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CONSIDERATIONS FOR DEVELOPING SEISMIC DESIGN CRITERIA FOR NUCLEAR WASTE STORAGE REPOSITORIES

April 1980

prepared for
United States Department of Energy
Nevada Operations Office
Under Contract DE-AC08-76DP00099

prepared by
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ABSTRACT

As part of a program being conducted by the U.S. Department of Energy, Nevada Operations Office, to assess the feasibility of establishing a nuclear waste storage repository at the Nevada Test Site, URS/John A. Blume & Associates, Engineers, is conducting a study of seismic design criteria. This report summarizes the considerations for developing these criteria as of September 1979. Its purpose is to determine what research is necessary to develop acceptable seismic design criteria for nuclear waste repositories.

The function of seismic design criteria is to reduce the potential for hazards that may arise during various stages of the repository life. During the operational phase, the major concern is with the possible effects of earthquakes on surface facilities, underground facilities, and equipment. The consequences of possible earthquake damage could create a hazard to operating personnel; however, it is not clear that any of the hypothesized damage would lead to a hazard to the public health. Qualitative assessments of the effects of earthquakes on underground structures can be made from reports of past performance and from current empirical procedures. However, quantitative assessments are preferable. Unfortunately, quantitative assessments are not possible for underground structures with the current technology. During the decommissioned phase, the major concern is with the potential effects of earthquakes on the geologic formation, which may result in a reduction in isolation capacity.

Existing standards and guides -- or criteria -- used for the static and seismic design of licensed nuclear facilities were reviewed and evaluated for their applicability to repository design. Some of these standards and guides are applicable to the design of the surface structures of repositories because these structures are similar to the surface structures of licensed nuclear facilities. Underground structures, however, have never been licensed, and there are no existing standards and guides on which to base a design. Thus, the report is directed mainly toward the development of seismic design criteria for the underground structures of repositories.

An initial step in the development of seismic design criteria for the underground structures of repositories is the development of performance criteria -- the minimum standards of acceptable behavior. These criteria would be based on the possible damage modes to which the structures are susceptible under seismic motion. A number of possible damage modes are identified for the operating phase of the repository; however, no damage modes are foreseen that would perturb the long-term function of the repository, except for the possibility of increased permeability within the rock mass. Currently there are no definitive performance criteria for the underground structures of repositories.

Subsequent steps in formulating acceptable seismic design criteria for the underground structures involve the quantification of the design process. At present, underground structures are designed most often using empirical methods. For purposes of licensing, however, the structures will likely be designed on the basis of stresses determined by analysis.

The report discusses the necessity of specifying the form of ground motion that would be needed for seismic analysis and the procedures that may be used for making ground motion predictions. Further discussions outline what is needed for analysis, including rock properties, failure criteria, modeling techniques, seismic hardening criteria for the host rock mass, and probabilistic considerations. The report concludes with recommendations for additional work needed to develop appropriate seismic design criteria for repositories.

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ACKNOWLEDGMENTS

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SUMMARY

The U.S. Department of Energy, Nevada Operations Office, is currently directing a program to determine whether a nuclear waste storage repository can be established at the Nevada Test Site. A part of this effort requires the development of appropriate seismic design criteria. These criteria, which are intended to be generic in nature and applicable to any site, will provide standards and guides for an engineering design that will mitigate the effects of earthquake shaking and underground nuclear explosions.

This report summarizes the considerations for developing seismic design criteria for repositories as of September 1979. Its purpose is to determine what research is necessary to develop acceptable seismic design criteria.

Repository Design Concept

A conceptual design was assumed for a prototype waste repository that would be adaptable to a variety of sites with different geologic conditions. The facility consists of a large number of excavated storage rooms and interconnecting tunnels located two or more thousand feet below the ground surface. Receiving and handling facilities for canisters that contain waste or spent fuel are located on the surface. Vertical shafts connect the surface-receiving facilities to the underground facility, where the waste canisters are delivered to a transporter vehicle that moves the canisters to their final storage location. There, the canisters are emplaced into holes in the floor or walls of the underground storage rooms. The holes are then backfilled and plugged for radiation shielding.

Typical Support Systems for Underground Excavations

It was assumed that two types of rock support systems may be used in a repository: (1) rock bolt system and (2) steel set system. A rock bolt system is preferred on the basis of cost and design considerations. A steel set system is useful in poorer rocks that require heavy support. From the point of view of engineering design and cost, it is preferable to excavate a repository in ground that requires minimal reinforcement and support. Current underground support system philosophy is to use support systems that make maximum use of the inherent strength of the rock mass itself.

Existing Design Criteria: Seismic Standards and Guides

Existing seismic standards and guides used for the design of licensed nuclear facilities were reviewed to determine if they could be used for the design of repositories. A number of these guides are possibly applicable to the seismic design of the surface structures and equipment of a repository, although some may have to be modified and rewritten. None of the standards and guides used for the design of licensed nuclear facilities are applicable to the underground structures of a repository, however.

Because static and seismic design criteria do not exist for the underground structures of a repository, it was necessary to examine the standard practices followed in the design of other types of underground structures. Standard practices followed in the static design of various underground structures are available and provide a starting point for developing specific static design criteria for the underground structures of a repository. However, very little attention has been given in the past to the seismic design of rock excavations, and thus standard practices do not provide a starting point for developing specific seismic design criteria. Consequently, additional research is needed to prepare the necessary seismic design criteria for the underground structures of a repository.

Seismic Damage Modes and Performance Criteria

An initial step in the development of seismic design criteria for the underground structures of a repository is the development of performance criteria -- the minimum standards of acceptable behavior. These criteria would be based on the possible damage modes to which the structures are susceptible under seismic motion. A review of the earthquake literature on the behavior of tunnels indicates that tunnels are safer than surface structures during strong seismic motion; however, some cases of severe damage, including collapse, have been reported.

A list was made of some possible damage modes and their possible consequences. One of the most important possible consequences due to a seismic event is increased permeability of the rock surrounding the repository. Changes in permeability may be hazardous to repository personnel if these changes lead to flooding of the tunnels. If they occur after the repository is decommissioned (underground shafts and tunnels backfilled and sealed), these changes might compromise the geologic isolation of nuclear waste by accelerating the transport of radioactive material to the biosphere. Additional research is needed to determine whether or not seismic motion might alter the permeability of the rock mass for various candidate host rocks. Furthermore, a determination is needed concerning whether such seismically induced changes will have long-term negative effects on the geological barriers or will simply be short-term perturbations. If long-term negative effects are predicted, they cannot be mitigated through design; they can only be avoided through proper siting. Apart from the possibility of increased permeability, there are no other foreseeable damage modes that would perturb the long-term function of the repository.

Other possible damage modes include rock falls, spalling, rock fracturing, and equipment damage. The consequences of these possible damage modes may create hazards to personnel while the repository is operational (while waste is being placed in the repository).

Because of the preliminary nature of this study of seismic design criteria, the list of damage modes may not be complete. Further research may reveal additional damage modes that need to be mitigated with appropriate design.

Ground Motion Criteria for Underground Structures

Subsequent steps in formulating acceptable seismic design criteria for the underground structures involve the quantification of the design process. At present, underground structures are designed using empirical methods. For purposes of licensing, however, the structures will likely be designed on the basis of stresses determined by analysis.

There are three commonly used methods for specifying ground motion for seismic analysis: the peak ground motion parameters, the response spectrum, and the time history. Neither peak ground motion parameters nor response spectra are appropriate for determining stresses within a rock mass. Although simplified methods using peak ground motion parameters may be used to estimate the seismic stresses within a rock mass, they do not address the matter of secondary wave reflection and refraction effects at a cavity. The most complete, or ideal, ground motion specification for use in the analysis of underground structures would be a three-component time history that includes the superposition of various types of seismic waves.

To characterize the ground motion for an underground repository by a three-component time history, it is necessary first to develop a three-component time history at the ground surface. It is not possible to determine a subsurface time history directly from a surface response spectrum. A reasonably reliable prediction of a surface time history can be achieved by defining a control response spectrum for the ground surface at the location of interest. The ground motion at a point below the ground surface can be obtained from the surface time history using analysis with appropriate assumptions about the nature of the seismic waves and the material properties of the rock mass. This assumes the existence of an appropriate analytic technique that can account for spatial variations and the presence of a cavity. Current analytic techniques address only ideal conditions free from nonhomogeneities and discontinuities. More developmental work is needed in this area.

Ultimately, to verify the analytical results, regardless of the type of specification, it would be advantageous to obtain additional instrumental data at the surface and at depth from strong-motion earthquakes.

Rock Property and Failure Criteria

Dynamic elastic moduli, Poisson's ratios, rock densities, and damping values are rock properties needed for seismic analysis. These properties would have to be determined experimentally for the candidate rock masses. The accuracy and limitations of the results of the tests used should be determined, and acceptable procedures for obtaining the dynamic rock properties for use in seismic analysis should be defined.

Failure* criteria quantitatively define stress states that are damaging to the rock mass (around an opening). Damage to the rock mass is assumed to

*The word *failure* as it is used here refers only to an engineering definition of damage; it does not refer to failure of the primary function of the repository to contain the nuclear waste.

occur when the sum of computed static and seismic stresses exceeds the failure criteria. Because a rock mass is composed of intact rock separated by discontinuities such as joints, criteria are needed to define damaging states of stress in intact rock and rock discontinuities. Two-dimensional criteria are available, but three-dimensional criteria may be needed for more refined stress analysis.

Seismic Analysis Criteria for Underground Structures

Seismic and static analyses are the key to a quantitative design process. In the general engineering practice, stresses due to static loads and stresses due to seismic loads are computed separately. These stresses are then combined for comparison with the failure criteria, which may be in the form of maximum allowable stresses, ultimate strength, or failure envelopes. Finally, design decisions are made on the results of the comparisons.

Although several methods are available for the static analysis of underground structures, few methods are available for seismic analysis. To lend confidence to design decisions based upon geological engineering experience, a more rigorous seismic analysis is needed for evaluating the underground structures of a nuclear waste repository. Ideally, the seismic analysis of stresses around an underground opening should be computed using a three-component time history and accounting for dilational, shear, and surface waves.

A rigorous method of analyzing three-component motion anywhere in a horizontally layered medium might be formulated from the motion at a point on the free surface by employing the Haskell-Thomson method, steady-state methods, and Fourier synthesis. Eventually it would be desirable to include nonhorizontal rock discontinuities. As idealized models are developed, verification studies will be required to evaluate the differences between the idealized model and the real geologic situation.

Simple procedures based on the one-dimensional wave equation have been used to calculate dynamic stresses underground. These simple procedures often utilize only peak motion parameters, ignoring other motion parameters that may be important. Furthermore, these procedures do not account for the presence of the cavity or for all possible types of wave motion. However, the attractiveness of these procedures lies in their simplicity for engineering analysis and design. The applicability and limitations of the simple analytic procedures need to be evaluated.

Seismic Hardening Criteria for Underground Structures

The need for seismic hardening of underground structures is determined by comparing the combined static and seismic stresses, as well as other system perturbations such as temperature, with the failure criteria and evaluating the results. The support system for the underground opening will have to be modified if the evaluation indicates a need for additional protection. At this time, procedures for hardening are understood qualitatively; however, to achieve a licensable repository design, quantitative measures for scaling the level of hardening from the stress level (or some other appropriate indicator) will probably be required.

Incremental increases in the hardening are needed to correspond to incremental increases in stress level (of the peak acceleration level or some other indicator) in order to satisfy the failure criteria. For example, a quantified hardening procedure should indicate the point on a scale of increasing stress level that rock bolts are required around the full circumferential area of the opening rather than from springline to springline. The development of such a procedure may depend more on the principles of geological engineering than on the principles of mechanics.

Risk Assessment

Engineering design implies choice from among alternatives. To choose the most desirable design from among the available alternatives, it is useful to evaluate and compare the total risk from each different design. Seismic activity is one of many disturbances that must be considered in the total risk assessment for a design, and may by itself be an important contributor to total risk.

Because geologic explorations do not provide a complete description of the geology and rock mass properties, the design parameters can be taken as random variables. With the appropriate distribution functions, design can be approached from a probabilistic point of view that can take local unpredictable variations into account. An important advantage of this probabilistic approach is that the design could conceivably be licensed for a range of variable ground and support conditions.

The occurrence of an earthquake simultaneously with the transport of waste through the repository could create a hazardous condition. Fault trees could be utilized to predict the probability of failure, and mitigating procedures could be developed to reduce risk.

Geologic events, such as earthquakes, play a part in risk assessment of the decommissioned facility. Engineered facilities could reduce the total risk by increasing the probability of the repository's integrity during approximately the first thousand years of the decommissioned lifetime.

Proposed Seismic and Static Design Philosophy

Extensive calculations for stresses around a waste repository will probably be required in order to ensure confidence in the integrity of the natural and engineered barriers between the nuclear waste and the biosphere following a seismic event. Computational models should be employed to investigate overstressing and to determine the optimum configuration and support of openings. Unfortunately, models that accurately represent local underground conditions are not possible until the opening has been excavated. This may present a problem for licensing a nuclear waste repository because licensing usually means approval of a complete design before construction may begin. However, for an underground opening, the design for support and configuration is not completed until construction is completed. A viable approach to solving this predicament is to adopt a multistage design philosophy in which design, licensing, and construction can be flexibly interwoven.

The multistage seismic and static design philosophy for underground structures presented in this report addresses design only after the site has been selected. Assuming that the selected site will be located within a relatively stable tectonic region and away from active faults, the seismic disturbance would be ground shaking at a relatively low intensity. The basic assumption implicit in this philosophy is that each stage of design would include considerations of loads, rock properties, failure criteria, analysis, support and reinforcement details, and reevaluation of stability. Therefore, each stage of design would use improved engineering geologic data that would yield more detailed analyses and designs than the previous stage. Because the multistage design philosophy allows uncertainties about geology and rock properties to be overcome to some extent with each succeeding exploration, stress calculations in the advanced design stages should be closer to the real stresses inasmuch as they will be based upon more complete data.

Conclusions and Recommendations

The function of seismic design criteria is to reduce the potential for hazards that may arise during various stages of the repository life. During the operational phase, the major concern is with the effects of earthquakes on surface facilities, underground facilities, and equipment, which might create hazards to operating personnel and, in certain circumstances, to the public. Qualitative assessments of the effects of earthquakes on underground structures can be made from reports of past performance and from current empirical procedures. However, quantitative assessments are preferable. Unfortunately, quantitative assessments are not possible for underground structures with the current technology. During the decommissioned phase, the major concern is with the potential effects of earthquakes on the geologic formation, which may result in a reduction in isolation capacity.

Specific recommendations for developing quantitative seismic design criteria are presented at the conclusion of this report.

1. INTRODUCTION

The U.S. Department of Energy, Nevada Operations Office (DOE-NV), is currently directing a research and development program to determine whether a nuclear waste storage repository in a deep geologic medium can be established at the Nevada Test Site (NTS).[1] A part of this effort requires the development of seismic design criteria that would be acceptable for a repository at NTS. These criteria, which are intended to be generic in nature and applicable to any site, will provide standards and guides for an engineering design that will mitigate the effects of earthquake shaking and underground nuclear explosions (UNEs).

This report completes the first phase of work in presenting a structural engineering view of the envisioned needs for repository seismic design criteria. The work represents about nine man-months of engineering effort and was carried out concurrently with other efforts under *Subtask 1.3, Facility Hardening Studies*,[2] of the NTS Nuclear Waste Storage Investigations. The report was preceded by a design cost scoping studies report[2] that presented a preliminary estimate of the added costs required to harden various structures of a repository at NTS to withstand ground motion caused by earthquakes and UNEs.

Seismic Design Criteria

For this report, criteria are defined as standards and guides on which an engineering design may be based. Seismic design criteria are part of the total design criteria for an engineering project.

A repository is made up of surface structures, equipment, and underground structures. The surface structures and equipment of a repository are similar to the surface structures and equipment of licensed nuclear facilities. Therefore, some of the standards and guides -- the criteria -- used for the seismic design of licensed nuclear facilities are applicable to the seismic design of the surface structures and equipment of a repository. Underground structures, however, have never been licensed, and there are no existing standards and guides on which to base a design. Thus, this report is directed mainly toward the development of seismic design criteria for the underground structures of a repository.

In the current practice, the design of underground structures, unlike that of surface structures, is often modified during construction because variations in the properties of the rock are not completely known before excavation. This complicates the relationship between static and seismic design criteria, the design, the construction, and the licensing of the structures because one of the principal premises of licensing is that the design process would be quantified; that is, the structures would be designed on the basis of stresses determined by analysis. Thus, although underground structures are designed using empirical methods at present, analytical methods may have to be incorporated into the design process for underground structures that are to be licensed.

The relationship between the design process and the seismic design criteria for underground structures that are to be licensed is presented schematically in Figure 1. The design process is illustrated on the left side of the figure, and the five components of the seismic design criteria are illustrated on the right side. The seismic design criteria provide guidelines for establishing performance criteria, defining loads and ground motion, establishing rock property and failure criteria, analyzing structural behavior, selecting the support and reinforcement system, comparing component behavior with failure criteria, and construction (steps 3 through 9, respectively). Construction is included as part of the design process because it is assumed from current mining practice that design modifications would be carried out during construction. It is also assumed that the design will be based on stresses in the rock determined by analysis (and in-situ tests).

<u>Objectives</u>

This report summarizes the considerations for developing seismic design criteria as of September 1979. The three major objectives of the report are (1) to identify those aspects of seismic design of repositories that do not require further developmental work, (2) to identify those aspects of the seismic design criteria that require developmental work and research, and (3) to outline other tasks that should be addressed in the future to achieve economic and practicable solutions to the repository engineering design problem.

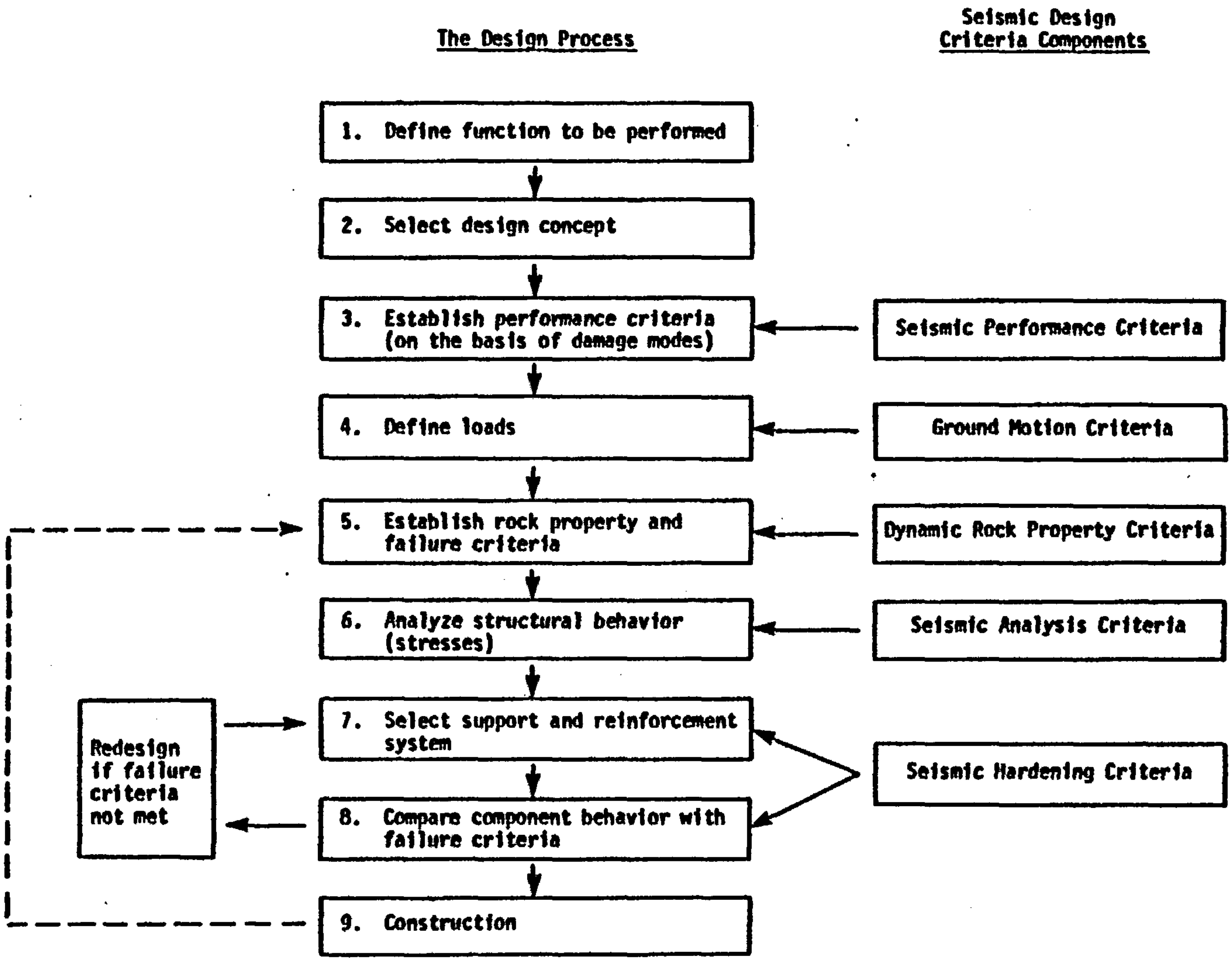


FIGURE 1 RELATIONSHIP BETWEEN THE DESIGN PROCESS AND SEISMIC DESIGN CRITERIA FOR UNDERGROUND STRUCTURES

Scope

The detailed scope of the work originally conceived for seismic design criteria studies[3] was somewhat altered as the work progressed; the emphasis of the report was redefined within the context of the evolving work. The final scope of the work includes the following:

- Identifying applicable repository configurations for adaptation to candidate sites at NTS (Chapter 2)
- Identifying support systems for underground excavations (Chapter 3)
- Reviewing existing nuclear industry standards and guides and identifying those that are applicable to repositories (Chapter 4)
- Reviewing possible seismic damage modes to repository structures (with emphasis on the underground structures) and recommending the performance criteria to which the structures would be designed (Chapter 5)
- Identifying the ground motion specification needed for seismic analysis of underground structures (Chapter 6)
- Identifying the rock* property and failure criteria needed for seismic analysis of underground structures (Chapter 7)
- Identifying the appropriate and needed analytical procedures for seismic analysis of underground structures (Chapter 8)
- Identifying the seismic hardening criteria for underground structures (Chapter 9)
- Defining risk assessment for repositories (Chapter 10)
- Proposing a seismic and static design philosophy for underground structures (Chapter 11)
- Stating the conclusions of the study of seismic design criteria (Chapter 12)
- Making recommendations for additional studies that are needed for the preparation of seismic design criteria (Chapter 13)

*The use of the word "rock" in this report is intended to include various host media, such as granite, shale, tuff, basalt, and salt.

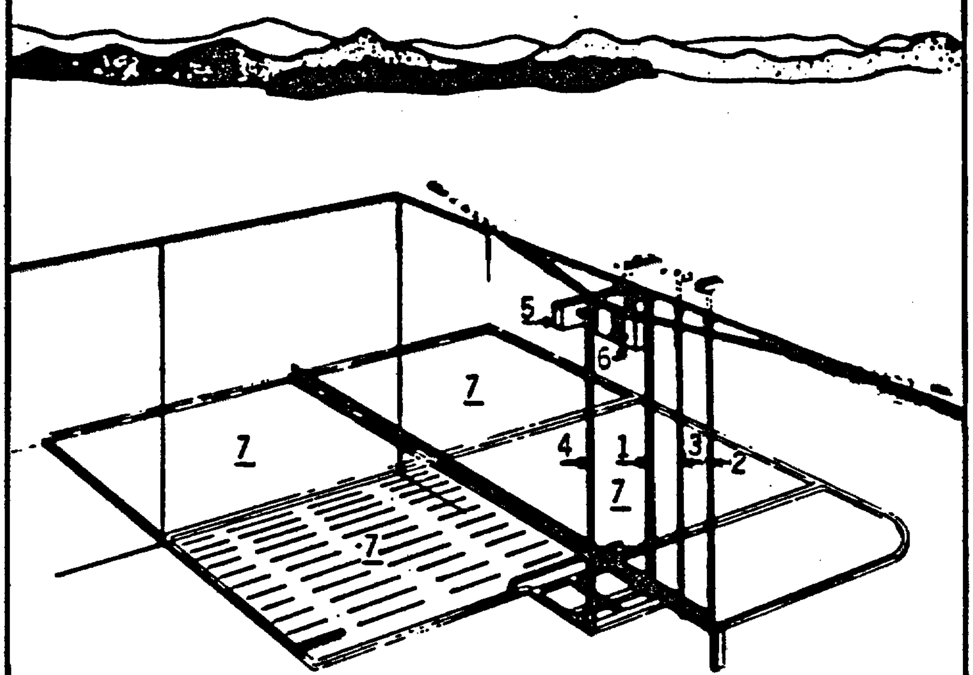
2. DESCRIPTION OF THE STRUCTURAL SYSTEM OF A REPOSITORY

A repository is designed to receive and store radioactive high-level waste (HLW) products. At the initiation of work on the seismic design criteria, the configuration and details of repository structures were not available. Thus, it was necessary to assume a configuration that would be representative of a typical repository adaptable to a variety of sites with different geologic conditions.

Several proposed repository concepts were reviewed, including bedded salt waste isolation facilities,[4,5,6,7] retrievable surface storage facilities,[8] a spent unreprocessed fuel facility,[9] and other deep geologic waste isolation facilities in salt, shale, basalt, and granite.[10,11,12,13,14] For deep repositories, References 5, 10, 11, 12, 13, and 14 present the most detailed configurations for both the surface structures and the underground structures.

Figure 2[14] shows a conceptual design of a repository. The facility consists of a large number of excavated storage rooms and interconnecting tunnels located two or more thousand feet below the ground surface. Receiving and handling facilities for canisters that contain waste or spent fuel are located on the surface. Vertical shafts connect the surface-receiving facilities to the underground facility, where the waste canisters are delivered to a transporter vehicle that moves the canisters to their final storage location. There, the canisters are emplaced into holes in the floor or walls of the underground storage rooms. The holes are then backfilled and plugged for radiation shielding. If spent fuel is delivered to the plant, it is assumed for this study that the canisters that contain it will be dealt with in the same way as reprocessed HLW.[15]

The extent of the land area required for particular repositories may vary depending on such conditions as the local geology. Surface facilities may occupy from 100 to 200 acres and are the only visible evidence of the repository.



1 Main shaft
2 Skip shaft
3 Ventilation shaft
4 Hoist shaft for waste canisters
5 Receiving and encapsulation station
6 Intermediate storage facility
7 Final repository

Source: Reference 14

FIGURE 2 CUTAWAY OF A REPOSITORY

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Surface Structures

Several surface structures are required for the operation of a repository. The structures are needed for the handling of waste, for administrative purposes, and for housing various equipment systems such as emergency power, hoists, water pumps, and filters for mine exhausts. The structures whose continual functioning or integrity is essential for the safe containment of waste material normally require seismic hardening beyond the requirements of local building codes. The remaining structures do not require such additional hardening.

It is expected that the critical structures will be reinforced concrete, shear wall structures.[2] The noncritical structures may be reinforced concrete, steel, or masonry structures.

Underground Structures

The underground structures include all the corridors (tunnels) and storage rooms at the underground level of the repository and the shafts that connect the surface structures to the underground level.

Several vertical shafts are required for the operation of a repository. The shafts are necessary for the conveyance of construction and waste materials and personnel to and from the underground level. In addition, ventilation shafts may be needed. The shafts will differ in size, design, usage, and functional constraints. The diameter of the shafts may range from 10 to 30 feet.

The underground facility (the HLW storage level) may encompass an area of several hundred acres.[10,11,12,13] The facility is made up of storage rooms (tunnels) that are interconnected by various access, transport, and ventilation tunnels. All these tunnels may be arranged in a rectilinear grid pattern; however, that pattern is not a requirement. The tunnels may have different cross sections, but it is expected that they will be approximately 20 feet across. The cross section of the tunnel will be designed to conform to the requirements and state of stress of the local geology. A small number of other rooms and staging areas are also located in the underground facility.

Equipment Systems

Several equipment systems are required for the operation of a repository. The most critical include the hoist system for the transport of HLW from the surface to the underground level, the ventilation system for the underground level, the emergency power system, the waste handling systems at the surface and at the underground level, the electrical control system, and, if required, the underground dewatering system.

Most of these equipment systems will be mounted on the floors of the structures and, because of their light weight, can be treated as appendages to the structures for the purposes of seismic analysis and design.

Classification of Structures and Equipment

Some of the repository structures and equipment house or process and control HLW. Therefore, for the purposes of licensing, it will be necessary to classify the structures, components, and systems selected in the design according to the importance of the safety function they perform and the seismic considerations.

The following is an example of a seismic safety classification system that can be adapted to repositories. These categories are not to be confused with other nuclear industry categories that cover a variety of design accidents that cannot occur in a repository. Structures, systems, and components are classified into one of three categories, according to their relative importance to safety. Categories I and II cover safety-related equipment, and Category III covers all nonsafety-related equipment. Safety-related equipment includes that required for protecting the health and safety of the public as well as equipment essential to the safety of plant personnel. It is recommended that the definitions for Category I and Category II equipment clearly separate equipment that is necessary to protect the health and safety of the public from equipment that is provided solely for the protection of onsite personnel. The definitions would read:

> Category I: Those structures, systems, and components whose failure could lead to offsite release of excessive amounts of radioactivity and those structures,

systems, and components that are essential for the safe shutdown of waste handling operations without endangering the public health and safety during or following an accident or severe natural phenomenon.

Category II: Those structures, systems, and components that are not included in Category I but that are essential for the safety of plant personnel in the event of an accident or severe natural phenomenon.

Category III: Those structures, systems, and components that are not included in Category I or Category II.

Only Category I systems should be required to retain their functional safety capability following a design earthquake. The remaining equipment, however, may have to meet the seismic requirements of the local building codes.

3. DESCRIPTION OF THE SUPPORT SYSTEMS FOR UNDERGROUND EXCAVATIONS

Very few underground structures have been built in rock that did not require some support. Several types of support systems are used to stabilize underground excavations. State-of-the-art rock reinforcement and support system design take maximum advantage of the natural strength of the host rock. This is accomplished by causing minimum disturbance to the rock mass during excavation and by using, whenever possible, systems that enhance the load-carrying ability of the rock adjacent to the opening. The two support systems that are expected to be used most frequently in the design of underground repositories are:

- Rock bolt system
- Steel set system

Either system may also be used for the shafts.

<u>Rock Bolt System</u>

A rock bolt reinforcement system (see Figure 3) would effectively stabilize a tunnel or shaft driven in a hard, jointed rock. In tunnels, rock bolt systems are used to develop the jointed, fractured rock into a load-carrying arch. The torque applied to the rock bolts when they are installed creates a zone of compression in the rock mass between the bolts.[16] The compression increases the strength of the rock in this zone, thereby forming a structural arch. In addition, the radial thrust applied to the rock by the bolts greatly increases the strength of the rock mass beyond the ends of the bolts by decreasing principal stress differences, though the thrust is small compared with the field stresses.[17] Rock bolts are frequently grouted after tensioning along part or all of their length to bond the rock to the bolt; thus, if the bolt anchorage or bearing plate fails, the tension in the bolt (the compression in the rock) is not lost. The grout also protects the bolt from corrosion by groundwater. The spacing and length of the bolts is based on the rock fracture frequency and on the span of the opening. The relationship between fracture frequency, opening span, and rock bolt spacing and length is known largely from experience.

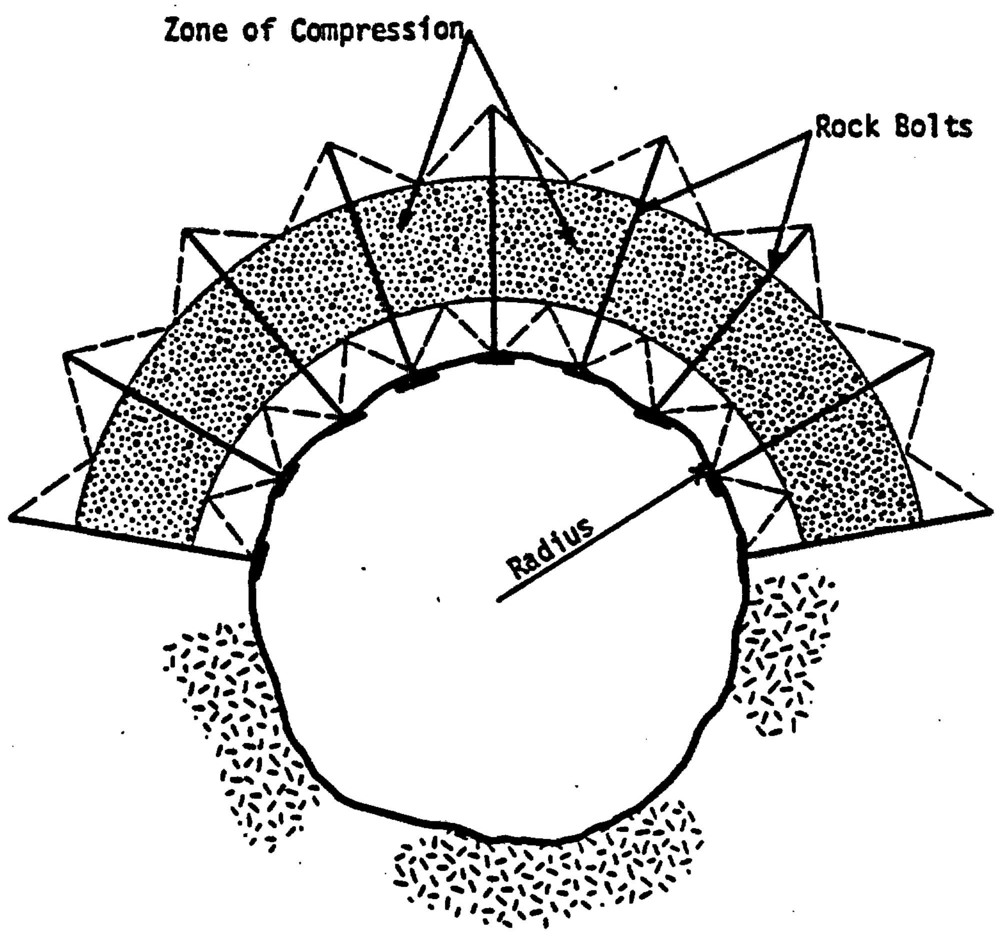

FIGURE 3 ROCK BOLT SYSTEM

Wire mesh and shotcrete, individually or in combination, are often used with the rock bolts in highly jointed rock. Wire mesh is stretched tightly on the surface of the excavation between the bolts and is kept as close to the rock face as possible. It prevents spalling and raveling of the jointed rock between the rock bolts. Shotcrete is frequently applied to the rock surface to enhance the load-carrying ability of the rock arch by locking together blocks of rock in the roof and walls of the tunnel. Shotcrete also helps retain the natural moisture content of the rock surface, thus preventing deterioration of the rock properties. Wire mesh in combination with shotcrete provides tension reinforcement at the bottom of the developed rock arch.

Steel Set System

Steel sets (see Figure 4) are used for stabilization in poor ground that is not reinforceable. For instance, steel sets in conjunction with spiling* can be used to stabilize tunnels driven in shale behaving as squeezing ground.** Lagging may be required to span the distance between the sets. In sections of heavy squeeze, occasional reblocking and relagging of the sets may be necessary. The vertical shafts in squeezing ground can also be supported with steel sets.

Steel sets provide passive support: they become loaded as the rock around the excavation deforms. Therefore, they are placed as soon as possible after the excavation and should be carefully backpacked. In the preliminary design of steel sets, the stresses in the sets can be analyzed by traditional empirical methods, but the loads acting on the sets can only be estimated. These estimates can be improved during construction from observations, from deformation and stress measurements, and by using more refined analysis as additional information becomes available.

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*Spiles are steel bars installed in bore holes drilled from the top of the tunnel face at an angle ahead of and above the advancing tunnel face. They improve the stand-up time (the time between excavation and rock fallout of the roof) by a combined beam and cantilever action.

**Clays tend to squeeze into underground openings whenever they are not supported. Therefore, some clay shales and decomposed metamorphic and igneous rock with clay characteristics are referred to as squeezing rock or squeezing ground.

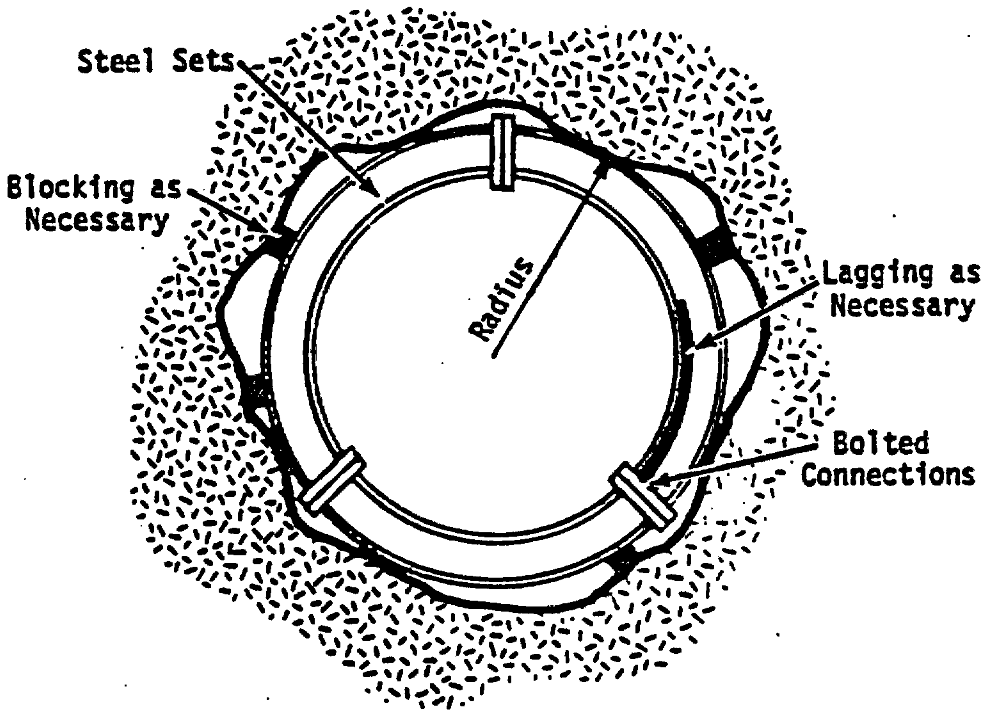

FIGURE 4 STEEL SET SYSTEM

4. EXISTING DESIGN CRITERIA: SEISMIC STANDARDS AND GUIDES

A review of the existing seismic standards and guides used for the design of nuclear facilities provides a context for discussing needed seismic design criteria for repositories.*

Numerous standards exist for the seismic design of nuclear facilities. These standards can be divided into two categories. Regulatory standards include those regulations that are obligatory for licensed nuclear facility design. Regulatory guides include codes and guides that delineate recommended practices but are not obligatory. For clarity, we shall use "standards" to describe mandatory requirements, and "guides" to refer to codes and guides that are recommended but not mandatory. Some of these guides, while not mandatory in the sense that alternative approaches are acceptable if they can be justified, are in fact mandatory because no alternative approaches have yet been accepted.

Licensed spent fuel storage installations historically have been integral parts of fuel reprocessing plants and nuclear power plants. Such plants have been licensed under standards 10 CFR Parts 30, 40, 70, and 100 in addition to 10 CFR Part 50.[18] Because of their association with licensed facilities, the spent fuel installations have been designed under a variety of existing U.S. Nuclear Regulatory Commission (NRC) guides.

A number of guides that have been used for licensed nuclear facilities are possibly applicable to the seismic design of the surface structures and equipment of repositories. For example, the surface structures that are important to safety may be designed according to guides that have been used for licensed surface structures in nuclear facilities; some of the equipment that is important to safety in a repository also may be designed to meet the requirements of existing guides. Although the surface structures and equipment of a repository are similar to the surface structures and equipment of other nuclear facilities (fuel reprocessing plants, nuclear power

*It should be noted that some important loads, such as thermal, that will have a significant impact on the criteria are not discussed.

plants, independent spent fuel storage installations, plutonium processing and fuel fabrication plants, uranium enrichment facilities, etc.), there are important differences in function and design. Therefore, some of the existing guides may have to be modified and rewritten to reflect these differences.

None of the standards and guides that have been used for licensed nuclear facilities are directly applicable to the underground structures of repositories. The NRC is proposing a new 10 CFR Part 60[19] to deal with licensing HLW repositories in geologic formations; however, the proposed standards were not available in time for review in this report.

<u>Surface Structures and Equipment</u>

As discussed above, the design of conventional structures in existing nuclear facilities is accomplished under a number of standards and guides, some of which can be directly applied to the seismic design of the surface structures and equipment of a repository. There are no foreseeable difficulties or unknowns in formulating static and seismic design criteria for the surface structures and the equipment of a repository on the basis of these documents. The fundamental question that needs to be resolved is what degree of protection should be afforded to these structures as compared with the various nuclear facilities in use today.

Seismic design criteria for equipment are normally written separately from static criteria for licensed facilities. It will be preferable to retain this practice for repositories.

Repositories will contain some equipment that is not found in other licensed nuclear facilities. In particular the hoist systems and the ventilation system between the surface and the underground structures will probably require the development of seismic (and static) design criteria. In addition, depending on the licensing requirements, the primary features of existing designs may need to be modified to provide increased safety and redundancy.

Table 1 lists the more important existing NRC regulatory guides that may be applicable to the seismic design of the surface structures and equipment of a repository. Other guides are published by a number of organizations,

TABLE 1

EXISTING NRC REGULATORY GUIDES THAT MAY BE APPLICABLE TO THE SEISMIC DESIGN OF THE SURFACE STRUCTURES AND EQUIPMENT OF A REPOSITORY

Number	Title
1.12	*Instrumentation for Earthquakes*
1.13	*Spent Fuel Storage Facility Design Basis*
1.29	*Seismic Design Classification*
1.48*	*Design Limits and Loading Combinations for Seismic Category I*
1.60	*Design Response Spectra for Seismic Design of Nuclear Power Plants*
1.61	*Damping Values for Seismic Design of Nuclear Power Plants*
1.70	*Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants*
1.92	*Combining Modal Responses and Spatial Components in Seismic Response Analysis*
1.100*	*Seismic Qualification of Electric Equipment for Nuclear Power Plants*
1.122	*Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components*
1.132	*Site Investigations for Foundations of Nuclear Power Plants*
1.137*	*Fuel-Oil Systems for Standby Diesel Generators*
1.138	*Laboratory Investigations of Soils for Engineering Analysis and Design of Nuclear Power Plants*
1.140*	*Design, Testing, and Maintenance Criteria for Normal Ventilation Exhaust System Air Filtration and Absorption Units of Light-Water-Cooled Nuclear Power Plants*
1.142	*Safety-Related Concrete Structures for Nuclear Power Plants (Other Than Reactor Vessels and Containments)*
1.143	*Design Guidance for Radioactive Waste Management Systems, Structures, and Components Installed in Light-Water-Cooled Nuclear Power Plants*
3.14	*Seismic Design Classifications for Plutonium Processing and Fuel Fabrication Plants*
3.17	*Earthquake Instrumentation for Fuel Reprocessing Plants*
3.24	*Guidance on the License Application, Siting, Design, and Plant Protection for an Independent Spent Fuel Storage Installation*
3.26	*Standard Format and Content of Safety Analysis Reports for Fuel Reprocessing Plants*
3.39	*Standard Format and Content of License Applications for Plutonium Processing and Fuel Fabrication Plants*
	NRC Standard Review Plan (SRP)

*Relates to equipment only.

including the American National Standards Institute, American Concrete Institute, American Society of Mechanical Engineers, American Society for Testing and Materials, American Institute of Steel Construction, and American Society of Civil Engineers. Some of these guides may also be applicable; however, they require further review.

Underground Structures

Static Design Criteria. Static design is always an essential component of the overall design process. Although standards and guides do not exist for the static design of the underground structures of repositories, the standard practices used in the engineering design of other types of underground structures are available. These standard practices provide a starting point for developing specific static design criteria for repositories.

Underground structures are currently designed by empirical methods based on past experience and, to a lesser degree, on analysis and test results. Engineering geologic exploration of the site provides data on rock types, discontinuities and jointing patterns, water regime, rock engineering properties, and in-situ stresses. This information enables the designer to select the best orientations, sizes, and shapes for the openings and to determine what support system is required. Usually, this exploratory information does not cover all eventualities that are encountered during excavation. The actual rock conditions generally cannot be fully determined until the rock has been excavated.

Rock quality and deformation behavior are typically observed as the excavation proceeds. To achieve a stable opening, designs must often be modified during construction to account for variations in ground conditions. After excavation is completed, checks of the cavern stability continue with instrumental measurements and visual observations. Opening shape and support are sometimes modified at this time to ensure long-term stability. Only after the cavern has been stabilized can the design be considered final.

The determination of rock loads, the calculation of stresses, and the design of support systems depend upon the type of support employed. The Terzaghi Method[20] for the design of steel sets estimates rock load according to rock condition and size of opening. Stresses are not calculated in the rock but only in the steel set. For a rock bolt system, it is the current practice to base the initial selection of rock bolt size and spacing on geologic exploration and empirical rules and not on stress calculations.

At present, calculations of the static stresses around underground openings play a limited role in design. In practice, the rock stresses are not usually calculated for tunnels. Rock stresses are often calculated for large openings (e.g., power plant caverns), but their main function is to serve as indicators of rock behavior and problems.

In summary, standard practice for static design of tunnels and other excavations in rock needs to be developed into acceptable design criteria. Various components of the current practice should be evaluated for their applicability to repository design.

Seismic Design Criteria. Very little attention has been given in the past to the seismic design of rock excavations. Consequently, current standard practice does not provide a starting point for developing quantitatively rigorous seismic design criteria.

Various reports indicate that natural and man-made openings generally experience either no damage or only minor rock falls during seismic events.[21,22,23] For this reason, designers usually ignore seismic ground motion in the design process for tunnels, caverns, and other underground openings. However, occasional severe damage to tunnels has been reported[22,23] (usually due to a combination of severe ground motion and poor rock or marginal support). Therefore, seismic ground motion cannot be ignored for critical underground projects such as petroleum reservoirs, underground nuclear power plants, and waste repositories. Yamahara et al.[24] address the safety of a rock cavern for petroleum storage, using a finite-element model to calculate stresses. URS/Blume[2] and Campbell and Dodd[25] have used simple, conservative calculations for seismic stresses in the rock to evaluate the safety of the openings. Dodds et al.[26] discuss the seismic criteria for mined rock caverns in a conceptual design of an underground nuclear power plant, indicating areas that require future study. Additional information on seismic design criteria for large underground structures is being obtained under a National Science Foundation Research grant to URS/Blume.[27]

Experiments with conventional and nuclear explosives have yielded some useful data. Engineering Research Associates[28] and Hendron[29] provide some damage limit criteria obtained from experiments with conventional explosives. Experience in hardening tunnels at NTS against UNEs[30] indicates that effective procedures for hardening include lengthening of rock bolts, grouting rock bolts along their full length, and reinforcing rock bolts with shotcrete and wire mesh.

Although the information gained through these various investigations is useful, it does not provide a sufficient basis for developing seismic design criteria for underground structures. Furthermore, it is difficult to pattern acceptable seismic design criteria for underground structures after existing criteria for surface structures because of two important differences in the design of surface and underground structures. First, the design of conventional surface structures, unlike that of underground structures, is based upon the availability of a variety of construction materials (concrete, steel, steel alloys, aluminum) that can be provided with fairly consistent values for material properties. Second, analytical theories used in the design of surface structures are sophisticated and thoroughly verified by experiments, whereas those used in the design of underground structures are not.

Summary. The codification of the seismic and static design of underground structures presents a new problem. Although some existing regulatory guides are applicable to the surface structures of nuclear waste repositories, the necessary seismic design criteria for the underground structures need to be developed. Much of this development work is generic in nature and can be applicable to all repository locations; however, some aspects of this work will be site-specific and would have to be addressed individually for different kinds of host media.

5. SEISMIC DAMAGE MODES AND PERFORMANCE CRITERIA FOR UNDERGROUND STRUCTURES

Seismic design criteria are written to provide an engineered system that satisfies the predetermined performance criteria -- the minimum standards of acceptable behavior. To establish performance criteria for the underground structures of a repository, it is necessary to consider the effects of the different damage modes to which the structures are susceptible under seismic motion.

The effects of different damage modes on the ability of a repository to isolate radioactive waste vary during the lifetime of the repository. The repository lifetime can be divided into three phases:

1. Design and Construction Phase - Construction of surface facilities and excavation of shafts and initial storage rooms; no hazardous material is present.
2. Operational Phase - Hazardous material is handled in the surface structures and transported through the shafts and tunnels to the storage rooms; additional storage rooms are excavated as needed.
3. Decommissioned Phase - Shafts have been backfilled and sealed; storage rooms and tunnels have also been backfilled.

Seismic damage to the repository during the first two phases is an engineering design concern because it can be mitigated with state-of-the-art engineering design and construction methods. Phase 3, the decommissioned phase, primarily involves long-term isolation of nuclear waste, which is assured through site selection; engineering design, however, may be useful in impeding radionuclide paths to the biosphere.

Seismic Damage Modes

Seismic loads are known to have caused a variety of problems in underground openings that were not designed to resist seismic motion. On occasion, tunnels have been severely damaged during earthquakes.[22,23] Thus, it can be assumed that seismic motion may result in damage to underground repository structures. Of course, damage attributed to a seismic disturbance is really due to the addition of seismic stresses to preexisting stresses resulting from in-situ conditions, alteration of the static stress field by the opening, and thermal loads generated by nuclear waste.

Table 2 lists some possible seismic damage modes and their possible consequences during the operational and the decommissioned phases of a repository lifetime. The design and construction phase is not included in the table because no hazardous material is present and public safety is not threatened.

As shown in the table, one of the most important possible consequences due to a seismic event is increased permeability of the rock surrounding the repository.* Changes in permeability can be hazardous to personnel during the operational phase because they can lead to flooding of the tunnels. During the decommissioned phase, these changes can compromise the geologic isolation of nuclear waste and thus may threaten public safety. It is important to note that, apart from the possibility of increased permeability, there are no other foreseeable earthquake effects that would perturb the long-term function of the repository.

Changes in the hydrologic flow regime have been observed following seismic events; for example, earthquakes have caused wells to dry up, springs to increase or decrease their flow rates, and alterations of groundwater flow in mines. Research recently conducted by Zoback and Byerlee[31,32] in the field of earthquake prediction supports these observations. Their studies indicate that permeability increases during dilatancy and that dilatancy can occur after many cycles of compressive stress. Because they used high tectonic stresses (in the kbar range), which are much greater than seismic stresses, their research has limited meaning for possible changes in permeability due to earthquakes. However, their research gives credence to the suggestion that the cyclic stressing of an earthquake may cause changes in the microcracks and the joint system, resulting in increased permeability.

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*The concern here is not with local changes in permeability around the tunnels. Possible increases in permeability around each tunnel due to the interaction of the tunnel and the earthquake waves should not affect the ability of the entire host medium to act as a barrier.

TABLE 2
SEISMIC DAMAGE MODES

Damage Mode	Possible Consequence During Operational Phase	Possible Consequence During Decommissioned Phase
<u>Underground Structures</u>		
Rock Fall (extent depends on seismic loading, rock quality, and support)	Injure personnel Block transportation Block ventilation Disrupt water management Damage canister Damage shaft wall	
Rock Slabbing (bursting)	Same as for rock fall	
Existing Rock Fractures and Seams Open, Rock Blocks Shift	Increase permeability -- increase water inflow Weaken rock structure	Increase permeability -- speed up transport of radioactive waste to the biosphere
Cracking of Waterproofing Liners in Shafts (if used)	Increase permeability -- increase water inflow	
Spalling of Shotcrete or Other Surfacing Material	Lead to rock fall if extensive	
Unraveling of Rock-Bolted Systems	Same as for rock fall	
Steel Set Collapse	Same as for rock fall	
<u>Equipment</u>		
Failure of Hoist Systems	Drop canister Injure personnel Canister sticking in shaft	
Damage to Ventilation Machinery	Accumulation of gases Heat build-up Preclude personnel access	

In addition to increased permeability, there are many other possible consequences due to a seismic event occurring during the operational phase. These consequences could create a hazard to operating personnel or a disruption to the repository operations. However, it is not clear that any of the damage modes would lead to a hazard to the public health during the operational phase.

Because of the preliminary nature of this study of seismic design criteria, the list of damage modes presented in Table 2 may not be complete. Further research may reveal additional damage modes that need to be mitigated with appropriate design. Historical tunnel and shaft responses to seismic and underground nuclear explosion loads might be investigated and the responses and any possible damage could be evaluated. For example, numerous old mines, some several thousand years old, are located in active seismic areas (Middle East, Egypt, Turkey, Germany, Italy, China, etc.); these might provide data concerning the effects of seismic loads -- specifically increases in permeability.

Additional research is also needed to determine whether or not seismic motion might alter the permeability of the rock mass for various candidate host rocks. Furthermore, a determination is needed on whether such seismically induced changes will have long-term negative effects on the geological barriers or will simply be short-term perturbations.

Performance Criteria

At present, the performance criteria for the surface structures and all equipment do not appear to present unusual problems, although these criteria need to be written. Many unanswered questions exist for performance criteria of the underground structures, however. What is the allowable size of a rock fall or a rock burst? Under what circumstances are tunnel closures allowable? Is cracking of the shaft lining permissible; if it is, what is the allowable crack width and fluid flow rate through the cracked surface, etc.?

One performance criterion is self-evident: no rock fall should be permitted in the shafts during the design and construction or operational phases. Even a small rock falling a great distance poses a serious threat to personnel safety. A larger rock could do considerable damage to the shaft wall and equipment. This criterion can probably be satisfied by application of wire mesh and/or shotcrete to the shaft walls. Of course, the primary performance requirement of the repository, regardless of time period, is that radioactive material remain separated from the biosphere.

The performance criteria will have a direct influence on the cost of a repository. It has been found that the construction costs of the underground structures of the repository will be sensitive to the assumed performance criteria.[2] More stringent criteria can cause significant increases in the capital and operating costs of the repository.

6. GROUND MOTION CRITERIA FOR UNDERGROUND STRUCTURES

Ground motion criteria usually include (1) the specification of the form of ground motion that is to be used in seismic design and (2) the manner in which this ground motion is to be determined. The second item is discussed only briefly and is outside the scope of the present report; the following discussion primarily covers the specification of the form of ground motion that could be used in the seismic analysis and design of repository structures.

Procedures are required to determine appropriate values for ground motion at the specific repository depth. The literature on the relationship between earthquake motion and its intensity at depth below the free surface indicates that, in general, motion attenuates with depth.[33,34,35] There are situations, however, in which instrumental and observational motions underground have been found to be as strong as (and sometimes stronger than) those on the surface.[21,33] Such findings are an indication of the general complexity of this phenomenon. The seismic motion at a particular depth consists of the superposition of the several body and surface waves. The motion at that point will reflect whatever seismic energy is present: body waves traveling directly from a seismic source, body waves reflecting off the Moho or other high-impedance contrast surface, body waves reflecting from the free surface or from some other interface below the surface, or surface waves. No simple statement can be made to describe the effect of depth upon seismic motion.

Few computer programs are available for the computation of motion at depth. The FLUSH[36] program treats the problem assuming only vertically propagating shear or compression waves and is, therefore, greatly limited in its ability to represent the complexities of underground motion. Furthermore, it is probably inappropriate to use FLUSH for repository depths because the program was intended for near-surface applications. Banister et al.[37] developed a program to study the stresses and strains due to the reflection of seismic body waves from the ground surface in a homogeneous medium. Nair and Emery[38] considered both surface and inclined shear waves in a linear, homogeneous, horizontally stratified soil structure.

There are three commonly used methods for specifying ground motion for design: the peak ground motion parameters, the response spectrum, and the time history. Estimated peak amplitudes of ground motion parameters (acceleration, velocity, or displacement) have been used in simplified design procedures and for some analytic evaluations of response effects of underground structures. There are circumstances in which this simplified characterization can be of considerable value -- for example, when major uncertainties exist in the procedures for obtaining more complex characterizations. Regulatory agencies have been specifying ground motions for the design of nuclear facilities by means of the response spectrum, primarily because response spectra can be generalized and are also more amenable to prediction than time histories. In addition, the response spectrum provides information concerning the amplitudes of the various frequency components in the spectral band of interest. Ground motion has also been specified in the form of three-component time histories, which may be artifically generated synthetic accelerograms or earthquake records from various sites. Synthetic time histories may be generated from random number sequences or selected power spectral density functions and are modified by appropriate filtering and shaping.

There are limitations to all three specification methods. Peak amplitudes of ground motion provide the least information about the design ground motion. Frequency content, duration, and periodicity are not included, nor is it known when the peak value occurs during the ground motion. A major limitation of response spectra is that they contain only frequency and amplitude information. Because this information alone is not sufficient for many design requirements (e.g., nonlinear analysis), time histories are frequently matched to the specified response spectrum and used for analysis. However, several different ground motion time histories can produce similar response spectra. If the design process requires a single time history, additional controls may be required to identify the one that is most suitable.

Of the three specification methods, time histories are the desirable ground motion specifications because they contain all the important ground motion parameters -- peak amplitudes, frequency content, duration, and periodicity. However, accurate prediction of time histories is beyond the current state of the art. When a synthetic accelerogram is used, the random motion may be an inappropriate description of the real phenomenon because the physical process involved in the ground motion may not have been correctly incorporated. When recorded time histories are desired and none exist at the site, it is difficult to establish the precise time history for that site. Response spectra, on the other hand, can be predicted with some assurance, given reasonable estimates of the location and nature of the seismic event and the geologic environment of the site. For this reason, regulatory agencies have specified response spectra for nuclear facilities, with provisions for developing a corresponding time history. As noted above, there is no unique time history for a given spectrum; consequently, other controls must also be applied to achieve the time history that is best suited to the circumstances.

In all of these specification methods, there is a problem with the relationship between the components of the motion. Most specifications require that (1) the two horizontal components be of equal strength and (2) the vertical component be equal to or a fraction of the horizontal components. The actual correlation between components would require decomposition of seismograms into the various individual seismic waves. To date no researcher has been able to do this successfully. The problem may not be tractable because there are too many independent parameters.

It is not clear at this time which specified ground motion will provide the optimum procedures. Simplified methods using peak ground motion parameters may be used to obtain upper bounds on the seismic stresses within a rock mass; however, they do not address the matter of secondary wave reflection and refraction effects at a cavity. Although these bounds will lack detailed information about the geology and the wave motion, they may be useful in making conservative engineering evaluations of stability during seismic activity. The peak ground motion methods do not estimate the stresses in the near vicinity of a tunnel (i.e., within a distance of approximately one tunnel diameter from the tunnel wall) and are probably valid only for wavelengths longer than the tunnel diameter. Research is needed to determine the applicability and limitations of simplified techniques. Before these simplified procedures can be accepted, extensive verification using experimental data or a more general theory with a three-component time history is required.

Response spectra are not appropriate for determining stresses within a rock mass. They would be useful for the design of equipment attached to the walls of the underground excavations, however. Response spectra would also be useful for estimating the peak ground motion parameters: in particular, peak ground acceleration and displacement can be reliably established from correctly calculated response spectra.

The most complete, or ideal, seismic motion characterization for use in underground structure analysis would be a three-component time history of motion that includes the superposition of various types of waves. The ground motion at a point below the ground surface can be obtained from the surface time history using analysis with appropriate assumptions about the nature of the seismic waves and the material properties of the rock mass. This assumes the existence of an appropriate analytic technique that can account for spatial variations and the presence of a cavity. Current analytic techniques address only ideal conditions free from nonhomogeneities and discontinuities.[27] More developmental work is needed in this area, as discussed further in Chapter 8.

To characterize the ground motion for an underground repository by a three-component time history, it is necessary to first develop a three-component time history at the ground surface. The present view is that to achieve a reasonably reliable prediction of a surface time history, the most workable procedure would be to define a control response spectrum for the ground surface at the location of interest. Such procedures are already well defined for nuclear facilities. The spectra could be similar to those specified by NRC Regulatory Guide 1.60;[39] the selected (or synthesized) time history would contain the frequency and power spectral densities of a suite of time histories in similar regimes. It would then be possible, assuming the existence of appropriate analytic techniques, to obtain a matching plausible time history for the subsurface location. It is not possible to determine a subsurface time history directly from a surface response spectrum.

Ultimately, to verify the analytical results regardless of specification, it would be advantageous to obtain additional instrumental data at the surface and at depth from strong-motion earthquakes.

7. ROCK PROPERTY AND FAILURE CRITERIA

The material properties of the rock mass are needed (1) for calculating stresses and strains around underground openings and (2) for formulating failure criteria.

Dynamic Rock Property Criteria

Dynamic rock mass properties are needed for use in linear elastic seismic stress analysis (as discussed in Chapter 8). The dynamic elastic moduli, Poisson's ratios, rock densities, and damping values would need to be determined experimentally for the candidate rock masses. The spatial variation of these properties would also need to be determined.

The dynamic elastic moduli, Poisson's ratios, and rock densities can be determined by field and laboratory tests. The accuracy and limitations of the results of these tests need to be determined. Acceptable procedures for obtaining the dynamic rock properties for use in seismic analysis need to be defined.

Failure Criteria

Failure criteria quantitatively define stress states that are damaging to the rock mass (around an opening). The computed static and seismic stresses are summed and compared with the failure criteria; damage to the rock mass is assumed to occur when the failure criteria are exceeded. Failure criteria are needed to define damaging states of compressive, shear, and tension stress in intact rock and along rock discontinuities because a rock mass is composed of intact rock separated by discontinuities such as joints.

Failure in this context refers only to the engineering definition of damage to rock; it in no way refers to the total loss of the primary function of the repository. Thus, even if the stresses in the rock exceed the failure criteria, this does not mean that the repository barriers have been breached.

Two-dimensional failure criteria are currently used in engineering rock mechanics practice to evaluate static stresses for their potential to damage rock masses. The Coulomb criteria and the Modified Griffith criteria are useful two-dimensional formulations that can be used in practical situations.[17] The formulation of these criteria requires testing of rock specimens in the laboratory or field to determine the basic parameters, such as unconfined compressive strength, tensile strength, and friction angles. More precise two-dimensional criteria of rock damage can be determined by empirically fitting a curve to a number of test results. The cap model,[40] which represents failure as well as other important characteristics of geologic materials, and joint slip models[41,42] should be considered.

A three-dimensional failure criterion may be needed in the advanced design levels in conjunction with more refined stress analyses. The Von Mises criteria and Murrell's extension of the Griffith criteria are three-dimensional failure criteria that have been used to study rock damage, although they do not fit the experimental results particularly well.[17] More sophisticated failure criteria may have to be developed by a combination of laboratory experimentation and analysis of the actual mechanisms of rock behavior under stress. In addition, the effect of the intermediate principal stress on rock behavior and the effects of stress gradients, size of specimen, and long-term temperature increases on test results are still largely unknown and may require further study to develop more sophisticated failure criteria.

In conclusion, failure criteria that would be acceptable for licensing underground structures need to be defined. The testing procedures and the theories needed to formulate the failure criteria also need to be defined.

8. SEISMIC ANALYSIS CRITERIA FOR UNDERGROUND STRUCTURES

Seismic and static analyses are the key to a quantitative design process. In the general engineering practice, stresses due to static loads and stresses due to seismic loads are computed separately. These stresses are then combined for comparison with the failure criteria, which may be in the form of maximum allowable stresses, ultimate strength, or failure envelopes. Finally, design decisions are made from the results of the comparisons.

There are several available methods for the static analysis of underground structures. Of these methods, finite-element programs using gravity loading seem to be the most useful. Not only do they compute the stresses throughout the structure, but any structure of arbitrary shape can be modeled.[43] With the choice of the appropriate computer program, three-dimensional problems can be treated as easily as two-dimensional problems. SAP IV,[44] for example, is a widely available code that can perform this function for linear elastic materials. BMINES is a three-dimensional computer code developed to analyze mining problems, including those involving slip joints and rock bolts.[45,46] Rock discontinuities in finite-element models for static analysis are discussed by Goodman et al.[47] and Roberds and Einstein.[41]

Seismic analysis is considerably more involved than static analysis because of the variation in ground motion below the ground surface. Few computer programs are available for underground seismic analysis. The FLUSH[36] program could be used to investigate near-surface openings for vertically propagating shear or compression waves; however, the program was intended only for analyzing the interaction between surface structures and the soil mass. The use of FLUSH to model any other situation (such as underground structures) is not advised. Its use for structures at repository depths would be both costly and inappropriate. Other finite-element models have been used to determine the stresses around underground near-surface structures loaded by vertically propagating shear waves.[24,48,49] General finite-element codes for analyzing dynamic problems, such as SAP IV,[44] could be applied to deep underground structures, accepting the restrictions on material properties within the program and ignoring reflections of seismic waves from the free ground surface. The inclusion of the ground in a finite-element model would require a very large mesh, which would be costly to run.

The development of a more rigorous seismic analysis is needed for evaluating the stability of the underground structures of a nuclear waste repository. The stability of underground openings during seismic events that occur in the operational phase and the changes in permeability that may result from seismic events occurring in the decommissioned phase should be investigated.* Analytical evaluations, based upon rigorous seismic analysis, will lend confidence to design decisions founded upon geological engineering experience.

An analytical method that uses three components of motion and accounts for dilational, shear, and surface waves would be a desirable development. It would also be desirable to develop an analytical method that includes nonhorizontal discontinuities with variable seam properties. A schematic of such a rigorous seismic analysis is shown in Figure 5.

Steady-state wave mechanics and Fourier synthesis may facilitate the development of rigorous seismic analysis procedures. At present, these analytic techniques permit an investigation of seismic stresses around an underground opening within an idealized geology of isotropic, homogeneous layers. Assuming that the model is excited by plane waves, the motion anywhere in a horizontally layered medium can be formulated from the motion at a point on the free surface using a variation of the Haskell-Thomson method.[50] This provides an easily programmable algorithm for the evaluation of transfer functions in the frequency domain between arbitrary points in the layered medium. Steady-state methods in wave mechanics provide a powerful tool for the reduction of complicated temporal convolutions to algebraic multiplications or divisions of Fourier transforms and frequency-dependent transfer functions. Fourier transforms of ground motions are easily evaluated using the Fast Fourier transform algorithm. Thus, arbitrary motions can be taken into account by Fourier synthesis. The inclusion of an underground structure in a horizontally layered medium can be handled using steady-state analysis and Fourier synthesis. The diffraction caused by an underground structure can be formulated for harmonic motion using integral equation techniques outlined by Mow and Pao.[51] These techniques require the use of Green's function for a layered medium. In general, Green's functions for harmonic waves are

*Although potential instabilities can be mitigated through design, possible deleterious effects of earthquakes on the rock-mass permeability during the decommissioned phase can only be avoided through proper siting.

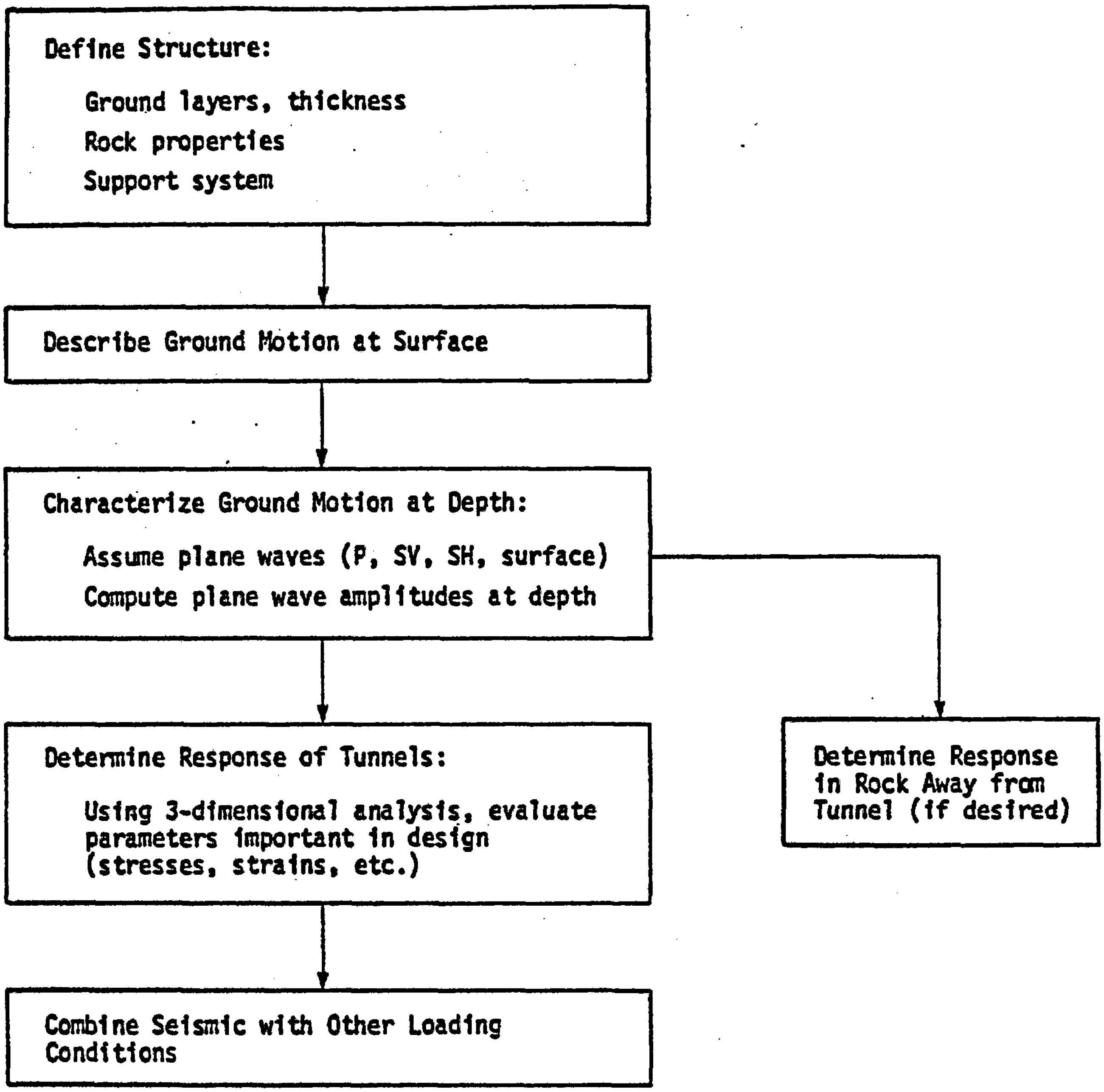

FIGURE 5 A SUGGESTED RIGOROUS SEISMIC ANALYSIS

expressed in terms of complex integrals. Until recently, only Green's functions for the simplest sources were known or available. However, in recent years there has been much interest in this area of engineering seismology. Many of these needed Green's functions are now becoming available and are in more widespread use.

The procedures outlined above are being used in a study by URS/Blume under a National Science Foundation grant.[27] Currently only a single component of motion, represented by horizontally polarized shear waves of arbitrary angle of incidence, is used in the investigation of stresses around a cylindrical cavity in an elastic half-space.[52] The next steps in development would be to include dilational waves, vertically polarized shear waves, and surface waves.

As idealized models are developed, verification studies will be required to determine the effects of the disparities between the idealized model and the real geologic situation. Nonhomogeneities of the actual ground may have a significant effect on tunnel stability. For example, it is well known that the size of the rock block important for static stabilization considerations varies according to the size of the tunnel. The aspects of nonhomogeneity important to seismic analysis are not yet known. It may be that certain types of joints will have no effect on seismic stresses, while others will have a significant effect. In addition, some joint systems may behave differently under high and low values of seismic stress.

The methods of analysis outlined herein are linearly elastic. Although strong motion leads to nonlinear material behavior, it is generally prudent to solve the elastic problem where no other solutions are available. There are many reasons for the use of this approach. Currently there are no economically feasible alternatives for evaluating the three-dimensional dynamic responses with other methods. In addition, because the elasto-dynamic problem is already so cumbersome, some years of experience with it will be necessary. Also many subtleties in the response of underground structures may become better understood as a result of work on the linear elastic approach and will explain the observations of tunnel responses to earthquakes. Moreover, the strains or stresses predicted in an elastic analysis of seismic waves are small compared with the rock strength This leads to some acceptability for the linear approach. Finally, linear analysis can always provide a starting point for more complex nonlinear methods.

The comment above regarding the small, calculated values for seismic stress should not be construed to mean that seismic waves will not lead to damage of the rock mass around an opening. The presence of the excavation will alter in-situ stresses, increasing compressive stresses in some zones and creating tensile stresses in other zones. The superposition of seismic stresses on this altered static state of stress may cause damage because some rocks (such as some shales) have relatively low compressive strength and most rocks are weak in tension.

Simple procedures based on the one-dimensional wave equation are also being used to calculate dynamic stresses underground.[2,25,49,53] These procedures are believed to provide a conservative estimate of the actual stresses, although this has not been verified. The simple procedures often utilize only peak motion parameters, ignoring other motion parameters that may be important. Furthermore, these procedures do not account for the presence of the cavity or for all possible types of wave motion. The attractiveness of these procedures lies in their simplicity for engineering analysis and design. The applicability and limitations of the simple analytic procedures need to be evaluated, however. Analytic methods using three-component time histories, as described above, could be used for this purpose.

In summary, a rigorous seismic analysis is desirable for evaluating the underground structures of a nuclear waste repository because it lends confidence to design decisions that are based upon geological engineering experience. Ideally the seismic analysis should involve three components of motion and a realistic description of motion and geologic parameters. Development of such procedures with some limitations on modeling motion and geology are within current capabilities. Although these rigorous procedures may prove to be inadequate for analyzing the more real nonhomogeneous geologic media, they can be used to explore the development of simple analytic procedures.

9. SEISMIC HARDENING CRITERIA FOR UNDERGROUND STRUCTURES

The need for seismic hardening of underground structures is determined by comparing the combined static and seismic stresses with failure criteria and evaluating the results. The support system for the underground opening will have to be modified if the evaluation indicates a need for additional protection. At this time, procedures for hardening are understood qualitatively. In order to achieve a licensable repository design, quantitative measures for scaling the level of hardening from the stress level (or some other appropriate indicator) will probably be required.

Qualitative Seismic Hardening Procedures

Qualitative seismic hardening recommendations were made as part of the site investigations for possible construction of a nuclear waste repository.[2,54] The dynamic responses of steel sets and rock bolts were evaluated by reviewing the reported experience from tunnels exposed to dynamic loads and by qualitatively considering the interaction between supports and surrounding rock. The following design concepts were established:[54]

1. It is not advantageous to harden these two systems in terms of stiffening them. An approach of maintaining flexibility is the better one. The incremental effort associated with dynamic loads should be focused on the quality of the details of the support and reinforcement systems selected for static loads and on the prevention of possible spalling or popping of rock blocks. In principle, a carefully executed, flexible stabilization system is preferable to a relatively stiff system of stabilization. Hence, attention is given to improving construction details to achieve a more coherent medium-tunnel system.
2. Consider first the steel support system selected for the tunnels in shale. Inherently, this system carries a substantial reserve, or resilience. Both the assessment of static load and the assessment of the capacity of the system, derived from the squeezing-ground load condition, are rather conservative. A steel set seldom fails because the ultimate strength of a given, continuous member of the steel set is exhausted. Rather, it is the failure of connections between the different parts of the set, or a situation of unbalanced loading, that results in the fail-

ure of the set. Consequently, the incremental support requires greater attention to construction detail and workmanship than normally would be required if only the static loads were considered. It is better to weld rather than simply to bolt together the different pieces of a steel set in order to establish continuity. Steel s^ts should be securely tied together in the longitudinal direction.

It is imperative that the ground and the support be continuously coupled under dynamic loads. Thus, continuous blocking is much preferable to spot blocking. This can be attained by using continuous shotcrete blocking of the steel set and, if needed, backpacked lagging or reinforced shotcrete between the sets.

3. Similar considerations are applicable for the rock reinforcement systems selected for the tuff and the granite. Rock bolt details are improved by grouting the full length of the bolt. It is necessary to increase the amount of rock reinforcement by bringing it around the full circumferential area of the opening rather than from springline to springline, as dictated by static conditions. The spalling of rock blocks between the fully grouted bolts can be prevented by the use of reinforced shotcrete.

The attention given to the details of the support systems in tunnels subject to strong ground motion must also be applied to the details of the support systems in vertical shafts. If a concrete lining is considered necessary for groundwater control, it will require special consideration. Some cracking may occur, and extra steel reinforcement might be required. Where the reinforced concrete collar connects to a lining, stress concentrations and hammering action between the two are to be avoided. Future studies should address the dynamic problems associated with the shaft collars.

Quantitative Seismic Hardening Procedures

A method for quantifying hardening procedures is required. Incremental increases in the hardening are needed to correspond to incremental increases in stress level (or the peak acceleration level or some other indicator) in order to satisfy the failure criteria. For example, a quantified hardening procedure should indicate at what point on a scale of increasing stress level rock bolts are required around the full circumferential area of the opening rather than from springline to springline. The development of such a procedure may depend more upon the principles of geological engineering than upon the principles of mechanics.

10. RISK ASSESSMENT

Design of engineered systems implies choice from among alternatives. To choose the most desirable design from among the available alternatives, it is useful to evaluate and compare the total risk for each different design. Total risk is the composite of the probability of the occurrence of events that lead to failure of the system and the consequences of each failure in terms of dollar and life losses.

In geologic isolation of nuclear waste, events that may lead to failure of the system can be caused by internal and external disturbances.[55] Examples of internal disturbances include radiation, temperature, aging, human intervention (through design), chemicals, and movement; examples of external disturbances include seismicity, tectonics, hydrology, erosion, glaciers, meteorites, volcanism, time, and human activity (nuclear warfare, sabotage, mining, storage, waste recovery, population centers, reservoirs, irrigation, and new technology). Seismic activity is thus one of many disturbances that must be considered in the total risk assessment for a design, and may by itself be an important contributor to total risk.

Risk assessment can be used to establish repository reliability and to facilitate more expedient and more practicable repository design. The following sections discuss risk assessment during the three phases in the life of a nuclear waste repository.

Design and Construction Phase

Geologic exploration of the site provides data that enable the designer to select the best orientations, sizes, and shapes for the openings and to determine what support is required. As this exploratory information does not cover all eventualities encountered during excavation, the parameters needed for design can be taken as random variables; that is, necessary design parameters would be identified in terms of expected values and variability. With the appropriate distribution functions assigned to these parameters, it is possible to approach design from a probabilistic point of view that takes into account the local variations. Performance criteria of the engineered surface and underground systems can be based on acceptable levels of total risk. An important advantage of this probabilistic approach is that the design could conceivably be licensed for a range of ground and support conditions. Available mathematical models[56] can be used for this type of design approach.

Experience, experimental data, and theoretical knowledge can be employed to define the needed probability functions. As the excavation proceeds, experimental measurements and observations of the actual rock conditions can be used to determine if the construction is within the range of initial design standards.

Operational Phase

Because hazardous materials are handled during the operational phase, the risks are different from those of the construction or decommissioned phases. The structures and the machines that handle hazardous materials interact and complicate risk assessment.

To evaluate the risk for the operational phase, a logical structure based on fault trees would be useful. Risks associated with the different damage modes can be computed independently with such a representation.[57]

The occurrence of an earthquake simultaneously with transport of waste through the repository could create a hazardous situation. The paths to failure of containment and the consequences of such failure have to be carefully studied. The probability of simultaneous occurrence of an earthquake and waste movement is low, but the total risk involved should be computed and compared with the other accepted risks. Mitigation procedures could evolve from this type of study.

Decommissioned Phase

The decommissioned phase may be a large contributor to total risk because the radioactive materials in the repository must remain in geologic isolation until they decay, which may, depending on the type of waste, take several thousands to several hundreds of thousands of years. During this long time span, geologic events have a high probability of occurring and thus play a role in the risk assessment of the decommissioned facility. Earthquakes occur more frequently than other geologic events, and it is considered highly probable that a severe earthquake will occur during the first thousand years of the decommissioned phase. Repository reliability during this time period is therefore important to geologic isolation of nuclear waste.

It would be desirable to increase the probability of the repository's integrity, particularly during the first thousand years of the decommissioned phase. Engineering of containers and shaft plugs could achieve added reliability of the repository during this important time period, thereby reducing the total risk.

11. PROPOSED SEISMIC AND STATIC DESIGN PHILOSOPHY

Extensive calculations for stresses around a waste repository will probably be required in order to ensure confidence in the integrity of the natural and engineered barriers between the nuclear waste and the biosphere following a seismic event. Seismic stresses when added to existing static and thermal stress may create excessive stresses around tunnels and shafts. If such excessive stresses were to occur during the operational phase, increased rock permeability, canister damage, or ventilation disruption could result; excessive stresses could cause only increased rock permeability if they were to occur during the decommissioned phase. Computational models should be employed to investigate overstressing and to determine the need for redesign of configuration and support of openings.

Unfortunately, models that accurately represent local underground conditions are not possible until the opening has been excavated. This may present a problem for licensing a nuclear waste repository. Usually licensing means approval of a complete design before construction may begin. However, for an underground opening, the design for support and configuration is not completed until construction is completed. This situation could conceivably lead to a very costly design process in which variable conditions of local rock and geology must be extensively analyzed in order to anticipate all probable underground conditions for the site. Alternatively, very conservative tunnel support systems could be selected. This would permit licensing to proceed, but it would also be expensive. Conditions other than those anticipated are likely to be encountered somewhere during the excavation of an underground system involving several hundred miles of tunnels. Redesign and relicensing, and possibly even work stoppages, would be inevitable. A viable approach to solving this predicament is to adopt a multistage design philosophy in which design, licensing, and construction can be flexibly interwoven.

A proposed multistage seismic and static design philosophy for underground structures is presented in Table 3. It addresses design only after the site has been selected. Assuming that the selected site will be located within a relatively stable tectonic region and away from active faults, the seismic disturbance would be ground shaking at a relatively low intensity. The

TABLE 3

A PROPOSED SEISMIC AND STATIC MULTISTAGE DESIGN PHILOSOPHY FOR UNDERGROUND STRUCTURES

Stage		Description
First Stage	Exploration	The given site is explored to obtain preliminary engineering geologic and rock mechanics data.
	Design	This is a seismic, static, and thermal design based on preliminary data. It is used to evaluate performance and cost.
		This design stage includes defining ground motion, static and thermal loads, establishing rock properties and failure criteria, analyzing underground structures, detailing of support, and comparing predicted behavior with failure criteria.
		Support and reinforcement requirements are specified in a variable form on the basis of some probabilistic distribution (see Chapter 10).
Second Stage	Exploration	Exploratory shaft(s) and drift(s) are made to obtain further details on geologic structure and rock mechanics properties.
	Design	This is a more detailed seismic, static, and thermal design based on improved data. This design stage includes the same considerations as the first design stage, except that it uses a better data base.
		Support and reinforcement requirements are specified in a variable form on the basis of appropriate probabilistic distributions (see Chapter 10).
Third Stage	Construction and Design	Construction constitutes the final exploration, yielding further data on geologic structures and rock mechanics properties.
		During construction, behavior of the opening is observed and analyzed to evaluate static stability. Support and reinforcement are modified, if required, using observations and geologic engineering principles.
		After construction and completion of static stabilization, the existing rock and support system are analyzed for combined seismic and static loads. Support and reinforcement may be modified, if required.
		The final design is evaluated for quality control on the basis of probabilistic concepts (see Chapter 10).

basic assumption implicit in this table is that each stage of design would include considerations of loads, rock properties, failure criteria, analysis, support and reinforcement details, and reevaluation of stability. Therefore, each stage of design would use improved engineering geologic data that would facilitate more detailed analyses and designs than the previous stage.

The first stage of design would be based on the engineering geologic and rock mechanics data obtained from the preliminary exploration. This exploration program would include geologic mapping, coring, and geophysical surveys. The second stage of design would be based on more complete data gathered during the second exploration, which would involve excavating exploratory shafts and drifts to obtain further details on the actual geologic structure and rock mechanics properties. Finally, construction constitutes the final exploration, yielding further data for the third stage of design; the design would be modified as needed during construction to meet the actual conditions. After completion of static stabilization of the underground openings, the existing medium and rock support or reinforcement system would be analyzed to evaluate stability and safety for combined static, seismic, thermal, and other loads. The support or reinforcement could be modified at this time, if required.

Because the multistage design philosophy allows uncertainties about geology and rock properties to be overcome to some extent with each succeeding exploration, stress calculations in the advanced design stages should be closer to the real stresses inasmuch as they will be based upon more complete data.*

It should be noted that probabilistic concepts are included in Table 3 as part of the various design stages. Probabilistic design may be advisable for underground excavations because the material (rock mass) varies from point to point. It is included in the proposed multistage design philosophy to suggest that it be given serious consideration.

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*Increased emphasis on the calculation of stresses does not eliminate the role of geological engineering in obtaining stable openings. Because of the complex and highly variable structure of most rock masses, design decisions must always be guided by the principles of geological engineering.

12. CONCLUSIONS

Several important conclusions have been drawn during the course of this study. These conclusions relate to two of the three phases of a repository lifetime: the operational phase and the decommissioned phase.

During the operational phase, the major concern is with the effects of earthquakes on the near-field systems, namely, surface facilities, underground structures, and operating equipment. Seismic damage to these systems may create hazards to the operating personnel and, in some circumstances (e.g., failure of the hoist system, which could result in the fall and rupture of a canister), may raise concerns about public safety. It is the function of seismic design criteria to reduce the potential for such hazards during the operational phase.

Although design criteria can be qualitative, common practice is to quantitatively specify criteria. This requires procedures for the quantitative prediction of earthquake effects. With reference to tunnel stability, experts in earthquake engineering are able to make qualitative assessments based upon reports of past performance and current empirical procedures. However, quantitative predictions of tunnel stability are not possible with the current technology.

During the decommissioned phase, the major concern is with the far-field effects of earthquakes, that is, potential effects on the geologic formation that may result in a loss of isolation capability. This concern should focus on determining whether or not seismic events (possibly in conjunction with the thermal loads) can produce long-term changes in the permeability of the rock mass.

13. RECOMMENDATIONS

The considerations presented in the previous eleven chapters indicate that some additional work is needed to develop quantitative design criteria for nuclear waste repositories.

Seismic design criteria guide the design of repository structures and equipment so that these systems remain functional and containment is not jeopardized during and following a seismic event. Therefore, the criteria most directly address the operational phase when engineered systems must ensure both operational safety and containment. In the long-term lifetime of the decommissioned repository, permanent isolation of radioactive waste from the biosphere by the host medium is primarily ensured by site selection criteria and little by engineering design criteria. Engineering for seismic events during this final phase is limited mainly to effective plugging of shafts to prevent direct water paths to the surface and proper tunnel configuration to avoid increased permeability following seismic events. Thus, although there are a few recommendations for the decommissioned phase, most of the recommendations are directed toward guaranteeing containment and operational safety during the operational phase of the repository.

For purposes of organization, the recommendations for the operational phase and for the decommissioned phase are grouped under major headings corresponding to the principal chapter headings.

Recommendations for the Operational Phase

Existing Design Criteria: Seismic Standards and Guides. It is recommended that existing seismic standards and guides applicable to the surface structures and equipment of the repository be rewritten. This task requires relatively simple modifications to standards and guides already used for other types of nuclear facilities.

In addition, the necessary guides for the seismic design of the underground structures should be prepared. To accomplish this task, some additional research is needed, as indicated below.

Seismic Damage Modes and Performance Criteria. The following three recommendations are made with regard to seismic damage modes and performance criteria:

- Conduct investigations of historical tunnel and shaft responses under earthquake and underground nuclear explosion motions to evaluate possible damage modes.
- Evaluate the significance of seismic damage modes under all important load combinations, and establish performance criteria for structures and equipment under seismic loads based on these evaluations.
- Develop guidelines for determining the effects of excavation methods on seismic performance.
- Identify the mechanisms and conditions that might lead to the collapse of underground openings or to the increased permeability of the rock mass following a seismic event.

Ground Motion Criteria. It would be desirable to collect strong motion data at underground and corresponding surface sites. These data would be useful in verifying analytical results on the effects of depth and cavity on underground motion. The collection of data might involve the continued recording of downhole ground motions during underground nuclear explosions (such as *Subtask 1.2 Seismic Investigations; Weapons Test Ground Motion Measurements of the Nevada Test Site Terminal Waste Storage Program*) and the placement of monitoring instruments in deep underground structures and boreholes in regions of high seismicity.

It would also be desirable to conduct analytical and experimental research to determine the effects of depth on underground seismic motion. The feasibility of simplified techniques to obtain subsurface motions from surface motions should be determined.

Rock Property and Failure Criteria. Failure criteria to define the damaging states of compressive, shear, and tension stress in intact and jointed rock should be developed. In addition, the need for more sophisticated failure criteria than are currently available should be investigated; the possible development of a three-dimensional failure criteria should be given special attention.

Seismic Analysis Criteria. The following three recommendations are made with regard to seismic analysis criteria:

- Develop and write computer codes for the static, thermal, and seismic analyses of underground structures. The optimum development would be a code to compute stresses around an opening using three components of motion. Evaluate applicability of existing codes in performing these functions.
- Determine the applicability and limitations of simplified techniques for predicting the response of underground openings. Analytic models using three-component time histories might be used to explore the feasibility of simple procedures.
- Conduct verification studies as analytical model and analyses techniques are developed so as to determine the effects of the disparities between the idealized analyses and the actual geologic situations and experiences.

Seismic Hardening Criteria. Guidelines for quantifying the type and degree of hardening required for a given seismic load level should be developed. For example, incremental increases in hardening corresponding to incremental increases in stress level could be defined.

Risk Assessment. The risk from earthquakes should be evaluated in relation to all other significant hazards for the operational phase.

Proposed Seismic and Static Design Philosophy. Because the current state of the art in static underground design cannot achieve a final design for the underground openings until the excavation itself is completed, the usual licensing approach of requiring a completed design prior to construction must be modified. Thus, a design philosophy is proposed employing two or more design stages, each stage using improved engineering geologic data and yielding more detailed analyses and designs than the previous stage. The alternative appears to be a costly initial design and licensing process, which would attempt to cover all eventualities, and inevitable redesign and relicensing. This multistaged design needs to be further evaluated for its feasibility.

In addition, the use of probabilistic methods in the design of underground structures should be considered; this implies that seismic analyses would have to include parameter variability.

Recommendations for the Decommissioned Phase

Seismic Damage Modes and Performance Criteria. Analytical and experimental research should be conducted to determine if seismic motion can result in long-term changes in the permeability of the rock mass for various candidate host rocks.

Risk Assessment. The risk from earthquakes in relation to all other significant risks for the decommissioned phase of the repository should be evaluated. In particular, the impact of various engineered barriers in comparison with geological barriers on the risk assessment should be evaluated.

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