SEP 10 1990

MEMORANDUM FOR: Raymond F. Fraley, Executive Director
Advisory Committee on Nuclear Waste

THRU: Abraham L. Eiss, ACNW Liaison
Special Issues Group
Office of Nuclear Material Safety
and Safeguards

FROM: Robert E. Browning, Director
Division of High-Level Waste Management
Office of Nuclear Material Safety
and Safeguards

SUBJECT: TRANSMITTAL OF PROPOSED DRAFT TECHNICAL POSITION (TP) ON "REPOSITORY DESIGN: THERMAL LOADS" TO THE ADVISORY COMMITTEE ON NUCLEAR WASTE (ACNW)

In accordance with the draft Memorandum of Understanding between the ACNW and the Executive Director for Operations, the Division of High-Level Waste Management is submitting the subject draft of the Public Comment Draft TP to the ACNW for its review and comment prior to noticing its availability in the Federal Register. Division of High-Level Waste Management staff will brief the ACNW at its November 1990 meeting.

/S/

Robert E. Browning, Director
Division of High-Level Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated

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Technical Position on Repository Design - Thermal Loads

U.S. Nuclear Regulatory Commission
Office of Nuclear Material Safety and Safeguards
Division of High-Level Waste Management

Public Comment Draft: August 1990

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ABSTRACT

This technical position is intended to provide the U.S. Department of Energy with a methodology acceptable to the NRC staff for demonstrating compliance with 10 CFR Part 60.133(i). Section 3.0 presents the staffs' positions and Section 4.0 provides the corresponding discussions.

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1.0 INTRODUCTION

The thrust of this Technical Position is to reflect the expectation of the NRC technical staff that the applicant will present a comprehensive, systematic and logical demonstration of the coupled thermal-mechanical-hydrologic-chemical responses associated with a particular repository design, based primarily on mechanistic understandings. However, the applicant may need to base its demonstration, initially, on empirical data from short-term tests.

The license application submitted initially, prior to construction of the repository, must be updated before issuance of a license to possess and emplace waste in the repository, and again upon application to close the repository. Staff understands that with the diligent pursuit of appropriate technical programs of site characterization and performance confirmation, the level of understanding and demonstration can develop and improve significantly over the long time-frame associated with the repository program.

As an example, staff has included a specific approach which, based on our understanding today, is acceptable. However, we do not believe that it is necessarily the "best" or "optimum" approach for all time. Staff expects that through the diligent pursuit of appropriate technical programs, DOE would develop information that would enhance considerably the specific approach included in this document. Therefore, NRC anticipates updating this position as the development of significant information and insights from site characterization and performance confirmation programs, as well as any other technical activities, may warrant.

10 CFR 60.133(i) requires that the underground facility of a geologic repository 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. The performance objectives are those in 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 repository is permanently closed.

The rule thus recognizes that an understanding of the thermal loads due to 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 of heat transfer and thermally induced responses such as rock deformations, groundwater flow, and the dissolution and precipitation of mineral species using adequate models.

The development of adequate models requires a thorough understanding of the thermal loads due to emplacement of nuclear waste and corresponding thermally induced responses in the host rock and surrounding geologic setting. An initial understanding will be gained from site characterization testing. Based on the current understanding of thermally induced responses in rock, the NRC staff finds that predictive models based on one-way coupled formulations (e.g., Tsang, 1987) of thermal, mechanical, hydrological, and chemical (T-M-H-C) responses may be used for demonstrating compliance with 10 CFR 60.133(i) at the Construction Authorization stage of the repository licensing process. However, the staff expects model development/refinement to continue as greater understanding of the thermally induced phenomena is gained during the period of repository construction and performance confirmation testing. This should result in more comprehensive models (for example fully coupled models) by the time of application for a license to receive and process source, special nuclear, or byproduct material and application for license amendment for permanent closure.

Many aspects of the underground facility design, including waste container spacing, opening configurations and dimensions, and support requirements, depend on a thorough understanding of the effects of the thermal load and may also influence the repository performance. The underground facility design must conform to the repository performance objectives of 10 CFR 60.111, 60.112, and 60.113. Further, the underground facility must also comply with the design criteria of 10 CFR 60.130, 60.131, and 60.133.

The approach presented in this TP is not contingent on a one-way T-M-H-C coupling, but can be extended to include fully coupled formulations (e.g. T-M-H-C, or T-M-H) if such coupling is deemed necessary from the standpoint of providing defensible predictions.

An important assumption in this methodology is that a total system performance assessment model will exist, which incorporates the predicted T-M-H-C responses associated with a specific underground facility design when evaluating the total system performance. Elaboration on the specifics of such a performance assessment model is outside the scope of this TP.

As stated above, this TP provides a methodology acceptable to the NRC staff for demonstrating compliance with the design criteria required in 10 CFR 60.133(i). In addition, the described approach will serve as a framework for a compliance determination methodology which will be developed as part of the License Application Review Plan (LARP).

This TP includes the following six sections: (1.0) Introduction, (2.0) Regulatory Background, (3.0) Technical Positions, (4.0) Discussion, (5.0) References, and (6.0) Bibliography. Section 2.0 identifies the specific regulations addressed by this TP. Section 3.0 describes the Staff's technical position on an acceptable methodology. An explanation and discussion of the position is provided in Section 4.0. Cited references are listed in Section 5.0. Uncited but related references are listed in the bibliography, Section 6.0.

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Technical Positions are issued to describe and make available to the public criteria for methods acceptable to the NRC staff for implementing specific parts of the Commission's regulations, or to provide guidance to the Department of Energy. Technical Positions are not substitutes for regulations, and compliance with them is not required. Methods and solutions different from those set out in the position 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.

In the event that DOE chooses a methodology different from that identified by the NRC staff in this TP and/or subsequent guidance, the NRC may require that DOE provide data and related information sufficient to allow the staff to perform an independent analysis using a methodology (such as that presented in this TP) selected by the staff. In addition, the staff will review in detail the information provided by DOE in light of Standard Format and Content Guide(s) to be prepared by the staff in preparation for license applications and such other guidance and regulatory documents (for example, those detailing Quality Assurance requirements) as may have been provided to the public and the DOE.

2.0 REGULATORY BACKGROUND

The regulatory requirements addressing thermal loads are identified in 10 CFR 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."

The performance objectives referred to in 60.133(i) are 60.111, 60.112, and 60.113(a)(1). These performance objectives and other applicable rules are stated in Appendix B. Information contained in NUREG's 0856 and 1373 is also relative to this technical position.

3.0 TECHNICAL POSITIONS

DOE must design the underground facility such that the performance objectives of 10 CFR 60.111, 60.112, and 60.113 (Section 2.0) will be met. In addition, the underground facility design must comply with the various design criteria as stated in 10 CFR 60.130, 60.131, and 60.133. The method presented below outlines the steps that can be used to evaluate the adequacy of the underground facility design as it is affected by the thermally induced responses in the host rock, surrounding strata, and groundwater system. The adequacy of the underground facility design is evaluated specifically by comparing predicted thermally induced responses to performance-based design criteria, and then by testing the performance of the geologic repository system by using the predicted thermally induced responses as input to a performance assessment model. The NRC staff believes that the following methodology, as outlined in Section 3.1, 3.2 and 3.3 which is ultimately based on a determination of fully coupled effects of thermally induced phenomena but acknowledges the potential need for one-way coupled formulation of thermally induced phenomena, is a suitable approach for use in demonstrating compliance with 10 CFR 60.133(i).

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3.1 The following steps, see Figure 1, can be used when demonstrating acceptability of underground facility design:

   3.1.1 Examine the thermally induced phenomena in the host rock and surrounding strata.

   3.1.2 Develop performance based design criteria for the underground facility.

   3.1.3 Obtain or develop predictive models for analyses.

   3.1.4 Perform analyses with predictive model(s) and compare results to performance based design criteria.

   3.1.5 Use the predicted results in a performance assessment model to evaluate compliance with the performance objectives of 10 CFR 60.111, 60.112, and 60.113.

3.2 It is expected that a mechanistic understanding of the fully coupled behavior will be the basis to develop models to predict the thermal and thermo-mechanical response of the host rock, surrounding strata, and groundwater system. DOE should implement a program to develop these fully coupled models such that they are available at the time of license application. In the event a satisfactory understanding of the synergistic effects of thermal, mechanical, hydrological, and chemical interactions cannot be gained prior to submittal of the license application, DOE should: (1) explain the current level of understanding and justify why a fully coupled model has not been developed, and (2) present plans and procedures to obtain a satisfactory level of knowledge during the performance confirmation program. Until predictive models can be developed through a mechanistic understanding of the fully coupled behavior, the methodology outlined in Section 3.3 may be a suitable approach for demonstrating compliance with 10 CFR 60.133(i) provided conservative data and assumptions are used and shown to account for uncertainties.

3.3 Until predictive models can be developed through a mechanistic understanding of the fully coupled (mechanical-thermal-hydrological-chemical) behavior, DOE should use the best available models. Analyses which cannot be performed with partially coupled models can then utilize an iterative analytical process based on multiple one-way coupled formulation of thermally induced phenomena to predict the response of the host rock, surrounding strata, and groundwater system as suggested by step 3.1.4 above. A detailed flow diagram of this process is presented in Figure 2.

4.0 DISCUSSION OF TECHNICAL POSITIONS

The steps outlined in Sections 3.1 through 3.3 represent a methodology suitable to the NRC staff for use in demonstrating compliance with 10 CFR 60.133(i). This systematic approach provides a means to evaluate, through predictive modeling, the effects of thermally induced phenomena (in the host rock, surrounding strata, and groundwater) on the repository performance associated with an underground facility design. This methodology is shown schematically in Figure 1.

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There are two points in the methodology (see #6 and #8 on Figure 1) where evaluations are made with respect to the acceptability of the underground facility design. The first evaluation point involves the comparison of the predicted responses with the response limits set by the performance based design criteria. If the predicted response exceeds design criteria response limits, the underground facility design should be changed with subsequent model application and reevaluation of predicted responses. The second evaluation point, performance assessment evaluation, takes place only after all performance based design criteria have been satisfied. If upon completion of the performance assessment test, the underground facility fails to comply with the pre- or post-closure performance objectives, a reassessment associated with each major step in the methodology should be conducted, before new responses are predicted and submitted to the performance assessment model for reevaluation. Several iterations may be required before it can be determined that the underground facility design complies with 10 CFR 60.133(i).

4.1.1

The underground facility host rock and surrounding strata will respond to the thermal loading associated with the disposal of the nuclear waste. It is likely that the repository thermal loading may be one of the most important underground facility design parameters (DOE, 1988). Therefore, to properly design an underground facility within the guidelines of the performance objectives of 10 CFR Part 60, it will be necessary to understand the transfer of heat as well as associated phenomena such as thermally induced mechanical, chemical, and groundwater response in the host rock and surrounding strata. This understanding would include an assessment of the level of phenomenological coupling that may be necessary to reasonably characterize the phenomena and predict their responses. The level of response may vary for different materials and different locations at different times, which could have an effect on the design of the underground facility.

An adequate characterization of thermally induced phenomena would require a characterization of the heat transfer in the host rock and surrounding strata. Information that would support such characterization of the heat transfer would need to come from the results of site characterization activities and performance confirmation testing. Essential information to obtain in this context would be the basic host rock thermal properties, such as thermal conductivity, density, and heat capacity. In addition, information about the host rock mineralogy, porosity, saturation level, and permeability would contribute to the understanding of the heat transfer environment, and thus, to the type of heat transfer that could be expected (conduction, convection, and/or radiant heat transfer). 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 thermal, mechanical, hydrological, and chemical processes. The dominant modes of heat transfer may be a function 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, while heat transfer associated with the vaporization of porewater 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. thermal load).

The position of Section 3.1.1 results from the need to bring about understanding of the occurrence of heat transfer and thermally induced effects in the host rock and surrounding strata as the basis for developing or qualifying adequate predictive models of thermally induced responses.

4.1.2

Although the host rock and surrounding strata 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 must be established. Underground facility design criteria derived from thermal, mechanical hydrological, and chemical response limits correlated to the repository performance objectives are expected to be essential in the development of the underground facility. The purpose of developing design criteria that are performance based is to contribute to the assurance that the design of the underground facility has the likelihood of meeting the performance objectives. The performance based design criteria are thought to be developed on the basis of the understanding of the thermally induced phenomena in the host rock and surrounding strata, 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 criteria would be:

1. Identify processes and events that could result from thermally induced phenomena (e.g., rock fracturing, groundwater flow, or mineral dissolution and precipitation) and could be of consequence to the performance of the repository (as defined by the performance objectives).

2. 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.

3. Determine the degree to which the processes and events are acceptable in order to limit any response that may be consequential to the performance objectives.

To establish response limits expressed by the performance based design criteria, it is likely that predictive thermal, mechanical, hydrological, and chemical analyses of conceptual underground facility designs would need to be conducted. Because the phenomenological responses to be considered are "thermally driven," it is conceivable that the design 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.

There are various levels of detail regarding the determination 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 and surrounding strata. New understanding about potential thermal, mechanical, hydrological, and chemical processes and events in the host rock and surrounding strata could be gained during the period of site characterization and performance confirmation testing. To better guide the development of the underground facility design, it is reasonable that such understanding be reflected in new and/or updated performance based design criteria. However, a documented rationale would be expected with any changes to such criteria.

4.1.3

The thermal load expected to result from the emplacement of spent nuclear fuel and HLW will affect the host rock and surrounding strata for thousands of years. Thus, the thermal load has the potential to alter the normal thermal, hydrological, mechanical, and chemical processes within the geologic setting throughout all of the waste containment and much of the waste isolation period. The staff expects DOE to develop a fully coupled model based on an understanding of the synergistic effects of the coupled thermal, mechanical, chemical, and hydrological interactions. The staff recognizes that acquiring the knowledge necessary to develop such a model may require information which will be obtained during the performance confirmation program. Provided it is not possible to develop an adequate fully coupled model prior to submittal of license application, the staff believes a reasonable interim approach to analyze the system would entail obtaining/developing four independent predictive models: thermal, mechanical, chemical, and hydrological. The scope of the heat transfer problem associated with geologic waste disposal is of such extent (e.g., geometric complexities, volume of host rock, and extended time frames) that it is not practical, nor even feasible, to conduct experiments that will enhance knowledge of the heat transfer, and thermally induced mechanical, hydrologic, and chemical responses at all locations of the host rock and surrounding strata for thousands of years into the future. However, reasonable estimates of these responses must be provided to allow an evaluation of the underground facility design against the requirements expressed by the performance objectives of 10 CFR Part 60. The position in Section 3.1.3, therefore, is based on the need to make predictions for evaluative purposes; the only approach that can provide such predictions is the development and application of predictive models.

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. Phenomenological details which may be important to the prediction of the response early in the history of the repository and which 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, repository scale, and regional scale problems are required to assure that appropriate phenomenological detail will be included in the analyses.

Assumptions must be made about host rock conditions and phenomenological details which 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 and validate, resulting in more uncertainty associated with its use. The ultimate test of a model is that it must be empirically adequate; if simplifications produce models that cannot preserve the empirical phenomena, they are, by definition, inadequate (see van Fraasen, 1980). These assumptions should be consistent with the understanding of heat transfer and thermally induced mechanical, hydrologic, and chemical responses as expressed in predictive models. The proposed methodology as presented in Figure 2 utilizes current knowledge of thermally induced responses. Further, the iterative process shown allows for analyses as a one-way coupling process with a feedback loop (Tsang, 1987).

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 the performance measures that enable such evaluations. For the heat transfer model this 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 also 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 supported by appropriate tests of sufficient number and duration, which allow for reliable estimates of spatial representativeness, as well as range and distribution of the data. In addition, every aspect of obtaining the necessary input data as well as analyzing the data (data reduction) must be conducted in strict accordance with quality assurance (QA) procedures. Adherence to quality assurance plans and procedures contributes to the assurance of data adequacy (Subpart G - 10 CFR 60.150).

Determination of the heat transfer and thermally induced mechanical, hydrological, and chemical behavior in the host rock and surrounding strata must give consideration to the effects of uncertainties associated with the values of the predictive model input parameters. To properly evaluate the underground facility design, 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 2-dimensional versus 3-dimensional analysis, refinement in the geologic stratigraphy and/or topography, orientation and frequency of rock joints, initial conditions, environmental conditions due to the range of anticipated processes and events, and to refinement in constitutive relations 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, a thorough 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 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 regarding the evaluation of the design of an underground facility. Such examination would (1) indicate whether or not significant additional accuracy in the prediction is attainable given the current parameter ranges and sensitivities, (2) indicate which parameters may be important in achieving more accurate predictions, and (3) provide useful guidance aimed at the development of an underground facility design which accommodates certain parameter ranges. The effects of assumptions could be assessed relatively, by varying the model in terms of alternatives (for example, using different constitutive relations and initial conditions), or directly by evaluating the model against physical experiments. The results of these activities create a notion of the reliability of a model, which would need to be expressed in qualitative and quantitative terms. It is expected that a statistical approach is needed to provide a systematic evaluation of the response uncertainties and their probabilities of occurrence. The position in Section 3.1.3, therefore, is based on the need to evaluate the underground facility design in a perspective which includes all the uncertainties associated with the predicted results.

Finally, all predictive models used for licensing should be verified and validated. Rigorous model verification and validation against laboratory and field experiments are expected to test the reliability of the models and are imperative if heat transfer and thermally induced effects are to be predicted with sufficient reliability to assure compliance of the underground facility design with the repository performance objectives. However, there may be different levels of model validation because factors which 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 phenomenologic 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 possibility/impossibility of physical access. NRC has provided guidance for model verification in NUREG-0856 (Silling, 1983). However, model validation and verification are complex issues with deserve more extensive discussion than can be provided in this TP.

4.1.4

The performance based design criteria which 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, thermally induced mechanical, hydrologic, and chemical response associated with a particular underground facility design must be available and compared to the design criteria. An example of such comparisons associated with heat transfer predictions can be found in NUREG/CR-5428. Meeting all of the performance based design criteria will provide confidence that the underground facility design has a higher likelihood of not adversely affecting the performance objectives.

4.1.5

Although it may be possible to show that the underground facility design meets individual performance based design criteria, the final evaluation of the underground facility design must be a test of its effect on the performance objectives of 60.111, 60.112, and 60.113. It is expected that models for the evaluation of performance objectives will be available, and will accept the predicted heat transfer, thermally induced mechanical, hydrologic, and chemical responses, including uncertainties, as input for analyses. A satisfactory evaluation by the performance assessment models, in addition to having met all the performance based design criteria, would demonstrate compliance with 10 CFR 60.133(i). An unsatisfactory evaluation by the performance assessment model would require a reassessment of the performance based design criteria, the predictive models, and/or the underground facility design. This reassessment would be required before any changes are made, which could be associated with performance based design criteria, predictive models, and/or the underground facility design. On the basis of any changes in design or evaluation approach, a reevaluation of the design is necessary against all the performance based design criteria and the performance assessment models.

4.2

The licensing process requires the DOE to demonstrate that the regulations embodied within 10 CFR 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 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 the information presented in the license application. Section 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.

In demonstrating compliance with design criteria of 10 CFR 60.133(i), it is expected that a mechanistic understanding of the fully coupled behavior will be utilized 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 sufficient information, by license application submittal, to fully understand these phenomena. Therefore, the iterative approach outlined in Section 3.3 may be a suitable interim approach to demonstrate compliance with 60.133(i). However, when following this approach, conservative data and assumptions must be used to compensate for the uncertainties, since otherwise such uncertainties may preclude the staff from finding, with reasonable assurance, that the performance objectives will be met.

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4.3

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 required, as stated in Section 3.1.4, which collectively would provide a perspective of the transient rock temperatures and associated rock stresses and deformations, groundwater flow, and chemical response such as the dissolution and precipitation of mineral species in the host rock and surrounding strata.

Until predictive models can be developed through a mechanistic understanding of the fully coupled (mechanical-thermal-hydrological-chemical) behavior, DOE should use the best available models. Analyses which cannot be performed considering partially coupled models can then utilize an iterative analytical process based on multiple one-way coupled formulation of thermally induced phenomena to predict the response of the host rock, surrounding strata, and groundwater system as suggested by step 3.1.4 above.

Based on the assumed one-way coupling processes (i.e., thermal/mechanical/hydrologic/chemical), it is necessary to perform the analyses by iterations (see Figure 2). Figure 2 shows a detailed flowchart as an example of the type of iterative process which can be used to perform the analyses described in Sections 3.1.4 and 4.1.4. This would involve an initial 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 dissolution and precipitation of mineral species in the rock (i.e., from the chemical model), and re-analysis producing a second set of predictions of heat transfer, thermally induced mechanical, hydrologic, and chemical responses. The iterative process would continue until changes in the prediction of the respective phenomena reach some acceptable level. The order in which the phenomena (thermal, mechanical, hydrological, chemical) are analyzed in Figure 2 is shown for example. DOE should determine the sequence of analysis which is most appropriate. The technical position in Section 3.3, therefore, 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 which allows an evaluation of the assumption of uncoupled processes.

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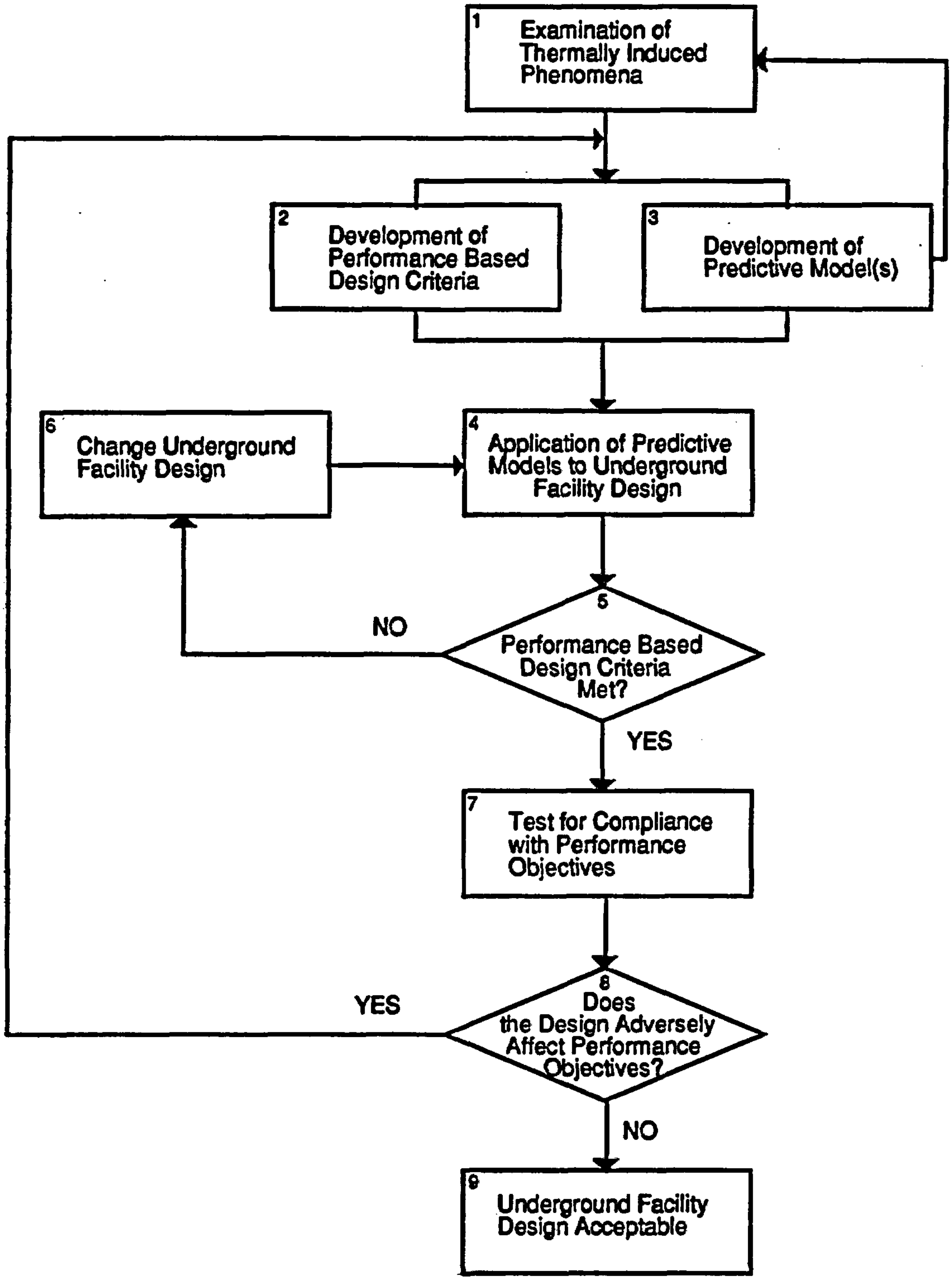

Figure 1. Steps Suitable for Demonstrating Compliance with 10 CFR 60.133(i)

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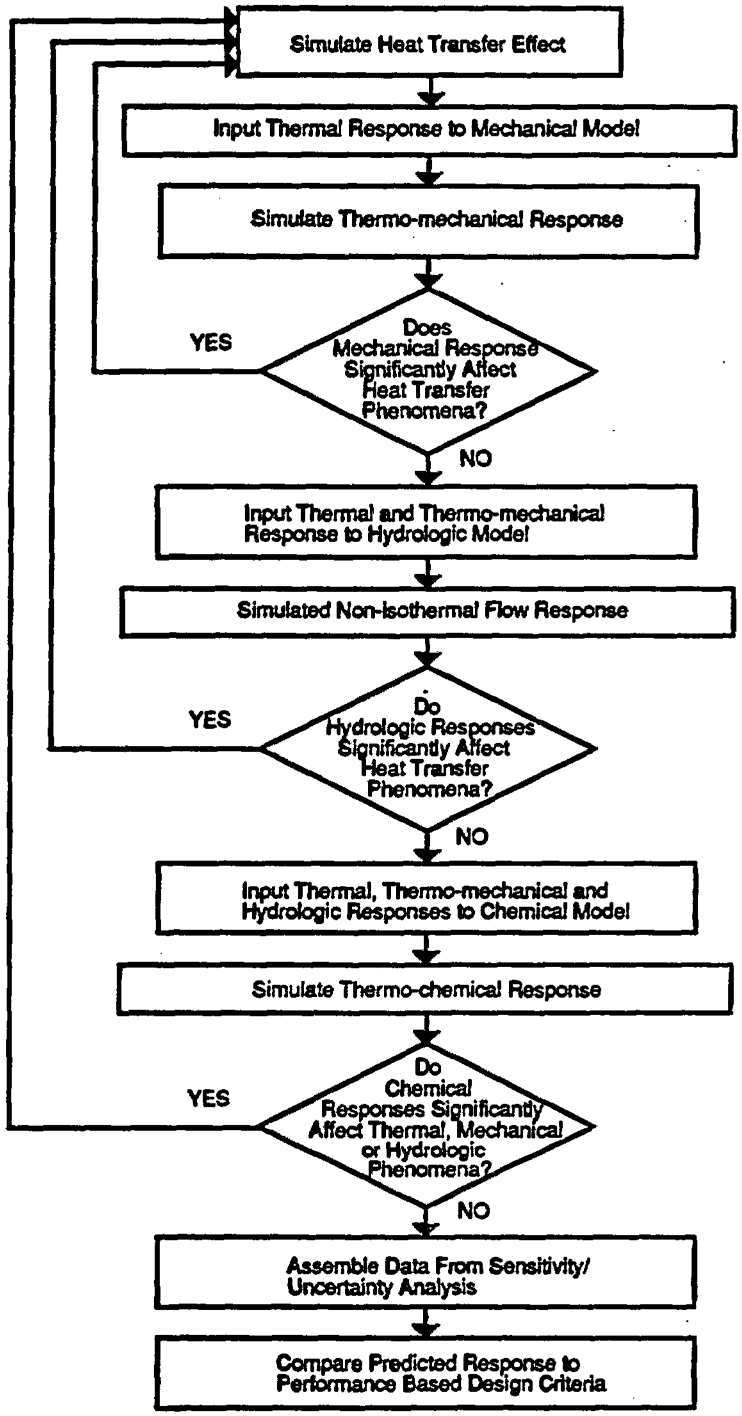

Figure 2. Iterative Process of Analyses Based on One-Way Coupling of the Thermally Induced Phenomena

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APPENDIX A

GLOSSARY

Fully Coupled Model - model which incorporates in it's formulation the interdependency of the four phenomena (thermal, hydrological, mechanical, chemical).

Geologic Repository - a system which 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 - 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 - the geologic, hydrologic, and geochemical systems of the region in which a geologic repository operations area is or may be located.

Host Rock - the geologic medium in which the waste is emplaced.

One-way coupled model - model which incorporates in it's formulation the dependency of one process on another (e.g., Determination of rock stresses is dependent on temperature but determination of temperature is not dependent on stress).

Partially coupled model - model which incorporates in its formulation the interdependency of any two or three of the phenomena (thermal, hydrological, mechanical, chemical).

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

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

Validation - assurance that a model as embodied in a computer code is a correct representation of the process or system for which it is intended.

Verification - assurance that a computer code correctly performs the operations specified in a numerical model.

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APPENDIX B

APPLICABLE 10 CFR PART 60 REGULATIONS

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 prior to 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.

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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 groundwater 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% 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 groundwater 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 groundwater; 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 practical, 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, 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.

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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 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. (1) 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 surrounding strata, groundwater system.