# An approach for thermal load considerations in a repository design methodology

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## 1 INTRODUCTION

The development of a mined geologic disposal system for high-level nuclear waste will have many similarities to the design, construction, and operation of underground mines for the extraction of natural resources, and large geotechnical civil engineering projects. Therefore, it is expected that much of the technology and experience gained from these projects can be used in developing a nuclear waste repository. There are, however, unique features of the repository development that are unprecedented in any mining or civil engineering experience, and must be given special considerations in a repository design. One such very important unique feature that must be reflected in the repository design is the consideration of "Thermal Load" (also called Areal Power Density) associated with the nuclear waste. Because of rock and groundwater responses associated with the transfer of induced heat over time, the effects of a thermal load may have important implications regarding the certainty with which we can assure the ability of a repository to provide safe storage of nuclear waste for the thousands of years required by law.

The distribution of the thermal load resulting from a particular waste emplacement scheme can affect the isolation capability of the host rock, as well as the ability of the waste packages to contain the waste. It is not necessarily evident, however, whether a high or low thermal load will be beneficial or detrimental to the containment and isolation characteristics of the disposal system. Regardless, the working hypotheses that must be established a priori about the mined geologic disposal system, and which can only be tested for a very short time in comparison to the repository life, must be sufficiently robust to contribute to reasonable assurance that the disposal system will perform as intended. The working hypothesis used in this paper includes: mechanistic understanding of coupled thermal-mechanical-hydrological-chemical (TMHC) processes, progressive development and utilization of fully coupled TMHC models for geologic repository operations area underground facility design, and use of conservative data and assumptions to compensate for the uncertainties associated with a lack of complete understanding of the thermally-induced coupled processes and their potential impacts on the complex repository system. Applying the experience which has been shown to work in mining and civil engineering projects, to the development of methodologies for repository development, contributes to the robustness of such a working hypothesis for the repository. Adapting established methodologies to developing new technology and experience needed for the repository development also contributes to the robustness of a working hypothesis. The logic behind the design methodology discussed in this paper is based on these principles.

## 2 RESPONSIBLE AGENCIES

The United States Department of Energy (DOE) has been given the responsibility by the U.S. Congress to site, design, construct, and operate this nation's first high-level nuclear waste repository. The United States Nuclear Regulatory Commission (NRC) has been assigned the responsibility for regulating the disposal of commercial spent nuclear fuel and high-level nuclear waste. To assure the radiological health and safety of the public, and to aid in the license application review process, NRC has issued regulations (U.S. Code of Federal Regulations, 1991a) which DOE must comply with in conducting its repository program. The regulations, which have the force of law, express requirements related to the siting process, design, and performance of a repository. In its license application, DOE must demonstrate compliance with these regulations. To further guide DOE's work, NRC prepares Staff Technical Positions (STPs) which convey NRC staff's views on specific technical matters related to the repository program.

A recent STP has been issued by NRC (NRC, 1991) which expresses staff views on the repository design process in the context of thermal loads, a subject of considerable uncertainty, complexity, and debate. The STP focuses on the requirement expressed in regulation 10 CFR 60.133(i) (U.S. Code of Federal Regulations, 1991a) which deals with the specific matter of repository design, taking into account effects associated with the thermal load induced by the emplaced nuclear waste. The purpose of the STP is to facilitate guidance to DOE regarding an acceptable methodology for demonstrating compliance specifically with regulation 10 CFR 60.133(i).

## 3 UNDERGROUND REPOSITORY DESIGN -- SIMILARITIES TO HARD-ROCK MINING

The conceptual design of the repository proposed by DOE (MacDougall et al., 1987) resembles a room-and-pillar mine in a shallow dipping orebody, with an extraction ratio across the repository horizon of probably less than 20 percent. It is reasonable to expect that if conventional practices for underground design and construction in hard-rock mining are applied to the repository, along with additional care to minimize adverse impacts on isolation characteristics of the host rock, stable underground excavations can be achieved. With respect to geomechanical considerations, the conditions described for the repository domain before the emplacement of waste are not significantly different relative to underground hard-rock mining experience, except for additional precautions required for minimizing disturbance due to excavations.

Because the development of a mined geologic disposal system will have many similarities to the design, construction, and operation of an underground mine for extraction of natural resources, it seems reasonable that an underground design methodology such as that illustrated in Figure 1 for hydromechanical conditions could be applied. As indicated by the methodology in this figure, the key to a successful design is first and foremost related to establishing an understanding of the in situ conditions through site characterization. The application of this design methodology for a geologic repository includes an understanding of the geologic structure, lithology, hydrology and geochemistry. Secondly, the site characterization data need to be used in the development of conceptual models which could be analyzed by appropriate analytical tools such as the limit equilibrium methods, or the use of more sophisticated methods such as the boundary element, finite element, or finite difference numerical models. Such tools are used routinely in mining and civil engineering design projects. The analytical tools could provide estimates of rock responses related to thermally induced, mechanical, hydrological, and geochemical phenomena. Collectively, these estimates would contribute to inferences of repository performance.

## 4 UNDERGROUND REPOSITORY DESIGN -- UNIQUE FEATURES

While it is expected that much of the technology and experience gained from underground mining can be used in the design, construction, and operation of an underground nuclear waste repository, unique features of a repository will require special design considerations. Such considerations must be reflected in the analysis and design methodologies of the underground facility. One important feature, which this paper is concerned with, is related to the effects of the increase in rock temperatures above ambient conditions with time. Elevated rock temperatures are caused by the presence of the nuclear waste, which continues to generate heat, although at decreasing rates, thousands of years after its initial emplacement in the repository. The significance of its impact on repository design must be determined for an unprecedented 10,000 years, the period of regulatory interest set forth in 40 CFR Part 191 (U.S. Code of Federal Regulations, 1991b) by the United States Environmental Protection Agency (EPA). While elevated rock temperatures are not uncommon, especially in many deep underground mines, they represent the ambient rock conditions, and therefore, do not serve well as analogs to repository rock conditions. The technology and experience with ventilation systems and the effects of ventilation in hot mines, however, would be useful in the repository development and operations.

Besides the thermal aspect of the repository design, a second unique feature of the repository is the presence of highly radioactive materials. While the radioactivity in itself is not expected to affect the response of the rock (Durham et al., 1986), the design of the repository must accommodate a safe handling of the radioactive waste during its transportation and final emplacement within the repository. However, this aspect of the design is not part of the discussion in this paper.

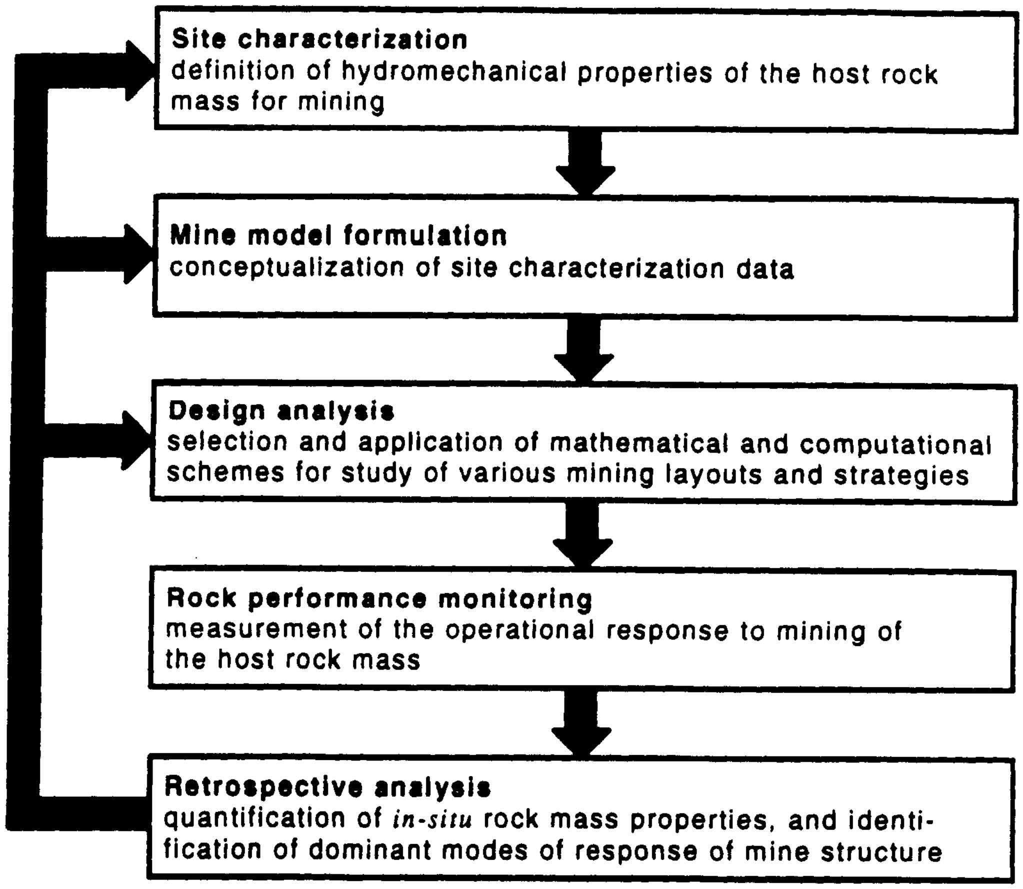


Figure 1. Components and Logic of a Rock Mechanics Design Program (After Brady and Brown, 1985)

Aside from the thermal and radiational aspects of a repository, the development and design of the repository is a highly sensitive social issue to a far greater extent than the development and design of any underground mining or civil engineering project. The coordination of legislative, judicial, scientific, and engineering disciplines in the quest to develop this nation's first repository by participating U.S. federal, state, and local agencies, is unprecedented in any engineering project. The repository design methodology should be sensitive to such social and legal considerations.

## 5 REPOSITORY THERMAL LOAD DESIGN FEATURES

The ultimate objective of the high-level nuclear waste repository is to provide isolation of the radioactive waste from the accessible environment. This objective is to be achieved by providing suitable engineered barriers to contain the waste for a specified period, and then to allow for a gradual release of radionuclides into the natural barriers at or below a specific rate. The geologic setting is to be selected in such a manner as to limit the transport of radionuclides into the accessible environment to be within the amounts specified by the EPA standards (U.S. Code of Federal Regulations, 1991a). The thermal load resulting from the emplacement of the high-level nuclear waste will impact the ability of the engineered barriers to contain the waste and the rate at which barriers will release the radionuclides into the natural barriers. The thermal load will also impact the transport of radionuclides into the accessible environment over the long duration of repository performance.

On the basis of observations of effects of induced heat on rock material it is reasonable to expect that the repository, if not properly designed for thermal load, could compromise the waste isolation capacity of the geologic disposal system (Lappin et al., 1985) and the containment characteristics of the waste packages. Certain rock materials are known to spall when subjected to heat (Gray, 1965). Thermal expansion of the rock with time will alter the state of stress in the rock hosting and surrounding the repository, and possibly will change the hydraulic properties of the rock. Changes in the geochemistry at elevated temperatures over time, such as alteration of minerals, could affect rock strength, and thus, compromise the structural integrity of the host rock. Therefore, there are several phenomena which may be induced by the thermal load, and could potentially affect the performance of the disposal system.

In general, concentrating the inventory of waste into a small repository area induces higher rock temperatures than dispersing the waste over a larger area. There are several design components of the repository that affect the concentration/or spatial distribution of the waste, and would directly affect the level of thermal load. Emplacement of individual waste containers vertically in the floor, horizontally in the walls, or simply letting them rest on the floor of a disposal room are different waste emplacement options. The repository design could accommodate different lay-outs of individual containers within a room (e.g., spacing between containers), and lay-outs of different rooms. A repository could also be designed as multi-level, a scheme that has been considered in the Canadian nuclear waste program. These are design options which would affect the level of the repository thermal load, and thus, influence the performance of the disposal system. Design options would depend on the amount of waste per individual container.

The design would also need to accommodate the fact that wastes of different types (e.g., high level waste, and spent nuclear fuel from boiling or pressurized water reactors, and fuels of different ages and burn-ups) would need to be stored. The characteristic thermal output of each waste form is different, and therefore should be appropriately factored into the repository design.

## 6 THERMAL LOAD - REPOSITORY DESIGN METHODOLOGY

A well conceived design methodology is a useful design management tool, because it guides the progression of a design in a logical manner, and allows decisions to be made along the way regarding the acceptability of the design. The more complex a project or process is, the more its design and development will benefit from a well conceived methodology.

In the repository license application, DOE must show compliance with the requirement expressed in 10 CFR 60.133(i). This requirement states that "The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical responses of the host rock, and surrounding strata, [and] groundwater system." Thus, it would be necessary for DOE to show that the repository design, when accounting for thermally induced effects in the host rock, surrounding strata, and the groundwater system, will meet the repository performance objectives stated in 10 CFR Part 60.

To assess the acceptability of the repository design in accordance with 10 CFR 60.133(i), NRC has outlined a methodology which focuses on the design of the repository for the potential effects associated with a thermal load (NRC, 1991). Central to the methodology is the development and use of analytical tools such as numerical models to predict thermally induced responses in the host rock, surrounding strata, and groundwater systems. In the hands of experienced scientists and engineers, models are tools which can contribute significantly to our understanding of the response of the disposal system, and thus our ability to design the repository to perform as intended. In a discussion of methodology for rock mechanics modeling, Starfield and Cundall, 1988, present case studies of numerical model applications associated with rock-fluid interaction, creeping sediments, and slope stability in sedimentary rocks. These case studies reflect similar approaches to modeling, and illustrate the usefulness of applying models to bring about understanding of observed physical behavior, even in data-limited cases.

Along with the use of natural analog data (e.g., from geothermal regions), and data from site characterization and performance confirmation testing, development and application of numerical models are expected to contribute to the understanding of the long term performance of the repository.

The uniqueness of a repository in the context of engineering design would suggest that its design methodology should reflect the regulatory framework which guides the design. In the context of thermal load, applicable regulatory requirements are expressed in 10 CFR 60.133(i), and in 10 CFR 60.111, 60.112, and 60.113 - the repository performance objectives. These requirements are worked into a logical sequence of steps in Figure 2 which form an approach for demonstrating compliance with the pertinent regulations. However, the sequence of steps also represents a logical methodology for repository design which takes into account the thermal load.

In this methodology, an evaluation is first made (in Step 1 of Figure 2) to determine if the performance objectives (i.e., 10 CFR 60.111, 60.112, and 60.113) are insensitive to thermal loading. The evaluation would be based on current scientific understanding and/or engineering experience with the expected thermal, mechanical, hydrological, and chemical phenomena involved (T-M-H-C), and the current understanding of the site specific conditions. In the event of a positive evaluation, the underground facility design would be considered independent of the thermal load.

If the evaluation turns out to be negative, it is next determined (in Step 2 of Figure 2) if reliable predictive models exist to quantify the sensitivity of the design to thermal loading. If such models exist, they should be used in the design process, and the development of new models would not be required (i.e., Steps 3 and 5 in Figure 2 would be bypassed).

If reliable models do not exist, an examination of the thermally induced phenomena in the host rock, surrounding strata, and groundwater system would be necessary (Step 3 in Figure 2), in order to develop new predictive models (Step 5 in Figure 2) that could be used in the design of the underground facility. This examination would be part of the site characterization process.

The development of repository design goals/criteria is a necessary step in the methodology (Step 4 of Figure 2). It would be important to base these goals/criteria on the repository performance objectives, as this will contribute to the assurance that the design will comply with the performance objectives 10 CFR 60.111, 60.112, and 60.113, and thus, with 10 CFR 60.133(i). Initial goals/criteria could be defined in the context of the current scientific and engineering experience with the physical phenomena involved for the specific repository site. With the expansion of scientific and engineering experience during the site characterization process, and the period of performance confirmation testing, it is reasonable to expect the response limits expressed by initial design goals/criteria could change.

Development of predictive models (Step 5 in Figure 2) is important from the stand point of providing tools to conduct reliable analyses of the response of the disposal system to specific underground facility designs. Because the development of such predictive models would utilize the conceptual models developed from the scientific and engineering experience gained from site characterization, several iterations may be necessary in the development process (indicated by the "loop-back" from Step 5 to Step 3 in Figure 2) before a satisfactory model, or set of models could be obtained.

The application of predictive models to site specific conditions (Step 6 in Figure 2) would provide estimates of the effect of the repository design on the performance of the disposal system. These estimates could be related to specific thermally induced rock deformations, groundwater flow, or chemical reactions, for

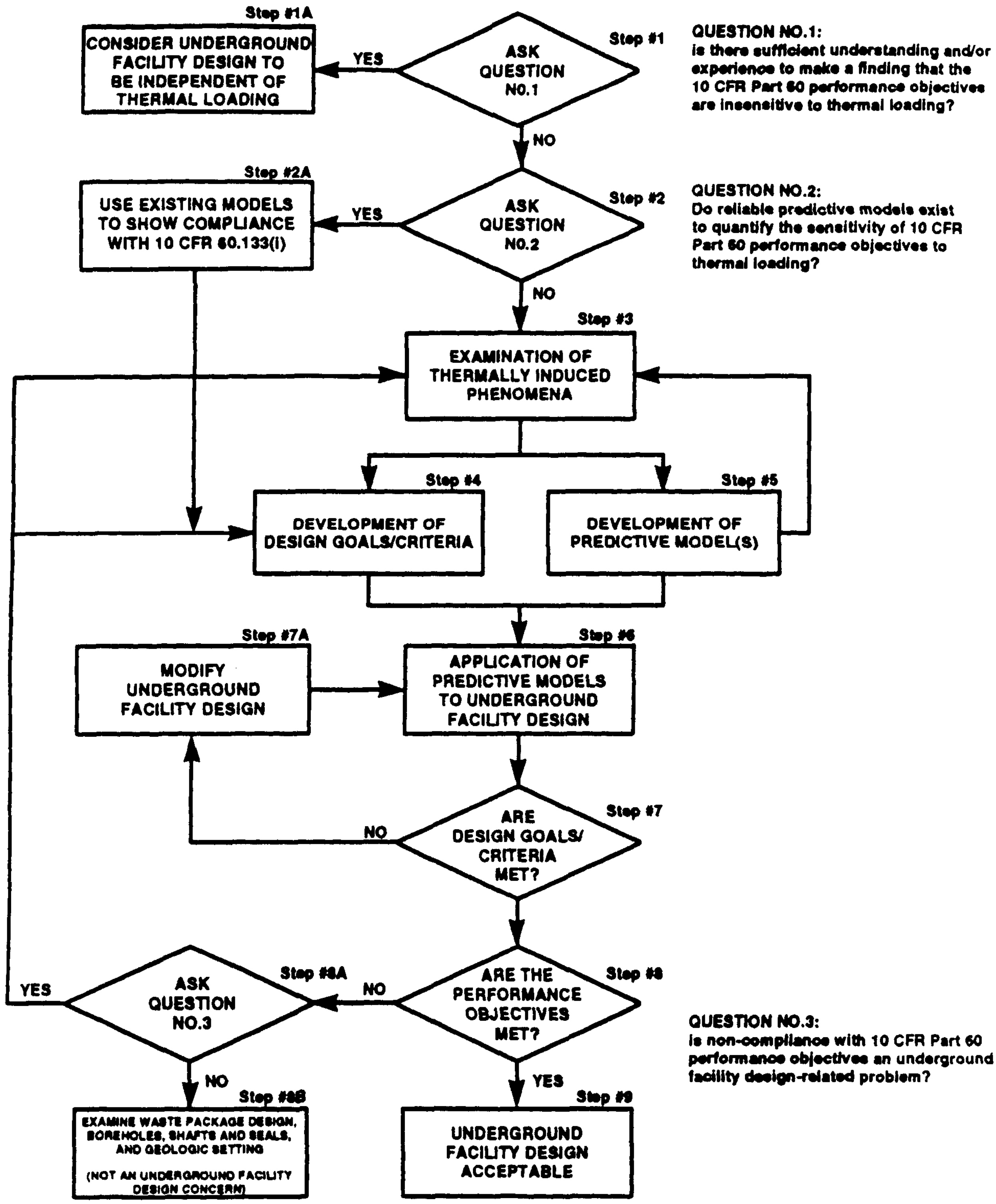


**Figure 2. The Logic Flow for an Example of an Acceptable Methodology for Demonstrating Compliance with 10 CFR 60.133(i).**

which design goals/criteria would exist.

The estimated responses would be compared (Step 7 in Figure 2) to the response limits expressed by the repository design goals/criteria. This comparison would provide the initial measure of design acceptability. Design modifications could result, depending on the outcome of the comparison. Many iterations are envisioned in this process as shown in Figure 2 by the "loop-back" from Step 7 to Step 6.

Because the repository design must not adversely affect the performance of the disposal system, the effects of the design on performance must be tested (Step 8 in Figure 2) against each of the objectives expressed in 10 CFR 60.111, 60.112, and 60.113. This test would involve the use of a performance assessment model(s) which could incorporate and process the model-predicted responses, along with information from site characterization, performance confirmation testing, and natural analog data.

Only after a positive evaluation by the performance assessment model(s) would the repository design be considered acceptable in the methodology depicted in Figure 2. It is conceivable that the test would result in an evaluation of the disposal system indicating an unacceptable performance. However, because the performance assessment model(s) would incorporate all the components of the disposal system (i.e., engineered and natural barriers) the source of such non-compliance would need to be established. If the source of the non-compliance was not an underground facility design-related problem, such problem would need to be resolved before an evaluation of the acceptability of the repository design could be made. In the event the non-compliance was associated with the repository design, a reevaluation of the premise of the design would need to be conducted, as indicated by the "loop-back" from Step 8 to Step 3 and/or Step 4 in Figure 2.

## 7 CONCLUDING REMARKS

The complexity of developing a geologic nuclear waste repository resulting from unique features such as the thermal loads and the period of performance, is unprecedented in any mining or civil engineering experience. Although many similarities exist between the development of a repository and many past and current mining and civil engineering projects, unique and important features of the repository exist which require special design considerations. Perhaps the most important feature includes the problem of designing the repository in the context of the thermal load associated with the stored nuclear waste. Although the thermal load will decrease with time, its presence in the repository and effect on the disposal system will remain for thousands of years. Thus, the repository would need to be designed without extended testing and measurement of the long term effects of the design on the capacity of the disposal system to contain the waste and provide safe isolation.

A methodology has been presented which specifically deals with the repository design and the thermal load within the framework of applicable regulations. While this methodology, in and of itself, does not guarantee that an acceptable design can be achieved, it provides the means to evaluate the acceptability of the design. An important component of the methodology is the development and application of numerical models to predict expected thermally induced mechanical, hydrological, and chemical responses in the rock.

The methodology acknowledges the evolutionary process of repository development, and provides flexibility to change the repository design as additional site and performance information are obtained. This methodology emphasizes the use of conservative data and assumptions to compensate for the uncertainties associated with a lack of complete understanding of the thermally induced coupled processes and their potential impacts on the complex repository system.

Clearly, other design methodologies may be assembled which could lead to an acceptable repository design. The current methodology, however, was developed specifically by NRC as a means for evaluating the design in the context of the regulatory framework.

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