^{-3})
C_v = volumetric heat capacity ($ML^{-1}\ T^{-2}\ Te^{-1}$)

The mass heat capacity, in conjunction with thermal conductivity, is needed to describe transient heat flow.

The mass heat capacity may be scale dependent. It may vary with temperature, state of stress, and pore fluid composition.

Volumetric Heat Capacity

The volumetric heat capacity, C_v, is defined as the amount of heat energy necessary to change the temperature of a unit volume of material by one degree:

$$C_v = \frac{Q}{V \Delta T} \quad (ML^{-1}\ T^{-2}\ Te^{-1})$$

$$= C_m \rho_d$$

where

Q = amount of heat energy ($ML^2\ T^{-2}$)
V = volume of material (L^3)
ΔT = change in temperature (T_e)
ρ_d = dry density of material (ML^{-3})
C_m = mass heat capacity ($L^2\ T^{-2}\ Te^{-1}$)

The volumetric heat capacity, in conjunction with thermal conductivity, can be used to express transient heat flow.

The volumetric heat capacity may be scale dependent. It may vary with temperature, state of stress, and pore fluid composition.

Specific Heat

Specific heat, C_p, expresses the ratio of the mass heat capacity of a material to that of water. The specific heat, in conjunction with thermal conductivity, can be used to express transient heat flow.

Specific heat may be scale dependent. It may vary with temperature, state of stress, and pore fluid composition.

Thermal Diffusivity

Thermal diffusivity, κ, expresses the rate at which a change in temperature spreads by conduction for one-dimensional transient heating.

It is related to thermal conductivity and volumetric heat capacity as follows:

$$\kappa_x = \frac{K_x}{C_v} \; (L^2 \; T^{-1})$$

where

K_x = thermal conductivity in the x-direction ($MLT^{-3}\;Te^{-1}$)
C_v = volumetric heat capacity ($ML^{-1}\;T^{-2}\;Te^{-1}$)

Thermal diffusivity may be anisotropic and scale dependent. It may vary with temperature, state of stress, and pore fluid composition.

G.2.3 THERMOMECHANICAL

Coefficient of Thermal Expansion

The coefficient of thermal expansion defines the change in length (linear coefficient), area (surficial coefficient), or volume (volumetric coefficient) of a body per unit length, area or volume, for a given change in temperature ΔT:

$$\alpha = \frac{\Delta L}{L\Delta T} \; (Te^{-1})$$

where α = coefficient of linear thermal expansion,

and

$$\beta = \frac{\Delta V}{V\Delta T} \; (Te^{-1})$$

where β = coefficient of volumetric thermal expansion.

In isotropic materials the coefficient of volumetric thermal expansion is approximately three times the coefficient of linear thermal expansion:

$$\beta = 3\alpha$$

The coefficient of linear thermal expansion may be anisotropic and scale dependent. It may vary with temperature, stress level, pore fluid composition, and possibly radiation dosage.

G.2.4 HYDROLOGIC

Hydraulic Conductivity

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

$$K_i = q_i \left(\frac{\delta h}{\delta x_i}\right)^{-1} (LT^{-1})$$

where

i = 1,2,3 refers to the principal coordinate axes
q_i = Darcy velocity in the i direction (LT^{-1})
$\frac{\delta h}{\delta x_i}$ = hydraulic gradient, or rate of change in hydraulic head per unit length, in the i direction (dimensionless)
K_i = principal hydraulic conductivity in the i direction (LT^{-1})

The hydraulic head, h, at any point (x,y,z) can be expressed as:

$$h\ (x,y,z) = E(z) + \frac{p(x,y,z)}{\rho g} \quad (L)$$

where

E = elevation above an arbitrary datum (L)
p = pore pressure ($ML^{-1}\ T^{-2}$)
g = acceleration of gravity (LT^{-2})
ρ = pore fluid density (ML^{-3}).

Hydraulic conductivity may also be defined in terms of the properties of the porous medium and the pore fluid:

$$K = \frac{k\rho g}{\mu} (LT^{-1})$$

where

k = intrinsic permeability of the porous medium (L^2)
μ = pore fluid dynamic viscosity ($ML^{-1}\ T^{-1}$)

The pore fluid density and viscosity depend on the pore fluid composition and vary with temperature.

Hydraulic conductivity may be anisotropic and scale dependent. It may vary with temperature, state of stress and pore fluid composition.

Intrinsic Permeability

Intrinsic permeabiliy, k, is a characteristic property of the porous medium. It is related to the hydraulic conductivity by the pore fluid properties:

$$k = \frac{K\mu}{\rho g} \ (L^2)$$

where

K = hydraulic conductivity (LT^{-1})
μ = pore fluid dynamic viscosity ($ML^{-1}\ T^{-1}$)
ρ = pore fluid density (ML^{-3})
g = acceleration of gravity (LT^{-2})

Intrinsic permeability may be anisotropic and scale dependent, and may vary with temperature and stress level.

Specific Storage

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

$$S_s = (nB+a)\rho g \quad (L^{-1})$$

where

n = total porosity, or the ratio of the volume of void space in the rock to the total volume (dimensionless)
B = compressibility of the pore fluid ($LT^2 M^{-1}$)
a = compressibility of the rock matrix, or the change in volume of the rock matrix per unit volume of the porous medium ($LT^2 M^{-1}$)
ρ = pore fluid density (ML^{-3})
g = acceleration of gravity (LT^{-2})

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

Specific storage may be scale dependent and may vary with temperature, stress level, and pore fluid composition.

Effective Porosity

Effective porosity, n_e, is defined as the ratio of void space through which fluid moves (i.e., interconnected voids) to the total volume. It is thus approximately equal to the ratio of the Darcy velocity to the true average pore fluid velocity:

$$n_e = \frac{q}{V} \qquad \text{(dimensionless)}$$

$$= \frac{K\left(\frac{\delta h}{\delta x}\right)}{V}$$

where

q = Darcy velocity in the x direction (LT^{-1})
V = true average pore fluid velocity (LT^{-1})
K = hydraulic conductivity in the x direction (LT^{-1})
$\frac{\delta h}{\delta x}$ = hydraulic gradient in the x direction (dimensionless)

The effective porosity is less than or equal to the total porosity. In fractured media, effective porosity may be much less than the total porosity because the majority of flow may occur through a relatively small number of fractures.

G.2.5 GEOCHEMICAL

Dispersivity

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

Dispersivity, a (the measure of dispersion), is a length property of the medium and is strongly dependent on the scale of the flow region under investigation. Values can range from 10^{-2} cm in laboratory tests to 10^{4} cm for regional systems. At the laboratory scale it is a consequence of the tortuosity of the medium pore space, velocity gradients in the pore spaces, and variations in the pore space dimensions. At the regional scale it is primarily due to the divergence of flow paths resulting from heterogeneities in aquifer properties, particularly hydraulic conductivity.

Dispersivity is anisotropic and is described by a lateral dispersion coefficient (perpendicular to the flow direction) and a longitudinal dispersion coefficient (in the direction of flow). The longitudinal dispersion coefficient is typically 5 to 20 times as large as the lateral dispersion coefficient.

Equilibrium Distribution Coefficient

For low to moderate solute concentrations, the mass of adsorbed solute per unit dry bulk mass of the medium and the mass of dissolved solute per unit volume of pore fluid are commonly related by the expression:

$$S = K_d C^b \text{ (dimensionless)}$$

where

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

C = solute concentration, or mass of dissolved solute per unit volume of pore fluid (ML^{-3})

K_d and b are determined experimentally and depend on the solute species and the geochemical character of the system. This relationship is known as the Freundlich isotherm. If b=1, then

$$K_d = S/C \quad (L^3\ M^{-1})$$

is a linear isotherm and K_d is known as the equilibrium distribution coefficient.

Equilibrium distribution coefficients are normally measured in the laboratory by batch or column tests. In these tests, a contaminant solution of known concentration is mixed with powdered rock (batch test) or circulated through a column of crushed rock (column test). When chemical equilibrium is achieved, the change in dissolved solute concentration is used to calculate the amount of solute adsorbed by the rock. In many tests the reaction rates are so slow that equilibrium conditions cannot be verified at the end of the test. In these cases, the calculated ratio S/C is called the sorption ratio, R . Measured sorption ratios are thus less than or equal to the equilibrium distribution coefficient.

Sorption Ratio

The sorption ratio, R_d, is the mass of adsorbed solute per unit dry bulk mass of the porous medium divided by the solute concentration of the pore fluid:

$$R_d = S/C \quad (L^3\ M^{-1})$$

where

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

C = solute concentration, or mass of dissolved solute per unit volume of pore fluid (ML^{-3})

For solutes which have linear adsorption isotherms, the sorption ratio under equilibrium conditions is equivalent to the equilibrium distribution coefficient.

Retardation Factor

The retardation of the front of a reactive solute relative to the bulk mass of groundwater is described by the retardation factor R:

$$R = 1 + \frac{\rho_b}{n} K_d = \frac{\bar{V}}{\bar{V}_c} \quad \text{(dimensionless)}$$

where

ρ_b = bulk density of the porous medium (ML^{-3})

n = total porosity (dimensionless)

K_d = equilibrium distribution coefficient ($L^3\ M^{-1}$)

$\bar{V}$ = average linear velocity of the groundwater (LT^{-1})

$\bar{V}_c$ = velocity of the ($C/Co = 0.5$) point on the concentration profile of the reactive solute (LT^{-1})

This relationship holds for fast reversible adsorption with linear isotherm ($S = K_dC$).

G.3 COMMON INSTRUMENTATION USED FOR IN SITU TESTING

In situ tests generally require the measurement of some of the following responses:

- Strain and displacement
- Stress (absolute and changes)
- Temperature
- Groundwater pressure

These responses are typically measured at discrete points by instrumentation and interpolations or extrapolations made to determine the complete response field. Many of the in situ tests described in the Appendix utilize the same instrumentation. The instrumentation that is common to several tests is described in this section of the Glossary. Two references have been used extensively for this section of the Glossary: Cording et al (1975) and IECO (1979).

G.3.1 STRAIN AND DISPLACEMENT

Strain or displacement in the rock mass can be measured by a variety of methods (see Table G-2), either within boreholes or on the exposed surface. Although the results are usually referenced to a discrete point in the rock mass, measurement of strain and displacement occurs over a finite length. Borehole extensometers measure displacements that are parallel to the axis of the borehole (i.e., longitudinal measurements), whereas deflectometers and inclinometers measure displacements that are transverse to the axis of the borehole. Strain gauges, which measure strain based on changes in electrical resistance, frequency of vibration, or electrical inductance, are often used as components in other instrumentation systems (including extensometers, inclinometers, deflectometers, load cells, stress cells, and piezometers).

Borehole Extensometers

Borehole extensometers consist of one or more anchors at various depths in the borehole and a reference head at the borehole collar (see Figure G-3). Units with a single anchor are called Single Position Borehole Extensometers or SPBX's; those with two anchors are called Double Position Extensometers, or DPBXs; those with more than two anchors are termed Multiple Position Extensometers, or MPBX's. The anchors in the borehole are connected to the reference head by steel rods or tubes in the rod type (see Figure G-3a), and by tensioned wires in the wire type (see Figure G-3b). A deformation sensor, such as a micrometer or strain gauge, is inserted between the ends of the rods or wires and the reference head so that relative movements between the anchors and reference head can be measured. Typical accuracies for rod units are of the order of ±0.002 in. over lengths of up to 100 ft. Relative displacements between anchors can be obtained since all the displacements are related to a common reference. If the bottom anchor is positioned outside the zone of movement, then that anchor can be considered fixed and absolute displacements of each anchor can be assessed.

Rev. ________
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SUMMARY OF STRAIN AND DISPLACEMENT MONITORING INSTRUMENTATION

Table G-2
1 of 3

INSTRUMENT	RANGE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	RELIABILITY	ESTIMATED COST (1982 U.S. DOLLARS)		
						ACQUISITION	INSTALLATION	CALIBRATION
LONGITUDINAL MOVEMENT IN BOREHOLES								
(BOREHOLE EXTENSOMETERS)								
Rod type extensometer		± 0.001 to ± 0.005 inches	Simple and precise. Multiple anchors possible. Can also accept remote readout transducers.		Good	$10,000*	$560	$140
Variable tension wire type extensometer	0.6 in. up to 3.5 in. Some can be reset	± 0.002 to ± 0.005 inches	Multiple anchors - up to 6 or 8. Some models designed for remote readings with transducers using bonded resistance or vibrating-wire strain gauges.	Variable tension requires varying calibration factors. Wire friction and hysteresis can seriously affect accuracy. Risk of electrical failure.	Fair - Short term	$6,000*	$560	$140
Constant tension wire type extensometer	2 in, can be reset	± 0.002 to ± 0.005 inches	Multiple anchors. Designed for remote readings using potentiometers. Constant calibration factor.	Wire friction and hysteresis can seriously affect accuracy. Risk of electrical failure. Complex mechanically.	Fair - Short term	$6,000*	$560	$140
TRANVERSE MOVEMENT IN BOREHOLES								
(INCLINOMETERS)								
Fixed multipoint borehole inclinometers		± 0.001 in. per 10 feet	Precise, removable for repairs or reuse. Uses standard inclinometer casing.	Complex, does not measure continuous profile. Accuracy lost when removed and replaced.		$13,000	$840	$210
Portable borehole inclinometers	± 12° optional to ± 25°	± 1 in. in 30 to 1000 ft.	Long experience record. Not sensitive to temperature.	Lengthy calculations. Reads one axis at a time. No provisions for automatic readout.	Good	$2,000	$840	$280

* For 30 m. borehole

Rev. ______

Dwg. No. 813-1638 40028 Date 1-82 Eng. wk

SUMMARY OF STRAIN AND DISPLACEMENT MONITORING INSTRUMENTATION

Table G-2
2 of 3

INSTRUMENT	RANGE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	RELIABILITY	ESTIMATED COST (1982 U.S. DOLLARS)		
						ACQUISITION*	INSTALLATION	CALIBRATION
(DEFLECTOMETERS)								
Fixed multi-point borehole deflectometers		± 20 arc sec. (Total displacement accuracy depends on pivot spacing).	Portable version available and double pivot version available to measure movement along two axes.	Complex, does not measure continuous profile.	Good	$13,000	$ 840	$ 210
TRANSVERSE AND LONGITUDINAL MOVEMENT IN BOREHOLES								
Iseth Extnso - Deflectometer	13 mm/m 17 mm/m	± 0.01 mm/m-longitudinal ± 0.03 mm/m-transverse	Rapid use. Precise.	Limited experience. Special casing needed. May not have enough range in areas of high strain. No remote readout possible.		$30,000-$40,000	$1,400	$700
TUNNEL CONVERGENCE								
(PORTABLE EXTENSOMETERS)								
Portable rod extensometer	3 to 25 feet	± 0.001 to ± 0.01 inches	Simple, precise, portable.	Limited span, accuracy limited by sag. Invar tubes can be used to minimize temperature corrections.	Excellent	$2,000	$35**	$10
Tape extensometer	2 to 200 feet	± 0.001 to ± 0.01 inches	Simple, precise, portable. Good for measuring tunnel diameter changes.	Accuracy limited by tension adjustment. Temperature correction required.	Excellent	$1,500	$35**	$10

** Per reference point

Rev.
Dwg. No. 8/1-1638 46021 Date 1-82 Eng.

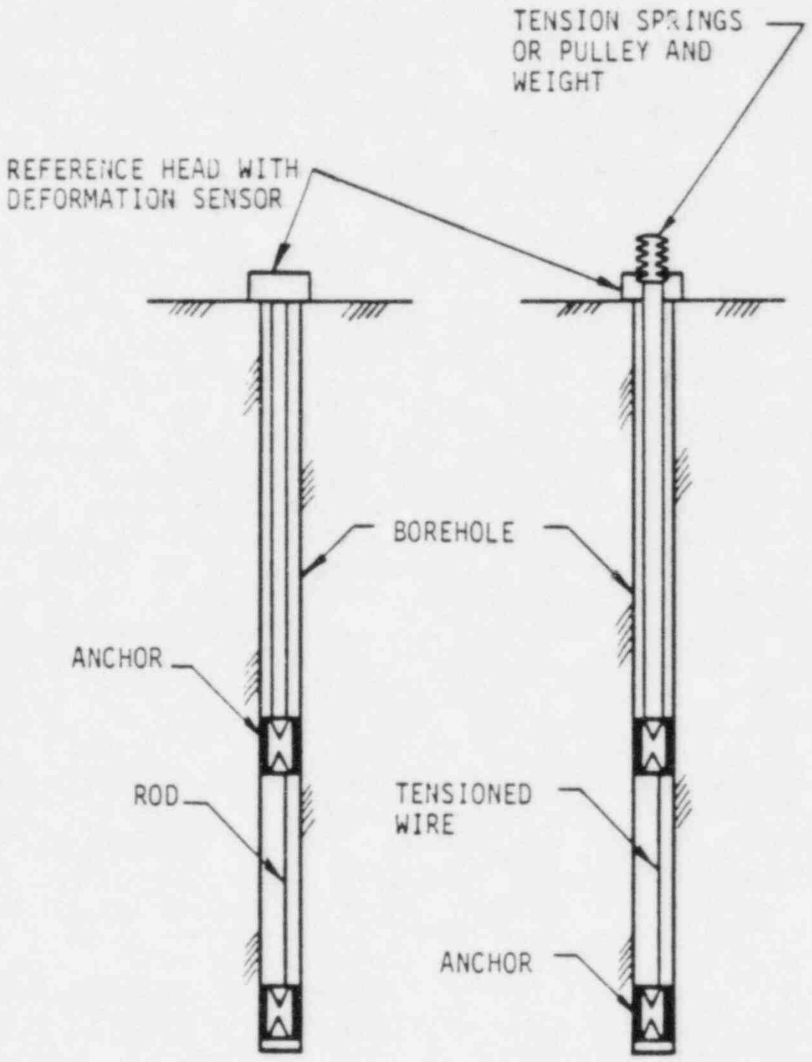
Table G-2
3 of 3

SUMMARY OF STRAIN AND DISPLACEMENT MONITORING INSTRUMENTATION

INSTRUMENT	STRAIN SENSITIVITY, MICROSTRAINS	GAGE LENGTH, INCHES	TYPICAL RANGE, MICROSTRAINS	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	RELIABILITY	ESTIMATED COSTS (1982 U.S. DOLLARS)		
							ACQUI-SITION	INSTALL-ATION	CALI-BRATION
SMALL SCALE STRAIN/DISPLACEMENT									
(RESISTANCE STRAIN GAUGES)									
Bonded electrical resistance gauge	2-4	.008-6	20,000 - 50,000	Small size, low cost. Temperature compensation available.	Errors due to lead wire and circuit resistance changes unless compensated. Long term stability may be poor due to cement creep. Meticulous installation procedure. Difficult to waterproof.	Poor - Fair	$5	$70	$35
Encapsulated, unbonded, electrical resistance (Carlson gauge)	4	8 - 20	700 tension, 1400 compression	Factory waterproofing, easy to install. Long experience record.	Errors due to lead wire and circuit resistance changes unless compensated. Small range. Temperature correction required.	Good			
(VIBRATING-WIRE STRAIN GAUGE)									
Vibrating- wire gauge	1-2	4 - 14	600 - 7,000	Not affected by lead wire resistance changes. Easy to install, factory waterproofing. Long experience record. Robust, reusable. Good long-term stability.	Small range. Temperature correction required.	Good	$35	$70	$10
(LINEAR DISPLACEMENT TRANSDUCERS)									
Linear Potentiometers	0.25-0.025 mm		1 - 60 cm	Easy to install. Direct remote readout.	Difficult to seal against moisture. Low sensitivity.		$50	$70	$35
DCDT/LVDT	10		1 - 60 cm	Little friction between components. Easy to install. Direct remote readout.			$50	$70	$35
(MECHANICAL STRAIN GAUGES)									
Mechanical Gauge	5-10	2-80	10,000 - 50,000	Simple, low cost, waterproofing not required. Removeable.	Requires skill in reading. Can not be read remotely.	Excellent	$450	$35	$35

BOREHOLE EXTENSOMETERS

Figure G-3



(a) ROD TYPE (b) WIRE TYPE

after Cording et al, 1975

Rev. ______
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Rod or wire extensometers are available that can use up to 8 anchor positions in a 76 mm diameter or smaller borehole. The deformation sensors can be mechanical (micrometer or dial gauge) or electrical (DCDT, linear potentiometer, vibrating-wire strain gauge, sonic pulse, or resistance strain gauge). The mechanical readouts are usually removed from the reference head between readings.

The type of anchor used depends on the characteristics of the material being monitored. Grouted anchors, using expansive grout or polyester resin, are the most reliable and are particularly useful in weak rock or rock that tends to creep (see Figure G-4). Mechanical expansion shell anchors or rock bolt anchors can be used in most sound rock. Spring-loaded wedge types and a hydraulically activated prong-type are also available. If any doubt exists on the ability of a particular anchor type to function adequately in a given material, lab or field tests should be conducted to test for slippage and adequate anchor strength.

In wire-type units, the wires are usually encased in a flexible, oil-filled, PVC tube for protection. At the level of each anchor, a special joint is placed and one wire is tied off to a washer at that point. The other wires pass through separate guide holes in the washer and extend to the deeper anchor points. The area between the tubing and borehole wall is fully grouted, thus anchoring the unit. The tubing must be strong enough to withstand the grout pressures, otherwise it may collapse and jam the extensometer rods or wires. The grout is relatively weak and moves with the rock, thereby displacing the anchor assembly. For the rod-type units, the rods are usually protected by individual PVC tubes down to the anchor position where a portion of one of the rods (or an extension consisting of a rebar or grooved anchor to improve bonding to the grout) is exposed. The borehole is then fully grouted.

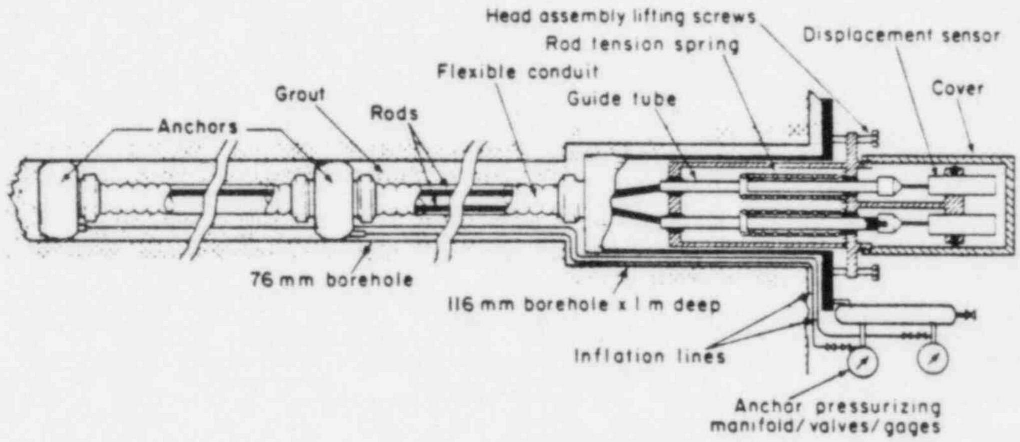
The wire extensometers may be used in boreholes that are less than 6 to 9 m deep. The friction between wires may result in large error in boreholes deeper than about 9 m. Rod extensometers are superior for deep boreholes because friction introduces much less error and the reliability of the anchor can be more easily tested.

Changes in temperature can produce significant errors in both rod and wire-type extensometers. If significant temperature changes are anticipated during the test, it may be necessary to install temperature sensors along the length of the extensometer so that temperature corrections can be applied. The use of super invar rods will reduce, but not eliminate, error due to temperature changes. Shown below are some coefficients of thermal expansion for some of the materials that are typically used in borehole extensometers:

Material	Coefficient of Thermal Expansion (in microstrains/°C)
Stainless steel	17.8
Mild steel	11.8
Aluminum	23.1
Super invar	0.36 to 1.0

TWO-ANCHOR EXTENSOMETER

Figure G-4



after Cording et al, 1975

Rev. ____
Dwg. No. 813-1163B A8004 Date 1-82 Eng. [illegible]

A 30 m long rod that is heated by 1°C will increase in length by 0.5 mm if it is stainless steel and by 0.03 mm if it is super invar.

Installation of a borehole extensometer involves drilling a borehole, determining anchor locations, assembling and testing the instrument, inserting it into the borehole, setting the anchors, and possibly grouting.

Borehole extensometers may require holes that are 40 to 90 mm in diameter, but many are designed for a 76 mm diameter hole because this is a common size used in geotechnical engineering. The hole is cored so that rock quality information may be obtained. Deep holes should be surveyed so that the drift of the hole can be included in analysis of results.

The anchor location is based on the anticipated rock movements and the quality of the core recovered from the hole. Some anchors are located in the areas where the greatest movements are anticipated and others are spaced out along the length of the borehole. Anchors should be located so that they will bracket zones of discontinuities and should not be located directly across a discontinuity. Once positioned, the anchors are set. If grouted anchors are used, neat cement grout is pumped into the grout tube so that it will fill the borehole from the bottom. If possible, horizontal holes are generally inclined downward a few degrees to facilitate grouting.

Assembly of the extensometer includes the following:

- Cut wire, rods, conduit, and grout tubes to length
- Straighten the wire or rods that will be used
- Thread wires (if used) into conduit
- Attach anchors to conduit and wires
- Fill conduits with oil.

The extensometer is then inserted into the borehole.

For wire extensometers, it may be necessary to use a mechanical or hydraulic anchor so that the wires can be tensioned before grouting the hole. For rod extensometers, the rods are installed in the conduit and the mechanical readout head is installed after the grout has set.

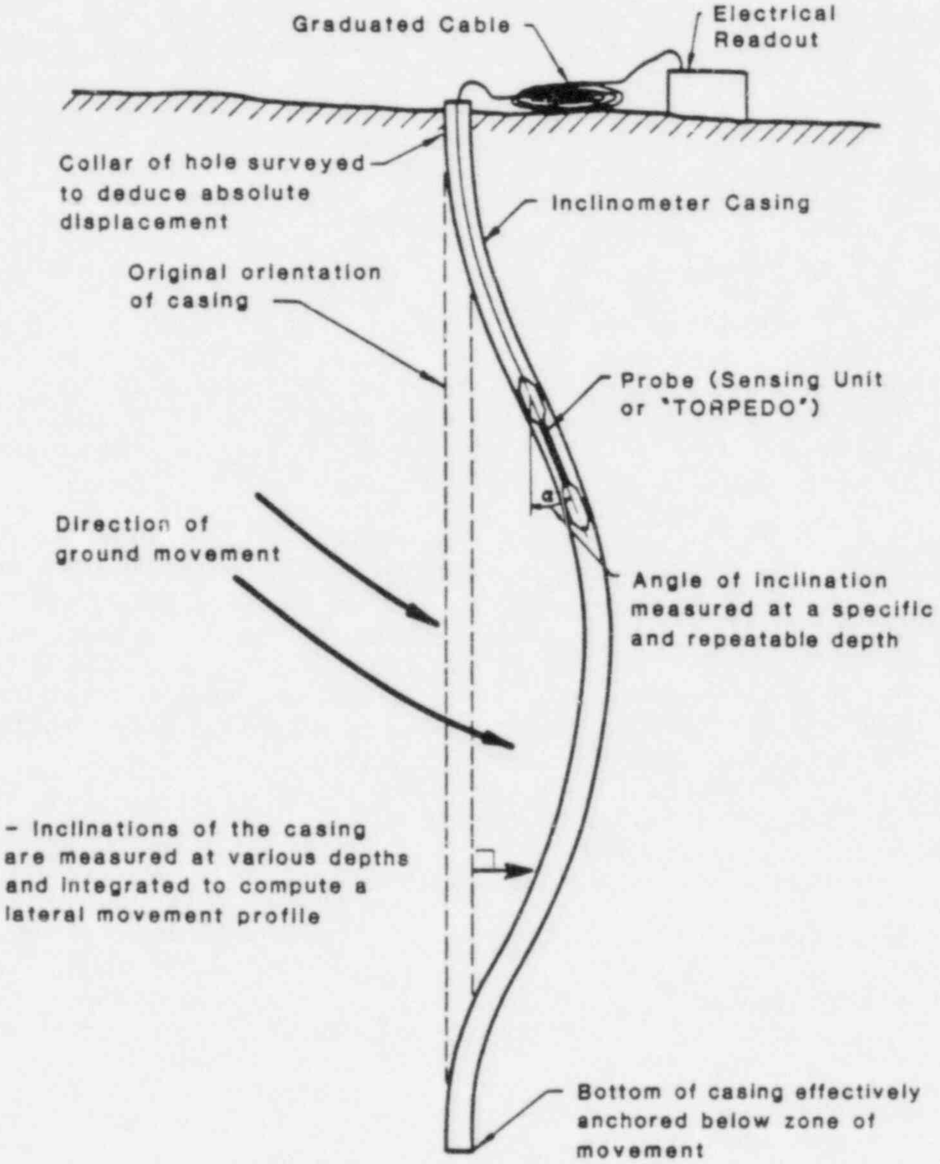
A mechanical readout rod extensometer requires little calibration. It simply requires an initial reading to be taken using a depth micrometer or dial gauge. The wire-type extensometer requires cycling of the tension with measurements taken after each cycle in order to measure the repeatability of the measurements. Electronic extensometers require a series of readings checked against the values obtained from the mechanical readout to determine the amount of zero drift.

Inclinometers

Displacement transverse to the borehole axis can be determined using a borehole inclinometer (see Figure G-5). This instrument measures the

PORTABLE BOREHOLE INCLINOMETER

Figure G-5



after Cording et al, 1975

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Dwg. No. 313-1838 AE005 Date 1-82 Eng. [illegible]

inclination of the casing emplaced within a borehole. Lateral displacement is detected by changes in the inclination and can be determined by integrating the changes in inclination over the length of the casing. The bottom of the inclinometer is usually placed deep enough below the zone of movement so that it can be regarded as fixed. Where large displacement occurs along discontinuities, the special casing may shear off. Hence, borehole inclinometers are generally applicable to soil or soft rock conditions.

Borehole inclinometers may be either permanently mounted or portable. Both types use the same casing. Fixed inclinometers have an accuracy of about 0.1 mm in 10 m, but this accuracy is lost if the instrument is removed from the hole for repair. Portable inclinometers generally have an accuracy of about 3 mm over a distance of 10 m, which may not be accurate enough for measuring the typically small displacements that occur in most rock types.

The inclinometer casing is installed in a borehole and grouted in place. Casing is available with outside diameters of 48, 70, and 85 mm. The borehole is sized for the couplings, which are 54, 78, and 94 mm in diameter. The borehole is cored (usually NX size, 76 mm diameter) and then reamed out to the size required for the couplings. The casing is installed with a grout pipe along the side and then grouted into place using neat cement grout. When the grout has set, the casing is surveyed to determine the amount of spiraling.

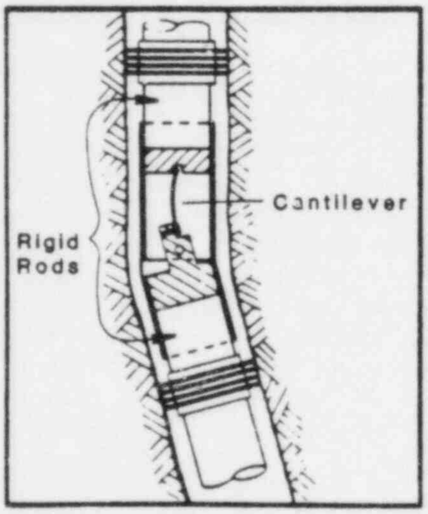
There is little calibration required except for taking of initial readings. The inclinometer probe is generally calibrated in a casing that is set in an area that will experience no movement. For the portable inclinometer, a probe is lowered down the hole and readings are taken at 30 to 60 cm intervals along the casing. A check on the accuracy is provided by turning the probe 180 degrees and repeating the process. The readings are later reduced manually or by computer to determine the slope and displacement along the casing.

The form of readout used depends on the type of sensing mechanism in the probe. Various probes are available which use Wheatstone bridge or vibrating wire readouts.

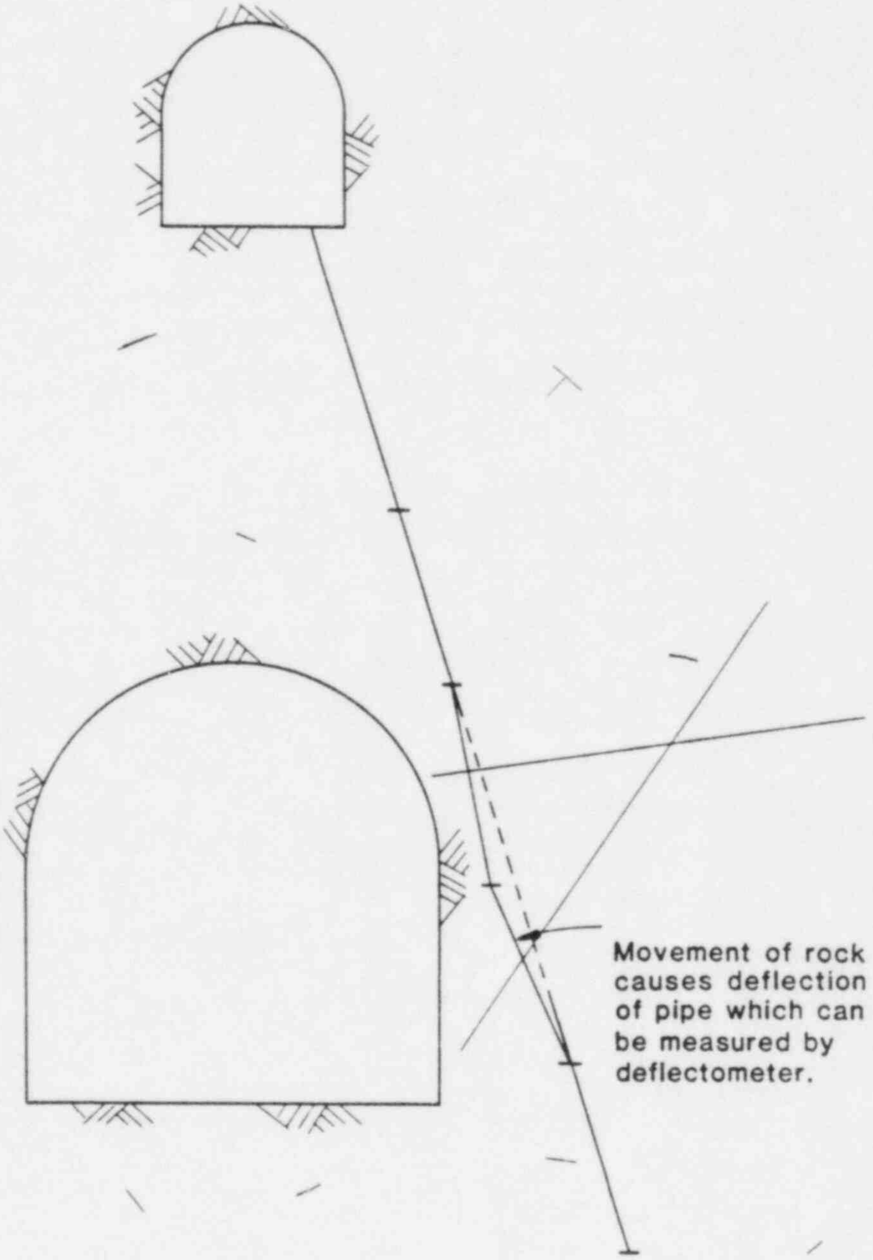
Deflectometer

A deflectometer consists of steel tubes that are connected by pivots installed in a borehole (see Figure G-6). Deflections of the pivots are detected by strain gauges that are mounted on cantilevers. The transverse movement along the borehole is calculated by summing the deflections along the length of the borehole. Up to 8 pivots may be used per borehole, at a maximum spacing of 6 m between pivots. The pivots are usually single axis, but dual axis models are also available. The deflectometer can be installed in 76 mm I.D. pipe that is grouted into the borehole. Portable deflectometers are also available that consist of two tube sections and a pivot that are designed to be inserted and withdrawn in standard inclinometer casings.

ROD TYPE MULTIPLE POSITION BOREHOLE DEFLECTOMETER Figure G-6



CROSS SECTION DETAIL OF PIVOT



Movement of rock causes deflection of pipe which can be measured by deflectometer.

Rev. ______
Dwg. No 813-11632 AK006 Date 1-82 Eng WW

Deflectometer pipe is installed in boreholes in the same way as inclinometer casing. The deflectometer requires 76 mm I.D. pipe, so it is necessary to install the pipe in a borehole that is about 95 mm in diameter. The pipe is grouted in place using a grout tube attached to the side of the pipe.

The deflectometer is installed in the pipe and the anchors are locked into place. For rock, the anchor spacing is generally based on the condition of the rock core that is recovered from the borehole and the location of the zone of expected greatest movement. The lowest anchor is usually set in an area where negligible movement is anticipated so that it can be assumed to be fixed.

The accuracy of the deflectometer is dependent on the spacing and number of pivots. The individual pivots are accurate to within about 30 seconds of arc (1 mm in 10 m).

The deflectometer is read using a standard Wheatstone bridge type readout unit.

Resistance Strain Gauges

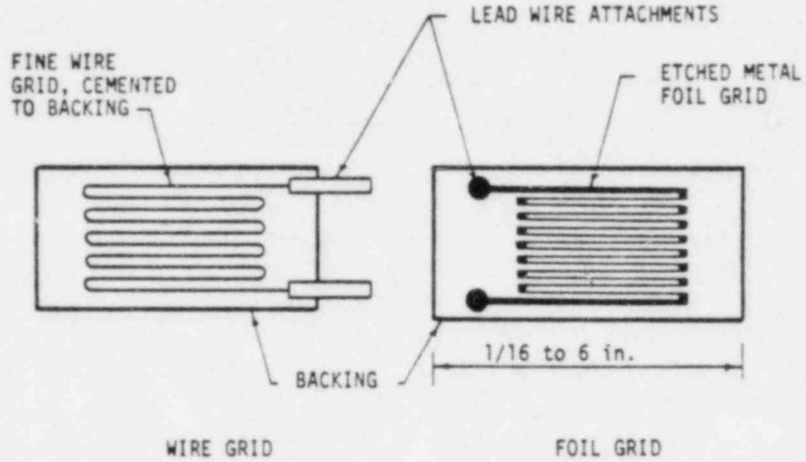
The electrical resistance of a wire is inversely proportional to its cross-sectional area. Straining of the wire changes its cross-sectional area and, consequently, its resistance. Thus, if the wire is attached to a surface, measurements of the changes in the wire's resistance can be used to determine the strains in the surface in the direction of the wire. This is the operating principle of the resistance strain gauge (see Figure G-7).

The most common form of the resistance strain gauge is the bonded gauge. In the bonded strain gauge, a thin wire filament or metal foil is formed into a pattern and bonded to a backing of paper-thin plastic or epoxy (see Figure G-7a). The backing is in turn cemented to the surface where the measurements are to be made. These gauges are available in a wide variety of sizes (gauge lengths from as small as 0.008 in. to as large as 6 in.) and shapes (including multi-element rosette configurations). Their strain sensitivity is usually around 2 to 4 microstrain with ranges up to 20,000 to 50,000 microstrain (2 to 5 percent strain) for normal gauges. Post-yield or high elongation gauges that work up to strains of 10 to 20 percent are available. Bonded strain gauges are primarily used for surface strain measurements.

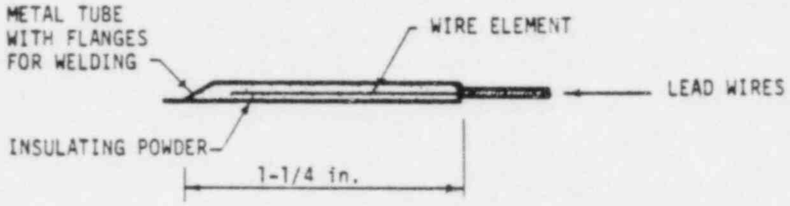
Bonded gauges are difficult to use under most field conditions because they require meticulous care and skill in preparing the measurement surface and cementing the gauge in place. They are very sensitive to moisture and good waterproofing is difficult to achieve under field conditions. Bonded resistance strain gauges can be mounted and sealed in the factory into a stainless steel or brass envelope (see Figure G-7b) that is then welded to the measurement surface or embedded into concrete. This gauge is termed an encapsulated gauge. One version of

ELECTRICAL RESISTANCE STRAIN GAUGES

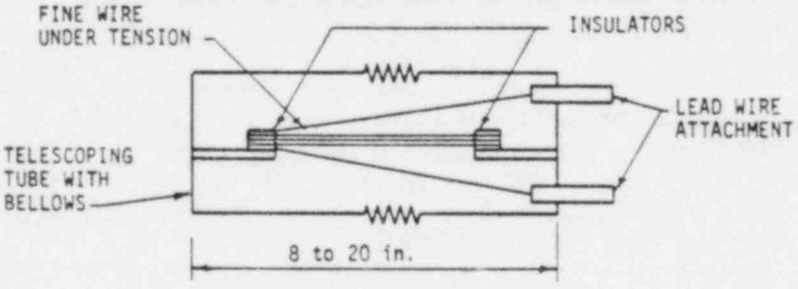
Figure G-7



a) BONDED RESISTANCE STRAIN GAUGES



b) ENCAPSULATED WELDABLE RESISTANCE STRAIN GAUGES



c) UNBONDED RESISTANCE STRAIN GAUGE

after Cording et al, 1975

Rev. ______
Dwg. No. 813-1163B A4002 Date 1-82 Eng [illegible]

the weldable encapsulated gauge uses a fine wire supported in an insulating medium and enclosed in a sealed stainless steel tube. To avoid heat damage, a small capacitive discharge welder is used to attach these gauges.

Another form of the resistance strain gauge is the unbonded, encapsulated gauge (see Figure G-7c). This gauge uses a fine wire strung under tension over ceramic insulators mounted on a flexible metal frame to form a resistance coil. Usually two coils are used and they are arranged so that one coil contracts while the other expands when the frame is strained. The coils and frame are factory sealed into a tubular metal cover. The gauge is mounted by bolting it to saddle brackets previously attached to the measurement surface. One version of this type of strain gauge, the Carlson strain meter, has a very long and successful experience record in field usage, e.g., Carlson meters embedded in concrete dams have worked successfully for periods of over 20 years. The Carlson system is also used in stress cells and piezometers.

Wheatstone bridge type readouts are used for resistance-type strain gauges. Correction must be made for the temperature of the gauge and the resistance of the lead wires.

Vibrating-Wire Strain Gauges

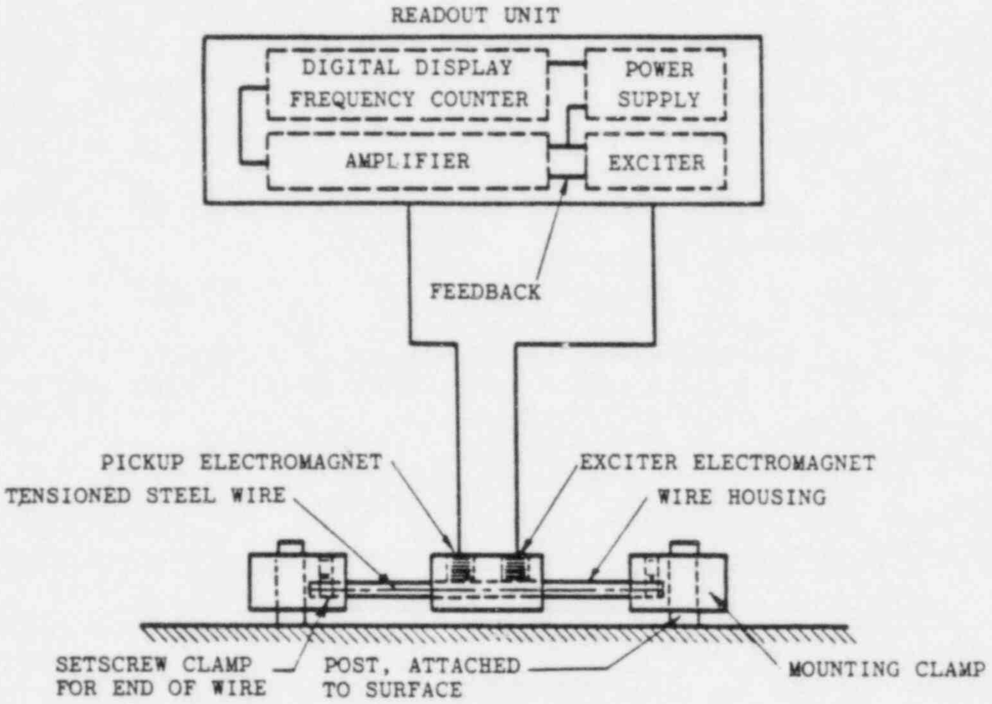
The vibrating-wire strain gauge consists of a length of steel wire that is stretched between two posts (see Figure G-8). The two posts are connected to the points between which the displacement is to be measured. Displacement between the two posts causes a change in the tension in the steel wire, which is sensed by determining the change in natural frequency of vibration of the wire. In order to allow for remote readout, the vibrating-wire strain gauge has a magnet, an exciter coil, and a sensor coil. The exciter coil is used to "pluck" the wire and set it vibrating. As the wire vibrates in the magnetic field, it induces an electrical current in the sensor coil which has a frequency equal to the frequency of vibration. The current is amplified by the readout unit and the frequency is measured by a frequency counter contained in the readout. Automatic electronic conversion of changes in frequency to strain are available.

The advantage of the vibrating-wire strain gauge is that the frequency that is measured is independent of the resistance of the leads and the currents that may be induced in the lead wires. The disadvantage is that they have a relatively small range, because the wire either may be stretched too tight or may become too slack if strain is excessive. During manufacture or during installation, the initial tension in the wire should be set so that 3/4 of its range is available in the expected direction of movement and 1/4 is available in the opposite direction.

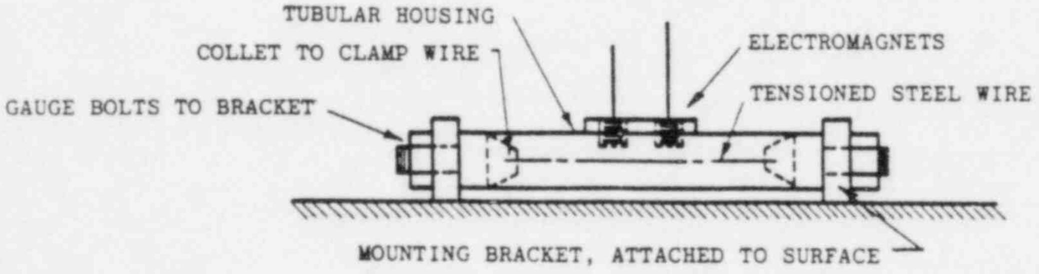
The strain gauge is generally installed by attaching the ends onto the surface that is to be monitored. Embedment-type gauges are cast in concrete or grouted in boreholes. Calibration consists of measuring the initial frequency and temperature after installation is completed.

VIBRATING-WIRE STRAIN GAUGES

Figure G-8



a) POST TYPE VIBRATING-WIRE STRAIN GAUGE



b) TUBE TYPE VIBRATING-WIRE STRAIN GAUGE

after Cording et al, 1975

Rev. ______
Dwg. No. A13-11638 14-004 Date 1-82 Eng. UW

Subsequent readings include measuring frequency and temperature. A thermistor may be mounted to the gauge for measuring temperature, or an additional circuit may be installed in the readout to measure the resistance of the exciter coil so that temperature may be calculated. A strain gauge which is physically isolated from structural strains can also be used to correct for temperature effects and to monitor temperatures.

The vibrating wire strain gauge is accurate to within about 5 to 10 percent. Although other strain gauges provide greater accuracy, the vibrating wire strain gauge has been the most successful for use in long-term monitoring of underground excavations where remote readout is necessary. This is because the vibrating wire strain gauge is completely waterproof and is not plagued by the electrical problems of the other types of strain gauges. Although zero drift can be a problem with vibrating wire strain gauges due to creep of the wire, this can be compensated by using dummy gauges.

Linear Displacement Transducers

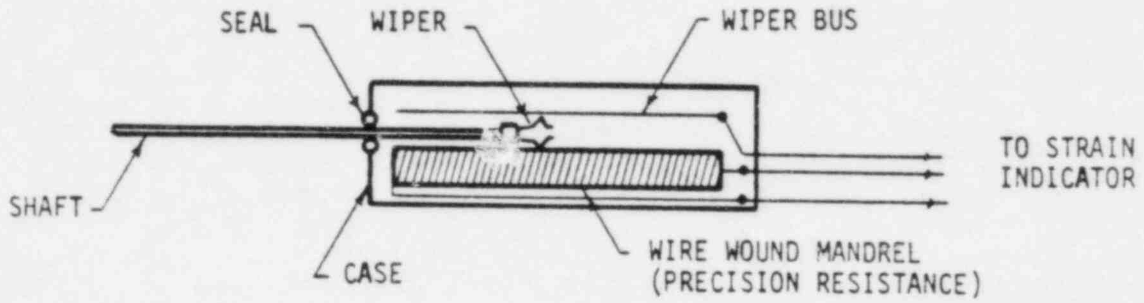
Two types of linear displacement measuring transducers, the linear potentiometer and the linear variable differential transformer or LVDT (see Figure G-9), are used extensively in many geotechnical instruments, such as extensometers. The LVDT is sometimes referred to as a DC to DC linear differential transformer or DCDT. The LVDT is sensitive enough that it can be used as a strain gauge.

The linear potentiometer is a resistance device. It consists of a mandrel wound with fine wire or conductive film. A wiper attached to a shaft rides along the mandrel and divides the mandrel resistance into two parts. The resistance ratio of these parts is measured with a Wheatstone bridge circuit to determine the displacement of the wiper and shaft. Linear potentiometers are available with ranges from 0.5 to 4 in. Average sensitivity is 0.01 in. to 0.001 in. Since linear potentiometers are a combined mechanical and resistance device, moisture can cause severe problems and waterproofing of potentiometers can be difficult. Usually the device is sealed into a case with a mechanical seal, such as an O-ring, at the shaft.

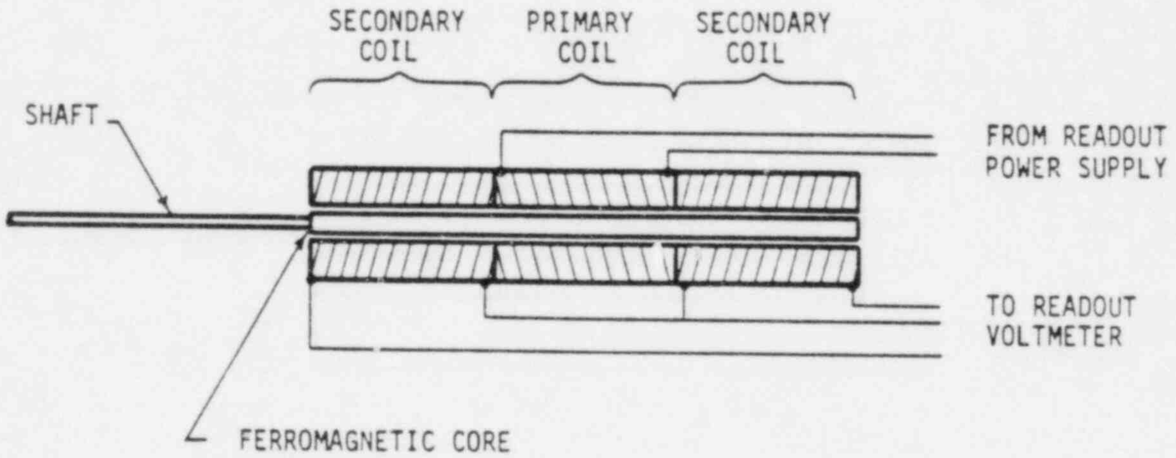
The LVDT converts a displacement into a voltage change by varying the inductance path between a primary coil and two or more secondary coils when an excitation voltage is applied to the primary coil. Variations in the output signal can be calibrated to displacements of the LVDT core. The calibration is usually linear. The coils are wound on a hollow mandrel. A ferromagnetic core slides within the mandrel to vary the inductive coupling. AC voltage is usually used, but DC models are available. Readout units contain an accurate voltmeter and a carefully regulated power supply. Since the output voltage is proportional to the input voltage, the power supply must be controlled. Since the electrical portions of the LVDT can be isolated and waterproofed by encasing the mandrel in potting compound, the LVDT is much less sensitive to

LINEAR DISPLACEMENT TRANSDUCERS

Figure G-9



a) Linear Potentiometer



b) Linear variable differential transformer (LVDT)

after Cording et al, 1975

moisture than a linear potentiometer. It is also less affected by temperature and is mechanically simpler. LVDT's are available with displacement ranges from 0.1 in. to several feet. Sensitivities of 10 microstrain are possible.

Mechanical Strain Gauges

An alternative to the remote-reading electrical gauges is a mechanical strain gauge that uses a dial gauge indicator for direct reading. Since dial gauges are easily damaged and cannot be left in place, systems have been designed that allow removal of the gauge between readings and replacement of the gauge in a way that provides sufficient repeatability in the readings. A typical mechanical strain gauge (such as the Whittemore or Huggenberger types) has two pointed arms that fit into conical holes or gauge points drilled and punched into the instrumented surface, or into studs set into or on the surface. The change in distance between the gauge holes is measured by determining the distance between the arms when inserted in the holes. Each arm is attached to the end of a tube. The two tubes are coaxial and slide one inside the other. A dial gauge indicator clamped to the inner tube measures the displacement between the tube ends. An initial measurement of the separation between the gauge holes is made. Changes in this distance recorded in subsequent measurements serve to determine the surficial strains. The gauges usually read to the nearest 0.0001 in., but the repeatability of the readings depends partially on the quality of the seat for the points and partially on the skill of the operator. Gauge lengths of 2 to 80 in. are available. For most engineering measurements, a 10-in. gauge length is used (with a sensitivity of about 10 microstrain).

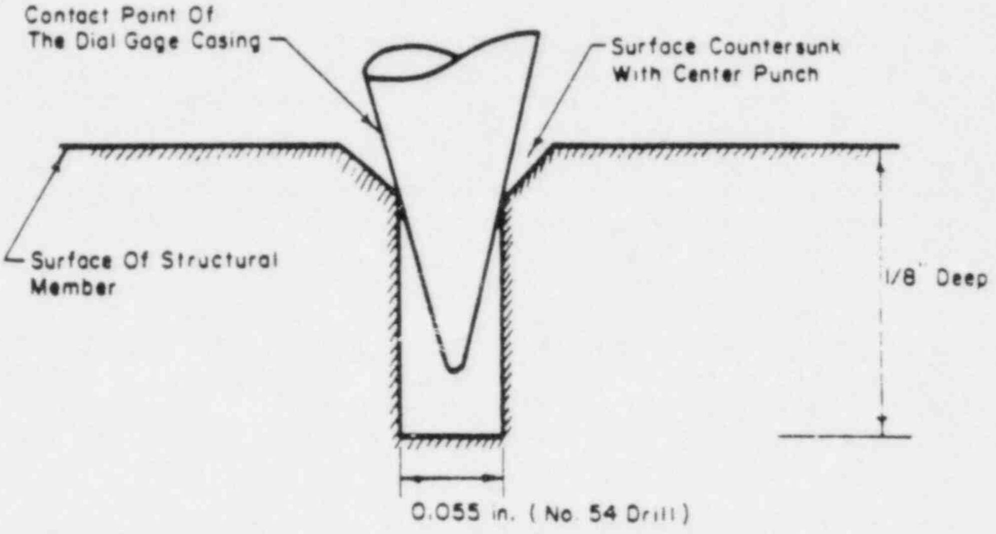
The holes for one of the typical mechanical gauges, the Whittemore gauge, are 1/8 in. deep and are made with a standard No. 54 drill. The holes are then countersunk with a 90-degree center angle conical punch. This forms a cylindrical edge upon which the measuring arm points, which have 30-degree conical points, can rest (see Figure G-10a). The punching action also serves to strain harden the surface where the measuring arm point and the side of the reference hole touch. An alternative procedure is to use a No. 1 high-speed combination drill and countersink to make a 1/8-in. deep by 1/32-in. diameter conical hole and to use spherical contact points that fit snugly in the holes (see Figure G-10b).

While gauge holes can be drilled directly into a steel or cast iron member, metal inserts are used for rock. These inserts are stainless steel bolts grouted into holes drilled into the rock. The gauge holes are then drilled into the ends of the inserts. For temporary readings, holes can be made on small pieces of steel which are then glued in place.

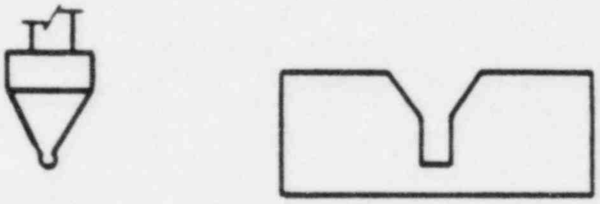
To ensure repeatability with the mechanical gauges, extreme care and precision must be exercised during their initial installation. The gauge holes must be drilled so that they are exactly perpendicular to

MECHANICAL STRAIN GAUGE REFERENCE HOLES AND CALIBRATION BAR

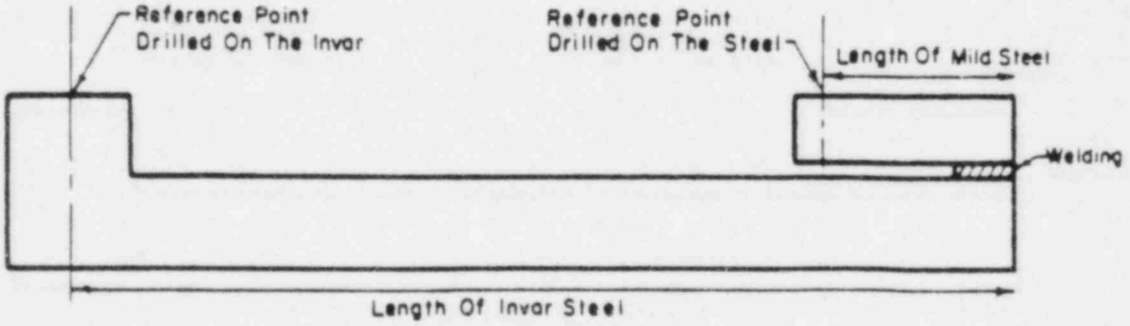
Figure G-10



a) CONICAL POINT AND CENTER PUNCHED HOLE



b) SPHERICAL POINT AND COUNTERSUNK HOLE



c) TEMPERATURE COMPENSATED CALIBRATION BAR

after Cording et al, 1975

Rev. ______
Dwg. No. 213-1463B A6210 Date 1-82 Eng WW

the line of the instrument gauge casing and at the required spacing. The field engineer should acquire some laboratory experience with such drilling prior to site installation.

Measurements are made by placing the gauge contacts into the gauge holes. The gauge is rocked back and forth gently to provide a secure junction of the contacts with the gauge holes. When the dial gauge has stabilized, a measurement is taken. An awkward location for measurements can often induce imprecision; thus, the gauge holes should be arranged so that they can be measured from a reasonably comfortable position. Multiple measurements are typically used to improve the reliability of results.

An important part of the mechanical strain gauge is a calibration bar. This bar is used to determine temperature compensation and also to provide a reference in case it is necessary to repair or replace the gauge. The bar is made of invar steel and mild steel and is designed so that the expansion of the invar will be cancelled by the expansion of the mild steel (see Figure G-10c).

Mechanical strain gauges are simple, reliable, relatively low-cost devices that can be used in a variety of situations. They are not as sensitive as most of the electrical type strain gauges, but their sensitivity and accuracy are adequate for verifying performance of other types of gauges or for use as a backup to other gauges. Since the mechanical gauge is removed between readings, its calibration can be checked at any time (a considerable advantage). The gauge holes are easy to protect from damage and water. The disadvantages of the mechanical gauges are that they cannot be read remotely, and the repeatability of the readings depends on the skill and experience of the operator.

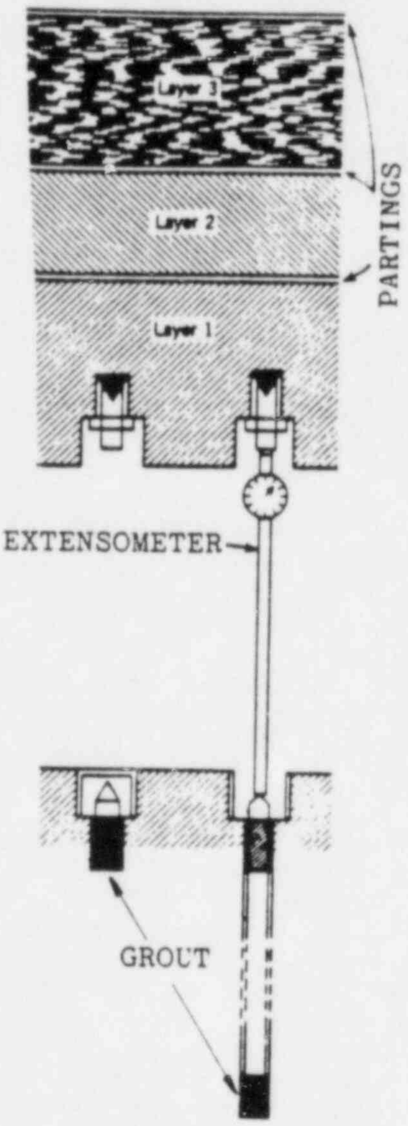
Portable Extensometers

The two common types of tunnel convergence gauges are the rod extensometer (see Figure G-11a) and tape extensometer (see Figure G-11b). The micrometer and dial gauge rod types can provide an accuracy of ±0.08 mm, while the tape extensometers have accuracies within the range of ±0.06 to 2.5 mm, depending on the spring tension force used in the tape. An error of one pound in the spring force can cause an inaccuracy of 0.1 mm (Dunnicliff, 1971). The rod types are bulkier and more easily damaged. Their use is generally limited to spans of 10 ft or less, unless sectioned rods are employed. For larger spans, flexure of the rod may reduce the accuracy to ±0.1 in. or less. The tape units are more versatile and can be easily used for spans up to 30 ft or more.

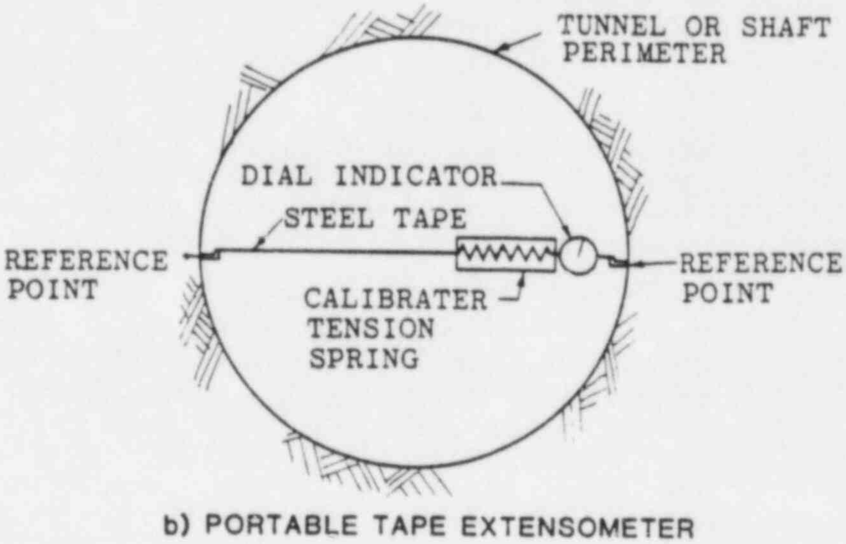
The rod and tape extensometers both use reference heads that are set in the rock. The reference heads are usually epoxied into small holes (3 to 15 mm diameter) that are drilled into the rock and protective covers are placed over the head to prevent damage between readings. The heads are designed to provide a positive, repeatable seating for the extensometers.

TUNNEL CONVERGENCE GAUGES

Figure G-11



a) PORTABLE ROD EXTENSOMETER



b) PORTABLE TAPE EXTENSOMETER

after Cording et al, 1975

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Dwg. No. 83-0512 A40U Date 1-82 Eng. WW

Both types of units are temperature sensitive and standard temperature corrections should be applied. Before taking measurements, the extensometers should be allowed to come to equilibrium with the surrounding air temperature. A calibration bar consisting of a steel bar with hook attachments for the tape can be placed in the tunnel to calibrate the steel tape before each set of measurements, and thus provide for mechanical adjustments of the unit.

G.3.2 STRESS

Strictly speaking, there is no way to directly measure and monitor the absolute stress at a point, as the installation of the monitoring instrument causes a change or redistribution in the stress field. Only changes in stress, once the instrument is installed, can typically be measured. However, procedures have been developed for back-calculating the original absolute stress from those types of measurements.

There are two borehole methods that are used to measure stress changes (see Table G-3): the hard inclusion cell and the soft inclusion cell. The hard inclusion cell is a stiff gauge that is placed in a borehole and is either cemented or grouted in place. If the stiffness of the cell is at least five times the stiffness of the rock, then the cell measures changes in the rock stress directly and is independent of the deformational properties of the rock. The soft inclusion cell is placed in the borehole and measures the deformations of the borehole wall. The stress changes are calculated from these displacements, based on elastic theory and elastic properties of the rock in the borehole wall.

Hard Inclusion Cells

There are three main types of hard inclusion cells, although there are many variations of these types available. The benefit of hard inclusion cells is that they read stress change directly and are not sensitive to the deformation properties of the rock.

The solid inclusion stressmeter is a brass or steel bar that has a strain gauge embedded in it. The bar is wedged or cemented into a borehole and it monitors stress changes that are parallel to the orientation of the strain gauge. Before installation, the cell may be calibrated in the laboratory by mounting it in a borehole drilled in a large block of rock. The block is then subjected to various stresses in a load frame and the response of the strain gauge is monitored. In the field, the stressmeter may be installed in boreholes up to 30 m deep. The vibrating wire stressmeter (see Figure G-12) uses a 37.5 mm diameter borehole and as many as three cells may be stacked in a single borehole.

The "stiff" hydraulic cell can be considered as another type of hard inclusion cell. This is a flatjack that is filled with a stiff fluid, such as mercury, so that the fluid has approximately the same stiffness as the rock. The flatjack may be installed in a slot cut in the wall of

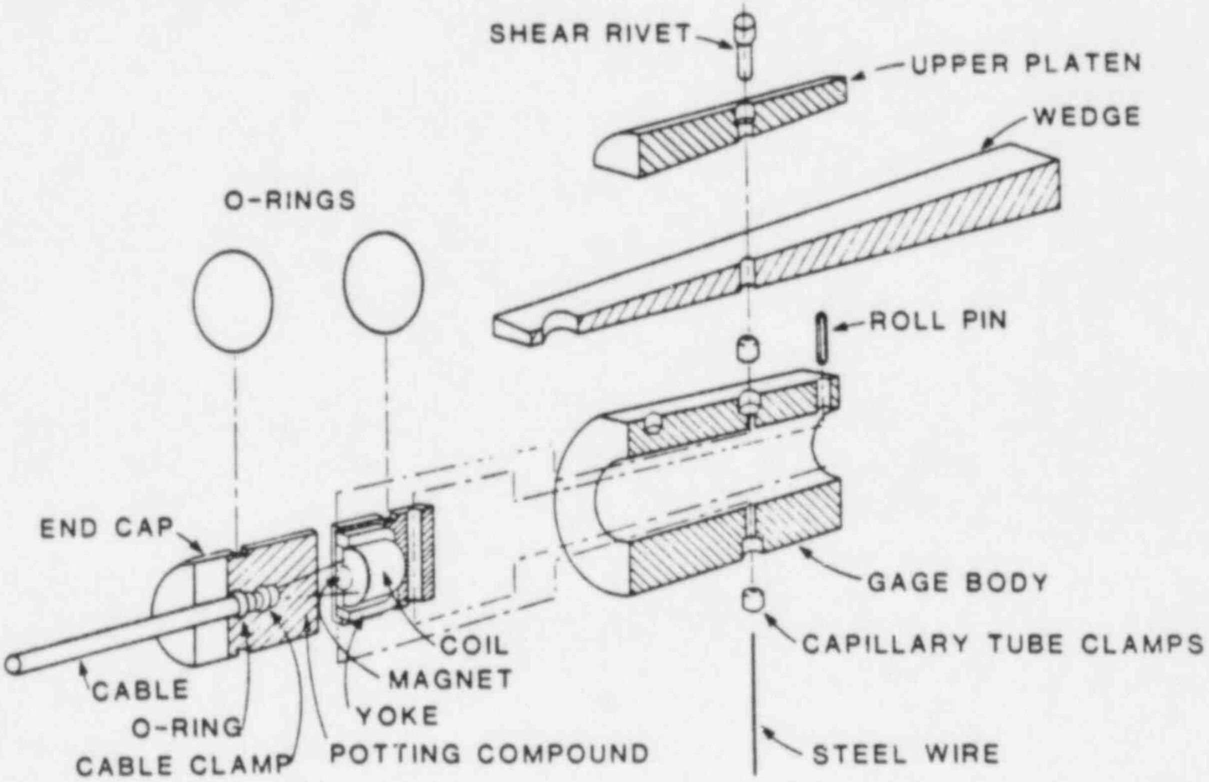
SUMMARY OF STRESS CHANGE MONITORING INSTRUMENTATION

Table G-3

INSTRUMENT	RANGE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	ESTIMATED COST (1982 U.S. DOLLARS)		
					ACQUI-SITION	INSTALL-ATION	CALI-BRATION
HARD INCLUSION CELLS			Calculation of stress is not dependent on elastic properties of the rock.	Measure only one stress direction.			
Vibrating wire stressmeter	69 MPa	± 0.1 MPa	Reusable	Need to correct for creep of wire for long-term measurements. Temperature calibration is required.	$500	$280	$280
Stiff Hydraulic Cell	20 MPa	± 1%	Simple, rugged	Stiff fluid must be used to ensure that the cell is stiffer than the rock.	$500	$280	$140
Glotzl Hydraulic Cell	30 MPa	± 1 MPa	Simple, rugged.	Requires constant volume pump. Cannot measure stress decreases.	$750	$280	$140
SOFT INCLUSION CELLS			Measure stress change tensor.	Stress is calculated based on measured deformation of borehole walls and the elastic rock properties. Cannot be used in fractured rock or rock that is creeping.			
USBM Borehole Deformation Gauge			Long experience. Reusable, rugged.	Can only calculate stresses perpendicular to borehole.	$2,500	$140	$140
Doorstopper			Can be used in rock subject to core discing.			$560	$560
CSIR Cell			All three principal stresses monitored in one cell.	Difficult to seal strain gauges against moisture.		$560	$560
CSIRO Triaxial Cell	100 MPa	± 0.2 MPa	All three principal stresses measured with one cell.		$600	$280	$560

VIBRATING-WIRE STRESSMETER

Figure G-12



after Cording et al, 1975

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a tunnel or in a borehole. In either case, it is pressurized approximately to the rock stress acting normal to the flatjack. Changes in stress are measured by monitoring changes in the pressure of the fluid in the cell. If the initial pressure in the cell is too low, then changes in stress will tend to arch over the flatjack and the measured pressure change will be too low. The pressure in the cell can be read using either a mechanical pressure gauge or a diaphragm connected to a strain gauge.

The Glotzl cell is similar to the "stiff" hydraulic cell, except that it is connected to a constant volume pump. It is assumed that the pressure required to maintain a constant volume in the flatjack is equal to the change in the rock stress normal to the flatjack. The Glotzl cell is cemented into a borehole and pressurized to the approximate in situ stress normal to the cell. Changes in pressure necessary to maintian constant volume are monitored.

The accuracy of the hard inclusion cells is limited because the inhomogeneities in a rock mass result in a nonuniform stress distribution at the measurement scale, i.e., the hard inclusion cells measure the stress changes in a small area which may not be representative of the rock mass. Also, the hard inclusion cells measure stress changes only in one direction (longitudinal to the strain gauge or normal to the flatjack faces). Thus, it is necessary to use six cells oriented in different directions to determine the changes in the entire stress tensor. In addition, there is always some disturbance of the rock around the cell and this may affect the stress changes measured by the cell. Under laboratory conditions, the hard inclusion cells have an accuracy of 5 to 10 percent, but under field conditions, the accuracy has been estimated at about 25 percent.

Soft Inclusion Cells

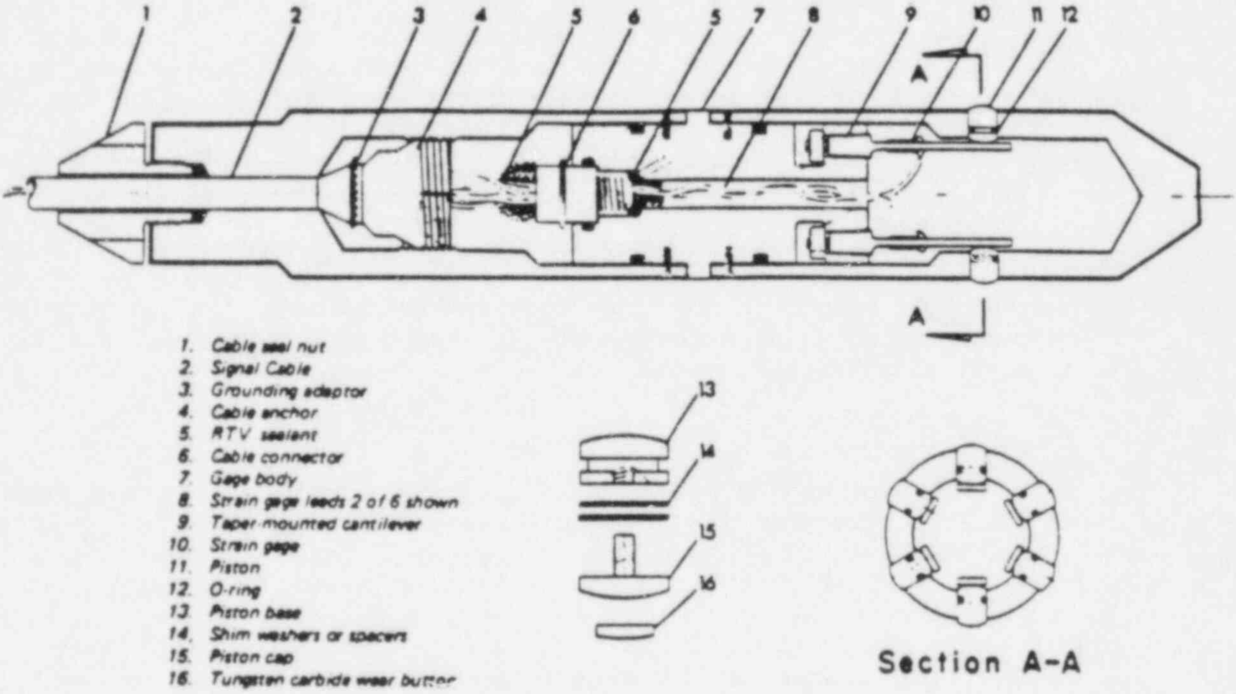
Soft inclusion cells monitor the deformation of the rock around a borehole, so that the stress changes can be calculated. There is one type of mechanical cell and three types of electrical cells that are commonly used. All four cells were originally developed to determine the in situ stress tensor using overcoring techniques (see Appendix, Section A.8), but they can also be used to monitor borehole deformation and stress changes by installing them in a borehole and not overcoring.

The USBM borehole deformation gauge (see Figure G-13) is a mechanical gauge that is installed in a 37.5 mm diameter borehole. The gauge measures three diameters of the borehole using resistance strain gauges mounted on cantilevers. The changes in the diameters are related to the stress changes in the rock around the borehole (see Appendix, Section A.8 for equations). The cell may be used in boreholes up to 30 m deep, and only one cell may be used per hole. The cell has two advantages compared to the other soft inclusion cells:

- The cell may be used in wet holes because it does not need to be bonded to the rock

U.S. BUREAU OF MINES (USBM) BOREHOLE DEFORMATION GAUGE

Figure G-13



after Cording et al, 1975

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- The cell may be easily removed for repair or calibration.

The cell can measure changes in diameter of as little as 0.08 mm, which would correspond to a stress change of about 0.1 MPa. Three boreholes with different orientation are required to determine the complete stress tensor. Calibration consists of checking changes in resistance of the strain gauges against known displacement.

The CSIR "Doorstopper" (see Figure G-14a) consists of a strain gauge rosette that is epoxied to the bottom of a borehole. The rosette is encased in a potting compound in order to protect it from water. Installation is as follows:

- A 37.5 mm diameter hole is drilled and the bottom is ground smooth using a special bit
- The hole is dried using compressed air
- The bottom of the doorstopper is coated with epoxy, placed in the hole, and pressed against the bottom of the hole using a special tool (see Figure G-14b) until the epoxy dries.

After installation, initial strain gauge readings are taken using a Wheatstone bridge type read out.

The CSIR triaxial strain cell (see Figure G-15) is an apparatus which glues three electrical strain gauge rosettes directly to the wall of a 37.5 mm diameter borehole.

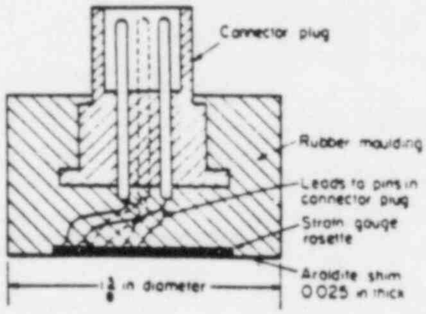
The cell measures 12 separate strains in 3 different planes, which by appropriate analysis can be related to the change in stress at that point within the rock. Only six independent measurements are required to determine the six components of the stress change tensor. However, as all the strain measurements contain some errors, the additional readings (six in the case of the four element rosette strain cell) can be included to improve the accuracy and obtain an indication of the precision of the data.

The CSIRO hollow inclusion triaxial strain cell (see Figure G-16) is identical in principle to the CSIR triaxial cell. In the CSIRO cell, however, the three strain guage rosettes are embedded in a hollow cylindrically shaped epoxy probe. When the cell is glued to the wall of a 37.5 mm diameter borehole, the strain gauges are separated from the wall by a thin layer (1 to 2 mm) of epoxy. This partially alleviates the difficult practical problem of bonding the gauges in the borehole.

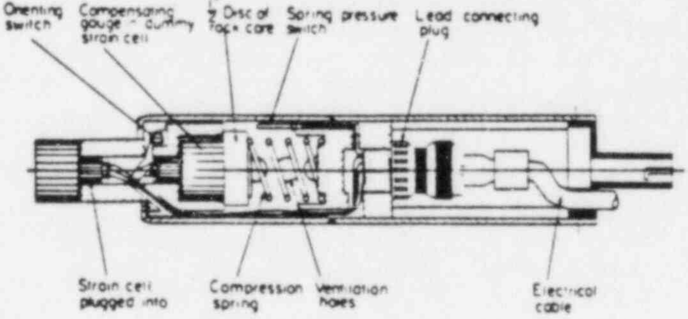
The boreholes for the soft inclusion cells are cored and the cells are installed in a location that is free of discontinuities. When the cell no longer needs to be used for stress change monitoring, it is overcored. Both the overcore and the core samples must be tested to determine the deformation characteristics of the rock around the cell.

CSIR "DOORSTOPPER" AND ACCOMPANYING SETTING HEAD

Figure G-14



a) Leeman 'doorstopper' borehole strain cell



b) Setting head for Leeman strain cell

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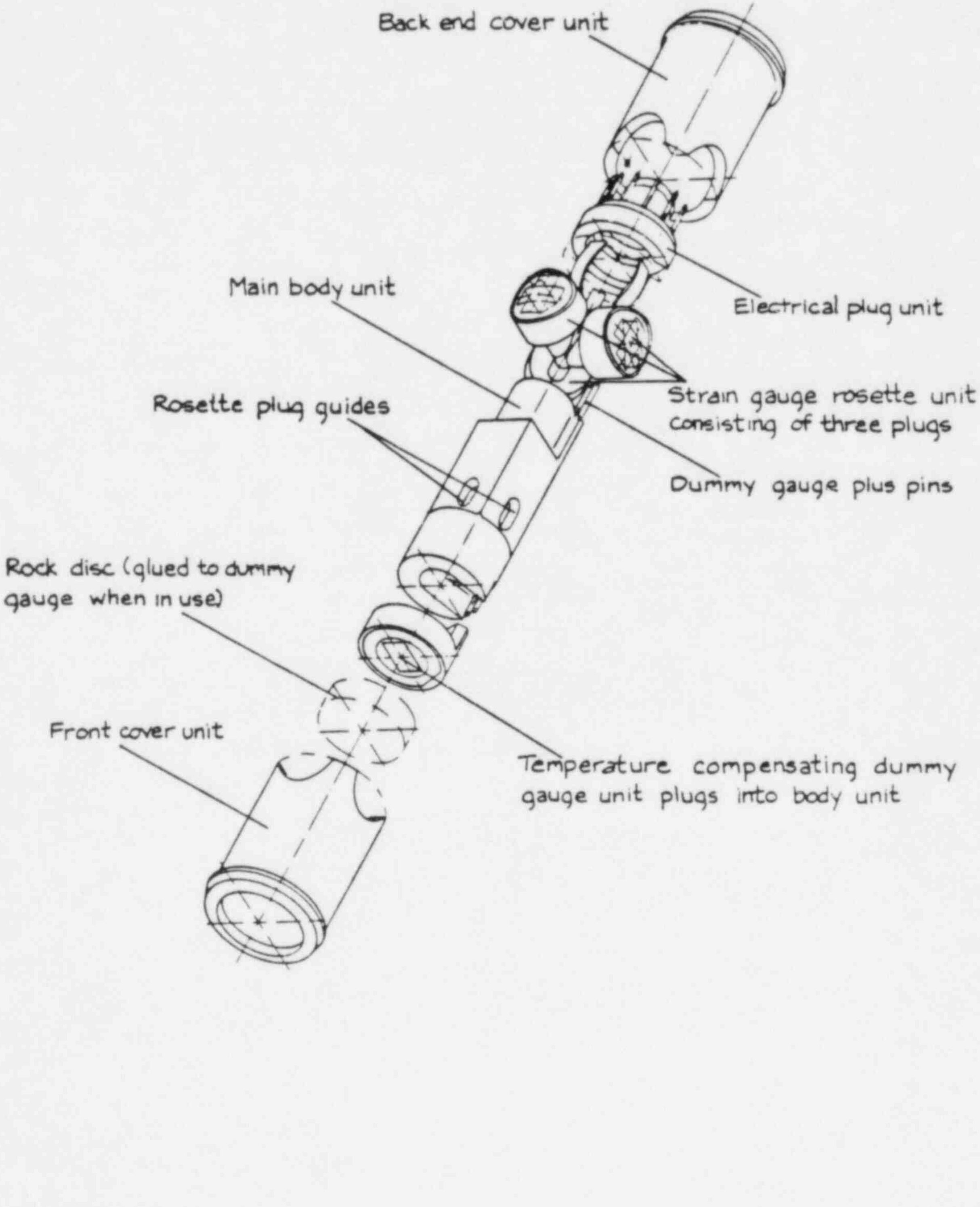
after Stagg and Zienkiewicz, 1968

CSIR TRIAXIAL STRAIN CELL

Figure G-15



after CSIR, 1973

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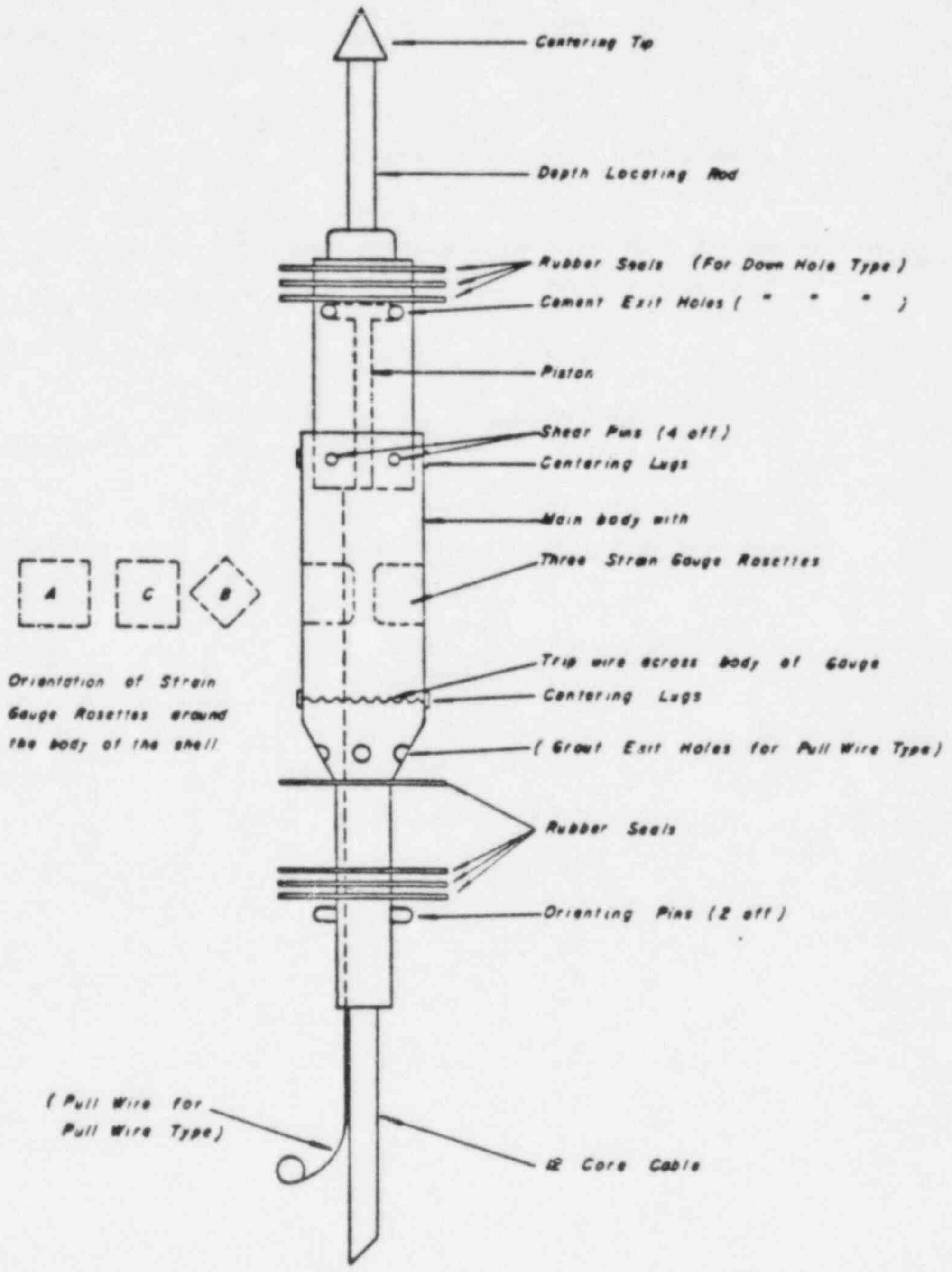
CSIRO HOLLOW INCLUSION TRIAXIAL STRAIN CELL AND INSTALLATION APPARATUS

Figure G-16



Orientation of Strain Gauge Rosettes around the body of the shell

after CSIRO, 1979

Rev. ____ Dwg. No. 8/3-11638 A16016 Date 1-82 Eng. YW

The main limitation of the soft inclusion cells is that the deformation properties of the rock must be relatively well known in order to calculate the stress changes in the rock. However, most analyses assume that the rock behaves as a linear elastic material. The cells cannot be used reliably in rock that is subject to creep or is fractured. The Doorstopper, CSIR and CSIRO cells are subject to some potential error because the epoxy may creep with time during stress change monitoring. The cells also are affected by inhomogeneities in the rock which result in a nonuniform distribution of stress in the rock mass at the measurement scale.

G.3.3 TEMPERATURE

The two most commonly used types of temperature sensors are thermocouples and thermistors (see Table G-4). However, vibrating wire gauges can also be used. The temperature sensors are mounted in probes and installed in boreholes to monitor the temperature of the rock. Also, the sensors may be mounted on other instruments, such as extensometer rods or strain gauges to facilitate making temperature corrections.

The same calibration method is used for both thermocouples and thermistors. The sensors are placed in baths of known temperature and the potential difference or resistance measured. Both types of probes are generally calibrated by the manufacturer, so little calibration is required in the field.

The probes may be installed practically anywhere that a temperature measurement is needed. For measuring the temperature of a rock mass, the sensor is placed in a borehole which is then backfilled with sand. A series of measurements is taken until the probe reaches equilibrium. This is necessary because the temperature of the rock around a borehole may be influenced by the temperature of the drill fluid used, the friction from the drill tools, and the temperature of the sand backfill. After equilibrium has been attained (this could take from a few hours to a few weeks), both types of temperature sensors have a very fast response to changes in temperature in the rock and both are very accurate.

Thermocouples

Thermocouples consist of two wires made of dissimilar metals, such as chromel and alumel. The wires are jointed together at the point where the temperature measurement is to be made. The free ends of the wires are maintained at a constant reference temperature. The difference in temperature results in a potential difference between the two free ends which can be measured with a potentiometer. The potential difference can be related to the temperature at the junction of the two wires. An advantage of the thermocouple is that the resistance of the leads is not critical. Hence, when long lengths of lead wire are required, the thermocouple is usually selected over the thermistor so that readings do not have to be corrected for the resistance of the wire.

Table G-4

SUMMARY OF TEMPERATURE MONITORING INSTRUMENTATION

INSTRUMENT	RANGE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	ESTIMATED COSTS (1982 U.S. DOLLARS)		
					ACQUISITION	INSTALLATION	CALIBRATION
Thermocouple		± 1°C	Reliable, rugged.	Reference temperature necessary	\$150	\$70	\$70
Thermistor	0 to 100°C	± 0.2°C	Long experience.	Correction for lead wire resistance is necessary	\$450	\$70	\$70

Thermistors

Thermistors measure temperature based on the change in electrical resistance with temperature. This change in resistance can be measured very accurately with a Wheatstone bridge. The resistance of the leads to the probe must be accurately known and readings must be corrected for lead wire resistance. It is thus necessary to measure the resistance of the leads at various temperatures so that corrections can be applied.

G.3.4 GROUNDWATER PRESSURES

Instruments used to monitor groundwater pressures are called piezometers. The data (pressure head) is used to determine the piezometric head (elevation head plus pressure head) in a flow field at the point of measurement and, if the flow is transient, the changes in head with respect to time. The piezometers are sealed within individual sections of a borehole and isolated from contact with other zones so that the location of the reading is accurately known.

Careful installation is required for accurate measurements (see Figure G-17). The piezometer tip must be sealed into the zone where pressure measurements are desired and the seal must not allow any leakage which could "short circuit" the pressure reading. Usually the piezometer tip is placed in the borehole and sand is tamped around the tip. Bentonite is then tamped on top of the sand. The bentonite has low enough permeability to prevent short circuiting. Pneumatic, mechanical, or hydraulic packers may also be used to isolate a portion of the borehole. Packers must be used in holes that are inclined upward. The piezometers may be stacked in a borehole to measure the distribution of water pressure along the length of the hole. The piezometer tip and the zone of measurement must be de-aired or erroneous measurements will result.

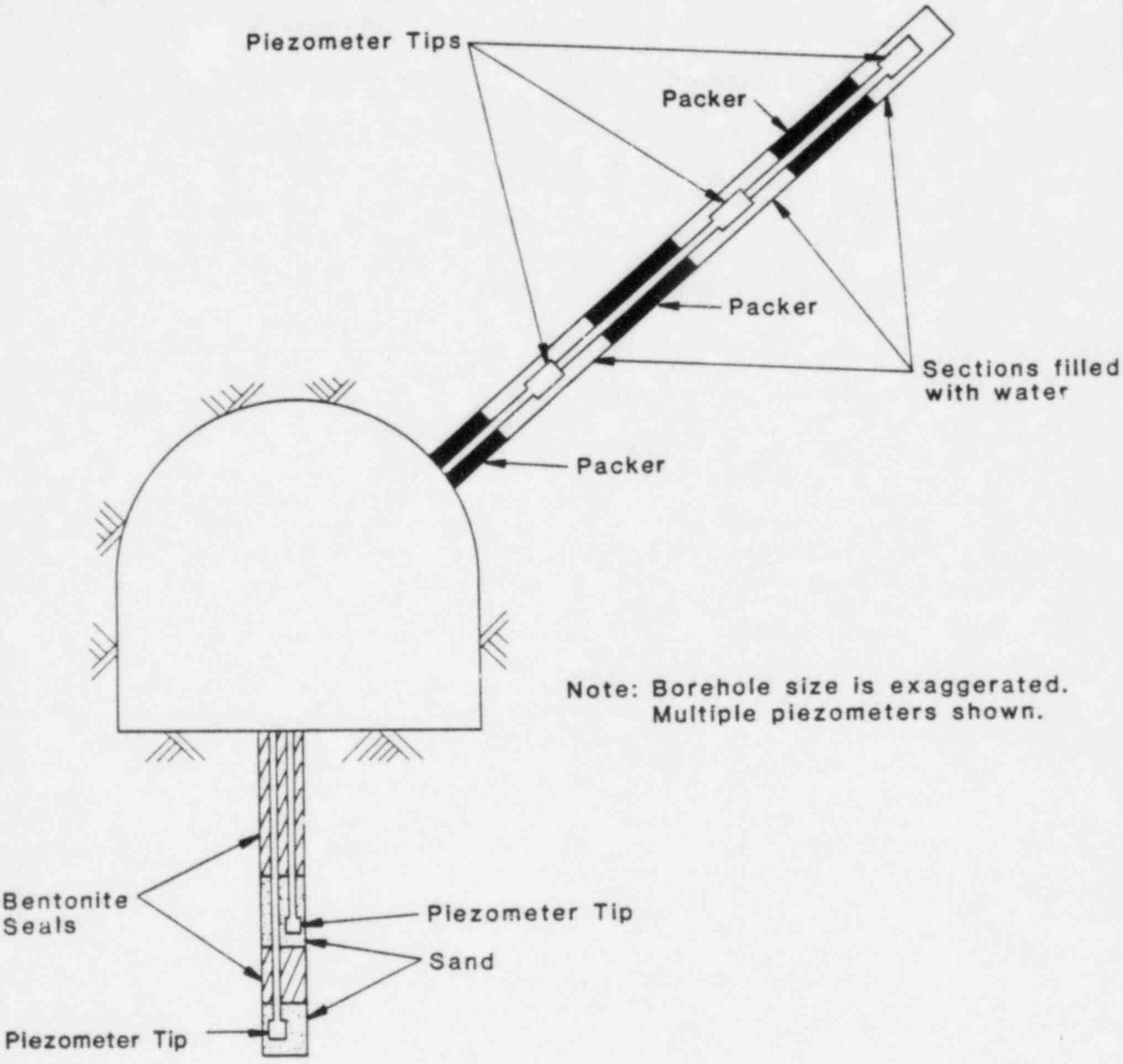
Piezometers all operate on the same basic principle. This involves the measurement of an internal pressure head which exactly balances the pressure (piezometric) head external to the instrument. The internal and external heads are usually balanced through a flexible membrane, which is located in a porous tip or filter installed in the ground at the point to be monitored. The tip of the piezometer is usually installed in a filter pack, such as Ottawa sand, to increase its collection area and sensitivity.

Piezometers are classified on the basis of the technique used for measurement. The three basic types of piezometers are open system, closed system and diaphragm piezometers.

Open System Piezometers

In an open system piezometer, the elevation of a free water surface that fluctuates with changes in external head is measured in a standpipe. The free water surface is located by dropping a probe down the standpipe until it contacts the water surface. The depth is measured on the

PIEZOMETER INSTALLED FROM A TUNNEL Figure G-17



Note: Borehole size is exaggerated.
Multiple piezometers shown.

marked probe cable. The open system piezometers are the most reliable and least expensive of the various piezometers. Their principal disadvantages are that they are very slow to respond to changes in piezometric head (because a considerable volume of water must flow into the standpipe to register a change in head), they cannot be used in upward inclined holes, and the location and source of flow into or from the hole is often not easily determined.

Closed System Piezometers

Closed system piezometers use a fluid filled hose to transmit the external head to a pressure measuring device, usually a Bourdon gauge or manometer. An open piezometer can usually be converted to a closed system by adding a pressure gauge, if the piezometric head rises above the top of the open system standpipe. Closed systems usually use two tubes to allow the flushing out of trapped air or gasses that would otherwise lead to erroneous readings. Closed systems are more expensive and difficult to maintain than open systems, but have advantages over open systems in that they can be connected to a central monitoring station, can measure negative pore pressures, and are more sensitive than open systems.

Diaphragm Piezometers

Diaphragm piezometers use a sealed, flexible or movable diaphragm to separate the interal and external heads. Diaphragm piezometers can be divided into fluid-actuated sensor and electrical sensor types (see Table G-5). Although these piezometers are more expensive, sophisticated, and prone to failure than other types, they do have high sensitivity and rapid response time. The diaphragm responds to very small head changes quickly because very little water flow is required to displace the diaphragm. These piezometers can be read remotely from a central station and can measure negative pore pressures. They are delicate and a 10 percent failure rate is common. However, they are often the only units which are sensitive and respond rapidly enough for low permeability materials.

In the fluid-actuated sensors, the fluid pressure is adjusted (either manually or automatically) to balance the external pressure on the diaphragm. When the differential pressure across the diaphragm is zero, the fluid pressure is measured at the surface. Various systems of valves and flow indicators are used to detect the balance condition. The sensitivity of the fluid-actuated sensors is a function of the deformation induced in the diaphragm per unit of differential pressure across the diaphragm. The measurements are usually repeated several times to improve the accuracy of the reading. The fluid can be hydraulic (e.g., oil, see Figure G-18) or pneumatic (e.g., air or nitrogen gas, see Figure G-19).

The electrical sensor types have a strain gauge or displacement transducer attached to the diaphragm. The deflection of the diaphragm under the external head is measured to determine the pressure head. Either

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SUMMARY OF DIAPHRAGM PIEZOMETERS

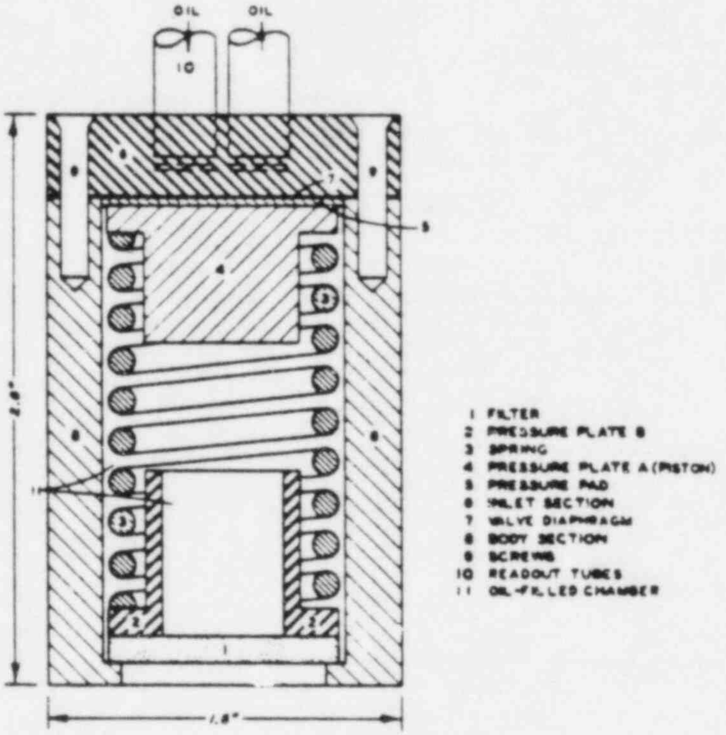
Table G-5

INSTRUMENT	APPLICABLE PERMEABILITY RANGE	ACCURACY	ADVANTAGES	LIMITATIONS AND PRECAUTIONS	RELIABILITY	ESTIMATED COST (1982 U.S. DOLLARS)		
						ACQUISITION	INSTALLATION*	CALIBRATION
DIAPHRAGM PIEZOMETERS	10^{-9} to 10^{-11} cm/sec	Depends on pressure gauge used Typically ± 1% or less of full scale	Very small time lag, usable in very low permeability media. Central observation system can be used. Can measure negative pore pressures.	Most costly and difficult to install and operate.	Good to Fair			
(FLUID ACTUATED SENSOR)								
Hydraulic Types			Simple. Easy to seal against leakage.	Can not measure negative pore pressures. Requires constant volume pumps.		$250	$280	$35
Pneumatic Types			Not subject to freezing. Smaller, less expensive tubing used and less sensitive to temperature, relative to hydraulic types.	Can not measure negative pore pressures. Leakage and moisture in lines are problems.		$200	$280	$35
(ELECTRICAL SENSOR)								
Electrical Resistance Strain Gauge Type		Depends on transducer. Typically ± 1% or less of range.	Can often be locally fabricated from commercially available parts. Adaptable to automatic data recording. Can measure negative pore pressures.	Service life of resistance type strain gauge is often limited. Susceptible to wiring damage. Correction for temperature needed.		$500	$280	$35
Vibrating-Wire Strain Gauge Type			More reliable than resistance strain gauge type. Adaptable to automatic data recording.	Correction for temperature needed.		$200	$280	$35

*Labor = $35/man-hour. Drilling costs not included

HYDRAULIC DIAPHRAGM PIEZOMETER

Figure G-18



after Cording et al, 1975

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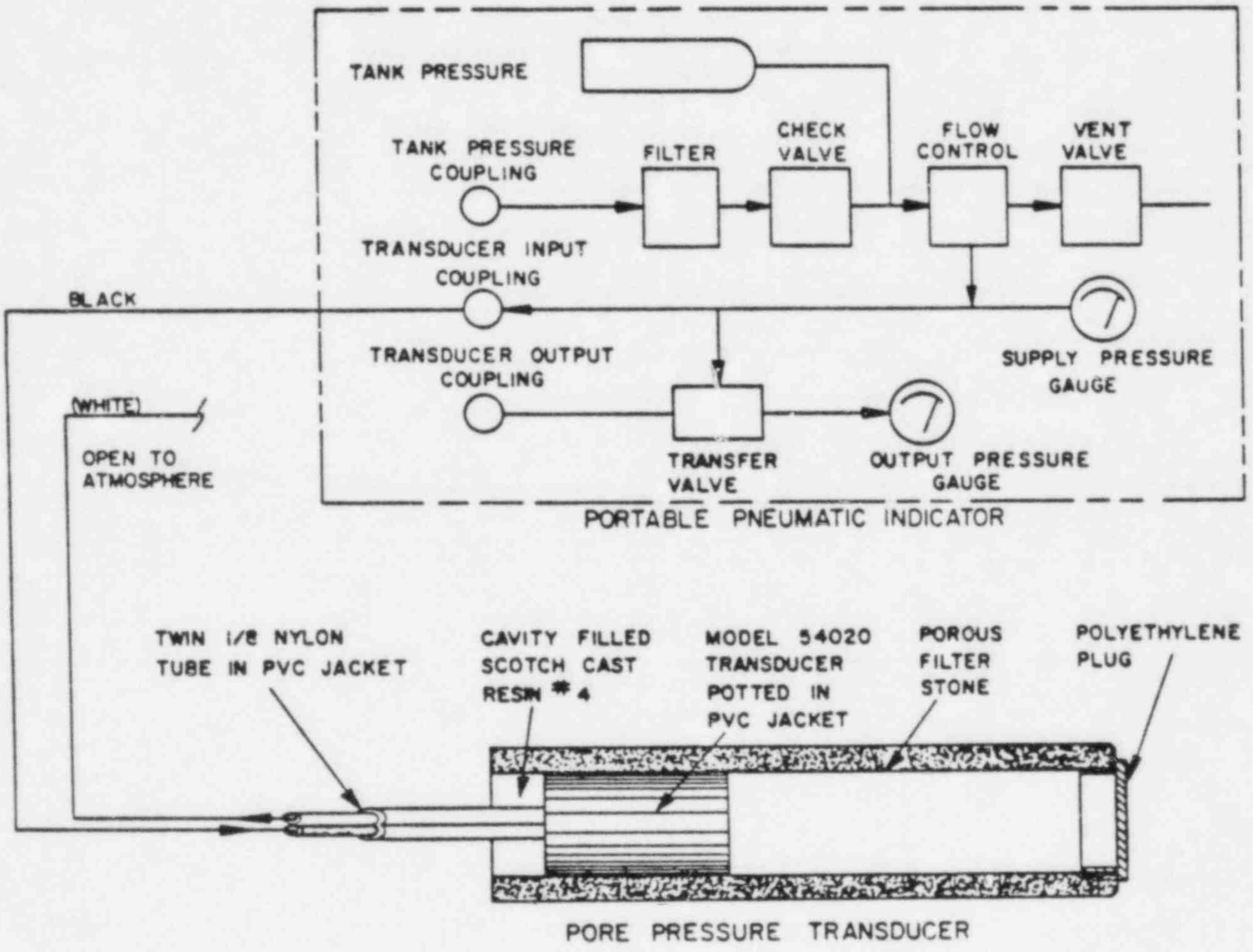
PNEUMATIC DIAPHRAGM PIEZOMETER

Figure G-19



after Cording et al, 1975

Rev. ____ Dwg. No. 313-11033 A6012 Date 1-82 ____ Eng. GG resistance or vibrating-wire strain gauges can be used as sensors (see Figure G-20a and b, respectively).

G.3.5 DATA ACQUISITION SYSTEMS

The advantage of electronic instrumentation is that it is compatible with the use of computerized data acquisition systems. Computerized data acquisition systems can increase the reliability of data measurement, and decrease costs by automating readings, and preprocessing data.

The functions that can be performed by data acquisition systems include:

- Automatic timed readings of instrumentation
- Recording of instrumentation data (analog)
- Conversion of analog signals to numerical (digital)
- Recording of digital information
- Preprocessing of data for analysis
- Graphical and tabular presentation of data
- Data analysis
- Graphical and tabular presentation of analytical results
- Storage of data and results
- Transfer of data and results to computing facilities.

Data acquisition systems can perform any number of these functions, and the cost of the system is directly proportional to its capabilities. In situ testing requires a sufficiently large number of readings so that the use of a computerized data acquisition system is generally justified.

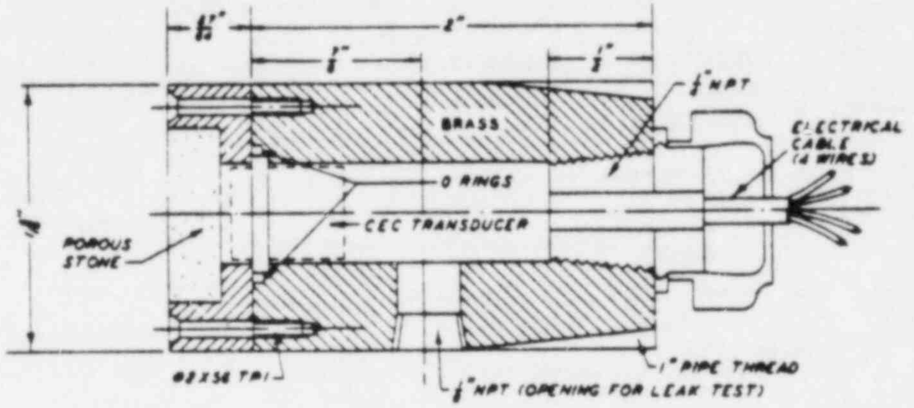
Data acquisition systems can be divided into two categories:

- Test specific devices which read and record data from only one test
- Centralized systems which read and record data from a number of tests simultaneously.

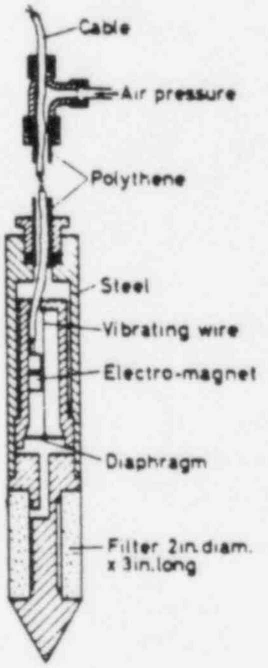
Test specific devices have the advantage that they are portable, and can be located at the test site. They can also be designed to provide exactly the needs of that specific test. Disadvantages include increases in expense due to duplication of reading and recording capabilities among data acquisition systems for different tests. In

ELECTRICAL SENSOR DIAPHRAGM PIEZOMETERS

Figure G-20



a) Electrical resistance strain gauge diaphragm piezometer



b) Vibrating-wire strain gauge diaphragm piezometer

after Cording et al, 1975

Rev.
Dwg. No. 813-11638 AK830 Date 1-82 Eng. KW

addition, individual reading and recording devices lack the advantages of centralized facilities, and data must be periodically transferred to a computer facility for reduction, analysis, and presentation.

Centralized facilities offer greater capabilities and flexibility, but suffer from problems of connection to instrumentation, data loss over greater distances, and risks of major disruption due to system malfunctions. Centralized facilities can offer on-line data analysis for continuous monitoring.

The choice between test specific and centralized facilities is one which must be made during the design of the overall test program. The magnitude of the data acquisition system required is related to the number of instruments to be read, the frequency of reading and the need for concurrent analysis of data.

A data acquisition system is made up of a combination of the following components:

- Central Processing Unit (CPU) controls the logic of data acquisition including control of measurement and recording devices, and reduction and analyses of data

- Real Time Clock provides the CPU with time signals required for scheduling of reading

- Analog-Digital (A-D) Converter converts analog signals from measuring devices (generally voltages) to digital signals understood by the CPU

- Multiplexer couples numerous input and output channels to the CPU

- Data Storage Devices include high speed (disk) and low speed (tape) storage systems. Storage devices provide both permanent and temporary storage of data from initial measurement through archiving.

- Input/Output (I-O) Devices include on-line terminals such as CRT's, teletypes, and decwriters, highspeed printers, and plotting devices. I-O devices provide the interface between the computer and engineering personnel.

- Software programs allow the engineer to control the data acquisition system through the CPU. Software includes the operating system for control of data storage and input/output devices, high-level programming languages such as Basic and Fortran, and applications programs written to perform the specific functions required from the data acquisition system.

The combination of components, and the size and speed of CPU, data storage, I-O devices, and software determines the capability of the data acquisition system. Typical unit costs for system components have been estimated (see Table G-6).

TYPICAL COSTS OF DATA ACQUISITION SYSTEM COMPONENTS

Table G-6

COMPONENT	SPECIFICATION*	MODEL	ESTIMATED COST (1982 U.S. Dollars)
Central Processing Unit	Nova 4/C 64 KB, 16 Slot	8391-H	6,092
Real Time Clock	Data Acquisition Control Subsystem	4300	2,670
Analog-Digital Converter	DG/DAC 50 KHZ A/D Converter (+/- 10V)	4280	1,820
Multiplexer	DG/DAC 16-Line Differential A/D MUX	4281	670
Data Storage Device (High Speed)	Winchester 12.5M Byte Moving Head Desk Including Controllers	6099	6,050
Data Storage Device (Slow Speed)	1600 BPI Streaming Tape Drive Subsystem	6125	6,800
I/O Devices (Video Terminal)	Dasher D200 Alphanumeric CRT Display	6109	2,350
I/O Devices (Printer)	Dasher TPI Printer	6043	2,200
Software (Operating System)	DOS-Initial License/STR/ CSS/ 1 YR SSS/ Install	3574-01F	2,000
Software (Programming Language)	DOS Fortran IV Initial License	3597-01F	1,100
Miscellaneous	19" Cabinet with Blower, Circuit Breaker, Auxiliary Blower	1144-A 4269	2,020

*Based on provisional quotation from Data General Corporation. The use of Data General equipment in this example does not signify endorsement of their products or an offering by Data General. Number of units, models and actual costs must be determined when the entire data acquisition system is designed.

G.4 COMMON SITE PREPARATION AND CHARACTERIZATION ACTIVITIES FOR IN SITU TESTING

G.4.1 EXCAVATION

There are two basic methods which are used to excavate underground openings: the drill and blast and mechanical excavation methods. Both of these methods may be used for the excavation of an in situ test facility and for the excavation of an HLW repository.

Drill and Blast

Drill and blast excavation uses high-energy explosives placed in holes that are drilled in the excavation in order to reduce the rock to blocks and fragments that may be easily removed from the tunnel. The method consists of three main operations:

- Drill blast holes
- Blast
- Muck removal.

Percussion drills are typically used for drilling the blast holes. These drills are often mounted on a drill jumbo (see Figure G-21) or, more typically for small excavations, single air leg drills are used. The holes are drilled in a pattern that is dependent on the geological conditions, the size of the tunnel, and the limitations of the mucking equipment. Various patterns may be used to minimize the disturbance to the rock around the tunnel while maximizing blasting efficiency.

The blast holes are charged with explosives such as dynamite or ammonium nitrate/fuel oil. The amount of explosive used in each of the blast holes depends primarily on the requirement to produce adequate fragmentation of the rock without causing excessive damage to rock around the tunnel. The explosives are ignited using various millisecond delays which allow the firing to occur in a sequence. The firing sequence is designed to maximize the number of charges that will blast towards a free face. Blasting towards a free face maximizes the efficiency of the blast and minimizes the damage to the surrounding rock.

The blasted rock is removed during the muck cycle. Tunnel supports may be installed during the muck cycle and prior to or during the following drill cycle.

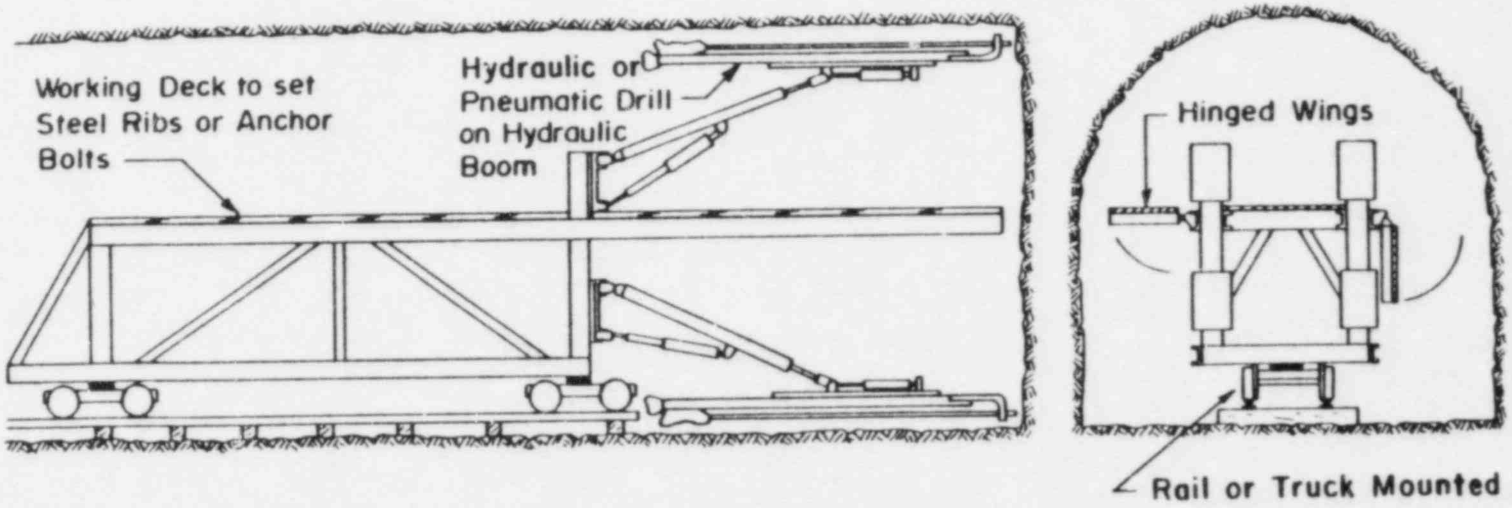
The disturbance to the rock surrounding the tunnel is a function of the following:

- Blast hole size, length, and orientation
- Charge per blast hole
- Blast hole pattern
- Firing sequence

Rev.
Dwg. No. 813-1034 A6021 Date 1 82 Eng. WW

DRILL JUMBO

Figure G-21



Note: This example is appropriate for intermediate size tunnels

after Golder Associates and MacLaren, 1976

- Rock strength, including the effects of discontinuities
- In situ stresses.

Various techniques can be used to minimize the amount of disturbance. One common technique is smoothwall blasting. This involves drilling small diameter "trim" holes at close spacing around the perimeter of the tunnel. The "trim" holes are loaded with a light charge. They are delayed so that they all fire simultaneously and are the last holes to fire. This ensures that they all fire towards a free face.

The advantages of the drill and blast method are:

- It can be used in any rock type

- It is versatile and adaptable to changing geological conditions along the alignment of the tunnel

- Any size and shape of opening can be excavated

- Mobilization costs are low.

Costs for drill and blast tunnel excavation and support of two sizes of tunnel in salt, welded tuff, basalt, and granite have been estimated (see Table G-7). In all cases, it has been assumed that the contractor and necessary equipment have already been mobilized at the site.

Mechanical Excavation

There are two mechanical excavation methods: full face and part face.

Tunnel boring machines (TBM's) excavate the full cross-sectional area of the tunnel in one pass, similar to a very large diameter drill. A TBM has a rotating shield or head that is about the same diameter as the tunnel that is to be excavated. Small cutting wheels are mounted on the rotating shield. The cutting wheels chip, grind, and fracture the rock as the shield is rotated and thrust forward. All but a few of the TBM's currently available excavate a circular cross section. TBM's have been used to excavate tunnels from 2 to 12 m in diameter. TBM's are best suited for use in tunnels with uniform, well-known geologic conditions where the rock is stable and is not very abrasive. TBM's are not very versatile and unexpected geologic conditions can result in long delays in excavation.

TBM's have the following advantages:

- Cause very little disturbance to the rock around the tunnel, so that less support is required

- May be more economical than drill and blast in long tunnels in suitable geologic conditions.

TUNNELING COST ESTIMATES

Table G-7

	ESTIMATED COST (1982 U.S. DOLLARS/LINEAR METER)			
Media	3 X 3 m Drill & Blast	3 m Ø TBM	6 X 6 m Drill & Blast	6 m Ø TBM
Salt	800	700	700*	500*
Welded Tuff	900	800	1,500	1,300
Basalt	1,200	NA	2,100	NA
Granite	1,000	NA	1,900	NA

*Unit cost for 6 X 6 m opening in salt is lower than 3 X 3 m opening because excavation and mucking equipment are well developed for the larger size, resulting in more efficient excavation.

Note: These estimated costs include excavation and support, but not mobilization.

- May have higher rates of advance than drill and blast method in suitable geologic conditions.

TBM's are usually not used in short tunnels because of the high costs for acquisition and the long time required for assembly and mobilization.

There are several types of part face tunneling machines available. One of the most commonly used types is the road header (see Figure G-22). The road header has a small cutting wheel mounted on an articulated boom. The operator moves the cutting wheel across the face in order to cut the desired cross section. The road header is suitable for tunnels less than about 6 m in diameter in weak to moderately strong rock. The road header has advantages over both drill and blast and TBM's:

- The amount of disturbance to the rock is comparable to that caused by a TBM
- The road header is very mobile and can easily be adapted to various geologic conditions. If rock is encountered that is too hard, it can easily be moved back from the face to allow intermittent drill and blast tunneling through the hard rock.
- Any cross-sectional shape can be cut.

Mechanical excavation is probably suitable for use in salt and tuff and probably not suitable in granite and basalt. A road header would probably be more feasible for the in situ test facilities because of the various shapes, sizes, and short lengths that are envisioned. Even though a full face TBM might be used in the final HLW repositories, a road header would be suitable for simulating the disturbance caused by a TBM.

Cost for mechanical tunnel excavation and support for two sizes of tunnel in salt and welded tuff have been estimated (see Table G-7). In all cases, it has been assumed that the contractor and the necessary equipment have already been mobilized at the site.

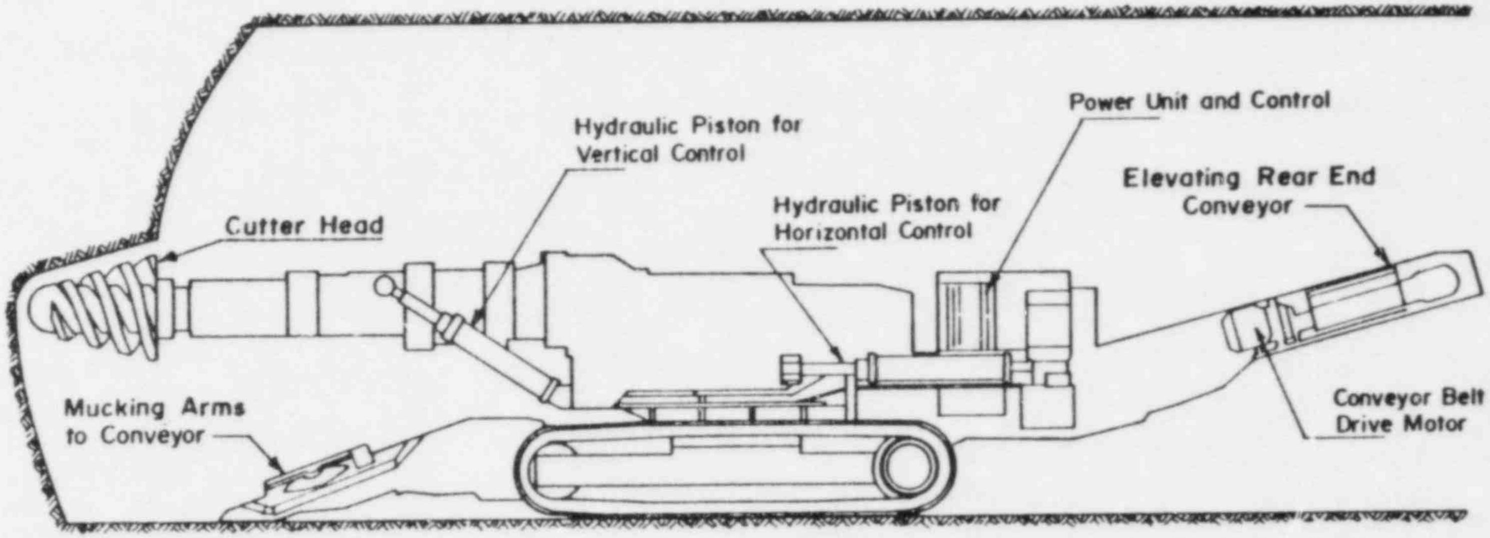
G.4.2 DRILLING, SAMPLING, AND LOGGING

The in situ test program will require drilling boreholes in various orientations from underground openings for installation of the instrumentation, as well as for assessment of characteristics (see Figure G-23). Boreholes may be bored using either coring or noncoring methods, depending on whether core samples are required. Borehole logging techniques may be used to provide additional information. Drilling and some direct logging costs have been estimated (see Table G-8); these estimated costs do not include mobilization or analysis/interpretation of data.

Rev.
Dwg. No. 813-11638 A6032 Date 1-82 Eng. WW

ROAD HEADER TUNNELING MACHINE

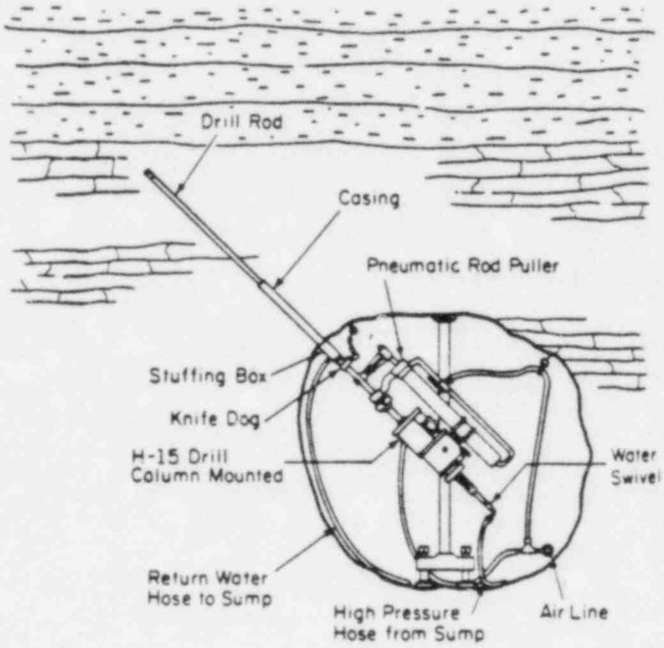
Figure G-22



after Golder Associates and MacLaren, 1976

UNDERGROUND DIAMOND DRILL

Figure G-23



after Goodman, 1976

DRILLING AND DIRECT LOGGING COSTS

Table G-8

A) CORING

Size Designation	Hole Diameter (mm)	Core Diameter (mm)	ESTIMATED COST (1982 U.S. DOLLARS)
EX	37.5	22.2	66
NX	75.8	47.6	100
PX	122.6	85.0	130
NX-Oriented	75.8	45±	130
Integral Sampling	122.6	85.0	250

B) NON-CORING	50	25

C) DIRECT LOGGING COSTS

Method		
Borehole Television		6
Seisviewer		
Caliper Logging	(typically included in standard suite of geophysical logs)	
Impression Packer		

Note: These estimated costs do not include mobilization or subsequent analysis/interpretation.

Core Drilling

The two general methods of core drilling in common use differ in the way core is retrieved from the hole. In the conventional method all of the drill rods and the entire core barrel are removed from the hole at the end of each run. In the wireline method, the inner tube of the core barrel is removed through the center of the drill rods by a cable. Wireline is not generally applicable for use in short boreholes drilled underground.

All drilling methods require a drill fluid to be pumped through the drill rods to the bottom of the hole to cool the bit and remove cuttings from the hole. The most frequently used fluid is water, sometimes with bentonite or soluble oil added. Compressed air may also be used. The disadvantage of using water for drilling in salt is obvious. The problems associated with using air is that it is difficult to blow cuttings from deep holes, and any moisture in the hole will result in the formation of a mud cake which can prevent the discharge of cuttings.

Core recovery is influenced by the type of bit used and the type of core barrel. The selection of the proper bit is greatly dependent upon the characteristics of the rock being cored, such as its solubility, hardness, abrasiveness, and degree of cementation. Diamond bits are usually used for coring, although tungsten carbide bits may be used in a soft rock. The type of barrel most often used is a double tube swivel-type design in which the inner barrel does not rotate with the outer barrel and cutting bit. In highly fractured or loosely cemented rock, a triple-tube core barrel in which the inner tube is split lengthwise is highly recommended. With this barrel, the inner tube is removed and opened lengthwise to expose the core, thereby assuring a relatively undisturbed sample for study and photography.

Two methods used to obtain additional information from cores are:

- Integral sampling - This specialized overcoring technique is used to recover badly fractured rock with a minimum of disturbance, i.e., complete recovery and with fracture aperture unchanged. A small-diameter hole is drilled and a steel rod is grouted into the hole. The rod is then overcored with a larger diameter bit, and the rod and surrounding cylinder of rock are removed as a unit (Rocha, 1971). This method is slow and difficult, and not feasible for deep holes.

- Oriented coring - Various instruments and techniques have been devised in an attempt to determine the original in situ orientation of drill core (Goodman, 1976). The objective is to allow determination of the absolute dip and strike of bedding planes and fractures. Mechanical, electrical, and magnetic methods have been attempted but no completely satisfactory system has yet been developed. Any attempt to obtain and utilize oriented cores, particularly from deep holes, should include a borehole survey.

Noncore Drilling

In some cases, it may not be necessary to obtain core samples from the boreholes, so that it is not necessary to use a coring method. There are three main types of noncore drilling methods:

- Blind bits are similar to coring bits, but they cut the full cross section of the rock. Blind bits may use either diamonds or tungsten carbide for cutting the rock.
- Rotary bits use three rollers with hardened steel teeth or tungsten carbide buttons to grind the rock.
- Percussion drills advance the hole by repetitious rapid blows, thereby crushing and chipping the rock ahead of the bit. Downhole hammers, which have a hydraulic or compressed air motor just behind the bit, are suitable for large diameter deep holes.

Noncoring methods are suitable for advancing a borehole down to the point where coring is required or for drilling holes that will be logged using geophysical or other methods. Noncoring methods generally are not suitable for drilling holes for installing instrumentation because of the need to know the geologic details that may affect the instrument installation and data interpretation.

Borehole Direct Logging

Valuable information may be obtained from observation and measurement of the borehole walls. Boreholes may be logged using direct observation and measurements or by geophysical methods which log some property of the rock in the walls of the borehole. The advantages and limitations of some of the common types of borehole logging methods are as follows:

- Borehole survey - Boreholes seldom follow their initial bearing and inclination. Even "vertical" boreholes drift and are seldom if ever plumb. A borehole survey measures the true inclination and direction of the borehole at frequent intervals in order to determine the true location of any point within that borehole.
- Borehole photography and TV - Photographic and TV cameras have been developed that can be lowered into boreholes three inches in diameter or larger. One of the cameras photographs the image on a conical mirror, which gives a donut-shaped photograph of the circumference of the hole; calculation of true strike and dip is possible. On one model of TV camera, the lens is directed downward onto an angled mirror that can be rotated from a control panel. Another model can be made to view axially, radially, or with a 180 degree lens opening and can be fitted with a zoom lens and a powerful floodlight. Dips and strikes can be estimated and the TV images can be recorded on tape for more detailed study. In addition to allowing determination of the spacing and orientation of fractures, joints and bedding, borehole cameras allow inspection of

zones of little or no core recovery. Their major disadvantage is that in holes filled with muddy or oily water they do not work well and are subject to frequent malfunction.

Under ideal conditions, camera surveys can give an understanding of subsurface conditions that is unobtainable by any other means except by direct inspection in large diameter shafts and adits.

A related instrument is the borehole televiewer which presents a continuous acoustic picture of the borehole produced by a rotating ultrasonic scanner. The reflected ultrasonic waves are converted into a visual image of the borehole. Fracture systems and the dip of fracture planes can be determined by this method (Zamanek, 1970). In order to obtain a good borehole picture, a slow and constant logging speed should be used and the suspended solids content of the borehole fluid should be low.

- Caliper logging - Caliper logging provides a continuous recording of borehole diameter versus depth. The caliper has three arms that can be controlled. The logs are used to determine borehole diameter, to locate caved zones, to identify fractures, and to correlate geologic boundaries. Geophysical logging methods can be correlated with the caliper logs to enhance the interpretation of the data and to obtain direct correlation with the actual rock condition. Thus, caliper logs are often obtained in conjunction with geophysical logs to aid the interpretation of the data.

- Impression packer logging - Impression packers are soft plastic packers that are inflated against the wall of the borehole in order to obtain an impression of the features that are present on the wall. The impression packer is oriented so it is possible to determine the strike and dip of fractures and other features on the borehole walls. It is also possible to obtain a rough estimate of joint aperture using the impression packer.

Borehole Geophysical Logging

Geophysical well-logging techniques test the earth with instruments inserted into boreholes; data are transmitted to recording devices. The logs give a detailed and continuous record of the borings and allow detection of subtle layer boundaries that can often be correlated between borings.

Qualitative interpretation of the logs enables estimating of porosity, permeability, lithology, pore-water chemical quality, geologic structure, fracturing, and fluid movement and distribution. Quantitative interpretation of porosity, permeability, and water salinity may also be performed. By correlating the logs obtained from boreholes, a subsurface geologic map can be drawn showing faults, structures, and changes in lithology and sedimentation.

Geophysical methods that have been applied in oil field well logging include electrical (self potential and resistivity), acoustic and nuclear logs. Caliper and temperature logs are also made to aid data interpretation. Generally, a standard ensemble of logs is run; the appropriate logging tools are selected according to the in situ rock conditions and the specific information required for the study. Costs for the standard set of logs is about 66 (1982 U.S.) dollars per meter, including interpretation.

The geophysical logs must be interpreted in conjunction with each other and with available core samples. Geophysical logs are made (by a field geologist, engineer, or technician) after drilling and core sampling have been completed and an initial evaluation of conditions has been performed. Depending on the method used, the borehole may be cased or uncased. For unstable rock in uncased holes, the boreholes should be kept open using a material such as drilling mud during the logging operation. Drilling mud also provides an electrolytic medium between the downhole probe and the wall of the borehole if electric logging is performed.

- Electrical logging - The physical properties measured in electrical well logging are electrical resistivity and self (or spontaneous) potential. Self potential and resistivity were the earliest and are still the most frequently applied methods of electrical logging. An electric log consist of simultaneously run measurements of electrical resistivity and self potential. Such logs are valuable for correlation between boreholes and for subsurface mapping.

    - self-potential (spontaneous potential) logging - Potentials in boreholes may be caused by a number of effects, e.g., streaming (electrokinetic) potential, shale (diffusion) potential, liquid junction, and mineralization. The principal effect encountered, however, is probably caused by electrochemical reactions occurring between the drilling fluid and the formation interstitial water (Wyllie, 1949).

      Measurements are usually made by recording electric potential differences between an electrode in a borehole and another electrode at the surface of the underground opening. In some instances, the potential gradient is measured between two downhole electrodes positioned at small spacings.

      The density and resistivity of the mud can seriously affect the measurement of potential. When the drilling mud is very salty, the potential curve is flat and may be useless. This condition may occur in salt.

    - resistivity logging - The electrical resistivity of a fluid-saturated rock depends mainly on the pore fluid conductivity, porosity, interconnection of voids, and bed thickness. In general, resistivity is inversely proportional to porosity and salinity. Usually, direct current or alternating current of low frequency is applied to current electrodes and the potential is measured between two or more potential electrodes. The result is a plot of apparent resistivity versus depth.

- Acoustic logging - Acoustic logs measure the elastic or seismic properties of the rock. In the acoustic logging method, sonic energy is generated by a transmitter in the borehole, and transmitted to one or more receivers. When the acoustic energy is recorded, identification can be made of four wave types. The first wave arrival is a compressional (P-) wave that travels in the rock surrounding the borehole. The second wave arrival is a shear (S-) wave that takes the same path. The third arrival is a fluid wave that travels through the fluid column in the borehole. The last (fourth) arrival is a Stoneley wave that travels along the area of contact between the borehole wall and the borehole liquid.

  The principal applications of sonic logs have been in detecting fractures (King and McConnell, 1973) and in determining porosity (Berry, 1959). Porosity can be determined using a standard formula that relates porosity to the wave velocity in the rock (formation) and the wave velocity in the fluid that fills the pore space (Wyllie et al, 1958).

- Nuclear logs - Some atomic nuclei emit natural radiation and others can be induced to do so. Although several types of rays are emitted (alpha, beta, and gamma rays, and neutrons), only gamma rays and neutron emissions have enough penetration to be of practical use in logging.

  Well logging instruments are basically of three types: (1) those that detect gamma radiation from the natural radioactive decay of uranium (U), thorium (Th), and potassium (K) in rocks; (2) those that use artificial gamma rays; and (3) those that induce nuclear processes using neutron sources.

  All natural rocks contain some radioactivity due to the presence of U, Th, and K^{40}. Radioactivity is generally lowest in basic igneous rocks, intermediate in metamorphic rocks, and highest in some sediments and granitic rocks. Shales, clays, and marls are generally several times more radioactive than sandstones, limestones, and dolomites. In a given area, the radioactivity of shales does not vary much, so that a gamma-ray log is an approximate measure of the amount of shale in the formation.

G.4.3 GEOPHYSICAL SEISMIC SURVEYS

Seismic surveys are useful for correlating rock units between boreholes, estimating rock quality, and estimating the elastic constants of the rock mass. There are three basic types of seismic survey: refraction, crosshole, and reflection. All three methods involve measuring the time required for the shear or compressional waves to travel between the source and the sensor. Seismic refraction and reflection are performed from inside of the tunnel while crosshole seismic is performed between boreholes (see Figure G-24).

Seismic Refraction

Seismic refraction measurements consist of creating a seismic impulse by explosive or mechanical means and recording arrival times of refracted seismic waves along a line of measurement (see Figure G-24a). Straight lines fitted to distance (from shot point) vs. arrival-time plots permit calculation of seismic velocities for the different layers encountered. Locations of velocity breaks in the travel-time curve are used to calculate distances to interfaces. In this method, the distance between shotpoints and detectors (geophones) is large compared to the distance to the seismic layers investigated; the separation needed is roughly three to five times the penetration.

Seismic body waves are either of the compressional (P-) or shear (S-) type. P-waves are always faster than S-waves in a given medium. For this reason, P-waves are used almost exclusively in seismic refraction, although experiments using S-waves have been performed and newer developments have made the use of S-waves in lithologic determinations potentially more interesting.

Seismic refraction is used primarily to determine seismic velocities and distance to adjacent layers. Such determinations are used not only for engineering purposes but also for corrections applied to seismic reflection surveys. In fact, seismic refraction invesigations of adjacent layers can be made part of a seismic reflection survey.

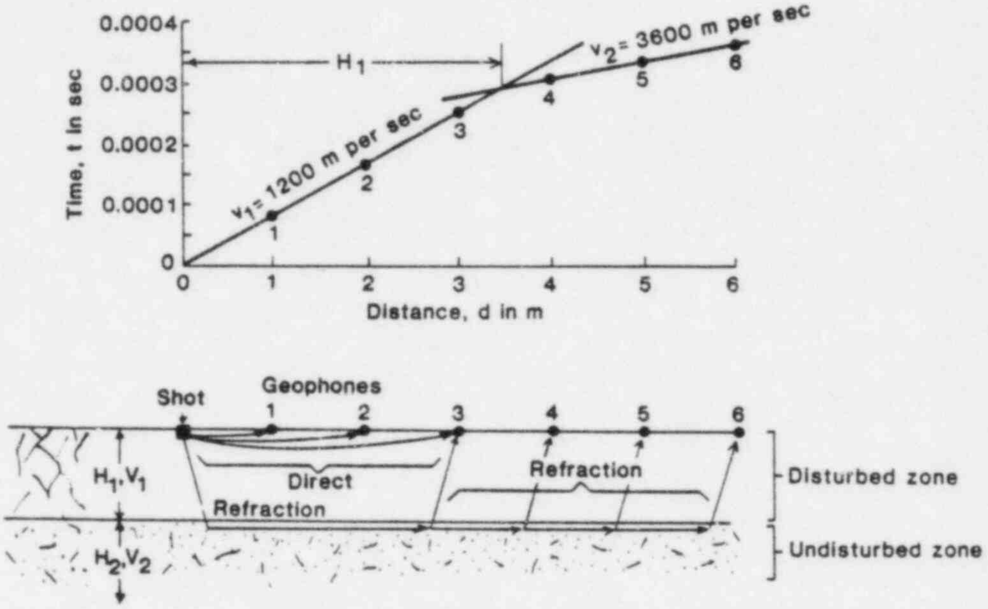
The usefulness of seismic refraction measurements is limited to investigation of the rock near the test opening. As the distance from the opening increases, the method becomes more and more approximate and difficult to interpret. The refraction method depends on the assumption that seismic velocities increase with distance from the source. If this assumption is not fulfilled, the method gives erroneous results.

Seismic velocities are directly related to the dynamic elastic constants of a medium, and velocities can be used to characterize the rock and soil types encountered.

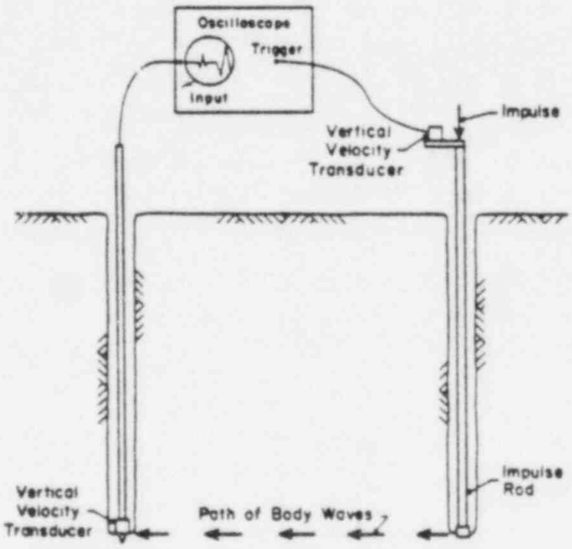
With reversed refraction profiles, location and dip of subsurface layers can be calculated. Other methods of interpretation exist for determining variations in subsurface depth for each geophone location.

Crosshole Seismic

In the crosshole shear-wave method, a seismic impulse is created in one borehole and wave arrivals are detected in an adjacent borehole (see Figure G-24b). It has been found that this method gives more accurate results and more detailed information concerning layers or fractured zones than other acoustic measurements, either in single boreholes or in uphole and downhole configurations (Mirafuente et al, 1974).



a) Seismic refraction



b)Schematic of a cross-hole seismic survey technique

after Stokoe and Woods, 1972

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Processing of crosshole shear-wave data is straightforward, and little or no interpretation is needed. The distance between boreholes divided by the travel time of shear waves gives the shear-wave velocity directly. The velocity can then be converted to dynamic shear modulus, if an estimate of density is available. Simultaneous measurement of compressional wave velocity can be used to estimate the dynamic elastic constants, e.g., Young's modulus or Poisson's ratio. Amplitudes of recorded shear and compressional waves can be used to determine attenuation characteristics of materials. These characteristics give additional information on rock quality and fracturing.

Seismic Reflection

Seismic reflection measurements are performed by measuring travel times of seismic waves artifically generated at or near a surface that return to that surface after being reflected. Compared with seismic refraction, shot-to-detector distances are small compared to distances investigated, and a smaller amount of energy is needed per shot for a given penetration. Normally, only P-waves are used.

Seismic reflection is by far the most expensive exploration method. However, it is also the most effective and most highly developed method which gives detailed and accurate information on the location of subsurface layers, faults, and cavities, as well as velocities. These are derived from measurements of reflection time vs. separation distance. In addition, amplitude measurements made on digital recordings define the reflection coefficient (velocity times density) and attenuation characteristics.

With accurate velocity information, distances to reflective layers can be calculated, usually to within a few percent. Correlation with nearby borings increases the accuracy. Resolution is a function of penetration distance and contrast in properties between layers. With increasing penetration distance, higher frequencies are attenuated, resulting in decreased resolution.

Seismic cross sections provide a wealth of data on the subsurface configuration, including faults and voids in, for example, salt. These structures are derived by interpreting the seismic cross section, and skill of the interpreter is a key factor in the quality of the interpretation. Voids may be indicated only by the presence of a diffraction pattern in the seismic section; however, if large enough, they may be completely resolved on a seismic section.

In spite of sophisticated methods used to attenuate multiple reflections, interpretation of the exact nature of a seismic horizon is still subject to critical evaluation by the interpreter.

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16. ABSTRACT *(200 words or less)*

The purpose of the complete project is to provide the NRC with technical assistance to enable the focused, adequate review by NRC of specific aspects related to design and construction of an in situ test facility and final geologic repository, as presented by DOE in Site Characterization Reports and License Applications (LA).

This report includes the general recommendation of available tests which should be considered in designing media/site specific in situ test programs. Tests will be conducted in an exploratory shaft and an underground test facility at the prospective repository horizon. Testing plans will be presented by DOE in an SCR and the complete results presented in the LA. A licensing perspective is outlined and a defensible rationale developed and utilized for the test selection process. This rationale consists of matching the capabilities of tests to the perceived information needs for LA. The information needs are a function of significant engineered components, site characteristics, available information and the acceptable level of confidence in satisfactory performance for each licensing step. Tests which are available and respond to the perceived media/site specific information needs, either by simulation or assessment of the characteristics, are identified and their capabilities assessed. Specific in situ tests are investigated and described in detail.

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