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Staff Technical Position on Geological Repository Operations Area Underground Facility Design -- Thermal Loads

U.S. Nuclear Regulatory Commission

Office of Nuclear Material Safety and Safeguards

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ABSTRACT

The purpose of this Staff Technical Position (STP) is to provide the U.S. Department of Energy (DOE) with a methodology acceptable to the Nuclear Regulatory Commission staff for demonstrating compliance with 10 CFR 60.133(i). The NRC staff's position is that DOE should develop and use a defensible methodology to demonstrate the acceptability of a geologic repository operations area (GROA) underground facility design. The staff anticipates that this methodology will include evaluation and development of appropriately coupled models, to account for the thermal, mechanical, hydrological, and chemical processes that are induced by repository-generated thermal loads. With respect to 10 CFR 60.133(i), the GROA underground facility design: (1) should satisfy design goals/criteria initially selected, by considering the performance objectives; and (2) must satisfy the performance objectives 10 CFR 60.111, 60.112, and 60.113. The methodology in this STP suggests an iterative approach suitable for the underground facility design.

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1.0 INTRODUCTION

This Staff Technical Position (STP) emphasizes that the Nuclear Regulatory Commission (NRC) staff expects that the U.S. Department of Energy (DOE) will demonstrate a systematic and logical understanding of the coupled thermal-mechanical-hydrological-chemical (T-M-H-C) responses associated with a particular geologic repository operations area (GROA) underground facility design. Moreover, the staff expects that DOE would achieve this demonstration to the level that is needed to support an understanding of repository performance. This demonstration is expected to be based primarily on a mechanistic understanding of the coupled processes. At the time of construction authorization, DOE may need to incorporate into its demonstration empirical data from short-term tests and simplified analyses. However, the license application submitted before construction of the GROA must be updated before issuance of a license to receive, possess, and emplace waste, and, again, updated upon DOE's application to permanently close the repository. The NRC staff understands that with DOE's pursuit of appropriate technical programs of site characterization and performance confirmation, DOE's level of understanding and demonstration can evolve, and is expected to improve significantly, over the long timeframe associated with the repository program.

In this STP, the staff has included an approach that, based on our understanding today, is acceptable for demonstrating compliance with 10 CFR 60.133(i) at the time of construction authorization. **This approach is based on the principle that, to demonstrate compliance with 10 CFR 60.133(i), DOE must consider coupling of T-M-H-C processes in a manner that is not likely to underestimate the unfavorable aspects of repository performance or overestimate the favorable aspects in the context of analyses and design.** It should be noted that the terms "coupled models," "coupled behavior," and "coupled effects" used in this STP reflect the adequacy principle implied above. (For a definition of "coupling," see Appendix A, "Glossary.")

The staff expects that at the time of construction authorization, DOE will need to clearly demonstrate, in its license application, that the analyses used to predict thermal responses comply with the above principle. Subsequently, the underlying assumptions used in the projected performances should be confirmed during the period of performance confirmation by appropriate testing and/or model refinements. The staff anticipates updating this STP if new information and insights become available that may enhance the approach suggested in this document.

The NRC staff assumes that performance assessment models will exist for evaluating compliance with 10 CFR Part 60 performance objectives. It is also assumed that these models will be capable of incorporating the predicted T-M-H-C responses associated with a specific GROA underground facility design. However, elaboration on the specifics of performance assessments, with respect to the individual 10 CFR Part 60 performance objectives, is outside the scope of this STP.

1.1 Background

Section 60.133(i) requires that the underground facility for the GROA be designed so that the performance objectives will be met, taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. The performance objectives are those in 10 CFR 60.111, 60.112, and 60.113. They deal, generally, with the maintenance of safe operating conditions, the ability to retrieve emplaced wastes for a specified period, and the containment and isolation of the wastes after the geologic repository is permanently closed. Further, the underground facility design for the GROA must also comply with the design criteria of 10 CFR 60.130, 60.131, and 60.133.

The rule thus recognizes that an understanding of the thermal loads,[1] because of the emplacement of nuclear waste, and corresponding thermomechanical response of the host rock and surrounding geologic setting, is essential to the design of the underground facility. One must also understand the uncertainties associated with predicting the thermal loading and corresponding rock and groundwater responses, so that these uncertainties can be accommodated by the design. Many aspects of the design, including canister spacing, opening configurations and dimensions, and support requirements, depend on predictions (using predictive models) of heat transfer, and thermally-induced responses such as rock deformations, groundwater flow (both liquid- and vapor-phase transport), and the dissolution and precipitation of mineral species.

The impact of thermal loads on repository performance can be a very complex technical issue,[2] depending on many factors, including the magnitude of the thermal loads themselves. For those repository-generated thermal regimes that are within the range of engineering experiences, the use of existing predictive models to evaluate the possible effects of thermal loads on repository performance may be a reasonable approach to

[1]Thermal output of emplaced radioactive waste per unit area of geologic repository, usually expressed in kilowatts per acre.

[2]For example, in its *Fifth Report to Congress and the U.S. Secretary of Energy*, the Nuclear Waste Technical Review Board (NWTRB) recently evaluated the impact of thermal loading issues on the design and performance of a geologic repository (see Chapter 3 in NWTRB, 1992).

demonstrate compliance with 10 CFR Part 60 regulatory requirements. On the other hand, repository-generated thermal regimes that are beyond the range of current engineering experience pose significantly more complex problems. Such thermal regimes, acting over the long timeframe of repository performance, may produce effects that involve prediction considerations that are well beyond current engineering practice. For such situations, the use of an existing model, to predict the likely repository effects of such loads, may not be satisfactory. For those situations where DOE makes programmatic decisions that produce repository-generated thermal regimes well beyond those for which engineering experience is available, it is expected that DOE will investigate and evaluate the effects of coupled processes in the predictions of the underground facility performance.

The guidance in this STP focuses on an approach that can be used to demonstrate an understanding of the effect of coupled T–M–H–C responses on geologic repository design. If, at any time, reliable information is gathered to convincingly demonstrate that further development of predictive models and codes would be unwarranted, nothing in this STP should be interpreted to suggest that the staff would expect that additional unnecessary steps would, nevertheless, be performed.

1.2 The Use of Models in Thermal-Response Predictions

The development of defensible predictive models requires a thorough understanding of the thermal loads generated by the emplacement of nuclear waste and corresponding thermally-induced responses in the host rock and the surrounding geologic setting. The staff expects model development/refinement to continue as a greater understanding of the thermally-induced phenomena is gained during the period of repository construction and performance confirmation testing. For example, the models that are used at the time of construction authorization must be sufficiently robust for the Commission, with reasonable assurance, to make the safety findings set out in 10 CFR 60.31. But this by no means calls for the models to be the most sophisticated that can be developed. On the contrary, they must be sufficient to meet the standard of 10 CFR 60.24(a), in that the application is to be "... as complete as possible in the light of information that is reasonably available at the time of docketing." If the models are those that are "reasonably available," they can be used for purposes of analysis and decision making. Of course, the judgment whether there is "reasonable assurance" of safety must take into account the uncertainty associated with the lack of more complete models; but that can be accomplished by appropriate conservatism. Accordingly, DOE will need to defend its design decisions on the level of T–M–H–C coupling it chooses to consider in a particular GROA design, including those aspects of T–M–H–C coupling it chooses to discount in such decisions.

The ongoing nature of model development is reflected at a number of places in 10 CFR Part 60. For example, for engineered and natural barriers important to waste isolation, DOE's license application is to provide "... a detailed description of the programs designed to resolve safety questions. ..." (10 CFR 60.21(c)(14)). If there is an unresolved safety question relating to model validation, this should be described in the application. The existence of such a question may, of course, reduce the Commission's confidence that the standards for issuance of a construction authorization have been satisfied. Depending on the significance of the unresolved safety question, there may be reasonable assurance that applicable requirements have been met and, on that basis, a construction authorization might be issued. Moreover, after a construction authorization is issued, DOE will have a continuing obligation to report to NRC on the "... results of research and development programs being conducted to resolve safety questions" (10 CFR 60.32(b)(4)); this too is addressed, among other things, to the progress in model development. The information will be reflected in DOE's updated application before NRC issuance of a license to receive and possess waste, or to amend or terminate geologic repository operations. Furthermore, as part of the performance confirmation program during construction, DOE's measurements and observations are to be compared with the original design bases and assumptions (including those pertaining to the correctness of models). If significant differences are noted during this comparison, the need for modifications to the design or construction methods is to be determined (10 CFR 60.141(d)). This recognizes that the program must be a dynamic one, and it must allow for changes that reflect the steady accumulation of more information and insight.

1.3 Document Scope

This STP includes the following five sections: 1.0—Introduction; 2.0—Regulatory Framework; 3.0—Staff Technical Positions; 4.0—Discussion; and 5.0—References. Section 2.0 identifies the specific regulations addressed by this STP. Section 3.0 states the staff's technical positions on an acceptable approach to achieve compliance with 10 CFR 60.133(i). An explanation and discussion for the position statements are provided in Section 4.0. Cited references are listed in Section 5.0.

STPs are issued to describe and make available to the public methods acceptable to the NRC staff for implementing specific parts of the Commission's regulations, or to provide guidance to DOE. Moreover, STPs are not substitutes for regulations, and compliance with them is not required. Methods and solutions different from those set out in the STP will be acceptable if they provide a basis for the findings requisite to the issuance or continuance of a construction authorization or license by the Commission. Therefore, the objective of providing guidance to DOE on thermal-load design during the pre-licensing phase is to identify what is needed to demonstrate compliance with the requirements of 10 CFR Part 60.133(i) and thereby minimize the potential for significant future problems.

2.0 REGULATORY FRAMEWORK

The regulatory requirement that forms the principal basis to address thermal load design requirements for the GROA underground facility is set forth in 10 CFR 60.133(i):

> "§60.133(i) *Thermal Loads.* The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, and (sic) surrounding strata, [and] groundwater system."

The performance objectives referenced in 10 CFR 60.133(i) are 10 CFR 60.111, 60.112, and 60.113 (NRC, 1990). A related regulatory requirement that provides an additional basis for the consideration of the effects of thermal loads is also found in 10 CFR 60.21(c)(1)(i)(F). The text of these and other applicable regulations are provided in Appendix B of this document. For the texts of other applicable 10 CFR Part 60 requirements, refer to *Code of Federal Regulations*, Title 10, "Energy."

Information contained in NUREG–1373 (Gupta and Buckley, 1989) and NUREG–1439 (Gupta, *et al.*, 1991) is also relative to this STP.

3.0 STAFF TECHNICAL POSITIONS

It is the NRC staff's position that DOE should develop and use a defensible methodology to demonstrate the acceptability of a GROA underground facility design. The staff anticipates that this methodology will include evaluation and development of "appropriate" coupled models to account for the T–M–H–C processes that are induced by repository-generated thermal load. With respect to 10 CFR 60.133(i), the GROA underground facility design: (1) should satisfy design goals/criteria initially selected by considering the performance objectives; and (2) must satisfy the performance objectives 10 CFR 60.111, 60.112, and 60.113.

The staff's technical position on an acceptable methodology for demonstrating compliance with 10 CFR 60.133(i) is outlined in the following sections. The approach described in this section is based on an expected understanding of the coupled effects of thermally-induced phenomena consistent with the principle stated earlier in Section 1.0. The technical position describes an approach that provides a means to evaluate, through predictive modeling, the effects of thermally-induced phenomena (in the host rock, surrounding strata, and groundwater system) on the repository performance associated with an underground facility design. Also, the methodology takes into account the performance objectives of 10 CFR 60.111, 60.112, and 60.113, all of which must be satisfied by any GROA underground facility design.

3.1 Example of An Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)

DOE should develop a defensible approach that can be used to demonstrate the acceptability of the GROA underground facility design. An example of an acceptable approach is described next and is illustrated in Figure 1.

Step No. 1—Preliminary Evaluation to Determine Sensitivity of the Performance Objectives to Thermal Loading

Make an evaluation to determine if the performance objectives (taking one at a time) are insensitive to the thermal loading to be considered in the GROA underground facility design, based on current scientific understanding and/or engineering experience. If such an evaluation results in a positive answer, as indicated in Step No. 1A of Figure 1, then the underground facility design for the GROA would be considered independent of the thermal loading.

Step No. 2—Determination of the Existence of Predictive Models to Quantify the Effects of Thermal Loading

If the underground facility design for the GROA cannot be established to be independent of thermal loading, determine if reliable predictive models exist to quantify the sensitivity of the GROA design to thermal loading. If such models exist, use them to quantify the effects of thermal loading. In this case, the process is continued with the development of design goals/criteria in Step No. 4, and since reliable models already exist, Step Nos. 3 and 5 are omitted.

Step No. 3—Examination of the Thermally-Induced Phenomena

If reliable models do not exist, examine the thermally-induced phenomena in the host rock, surrounding strata, and groundwater system, to provide a basis for developing predictive models for use in the design of the underground facility for the GROA.

Step No. 4—Development of Design Goals/Criteria

Develop initial design goals/criteria for the GROA underground facility, based on performance objectives, using simplified analyses.

Step No. 5—Development of "Appropriate" Predictive Models

Develop predictive models for detailed analyses. Several iterations may be necessary between Step Nos. 5 and 2 (in Figure 1) before a satisfactory set of predictive models can be developed.

Step No. 6—Application of Predictive Models to the Underground Facility Design

Perform detailed analyses on the underground facility design for the GROA, with predictive models.

Step No. 7—Iterative Predictions to Check if Design Goals/Criteria are Met

Compare results of predictive models to initial design goals/criteria for the GROA underground facility. If necessary, modify the underground facility design (Step No. 7A in Figure 1) until it complies with the GROA design goals/criteria.

Step No. 8—Incorporation of Predicted Results in Pre- and Postclosure Performance Assessment Models

Incorporate the predicted results in performance assessment models, to evaluate compliance with the individual performance objectives of 10 CFR 60.111, 60.112, and 60.113.

If 10 CFR Part 60 performance objectives are not met, determine whether noncompliance with performance objectives results from deficiencies in the underground facility design for the GROA, as shown in Step No. 8A (see bottom of Figure 1). If initial design iterations result in noncompliance with the performance objectives, reexamination of the design process should be considered beginning with Step Nos. 2, 3, or 4. If, after numerous design iterations, noncompliance with 10 CFR Part 60 performance objectives persists, examination of other criteria not related to the GROA underground facility design should be considered (Step No. 8B).

Step No. 9—Acceptability of Underground Facility Design

The underground facility design for the GROA would be considered acceptable if 10 CFR Part 60 performance objectives are met.

3.2 Development of Detailed Predictive Models

To the extent practical, DOE should develop models to predict the thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system, based on a mechanistic understanding of coupled T–M–H–C behavior.

3.3 Alternative Predictive Models

If a detailed understanding of coupled T–M–H–C effects cannot be gained before submittal of an application for construction authorization, DOE should:

(a) develop models that approximate coupled behavior in a manner that is not likely to underestimate the unfavorable aspects or overestimate the favorable aspects of repository performance; and

(b) present such plans for *in-situ* and laboratory monitoring and testing, and for additional model development/refinement, as may be appropriate to confirm the adequacy of the analytical methods used to support the application for construction authorization.

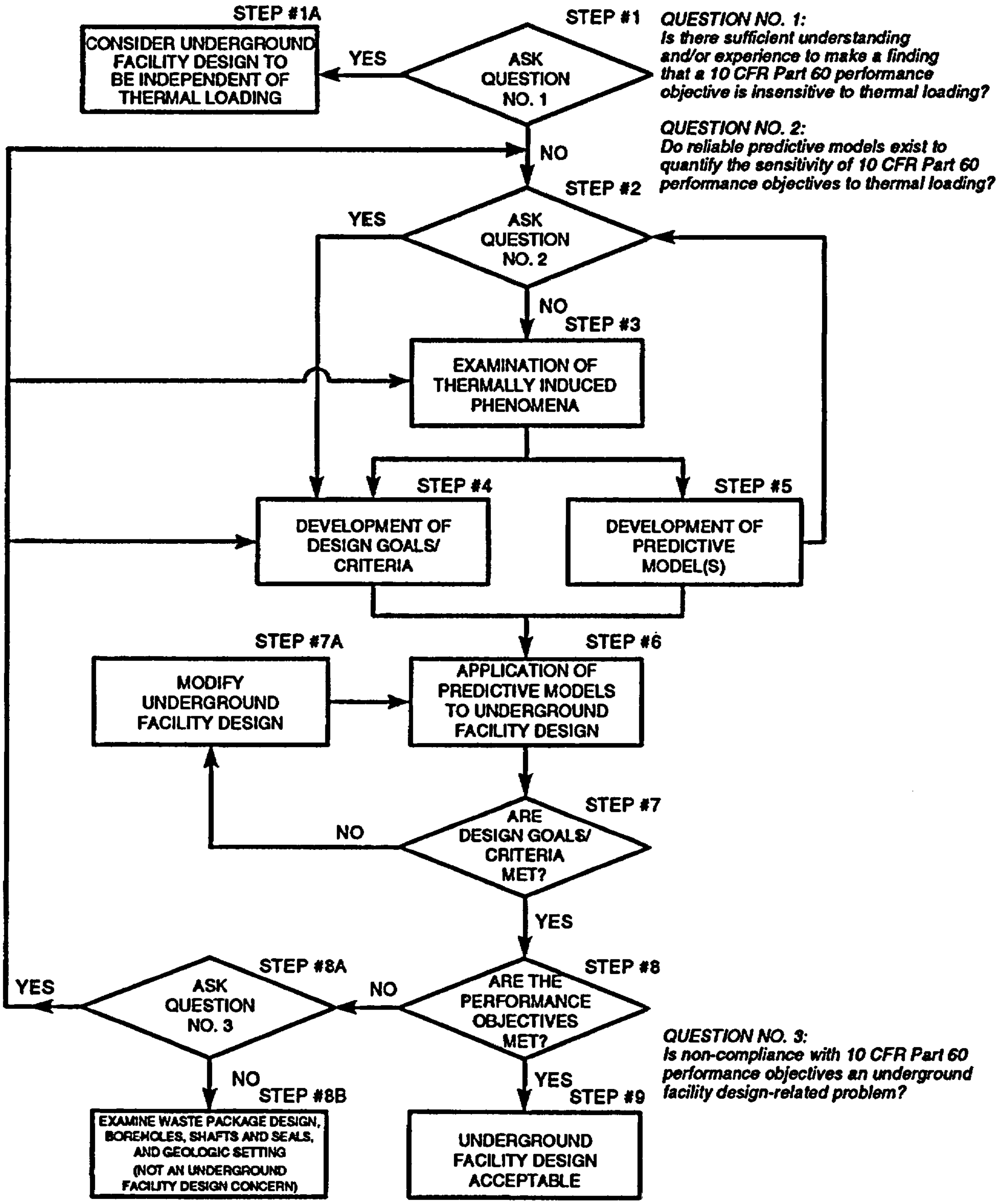

Figure 1. The Logic Flow of an Acceptable Methodology for Demonstrating Compliance with 10 CFR 60.133(i).

4.0 DISCUSSION

The approaches described in Sections 3.1 and 3.2 are acceptable to the staff because it believes that these approaches would lead to a rigorous and objective evaluation of the underground facility design for the GROA, relative to the requirements specified in 10 CFR 60.133(i).

The following discussions parallel the list of staff technical positions given in Section 3.0.

4.1 Example of An Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)

There are five decision points in the example approach shown in Figure 1 (see Step Nos. 1, 2, 7, 8, and 8A). The first two steps in the example approach are programmatic decision points. In Step No. 1, a decision will be made if the thermal loads have significant impacts on the performance of the geologic repository. In Step No. 2, a decision will be made on whether a need exists for the development of detailed predictive models.

In the next two decision points in the example approach (see Step Nos. 7 and 8), evaluations are made of the acceptability of the underground facility design for the GROA. The evaluation point in Step No. 7 involves the comparison of the predicted responses with the response limits set by the design goals/criteria for the underground facility; those, in turn, are derived by considering the performance objectives in 10 CFR 60.111, 60.112, and 60.113. If the predicted response fails to meet the design goals/criteria for the underground facility for the GROA, the design should be changed, with subsequent model application and reevaluation of predicted responses.

For each iteration cycle, the fourth evaluation point, performance assessment evaluation (Step No. 8 of Figure 1), takes place only after all the underground facility design goals/criteria for the GROA have been satisfied. If, on completion of the performance assessment evaluation, the GROA underground facility design fails to comply with 10 CFR Part 60 pre- or postclosure performance objectives, or has a potential for adversely affecting the performance objectives, a reassessment associated with each step (or at least some of the steps) in the methodology should be conducted, before new responses are predicted and incorporated into the performance assessment models for reevaluation. Several iterations may be required before it can be determined that the underground facility design for the GROA complies with 10 CFR 60.133(i). (It should be noted that this approach does not preclude the use of performance assessments for other purposes, utilizing interim design assumptions.)

The fifth and last decision point (Step No. 8A) determines if noncompliance with 10 CFR Part 60 performance objectives arises from underground facility design-related problems, or is the result of other design- and/or site-related problems.

The following discussions are a further amplification of Step Nos. 1 through 9, presented in Section 3.1.

Step No. 1—Preliminary Evaluation to Determine Sensitivity of the Performance Objectives to Thermal Loading

Upon emplacement of spent nuclear fuel and high-level radioactive waste (HLW) in the underground facility, the host rock, surrounding strata, and groundwater system will respond to thermal loading generated by the waste. This response will depend on many factors, such as the T-M-H-C characteristics of the host rock, and those of the surrounding strata; hydrological and geochemical environment; the age of the waste and its thermal decay characteristics; and the designs of the underground facility and the waste package. Such a response will likely affect the preclosure performance objective 10 CFR 60.111, as well as the postclosure performance objectives in 10 CFR 60.113 and 60.112.

Therefore, a logical starting point for a strategy for demonstrating compliance with 10 CFR 60.133(i) would consist of an evaluation to determine the sensitivity of the performance objectives (taking one at a time) to the thermal loading to be considered in the underground facility design for the GROA. This is Step No. 1 in Figure 1. If it is determined on the basis of scientific understanding and/or engineering experience that the GROA underground facility design is insensitive to the effects of thermal loading, then the design of the underground facility could proceed, without further developmental work, to show compliance with 10 CFR 60.133(i), as indicated in Step No. 1A. The design in this case is shown to be independent of the thermal loading.

Step No. 2—Determination of the Existence of Predictive Models to Quantify the Effects of Thermal Loading

If it is determined from Step No. 1 that the performance objective(s) is (are) sensitive to the thermal loading, then it will be necessary to establish whether reliable predictive models exist to quantify the degree of sensitivity. If predictive models exist that can reasonably represent coupled T-M-H-C behavior, then there is no need to develop new models. Instead, the existing models can be used to carry out the design analyses. Subsequently, Step Nos. 3 and 5 in Figure 1 may be skipped, and the process continued with the development of design goals/criteria (Step No. 4). If reliable predictive models do not exist, the process continues to Step No. 3.

Step No. 3—Examination of the Thermally-Induced Phenomena

It is likely that repository-induced thermal loading of the host rock, surrounding strata, and groundwater system may be one of the most important underground facility design parameters for the GROA (DOE, 1988, p. 8.3.2.2–70). The level of response may, vary among different geologic materials and in different locations, in the geologic repository, for the GROA, at different times, which could have an effect on the design of the underground facility. Therefore, to ensure that the design of the underground facility for the GROA complies with the design criterion stated in 10 CFR 60.133(i), it will be necessary to understand the transfer of heat and the associated phenomena such as the thermally-induced mechanical, chemical, and hydrologic response of the host rock, surrounding strata, and groundwater system. This understanding would include an assessment of the level of T–M–H–C coupling that may be necessary to reasonably characterize the phenomena and predict the responses.

Predictive capabilities of thermally-induced phenomena would require characterization of the heat-transfer properties of the host rock, surrounding strata, and groundwater system. Essential information to obtain in this area would be the host rock basic thermal properties, such as thermal conductivity, density, and heat capacity. In addition, information about the host rock mineralogy, porosity, degree of saturation, and permeability would contribute to the understanding of the heat-transfer environment and heat-induced flow of liquids and gases. Information that would support such characterization of the heat-transfer properties would initially come from site characterization activities and subsequently from performance confirmation testing.

Field and laboratory experiments would be necessary to provide evidence of the dominant modes of heat transfer that can be expected, including the degree to which these modes of heat transfer are affected by coupled T–M–H–C processes. The dominant modes of heat transfer may be functions of geometric scale and time. For instance, radiant heat transfer may only be of importance in openings around waste containers, disposal rooms, and access drifts that are not backfilled, whereas heat transfer associated with the vaporization of pore water and transfer of the vapor phase (i.e., convection/diffusion) may have to be considered on larger scales, perhaps tens to hundreds of meters from the underground facility, depending on the presence of water and the amount of waste to be stored per unit area (i.e., the thermal load). In addition, the identification and analyses of natural analogues could lend support to repository-related field and laboratory experiments.

Step No. 3 results from the need to bring about an understanding of the occurrence of heat transfer and thermally-induced effects in the host rock, surrounding strata, and groundwater system, as the basis for developing or qualifying adequate predictive models of thermally-induced responses.

Step No. 4—Development of Design Goals/Criteria

Although the host rock, surrounding strata, and groundwater system are expected to respond to the transfer of heat, the level of such response, which is acceptable from the standpoint of the repository performance objectives, needs to be established. GROA underground facility design goals/criteria derived from T–M–H–C response limits correlated to the repository performance objectives are expected to be essential in the development of the underground facility design. The purpose of developing design goals/criteria that are derived by considering the 10 CFR Part 60 performance objectives is to contribute to the assurance that the design of the underground facility has the likelihood of meeting these performance objectives. The design goals/criteria are to be developed on the basis of the understanding of the thermally-induced phenomena in the host rock, surrounding strata, and groundwater system, and the expected consequences to the waste isolation capability of a site associated with the presence of an underground facility, including the thermal load. Thus, an approach to developing performance-based design goals/criteria would be:

(a) identify processes and events that could result from thermally-induced phenomena (e.g., rock fracturing, groundwater flow, or mineral dissolution and precipitation) that could be of consequence to the performance of the repository (as defined by 10 CFR Part 60 general and specific design criteria and by preclosure and postclosure performance objectives);

(b) determine quantitatively and/or qualitatively in what way and to what extent these processes and events affect (or potentially affect) the performance of the repository; and

(c) determine the degree to which the processes and events are acceptable, to limit any adverse responses that may be of significance in meeting the performance objectives.

To establish response limits expressed by the design goals/criteria, it is likely that "simplified" predictive

T-M-H-C analyses of conceptual underground facility designs would be conducted. Because the responses to be considered are "thermally driven," it is conceivable that the design goals/criteria could be expressed in terms of a maximum rock temperature, temperature gradient, or flux. However, they could also be expressed in terms of limiting rock stresses and displacements, groundwater flow rates, and mineral dissolution and precipitation rates. All these analyses require a certain level of scientific understanding, experimental evidence, predictive techniques (albeit simplified) and professional judgment.

There are various levels of details regarding the evaluation of thermal effects on repository performance upon which the development of such criteria could be based. However, the criteria are expected to be developed based on the available information and understanding about the host rock, surrounding strata, and groundwater system. New understanding about potential T-M-H-C processes and events in the host rock, surrounding strata, and groundwater system could be gained during the period of site characterization and performance confirmation testing. To better guide the development of the design process of the GROA underground facility, it is reasonable that an improved understanding of the effects of T-M-H-C processes and events might be reflected in the design process by new and/or revised design goals/criteria. However, a documented rationale would be expected with regard to any changes to baseline design goals/criteria.

Step No. 5—Development of "Appropriate" Predictive Models

The discussion for Step No. 5 in Figure 1 is contained in Section 4.2, "Development of Predictive Models."

Step No. 6—Application of Predictive Models to the Underground Facility Design

The design goals/criteria that may relate response limits (such as maximum rock temperature, displacements, stresses, flow rates, and mineral dissolution and precipitation rates) to the performance objectives serve as the initial gauge by which the underground facility design should be tested. This means that the predicted results (including the uncertainties) of heat transfer and thermally-induced mechanical, hydrologic, and chemical responses associated with a particular underground facility design must be available and compared to the design goals/criteria. An example of such comparisons associated with heat-transfer predictions can be found in NUREG/CR-5428 (Brandshaug, 1989). Meeting all the design goals/criteria will provide confidence that the underground facility design has a higher likelihood of meeting and/or not adversely affecting 10 CFR Part 60 preclosure and postclosure performance objectives.

Step No. 7—Iterative Predictions to Check if Design Goals/Criteria Are Met

Step No. 7 is a decision point to determine whether the design goals/criteria for the GROA underground facility have been met. If the design goals/criteria have not been met, then the underground facility design for the GROA needs to be modified (Step No. 7A in Figure 1) and the design needs to be re-evaluated in the manner described in Step No. 6. If the design goals/criteria have been met, then the process continues to the next decision point found in Step No. 8.

Step No. 8—Incorporation of Predicted Results in Performance Assessment Models

Although it may be possible to show that the underground facility design meets individual design goals/criteria, the final evaluation of the underground facility design must be a test of the effect of the design on the performance, as measured against the objectives 10 CFR 60.111, 60.112, and 60.113. It is expected that models for the evaluation of performance objectives will be available, and will incorporate the predicted heat transfer and thermally-induced mechanical, hydrologic, and chemical responses, including uncertainties, as input for analyses. Compliance with 10 CFR 60.133(i) would be demonstrated by meeting: (1) the design goals/criteria; and (2) the performance objectives.

An unsatisfactory performance assessment result would require a return to Step No. 4, to perform a reassessment of the design goals/criteria. On the basis of the reassessment, a re-evaluation of the design may be necessary. If unacceptable results persist, it may become necessary to return to Step No. 2 or 3, from Step No. 8 (see Figure 1).

It is conceivable that a noncompliance determination is not necessarily related to a deficiency in the GROA underground facility design (Step No. 8A). This would be evident if repeated examinations of the design process (e.g., Step Nos. 2 or 3 through 7 in Figure 1) fail to yield a satisfactory evaluation by the performance assessment model (Step No. 8). In this case, a decision would be made to look for problems related to waste package design, borehole and shaft seals design, and/or geologic setting concerns (Step No. 8B); however, discussions of such analyses are beyond the scope of this STP.

Step No. 9—Acceptability of Underground Facility Design

This is the final step in the design of the GROA underground facility. It is only reached when the design goals/criteria as well as the performance objectives have been satisfied. As indicated in Step No. 8, several iterations may be required before it can be concluded that 10 CFR 60.133(i) requirements have been complied with.

4.2 Development of Detailed Predictive Models

The thermal load expected to result from the emplacement of spent nuclear fuel and HLW will affect the host rock, surrounding strata, and groundwater system for thousands of years. Thus, the thermal load has the potential to alter the normal T–M–H–C processes within the geologic setting throughout the entire waste containment period and much of the waste isolation period. Predictions of the heat transfer and thermally-induced mechanical, hydrologic, and chemical response of the underground facility host rock, surrounding strata, and groundwater system must be part of the basis upon which the underground facility is designed. Analyses will be needed that collectively would provide a perspective on the transient rock temperatures and associated rock stresses and deformations, groundwater flow (i.e., liquid- and vapor-phase transport), and chemical response such as the dissolution and precipitation of mineral species in the host rock and surrounding strata. The staff expects DOE to pursue the development of coupled T–M–H–C models based on an understanding that is proportional to the impact of coupling on the overall performance of the geologic repository.

Because of the transient nature of the heat transfer associated with the disposal of nuclear waste, the thermally-induced mechanical, hydrologic, and chemical response levels will also change with time. Details that may be important to the prediction of the response early in the history of the repository and that may occur relatively close to individual waste containers (for example the occurrence of pore water boiling), may not necessarily occur later in the history of the repository and much farther from the vicinity of the waste containers. Thus, predictive models capable of analyzing canister-scale, room-scale, repository-scale, and regional-scale problems will be needed to ensure that **an appropriate level of detail will be included in the analyses.**

The staff recognizes that assumptions must be made about host rock conditions and level of details that will be reflected in the predictive models. To include great complexity in the characterization of material behavior, for example, does not necessarily provide more accurate predictions, because (even if the complex details can be characterized at the scales needed) a complex model is often more difficult to verify, validate, and use. The staff also recognizes, on the other hand, that oversimplification in modeling may obscure the understanding of those processes that might have significant impact on design goals/criteria and/or performance. The analyst should choose a model that strikes a balance between unworkable detail and oversimplification of the processes that are being modeled. Such a balance can reduce the model uncertainty to a degree. Nevertheless, there remains residual model uncertainty that results from the simplification and lack of knowledge of the phenomena being modeled.

Since the purpose of the predictive models is to assist in the evaluation of the adequacy of the underground facility design, the models must provide a measure of response that enables such evaluations. Relationships need to be established between the response measures and the performance measures. For the heat-transfer model, this response measure would be the transient temperatures in the host rock and surrounding strata. For the mechanical model, the measure would be the components of stress, strain, and displacement. For the hydrologic model, this measure would be the specific discharge of fluid through the host rock and surrounding strata and the directional flow vectors. For the chemical model, this measure would be the activities of components in the aqueous phase, the composition and concentration of mineral components, the fugacity of gaseous components, and the porosity and intrinsic permeability of the geologic material.

The reliability of model predictions is affected to a great extent by the reliability of the information upon which the predictions are derived. Input data to the predictive models for heat transfer and thermally-induced mechanical, hydrologic, and chemical responses must be representative of the prevailing conditions at the repository site. Thus, the data must be derived by appropriate tests of a sufficient number and duration, which allow for reliable estimates of spatial representativeness, as well as range and distribution of the data. In addition, the acquisition of the necessary input data, as well as the analysis of the data (e.g., data reduction) must be conducted in accordance with quality assurance procedures (see Subpart G to 10 CFR Part 60).

Determination of the heat transfer and thermally-induced mechanical, hydrological, and chemical behavior in the host rock, surrounding strata, and groundwater system must give consideration to the effects of uncertainties associated with the values of the parameters used in the predictive model input. To properly evaluate the underground facility design for the GROA, the effects of uncertainty in model input parameters must be established with respect to the predicted results. This includes assumptions upon which the models rely, which tend to idealize a problem into manageable proportions. Assumptions and uncertainties could be related to geometric aspects of a problem such as two-dimensional versus three-dimensional analysis, simplified representation of the geologic stratigraphy and/or topography, orientation and frequency of rock joints, initial conditions, environmental conditions resulting from a range of anticipated processes and events, and to idealizations in constitutive relationships of phenomena. From the standpoint of model reliability, it is essential that assessments be made of the effects of uncertainties associated with model assumptions on the predicted results. Thus, an evaluation of the uncertainties must be provided with respect to the predicted results and be included in the evaluation of performance as it may relate to the design of the GROA underground facility. The effects of uncertainties related to material properties could be assessed by using the range or statistical distribution of the properties. Examination of the change in response with respect to a variation (e.g., one standard deviation) in model-specific parameters provides a useful perspective on the evaluation of the design of an underground facility. Such examination would:

- indicate whether significant additional accuracy in the prediction is attainable, given the current parameter ranges and sensitivities;
- indicate which parameters may be important in achieving more accurate predictions; and
- provide useful guidance aimed at the development of an underground facility design, that accommodates certain parameter ranges.

The effects of assumptions could be assessed relatively, by varying the model in terms of alternatives (e.g., using different constitutive relationships and initial conditions), or directly, by evaluating the model against physical experiments. The results of these activities provide confidence in the reliability of a model, which would need to be expressed in qualitative and quantitative terms. It is anticipated that a statistical approach will be needed to provide a systematic evaluation of the response uncertainties. The NRC staff expects that DOE will use statistical methods that are consistent with the quality and quantity of data available in its approach to dealing with data uncertainties.

The licensing process requires that DOE demonstrate that the regulations embodied within 10 CFR Part 60 have been met. However, as stated in 10 CFR 60.101(a)(2), "... it is not expected that complete assurance that they will be met can be presented. A reasonable assurance, on the basis of the record before the Commission, that the objectives and criteria will be met is the general standard that is required." The Commission must, therefore, make a finding that the issuance of a license will not constitute an unreasonable risk to the health and safety of the public. Further, this finding must be made on the basis of information presented in the license application. Section 10 CFR 60.24 of the rule requires that the application be as complete as possible at the time of docketing and, further, that DOE update its application as additional information becomes available. To the extent that the information in the application may be incomplete, it must nevertheless be sufficient (taking into account plans for performance confirmation) to support the findings stated above.

Finally, all predictive models and their numerical representations (i.e., computer codes) used for licensing will need a certain degree of validation and verification, respectively. Rigorous model validation and computer code verification against laboratory and field experiments are expected to test the reliability of the models. Both model validation and computer code verification are imperative if heat transfer and thermally induced effects are to be predicted with sufficient reliability to ensure compliance of the underground facility design with the performance objectives. However, there may be different levels of model validation, because factors that constitute a rigorous validation depend on the information obtained from the laboratory and field experiments. For example, it is reasonable to expect that a more rigorous model validation could be achieved for short-term (e.g., less then 10 years) predictions than for long-term predictions. It is also reasonable to expect that a more rigorous model validation could be achieved for predictions of T–H–M–C response in the close vicinity of the underground facility, including the individual waste containers, than for predictions of responses at greater distances from the underground facility, simply because of the problems associated with physical access. (NRC has provided guidance on computer code verification in NUREG–0856 (see Silling, 1983). However, model validation and code verification are complex issues that deserve a more extensive discussion than can be provided in this STP.)

4.3 Alternative Predictive Models

In demonstrating compliance with design criteria of 10 CFR 60.133(i), it is expected that a mechanistic understanding of coupled behavior will be used to predict the thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. The staff realizes, however, that it may not be possible to obtain a thorough mechanistic understanding of coupled T-M-H-C behavior, as discussed in Section 1.2, particularly before an application is submitted to construct a geologic repository. Therefore, in the design of the underground facility, DOE may need to develop and use models that express coupling between processes based on less than a thorough mechanistic understanding of T-M-H-C behavior. Note that analysis using such empirical models must provide for an evaluation of the effects of the assumptions of coupling on the predicted results and the conservatism of the empirical models used.

The lack of a thorough mechanistic understanding may lead to the use of models that do not directly account for coupling between two or more of the T-H-M-C processes involved. Appendix C gives an example of an iterative process for the analysis of thermally-induced phenomena using such "approximate" models.

In the application of empirical models that rely on a limited mechanistic understanding of coupled processes, and/or that do not directly account for coupling between two or more processes, conservative data and assumptions must be used. Such conservatism should compensate for the uncertainties resulting from the lack of a detailed understanding, since otherwise such uncertainties may preclude the staff from finding, with reasonable assurance, that the performance objectives will be met.

If DOE decides to use alternative predictive models, as discussed above, the staff expects DOE's license application to demonstrate that such models are not likely to underestimate the unfavorable aspects, or overestimate the favorable aspects of geologic repository performance, in the context of analysis and design.

The staff also expects that, as a part of its performance confirmation program (10 CFR 60.140–143), DOE will perform *in-situ* and laboratory monitoring and testing to confirm the assumptions made in the license application, with respect to the alternative predictive models used in underground facility design analyses. The results of the performance confirmation program should provide the bases for model refinement, if needed, as discussed in Section 1.2.

5.0 REFERENCES

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U.S. Department of Energy, "Chapter 8, Section 8.3.2.2, Configuration of Underground Facilities (Postclosure)" in "Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," Office of Civilian Radioactive Waste Management, Report DOE/RW-0199, Vol. VI, Part B, December 1988.

APPENDIX A

GLOSSARY

As used in this guidance:

"Coupled Model" means a model that takes into account the effect at least one process has on the initiation and propagation of another. Figure A1(a and b) show examples of Thermal, Mechanical, Hydrological, Chemical (T–M–H–C) coupled models.

"Geologic Repository"* means a system that is intended to be used for, or may be used for, the disposal of radioactive wastes in excavated geologic media. A geologic repository includes:

(1) The geologic repository operations area; and

(2) the portion of the geologic setting that provides isolation of the radioactive waste.

"Geologic Repository Operations Area"* means a high-level radioactive waste facility that is part of a geologic repository, including both surface and subsurface areas, where waste handling activities are conducted.

"Geologic Setting"* means the geologic, hydrologic, and geochemical systems of the region in which a geologic repository operations area is or may be located.

"Host Rock"* is the geologic medium in which the waste is emplaced.

Code of Federal Regulations, Title 10, "Energy."

"Retrieval"* means the act of intentionally removing radioactive waste from the underground location at which the waste had been previously emplaced for disposal.

"Underground Facility"* means the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals.

"Validation" means the assurance that a model as embodied in a computer code is a correct representation of the process or system for which it is intended (Silling, 1983, p. 3).

"Verification" is the assurance that a computer code correctly performs the operations specified in a numerical model (Silling, 1983, p. 3).

For definitions of other relevant terms, see 10 CFR 60.2.

References

Code of Federal Regulations, "Disposal of High-Level Radioactive Wastes in Geologic Repositories," Part 60, Chapter I, Title 10, "Energy."

Silling, S.A., "Final Technical Position on Documentation of Computer Codes for High-Level Waste Management," Nuclear Regulatory Commission, NUREG–0856, June 1983.

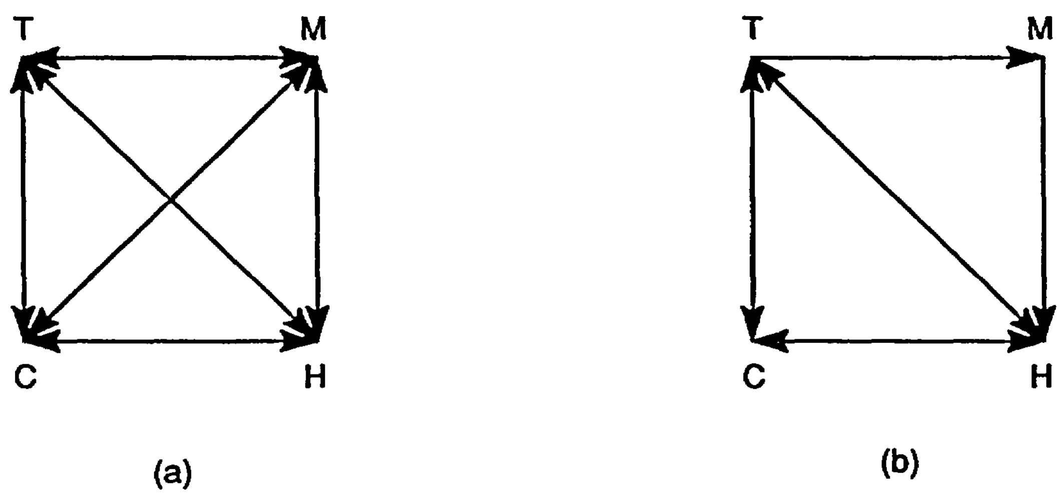

Figure A1. Examples of Coupled Models. Figure A1(a) is an example of a coupled model in which each of the T, M, H, and C processes has an effect on the initiation and propagation of any or all of the other processes. Likewise, Figure A1(b) is an example of a coupled model similar to that shown in Figure A1(a), with the exception that the coupling between the mechanical (M) processes and the chemical (C) processes is absent, and the mechanical and hydrologic (H) processes do not express an effect on the initiation and propagation of the thermal (T) and mechanical (M) processes, respectively.

APPENDIX B

APPLICABLE 10 CFR PART 60 REGULATIONS

§60.21(c)(1)(i)(F) Content of application.

[(c) The Safety Analysis Report shall include:

(1) A description and assessment of the site at which the proposed geologic repository operations area is to be located with appropriate attention to those features of the site that might affect geologic repository operations area design and performance. The description of the site shall identify the location of the geologic repository operations area with respect to the boundary of the accessible environment.

(i) The description of the site shall also include the following information regarding subsurface conditions. This description shall, in all cases, include such information with respect to the controlled area. In addition, where subsurface conditions outside the controlled area may affect isolation within the controlled area, the description shall include such information with respect to subsurface conditions outside the controlled area to the extent such information is relevant and material. The detailed information referred to in this paragraph shall include:

(F) The anticipated response of the geomechanical, hydrogeologic, and geochemical systems to the maximum design thermal loading, given the pattern of fractures and other discontinuities and the heat transfer properties of the rock mass and groundwater.

§60.111 Performance of the geologic repository operations area through permanent closure.

(a) *Protection against radiation exposures and releases of radioactive material.* The geologic repository operations area shall be designed so that until permanent closure has been completed, radiation exposures and radiation levels, and releases of radioactive materials to unrestricted areas, will at all times be maintained within the limits specified in Part 20 of this chapter and such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency.

(b) *Retrievability of waste.* (1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission. This different time period may be established on a case-by-case basis consistent with the emplacement schedule and the planned performance confirmation program.

(2) This requirement shall not preclude decisions by the Commission to allow backfilling part or all of, or permanent closure of, the geologic repository operations area before the end of the period of design for retrievability.

(3) For purposes of this paragraph, a reasonable schedule for retrieval is one that would permit retrieval in about the same time as that devoted to construction of the geologic repository operations area and the emplacement of wastes.

§60.112 Overall system performance objective for the geologic repository after permanent closure.

The geologic setting shall be selected and the engineered barrier system and the shafts, boreholes and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency with respect to both anticipated processes and events and unanticipated processes and events.

§60.113 Performance of particular barriers after permanent closure.

(a) *General provisions*—(1) *Engineered barrier system.* (i) The engineered barrier system shall be designed so that assuming anticipated processes and events: (A) Containment of HLW will be substantially complete during the period when radiation and thermal conditions in the engineered barrier system are dominated by fission product decay; and (B) any release of radionuclides from the engineered barrier system shall be a gradual process which results in small fractional releases to the geologic setting over long times. For disposal in the saturated zone, both the partial and complete filling with ground water of available void spaces in the underground facility shall be appropriately considered and analyzed among the anticipated processes and events in designing the engineered barrier system.

(ii) In satisfying the preceding requirement, the engineered barrier system shall be designed, assuming anticipated processes and events, so that:

(A) Containment of HLW within the waste packages will be substantially complete for a period to be determined by the Commission taking into account the factors specified in §60.113(b) provided, that such period shall be not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository; and

(B) The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure, or such other fraction of the inventory as may be approved or specified by the Commission; provided, that this requirement does not apply to any radionuclide which is released at a rate less than 0.1 percent of the calculated total release rate limit. The calculated total release rate limit shall be taken to be one part in 100,000 per year of the inventory of radioactive waste, originally emplaced in the underground facility, that remains after 1,000 years of radioactive decay.

(2) *Geologic setting*. The geologic repository shall be located so that pre-waste-emplacement ground water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission.

(b) On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied. Among the factors that the Commission may take into account are:

(1) Any generally applicable environmental standard for radioactivity established by the Environmental Protection Agency;

(2) The age and nature of the waste, and the design of the underground facility, particularly as these factors bear upon the time during which the thermal pulse is dominated by the decay heat from the fission products;

(3) The geochemical characteristics of the host rock, surrounding strata and ground water; and

(4) Particular sources of uncertainty in predicting the performance of the geologic repository.

(c) Additional requirements may be found to be necessary to satisfy the overall system performance objective as it relates to unanticipated processes and events.

§60.130 Scope of design criteria for the geologic repository operations area.

Sections 60.131 through 60.134 specify minimum criteria for the design of the geologic repository operations area. These design criteria are not intended to be exhaustive, however. Omissions in §§60.131 through 60.134 do not relieve DOE from any obligations to provide such safety features in a specific facility needed to achieve the performance objectives. All design bases must be consistent with the results of site characterization activities.

§60.131 General design criteria for the geologic repository operations area.

(a) *Radiological protection*. The geologic repository operations area shall be designed to maintain radiation doses, levels, and concentrations of radioactive material in air in restricted areas within the limits specified in Part 20 of this chapter. Design shall include:

(1) Means to limit concentrations of radioactive material in air;

(2) Means to limit the time required to perform work in the vicinity of radioactive materials, including, as appropriate, designing equipment for ease of repair and replacement and providing adequate space for ease of operation;

(3) Suitable shielding;

(4) Means to monitor and control the dispersal of radioactive contamination;

(5) Means to control access to high radiation areas or airborne radioactivity areas; and

(6) A radiation alarm system to warn of significant increases in radiation levels, concentrations of radioactive material in air, and of increased radioactivity released in effluents. The alarm system shall be designed with provisions for calibration and for testing its operability.

(b) *Structures, systems and components important to safety*—(1) *Protection against natural phenomena and environmental conditions.* The structures, systems, and components important to safety shall be designed so that natural phenomena and environmental conditions anticipated at the geologic repository operations area will not interfere with necessary safety functions.

(2) *Protection against dynamic effects of equipment failure and similar events.* The structures, systems, and components important to safety shall be designed to withstand dynamic effect such as missile impacts, that could result from equipment failure, and similar events and conditions that could lead to loss of their safety functions.

(3) *Protection against fires and explosions.* (i) The structures, systems and components important to safety shall be designed to perform their safety functions during and after credible fires or explosions in the geologic repository operations area.

(ii) To the extent practicable, the geologic repository operations area shall be designed to incorporate the use of noncombustible and heat resistant materials.

(iii) The geologic repository operations area shall be designed to include explosion and fire detection alarm systems and appropriate suppression systems with sufficient capacity and capability to reduce the adverse effects of fires and explosions on structures, systems, and components important to safety.

(iv) The geologic repository operations area shall be designed to include means to protect systems, structures, and components important to safety against the adverse effects of either the operation or failure of the fire suppression systems.

(4) *Emergency capability.* (i) The structures, systems, and components important to safety shall be designed to maintain control of radioactive waste and radioactive effluents, and permit prompt termination of operations and evacuation of personnel during an emergency.

(ii) The geologic repository operations area shall be designed to include onsite facilities and services that ensure a safe and timely response to emergency conditions and that facilitate the use of available offsite services (such as fire, police, medical and ambulance service) that may aid in recovery from emergencies.

(5) *Utility services.* (i) Each utility service system that is important to safety shall be designed so that essential safety functions can be performed under both normal and accident conditions.

(ii) The utility services important to safety shall include redundant systems to the extent necessary to maintain, with adequate capacity, the ability to perform their safety functions.

(iii) Provisions shall be made so that, if there is a loss of the primary electric power source or circuit, reliable and timely emergency power can be provided to instruments, utility service systems, and operating systems, including alarm systems, important to safety.

(6) *Inspection, testing, and maintenance.* The structures, systems, and components important to safety shall be designed to permit periodic inspection, testing, and maintenance, as necessary, to ensure their continued functioning and readiness.

(7) *Criticality control.* All systems for processing, transporting, handling, storage, retrieval, emplacement, and isolation of radioactive waste shall be designed to ensure that a nuclear criticality accident is not possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. Each system shall be designed for criticality safety under normal and accident conditions. The calculated effective multiplication factor (k_{eff}) must be sufficiently below unity to show at least a 5% margin, after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the method of calculation.

(8) *Instrumentation and control systems.* The design shall include provisions for instrumentation and control systems to monitor and control the behavior of systems important to safety over anticipated ranges for normal operation and for accident conditions.

(9) *Compliance with mining regulations.* To the extent that DOE is not subject to the Federal Mine Safety and Health Act of 1977, as to the construction and operation of the geologic repository operations area, the design of the geologic repository operations area shall nevertheless include such provisions for worker protection as may be necessary to provide

reasonable assurance that all structures, systems, and components important to safety can perform their intended functions. Any deviation from relevant design requirements in 30 CFR, Chapter I, Subchapters D, E, and N will give rise to a rebuttal presumption that this requirement has not been met.

(10) *Shaft conveyances used in radioactive waste handling.* (i) Hoists important to safety shall be designed to preclude cage free fall.

(ii) Hoists important to safety shall be designed with a reliable cage location system.

(iii) Loading and unloading systems for hoists important to safety shall be designed with a reliable system of interlocks that will fail safety upon malfunction.

(iv) Hoists important to safety shall be designed to include two independent indicators to indicate when waste packages are in place and ready for transfer.

§60.133 Additional design criteria for the underground facility.

(a) *General criteria for the underground facility.* (1) The orientation, geometry, layout, and depth of the underground facility, and the design of any engineered barriers that are part of the underground facility shall contribute to the containment and isolation of radionuclides.

(2) The underground facility shall be designed so that the effects of credible disruptive events during the period of operations, such as flooding, fires and explosions, will not spread through the facility.

(b) Flexibility of design. The underground facility shall be designed with sufficient flexibility to allow adjustments where necessary to accommodate specific site conditions identified through in situ monitoring, testing or excavation.

(c) Retrieval of waste. The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of §60.111.

(d) Control of water and gas. The design of the underground facility shall provide for control of water or gas intrusion.

(e) Underground openings. (1) Openings in the underground facility shall be designed so that operations can be carried out safely and the retrievability option maintained.

(2) Openings in the underground facility shall be designed to reduce the potential for deleterious rock movement or fracturing of overlying or surrounding rock.

(f) *Rock excavation.* The design of the underground facility shall incorporate excavation methods that will limit the potential for creating a preferential pathway for groundwater to contact the waste packages or radionuclide migration to the accessible environment.

(g) *Underground facility ventilation.* The ventilation system shall be designed to:

(1) Control the transport of radioactive particulates and gases within and releases from the underground facility in accordance with the performance objectives of §60.111(a).

(2) Assure continued function during normal operations and under accident conditions; and

(3) Separate the ventilation of excavation and waste emplacement areas.

(h) *Engineered barriers.* Engineered barriers shall be designed to assist the geologic setting in meeting the performance objectives for the period following permanent closure.

(i) *Thermal loads.* The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, and (sic) surrounding strata, [and] groundwater system.

APPENDIX C

EXAMPLE OF AN ITERATIVE PROCESS FOR THE ANALYSIS OF THERMALLY-INDUCED PHENOMENA

Figure C1(a) illustrates a level of coupling that accounts for all the thermal-mechanical-hydrological-chemical (T–M–H–C) processes affecting each other's initiation and propagation (indicated by arrows pointing in both directions between the processes in Figure C1(a)). Such a model would be based on a detailed mechanistic understanding of the coupled T–M–H–C processes. Figure C1(b) shows a second example, of a coupled model, that may be based on either: (1) a detailed mechanistic understanding of the coupled T–M–H–C processes, reflecting the understanding of negligible effects of some of the processes on others (i.e., arrows pointing only in one direction between the affected T–M–H–C processes); and/or (2) less than a thorough understanding of the coupled processes. Figure C2 shows an example of the analysis approach, to approximate the coupled models shown in Figure C1. The example analyses depicted in Figure C2 would initially involve a set of predictions of heat transfer, thermally-induced mechanical, hydrologic, and chemical responses, with subsequent changes to the thermal properties consistent with the predictions of mechanical, hydrologic, and chemical responses (e.g., changes in thermal properties because of dissolution and precipitation of mineral species in the host rock, as predicted by the chemical model). Subsequent analyses would produce a second, and third, etc. set of predictions of heat-transfer and thermally-induced mechanical, hydrological, and chemical responses. The iterative process would continue until changes in the prediction of the respective phenomena converge to some acceptable level.

The order in which the phenomena (e.g., T–M–H–C) are analyzed in Figure C2 is shown only as an example. The responsibility to determine the most appropriate sequence of analysis rests with the applicant. The process depicted in Figure C2 is based on the need to not only provide predictions about the heat-transfer and thermally-induced effects in the host rock, surrounding strata, and groundwater system, but to provide it in a manner that allows an evaluation of the level of coupling used.

The applicant may choose to use approximate methods similar to that illustrated in Figure C2, for assessing the effects of thermal loads in the context of the underground facility design. However, regardless of the methods, assumptions, or approximations used in the design process, the applicant must demonstrate, at the time of license application, that the proposed underground facility design will conform to the performance objectives of 10 CFR 60.111, 60.112, and 60.113, as required by 10 CFR 60.133(i).

It is also important to note that not every design goal/criterion needs consideration of mechanical/chemical/hydrological changes resulting from thermal loading. For each performance objective, the scale of the problem (canister/room/repository/region) and duration of interest (0 to 100 years, 0 to 300/1000 years, 0 to 10,000 years) will be different. The analyses should consider the existing information such as laboratory and field test data, "simplified" model studies, and natural analogues, before embarking on any detailed analyses. For certain cases, it may be possible to terminate the analysis procedures in Figure C2 at the end of first or second iteration.

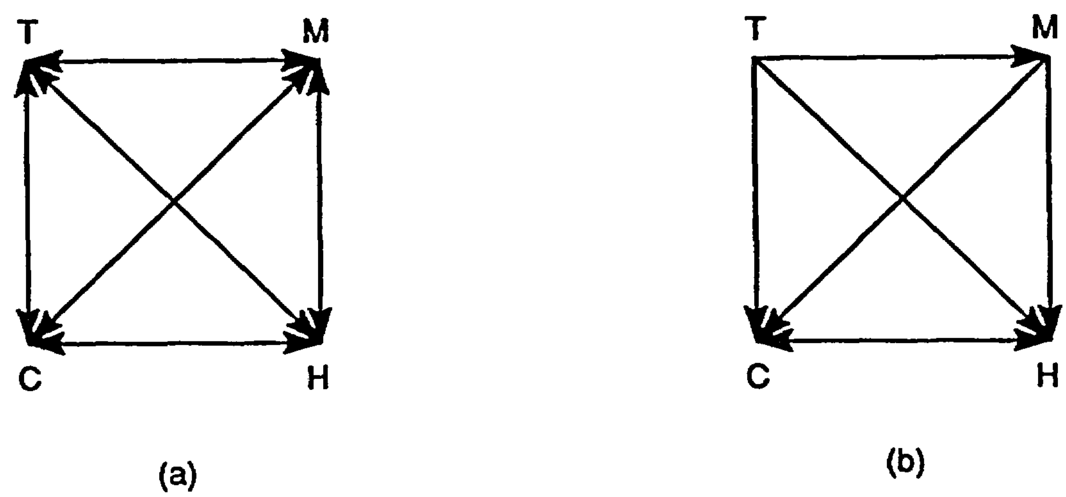

Figure C1. Coupled T-M-H-C Models. "T," "M," "H," and "C" refer to thermal, mechanical, hydrological, and chemical responses, respectively.

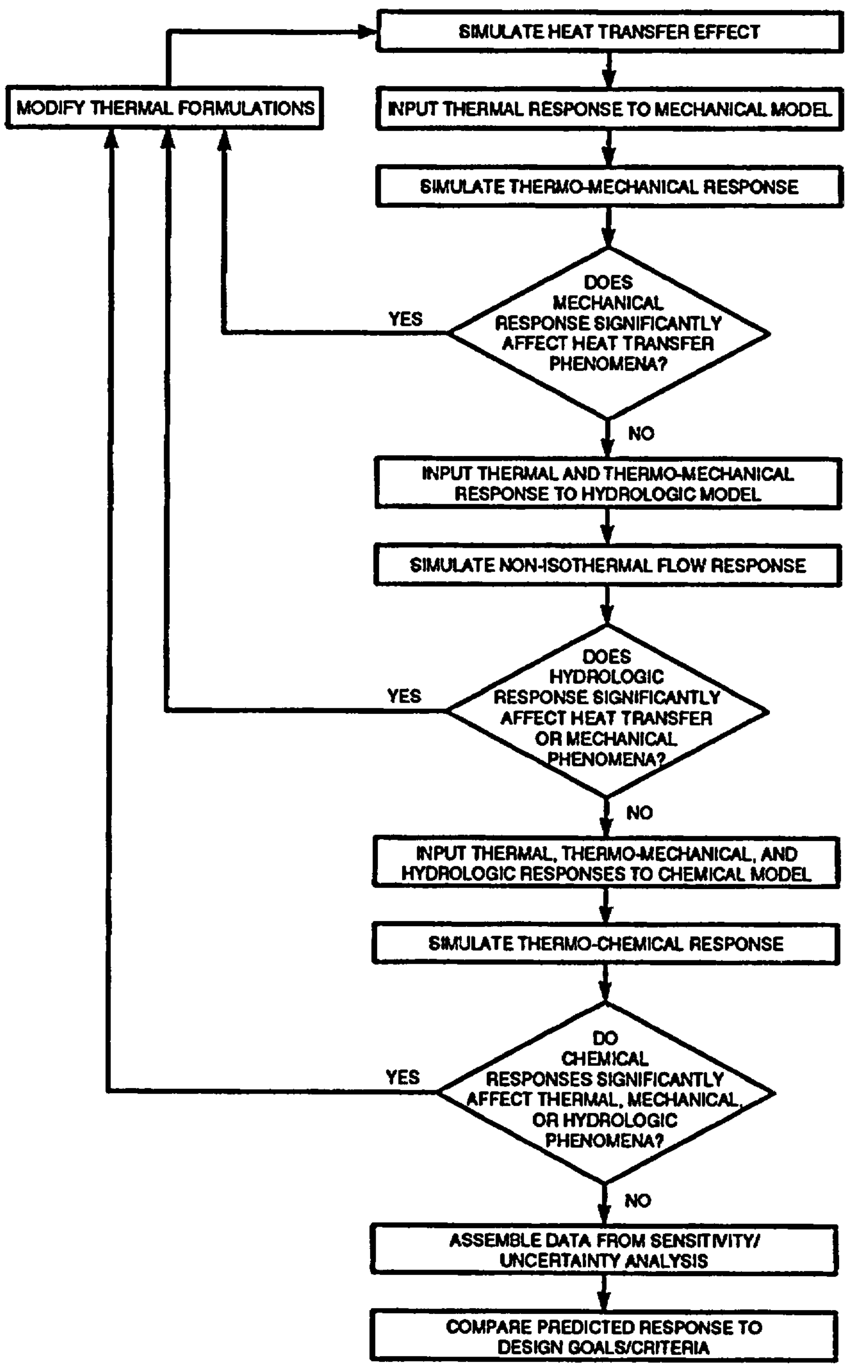

Figure C2. Example of an Iterative Process for the Analysis of Thermally-Induced Phenomena.

APPENDIX D

DISPOSITION OF PUBLIC COMMENTS

Note: Throughout this comment response package, "STP" refers to the staff technical position noticed in the *Federal Register* on July 22, 1991 (NRC, 1991; 56 FR 33478).

Department Of Energy (DOE) Comments

General Comments

Over the past ten years, the U.S. Nuclear Regulatory Commission (NRC) staff has urged the U.S. Department of Energy (DOE) to assess the coupled thermal (T), mechanical (M), hydrological (H), and chemical (C) responses associated with a geologic repository. In response, the Yucca Mountain Site Characterization Plan (SCP) stated that although not completely defined, tests will investigate coupled interactions (DOE, 1988c, p. 8.3.2.1–14). Also, in our Exploratory Shaft Facility (ESF) Alternatives Study (Dennis, 1991), we examined different testing layouts and chose one that would accommodate most testing programs, including tests for coupled interactions. Test Planning Packages and the Title II design of the ESF should give the NRC staff more information, but we have no immediate plans to examine coupled interactions at the level of detail that the draft Staff Technical Position (STP) recommends.

The STP outlines a step-wise approach by which the T–M–H–C assessment would be accomplished. It is a demanding approach entailing many computer codes whose development will push DOE well beyond the state-of-the-art. Ultimately, the NRC staff expects DOE to "... demonstrate a comprehensive, systematic, and logical understanding of the coupled T–M–H–C responses associated with a particular geologic repository operations area (GROA) underground facility design." (page 1). We seriously doubt that the staff's expectations will be realized, at least within the next five to ten years.

The STP does not convince us that a "fully coupled" model is needed for demonstrating compliance with 10 CFR 60.133(i) or, for that matter, any requirement in 10 CFR Part 60. We believe that "simplified" models would work as well, if not better. The STP does not explain what makes a model "fully coupled." An example would be helpful. The STP voids the NRC's justification for requiring a disturbed zone and a containment period. Both were justified because they permitted simplified analyses, not the highly complex and possibly unattainable analyses that the STP expects.

We suggest that the NRC staff limit this STP to one-way thermomechanical coupling as the title suggests, as other NRC guidance (NUREG/CR-5428) has done, and as 10 CFR 60.133(i) requires. We discourage the staff from pursuing "fully coupled" models at least until the staff and DOE know more about them.

The STP lacks a regulatory basis. It cites the requirements that supposedly require an assessment of coupled processes, yet the terms "coupled processes" or "fully coupled models" never appear in 10 CFR Part 60, in the draft rule, or in the supplementary and background information. To the contrary, NRC sought to avoid analyses of these highly complex and uncertain interactions. To do so, NRC confined thermally driven phenomena to the "disturbed zone" a portion of the host rock for which DOE could not take credit. Likewise, NRC required containment until the thermal loads subside. By doing so, NRC sought to simplify DOE's evaluation of the repository's performance. In short, by requiring a "... comprehensive, systematic, and logical understanding of the coupled T–M–H–C responses," this STP voids NRC's justification for requiring a disturbed zone and a containment period.

The STP is too generic and lacks pertinent details to meet its stated purpose. The acceptable methodology for demonstrating compliance with 10 CFR 60.133(i), as described on pages 7–10, is incomplete and lacks some crucial details of acceptable method for decision making, especially in the case where the available information will reflect large uncertainty at the programmatic and technical decision points shown in Figure 1.

On pages 1–5 of the STP, the expectations of the NRC staff at each stage of the program such as Construction Authorization, Construction, Waste Acceptance, Performance Confirmation Monitoring, and Closure, are not clearly stated. The text switches back and forth between these various stages of the program, leaving the reader somewhat confused about the various expectations. It would be useful to the designers and modelers of the repository if the expectations of the NRC staff were stated clearly at each stage of the program.

Response

Regulatory requirement 10 CFR 60.133(i) is one of several criteria to be considered in the design of the underground facility. It requires that the underground facility for the geologic repository operations area (GROA) be designed so that the performance objectives will be met, taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. This regulation specifically refers to the groundwater in the context of thermal loads and the design of the underground facility. The effect of temperature on the groundwater must, therefore, be considered. Because the hydrology/radionuclide-transport is "tied" strongly to the *in-situ* geochemistry, it becomes necessary to include chemical effects in the evaluation of the thermal load, to the extent that they have impacts on the repository performance. Therefore, the staff believes that the compliance evaluation of 10 CFR 60.133(i) should include an investigation of thermally-induced M–H–C effects. This STP provides an acceptable methodology to demonstrate compliance with 10 CFR 60.133(i).

The governing principle that serves as the foundation for the STP is that to demonstrate compliance with 10 CFR 60.133(i), **DOE needs to consider thermal coupling of processes in a manner that is not likely to underestimate the unfavorable aspects of repository performance, or overestimate the favorable aspects, in the context of design and analyses.**

DOE's general comment states that the guidance in the STP is too demanding, and therefore, the Department does not think that NRC's expectations will be fulfilled. In this regard, the staff does not expect DOE to develop "fully coupled" models and, as noted below, the final version of the STP has been modified in a number of places, to clarify the staff's expectations regarding model development. The staff wishes to emphasize that the technical positions expressed in Sections 3.1, 3.2, and 3.3, when considered **collectively**, provide guidance and a realistic approach for dealing with the complexities of coupled processes, in light of the principle stated above. Moreover, the text of the STP shows ample recognition of the difficulties involved in developing defensible predictive models, and has provided alternative approaches (see Technical Position 3.3) for dealing with the long time periods that must be considered. This STP also emphasizes the progressive development of predictive models. As more information is gathered, and mechanistic understanding advanced, the capability of the predictive models is expected to evolve progressively at different stages of the underground facility design, construction, and operations. The staff believes that such an approach can be achievable, but only if DOE makes an early commitment to its implementation.

The staff also does not agree with the assertion that "Simplified models would work as well, if not better. . . [than] . . . 'fully coupled'" models, as mentioned in DOE's "General Comments." However, as noted above, the staff notes the concern raised by DOE in its comment and has modified the final version of the STP in a number of places to reflect its position that if DOE substantiates that its use of such models is consistent with the principle stated in Section 1.0 ("Introduction") and repeated above, the staff has no objection to the use of such models in demonstrating compliance with 10 CFR 60.133(i).

In a related matter, DOE notes that the definition of "fully-coupled" models in this STP is "unconventional" and "ambiguous," and suggests that this term be defined in more detail. The staff agrees with this comment and has made the following revisions to the STP:

(1) changed the terms "fully coupled," "partially coupled," and "one-way coupled" models to the term "coupled" models; and

(2) defined the term "coupled" models.

In the context of thermal load considerations, "coupled behavior" means that at least one of the processes (i.e., T, M, H, or C) has an effect on the initiation and propagation of any or all of the other processes.

DOE asserts that this STP voids NRC's justification for requiring the "disturbed zone." The staff points out that the boundary of the "disturbed zone" (see 10 CFR 60.2) is used to facilitate the calculation of the pre-emplacement groundwater travel time (10 CFR 60.113(a)(2)). The disturbed zone boundary will need to be established, during the site characterization phase, on the basis of an understanding of physical and chemical changes within the rock surrounding the waste emplacement area, as a result of underground facility construction and heat (thermal load) generated by emplaced radioactive waste. It should be noted that the "disturbed zone" concept is only associated with one of the six performance objectives; other performance objectives must also be complied with. Compliance with these other performance objectives would also need an understanding of the thermally induced responses and their associated uncertainties. Therefore, the staff believes that the "disturbed zone" concept does not relieve DOE from considering the effects of thermal impacts and associated uncertainties on repository performance. (For a related discussion on this issue, DOE is referred to the staff's response to DOE Specific Comment No. 2.)

The DOE general comment implies that, because the waste packages are to be designed for a containment life of 300 to 1000 years, at the end of which time the thermal loads would have subsided, there is no need to understand the near-field environment of the waste packages.

However, the staff believes that the understanding of the near-field T-M-H-C environment would contribute to the design of the engineered barrier system (EBS), in particular, the thermal loads aspect of the underground facility design. Therefore, the staff disagrees with DOE's contention that the containment period provision of the rule relieves DOE of a need to understand and analyze the T-M-H-C processes that affect the waste package performance.

Regarding the need for coupled models, the staff maintains that DOE should develop models to predict the thermal impacts, based on a mechanistic understanding of T-M-H-C interactions, to the extent practical and necessary. There are plausible conditions under which T-H-C effects can result in changes to a repository host rock environment (Lin and Daily, 1989). The staff's intent is that a logical approach be used to predict the M-H-C response of the system, to the maximum design thermal loading. The "level of coupling" that needs to be considered should be determined from an established technical basis. It is not the intent of the staff to require DOE to develop a highly complex numerical code from the T-M-H-C coupled model. The staff believes that, although "simplified" models are necessary and useful, they may not be sufficient to demonstrate the adequacy of the GROA underground facility design with the requirements of 10 CFR 60.133(i). NUREG/CR-5428 (Brandshaug, 1989), referenced by DOE in its general comment, is strictly a description of a three-dimensional analysis of the single process of transient conduction heat transfer in the host rock in the vicinity of waste packages and storage rooms. It neither contains an evaluation of thermally induced mechanical effects (i.e., T-M) as mentioned in the DOE general comment, nor does it consider the combined effects of heat and water, which may be important to EBS design. The sole purpose of this reference in the STP is to provide a specific example of the process of performing analyses and comparing the results of these analyses to "design goals" (i.e., Step Nos. 6 and 7, in Figure 1) over a range of design conditions. The reference should in no way be construed to mean that the staff endorses the single process model used in the report.

As regards DOE's comment concerning a lack of regulatory basis for this STP, the staff does not agree with the Department's comment. As stated earlier in the staff's response, regulatory requirement 10 CFR 60.133(i) is one of several criteria for the design of the underground facility. It requires that the underground facility for the GROA be designed so that the performance objectives will be met, taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. This regulation specifically refers to the groundwater in the context of "thermal loads" and the design of the underground facility. The effect of temperature on the groundwater must, therefore, be considered. Because the hydrology/radionuclide transport is "tied" strongly to the *in-situ* geochemistry, it becomes necessary to include chemical effects in the evaluation of the thermal load, to the extent that it has an impact on the repository performance. Therefore, the staff believes that the compliance evaluation of 10 CFR 60.133(i) should include an investigation of thermally-induced M-H-C effects.

The requirement in 10 CFR 60.133(i) alone provides the necessary and sufficient regulatory basis for this STP. However, there are other regulatory requirements that provide additional bases. For example, in 10 CFR 60.21(c)(1)(i)(F), the content of the license application is specified to include, "The anticipated response of the geomechanical, hydrogeologic, and geochemical systems to the maximum design thermal loading, given the pattern of fractures and other discontinuities and the heat transfer properties of the rock mass and groundwater." Such an evaluation of thermal responses should be based on an understanding of the T-M-H-C processes, and their interactions. Therefore, the staff disagrees with DOE that the STP lacks a regulatory basis.

The staff does not agree with the next portion of DOE's comment that "The STP is too generic and lacks pertinent details to meet its stated purpose." It is the staff's intent, in this STP, to outline an acceptable methodology for demonstrating compliance with 10 CFR 60.133(i) without unduly constraining DOE in its choice of methods that may be used in implementing the intent of the STP. This approach identifies several programmatic and technical decision points, to facilitate the process for compliance demonstration. The methods that may be used for decision-making at each decision point should be selected by DOE under the premise that they are defensible and consistent with the overall repository design and performance assessment philosophy and strategy. Regarding the DOE concern on "... decision making ... where the available information will reflect large uncertainty ...," it is the staff's position that DOE should apply appropriate conservatism in its design and performance calculations, so that NRC will be able to make the necessary findings, under 10 CFR 60.31, with reasonable assurance.

Finally, regarding DOE's comment related to the staff's expectations not being clearly stated in the STP, the following clarification is provided. The staff expects, at the time of construction authorization, that DOE clearly demonstrate that the models used to predict thermal responses are not likely to underestimate the unfavorable aspects of repository performance or overestimate the favorable aspects, in the context of design and analyses. Subsequently, the underlying assumptions used in the projected performances should be confirmed, during the period of performance confirmation, by appropriate continued testing and/or model refinements.

Specific Comments

1. Page iii, "Abstract"

The NRC staff anticipates that the methodology to demonstrate compliance with 10 CFR 60.133(i) "... will require development of 'fully coupled' models." No such requirement appears in 10 CFR Part 60 nor has this STP justified the need for one. Moreover, STPs cannot "require" but may recommend or suggest a particular approach.

Response

With regard to the first portion of DOE's specific comment, the staff agrees that 10 CFR 60.133(i) does not explicitly "require" the development of coupled models. The staff notes the concern raised by DOE in its comment and has modified the final version of the STP in a number of places to clarify the staff's position that it does not require the development of "'fully coupled' models." However, as discussed in the staff's response to DOE's "General Comments," the staff believes that any demonstration of compliance with 10 CFR 60.133(i) would need to be based on an understanding of thermally-induced M–H–C effects on geologic repository design and/or performance. Moreover, as noted in the final version of the STP, the staff further believes that such understanding would need to include an assessment of the importance of coupled processes in quantifying the extent of these effects as part of the design process, before such a need can be dismissed.

At the present time, in the repository program, with limited site-specific information, it is not clear what level of coupling (if any) will be adequate in expressing the anticipated thermally-induced M–H–C responses associated with a thermal load. From the viewpoint of the NRC staff, it seems that a prudent approach to demonstrating compliance with 10 CFR 60.133(i) should not dismiss the need to take account of coupled processes, before such a need has been investigated. As a result, therefore, the staff considers it prudent to follow a conservative course and thus recommends the use of coupled models in the demonstration of compliance with 10 CFR 60.133(i).

Finally, the Department has correctly noted in its comment that STPs do not express requirements *per se*. Rather, as noted in Section 1.0 of the STP:

> "STPs are not substitutes for regulations, and compliance with them is not required. Methods and solutions different from those set out in the STP will be acceptable if they provide the basis for the findings requisite to the issuance or continuance of a construction authorization or license by the Commission."

However, in view of the fact that the use of the term "require" has a potential to be misinterpreted, the "Abstract" has been changed by replacing the phrase "... will require development ..." with "... will include evaluation and appropriate development ...." This alternative language was selected because it is expected that DOE would investigate the attendant coupled T–M–H–C effects commensurate with the uncertainties generated as a result of a given thermal load.

2. Page 2, Section 1.1, "Background"

The STP states, "One must also understand the uncertainties associated with predicting the thermal loading and corresponding rock and groundwater responses so that these uncertainties can be accommodated by the design." According to 10 CFR 60.2, thermal loads that "may have a significant effect on the performance of the geologic repository" are confined to the "disturbed zone." Provisions at 10 CFR 60.113(a)(2) exclude this thermally disturbed rock from the calculation of groundwater travel time, i.e., the calculation cannot take credit for the rock within the disturbed zone. By creating a disturbed zone, NRC relieved DOE from having to understand the uncertainties associated with predicting thermal loads. NRC justified a disturbed zone because physical and chemical processes therein "are especially difficult to understand in the area close to the emplaced wastes because that area is physically and chemically disturbed by the heat generated by those wastes." (NRC, 1981; 46 *FR* 35281)

Likewise, NRC requires containment for at least 300 to 1,000 years because during this time, decay heat would drop three orders of magnitude. (*Ibid.*) NRC wanted containment "during the period when the thermal conditions around the waste packages are most severe ... [so that] ... evaluation of repository performance ... [would be] ... greatly simplified ...." (*Ibid.*). The rationale for 10 CFR Part 60 elaborates:

> "During this critical [thermal] period the uncertainties in predicting release rates are very great. Even if we did understand the mechanisms completely, the data scatter increases with temperature so that test programs to gather the data to narrow the uncertainties to reasonable bounds are very cumbersome." (NRC, 1983, p. 472)

This STP burdens DOE with the types of assessments that NRC sought to avoid. The STP would have DOE assess the "fully coupled" thermal, hydrological, mechanical, and chemical processes, plus all uncertainties. But NRC sought to avoid these assessments by confining these processes to a disturbed zone and by requiring that the waste be contained until the processes have attenuated. If DOE must provide the information that this STP requests, there is no longer any justification for 10 CFR Part 60 to require a disturbed zone or a containment period.

It is also worthwhile to note that other uncertainties in the overall systems, such as the model and parameter uncertainties and the highly uncertain probability and consequences of human intrusion, far outweigh the uncertainties resulting from the use of uncoupled or partially coupled models.

The NRC staff should state that this STP does not apply to the rock within the disturbed zone nor does it apply during the containment period. The disturbed zone includes "that portion of the controlled area the physical or chemical properties of which have changed as a result of. . . heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository" (10 CFR 60.2). The containment period would last, at the minimum, 300 to 1,000 years.

We must add, however, that if the STP applies after the containment period and only to the rock beyond the disturbed zone, most of the guidance would be irrelevant. When attenuated in time and space, thermal loads and gradients as well as "fully coupled" T-M-H-C processes would not significantly affect the repository's long-term performance.

Response

In its specific comment, DOE seeks to dismiss the need to understand the effects of thermally-induced M-H-C processes and the uncertainties associated with those processes in dealing with the GROA underground facility design. It is stated that the "disturbed zone" concept (10 CFR 60.2) and the "containment period" requirement (10 CFR 60.113(a)(1)(ii)(A)) were introduced by NRC to relieve DOE from such understanding.

The boundary of the "disturbed zone" is used to facilitate the calculation of the pre-emplacement groundwater travel time (10 CFR 60.113(a)(2)). The disturbed zone boundary is established during the site characterization phase, on the basis of an understanding of physical and chemical changes within the rock surrounding the waste emplacement area. Although necessary for all conceptual designs, understanding of the character and extent of the disturbed zone is particularly important in those design options that call for elevated temperatures being maintained for extended time periods. Whereas the pre-waste emplacement groundwater travel time calculation is associated with one of the six performance objectives, 10 CFR 60.133(i) deals with all six performance objectives. The design of the waste package that deals with two other subsystem performance objectives (e.g., 60.113(a)(1)(ii)(A-B)) and contributes to the overall performance of the repository (under 10 CFR 60.112), requires a clear understanding of the near-field environment (which is contained within the disturbed zone). The staff refers DOE to 10 CFR 60.135(a).

In view of the aforementioned discussion, the staff disagrees with DOE's interpretation that the "disturbed zone" concept relieves DOE from considering thermal impacts on repository performance in the pre- and post-closure periods, as specified in 10 CFR 60.133(i). The staff believes that a prudent evaluation of thermal impacts would also include an assessment of the effects of uncertainties, which should be incorporated into the underground facility design.

The staff further believes that the understanding of the near-field T-M-H-C environment would contribute to the design of the EBS, in particular, the thermal loads aspect of the underground facility design. The capacity of a canister to contain waste depends on, among other things, the local environment of the canister. Under different environments, the rate, mechanisms, and processes of canister degradation may be different. Therefore, assessment of the performance of substantially complete containment must rely on the understanding of the T-M-H-C processes at the container scale, including an understanding of the importance of the effects of coupled processes and related uncertainties.

The staff recognizes, however, that there are other potential uncertainties associated with the overall system, as indicated in DOE's comment; some of them may very well outweigh the uncertainties resulting from the use of predictive models for thermal loads. However, this is not to say that an understanding of the thermally induced phenomena is not necessary. It is the staff's contention that DOE first will have to demonstrate that the uncertainties associated with thermal load consideration is indeed less important and, second, to demonstrate that reasonable assurance for compliance with the performance objectives will still be obtained without quantifying and/or reducing these uncertainties. Until such time, the staff considers that it is appropriate and necessary to obtain a better understanding of the T-M-H-C effects on the repository performance.

Finally, DOE notes in this comment that "When attenuated in time and space, thermal loads and gradients as well as 'fully coupled' T-M-H-C processes would not significantly affect the repository's long-term performance." The staff is concerned that this statement conveys the notion that the Department's current understanding of the T-M-H-C processes associated with a thermal load is sufficient to proceed with an advanced design of the GROA underground facility, in advance of extensive site characterization, and well before a reference thermal load has been established and its effects have been evaluated. Based on the staff's review of DOE's program to date, the staff can find no basis on which to concur in the Department's observation.

3. **Page 3, Section 1.1, "Background"**

   In line 5 and elsewhere the STP references heat-induced effects on groundwater flow. The STP should also acknowledge the possibility for steam generation and water-vapor transport. Otherwise, the term "groundwater" could be interpreted narrowly to mean only liquid-phase transport.

Response

The staff agrees with this recommendation. It is conceivable that the level of the thermal load will be sufficiently high to induce rock temperatures that result in boiling of porewater. Accordingly, the meaning of the term "flow" in the STP has been expanded to include both liquid- and vapor-phase transport.

4. **Pages 3 and 4, Section 1.1, "Background"**

   The STP states that for "repository-generated thermal regimes that are beyond the range of current engineering experiences," the use of existing models as a first step in establishing an expected range of effects of thermal loads is "not satisfactory" unless there is "a programmatic need for evaluation of such thermal loads."

   This STP should not discourage the use of established models in preliminary programmatic evaluations of thermal loadings. Some established models would be useful in sensitivity and tradeoff studies.

   Also, the above passage contradicts statements made on page four that state that an initial understanding of thermally induced phenomena is expected to be gained from the use of models that are reasonably available. The guidance stated above is hardly new, and does not contribute to a demonstration of compliance. There is a need to demonstrate what the thermal loads are, the effects of those loads, and whether the effects are significant to performance and/or design. (Thermomechanical testing is described in SCP section 8.3.1.15.)

Response

The STP does not discourage the use of existing models as long as they are reliable (refer to Step No. 2 in Technical Position 3.1). Some "established" models may be reliable, and therefore, could be useful in sensitivity and tradeoff studies. The staff notes that DOE finds an apparent contradiction in the STP text between Sections 1.1 and 1.2. However, in an effort to avoid the potential for misunderstanding in the future, the third, fourth, and fifth paragraphs of Section 1.1 have been combined and revised as follows:

> "The impact of thermal loads on repository performance can be a very complex technical issue, depending on many factors, including the magnitude of the thermal loads themselves. For those repository-generated thermal regimes that are within the range of engineering experiences, the use of existing predictive models to evaluate the possible effects of thermal loads on repository performance may be a reasonable approach to demonstrate compliance with 10 CFR Part 60 regulatory requirements. On the other hand, repository-generated thermal regimes that are beyond the range of current engineering experiences pose significantly more complex problems. Such thermal regimes, acting over the long time frame of repository performance, may produce effects that involve prediction considerations that are well beyond current engineering practice. For such situations, the use of an existing model, to predict the likely repository effects of such loads, may not be satisfactory. For those situations where DOE makes programmatic decisions that produce repository-generated thermal regimes well beyond those for which engineering experience is available, it is expected that DOE will investigate and evaluate the effects of coupled processes in the predictions of the underground facility performance."

5. **Page 3, Section 1.1, "Background"**

   In the second paragraph, the authors of the STP appear to believe that DOE will make a decision that results in an extraordinarily high repository-generated thermal regime. This may be a reflection of NRC using available but outdated information on repository conceptual design in the Conceptual Design Report or in the Site Characterization Plan (SCP), Chapters 6 and/or 7. Currently, there is no reference waste package design or heat load. DOE is currently reviewing EBS concepts. Even if this assumption was true and DOE developed "state-of-the-art" models, how would NRC independently evaluate the unproven methodology?

Response

The recommended approach adopted in the STP is generic in nature. It was not formulated using information on the repository conceptual design contained in DOE's Conceptual Design Report (MacDougall *et al.*, 1987) nor in SCP Chapters 6 and 7 (DOE, 1988a and 1988b). The recommended approach requires a determination of whether there is a sufficient scientific understanding and/ or engineering experience to conclude that the performance objectives are insensitive to the effects of thermal loading. To make such a determination, it is self-evident that parameters such as waste package design and thermal load will need to be considered.

In response to DOE's question regarding how NRC would develop an independent review capability, it should be noted that NRC has an ongoing research activity to investigate and examine thermally induced phenomena, including T-M-H-C coupled effects, and also, NRC is actively participating in an international joint effort on developing coupled predictive models, referred to as DECOVALEX (an acronym for "International Cooperative Project for the **DE**velopment of **CO**upled models and their **VAL**idation Against **EX**periments in Nuclear Waste Isolation"). These activities are part of NRC's plans to develop an independent capability for the purpose of determining compliance with 10 CFR 60.133(i).

6. **Page 4, Section 1.1, "Background"**

   The second sentence states, "If, at any time, reliable information is gathered to convincingly demonstrate that further development of predictive models and codes would be unwarranted, nothing in this STP should be interpreted to suggest that the staff would expect that additional unnecessary steps would, nevertheless, be performed."

   This statement gives DOE flexibility, but it is inconsistent with the rest of the STP. Overall, the STP implies that "fully coupled" models and an understanding of "fully coupled" processes are required. For example, the STP recommends a methodology which "is based on an expected understanding of the 'fully coupled' effects of thermally induced phenomena" (Section 3.0). Apparently, the staff believes that only "fully coupled" models can produce reliable information. We believe that reliable information can be obtained from simplified uncoupled or partially coupled models and codes.

Response

The staff does not agree with the conclusion reached by DOE in its specific comment that the statement, "If, at any time, reliable information is gathered to convincingly demonstrate that further development of predictive models..." is generally inconsistent with the staff's overall technical position expressed in this document. The staff believes that the technical positions described in Sections 3.1, 3.2, and 3.3, when considered collectively, provide guidance and alternative approaches to demonstrating compliance with 10 CFR 60.133(i). If DOE can demonstrate that the use of "simplified" models is consistent with the principle stated in Section 1.0 of the final version of the STP, then the staff has no objection to the use of such models. (This position is described in detail in Step No. 2 of Sections 3.1 and 4.1, respectively, of the STP.)

7. **Page 4, Section 1.2, "The Use of Models in Thermal-Response Predictions"**

   The third sentence of the first paragraph states, "The NRC staff finds that predictive models based on approximations of coupled formulations of T-M-H-C responses may have to be used for demonstrating compliance with 10 CFR 60.133(i) at the construction authorization stage of the repository licensing process." The staff expects "fully coupled" models by the time of application for the license to receive, possess, and emplace waste...."

   If NRC finds, with reasonable assurance, that the models are sufficient at the time of construction, there is no reason to develop "fully coupled" models at the time of licensing. Up until the repository is closed, we will continue improving our models and our understanding of coupled responses. But it is premature for the staff to expect that the processes will ever be fully understood and that these models will be fully coupled.

Response

The staff disagrees with DOE's specific comment, that the STP conveys an expectation of DOE to develop coupled T-M-H-C models "... by the time of application for the license to receive, possess, and emplace waste...." Rather, Section 1.2 of the STP expresses an expectation of progressively better understanding the M-H-C responses associated with the repository thermal load, and that this understanding be reflected through the development of new predictive models. This expectation seems to be consistent with the idea expressed in the second sentence of the second paragraph of DOE's specific comment. It is certainly conceivable that "This could result in more comprehensive models (e.g.,fully coupled models) by the time of application for license to receive, possess, ..., and, subsequently, an application for license amendment for permanent closure."

Furthermore, the staff would like to clarify the points raised in the second paragraph in DOE's specific comment. At the time of issuance of license for construction, the judgment of reasonable assurance may very well rely on projections of performance, together with a proposed performance confirmation program required under 10 CFR 60.137. Then, as the repository program moves along, further information will be obtained through confirmation of the understanding of the site and the ability to predict thermal and thermomechanical responses of the host rock, surrounding strata, and groundwater system. It is entirely possible that there is no need to further develop predictive models after the construction authorization stage, so long as DOE can demonstrate in the License Application that there is no such need. Otherwise, DOE may be required to provide in its License Application "... a detailed description of the programs designed to resolve safety questions ...," as stated in 10 CFR 60.21(c)(ii)(F)(14) and explained in Section 1.2 of the STP. Whether or not a construction authorization will be granted depends on the nature of the unresolved safety questions. As part of the performance confirmation program (see Subpart F of 10 CFR Part 60), the staff expects model development/refinement to continue as needed. The need for development/ refinement of models should be viewed in the context of confirming the projected performance used in arriving at reasonable assurance at the time of construction authorization.

8. **Page 7, Section 3.0, Staff Technical Positions**

   The fourth sentence states that the staff's approach for demonstrating compliance with 10 CFR 60.133(i) "is based on an expected understanding of the fully coupled effects of thermally induced phenomena."

   The protection of public health and safety and compliance with 10 CFR Part 60 do not necessarily depend on understanding the fully coupled effects of thermally induced phenomena. The restricted spatial and relatively short temporal extent over which the coupled effects are significant, combined with other precautions mandated by the regulations (i.e., the disturbed zone and a containment period), remove the necessity to fully understand coupled effects. From our reading of the regulations, we conclude that a safety analysis need only demonstrate that thermal loads will not adversely affect the design of the underground facility, and that the design will not preclude compliance with the performance objectives.

Response

The staff response to this specific comment has already been addressed in its responses to DOE's "General Comments" and Specific Comment No. 7. Although a complete understanding of coupled processes may never be fully realized, the staff maintains that understanding of the T–M–H–C processes should be pursued, consistent with the principle stated in Section 1.0 ("Introduction") of the STP. Thus, the "disturbed zone" concept (10 CFR 60.2) and the "containment period" requirement (10 CFR 60.113(a)(1)(ii)(A)), the staff believes, does not relieve DOE from pursuing an understanding of T–M–H–C processes in the context of the overall repository. Section 60.133(i) is specific in the requirement that "... the underground facility shall be designed so that the performance objectives will be met ...." The staff interprets the requirement to imply that an evaluation of the design process for the GROA should lead to the conclusion that the underground facility design meets the pertinent requirements. Thus, in practice, the staff believes that the design goals/criteria for the GROA underground facility, with due consideration to the effects of thermally induced loads, need to be correlated to the pertinent 10 CFR Part 60 performance objectives in order to ensure that the design will meet these objectives. On the contrary, if the requirement were as DOE suggests, the design process may not take into consideration the performance objectives, and consequently may face the risk of not meeting the 10 CFR Part 60 performance objectives.

9. **Pages 8 to 10, Section 3.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"**

   This section suggests a step-wise approach for developing a fully coupled model which, according to the STP, is needed to demonstrate compliance with requirements for the underground facility at 10 CFR 60.133(i).

   Before requesting a fully coupled model, this STP should establish that the model is needed to design an underground facility. The recommended approach does not establish the need for a fully coupled model nor does it explain the degree of coupling that the NRC desires (see our "General Comments" and comments on the definition of "fully coupled models"). The need for a fully coupled model cannot be simply presumed by the authors.

   NRC should at least admit that a "fully coupled" model is not necessary to resolve all design problems. We recommend that the approach presented in this section expand upon the more sensible approach described in Appendix C, paragraph 4.

Response

The intent of Technical Position 3.1 is not to develop a fully coupled model, but to describe an example approach for meeting the requirements of 10 CFR 60.133(i). Elements of the example approach include gaining understanding of the T–M–H–C processes associated with a repository-induced thermal load, and the conversion of this understanding into predictive models. The "expectation" of the staff regarding the need for "fully coupled" T–M–H–C models has already been addressed in the staff response to DOE's "General Comments" and Specific Comments Nos. 1, 6, and 7 and, therefore, will not be repeated here.

The need for, and desired level of coupling, depend on what is learned through the examination of thermally-induced phenomena, as indicated in Step No. 3 of Figure 1. Certain levels of coupled processes may turn out not to be important and therefore may be excluded from the predictive models. At the present stage, with limited knowledge on the site information and coupled processes, it is not clear what level of coupling will be adequate. It is expected that DOE will assume the responsibility to advance the state-of-the-art, as appropriate, in its pursuit to understand the importance of T–M–H–C coupled processes.

Finally, the approach described in Appendix C of this STP is intended as an example of a model that could be developed through iterations between Step Nos. 2 and 5 of Figure 1 (i.e., gain an understanding, and convert this understanding into a predictive T–M–H–C model). It is not intended to replace the overall concept of the acceptable methodology for demonstrating compliance with 10 CFR 60.133(i). Rather, if DOE can show that this approach satisfies the principle stated in Section 1.0 ("Introduction") of the STP, it would be acceptable to the staff.

10. Page 8, Section 3.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

The proposed approach suggests eight steps that "can be used to demonstrate the acceptability of the underground facility design."

Steps two and four should be reversed. Step two would use existing models to show compliance with 10 CFR 60.133(i), and step four would develop design goals/criteria for the underground facility. Even if the existing models were adequate, they cannot be used to show compliance until after design goals and criteria are developed. Later, the STP says the same, "The purpose of developing design goals/criteria . . . is . . . to contribute to the assurance that the design of the underground facility has the likelihood of meeting these performance objectives" (pages 14–15).

Response

This comment is noted. However, the staff believes that the Department's recommendation would lead to an internal inconsistency that violates the overall logic detailed in Technical Position 3.1 and depicted in Figure 1. The staff's reasoning behind this position is that if there is an affirmative response to the question asked in Step No. 2, then the need to perform the analyses described in Step Nos. 3 and 5 would be obviated because existing models would already have these capabilities.

However, DOE's recommendation has caused the staff to re-evaluate the logic depicted in Figure 1 and in an attempt to clarify this logic, the staff has modified the figure in the final version of the STP in two ways. First, Step No. 2A ("Use existing models to show compliance with 10 CFR 60.133(i)") in the draft version of the STP was deleted because there is no activity associated with this step *per se*. Second, the logic flow from Step No. 5 to Step No. 3 in the draft version of the STP has been changed to now indicate an iteration between Step Nos. 5 and 2. The change was made so that the approach includes an explicit check of the adequacy of any predictive models developed with existing technology.

11. Page 8, Section 3.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

Step No. 3 needs to be clarified since it is not apparent if "defensible models" used in Step No. 3 are in fact those "existing models" that will show compliance with 10 CFR 60.133(i), as illustrated in Step No. 2A, Figure 1.

Response

The staff notes the concern raised by this comment and has changed the term "defensible methods" to reliable models" in order to be consistent with the discussion contained in Step No. 2 of Technical Position 3.1.

12. Page 9, Section 3.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

In Step No. 8, the incorporation of predicted results in the pre- and post-closure performance assessment models appears to contradict other NRC guidance. NRC has consistently advised DOE to perform preliminary and iterative performance assessments using available models. DOE might be able to perform preliminary performance assessments using the models examined in Step No. 2 or developed in Step No. 5. The NRC's performance assessment staff might think DOE remiss were it not to use these available models. NRC should consider revising the STP in consultation with its performance assessment staff. DOE would appreciate a clarification of guidance on this point as it may apply to other modeling and performance assessment effects.

Response

The staff does not believe that incorporating the predicted results from the approach outlined in this STP in the performance assessment model(s) contradicts other NRC guidance. The approach described in Technical Position 3.1 and illustrated in Figure 1 clearly suggests that the entire process is iterative (see the loop-back from Step No. 8 to Step No. 3 in Figure 1).

Regardless of which types of models are used for performance assessment, simple or complex, the reasonableness and adequacy of the input data (in this case the results from the predictive T–M–H–C model(s)) are of primary concern. Without a reliable data set, there is no reason to believe that the results generated from the performance assessment models will be reliable. The predictive models developed through the systematic approach outlined in this STP will provide a portion of the input data needed for the performance assessment models. In the context of NRC's iterative performance assessment efforts (see Codell *et al.*, 1992), the staff positions advocated in this STP are consistent with this on-going effort.

13. Page 10, Section 3.2, "Development of Detailed Predictive Models"

The STP states, "To the extent practical, DOE should develop models . . . based on a mechanistic understanding of fully coupled T–M–H–C behavior."

As commented earlier, NRC has not clearly explained what constitutes a fully coupled model, what these models will accomplish in terms of meeting NRC regulations, or what advantage these models have over simple uncoupled models. In short, NRC has not provided any compelling reason to develop "fully coupled" models.

Also, this type of "fully coupled" mechanistic model may be impossible to validate in the classical sense of the term. NRC's performance assessment staff has stated that classical model validation cannot be accomplished for a repository. Consultation with NRC's performance assessment staff should be considered in revising the STP, concerning the listing of scenarios and use or formulation of strategies on how DOE could make a demonstration with reasonable assurance.

Response

As regards the first portion of this comment, the STP has been revised to reduce the potential for the misinterpretation that might have been created by the use of the phrase "fully coupled" models. (These changes are described in the staff's response to DOE's "General Comments.")

As regards the second portion of this comment, as previously stated in the staff response to DOE Specific Comment Nos. 1 and 9, the need for and desired level of coupling depends on the understanding developed through the examination of thermally-induced processes, as indicated in Step No. 3 of Figure 1. Such a need cannot be simply dismissed without some assessment of the importance of T–M–H–C coupling in evaluating the performance of the repository. Therefore, at this point, whether or not coupled models are better than simple uncoupled models should not be a concern. The main concern should be whether there is sufficient understanding of the *in-situ* site conditions, including coupled T–M–H–C processes, to determine what level of coupling (if any) is adequate for demonstrating compliance with the requirements of 10 CFR 60.133(i). For this reason, Step No. 3 of the example approach establishes a requirement to evaluate the need and extent of coupling for development of predictive models.

The comment also raises the issue of validation suggesting that "fully coupled" models may be impossible to validate in the classical sense. The staff agrees, but would note that this is also true of models exhibiting lesser degree of coupling. The real issue the staff believes is whether such models can adequately represent the effects of coupling on repository performance.

14. Page 10, Section 3.3, "Alternative Predictive Models"

This section or the glossary in Appendix A should clarify or provide a precise meaning of "the synergistic effects of T–M–H–C interactions." This phrase is also found on page 18, Section 4.2, first paragraph, last sentence.

Response

The staff agrees that there has been considerable difficulty in interpreting the phrase "synergistic effects of T–M–H–C interactions." In the draft version of the STP, the staff had used several terms to describe coupled effects (e.g., synergistic effects, interactions). However, for consistency, these terms have been replaced with the term "coupled effects" in the final version of the STP, the definition of which has been included in Appendix A ("Glossary"). DOE is directed to the staff's response to the Department's "General Comments," where the staff specifically described the revisions made to the final version of the STP, to clarify the meaning and intent of these terms.

15. Page 10, Section 3.3, "Alternative Predictive Models"

The suggested action in Section (a) should be clarified. Models cannot affect performance objectives in any way. They can affect one's ability to demonstrate compliance or the receptivity of a reviewer to the information presented.

Response

The staff agrees that models cannot affect performance objectives. Accordingly, Section (a) of the technical position has been modified, as suggested in this comment.

16. **Page 10, Section 4.0, "Discussion"**

    The STP repeatedly states that a repository's design must comply with the 10 CFR Part 60 performance objectives. Here it states, "Also, this methodology [for demonstrating compliance with 10 CFR 60.133(i)] takes into account the performance objectives of 10 CFR 60.111, 60.112, and 60.113, **all of which must be satisfied by any design.**" (Emphasis added)

    Two of the six performance objectives, a repository's overall performance (10 CFR 60.112) and groundwater travel time (10 CFR 60.113(a)(2)) are more oriented toward natural barriers that cannot be designed. Moreover, according to 10 CFR 60.133(i), "The underground facility shall be designed so that the performance objectives will be met . . . ." Thus, the STP should state that the design of the underground facility should not **preclude compliance** with the performance objectives; rather that the design must **satisfy** the performance objectives.

Response

The staff disagrees with the recommendation made by DOE in its comment. Section 60.133(i) is specific in the requirement that "The underground facility shall be **designed** so that the performance objectives **will be met** . . . ." (Emphasis added) The staff interprets the requirement to imply that the design process for the GROA should lead to the conclusion that the underground facility design meets the pertinent requirements. Thus, in practice, the staff believes that the design goals/criteria for the GROA underground facility, with due consideration to the effects of thermally induced loads, need to be correlated to the pertinent 10 CFR Part 60 performance objectives in order to ensure that the design will meet these objectives. The staff views the terms "preclude compliance" or "satisfy," as alternatively recommended by the Department in this comment, to change the intent of the current language of the rule.

As regards DOE's reference to "natural barriers" and 10 CFR Part 60 performance objectives, it should be noted that the staff agrees that natural barriers cannot be designed, and the staff believes that there is nothing in the STP to suggest that this would be the case. However, a particular GROA design may impact the ability of the underground facility to meet the performance objectives, particularly those of the natural system. Thus, as part of the GROA design process, consideration must be given to which design parameters for the underground facility have the potential to adversely affect the ability of the site to meet the performance objectives.

17. **Page 11, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"**

    The first paragraph states that "a decision will be made if the thermal loads have *significant impacts* on the performance of the geologic repository." Later, the STP states that this would be an early "programmatic" decision.

    Since "fully coupled" models do not exist (and probably never will), early programmatic decisions must be based on the results of "simplified" models. DOE recommends that the NRC staff explicitly connect early decisions with "simplified" models.

Response

The staff recognizes the need to make preliminary programmatic decisions based on existing models. However, if these models reflect the understanding and experience that are necessary to make a finding that a 10 CFR Part 60 performance objective is insensitive to the effects of thermal loading, and the models used are reliable and defensible, then the need for more sophisticated models is obviated, as noted in the STP. (Also see the staff response to DOE Specific Comment No. 4.)

18. **Page 11, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"**

    These are six performance objectives, not three, as stated in the second paragraph, second sentence.

Response

The three 10 CFR Part 60 performance objectives referred to in the STP are 10 CFR 60.111, 60.112, and 60.113. The staff acknowledges the need to clarify the STP in this area and has modified the text accordingly.

19. **Page 11, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"**

    That performance assessment takes place, as stated in the STP, only after all design goals/criteria have been met, is inconsistent with the advice [previously] given to DOE by NRC. Performance assessment only at the end of the process would be too late, particularly if goals and criteria can be met, but performance objectives may not be met. The STP should be clarified on this point.

Response

Regarding the first portion of DOE's specific comment, the example approach described in Technical Position 3.1 and illustrated Figure 1 clearly suggests that the entire process is iterative (see loop-back from Step No. 8 to Step No. 2 in Figure 1). The text to which DOE refers in Section 4.1 ("Discussion") speaks of the sequence of the logic process within one iteration. The staff disagrees with the DOE contention that the approach is inconsistent with previous advice given to DOE by NRC.

Regarding the second portion of DOE's specific comment, DOE is directed to the text in Step No. 4 of Section 4.1, which expresses that ". . . design goals/criteria ... correlated to the repository performance objectives are expected to be essential in the development of the underground facility design." An approach to developing the performance-based design goals/criteria is suggested by Steps (a) through (c) in Section 4.1. Although not explicitly stated, Step (c) in this approach may very well include an evaluation of the design goals/criteria by a performance assessment model(s). The specific procedures by which this is accomplished are left up to DOE.

However, in consideration of DOE's overall comment, the first sentence of Paragraph 3 of Section 4.1 has been changed to avoid further confusion on this issue. This sentence now reads as follows:

> "For each iteration cycle, the fourth evaluation point, performance assessment evaluation (Step No. 8 of Figure 1), takes place only after all of the GROA underground facility design goals/criteria have been satisfied."

20. Page 12, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

The second paragraph states, "As illustrated in Figure No. 1, the process may be terminated at different decision points, depending on the state of the knowledge and complexity of the information needs."

Other than the first step, Figure 1 does not indicate decision points at which the process may be terminated. Either add these decision points or do not say that they are present.

Response

The staff agrees that the flow logic shown in Figure 1 for Technical Position 3.1 does not indicate any decision points for termination of the process other than the first step. Consequently, the 5th paragraph of Section 4.1 ("Discussion") has been deleted from the final version of the STP.

21. Page 13, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

At Step No. 3, the first paragraph, last sentence states, "This understanding would include an assessment of the level of phenomenological coupling that may be necessary to reasonably characterize the phenomena and predict the responses."

NRC should define "phenomenological coupling" and specify the degree of coupling desired. For example, does the staff want only direct couplings or both direct and crossed couplings? As commented earlier, the staff has not established a need for such a detailed assessment particularly when the total number of direct and crossed couplings are so numerous. If the staff can justify an assessment of phenomenological coupling, the assessment should be limited to direct couplings.

Response

The staff notes the concerns raised with the use of the term "phenomenological." Accordingly, this term has been deleted from the STP and the sentence in question has been modified to read as follows:

> "This understanding would include an assessment of the level of coupling that may be necessary between processes to reasonably predict the responses."

Also, a definition of "coupled behavior" is now provided in the STP, as well as in the "Glossary." (For a description of what is meant by "coupled behavior," see the staff's response to DOE's "General Comments.")

22. Page 16, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

At Step No. 6, the STP cites NUREG/CR-5428 (Brandshaug, 1989) as an example of "heat-transfer predictions." This citation conflicts with previous text where the STP expects an understanding of "fully coupled effects of thermally induced phenomena" (page seven). Brandshaug's model only represents the one-way T-M coupling. We recommend that NRC reconcile the conflict by acknowledging that valuable insight can be gained by using "simplified" models.

Response

The reference in the STP to NUREG/CR-5428 is strictly intended as a description of a three-dimensional analysis of the single process of transient conduction heat transfer in the host rock in the vicinity of waste packages and storage rooms. The reference does not contain an evaluation of thermally induced mechanical effects (i.e., T–M), as mentioned in DOE's "General Comments," nor does it consider the combined effects of heat and water, which may be important to the EBS design. The sole purpose of the use of this reference in the STP is to **provide a specific example** of performing analyses and comparing the results of these analyses to "design goals" (i.e., Step Nos. 6 and 7 in Figure 1) over a range of design conditions. The reference should in no way be construed to mean that the staff endorses the single process model used in the report. Therefore, the staff does not consider that any conflict exists, as suggested by DOE in its specific comment.

23. Page 17, Section 4.1, "Example of an Acceptable Approach for Demonstrating Compliance with 10 CFR 60.133(i)"

At Step No. 9, the second sentence states that the final step is reached "when the design goals/criteria as well as the performance objectives have been satisfied . . . [then] . . . it can be concluded that 10 CFR 60.133(i) requirements have been complied with."

This step falsely implies that compliance with the performance objectives (10 CFR 60.111, 60.112, and 60.113) is a prerequisite for the demonstration of compliance with 60.133(i). As we read 10 CFR 60.133(i), the sequence should be: (1) design an underground facility; and (2) meet the performance objectives.

Response

Section 60.133(i) requires that "The underground facility shall be designed so that the performance objectives will be met . . . ." Clearly, there are many aspects of repository siting and design that contribute to meeting the 10 CFR Part 60 performance objectives. Demonstrating compliance with 10 CFR 60.133(i) is one such aspect of the repository design that contributes to meeting the performance objectives. Because the design contributes to meeting the performance objectives, it must be conducted in parallel and/or iteratively with the evaluation of the performance objectives. Sequential but independent design and performance objective evaluations, as suggested by DOE's specific comment, would not accomplish the intent of the regulations. The methodology in this STP recognizes that the product of such a design process might lead to an underground facility design that fails to meet the performance objectives. Therefore, Figure 1 in the STP describes a process with appropriate feedback loops to avoid this.

Accordingly, for the reasons noted above, the staff does not agree with the interpretation of 10 CFR 60.133(i) made by the Department in this comment.

24. Page 18, Section 4.2, "Development of Detailed Predictive Models"

The second paragraph, last sentence, states, "Thus, predictive models capable of analyzing canister-scale, room-scale, repository-scale, and regional-scale problems are required to ensure that appropriate phenomenological detail will be included in the analyses."

We do not believe that this is possible. Predictive models, at their best, can discern the engineered from the natural barriers, but they could never analyze canister-scale, room-scale, repository-scale, and regional-scale with phenomenological detail. Instead, bounding analyses can insure that the repository will meet the performance objectives. It should also be noted that the system performance objectives at 10 CFR 60.113 were crafted to accommodate the uncertainties that may arise from the lack of mechanistic understanding of the phenomenological couplings (see our "General Comments).

Response

This comment is noted. However, the staff believes that it is possible to develop predictive models that are capable of analyzing canister-scale, room-scale, repository-scale, and regional-scale problems with appropriate levels of detail. Thus, the staff emphasized the words "appropriate levels of detail" in the STP and refers the Department to examples of computer codes that have been developed that are based on coupled models and have been applied to different geometric scales (see Noorishad and Tsang, 1989; Kelkar and Zyvoloski, 1990; and Ohnishi *et al.*, 1990). The knowledge of the T–M–H–C processes and site characteristics for the different scales of resolution may vary. For this reason, the levels of detail included in the models may vary accordingly.

Finally, as noted earlier, the word "phenomenological" has been deleted from the STP to avoid any misinterpretation that it applies equally to all four scales of resolution.

25. Page 19, Section 4.2, "Development of Detailed Predictive Models"

The STP states in the first paragraph, second sentence, "The staff also recognizes, on the other hand, that oversimplification in modeling may obscure the understanding of those processes that might have significant impact on design goals/criteria and/or performance."

Please delete this statement. Overly complex models, even more so than simple models, may obscure (through the influence of competing effects) an understanding of one of the coupled processes.

Response

This comment is noted. However, the staff directs DOE's attention to the paragraph to which DOE's specific comment refers, in which it is noted:

"To include great complexity in the characterization of material behavior, for example, does not necessarily provide more accurate predictions, because (even if the complex details can be characterized at the scale needed) a complex model is often more difficult to verify, validate, and use. The staff also recognizes, on the other hand, that oversimplification in modeling may obscure the understanding of those processes that might have significant impact on design goals/criteria and/or performance. The analyst should choose a model that strikes a balance between unworkable detail and oversimplification of the processes that are being modeled."

The staff considers that in the context of the overall STP, the sentence in question is appropriate. Thus, the staff does not believe that the STP warrants modification, as suggested by this specific comment.

26. Page 19, Section 4.2, "Development of Detailed Predictive Models"

The last sentence of the second paragraph indicates that "porosity and permeability of the geologic material" should be considered for the chemical model. The sentence should be corrected to reflect the fact that porosity and permeability are hydrologic properties, and therefore, should be considered in the hydrologic model. In addition, working the porosity and permeability into a chemical model without also employing the range of grain sizes would prove difficult, since particle surface area per unit volume is a major factor in determining reaction rates.

Response

The major focus of the cited paragraph (4th paragraph of Section 4.2) is to give examples of the potential response measures that may be used for the evaluation of the adequacy of the underground facility design. This paragraph does not discuss input parameters that are needed for proper modeling. Thus, the staff does not believe that the STP warrants modification, as suggested by this specific comment.

27. Page 21, Section 4.2, "Development of Detailed Predictive Models"

The first sentence in the last paragraph states, "Finally all predictive models used for licensing are likely to require a certain degree of verification and validation."

Unless offered only for information, the text on model validation and code verification should be deleted. All model validation issues, whether the model is coupled or uncoupled, should be confined to NUREG–0856, or a separate STP. If the NRC staff keeps the text, please use the terms "verification" and "validation" consistently with the way they are defined in Appendix A and NUREG–0856. Models are not verified; rather models are validated and computer codes are verified.

Response

The staff agrees with the alternative recommendation made in this comment and has modified the final version of the STP to reflect the distinction between the terms "verification" and "validation."

28. Page 25, Figure 1

The logic flow after Step No. 8B is not closed. Clarification should also be provided as to what drives Step No. 7A, "Modify underground facility design," and how it enters the logic flow for an example of an acceptable methodology for demonstrating compliance with 10 CFR 60.133(i).

Response

Regarding the first portion of this comment, DOE is referred to the last paragraph of Step No. 8, under Section 4.1 ("Discussion"), where a discussion is provided of what takes place beyond Step No. 8B. Accordingly, the staff believes that the logic flow after Step No. 8B in Figure 1 is closed.

Regarding the second portion of DOE's specific comment, concerning what drives Step No. 7A (e.g., the need to modify the underground facility design), Step No. 7A will result if there is noncompliance with the design goals/criteria evaluated in Step No. 7. For example, if a goal/criterion exists for a maximum borehole wall temperature, and this criterion is exceeded as a result of either a very high initial power output from the waste package, or very close spacing between emplacement boreholes, this would result in a "visit" to Step No. 7A. Once the underground facility design is modified, as shown in Step No. 7A, the iterative process returns to Step No. 6.

29. **Page 26, Appendix A, "Glossary"**

Appendix A defines "fully coupled" model as "a model that incorporates **in its formulation** the interdependency of the four phenomena (thermal, mechanical, hydrological, chemical)." (Emphasis added)

The interdependency of the phenomena can be incorporated in the formulation at many different levels. Individual codes representing each phenomenon can be incorporated under a system code in which the output of one code provides the input to the other code(s), in an iterative manner until the problem is solved. Alternatively, a model can be constructed with all equations formulated with the interdependencies built in and solved simultaneously. Whether such a detailed formulation is possible with the current scientific understanding of the phenomena and their interdependency, or whether the equations can be solved considering the nonlinearities in the equations, is beside the issue. What is really meant by the definition is not at all clear.

Most natural phenomena occur through many competing interactive processes. Any change in one process, be it thermal, mechanical, hydrological, or chemical, influences the other processes, which, in turn, affect the original process, by either enhancing it or counteracting it. The degree of interaction among the processes, i.e., degree of coupling, can be strong or weak. From a thermodynamic point of view, the coupling can also be classified as primary or secondary, depending on the flux and the gradient relationship. The secondary couplings are generally weak. Under certain conditions, however, they could be several orders-of-magnitude higher than the effects from primary coupling. For example, the Soret effect (mass flux due to thermal gradient) in a clay backfill could easily exceed any water influx due to hydraulic gradient (Jamet *et al.*, 1990). This is why for some processes the secondary effects cannot be ignored and a "fully coupled" model that includes weak couplings may be needed.

The secondary effects, sometimes called Onsager's coupled processes (Carnahan, 1987), are very complicated, as shown below [see Table D1] with a few examples of such couplings in a fluid medium (de Marsily, 1986).

A "fully coupled" model generally means a model that includes both the primary and secondary couplings. There are debates in the scientific community about whether such models are needed or even technically feasible within practical limits of current state of knowledge, and whether a numerical code implementing a "fully coupled" model can be run efficiently on currently available computer hardware.

In addition, even if we ignore the secondary effects, 11 distinct combinations of processes can be considered by combining the T, M, H and C processes. There can be six two-process, four three-process, and one four-process combinations (Tsang, 1987). Any of these combinations could be modeled fully uncoupled, sequentially coupled, one-way coupled or two-way (feedback) coupled. In other words, they can be fully coupled with only two, three, or with all four processes, as they are needed. A "fully coupled" model does not necessarily have to include all four processes, unless the need for such a "fully coupled" model is established.

It also appears that this STP uses the word "model" to represent both the conceptual model and numerical codes. In this sense, it is not clear whether the term "fully coupled model" is also intended to mean fully coupled codes, whose meaning could be controversial.

The definition of "fully coupled" model is unconventional and ambiguous. It needs to be defined with more details. Also, NRC staff should demonstrate the feasibility of its STP by giving an example of a "fully coupled" model. Aside from this debate of technical feasibility, it is not clear in this STP (text and the definition in Appendix A) what degree of coupling NRC expects when it requests a "fully coupled" model.

Response

The staff notes the difficulty in interpreting the meaning of the phrase "fully coupled," as it appears in the "Glossary" of the draft version of the STP. In this regard, DOE is directed to the fourth paragraph of the staff's response to DOE's "General Comments," where the staff describes the revisions that have been made to the final version of the STP, to clarify what is meant by the staff's use of this and other terms.

The NRC staff also recognizes the difficulties and complexities associated with the characterization of coupled processes. Despite these difficulties, the staff recognizes that the importance of coupled processes should be explored, so that their effects, if necessary, could be: (1) included in a model(s) for use to predict the M–H–C responses associated with a thermal load, and the effects on the performance of the repository; and/or (2) included as an uncertainty in the results of models that may not directly account for the effects of such coupling. As DOE's specific comment points out, ". . . for some processes" [even] the secondary effects cannot be ignored

Table D1. A Few Examples of Possible Couplings in a Fluid Medium (from de Marsily, 1986)

Flux \ Force	**Temperature Gradient**	**Potential Gradient (Pressure \ Concentration)**	**Electric Field**
HEAT	*Fourier's Law*	Thermal osmosis \ Dufour effect	Electrothermal effect
MASS	Soret effect	Reverse osmosis \ *Fick's Law*	Electrophoresis
CURRENT	Seebeck effect	Electrochemical effects	*Ohms's Law*
PERCOLATION	Thermoosmosis	*Darcy's Law* \ Chemical osmosis	Electroosmosis

and a 'fully coupled' model that includes weak coupling may be needed." The staff recognizes that the characterization of coupled processes and the evaluation of their importance to the prediction of the T–M–H–C responses in the context of the repository may not be fully accomplished by the time of issuing the license to close the repository. However, an assessment of the importance of the coupled effects will contribute to the "reasonable assurance finding" that the repository will perform as intended.

Finally, the term "model," as used in the STP, does not refer to a numerical code.

State of Nevada Comments

General Comments

The STP is a generic, non-technical document which, based on a flow diagram, discusses and recommends an iterative procedure for demonstrating compliance of the underground repository facility with the requirements pertaining to thermal loads as they appear in applicable portions of 10 CFR Part 60 regulations. There is no indication of when this iterative process should be initiated, since there is little reference to the process of site characterization or of what kinds and levels of data are expected to be derived from site characterization for use in the procedure developed in this STP. This is of more than passing importance since, the DOE is planning that the Exploratory Shaft (now "Studies") Facility (ESF) be incorporated into the underground repository facility and it is already in the design process without benefit of the considerations outlined in the STP.

The DOE's assumption appears to be that thermal loading can be back-fit to any repository design, which is an approach opposite to that advanced in the STP. This is important in the context of this STP since implicit in the DOE assumption is the notion that thermal loading is a design feature of an underground repository facility, rather than a potential adverse impact that has waste isolation implications, as appears to be the case in the STP. If it is to be treated as a design feature, then the NRC, in its STP, should be concerned also with the design basis of the selected magnitude and rate of thermal loading and should require that the selection be supported by a thorough evaluation of alternative loads and their consequences for waste isolation performance. These incompatible views of the role of thermal loading in a repository must be reconciled before further development of a thermal load STP is undertaken.

The STP is based on the premise that performance assessment models for the evaluation of compliance with the performance objectives of 10 CFR Part 60 will exist at the time of license application. The suggested iterative process involves the use of increasingly advanced models, which are referred to as fully, partially, or one-way coupled thermal-mechanical-hydrological-chemical (T–M–H–C) models. These are inadequately defined in the STP in regard to their underlying assumptions and the kinds and levels of information needed for their acceptable application. This leads to what appears to be an endorsement of the use of expert judgment when either the data base is insufficient or the iterative process fails to resolve an issue.

In general, the STP lacks sufficient technical specificity to determine whether the suggested methodology is feasible for implementation, but more important, the suggested methodology is not compatible with the ongoing implementation of the DOE site characterization program, and therefore likely will be of little use as guidance to DOE.

Response

In the first portion of its general comment, the State of Nevada notes that "The STP is a generic non-technical document which, based upon a flow diagram, discusses and recommends an iterative procedure for demonstrating compliance . . ." and raises questions as to when such an iterative procedure should be initiated. The staff agrees with the State of Nevada that this STP is generic in nature because it is intended to be applicable to any site or design. However, the staff disagrees with the State that the STP is a nontechnical document because the STP is based on complex technical concepts related to the interaction of T–M–H–C processes.

As for when this iterative process is initiated, the staff notes, in Section 1.3 of this STP, that "The objective of providing guidance to DOE on thermal-load design during the pre-licensing phase is to identify what is needed to demonstrate compliance with the requirements of 10 CFR 60.133(i) and thereby minimize the potential for significant future problems, so that they can be avoided." Therefore, given the progressive nature of the approach, it is apparent that DOE's iterative design process should start as early as possible. The STP emphasizes that this is an evolving process that covers the entire period of repository design, construction, and operation.

Regarding the kinds and levels of data derived from site characterization for use in the iterative process recommended in the STP, the staff believes that it is DOE's responsibility to demonstrate that it identified and obtained the appropriate kinds and levels of data as part of its demonstration of compliance with 10 CFR 60.133(i). The State of Nevada should recall that the NRC staff will use "Draft Regulatory Guide DG-3003, 'Format and Content Regulatory Guide for the License Application for the High-Level Waste Repository' (FCRG)" (which has already been issued; see NRC, 1990; 55 *FR* 48307) to indicate to DOE the information to be provided in the License Application. The License Application Review Plan, which will guide the NRC staff's review of the License Application, will be publicly available and should provide additional insight to DOE. It is further noted that DOE's submittal of data and analyses are subject to continued pre-licensing review by NRC.

The State of Nevada is also concerned that DOE is proceeding with the ESF design process without the benefit of the guidance provided in this STP. The staff wishes to note that it has already provided guidance to DOE on the design process for the ESF (see Gupta *et al.*, 1991) and in doing so, has identified 10 CFR 60.133(i) as one of the applicable technical criteria that needs to be considered (*opt. cit.*, p. C-4). Although the design of the ESF is currently underway, the staff expects the final design of the ESF, as it relates to 10 CFR 60.133(i), should reflect consideration of the principles described in this STP.

The second portion of the general comment suggests that DOE's approach in dealing with thermal loading is incompatible with the approach advanced in the STP, and therefore recommends that no further development on this STP be made until the two approaches have been reconciled. In this regard, the State of Nevada is referred to Section 1.3 of this STP, where the role of STPs is discussed, including the fact that STPs are not substitutes for regulations, and compliance with them is not required. In view of this discussion, the staff does not find any reason not to proceed with the publication of this STP in its final form.

Furthermore, the State of Nevada is concerned that DOE treats the thermal load as a design feature. For this reason, it recommended that the STP should be concerned with the design basis of the thermal load and that the basis should be supported through an evaluation of alternative thermal loads, regarding their effect on waste isolation performance. The staff refers the State to 10 CFR 60.21(c)(ii)(D), which specifically calls for a comparative evaluation of alternatives to major design features, that are important to waste isolation, for assessing the effectiveness of engineered and natural barriers. Therefore, the staff believes that, as long as a design goal/criterion associated with a design feature is tied to the performance objectives, as suggested in this STP, the resulting underground facility design would evolve from a thorough evaluation of alternative thermal loads. Moreover, the analysis of waste isolation implications and establishment of the design basis for the thermal load are integral parts of this iterative process.

As regards the third portion of the State of Nevada's "General Comment," the staff agrees that there has been considerable difficulty in interpreting the meaning of the various terms such as "fully," "partially," and "one-way coupled" T–M–H–C models, as used in this STP. The staff agrees that there is a need to more clearly define these terms, and has made the following revisions to the STP:

(1) changed the terms "fully coupled," "partially coupled," and "one-way coupled" models to the term "coupled" models; and

(2) defined the term "coupled" models.

In the context of thermal load considerations, "coupled behavior" means that at least one of the processes (i.e., T, M, H, or C) has an effect on the initiation and propagation of any or all of the other processes.

As to the kinds and levels of data needed for the acceptable application of these models, the staff reiterates that it is DOE's responsibility to demonstrate the acceptability of these models and the associated data needs. Such demonstration and assessment of data needs will be subject to NRC review. Also, the State of Nevada raises an issue with the use of expert judgment. As Bonano *et al.*, (1990, p. 46) have noted:

> "Expert judgments should not be considered equivalent to technical calculations based on universally

accepted scientific laws or to the availability of extensive data on precisely the quantities of interest . . . . Expert judgments are sometimes inappropriately used to avoid gathering additional management or scientific information."

The staff agrees with Bonano *et al.*, and has stated that expert judgment should not be used as a substitute for investigations needed to support a complete and high-quality license application. This is particularly true for reasonably available or obtainable data and/or analyses. Finally, in its "General Comments," the State of Nevada questions the feasibility of the proposed methodology in this STP on the grounds that the STP lacks sufficient technical specificity and that it is incompatible with the ongoing DOE program. The State concludes that this STP will be of little use as guidance to DOE. The staff has no reason to believe that the proposed methodology in this STP is not feasible, because the STP is based on a logical, comprehensive, and systematic approach. The staff points out that the intent of this STP is to provide sufficient generic guidance to DOE without being too prescriptive or overly restrictive with regard to the implementation techniques that may be chosen by DOE. In the staff's view, the guidance in this STP is not incompatible with the ongoing DOE program, as known to the staff through its pre-licensing consultations. Therefore, the staff believes that useful and timely guidance is being provided in this STP, for DOE to develop its ability to demonstrate compliance with 10 CFR 60.133(i).

Specific Comments

1. **Page 1, paragraph 1**

   It is emphasized in the STP that the DOE is expected to demonstrate a comprehensive, systematic and logical understanding of T-M-H-C [responses] of the underground facility. This should be elaborated. It is not clear how such a demonstration is expected to be accomplished, and whether both the theoretical and site-specific basis for such understanding should be presented.

Response

The staff believes that sufficient details are provided, in the STP, to demonstrate a systematic and logical understanding of the coupled T-M-H-C responses associated with a particular GROA underground facility design. (These details are discussed in Sections 3.0 and 4.0, respectively, of the STP.) The approach described by the staff relies on the development of a generic (i.e., theoretical) model, based on site-specific data.

2. **Page 2, Paragraph 1**

   The STP states: "The staff expects that, through the pursuit of appropriate technical programs, DOE would develop information that would enhance considerably the approach in this document."

   This presumes that DOE will choose to adhere to the staff approach (see "General Comments"), and if DOE does so choose, the statement suggests that the staff has some doubts about whether the approach, as presented, will lead to an adequate determination of compliance. If such doubts exist, the staff itself should attempt to enhance the approach before it is reissued as information and guidance.

Response

Since STPs are not substitutes for regulations, and compliance with them is not required, DOE may or may not choose to follow the example approach recommended in this STP. However, if DOE chooses to follow the recommended methodology, the staff believes, at the present time, that this methodology will lead to an adequate demonstration of compliance with 10 CFR 60.133(i). Likewise, a different methodology chosen and implemented by DOE may also lead to a demonstration of compliance that too would be acceptable to the NRC staff. This is recognized by the staff, as stated in the last paragraph of Section 1.3 of the STP. The staff will make every attempt to enhance the suggested methodology if and when new information warrants such enhancement.

3. **Page 2, Paragraph 2**

   The STP states: "In this STP, the NRC staff assumes that performance assessment models will exist for evaluating compliance with 10 CFR Part 60 performance objectives." See discussion of this assumption in "General Comments."

Response

The staff's statement that "... performance assessment models will exist," it believes, is a reasonable assumption. This judgment is based on the observation that both the DOE and NRC programs (as well as those of groups such as the Electric Power Research Institute) are focused on developing and testing such models, using such broad-based approaches as those used in Performance Assessment Calculational Exercises (PACE), and the respective NRC/DOE Performance Assessment activities.

4. **Page 2, Paragraph 2**

   The STP states: "However, elaboration on the specifics of performance assessments, with respect to the individual 10 CFR Part 60 performance objectives, is outside the scope of this STP."

Some elaboration would be helpful in this STP in order to expose at least some of what the staff believes is appropriate for data collection and analysis during site characterization. This could result in a beneficial reduction in uncertainty in the thermal loading assessment in a license application, since the STP appears to expect that uncertainties will be relatively large at the time of license application, and will reduce significantly during construction and operation.

Response

The staff agrees with this specific comment that elaboration on the different aspects of performance assessments would be helpful in identifying appropriate data collection; however, the staff maintains that doing so is beyond the scope of this STP.

In this regard, the NRC staff has previously noted that it will use the FCRG (which has already been issued in draft form) to provide additional guidance to DOE regarding the kinds of data to be presented in the License Application. It is further noted that DOE's submittal of data and analyses are subject to continued NRC review.

5. **Page 4, Paragraph 1**

   The STP states: "The guidance in the STP focuses on the prediction of repository-generated thermal regimes beyond the range of current engineering experience."

   "Current engineering experience" should be elaborated in this section in order to better understand the focus of this STP. Is there "current engineering experience" that the staff believes is relevant under the range of thermal load scenarios that the DOE is likely to consider, given the repository development and operation schedule it is attempting to meet?

Response

The staff believes that current hard-rock mining experience, at very deep levels (e.g., 10,000 feet), where the geothermal gradient results in a very warm environment, would be relevant to the operational period of the repository. The staff believes that this experience could be useful in DOE's efforts to demonstrate that its design complies with the pre-closure performance objectives (e.g., 10 CFR 60.111). In addition, as natural analogs, conditions associated with geothermal regions could be used in guiding post-closure performance evaluations (e.g., 10 CFR 60.112 and 60.113).

6. **Page 5, Paragraph 2**

   The STP states: "If there is an unresolved safety question relating to model validation, this could be described in the application and need not stand in the way of issuance of a construction authorization (so long as there is reasonable assurance of safety)."

   The word "could" should be replaced by "should." If there is an unresolved safety question relating to model validation, the standard of reasonable assurance will be diminished unnecessarily to some extent if the issues involved in the lack of resolution are not described.

Response

The staff agrees with the recommended change suggested by the State of Nevada's specific comment. The third sentence of the last paragraph in Section 1.2 has been revised to read as follows:

> "If there is an unresolved safety question relating to model validation, this should be described in the application. The existence of such a question may, of course, reduce the Commission's confidence that the standards for issuance of a construction authorization have been satisfied. Depending on the significance of the unresolved safety question and the prospects for resolving it favorably, there may be reasonable assurance that applicable requirements have been met and, on that basis, a construction authorization might be issued."

Moreover, the staff also points out the prerogative of the Commission to place "conditions" on the construction authorization, in accordance with 10 CFR 60.32. More specifically, 10 CFR 60.32(b)(4) identifies "programs being conducted to resolve safety questions" as a particular basis for placing certain "conditions" on a potential licensee.

7. **Page 8, paragraph 2**

   Step No. 1 calls for a preliminary evaluation of the sensitivity of the performance objectives to thermal loading. The STP should outline the type and level of data and the maturity of facility design necessary to make this evaluation since the Step No. 1 determination, according to the STP approach, may never be revisited.

Response

The staff believes that a preliminary, conceptual understanding of the GROA underground facility design is sufficient when considering Step No. 1 in the recommended approach. The staff believes that it is DOE's, not

NRC's, responsibility to justify the type and the level of the data used in the evaluation of each step, including Step No. 1. The suggested methodology applies to any given thermal load design concept. Therefore, whenever significant changes are made to the design concept, the suggested methodology depicted in Figure 1 should be reapplied, based on these changes.

8. Page 8, Paragraph 3

Step No. 2 calls for the determination of the existence of predictive models to quantify the effect of thermal loadings. This step should require, in addition, a demonstration of the reliability of such models relative to the specific site being evaluated by DOE. According to the STP approach, this determination may never be revisited.

Response

Regarding the need for site-specific information to demonstrate the reliability of the models described in Step No. 2, the staff points out that in Section 3.0 of the STP, Step No. 2 requires that models be reliable. For a discussion on the use of reliable models, the State of Nevada is referred to Section 4.2 of the STP.

The staff agrees with the State of Nevada comment regarding the need to revisit Step No. 2, and has modified the recommended approach accordingly. The modification involves a return from Step No. 5 to Step No. 2 in Figure 1. In addition the text for Step No. 5 has been changed in Technical Position 3.1.

9. Page 8, Paragraph 4

Step No. 3 calls for an examination of the thermally induced phenomena. The STP should outline the type and level of data necessary for this examination, and should elaborate on what methods and scope of examination might be expected to be employed.

Response

The staff agrees that the types and the levels of data, and methods of examination are important issues. However, the staff does not believe that it is appropriate to include such information in this STP. Also, the selection of methodologies or approaches that may be used for accomplishing the objective of each step in the example methodology should again be left to the purview of DOE.

In this regard, the NRC staff has previously noted that it will use the FCRG (which has already been issued in draft form) to provide additional guidance to DOE regarding the kinds of data to be presented in a potential license application. (It is further noted that DOE's submittal of data and analyses are subject to continued NRC review.)

As regards the levels of data that might be necessary for this examination, the staff believes that DOE should collect sufficient data that could lead to a **reasoned conclusion** that the regulatory requirements have been complied with.

10. Page 8, Paragraph 5

Step No. 4 calls for development of design goals/criteria.

In such development, the STP should call for an evaluation of alternative design goals/criteria based on varying the magnitude and rate of thermal loading. The basis for the design goals/criteria selected should be demonstrated.

Response

The recommended approach in the STP calls for the development of design goals/criteria that are derived from 10 CFR Part 60 performance objectives. Design goals/criteria should not be determined on the basis of a variation of thermal loads, as the State of Nevada suggests. Rather, alternative thermal loads should be determined on the basis of the design goals/criteria, derived from the performance objectives. The State of Nevada is referred to Step No. 4 of Section 4.1 for a detailed discussion of the development of design goals/criteria.

11. Page 9, Paragraph 6

The STP states: "If, after numerous design iterations, noncompliance with 10 CFR Part 60 performance objectives persists, examination of other criteria not related to the underground facility design should be considered (Step No. 8B)." This step suggests that the "other" engineering criteria have been set independent of thermal load considerations and their relationship to thermal loading need not be considered except as a means of compensating for unresolvable problems in performance of the underground facility and its design. It should not be acceptable that the underground facility design be considered the "weak link" in performance relative to thermal loads.

Response

The State of Nevada's comment implies that the example approach in the STP precludes thermal load considerations for waste package design, boreholes, shafts, and seal design and the assessment of the geologic setting. The staff disagrees that the suggested methodology conveys this implication. The staff points out that the suggested methodology is specifically to demonstrate compliance with 10 CFR 60.133(i) (i.e., the GROA underground facility design in the context of the thermal load).

Thermal load considerations will also need to be included in the waste package design, borehole, shaft, and seals design and the geologic setting concerns; however, these design concerns are outside the scope of this STP.

12. **Page 10, Paragraph 3**

    The STP states: "Develop models that approximate fully coupled behavior in a manner that is not likely to adversely affect the performance objectives . . . ." This could be stated more clearly. Performance objectives are not affected by behavior.

    The STP should [also] provide some guidance on the intended bounds of such an approximation, and the type and level of data necessary to make and demonstrate such an approximation.

Response

The staff agrees with the first portion of the State of Nevada's specific comment that models cannot affect performance objectives. Therefore, Section (a) of Technical Position 3.3 has been modified to read as follows:

> "(a) Develop models that approximate coupled behavior in a manner that is not likely to underestimate the unfavorable or overestimate the favorable aspects of repository performance."

As regards the second portion of the State of Nevada's specific comment, the staff believes that the issue of providing guidance on the type and level of data necessary to demonstrate compliance with 10 CFR Part 60.133(i) has been adequately covered in Section (b) of Technical Position 3.3, and the "Discussion," in Section 4.3 of the STP.

13. **Page 17, Paragraph 2**

    The STP states: "If unacceptable results are encountered, it may become necessary to return to Step No. 3, from Step No. 8 (see Figure 1)."

    If there is continued noncompliance, then disqualification of the site should be considered also.

Response

The staff notes the State of Nevada's comment regarding continued noncompliance of a design and the recommendation for the subsequent disqualification of the site. However, this STP is concerned specifically with the demonstration of compliance with 10 CFR 60.133(i), and not with the overall question concerning the determination of site qualification. The steps that are part of the example approach described in this STP cannot, and are not designed to, lead to a determination whether or not the site would qualify for licensing.

If, after numerous iterations, an underground facility design for the GROA is not found to be acceptable, according to the derived design goals/criteria, the recommendation in the STP is to look at components of the "disposal system" other than those of the underground facility (e.g., Step Nos. 8A and 8B). Whether a site qualifies for licensing is an issue that should be determined from a demonstration of the site's ability to meet all pertinent 10 CFR Part 60 regulatory requirements.

14. **Page 17, Paragraph 3**

    The STP states: "In this case, a decision would be made to look for problems related to waste package design, borehole, and shaft seals design, and/or geologic setting concerns (Step No. 8B); however, discussions of such analyses are beyond the scope of this STP."

    See Comment No. 11 above.

Response

See staff response to State of Nevada Specific Comment No. 11.

15. **Page 19, Paragraph 1**

    The STP states: "The analyst should choose a model that strikes a balance between unworkable detail and oversimplification of the processes that are being modeled. Such a balance can reduce the model uncertainty to a degree. Nevertheless, there remains residual model uncertainty that results from the simplification and lack of knowledge of the phenomenon being modeled."

    This statement alone does not provide useful information or guidance. It suggests that the analyst is encouraged to use his expert judgment as to what represents the proper balance, but it does not specifically require that there be a demonstration of the extent to which a lack of knowledge contributes to the balance.

Response

The statement referenced by the State of Nevada's specific comment is meant to demonstrate the staff's recognition of the complexity of the T–M–H–C coupled problem, and to recommend a reasonable and balanced approach to understanding this behavior. The statement of concern in the STP should be viewed in the context of the **overall**, more extensive discussion of the development of detailed predictive models, as described in Section 4.2, rather than in the manner interpreted by the State of Nevada in its comment.

Regarding the portion of this comment related to the use of expert judgment, the State of Nevada is referred to the staff's response to the State of Nevada's "General Comment."

16. Page 34, Paragraph 2

The STP states: The order in which the phenomena (e.g., thermal, mechanical, hydrological, or chemical) are analyzed in Figure C1 is shown only as an example. The responsibility to determine the most appropriate sequence of analyses rests with the licensee."

The STP should require that alternative orders of consideration be evaluated and that the basis for selection be demonstrated. Further, by using the word licensee, the suggestion is that this exercise is not one which is to be carried out prior to license application. Surely this is not intended by the staff.

Response

This comment is noted. However, the staff reiterates that the order in which the sequence of analyses is performed should be that which is demonstrated to be the most appropriate.

Also, the staff agrees that the word "licensee," should not be used in this STP and has been replaced by "DOE" throughout.

17. Page 34, Paragraph 3

Regarding the use of "licensee," see Specific Comment No. 16 above.

Response

See staff response to State of Nevada Specific Comment No. 16.

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APPENDIX E

DISPOSITION OF ACNW COMMENT

Note: The Advisory Committee on Nuclear Waste (ACNW) comments listed in this appendix were made on the final draft of the subject Staff Technical Position (STP), dated July 1992.

ACNW Specific Comment *

We recommend that the STP be modified to include explicit mention of the applicability of empirically-derived models in the assessment process.

Response

The staff agrees with the recommendation made by the ACNW in its comment and has modified the final version of the STP, as suggested. Section 4.3 ("Alternative Predictive Models") in the "Discussion" section has been modified as follows:

"In demonstrating compliance with design criteria of 10 CFR 60.133(i), it is expected that a mechanistic understanding of coupled behavior will be used to predict the thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. The staff realizes, however, that it may not be possible to obtain a thorough mechanistic understanding of coupled T-M-H-C behavior, as discussed in Section 1.2, particularly before an application is submitted to construct a geologic repository. Therefore, in the design of the underground facility, DOE may need to develop and use models that express coupling between processes based on less than a thorough mechanistic understanding of T-M-H-C behavior. Note that analysis using such empirical models must provide for an evaluation of the effects of the assumptions of coupling on the predicted results and the conservatism of the empirical models used.

The lack of a thorough mechanistic understanding may lead to the use of models that do not directly account for coupling between two or more of the T-H-M-C processes involved. Appendix C gives an example of an iterative process for the analysis of thermally-induced phenomena using such "approximate" models.

In the application of empirical models that rely on a limited mechanistic understanding of coupled processes, and/or that do not directly account for coupling between two or more processes, conservative data and assumptions must be used. Such conservatism should compensate for the uncertainties resulting from the lack of a detailed understanding, since otherwise such uncertainties may preclude the staff from finding, with reasonable assurance, that the performance objectives will be met.

If DOE decides to use alternative predictive models, as discussed above, the staff expects DOE's license application to demonstrate that such models are not likely to underestimate the unfavorable aspects, or overestimate the favorable aspects of geologic repository performance, in the context of analysis and design.

The staff also expects that, as a part of its performance confirmation program (10 CFR 60.140-143), DOE will perform *in-situ* and laboratory monitoring and testing to confirm the assumptions made in the license application, with respect to the alternative predictive models used in underground facility design analyses. The results of the performance confirmation program should provide the bases for model refinement, if needed, as discussed in Section 1.2."

Moreover, the first paragraph of Section 1.0 ("Introduction") has also been modified to address this recommendation.

*The staff also responded to minor and editorial comments on the STP made by the ACNW, as noted in the *Transcript for the 45th Meeting of the ACNW – July 29-30, 1992.*

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The purpose of this Staff Technical Position (STP) is to provide the U.S. Department of Energy (DOE) with a methodology acceptable to the U.S. Nuclear Regulatory Commission (NRC) staff for demonstrating compliance with 10 CFR 60.133(i). The NRC staff's position is that DOE should develop and use a defensible methodology to demonstrate the acceptability of a geologic repository operations area (GROA) underground facility design. The staff anticipates that this methodology will include evaluation and development of appropriately coupled models, to account for the thermal, mechanical, hydrological, and chemical processes that are induced by repository-generated thermal loads. With respect to 10 CFR 60.133(i), the GROA underground facility design: (1) should satisfy design goals/criteria initially selected, by considering the performance objectives; and (2) must satisfy the performance objectives 10 CFR 60.111, 60.112, and 60.113. The methodology in this STP suggests an iterative approach suitable for the underground facility design.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

High-Level Radioactive Waste
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Key Technical Uncertainties (KTUs) for RDCO Program Element:

1). **Thermal Loads** : Design the Underground Facility taking into account TMHC coupled responses of host rock, surrounding strata, and groundwater system (10 CFR 60.133(i)).

2). **Seals** : Design the long-term seals for Shafts, Ramps, and Boreholes in such a way that they do not become preferential pathways (10 CFR 60.134).

3). **Waste Retrievability** : Maintain retrievability option and be able to retrieve safely (60.133(c), 60.111(a), and 60.111(b)).

KTUs associated with CDSs:

	Surface Facility 4.2	Shafts and Ramps 4.3	Underg. Faci. Design 4.4	Waste Retriv. 4.5.2
Period of Interest	Pre-Closure	Pre-closure / Post-closure	Pre-closure / Post-closure	Pre-closure
KTU- TMHC	None	●	X	●
KTU- Seals	None	X	(●)	N/A
KTU- Retriv.	None	●	●	X
P.O. Non-Compliance	None	60.111, 112, & 113	60.111, 112, & 113	60.111, 112, & 113

Key: ● - Shared KTUs referenced here.

X - KTU will be handled in this CDS.

(●)- Seals is not specified in the underground facility design, but should be considered.

Key Technical Uncertainties(KTUs) for the GROA

1. Thermal Loads - 10 CFR 60.133(i)

- Prediction of thermomechanical (including seismic loads) effects on drift and emplacement boreholes for retrievability

- Prediction of thermal-mechanical-hydrological effects on emplacement drifts and emplacement boreholes to provide input for waste package design (10 CFR 60.113)

- Prediction of thermal-mechanical-hydrological for effects on emplacement drifts and emplacement boreholes to provide input for performance assessments (10 CFR 60.112)

- Extrapolation of short-term laboratory and field test results to predict long-term T-M-H-C effects

2. Long-term seals performance - 10 CFR 60.134

- Prediction of thermal-mechanical effects on the performance of seals including surrounding rock mass

- Prediction of thermal-hydrological effects on the chemical properties of seal material

- Extrapolation of short-term laboratory and field test results to predict long-term performance of seals

3. Waste retrievability - 10 CFR 60.133(c) and 10 CFR 60.111(b)

- Prediction of thermal-mechanical effects on drifts and emplacement boreholes for retrievability

- Retrieval operations (no experience)

CDS 4.4 Assessment of Compliance with Design Criteria for the Underground Facility

- **60.133 (i):** The underground facility shall be designed so that the **performance objectives*** will be met taking into account the predicted thermal and thermomechanical response of the host rock, and surrounding strata, groundwater system

  * **Staff Position 60-003** clearly states that both pre- and post-closure performance objectives need to be considered (August, 1990)

  * In **NUREG 1466**, the staff re-affirmed that when addressing 60.133(i), the performance objectives at risk are 10 CFR 60.111, 60.112, and 60.113 (December, 1992)

- **KTU: Prediction of TMHC Responses of the Host Rock, Surrounding Strata, and Groundwater System to Thermal Loads**

  - TMHC KTU affects many CDSs
  - Canister scale analyses will be reviewed under CDS 5.3 (EBS Design)
  - Canister, room, and drift scale analyses will be reviewed under CDS 4.4 (Underground Facility Design)
  - Repository scale analyses will be reviewed under Performance Assessments
  - TMHC impacts on seals will be reviewed under CDS 4.3 (Shafts and Ramps)
  - TMHC impacts on Retrievability will be reviewed under CDS 4.5.2 (Retrievability)

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