IN SITU TESTING REQUIREMENTS FOR HIGH LEVEL NUCLEAR WASTE DEEP GEOLOGIC REPOSITORIES

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1. Introduction

For the past eight years, Golder Associates, Inc., has been assisting the U.S. Nuclear Regulatory Commission (NRC) in their role of regulating the disposal of high level nuclear waste (HLW) in the United States. This technical assistance has included, among other activities, a detailed study regarding in situ testing requirements for repository development; the final report of this study was made publicly available in March 1983 (from NTIS) and is entitled In Situ Test Programs Related to Design and Construction of High-Level Nuclear Waste (HLW) Deep Geologic Repositories (NUREG/CR-3065). This paper briefly discusses the methodology for developing in situ testing requirements, as presented within that report.

2. Overview

In the United States, recent legislation (i.e., the Nuclear Waste Policy Act of 1982) has established a federal program for the storage and ultimate permanent disposal of HLW in deep geologic repositories. Within this program, the various federal agencies have the following responsibilities:

- The U.S. Environmental Protection Agency (EPA) will establish environmental standards for HLW disposal, as currently embodied in the draft 40CFR191;
- The NRC will ensure that EPA's long-term performance criteria, as well as other criteria related to public health and safety, will be achieved; a formal licensing process and, recently, technical criteria have been established by NRC in 10CFR60;

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- The U.S. Department of Energy (DOE) will select and investigate potential site(s), and design, construct, operate, and decommission the repository, as approved by NRC through the licensing process.

The sequence of repository development, including the licensing process, is depicted on the horizontal axis of Figure 1. Within this sequence, DOE is currently investigating several potential sites in different media (i.e., basalt, tuff and salt), and is expected to submit Site Characterization Reports (SCR) and Plans (SCP) for certain selected sites in 1983/1985. Such SCR/SCP's will present the available information regarding a site and repository design, identify outstanding issues, and present plans for their resolution.

The EPA performance criteria (draft) consist of the maximum allowable radionuclide release to the accessible environment for events of specified probabilities. The NRC has established (1) performance criteria for certain components of the system which are deterministic and intended to assure satisfaction of EPA criteria, and (2) other criteria pertaining primarily to safety during repository construction and operation.

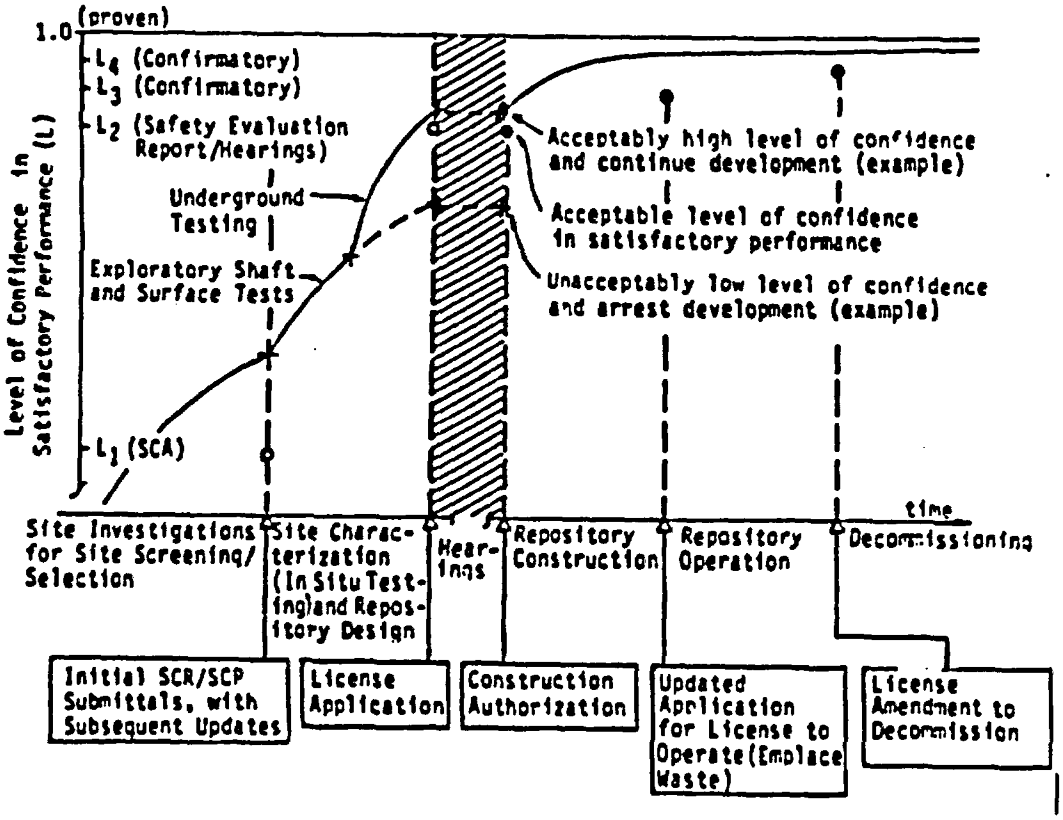

Fig. 1 Repository Development and Associated Levels of Confidence in Satisfactory Performance

It will be necessary to demonstrate sufficiently at each step of the licensing process that repository system performance will satisfy EPA and NRC criteria with an acceptable level of confidence. It will thus be necessary to either measure or predict repository performance and compare it with the criteria. Predictions must necessarily be based on either extrapolation of measured results or numerical models of the repository (engineered and geologic) system. However, any prediction of performance will contain significant uncertainty, due especially to the long time-frame of interest and the potential physical complexity of a geologic disposal system. For modeling, this uncertainty will be composed of the inherent uncertainties associated with the input (i.e., site characteristics and descriptions/parameters of constructed engineered components, including loading functions such as heat, etc.) and the models themselves. It will be necessary to quantify these uncertainties, and in most cases reduce them, in order to demonstrate that the criteria will be met with an acceptable level of confidence.

The acceptable level of confidence for meeting the performance criteria will increase with respository development. These acceptable levels, not currently specified, can be determined implicitly, as presently being done by NRC through discussions with DOE, or explicitly, e.g., by defining the acceptable level for the final step and assuming the number of sites being considered during each activity. As shown in Figure 1, if the probability of achieving the performance criteria must be relatively high at the initial license application in order to grant a Construction Authorization, then the uncertainties in predicted performance may need to be significantly reduced during site characterization by in situ testing. Such in situ testing can provide:

- Validation of predictive models;
- Improved assessment of significant site characteristics; and
- Simulation of some engineered system components (regarding construction and performance).

3. Approach

A defensible rationale for identifying in situ testing requirements has been developed, as shown in Figure 2, which consists of:

- Identifying information needs based on the existing site information with respect to the information required for licensing.
- Identifying and evaluating the capabilities of all available tests for responding to the information needs.
- Designing the in situ test program by (1) identifying tests or combinations of tests (if any) which will satisfy the information needs, (2) selecting the most efficient of the suitable tests, (3) determining

development and validation of tests which is required where the test capabilities are currently insufficient, and (4) designing each test in detail to satisfy the specific objectives regarding information needs; the in situ tests selected and the required in situ test development comprise the in situ test program, while the supplemental surface, borehole, and laboratory testing comprise another portion of the site characterization program.

- Conducting the in situ test program, i.e., developing/validating tests (as required), performing tests (according to specified procedures), and analyzing/interpreting test results (including assessment of uncertainties).
- Reevaluating the in situ test program with respect to licensing requirements as the information needs change (as more site information becomes available) and the test capabilities change (as test development occurs).

4. Information Needs

More specifically, the identification of information needs, i.e., the additional information needed for license application for construction, consists of:

- Identifying the information required for license application for construction, including:
  - performance criteria, and associated required levels of confidence (or probabilities), and
  - predicted performance and the inherent uncertainty in the prediction, which is a function of
    - performance assessment methodology
    - assessment of site characteristics, including variability and uncertainty
    - repository design, including planned contingencies;

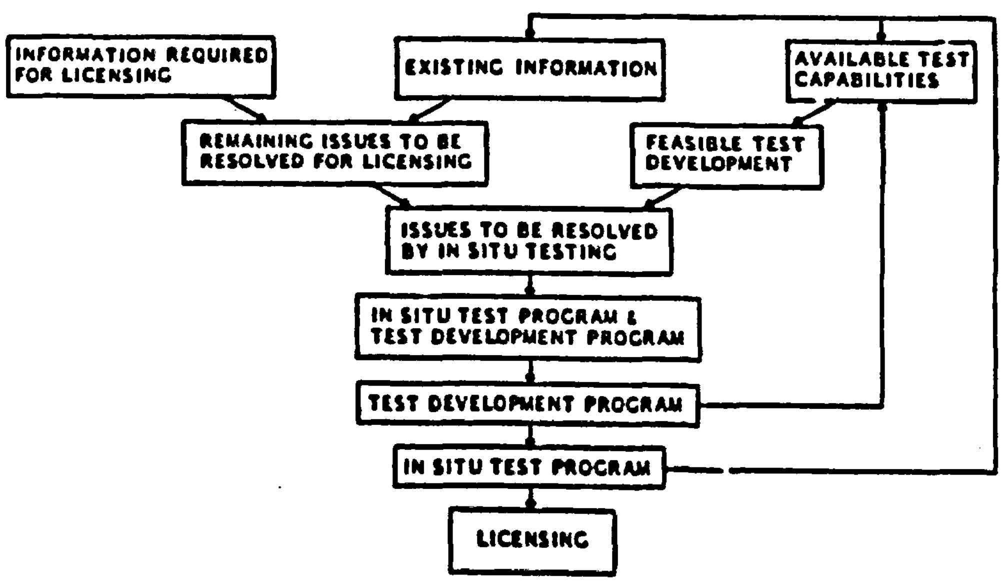

Fig. 2 Approach to Identifying In Situ Testing Requirements

- Identifying and assessing the existing information (e.g., as presented in the SCR/SCP), including:
  - existing data base on site characteristics,
  - current interpretation of data base, including uncertainty in assessment and correlations between characteristics,
  - current repository design,
  - current performance assessment methodology (i.e., predictive models), and model uncertainty, and
  - current performance assessment (i.e., prediction of performance), and uncertainty; and

- Comparing the existing information with that required for licensing to identify additional information needed.

Hence, current information needs, consisting of the type of information required, as well as the amount, to sufficiently reduce the uncertainty in performance predictions for licensing decisions to be made, can be identified for any site. It should be noted that as more information becomes available, or as the repository design, performance assessment methodology, or license requirements change, the information needs may change. The information needs must thus be periodically reevaluated during site characterization to ensure acquisition of all licensing-related data.

Regarding the information required for license application for construction, the following two primary generic technical issues of HLW disposal have been identified:

- Adequacy of site and engineered components (as designed) to ensure isolation of radionuclides from the accessible environment; and
- Suitability of construction techniques and operational procedures to ensure safety of personnel and implement design of engineered components.

From these, a comprehensive and specific set of generic technical issues has been explicitly derived, as given in the left column of Table 1.

Each issue must be sufficiently resolved at license application. Such resolution can be provided by either:

- Physical simulation; or
- Analytical prediction, which requires:
  - perception of physical processes,
  - development of models to represent the perceived physical processes,
  - assessment of site characteristics, and
  - understanding and description of engineered system.

The specific types of information needed to resolve each of the identified issues has been identified in Table 1. For example, there are two types of site characteristics which are needed for performance assessment, those which describe the geologic setting and those which describe the response/behavior of the site. The geological setting includes the in situ hydraulic head, stress and temperature fields, lithology and discontinuity structure of the rock mass, the pore fluid characteristics, and tectonics. The response characteristics are those which describe the mechanical (i.e., strength, deformation, creep/fusing), thermal (i.e., thermal conductivity, heat capacity, thermal expansion), hydrologic (i.e., hydraulic conductivity, effec-

● PRIMARY INFORMATION NEEDED
○ SECONDARY INFORMATION NEEDED

ISSUES	PHYSICAL SIMULATION	SITE CHARACTERISTICS: GEOLOGIC SETTING					SITE CHARACTERISTICS				MODELS				DESIGN
		STRAT STRUCT	TECONTIC	STRESS	HEAD	TEMP	MECH.	THERMO.	HYD.	GEOCHEM.	MECH	THERMO.	HYD.	GEOCHEM.	
CONSTRUCTION TECHNIQUES															
SHAFT CONSTRUCTION	●	●		○	○		○		○		○		○		●
ROOM/TUNNEL CONSTRUCTION	●	●		○			○				○				●
EMPLACEMENT HOLE CONSTRUCTION	●			○			○				○				●
ENGINEERED BARRIER CONSTRUCTION	●	○													●
RETRIEVAL TECHNIQUES	●	○		○	○	○	○	○	○	○	○	○	○	○	●
OPERATIONAL PROCEDURES															
HOISTING SYSTEMS	●														●
TRANSPORT SYSTEMS	●														●
VENTILATION/COOLING SYSTEM	●					○		○				○			●
DEWATERING SYSTEM	●				○				○				○		●
WASTE HANDLING SYSTEM	●														●
SAFETY SYSTEMS	●														●
PRE-CLOSURE PERFORMANCE															
SHAFT STABILITY/DEFORMATION	●	●	○	●	○	○	●	○	○	○	●	○	○	○	●
SHAFT SEAL INTEGRITY	●	●	○	○	●	○	○	○	●	●	○	○	●	●	●
ROOM/TUNNEL STABILITY/DEFORMATION	●	●	○	●	○	○	●	●	○	○	●	●	○	○	●
ROOM BACKFILL INTEGRITY	●		○	●	○	○	●	●	○	●	●	●	○	○	●
OPERATING TEMPERATURES IN ROOMS/TUNNELS	○	○			○	●		●	○			●	○		●
WATER INFLOW INTO ROOMS/TUNNELS	●	○	○	○	●	○	○	○	●	○	○	○	●	○	●
EMPLACEMENT HOLE STABILITY/DEFORMATION	●		○	●	○	○	●	●	○	●	●	●	○	●	●
EMPLACEMENT HOLE BACKFILL INTEGRITY	●		○	●	○	○	●	●	○	●	●	●	○	●	●
WASTE PACKAGE CORROSION	○			○	○	○	○	○	○	●	○	○	○	●	●
POST-CLOSURE PERFORMANCE															
WASTE PACKAGE LIFE AND SUBSEQUENT NUCLIDE RELEASE RATE				○	○	○	○	○	○	●	○	○	○	●	●
NUCLIDE TRANSPORT THROUGH ENGINEERED SYSTEM		○	○	○	●	●	○	●	●	●	○	●	●	●	●
NUCLIDE TRANSPORT THROUGH GEOLOGIC SETTING TO ACCESSIBLE ENVIRONMENT		●	○	○	●	○	○	○	●	●	○	○	●	●	○
OTHER SURFICIAL EFFECTS		●	○	○	○	○	●	●	○		●	●	○		○

Table 1 Specific Generic Technical Issues and Information Required for Their Resolution

tive porosity, specific storage), and geochemical (i.e., dispersivity/diffusion, adsorption/retardation, alteration/solubility) behavior of the rock mass. Many of these response characteristics are correlated to some degree with each other (e.g., modulus and strength) and with physical descriptors of the rock mass (e.g., strength correlates with jointing). The values of response characteristics are often a function of orientation, duration, stress level, pore pressure, temperature, radiation dose, and scale of measurement; these functions are discussed and presented in NUREG/CR-3065, and not repeated here. However, as an example and depending on rock type, thermal conductivity is often somewhat anisotropic and scale dependent, a strong function of temperature and a weaker function of stress level and pore pressure, and relatively unaffected by time-dependence and radiation dose. In addition, there may be natural variability of characteristics on the repository scale, due to possible inhomogeneity and discontinuities in the rock mass.

As an example of information requirements, the issue of room/tunnel stability/deformation (under preclosure performance) can be resolved by:

- Physical simulation; or
- Analytical prediction, for which the following information is needed:
  - site characteristics near room/tunnel
    - geologic setting
      - stratigraphy/structure
      - in situ stress
    - mechanical properties
      - strength
      - deformability
      - creep
    - thermomechanical properties
      - thermal conductivity
      - heat capacity
      - thermal expansion,
  - models
    - mechanical response
    - thermomechanical response, and
  - design
    - opening geometry/orientation
    - structural support.

As previously discussed, however, the resolution of any issue will be determined by the uncertainties inherent in the simulation or prediction of performance, and thus in the models, the constructed engineered components, and especially in the assessment of site characteristics. For example, the uncertainty in the estimate of each characteristic will be related to:

- The range in physically possible values;
- Natural variability; and
- Quality of the data base, i.e.,
  - sufficient number of data points, and
  - appropriateness of each data point, regarding
    - representativeness of sample (e.g., appropriate scale, no sampling disturbance, no change in pore fluid)
    - representation of appropriate environmental conditions (e.g., stress level, temperature)
    - test control/accuracy.

In situ testing can and should improve the quality of the data base in order to reduce the uncertainty in the assessment of site characteristics, as well as reduce the uncertainty in models (by validation) and constructed engineered components (by simulation).

5. Available Tests and their Capabilities

There are a wide variety of currently available test methods for assessing the significant site characteristics. These methods can be categorized as being either surface tests, borehole tests, laboratory tests, or subsurface tests (from an adit or shaft). A relatively comprehensive list of available tests in each category for assessing each of the site characteristics has been compiled, based on experience and previous in situ testing programs, and presented in NUREG/CR-3065 (and not repeated here). However, as an example, the following tests are available for assessing thermal conductivity:

- Borehole tests:
  - rock coring for subsequent laboratory testing,
  - thermal probe (single borehole, small scale heater test), and
  - heater test (x-hole, small scale);

- Laboratory tests:
  - heated rock sample,
  - heated unconfined compression test on rock core, and
  - heated triaxial test on rock core; and

- Subsurface tests:
  - rock mass sampling for subsequent laboratory testing,
  - thermal probe (in borehole from underground),
  - heater test (x-hole, small scale, in borehole from underground),
  - heater test (large scale),
  - heated block test (with or without stress),
  - pillar test (either jacking axially or reducing lateral dimensions) with heat,
  - chamber test with heated water, and
  - monitor temperature in rock mass and excavation (with ventilation and cooling).

In addition to assessing site characteristics, predictive models must be validated by testing. Such validation will generally require simulation, although not necessarily at full scale, of some aspect of repository performance. In addition to providing model validation, the results of such simulation tests can sometimes be extrapolated directly to predicting repository performance. A list of representative simulation tests has also been compiled and presented in NUREG/CR-3065 (and not repeated here).

Clearly, some tests provide a variety of information to be used in resolving identified issues, not just assessing one characteristic nor simulating one aspect of performance. The information provided by each currently available test method has been identified and presented in NUREG/CR-3065 (and not repeated here). However, as an example, the large scale heater test can provide the following information:

- Physically simulates:
  - emplacement hole construction,
  - waste emplacement hole backfill construction,
  - retrieval techniques,
  - emplacement hole stability/deformation,
  - emplacement hole backfill integrity, and
  - waste package corrosion; and

- For analytical predictions:
  - assesses thermomechanical properties,
  - validates thermomechanical models, and
  - directly evaluates design (heat loading) options.

The various test methods available for assessing each significant site characteristic do so with various limitations and levels of uncertainty. The correlation between the test results and the actual site characteristic is determined by whether or not the sample is likely to be representative, the environmental conditions can be appropriately represented, and the test can be adequately controlled, i.e., the measured results considered accurate. However, 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. Hence, the resulting level of uncertainty will typically be media and site dependent.

Differences between the various tests related to the uncertainty in the assessment of values of site characteristics are primarily a result of the following general factors:

- Surface tests:
  - able to effect large scale (regional) characterization,
  - test volume sometimes inhomogeneous (too large),
  - minimal sampling disturbance,
  - data must be extrapolated to great depths,
  - poor resolution, and
  - cannot test characteristic for a range of environmental conditions;

- Borehole tests:
  - able to effect large scale (regional) characterization,
  - test volume often unrepresentatively small,
  - limited ability to vary environmental test conditions,
  - poor control of test due to remoteness, and
  - drilling disturbance may be significant;

- Laboratory tests:
  - test volume often unrepresentatively small,
  - undisturbed samples difficult to obtain,
  - able to test for a wide range of conditions, and
  - good test control; and

- Subsurface tests:
  - generally unable to effect large scale (regional) characterization,
  - able to test representative volumes,
  - accurate evaluation of local rock mass properties, and
  - minimal sample disturbance.

The site characteristic assessment variables which can be incorporated in each of the available test methods have been identified, based on standard test methodologies, and presented in NUREG/CR-3065 (and not repeated here). However, as an example, in assessing thermal conductivity, the large scale heater test adequately incorporates anisotropic, scale, and temperature conditions, but does not investigate stress dependency; duration and radiation dose are not significant. Clearly, in order to adequately assess a characteristic, a test method should incorporate those assessment variables to which that characteristic is sensitive.

In terms of <u>simulation tests</u> for model validation, the uncertainty is primarily a function of (1) the assessment of material characteristics to be used as input to the model, where there is inherent uncertainty in this assessment and often natural variability of characteristics throughout the affected zone, and (2) the control or knowledge of the boundary conditions. In terms of simulation tests for direct extrapolation of results to predicting repository performance, the uncertainty in extrapolation will be a function of the similarity between the test case and prototype.

The capabilities of many of the currently available tests can be significantly improved by development. Potential research and development activities to improve specific existing in situ tests, especially improving the accuracy of test results as well as incorporating additional assessment variables, have been discussed in NUREG/CR-3065 and are not repeated here. Much of this is focused on improving the accuracy/reliability of the instruments used to measure and record test results under often adverse conditions.

In addition to improving existing tests, new or hybrid tests with significantly different capabilities might be developed to adequately respond to the information needs. Also, as site-specific experience is gained with various tests, especially as site-specific correlations are developed for simpler tests, the uncertainty in the test results for these tests will generally decrease.

Clearly, test capabilities will be continually changing as test development occurs. Hence, test capabilities should be periodically reevaluated during test development to ensure that the information needs for license application will be met in an efficient manner.

6. In Situ Test Programs

As previously discussed, the identification of in situ test programs, i.e., in situ testing and associated test development for a specific site, consists of:

- Matching current test capabilities with current information needs and selecting those tests (or combinations of tests) which adequately respond to the current information needs in the most efficient way (in terms of cost and schedule); and
- Identifying information needs which cannot be satisfied with existing test methods, and selecting that test development which will sufficiently improve the test capabilities in the most efficient way to satisfy the remaining information needs.

Based on current test capabilities and perceived information needs for sites presently being considered by DOE, example in situ test plans have been developed for each and presented in NUREG/CR-3065 (and not repeated here). However, as an example, the tests comprising an in situ test plan for a site in salt are given in the left column of Table 2. As shown in Table 2, these tests would be expected to provide the information necessary for issue resolution by either physical simulation or analytical prediction. Most of these tests, as well as additional hydrologic tests (i.e., x-hole permeability and tracer tests, and chamber tests) suitable for other media, have been described in great detail, and recommendations made, in NUREG/CR-3065.

Similarly, based on the current limitations of available tests (with respect to the information needs) and on feasible test improvements, example test development plans have been developed. Many of the test components (i.e., equipment, instrumentation or procedures, including flatjacks, heaters, stress measuring, extensometer or inclinometer installation/monitoring, water/brine collection, data acquisition system) which might need development or validation prior to actual in situ testing could be sufficiently tested, for example, by performing a partial (or modified) heated block test. Other aspects (e.g., coring, groundwater sampling, permeability testing, piezometer installation/monitoring, hydrofracturing, overcoring, geophysical/seismic/radar testing, acoustic emission monitoring) could be relatively simply performed individually or in conjunction with such a block test.

As previously discussed, the test capabilities may change as a result of development and the information needs may change as more information is obtained; hence, both must be

● Primary information provided by test

● Secondary information provided by test

TESTS	PHYSICAL SIMULATION [illegible]	PHYSICAL SIMULATION [illegible]	PHYSICAL SIMULATION [illegible]	PHYSICAL SIMULATION [illegible]	ANALYTICAL PREDICTION: SITE CHARACTERISTICS (Geologic Setting)	SITE CHARACTERISTICS [illegible]	MODELS	DESIGN
I. Exploratory Excavation with Geologic Mapping of Surfaces	● ● ●		● ● ●		● ● ●	● ● ●		
II. Tests								
● Index Tests					●	● ● ●		
● Geophysical Testing					●	●		
● Groundwater and Rock Sampling for Laboratory Tests					●	● ● ● ●		
● Boreholes with Appropriate Logging					● ●	● ● ●		
● Single Borehole Permeability Tests						●		
● Borehole In Situ Stress Tests					●			
● Flatjack Tests (10)					●	●	●	
● Heater Tests - Small (4) Large (1)	● ● ●		● ● ●			● ● ● ●	● ● ●	●
● Block Tests (?)					●	● ● ● ●	● ● ● ●	
● Mine By Test (1)	●		●		● ●	●	●	●
III. Monitoring								
● Monitor Excavation Behavior						●	●	
● Monitor Drainage and Air Moisture from Excavation			●		●	●		●
● Monitor Hydraulic Heads, Temperature and Displacements in and around Excavation			● ● ● ● ●		● ● ●	● ● ● ●	● ● ●	●
● Seismic, Acoustic Emission Monitoring					● ●	●		
● Other Construction and Operation Monitoring	● ● ● ● ●	● ● ● ● ● ●						●

Table 2 Resolution of Issues by In Situ Testing

periodically reevaluated during site characterization. The in situ test program must therefore contain the flexibility to be efficiently revised during its performance as the test capabilities and/or information needs change. It should be emphasized that if (1) the test capabilities change as anticipated during test development, (2) the uncertainty in site characteristics and modeling simply reduces as anticipated during in situ testing, and (3) no other unanticipated changes in the information needs occurs (e.g., due to changes in licensing requirements, repository design, performance assessment methodology, or expected value of site characteristics), then the in situ testing program would be on target and the plan would not need revision. It must be expected that some unexpected changes, especially in the information needs, will occur. Provisions must be taken to periodically update the information needs and test capabilties and monitor the progress of the in situ test program. This would allow corrective action to be taken as early as possible by DOE to ensure that licensing requirements are most efficiently achieved.

7. Conclusions

A logical and defensible methodology has been developed for determining in situ testing requirements for HLW repositories. This approach ensures that the information required to sufficiently resolve outstanding issues, and adequately demonstrate that the various criteria will be met, at license application for construction will be obtained in an efficient manner.

8. Acknowledgements

The author wishes to thank the U.S. Nuclear Regulatory Commission for their assistance in funding this study, and also acknowledges the contributions of his colleagues at Golder Associates in undertaking this study.

This paper was prepared as an account of work sponsored by an agency of the United States Government (under Contract No. NRC-02-81-037). Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this paper, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

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