Performance Confirmation for the Candidate Yucca Mountain Repository

Interim Report

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ABSTRACT

Activities surrounding the candidate spent fuel and high-level radioactive waste repository at Yucca Mountain are nearing a critical juncture. Within a year, it is likely that the U.S. Department of Energy will have submitted a 'Site Recommendation' (SR) to the President and Congress to consider whether DOE should be allowed to proceed into licensing with the U.S. Nuclear Regulatory Commission (NRC).

Accompanying the SR letter will be a very large amount of documentation with the technical bases for the Recommendation. The documentation supporting the construction license application (LA) submittal to the NRC will be even more extensive. The technical bases, while drawing on more than 13 years of research and analyses, necessarily contain some uncertainties about the very long-term evolution of the candidate Yucca Mountain repository. Uncertainty in the projections of consequences is why both NRC and the U.S. Environmental Protection Agency recommend a risk-based approach to demonstrating, with reasonable assurance, that future human health in the Yucca Mountain vicinity will be adequately protected.

NRC will be required to make separate determinations on whether or not to authorize DOE to first construct, then operate, and finally close the repository. These determinations will be spaced years apart. In the intervening time between decision-points DOE's data and modeling projections will evolve and improve. They will submit and re-submit, under rigorous quality assurance standards, increasingly detailed analyses of the processes upon which the original LA was based. The continuing scientific research program that will take DOE from the initial SR decision, through the licensing process, to the final decision to close the repository is known as "Performance Confirmation". Work done under this program is vital to demonstrating that reasonable assurance that future populations will be protected can withstand the test of time.

EPRI has embarked on a two-year effort to identify the testing, monitoring, and other related activities that should be included in a performance confirmation program, and define why each particular activity should be included. The purpose of this interim report is to begin to establish the bases for the performance confirmation activities, and explore some of the potential activities proposed previously by DOE and EPRI. This interim report will establish the approach to identifying the components of the performance confirmation plan. It is expected that the final EPRI report on performance confirmation will provide more detail regarding both the specific activities and the quantitative criteria by which they can be said to 'confirm' the models and parameter values upon which DOE's long-term performance projections are based.

CONTENTS

1
INTRODUCTION

1.1 Background

The U.S. Department of Energy (DOE) is currently embarked on a program to evaluate the suitability of a candidate spent fuel and high-level radioactive waste (HLW) repository at Yucca Mountain, Nevada. DOE has conducted extensive testing, both in situ and in the lab, of the properties of the natural system and the underground engineered barrier system (EBS). Other field observations worldwide from 'natural analog' sites have provided additional information on the potential long-term behavior of the candidate repository at the Yucca Mountain site. These laboratory and field data and observations have been used to develop detailed conceptual and numerical models of subsystem and total system behavior. In turn, these models have been used to develop projections of the potential long-term radiological exposures to a hypothetical population living downstream of the candidate repository due to the presence of the HLW repository. DOE now has over 13 years of data collection and modeling experience behind them.

If DOE determines that the site is suitable, the anticipated release of the 'Site Recommendation' report in 2001 will mark a change in roles for DOE. The Department will, at that time, shift from being a site investigator to advocating use of the site for permanent HLW disposal. The intent of the 'Site Recommendation' (SR) report, as defined by the Nuclear Waste Policy Act (NWPA), is to formally recommend the Yucca Mountain site to Congress and the President for their approval to proceed into licensing. Assuming DOE receives this approval from Congress and the President the next step will be for DOE to submit a license application (LA) to the U.S. Nuclear Regulatory Commission (NRC) to begin construction and loading of the repository.

Both the SR report and subsequent LA documentation are expected to be extensive. The SR report will provide not only the recommendation, but will include the detailed technical bases for the recommendation. Advocating the use of a deep geologic repository for HLW disposal requires consideration of a combination of engineered, and complex natural systems, and projections of radiological consequences over time frames of 10,000 years or more. Thus, the data and modeling projections involve very large-scale processes in both space and time.

The LA process and documentation will be even more extensive. Uncertainty in the projections of consequences over these large scales is why both NRC and the U.S. Environmental Protection Agency recommend a risk-based approach to demonstrating, with reasonable assurance, that future human health in the Yucca Mountain vicinity will be adequately protected. It is also why the NWPA prescribes a three-step licensing process. NRC will be required to make separate determinations on whether or not to authorize DOE to first construct, then operate and finally close the repository. These determinations will be spaced years apart. In the intervening time between decision-points DOE's data and modeling projections will evolve and improve. They will submit and re-submit, under rigorous quality assurance standards, increasingly detailed analyses of the processes upon which the original SR was based. NRC will conduct rigorous reviews of all of this information and they will ask many questions that DOE will be required to answer. This entire process will be open to public scrutiny and participation. The continuing scientific research program that will take DOE from the initial SR decision, through the licensing process, to the final decision to close the repository is known as "Performance Confirmation". Work done under this program is vital to demonstrating that a reasonable assurance that future populations will be protected can withstand the test of time.

1.2 Managing Uncertainty

DOE must provide a sufficiently high level of confidence to decision-makers that the candidate Yucca Mountain site, when properly designed, loaded with HLW, and closed, will adequately protect human health over 10,000 years or more. In order to achieve this goal, DOE is building an appropriate safety case upon an extensive knowledge base about the mountain's natural features and additional engineered barriers that DOE intends to place in the repository. One of the main features of such a safety case is the appropriate management of uncertainties [EPRI, 2000, DOE, 2000a]. Appropriate management of uncertainties should provide decision-makers confidence, that: 1) the design of the repository is sufficiently robust to withstand a range of insults to its integrity and still perform well enough to adequately protect future human health; and 2) even if the future evolution of the repository site and vicinity are not perfectly known today, projected negative consequences of placing HLW in the repository are both below conservatively established regulatory limits, and not likely to have been underestimated.

After identifying which features, events, and processes (FEPs) have significant uncertainty (or variability), there are several options for managing them [EPRI, 2000; DOE, 2000a]:

- Reduce them with additional research and/or modification of the repository engineered design;
- Make conservative assumptions or use conservative parameter values. 'Conservative' is used here to mean those assumptions or parameter values such that, when applied to consequence analyses, negative consequences are unlikely to be underestimated;
- Provide 'margin' in the design: the repository should be designed such that estimates of consequences (such as radiological doses to individuals living downstream of Yucca Mountain) should be well below the regulatory limits;
- Provide 'defense-in-depth': there should be multiple 'barriers' to the release of radionuclides from the repository into the biosphere such that there is not undue reliance on any single barrier; and
- Establish a "Performance Confirmation" program of long-term committed research and development to provide additional confidence (prior to repository closure) that the long-term projections of repository performance, based on knowledge available at the time of the SR or LA, *still* provide reasonable assurance that long-term public health protection can be

maintained. A well conceived and executed performance confirmation program will not only provide improved confidence in and of itself, but will also bolster each of the methods of managing uncertainties described above.

DOE is currently using a combination of all of the above approaches to managing uncertainty at Yucca Mountain [DOE, 2000]. This is appropriate. In a separate report [EPRI, 2000] EPRI explored the impacts of uncertainty reduction, margin, the degree of conservatism, and defense-in-depth on repository design and long-term performance. The EPRI [2000] report also identifies those features, events, and processes that most impact long-term performance and which are uncertain.

The long-term committed R&D, or 'performance confirmation' program is a key component in providing the necessary confidence to proceed into the construction, loading, operation, and final closure of the candidate Yucca Mountain repository. EPRI has embarked on a two-year effort to identify not only what kinds of testing, monitoring, and other related activities should be included in a performance confirmation program, but why each particular activity should be included. The purpose of this interim report is to begin to establish the bases for the performance confirmation activities, and explore some of the potential activities proposed by DOE [DOE, 2000b] and EPRI [EPRI, 2000]. This interim report will establish the approach to identifying the components of the performance confirmation plan. It is expected that the final EPRI report on performance confirmation will provide more detail regarding both the specific activities and the quantitative criteria by which they can be said to 'confirm' the models and parameter values upon which DOE's long-term performance projections are based.

1.3 The Meaning of 'Performance Confirmation'

In the 'Supplementary Information' section of their draft regulation for the candidate spent fuel and high-level radioactive waste repository at Yucca Mountain, 10 CFR Part 63, NRC notes that:

> The Commission expects that DOE will take reasonable and practical measures to ensure that its performance assessment provides a credible representation of a geologic repository at Yucca Mountain. For example, assurance of the soundness of the performance assessment cannot and will not involve the comparison of simulated behavior of a geologic repository with empirical observation over tens of kilometers and tens of thousands of years. At best, assurance for the performance assessment will involve comparison of simulations with observations drawn from an integrated program of laboratory tests, field tests, and analog studies that starts with site characterization and continues, as appropriate, through the performance confirmation period. [NRC, 1999, pg. 8650]

Thus, NRC defines 'Performance confirmation' as "the program of tests, experiments, and analyses that is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objective ... will be met." [NRC 1999, §63.2] NRC requires that DOE conduct such a program in §63.102(m):

> *Performance confirmation.* A performance confirmation program will be conducted to verify the assumptions, data, and analyses that support the performance assessment, and

> any findings, based thereon, that permitted construction of the repository. Key geologic, hydrologic, geomechanical, and other physical parameters will be monitored throughout site characterization, construction, emplacement, and operation to detect any significant changes in the conditions assumed in the performance assessment that may affect compliance with the performance objective.... .

In Chapter 4 of their Performance Confirmation Plan [DOE, 2000b], DOE provides the following general definition:

> "Performance confirmation is the program of tests, experiments, and analyses which is conducted to evaluate the accuracy and adequacy of the information used to determine that the performance objectives for the period after permanent closure will be met with reasonable assurance." [pgs. 4-7,8]... "Any postclosure predictions performed during the performance confirmation period will be compared with the LA predictions, including any change[s] in the assessment of compliance with the overall system postclosure performance standards." [pg. 4-15]

Finally, the NRC notes when performance confirmation testing ends:

> §63.102(c) "Stages in the licensing process. ... Permanent closure represents the end of the performance confirmation program; final backfilling of the underground facility, if appropriate; and the sealing of shafts, ramps, and boreholes."

Thus, the performance confirmation program is meant to provide reasonable assurance that the information used to support the license application at the time of construction is still adequate after repository construction and loading have been completed – a time which is likely to be several decades into the future. Performance confirmation ends at the time the repository is closed.

The use of the term 'reasonable assurance' implies that DOE should use a risk-informed approach to developing an appropriate performance confirmation program. That is, emphasis should be placed on those tests, experiments and analyses that address those Features, Events, and Processes (FEPs) for which projections of long-term repository performance are particularly sensitive, *and* which have a significant degree of uncertainty. Other FEPs for which performance is less sensitive or that are less uncertain should be given lower priority in a performance confirmation plan.

It is important to distinguish between tests, experiments, observations, and analyses conducted in the next year or two to support the SR report and construction LA from the long-term committed R&D program associated with 'performance confirmation'. That is, any activities conducted under a performance confirmation program should *not* be a prerequisite to the approval of either the SR or the construction LA. The near-term testing that DOE already has underway, when combined with the over 13 years of testing and analyses conducted to-date, should be adequate for DOE to make a safety case that supports SR and construction LA decision making. Indeed, EPRI feels that DOE *has* made such a case with their current approach to managing uncertainties [EPRI, 2000]. Rather, the goal of an appropriate performance confirmation program should be to help provide the additional assurance required to support repository closure. A performance confirmation program can also provide data to make possible modifications to the repository design prior to closure. Coupled with other aspects of the safety case, such as assuring that a viable option for retrieving wastes back out of Yucca Mountain prior to closure exists, an appropriate performance confirmation program should provide the necessary assurance that the Yucca Mountain repository can be safely closed.

2 PERFORMANCE CONFIRMATION PLAN DEVELOPMENT: GENERAL CONSIDERATIONS

2.1 Performance Confirmation Objectives

DOE provides the following set of objectives for a performance confirmation program:

> The objectives for the program focus on compliance with regulatory requirements with an emphasis on postclosure sensitive items. The program is part of a reasonable assurance argument that postclosure conditions with long-term performance sensitivity will behave as expected. The program objectives are to: 1) provide data that subsurface conditions encountered and changes in those conditions during construction and waste emplacement operations are within the limits assumed in the licensing review, 2) provide data that natural and engineered systems and components that are required for repository operations and designed or assumed to operate as barriers after permanent closure are functioning as intended and anticipated, and 3) comply with U.S. Nuclear Regulatory Commission requirements for performance confirmation. Additionally, data obtained during performance confirmation will be used to support an evaluation of the repository's readiness for permanent closure. [DOE, 2000b, page xi]

Generally, this is a good set of objectives for a performance confirmation program. However, given that the existing DOE analyses are based on a number of judgments that occasionally result in 'departures from reality' (mostly conservatisms, and a few optimisms) it cannot be said that performance confirmation will help confirm "long-term performance sensitivity will behave as expected." This would be possible only if DOE were to use only 'best estimate' conceptual and numerical models and parameter values. Since DOE uses many conservatisms, performance confirmation testing will probably show, in many cases, that long-term performance will be *no worse and probably better* than has been assumed and projected in the DOE analyses. While this may be considered a subtle point, it is useful to remember this so that some long-term testing can be used to help eliminate some conservatisms and instances where simplicity may have led to optimisms. Eliminating conservatisms and/or optimisms implies that the licensing basis will evolve over time (i.e., one should expect that some performance confirmation testing results would modify "the limits assumed in the licensing review" where conservatisms or optimisms have been used). A staged licensing process that occurs over a period of several decades or more is well-suited to accommodate this eventuality.

DOE [2000b] notes that performance confirmation is part of an overall test and evaluation program. The four components of performance confirmation testing include:

- testing and monitoring required by NRC regulations (discussed in Section 2.2);

- self-imposed DOE requirements and directives (discussed in Section 2.3);
- testing to address data needs identified by PMRs "included in lieu of TSPA sensitivity analyses"; and
- testing of factors important to postclosure safety (discussed in Chapter 3).

All four components seem appropriate. As will be discussed in subsequent chapters, some of the tests required by regulations, requirements, and directives will provide very little information to provide additional confidence in long-term postclosure safety. As such, they do not conform to the definition of 'performance confirmation' by NRC and DOE as summarized in Section 1.3.

2.2 Regulatory Requirements

In their draft regulation for Yucca Mountain, 10 CFR Part 63, NRC provides a significant amount of guidance on what constitutes an appropriate performance confirmation program. The following three quotes provide more detail regarding what general sort of information NRC is looking for regarding performance confirmation testing:

> §63.21(c)(21): "[The Safety Analysis Report shall include]: An identification of those structures, systems, and components of the geologic repository, both surface and subsurface, which require research and development to confirm the adequacy of design. For ... the engineered and natural barriers important to waste isolation, DOE shall provide a detailed description of the programs designed to resolve safety questions, including a schedule indicating when these questions would be resolved."

> §63.32 Conditions of construction authorization: "(b) The Commission will incorporate, in the construction authorization, provisions requiring DOE to furnish periodic or special reports regarding: ...(2) Any data about the site, obtained during construction, that are not within the predicted limits on which the facility design was based; (3) Any deficiencies, in design and construction, that, if uncorrected, could adversely affect safety at any future time; and (4) Results of research and development programs being conducted to resolve safety questions."

> §63.51 License amendment for permanent closure: "(a) DOE shall submit an application to amend the license before permanent closure of a geologic repository at the Yucca Mountain site. The submission shall [include]: (1) An update of the assessment of the performance of the geologic repository for the period after permanent closure. ... (4) Geologic, geophysical, geochemical, hydrologic, and other site data that are obtained during the operational period... (5) The results of tests, experiments, and any other analyses relating to backfill of excavated areas, shaft, borehole, or ramp sealing, waste interaction with the host rock, and any other tests, experiments, or analyses... (7) Other information bearing on permanent closure that was not available at the time a license was issued."

Subpart F of the draft Part 63 [NRC, 1999] contains the bulk of the NRC requirements for performance confirmation. While it is fairly long, it is central to what needs to be included in an appropriate performance confirmation plan, so is reproduced, with comments, here.

Subpart F-Performance Confirmation Program [NRC, 1999]

§ 63.131 General requirements.

(a). The performance confirmation program shall provide data that indicate, where practicable, whether:
1. Actual subsurface conditions encountered and changes in those conditions during construction and waste emplacement operations are within the limits assumed in the licensing review; and
2.Geologic and engineered systems and components required for repository operation, and that are designed or assumed to operate as barriers after permanent closure, are functioning as intended and anticipated.
(b). The program shall have been started during site characterization and it will continue until permanent closure.
(c). The program shall include in-situ monitoring, laboratory and field testing, and in-situ experiments, as may be appropriate to provide the data required by paragraph (a) of this section.
(d). The program shall be implemented so that:
1. It does not adversely affect the ability of the geologic and engineered elements of the geologic repository to meet the performance objectives.
2. It provides baseline information and analysis of that information on those parameters and natural processes pertaining to the geologic setting that may be changed by site characterization, construction, and operational activities.
3. It monitors and analyzes changes from the baseline condition of parameters that could affect the performance of a geologic repository.

§ 63.132 Confirmation of geotechnical and design parameters.

(a). During repository construction and operation, a continuing program of surveillance, measurement, testing, and geologic mapping shall be conducted to ensure that geotechnical and design parameters are confirmed and to ensure that appropriate action is taken to inform the Commission of changes needed in design to accommodate actual field conditions encountered.
(b). Subsurface conditions shall be monitored and evaluated against design assumptions.
(c). As a minimum, measurements shall be made of rock deformations and displacement; changes in rock stress and strain; rate and location of water inflow into subsurface areas; changes in groundwater conditions; rock pore water pressures, including those along fractures and joints; and the thermal and thermomechanical response of the rock mass as a result of development and operations of the geologic repository.
(d). These measurements and observations shall be compared with the original design bases and assumptions. If significant differences exist between the measurements and observations and the original design bases and assumptions, the need for modifications to the design or in construction methods shall be determined and these differences, their significance to repository performance, and the recommended changes reported to the Commission.
(e). In-situ monitoring of the thermochemical response of the underground facility shall be conducted until permanent closure, to ensure that the performance of the geologic and engineering features is within design limits.

§ 63.133 Design testing

(a). During the early or developmental stages of construction, a program for in situ testing of such features as borehole and shaft seals, backfill, and the thermal interaction effects of the waste packages, backfill, rock, and groundwater shall be conducted.
(b). The testing shall be initiated as early as practicable.
(c). A backfill test section shall be constructed to test the effectiveness of backfill placement and compaction procedures against design requirements before permanent backfill placement is begun.
(d). Test sections shall be established to test the effectiveness of borehole, shaft, and ramp seals before full-scale operation proceeds to seal boreholes, shafts, and ramps.

§ 63.134 Monitoring and testing waste packages

(a). A program shall be established at the geologic repository operations area for monitoring the condition of the waste packages. Waste packages chosen for the program shall be representative of those to be employed in the underground facility.
(b). Consistent with safe operation at the geologic repository operations area, the environment of the waste packages selected for the waste package monitoring program shall be representative of the environment in which the wastes are to be emplaced.
(c). The waste package monitoring program shall included laboratory experiments that focus on the internal condition of the waste packages. To the extent practical, the environment experienced by the emplaced waste packages within the underground facility during the waste package monitoring program shall be duplicated in the laboratory experiments.
(d). The waste package monitoring program shall continue as long as practical up to the time of permanent closure.

The first part of Subpart F, §63.131 General requirements, provides good guidance. NRC needs to recognize, however, that some of the data will *not* be "within the limits assumed in the licensing review" since some bounding parameters will be assumed (although one can say with bounding values the data will most certainly be within the limits). Other assumptions used in TSPA will not be 'verified' because they are conservative. This should be acceptable to NRC. Again, this section clearly states performance confirmation ends with permanent closure.

The remaining paragraphs in Subpart F, §63.132 through §63.134, contain too much detail. It is hoped that NRC will revise these sections in the final rule to be more consistent with its own requirements that performance confirmation testing should be geared to those factors important to long-term performance. As proposed, these paragraphs include some requirements that will probably provide only minimal insight on long-term performance. Examples of overly prescriptive requirements in this section are found in §63.132 subparts (c) and (e), §63.133 subparts (c) and (d) (subparts (a) and (b) are sufficient for a high-level regulation such as this), and all but subpart (a) of §63.134. While some of the requirements are reasonable, others are not necessary if the intent is to collect data to support long-term projections of repository performance. Furthermore, the detailed lists in these sections are incomplete if NRC's intent was to be detailed. Thus, NRC's approach to performance confirmation requirements is inconsistent.

One final concern about the detail provided in the Subpart F is that some of the required monitoring may interfere with the proper performance of the very barriers they are supposed to measure. Thus, it would be better to provide less specifics and leave the *complete* set of detailed specifications for DOE to propose.

2.3 Other Self-imposed DOE Requirements

Table 3-7 in DOE [2000b] lists the performance confirmation activities prescribed in various DOE guidance documents. The items in Table 3-7 are discussed below:

- *Monitor the waste package surface temperature to assess the condition of the cladding.* It is unclear, at this point in time, what the exact purpose of such monitoring will accomplish in terms of the goals of a performance confirmation program. It is not that cladding is unimportant; rather, it is not clear whether monitoring container surface temperatures during the operations period will be able to provide much insight into the long-term competency of the cladding. This is because there is unlikely to be any additional degradation of the cladding that will occur at the planned repository temperatures during the repository operations period. Thus, monitoring the container surface temperature will only be useful to confirm that container surface temperatures are not dramatically higher than projected by models during the repository operations period. Probably a few spot checks of container surface temperatures would be all that was necessary for such a purpose. Maintaining a container surface temperature monitoring program for *all* the containers for the express purpose of assessing cladding condition would probably not be worth the expense.
- *Monitor air temperatures entering and exiting the drifts to assess heat removal.* This will be a useful test to do since the current projections of peak repository temperatures after repository closure are dependent on the amount of heat and, to a lesser extent, moisture that is removed from the repository during the ventilation period. Peak repository temperatures are important to long-term performance for a variety of reasons. It is important to remember, however, that dependence on convective cooling as the primary cooling process for the engineered barrier system (EBS) forces the need to monitor the temperatures in each drift. If the design were to be modified to limit the need for convective cooling, the need to monitor the air temperature exiting each drift would be eliminated.
- *Visual monitoring of water accumulation in the drift to confirm free drainage of the invert.* This test sounds appropriate IF there is any water entering the drifts, that is. If not, then perhaps an alternate way of determining free drainage of the invert will need to be produced.
- *Monitoring seepage in test alcoves to confirm the waste package environment.* Monitoring anticipated seepage locations is important to confirm long-term predictions. The testing program should also include seepage for thermally disturbed and undisturbed conditions. Since there is more time to conduct this test during the performance confirmation period, the thermally disturbed test should be under more realistic heat loading conditions than the very aggressive thermal conditions in the existing single drift heater test.
- *Geologic observation, mapping and "index" laboratory testing to observe the encountered subsurface (geologic) conditions along the repository horizon.* Yes, this should be done since the assumed geologic conditions need to be confirmed. This is probably one of the few 'tests' (not really a test per se) that can unequivocally 'confirm' the bases for the models since all the drifts can be observed.

- *Rock mass monitoring (temperature and displacement) near emplacement drifts.* These also sound like useful tests for the performance confirmation program. Measuring displacement is going to be of some interest in confirming rockfall predictions. Rock temperatures will have to be known along with the strain/displacements to make the measurements. It is recommended that a reasonable number of locations be selected to represent the repository behavior.

- *Field testing of borehole, ramp and shaft seals to confirm performance and constructability.* Since long-term TSPA calculations assume there are no man-made 'short-circuit' pathways in or around the repository, the adequate sealing of boreholes, ramps, and shafts is important to understanding long-term performance. This is also an NRC requirement. If part of the testing is to evaluate the long-term durability of the seals (in addition to making sure the seal is adequate upon installation), then it will be necessary to understand how much degradation of the seals is tolerable before the assumption of adequate sealing for long-term performance assessment would need to be revisited.

- *Field testing of engineered barrier system postclosure configuration to check the EBS interaction response of waste packages, rock, and groundwater.* This set of activities is more fully described in Appendix G, Description PM-09 of DOE [2000b]: "Dummy Waste Package Testing". Using a dummy drip shield and waste package as part of a larger closed drift long-term thermal test might provide useful information within 50 years.

- *Remote monitoring of waste packages in emplacement drifts.* This set of activities is more fully described in Appendix G, Description PM-02 of DOE [2000b]: "In Situ Waste Package Monitoring." "The purpose of this testing activity is to make real time measurements of the condition of the waste package and the environment within the emplacement drifts. This testing will be performed periodically for all emplacement drifts." DOE proposes to use Remotely Operated Vehicles (ROVs) to measure WP surface temperature, air temperature and humidity, and rock wall temperature, along with visual inspections for presence of corrosion, microbial activity, and joint conditions. While it would be expected that no negative conditions would be found from conducting these tests, it would be prudent to perform a few spot checks on some containers and drifts. It would seem unnecessary to check each and every container and joint on a periodic basis. This would provide only marginal additions to performance confirmation. A proper statistical sampling regime should be all that is necessary. Regarding drip shield joint integrity, TSPA analyses conducted to-date suggest that failure of a few joints will have only a marginal impact on long-term performance. Finally, these sorts of tests, where a 'null' result is expected, provide little additional confidence in the appropriateness of the models and assumptions used to form the basis for long-term repository performance projections. Other testing that *would* provide more confidence in long-term projections should be given higher priority. There may, however, be public confidence issues that will cause DOE to check each and every container and drip shield on a periodic basis.

- *Laboratory materials testing of internal waste package materials.* These could be useful tests to include in a performance confirmation plan. It would depend on the specific tests that would be proposed. Sorption onto degraded internals would be useful since this was found to be a potentially important barrier.

- *Well monitoring both down gradient (at point of compliance) and upgradient.* These monitoring activities should provide information for performance confirmation. Monitoring should include measurements of temperature, chemistry and hydraulic heads. Additional, long-range cross well testing would also be useful if they can be done on a sufficiently larger scale in space and time.
- *'Precise' leveling surveys over the repository for disruptive events.* While these tests should be done it must be kept in mind that it is unlikely that even 50 years of data could be reliably extrapolated since inflation/deflation events are not processes that are steady in time. Rather, the geologic record is full of instances where relatively rapid inflation/deflation is followed by long periods of quiescence.
- *Subsurface seismic monitoring.* Such testing will improve the understanding of seismic dampening at depth, which is important to help confirm the assumed impact of seismicity.

2.4 General Procedure for Executing a Performance Confirmation Program

DOE [2000b] notes there are eight steps in carrying out a performance confirmation plan. The eight steps in DOE [2000b] are:

1. "Identify which processes are to be measured, the 'key' performance confirmation factors";
2. "Define a performance confirmation database and predict performance. This includes identifying the processes and parameters important to postclosure performance and for which preclosure measurements can discern and that pre- and postclosure values will be within predicted ranges. Part of this step is to predict values and variations of critical performance measures for the key parameters; these establish expectations during construction and operations.";
3. "Establish tolerances or predicted limits or deviations from predicted values of the parameters";
4. "Identify completion criteria (which determine when data are sufficient) and guidelines for corrective actions to be applied when variances occur";
5. "Conduct detailed test planning of test and monitoring activities to measure the key parameters";
6. "Monitor performance, perform tests, and collect data";
7. "Analyze and evaluate the obtained data; these evaluations can include the use of process models, analyses, statistical tests, and total system performance assessments; and
8. "Recommend and implement appropriate actions if there are deviations from what was predicted or assumed."

These are an excellent summary of the steps required to conduct a successful performance confirmation program. Each of the eight steps will be discussed in turn.

Step 1. Identify which processes are to be measured

The results of performance assessments will generally be the source of the important FEPs for which measurements can be accomplished over the performance confirmation period. These will be discussed in more detail in Chapter 3. The use of sensitivity studies and uncertainty analyses in TSPA will be the main tools to identify relevant FEPs for performance confirmation testing. Several categories of sensitivity/uncertainty emerge from these analyses:

- *Low sensitivity/low uncertainty.* FEPs falling into this category should not be included in the performance confirmation plan at all.
- *Low sensitivity/high uncertainty.* FEPs in this category are also unlikely to need to be part of any performance confirmation plan.
- *High sensitivity/low uncertainty.* FEPs in this category could be included in the plan, but these would be lower priority tests that could be cut if funding was inadequate.
- *High sensitivity/high uncertainty.* These FEPs will be the main focus of the performance confirmation plan, so should receive the highest priority for funding.

Both NRC and DOE provide guidance regarding what parameters should be obtained in a performance confirmation program. The parameters required by NRC were discussed in Section 2.2.1. DOE [2000] provides some general parameter screening recommendations:

> 1. "The parameter must be relevant: the parameter must describe subsurface conditions, must be affected by construction or emplacement, or must be a time-dependent variable."
> 2. "The parameter must be clearly defined: the parameter (or its basis) must be both measurable and predictable."
> 3. "The parameter must be important to postclosure performance: the parameter has been shown (as determined by sensitivity analyses) to influence postclosure performance results."
> "In addition, parameters are excluded from consideration if the associated processes are not expected to occur in the preclosure phase and, consequently, cannot be monitored or tested."

One could argue that the first of the three criteria is unnecessary, or should be defined more clearly. If the parameter were not important to long-term performance then even if it did describe subsurface conditions or was affected by construction or emplacement, it still should not be included in a performance confirmation program. The second two criteria are the important ones for performance *confirmation.* Both of these two criteria must be met in order for the parameter to be a candidate for inclusion into a performance confirmation program.

Step 2. Define a performance confirmation database and predict performance

This database will include all information collected during the phases of the project up to the time of the granting of the construction license. The majority of these data will have been collected to support the construction license application (LA). Performance predictions should be largely based on those used to support the LA. However, the same models should be used to estimate performance during the performance confirmation period so that it is clear how results from the performance confirmation period can be applied to 'confirming' long-term performance.

DOE [2000b] also discusses 'baseline' data to be collected prior to and during repository construction and loading to be used to determine the impacts on key FEPs due to construction and loading. Much of this baseline data will be necessary to be able to convert testing during the performance confirmation period into proper assessments of whether or not the repository will perform at least as well as projected.

The developed database should be limited, however, to only those data required to establish an adequate baseline. Therefore, it will be necessary to carefully define the scope of the baseline.

Step 3. Establish acceptable tolerances, limits, or deviations from predictions

This is a key step in establishing a successful performance confirmation program. Without the ability to know when any projection over 10,000+ years based on a few decades of testing is outside the tolerance limit, the performance confirmation testing will be unsuccessful. It should be clear to decision-makers that such tolerances, limits, and deviations *can* be determined, as appropriate.

Figure 2-1, taken from Figure 2-1 in DOE [2000b], shows the conceptual approach DOE proposes for the performance confirmation process. Of primary interest on this figure is the use of baseline data to establish predicted bounds on performance during the performance confirmation period. This figure provides insight into how baseline data, along with data collected over the past years, will be used. Given that many of DOE's assumptions, conceptual models, and parameter values are based on reasonably bounding analyses, it would be appropriate, in such cases, to include only an upper bound. The predicted bound(s) during the performance confirmation period should be based on the same models used to support SR and the construction LA. What requires further elucidation are the criteria DOE will use to establish meaningful bounds. Some of the potential criteria for establishing these bounds could be as follows:

- *Avoid exceeding the parameter value range used in the SR and construction LA total system performance assessment (TSPA).* This is probably the most commonly understood potential criterion for setting tolerance limits on the performance confirmation test results. If the test results, when projected to 10,000 years (or more, as appropriate), would suggest the parameter range would be different from that used in the SR and LA TSPAs, then such a tolerance limit would provide an indication that, at the least, the parameter range needs to be revisited. It might also require a revision to the conceptual or numerical model.
- *Avoid exceeding regulatory criteria.* This criterion would be a 'limit' on the parameter value such that if the measurements during the performance confirmation period exceed this limit, then performance of the repository will likely exceed the regulatory limit(s). In this case, the acceptable tolerance range would have to be established only with full knowledge of the totality of the entire performance confirmation program. This is because the tolerance criterion for any one parameter would have to be optimized based on the revised understanding of all the parameters used in the performance assessment.

- *Support the refinement of the engineered system.* If the performance confirmation test results show that actual repository performance is actually better than that assumed in the TSPA, it may be possible to revisit the role of particular engineered features such as drip shields, waste package thermal limits, or package spacing specifications. A tolerance criterion could be developed to indicate under what circumstances the modification or elimination of a particular barrier could be supported.
- *Avoid the need to re engineer the repository to meet the regulatory criteria.* An alternative tolerance band would be that which would cause the need for some engineered solution that may be difficult to backfit.

In many cases, establishing appropriate limits will require considerable thought. For example, DOE models that make projections over 10,000 years with too coarse a temporal discretization would not, without modification, be useful for projecting performance over the first few decades. In other cases, DOE has used conservative assumptions or model parameters such that actual performance, while deviating from predictions based on these conservatisms, will still be within regulatory limits.

Step 4. Identify completion criteria.

This is another obviously necessary step. A clear end point for each performance confirmation test must be established. Thus, the purpose of each performance confirmation activity must be clearly defined beforehand.

This step should also include criteria for adequately sampling over the repository in cases where it may not be necessary to examine the repository in detail. For example, it may not be necessary to test or monitor each and every waste container or drip shield for particular FEPs; rather, it may be possible to identify a more limited sampling program in space and time while still being able to 'confirm' repository-wide behavior.

Step 5. Conduct detailed test planning.

This step should include considerations such as: cost and other required resources; health impacts to workers and the nearby population; timing with respect to other repository activities; potential interference with other activities; and whether the performance confirmation activity might jeopardize the long-term performance of the particular FEP or FEPs the testing was supposed to confirm.

Step 6. Conduct the performance confirmation activities.

Step 7. Analyze and evaluate the test data.

As described above, DOE should use a variety of techniques to analyze the data collected during the performance confirmation period. As part of this step, a complete revision of the TSPA for closure purposes should be performed using all of the information collected during the performance confirmation period. For example, additional data collected may help DOE relax some of the conservatisms in the models applied for the construction LA, or may even allow the repository design to be modified prior to closure (see Chapter 4).

As with the data collected during the initial period leading up to the construction LA, some judgement will be required in interpreting the results. It cannot be expected that even several additional decades of results will dispel all uncertainty. DOE will need to provide analyses to show the performance confirmation results provide reasonable assurance that the long-term performance of the repository will remain within regulatory limits over the long term.

Step 8. Recommend and implement appropriate actions.

Depending on the results of the performance confirmation testing and analyses, a range of possible actions could be recommended. The recommended actions could range from none (if the performance confirmation testing confirmed the adequacy of the models and data), to some limited, additional testing, to modification of particular models, to providing additional engineered barriers, or to the abandonment of the repository.

One would expect a good performance confirmation plan (prior to test initiation) to have provided considerable detail for steps 1-4, part of 7 (likely evaluation approaches can be identified ahead of time), and 8 (appropriate actions should be identified, up front, on a 'contingency' basis). Also, the repository safety strategy (RSS) needs to address those issues important to safety for which there is a high degree of uncertainty, but also for which no performance confirmation plan over 50 years (or so) could effectively address. The RSS should discuss how to disposition such FEPs. Finally, there are aspects of a performance confirmation plan that are more 'monitoring' in the sense that, while important for building confidence, they don't directly 'confirm' long-term behavior.

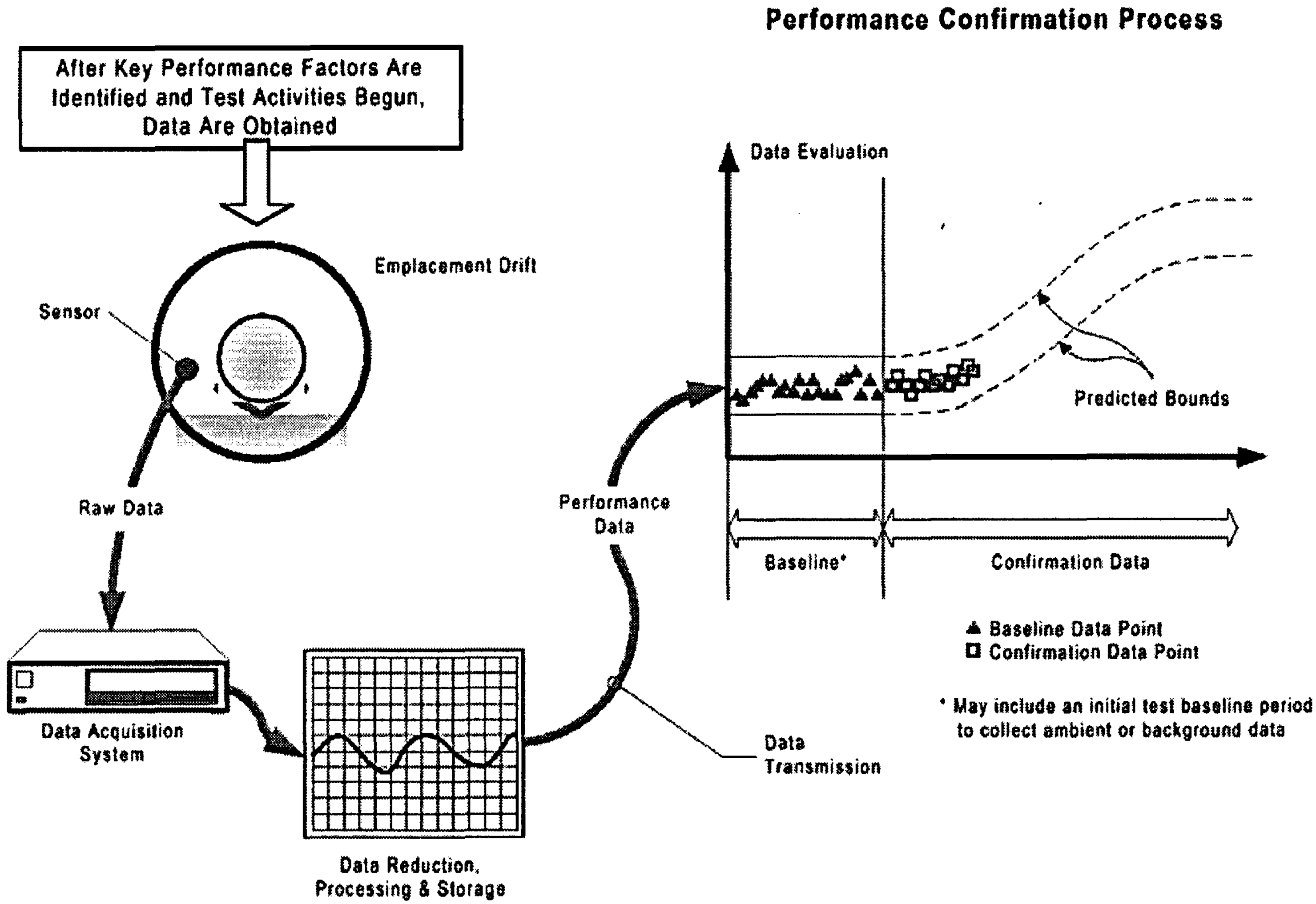

Figure 2-1. Schematic Diagram of Performance Confirmation Process From Testing to Data Evaluation

3
EVALUATION OF CANDIDATE PERFORMANCE CONFIRMATION ACTIVITIES

3.1 Prioritization of Potential Performance Confirmation Activities

As discussed in Section 2.1, DOE [2000b] notes that the four sources of recommended performance confirmation testing are:

1. testing and monitoring required by NRC regulations (discussed in Section 2.2);
2. self-imposed DOE requirements and directives (discussed in Section 2.3);
3. testing to address data needs identified by PMRs "included in lieu of TSPA sensitivity analyses"; and
4. testing of factors important to postclosure safety (discussed in Section 2.3 and in this chapter).

These four sources are not mutually exclusive lists of potential performance confirmation activities; considerable overlap exists.

Since stable, long-term funding from Congress for the type of testing characteristic of a performance confirmation program is not assured, it would be appropriate to prioritize the activities to be performed under this program. This chapter will provide general guidance on which performance confirmation activities should receive the highest priority, along with other activities that, while somewhat useful in confirming long-term performance estimates, could be reduced in scope or eliminated if stable, adequate funding is not available.

The following general requirements can be used to help determine the highest priority FEPs to include in performance confirmation activities. These FEPs will provide the greatest degree of long-term 'confirmation' that the assumptions, models, and parameters adequately describe the long-term conditions of the repository behavior. The highest priority FEPs to be included in performance confirmation activities are those for which:

- the sensitivity to long-term performance is high; and
- the uncertainty is large; and
- monitoring or testing activities carried out over a period of several decades are likely to provide adequate information to test the adequacy of the assumptions, models, and parameters used in TSPA to model behavior of those FEPs over ≥10,000 years.

All of the above conditions must be satisfied for these highest priority FEPs. It is likely that all of the highest priority items will be found in item #4 in Section 3.1, "factors important to postclosure safety".[1] However, the highest priority performance confirmation factors will probably not include all factors important to postclosure safety since it may be that an 'important' factor is considered one for which only the sensitivity to long-term performance is high. To be considered high priority in a performance confirmation plan, the last two requirements listed immediately above must also be satisfied.

TSPA sensitivity studies and barriers importance analyses will be the main tools used to identify the highest priority FEPs to be considered for inclusion in a performance confirmation plan. A more thorough discussion of the highest priority items will be included in the final report on performance confirmation to be issued next year. Section 3.2 includes a discussion of possible considerations DOE may wish to employ for identifying the highest priority activities based on recent EPRI TSPA analyses for Yucca Mountain [EPRI, 2000].

Another category of high priority performance confirmation activities, distinct from those described above, are those that explore opportunities for significant improvements in engineered systems, leading to a more robust, simpler, or more cost-effective final design prior to closure. SR decision-makers should consider not just whether the candidate Yucca Mountain site can be designed to provide reasonable assurance the regulatory criteria can be met, but also whether additional research during the pre closure period has the potential to produce design changes that will increase confidence in repository performance and/or decrease its cost. Two examples of such activities would be those to provide the technical bases to perhaps eliminate the need for the drip shield or to modify thermal loading parameters. If an appropriate set of testing activities could be carried out during the performance confirmation period, and the results were appropriate, elimination of the drip shield and/or increasing the thermal loading could provide significant cost savings over the existing repository design. These examples will be discussed in somewhat more detail in Chapter 4.

Lower priority should be given to potential performance confirmation activities that investigate FEPs:

- that are of lesser importance to long-term performance (TSPA predictions are not greatly sensitive to the assumptions, conceptual modeling, and parameter value(s) chosen for that FEP);
- for which the uncertainty in the FEP is not large (the FEP is considered adequately known such that, at the least, there is high confidence that the behavior has been bounded in the TSPA analyses conducted to support SR and the construction LA);
- for which all three of the parameter screening criteria provided in 'Step 1' in Section 2.4 *cannot* be met; or
- for which it is unlikely that even several decades of monitoring or testing will be adequate to greatly improve the bases for making very long-term performance projections.

[1] It may be that some of these factors will also be included in the other three items.

As discussed in Sections 2.2 and 2.3, there are several NRC and internal DOE requirements for performance confirmation testing that should be given lower priority.

3.2 Highest Priority Performance Confirmation Activities

For the purposes of this interim report, an initial analysis of the most recent EPRI TSPA for Yucca Mountain [EPRI, 2000], will be considered to identify potential FEPs for which the highest priority should be given to being included in a performance confirmation plan. The EPRI [2000] report includes both sensitivity studies in the form of 'one off' analyses from the base case results, and 'barrier importance' identification analyses. In this interim report, examples of a few performance confirmation activities will be suggested; more detail will be provided for these activities in the final report next year.

3.2.1 EPRI TSPA sensitivity studies

The following FEPs are identified in EPRI [2000] as contributing significantly to the estimated long-term dose rates, and the long-term (up to several decades) testing of which will result in significantly increased confidence in long-term dose projections.

<u>Flow heterogeneity (rates and spatial distribution)</u>

We support further field and modeling work to narrow the range of uncertainty regarding the fraction of the repository that may experience active dripping under various conditions, and the flow rates of groundwater where dripping occurs. Specifically, work to reduce the reasonable upper bound on the fraction of the repository experiencing active dripping will be of significant value to overall performance. It is likely that long-term testing of large sections of drifts, and continued observation of various alcoves will help narrow the uncertainty and possibly lower the estimate of the fraction of the repository waste containers that may experience active dripping.

Any performance confirmation testing of flow heterogeneity at Yucca Mountain will obviously be limited to conditions imposed by the current, and very near-term climate. We encourage DOE to continue monitoring local climate[2] and net infiltration[3], over 10,000 years or more, at least some change in local climate that will affect both the amount and distribution of groundwater flow at the repository horizon is likely. Thus, it will be necessary to explore analog sites representing the currently assumed range of possible climates in the Yucca Mountain vicinity over the next 10,000 years or more. While DOE has engaged in some work at analog sites, it may be possible to initiate additional, limited monitoring and testing that could further reduce the uncertainty in projections of flow heterogeneity during future climate scenarios. We also encourage DOE to monitor improvements in global and local circulation models used to estimate long-term global and regional climate details in the far future.

[2] E.g., temperature, precipitation, wind speed and direction.
[3] E.g., run-on, runoff, factors affecting evapotranspiration and storativity.

Drip Shield/Container/Cladding

These three barriers within the EBS are shown to have very significant importance in mitigating radiological consequences of the candidate Yucca Mountain HLW repository. Thus, the current performance of these three barriers must be shown to be adequately reliable. Some of the fundamental assumptions about constructability, and long-term corrosion behavior certainly warrant additional, long-term R&D. We encourage the continuation of the work at the Long Term Corrosion Test Facility and continued review of the test plan for this facility to make sure a sufficiently wide range of thermal, mechanical, and chemical conditions are used.

Furthermore, considerable reliance on the integrity of the closure welds is assumed in making the safety case for Yucca Mountain. The critical feature of the waste package remains the possible susceptibility of the final closure welds to stress corrosion cracking (SCC). Testing has shown that SCC of Alloy-22 can occur under sufficiently aggressive conditions. These SCC tests should continue, in a range of environments, in an attempt to place bounds on the conditions under which it might occur.

It is assumed that the remote welding and stress-relief operations can be tightly controlled and the properties of the resulting welds are adequately known and consistent. For example, it would be useful to continue to gather additional data on flaw densities in both plate and weld Alloy-22, since this is an essential feature in eliminating the possibility of SCC.

We encourage DOE to develop alternative lines of reasoning regarding the very long-term passivity of the corrosion layer on Alloy 22. This issue should be included in a long-term research program.

Solubility/sorption data

The M&O has noted that one of the most significant conservatisms leading to their current dose projections over the very long term is that they do not assume some radionuclides are incorporated into secondary phases. This results in higher solubility estimates for neptunium, for example, than actually might exist. Since neptunium is the leading contributor to very long-term dose in the DOE model, and one of the major contributors in the EPRI model, it would be useful to do additional work to make a case for incorporation of neptunium, and other similar radionuclides into secondary phases. It is likely that long-term experiments in the laboratory and/or field could provide more definitive evidence of the presence or lack of significant secondary phases for some species, like Np, which could lower the current estimates of solubility limits.

Unsaturated and saturated zone fracture/matrix coupling and dilution

The analyses presented in EPRI [2000] assume considerable credit for fracture/matrix interaction in slowing the migration of all species be they nonsorbing or sorbing. Chapter 7 in EPRI [2000] provides additional evidence to back up this claim. Additional work to determine the degree of fracture/matrix interaction under natural flow conditions would prove valuable. To understand the extent of fracture/matrix coupling for the purposes of long-term performance will require fairly large scale testing in space and time. While the Busted Butte facility has provided considerable insight into fracture/matrix coupling in the UZ, additional confidence could be gained in the degree of fracture/matrix coupling if this sort of experiment could be repeated on a larger scale and at several locations with respect to major fractures.

The degree of retardation in the matrix and on fracture surfaces has significant uncertainty for some key radionuclides. Extrapolating small scale batch and column sorption tests up to the time and space scales of interest introduces additional uncertainty. It may be useful to conduct limited additional, larger scale sorption tests if a meaningful test can be designed and executed.

A considerable amount of dilution is thought to occur between the EBS and the accessible environment. EPRI [2000] estimates concentrations between the bottom of the EBS and the accessible environment to be lowered by at least five orders of magnitude. This estimate is based on assumptions about the amount of dispersion that can be expected mostly in the saturated zone. Improving estimates of dispersion in the SZ will require well thought out, large scale (in both space and time) testing. This could be another important aspect of a long-term research program assuming such a test could be designed and executed.

<u>Volcanism</u>

Given the projected excellent, long-term performance of the EBS components of the new repository design, only the volcanism and human intrusion scenarios have the potential to contribute substantially to the dose projections during the first 10,000 years after repository closure. The current M&O and NRC volcanism consequence models are thought to be significantly conservative. Given that volcanism consequences appear to dominate dose estimates during the likely regulatory compliance period, it would be very useful if more reasonable dose consequence analyses were available to augment the current conservative analyses. More can and should be done to provide projections of performance that are more 'best estimate' and less 'bounding'. Such projections should and can be made available to Site Recommendation decision-makers within the next year based on available information within the project and in the open literature. However, some longer term testing or observations at natural analog sites could further reduce the uncertainties and conservatisms currently adopted in the volcanism consequence scenarios. Additional monitoring for the recurrence of volcanic activity, as suggested by DOE and summarized in Section 2.3 above, could also provide some limited improvement in the probability of occurrence.

3.2.2 Support of multiple barriers

A key aspect of an appropriate repository safety strategy is to identify the key barriers to radionuclide release in the repository system. In their draft regulation for Yucca Mountain, 10 CFR Part 63, the US Nuclear Regulatory Commission (NRC) states:

> §63.102 (h): "*Multiple barriers.* §63.113(a) requires that the geologic repository include multiple barriers, both natural and engineered. Geologic disposal of HLW is predicated on the expectation that a portion of the geologic setting will be capable of contributing to the isolation of radioactive waste, and thus be a barrier important to waste isolation. ... It

> is intended that natural and the engineered barrier system work in combination to enhance the resiliency of the geologic repository and increase confidence that the postclosure performance objective ... will be achieved."

Thus, multiple barriers are required, some of which must be predominately natural, and some must be predominately engineered. The barriers important to waste isolation must be identified, quantified, and defended. A "barrier" is assumed to be any single or readily distinguishable suite of features, events, and processes (FEPs) that act to:

- prevent or substantially delay[4] movement of the radionuclides to the biosphere; and/or
- substantially reduce their concentration[5] by action of either radioactive decay *or dilution*

In EPRI [2000] a list of 12 'barriers' were identified that are considered important to lowering the annual effective dose rate to an average member of the critical group:

	Barrier	**Engineered or Natural?**
1	4% of repository wet	engineered/ natural
2	3,000 year waste form alteration time	engineered/ natural
3	Moderate solubility	natural
4	Cladding	engineered
5	Waste package	engineered
6	Drip shields	engineered
7	Dilution in the unsaturated zone	engineered/ natural
8	EBS corrosion products sorption	mostly engineered
9	Accessible environment at 5 km	natural
10	UZ/SZ 'moderate' retardation	natural
11	Saturated zone in front of alluvium	natural
12	Saturated zone at 20 km	natural

A description of each barrier and potential 'high' priority performance confirmation testing follows.

4% of repository wet: This accounts for the suite of individual FEPs that cause only a portion of the containers to come into contact with groundwater. The remaining 96% of the containers are assumed to remain free of liquid water advection due to the following assumptions:

- For the smaller local percolation rates, the fact that the drifts are air-filled and curved causes the vast majority of the percolating water (for the lower local percolation rates only) to be diverted around the drifts;
- Groundwater flow through the repository horizon is heterogeneous. So, on average, only 4% of the repository area has local percolation rates high enough to allow water to drip into the drifts and onto containers.

[4] A 'substantial' delay may be on the order of 10^4 years or longer since both EPA and NRC have proposed the time period of regulatory compliance be 10,000 years.
[5] A 'substantial' concentration reduction is arbitrarily assumed to be a factor of ten or larger.

The FEPs contributing to the assumption that, on average, only 4% of the waste will ever be contacted by flowing liquid water are mostly due to natural features of the repository (flow heterogeneity due to the presence of fractured, porous rock). However, the engineered feature of the drift being placed in the unsaturated zone with a drift radius small enough to divert low percolation rates around, rather than through, the drift also is an important FEP. These natural and engineered FEPs act in concert, so cannot be separated further.

Potential high priority performance confirmation activities to support this barrier were briefly discussed in the "Flow heterogeneity" subsection in Section 3.2.1.

3,000 yr waste form alteration time: This is representative of the barrier provided by the waste form itself. For this barrier addition it is assumed that the waste form dissolves uniformly over 3,000 years, and all radionuclides are released congruently. Alteration time is a function of both natural and engineered features acting in concert. That is, the dissolution rate is a function of "engineered" features, such as the waste form properties (e.g., the UO_2 matrix), and the degree to which the rest of the waste package and any other engineered materials in the engineered barrier system affect the chemistry or flow rate of the groundwater contacting the waste form. The alteration time must also be considered a function of the "natural" features of groundwater chemistry and flow rate.

While this barrier was found to be important when the three other major EBS barriers (cladding, waste package, and drip shield) were non functional, its importance is diminished by the presence of any of these other EBS barriers. Thus, while it might be useful to conduct longer term studies to confirm the dissolution time is on the order of 3,000 years, such testing should not be given as high a priority as other tests.

Moderate solubility: This 'barrier' can be considered due to the "natural" system in the sense that natural groundwater chemistry is assumed to control the solubility limits. An exception to this may be if an "engineered" feature, such as the presence of reducing or chelating agents, affected the local solubility limits.

The importance of conducting limited, confirmatory solubility limit testing was discussed in the 'Solubility/sorption data' subsection within Section 3.2.1.

Cladding Fails over Time: This represents adding in the cladding barrier. While some of the cladding is assumed 'failed' at the time of container emplacement, mean cladding lifetime is assumed to be several tens of thousands of years. Taking credit for the presence of cladding was found to add considerably to the defense-in-depth argument for the drip shield and waste package: if the function of the waste container and drip shield are significantly degraded, cladding credit becomes important. Cladding is considered a pure engineered barrier.

At least two aspects of the DOE assumptions about cladding behavior would be useful to explore during the performance confirmation period: the fraction of cladding assumed failed at emplacement; and the assumption that fluoride will concentrate on a single, one centimeter-long rod segment. The fraction of cladding assumed failed at emplacement governs the earliest release from a degraded container. This fraction will likely be dominated by cladding failures caused during reactor operation, and, to a much lesser extent, during wet and dry storage prior to disposal. DOE has done a commendable job collecting information on cladding failures during reactor operation. However, data on potential additional cladding damage in storage prior to disposal are sparse, and DOE has resorted to some fairly conservative modeling assumptions to estimate the additional cladding failures that will occur during longer-term dry storage. DOE is encouraged to continue to support the ongoing joint NRC/DOE/utility-funded effort to investigate irradiated cladding that has been in dry storage for approximately 15 years.

The DOE assumption that all the fluoride dissolved in the groundwater entering a degraded container reacts with just a single rod along an isolated one centimeter length is very conservative. Laboratory simulations of dripping groundwater through a degraded container onto cladding could explore the degree of conservatism. It would be preferable to perform the tests on actual reactor-exposed cladding, if possible.

Containers fail over time: This represents adding in the container barrier. Containers are assumed to fail over many thousands of years. This is probably what most consider the primary engineered barrier.

Testing of the containers and welds are potentially major components of a performance confirmation program. Several of the possible tests on the containers have been discussed in earlier sections.

Drip shields fail over time: This represents adding in the drip shield barrier. One drip shield is assumed failed at emplacement; the rest fail over many thousands of years.

A substantial database of general corrosion rates (the predominant corrosion process anticipated on the drip shield) for the Ti-16 alloy from which the drip shields are proposed to be made is now available. Over the two years of testing completed so far at Lawrence Livermore National Laboratory (LLNL), the rates are decreasing with exposure time. Confirmation that these rates are appropriate requires that these tests continue with the aim of confirming that this decrease will continue, or that a steady low rate will finally be achieved.

Since general corrosion is also the main possible source of absorbed hydrogen, which could eventually render the drip shield susceptible to hydrogen-induced cracking, tests should be performed to determine the concentrations of absorbed hydrogen in these exposure tests. There are good grounds to believe that the accumulation of hydrogen in titanium will not occur except as a surface phenomenon during general corrosion.

The only possible scenario leading to extensive hydrogen absorption by the drip shield appears to be through the formation of a galvanic couple with fallen steel sets. Presently, no convincing assessment of this process has been performed. There are grounds to believe such couples can only be temporary and produce only locally hydrided "hot spots", but no test data are available. In the absence of such tests, modeling assessments are likely to be conservative. Thus, some confirmatory testing to establish whether or not significant hydrogen absorption leading to failure from hydrogen-induced cracking would be in order.

Dilution in the unsaturated zone: Any radionuclides exiting the EBS are assumed to become dispersed through 4% of the cross-section of the repository (the fraction of the repository in which flowing groundwater is assumed to be present) by the time the radionuclides reach the water table. This is likely to be a somewhat optimistic assumption. However, arguments were made in EPRI [2000] to suggest that an overestimate of dilution in the unsaturated zone is likely to be compensated by a subsequent underestimate of dilution in the saturated zone. Thus, the amount of dilution assumed to occur by the time any radionuclides reach a position several kilometers downstream is likely to be reasonable.

As discussed briefly in previous sections, if it is possible to carry out large scale contaminant transport tests in the unsaturated and/or saturated zones, given that several tens of years may be available during performance confirmation, then DOE should consider performing such a test or tests.

EBS corrosion product sorption: This barrier includes those FEPs that cause sorption of radionuclides on container corrosion products (iron oxyhydroxides) and backfill (crushed tuff). At very long times this barrier was considered in the EPRI barrier importance analyses to be significant since many of the long-lived actinides of importance are found to sorb significantly to these materials in lab tests conducted to-date. This can also be considered mostly an "engineered" FEP.

Additional testing would be useful to establish whether the currently assumed sorption values onto iron oxyhydroxides are appropriate, and whether crushed tuff causes the retardation currently assumed in the EPRI models.

AE [Accessible Environment] at 5 km: This barrier represents the suite of FEPs responsible for causing the delay due to travel time through the UZ and the first five kilometers of the SZ. Sorption in the UZ and SZ are still neglected. This causes the peak theoretical dose rates to be reduced by another factor of over 10^2 due to additional dispersion in the SZ. This FEP can be considered mostly "natural". Testing of this barrier should be considered with the UZ dilution 'barrier' described above. Consideration should be given to analog site data and additional literature information to lend further support to this barrier.

Unsaturated Zone/Saturated Zone Moderate Retardation: This introduces "moderate" sorption values to the tuff. This can be considered a "natural" FEP. Potential performance confirmation testing related to retardation in tuff was briefly described in the 'Unsaturated and saturated zone fracture/matrix coupling and dilution' subsection within Section 3.2.1.

AE in front of Alluvium: These curves add in the effect of another 11 km of travel time in the SZ through volcanic tuff due to sorption and groundwater travel time. This is a natural barrier. No special testing not already included above is required.

AE at 20 km: The effect of moving the measurement point another 4 km downstream is meant to include the assumed four kilometers of alluvium in the SZ. While the additional amount of dispersion on hazard reduction between 16 and 20 km is nearly negligible, the effect is more dramatic for those radionuclides that strongly sorb onto alluvium. This is a "natural" FEP.

Additional large-scale field testing in the alluvium to confirm the amount of sorption assumed in the SR and LA TSPAs would help add confidence in this barrier.

3.2.3 Other potentially high priority testing not identified in EPRI [2000]

The following are examples of the type of performance confirmation testing that could be considered. While some of these were not directly identified in the EPRI TSPA results, they were identified as important inputs to those results that warrant confirmatory testing. The one item on remotely operated vehicles is based on an assessment of the proposed performance confirmation activities found in DOE [2000b].

Coupled thermal processes and thermal performance inside and outside the EBS: The Site Recommendation design incorporates tight waste package spacing and wide drift spacing. The wide drift spacing allows the center of the pillars to be a path for moisture to drain, if any exist. An 81-meter drift to drift spacing was selected. In contrast the waste packages are spaced at 0.10-meter spacing. This very tight spacing will force a great deal of energy to be deposited onto the drift walls. One of the benefits to drift emplacement is the low thermal load to the host rock; by placing the waste package close together this benefit is negated.

To compensate for the high thermal load within the drift, the DOE has opted to use convection and a thermal cap on the initial thermal output of each waste package. Since convection is very geometry dependent it is recommended that additional tests be performed and computer codes be benchmarked to ensure analytical predictions. Since convection is so dependent on the geometry that is being evaluated a three-dimensional evaluation is required to gain insight. The SR convective heat removal is based on a two-dimension mine cooling evaluation that does not take into consideration a heat source within the drift. A relatively high convective cooling efficiency of 70% was used. Therefore it is recommended that a three-dimensional computer code be used in conjunction with some field testing to develop a realistic convective cooling efficiency.

There has been some controversy about the relative importance of coupled, thermally-driven processes that will exist within the repository during the first few thousand years when temperatures are the highest. DOE has argued that their current thermal loading plan is manageable and adequately predictable. DOE also states that, while short-term effects on groundwater flow and geochemistry due to heat are considerable, there appear to be no, significant, irreversible effects on the 'natural' (non-engineered) FEPs in the repository system due to the planned thermal loading approach. DOE has already conducted two major thermally-driven coupled process experiments to support these claims. A 'large block test' was completed mostly with the intent to check out equipment to be used later. A 'single drift heater test' is currently under way that will be capable of measuring coupled process effects on the scale of tens of meters.

A decades-long performance confirmation period provides the opportunity to conduct even larger scale (both space and time) tests. As suggested by DOE and discussed above, these tests could be conducted in perhaps an end drift using a higher thermal loading to look for changes in chemistry, fracture and matrix permeability, rock stability, net percolation, and drift stability. Such large-scale testing could answer questions about upper bounds on fraction wet, flow rates, and whether permeabilities are significantly affected. Other things a full-scale thermal test could help with include the functionality of all active and passive EBS systems to assure proper placement and retrievability.

Other general drift stability issues: Field testing after at least one disposal drift is completed will have to be conducted to address whether drip shields can be installed after a very long time. Additional testing could be done to explore whether certain rockfall from keyblocks result in geometry change in roof sufficient to allow localized dripping.

3.3 Lower Priority Performance Confirmation Activities

There are some potential performance confirmation activities that are not considered 'high' priority. A few examples of activities that should have a lower priority are:

- *Extensive* monitoring of container surface temperatures. While monitoring of container surface temperatures will be a fairly high priority, probably a few spot checks of container surface temperatures would be all that is necessary to assure the understanding of thermal behavior of the containers is adequate.
- Precise leveling surveys over the repository to check for disruptive events.
- To the extent that mountain-scale convection can significantly alter temperatures during the first few hundred years when temperatures are highest, its omission from DOE thermohydrologic models is significant and should be remedied if feasible. Even if convection does not change temperatures appreciably, convective gas flow might move a significant amount of water vapor upward through the repository.

4 TESTING TO SUPPORT POTENTIAL REPOSITORY DESIGN MODIFICATIONS

As discussed in Section 3.1, another category of high priority performance confirmation activities, distinct from those described above, are those that explore opportunities for significant improvements in engineered systems, leading to a more robust, simpler, or more cost-effective final design prior to closure. SR decision-makers should consider not just whether the candidate Yucca Mountain site can be designed to provide reasonable assurance the regulatory criteria can be met, but also whether additional research during the pre closure period has the potential to produce design changes that will increase confidence in repository performance and/or decrease its cost. Two examples of such activities would be those to provide the technical bases to perhaps eliminate the need for the drip shield or to modify thermal loading parameters. If an appropriate set of testing activities could be carried out during the performance confirmation period, and the results were appropriate, elimination of the drip shield and/or increasing the thermal loading could provide significant cost savings over the existing repository design. These examples will be discussed in somewhat more detail in Chapter 4.

4.1 Decay Heat Management

DOE has concluded that thermally-driven coupled processes, as would be manifested using the current decay heat management plan for Yucca Mountain[6], are sufficiently understood to have confidence in long-term performance. However, some, such as the U.S. Nuclear Waste Technical Review Board (TRB), consider these processes to be highly uncertain and potentially detrimental to the long-term performance of the repository. The TRB intimates that significantly lower peak temperatures than those projected for the current thermal loading design are required for the uncertainty in these coupled processes to be sufficiently small [see, for example, TRB 2000].

Some thermally-driven coupled processes only establish themselves over fairly large spatial and temporal scales. Coupled thermal-hydrological-chemical processes have the potential of causing dissolution of minerals along some fractures and precipitation along others. While this process may be slow, it may have the potential for permanently altering the hydraulic characteristics of the rock surrounding the repository horizon.[7] Another example of a large-scale coupled process would be mountain-scale convection. This process has been identified as important in removing

[6] The decay heat management plan is commonly referred to as the 'thermal loading' or the 'area mass loading' scheme – the spatial and temporal distribution of decay heat within the repository generated from the disposed spent fuel and HLW.

[7] DOE, however, has noted that this effect is not significant enough to warrant being included in the long-term performance models.

decay heat considerable distances away from the repository horizon, yet takes a significant amount of time to establish itself. The performance confirmation period presents an excellent opportunity to better explore the magnitude of processes like these.

It *may* be necessary for DOE to consider lowering the area mass loading below that proposed in the current design – at least initially – to provide confidence that the uncertainties associated with thermally-driven coupled processes are sufficiently small for SR decision-making. If sufficient testing of thermally-driven coupled processes can be performed during the performance confirmation period to support a higher mass loading later on, then DOE could increase the mass loading prior to repository closure. Such an approach is possible since the waste receipt at the repository is initially low and only increases after several years of the repository operation. Thus, fairly low mass loadings can be used initially while confirmatory testing of the effects of thermally-driven coupled processes at higher area mass loadings are carried out. While EPRI proposes to provide more details for this plan in the final performance confirmation report to be issued next year, we encourage DOE to begin developing such an interim plan as soon as possible.

4.2 Possible Engineered Barrier System Design Simplifications

Due to a variety of, what are thought to be major conservative assumptions for certain FEPs, the DOE has adopted a very robust engineering design. This robust design comes at some cost. The cost is not only economic, but also in the form of complex engineering designs and operations. If additional data collected during the performance confirmation period allow a relaxation of some of the conservatisms, then some of these robust design features may not be necessary. Although there are probably many possibilities for testing, two examples are provided here: the need for the drip shields, and the complexity of the container lid design.

The current, very robust design of the Engineered Barrier System (EBS) is in partial response to uncertainties in the amount and distribution of groundwater that may drip into the tunnels containing the waste (seepage) and the subsequent effects of that groundwater on radionuclide release from the EBS. EPRI supports performance confirmation work related to further reducing the variety of uncertainties that govern the current approaches to modeling radionuclide release from the EBS. As discussed in Chapter 5 of EPRI [2000], the 'drip shield' feature has been added specifically to reduce the dependence on knowing the details of seepage patterns. It also mitigates the potential corrosion-enhancing effects associated with the concentration of aqueous species in the groundwater as it evaporates on the hot metal surfaces of the waste container. Since the performance confirmation plan should include long-term measurements of seepage and container degradation due to concentrated groundwater solutions it may be possible to reduce the uncertainties of these processes significantly prior to closure. If the revised knowledge of these processes would support the elimination of the drip shield, considerable cost and operational savings could be realized.

Because screening stress corrosion cracking (SCC) test results on container welds suggest SCC is a remote possibility, the DOE has adopted a final closure weld configuration that is very complex in order to further reduce the likelihood of SCC failure. It is recommended that further studies be performed to investigate the many apparently conservative assumptions having to do not only with SCC, but also with weld flaw frequency and orientation. Such additional testing may eliminate, for example, the need for the two Alloy 22 lids, or the need to perform a full solution anneal of the final weld. Based on the DOE's and EPRI's weld flaw size and distribution reports, imperfection sizes, orientation, and number, the likelihood of SCC failure is already very small. It is anticipated that a study based on weld data that the probability of SCC in Alloy 22 is extremely low and those extraordinary processes may not need to be implemented.

5

OTHER ACTIVITIES DURING THE PERFORMANCE CONFIRMATION PERIOD TO PROVIDE ADDITIONAL CONFIDENCE

Like the performance confirmation plan discussed in the previous chapters, there are several other longer-term activities that are required (or would be of use) to provide the necessary confidence that a Site Recommendation (SR) decision can be made to proceed into the construction license application (LA) phase. Since there are lengthy performance confirmation activities that need to be completed prior to NRC having reasonable assurance the repository can meet the postclosure regulatory criterion, DOE will be proceeding somewhat 'at risk' in the interim. The risk of the Yucca Mountain site being inadequate seems low, however. More than 13 years of data and analyses conducted to-date have already provided a fairly high degree of confidence that the combination of the site and engineered features will keep the health impacts of the proposed repository well below regulatory limits [see, for example, EPRI 2000 and recent DOE analyses].

Yet DOE will still need to make sufficient contingency plans in the event that further research shows that the repository would need to be redesigned or even abandoned altogether. Such contingency plans probably should be integrated into the final performance confirmation plan. It appears that by expanding DOE's Step #8, "recommend and implement appropriate actions if there are deviations from what was predicted or assumed", such contingencies can be included directly into their performance confirmation planning process.

5.1 Developing a 'Reversibility' Plan

Central to the development of contingency plans is the maintenance of a workable plan to remove any waste emplaced in the Yucca Mountain facility. Such a plan must consider all phases of the project from the time waste is being prepared to be shipped to Yucca Mountain through the end of the performance confirmation phase. It will involve not only a detailed description of the engineering operations, but also all appropriate institutional, economic, and regulatory activities associated with placing the waste in safe storage for at least a few decades while DOE develops an alternative waste management approach. The plan should also include the orderly closure of the Yucca Mountain facility. Examples of a few of the many considerations that need to be made in the development of a reversibility plan are:

- How to recover from tunnel collapse and container failures during the preclosure period;
- How to take the containers back out from underground;

- Where to put the retrieved containers at the surface considering the fact that the current disposal containers are not designed to be transportable over great distances;
- Develop a plan to recover fissile material if economics and national policy support doing so. However, there will still be a significant amount of long-lived radioactive waste after reprocessing that will need to be disposed of. This option, economic recovery of fissile material in the spent fuel rods at Yucca Mountain, will *not* eliminate the need for a repository; rather, it would only change the source term, the EBS design, and probably the long-term dose estimates.

In the final performance confirmation report next year, EPRI will review DOE's current contingency plans for the safe retrieval of wastes and shutdown of the Yucca Mountain facility. The purpose of the review will be to evaluate whether it provides SR and LA decision-makers adequate assurance that disposal of the waste can be reversed if the need arises.

5.2 Post-closure Monitoring

Repository monitoring activities after the repository has been closed is not considered part of any performance confirmation plan by either NRC or DOE. However, NRC, in their draft regulation for Yucca Mountain, holds open the possibility that they may request some post-closure monitoring. The purpose of the post-closure testing would have to be well defined since the point of the performance confirmation program is to provide all the necessary information to provide reasonable assurance the repository will meet post-closure regulatory criteria.

Nye County is installing a series of monitoring wells well downstream of Yucca Mountain that they intend to use indefinitely. While unlikely to provide much information regarding radionuclide transport for many thousands of years, these wells are already providing much needed information on the hydrology and geochemistry of the groundwater several kilometers downstream.

At this point in time, it is unclear what sort of testing would be appropriate in the post-closure period. There may be some reasonable set of very long-term surface monitoring activities that could conceivably improve the data set on very infrequent events, such as extreme rainfall or large earthquake events, for example. It will also be difficult, if not impossible, to maintain any monitoring activities within the repository itself after it has been completely sealed. If some additional information is needed after, say, 50 years, it would be better to leave the repository open for longer rather than attempting to monitor a sealed repository. Existing DOE internal guidance already suggests such an approach:

> ...the performance confirmation program shall extend to a minimum of 50 years after the start of emplacement, or up to the time to keep drift walls below the boiling point of water during postclosure. This requirement also provides a bound on the program, so in the event that systems perform as anticipated and performance confirmation is successful, the program can be ended 50 years after the start of emplacement. In addition, the design of the performance confirmation program shall allow (with appropriate modifications) for a closure deferral up to 300 years after the start of emplacement. [DOE 2000b, Table E-1, Item 3.2H]

5.3 Future Technology Development

There may be technological developments over the next few decades that will prompt fundamental changes in the nature of the Yucca Mountain repository design. While one could speculate at great length about the many possible developments, a few examples are included here for the purpose of exploring what effect they may have on repository design and operations.

If improvements in reprocessing occur, and reprocessing is allowed, it might make economic sense to discontinue direct disposal of irradiated fuel and replace it with disposal of HLW only. This altered source term would likely prompt modifications to the waste container since criticality concerns would be almost completely eliminated, and the thermal source term and waste form would be different. It is also possible that a different set of dominant radionuclides would also exist. If the nascent transmutation research proved both technologically achievable and economical then additional modifications to the source term to be disposed of at Yucca Mountain would occur. In either case, spent fuel that had already been emplaced might need to be retrieved, shipped to the processing facility, and the remaining HLW shipped back to Yucca Mountain for disposal. In such a case DOE should be able to implement part of its reversibility plan to retrieve the previously emplaced waste containers.

Improvements in material design and welding processes could also prompt modifications to the EBS. It may be that improved materials or welding techniques would lead to container designs with, for example, dramatically lower uncertainties in long-term performance. If such designs became available after some of the current containers have already been loaded DOE would have to evaluate whether it would be useful to replace them with the improved system.

Improvements in measurement techniques may also help to reduce uncertainty. For example, improved techniques to estimate long-term materials degradation could help eliminate the uncertainty about whether or not stress-corrosion cracking occurs in some circumstances, or the passivity of the corrosion layer. Lowered detection limits for commonly used groundwater tracers could help pave the way for larger scale unsaturated zone and saturated zone tracer testing.

All of the technological improvements that could be considered for use at Yucca Mountain should only act to improve the performance of the repository with the present-day design. Assuming the present-day design provides NRC reasonable assurance that long-term regulatory criteria can be met, then, from a regulatory standpoint, implementing any technological improvement should be purely optional. Only if NRC chose to apply the ALARA (As Low As Reasonably Achievable) principle would DOE perhaps be required to adopt these new technologies. However, the National Academy of Sciences committee on the Technical Bases for Yucca Mountain Standards noted that "there is no scientific basis for incorporating the ALARA principle into the EPA standard or USNRC regulations for the repository" [NAS, 1995].

Thus, the choice whether or not to adopt technological improvements should be based on other considerations (e.g., economic, institutional).[8]

[8] NRC has, however, retained the ALARA principle for operations during the preclosure phase in its draft regulation for Yucca Mountain. So if technological improvements resulted in lower doses to workers or the public during this phase DOE may be required to adopt them.

6
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