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Dr. V. Rajaram
Engineers International, Inc.
98 E. Naperville Road
Westmont, IL 60559

Dear Dr. Rajaram:

We have completed our review of your draft 2 of the Appendix on Stable Openings completed under Task 1 of Task Order 003 under the Nuclear Regulatory Commission (NRC) Contract No. NRC-02-82-030. A marked-up copy of the appendix is attached providing general comments and specific comments which shall be addressed prior to preparing the final letter report as required in the contract. We expect that following resolution of these comments, the report will assist NRC in preparing the Staff Analysis of the Basalt Site Characterization Report. If you have any questions regarding these comments, please contact the NRC Project Manager, T. L. Seamans, at (301) 427-4679.

The action taken by this letter is considered to be within the scope of the current contract No. NRC-02-82-030. No change to costs or delivery of contracted products is authorized. Please notify me immediately if you believe this letter would result in changes to costs or delivery of contract products.

Sincerely,

"ORIGINAL SIGNED BY"

Trueman L. Seamans, Project Manager
High-Level Waste Technical
Development Branch
Division of Waste Management

cc: M. M. Singh, EI

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Design of Stable Openings

1.0 INTRODUCTION

The objectives of constructing a nuclear waste repository are to terminally store the waste and isolate the radionuclides from the biosphere. In an effort to verify the performance of the repository and ensure that its objectives are fulfilled, the proposed 10CFR60 rules specify a retrievability period of 50 years from the initiation of waste emplacement. There are several openings in a repository and the stability of these openings must be maintained, at least during the retrievability period. The design of stable shafts, main access drifts, waste emplacement rooms and holes is a major consideration in repository design.

The Nuclear R~~E~~egulatory Commission (NRC) has proposed a set of rules in 10CFR60 which will provide a framework for licensing nuclear waste repositories. 10CFR 60.132 provides the design requirements for the underground facility. 10CFR 60.141 provides the guidelines for the confirmation of geotechnical and design parameters during repository construction and operation. In this appendix, a design logic is presented which will assist in compliance with the requirements in 10CFR 60.132. A phased approach to design is described which will permit the use of data obtained from the surface to develop a conceptual design, and refine the design as in-situ data is obtained from test excavations in the repository horizon.

The applicability of the design approach to the Basalt Waste Isolation Project (BWIP) is briefly discussed, and areas of concern in the conceptual design presented in the BWIP Site Characterization Report (SCR) are described.

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2.0 DESIGN LOGIC FOR NUCLEAR WASTE REPOSITORIES

A sound design philosophy, for any opening requiring long-term stability in rock, follows a pattern in which greater accuracy and detail is obtained as additional information becomes available. The design is complete when it fully addresses all geological conditions that may impact the stability of the opening under the conditions and nature of its use.

2.1 A Phased Approach to Design

Engineering for underground openings begins with assessments of the properties of the medium to be used in construction —. the naturally occurring rock mass. The engineering properties of the rock mass are never known accurately and have to be estimated. They are expressed in terms of probabilities that the estimates agree with actual geological conditions as they are distributed in the ground.

The accuracy of geological assessments, and therefore the efficiency and reliability of design concepts based on them, is the lowest at early phases of exploration and increases as progress is made in exploration and construction. Modern rock engineering practice recognizes that although the accuracy of geological predictions must be improved as the exploration effort progresses, the scope of those same predictions must at all stages include the range of factors expected to impact the performance of the opening, i.e., rock mass mechanical properties, in-situ stress and hydrogeology.

Certain factors influence the performance of rock masses for all openings, regardless of the nature of the geologic medium or the purpose of the opening. These include the distribution of rock mass strengths, the stress field, and hydrogeologic setting. Methods exist for assessing these complex and spatially variable characteristics. In arriving at a preliminary design such methods are comprehensive, but must be carefully utilized to cover specific project requirements.

Basic rock engineering principles and specific project requirements should be incorporated into preliminary design concepts using methodology appropriate to the accuracy of the data at hand. Early in the project, geologic data are obtained remotely, and are regarded as somewhat speculative. Conceptual designs are therefore generalized and tend to be conservative. As further data are gained, a more accurate description of the rock mass is obtained. At these early stages, empirical design approaches are appropriate. They enable preliminary design concepts to be evaluated and compared.

Subsurface exploration by drilling and later firsthand examination of the rock from test drifts, shafts, or rooms affords a level of detail that justifies closed-form or numerical analysis. The resulting design may still be conservative, but a better estimate of the degree of conservatism is obtained. Depending on the project, specialized, in-situ tests may be required to address specific design requirements in detail.

Current methodology for a comprehensive design approach with preliminary or generalized geologic data incorporates empirical rock classification systems. The recommendations thus generated can be modified to allow for specific concerns. For a nuclear waste repository, such concerns relate to thermal loading, the need for stability during the retrieval period, and the need for long-term isolation of radionuclides.

A comprehensive design approach based on more detailed geologic data may incorporate analytical or numerical modeling techniques. Analytical techniques commonly require some simplification and generalization of site conditions. While some detail is necessary in the data, a high level of detail is inappropriate. Numerical modeling techniques require a well-defined data base consisting of reliable geologic data and workable underground layout concepts. The proper use of empirical and analytical techniques during the earlier design stages may limit the number of alternatives considered during numerical analysis, with consequent savings in time, effort, and cost.

The following sections will introduce this phased approach and outline some accepted methods for carrying out the strategy. For the case of a nuclear waste repository, the strategy should enable the numerous repository design concepts to be compared in light of a full range of geologic factors.

2.2 Critical Design Input Parameters

Design input parameters that govern or constrain repository planning must include geological/hydrological considerations and parameters relating to repository layout and use. Geological/hydrological considerations relate to the basic fact that a geological repository is an underground structure excavated in rock which is governed by rock mass characteristics. Design considerations also depend on repository layout and use, and extend to thermal loading, the retrievability criteria, repository life, isolation of radionuclides, operational factors such as rate of emplacement of and capacity for nuclear waste, and safety. These factors dictate the repository layout and support facilities, and, hence, govern the selection of design criteria and specifications.

Geologic factors that should be addressed at all stages of the design process are as follows:

1. Rock strength is one of several factors controlling the deformation of the rock surrounding the opening, and needs to be assessed in terms of shear, tension, compression, time, and temperature.

2. Rock fracturing also contributes to rock deformation. Where the intact rock strength is high compared to the stresses to be imposed, rock fracturing may be a determinant of rock mass behavior. Important aspects are the orientations of the fractures (with respect to the opening), their inherent shear strength, continuity, extent, and spacing. Laboratory testing should determine the shear strength of the full range of fracturing conditions, both wet and dry.

3. In-situ stresses affect the location and magnitude of stress concentrations around the opening, and the mode of rock mass deformation that must be designed for. Opening shape and orientation, and rock reinforcement pattern, will depend in large part on the stress field. Some fractures will be more favorably oriented than others. Opening shapes and orientations tending to cause very high compressive stresses or large tensile areas in the crown should be avoided. The stress field is therefore important even in preliminary design and early assessments should be obtained. The hydrofracturing technique is suitable for measuring in-situ stresses at depth; however, interpretations of test results should consider the limitations of the technique. Overcoring and other stress relief techniques are desirable when greater accuracy is required in later site characterization efforts, but the data reduction and procedures selected should be adaptable to fractured rock.

4. Elastic properties of the rock and fractured rock mass are required for numerical modeling and some analytical design techniques. The laboratory Young's Modulus and Poisson's ratio from compression and sonic velocity tests are required to compute deformability of intact rock blocks and theoretical stress distributions. Rock mass elastic properties can be estimated through seismic geophysical testing (yielding a "dynamic" modulus) or in-situ jacking tests that yield a modulus of deformation from which the static elastic rock mass properties can be obtained through back-calculation. Borehole geophysical testing, which for many rock masses yields a higher modulus value than static jacking tests, is nonetheless a rock mass value and can be obtained early in the design effort. The effect of natural discontinuities can be conceptualized through comparison of seismic dynamic modulus and laboratory sonic modulus.

5. Thermal response of the rock mass must be determined to ensure that the heat generated by the emplaced waste does not threaten the long-term integrity of the structure. A data base on the properties of the rock at elevated temperatures is needed, to determine the coefficient of linear thermal expansion, thermal conductivity, and specific heat of the rock mass.

   Heater tests are required to determine the thermal response of the rock mass. These can be conducted after test excavations have been completed in the horizon of interest. The data can then be utilized to refine the preliminary design.

6. The Hydrogeologic regime affects the stability of the opening and poses a potential pathway for radionuclide migration. The presence of groundwater creates an internal pressure that must be overcome by the support system, weakens potential failure surfaces, and complicates construction operations. Testing should determine the hydraulic conductivities and storage coefficients at the repository horizon, hydraulic gradient, the hydraulic head, and whether constituents are present that could be damaging to the support system (steel and grout).

   In addition, hydrologic monitoring should be planned so that verification of design assumptions is possible. Finally, the hydrological impact on the near field, under thermomechanical loads, must be assessed.

7. A definition of instability is necessary so that conformance of the rock behavior with stability criteria can be verified. This definition provides a framework for design by establishing the extent of deformation or localized failure that can be tolerated in the repository.

8. The expected performance of rock support systems needs to be established prior to inclusion of such systems in the repository design. Principal concerns relate to temperature effects and creep.

2.3 Design Approaches

The design of stable openings, as discussed earlier, is a phased process in which the conceptual design is refined as more data become available from in-situ testing. The sequence begins with empirical, general concepts, which allow selection of several suitable options for further study. Information needs are identified, data are collected accordingly, and designs based on engineering mechanics are

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carried out (analytical techniques). A comparison of the designs is then possible, perhaps based on cost and technical criteria. A few alternatives are then selected for detailed consideration, in which the interaction of all critical design factors is evaluated through numerical modeling; this design phase should be supported by in-situ testing for specific input parameters. From this effort, design specifications and performance criteria are formulated. Finally, the conformance of the rock mass behavior with performance criteria is established by monitoring.

2.3.1 Engineering Mechanics

Design approaches based on engineering mechanics considerations are the rock classification schemes, and analytical solutions to analyze stability. Rock classification systems address most of the factors governing the stability of underground openings in rock, i.e., basic rock strength, fracturing, water conditions, and overall geologic setting. The RMSD method proposed by Kendorski (1980) is basically a discounting method in which the intact rock strength is discounted according to the nature and degree of fracturing to obtain the rock mass strength. This value can be used for analytical computations as well as an indicator of overall rock mass competence. The Geomechanics System of Bieniawski (1979) develops a relationship of span versus stand-up time. The Q-System of Barton, Lien, and Lunde (1974) is a detailed system with the chief advantages of considering span and in-situ stress. The RSR Concept of Wickham and Tiedemann (1974) is fairly simple but is not recommended for the design of shotcrete and rock reinforcement. The system proposed by Terzaghi (1946) computes a dead rock load due to loosening, and is widely used for the design of steel arch support in tunnels.

WHY IS THE RSR METHOD NOT CONSIDERED TO BE AN APPROPRIATE DESIGN PROCEDURE.

These systems either enable or directly yield generalized support recommendations. Application of these systems to circumstances outside the classification data base requires discretion by the user. Thus, the particular requirements of nuclear waste repositories, especially thermomechanical effects, will require some modification of the direct results obtained from classification systems before an adequate preliminary design is obtained for any single repository concept. However, various repository concepts can be readily compared for long-term stability and constuctibility using classification approaches. Typically, recommendations from the various classification systems are compared to obtain preliminary rock mechanics design concepts.

Classical engineering mechanics approaches are based on arriving at a balance of forces acting on an opening. Driving forces are the rock loads, and resisting forces come from the rock mass competence and the support system. The in-situ material properties of the rock and support must be known for such an approach to be meaningful.

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Simple elastic theory (Obert and Duvall, 1967) gives a first approximation of the distribution and magnitude of stresses and destressed zones surrounding an opening. However, the assumptions of homogeneity, isotropism, and linear elasticity implicit in elastic theory are seldom met in rock masses. Elastic theory also does not allow for the effects of rock reinforcement. However, even with these limitations, simple elastic analyses yield useful, though conservative, information for conceptual design of structures in rock.

PROVIDE ADDITIONAL DISCUSSION TO FURTHER DEFINE THIS PROCEDURE

Elastic-plastic ground reaction curve methods seek to match the support to the rock mass such that the amount of deformation allowed for corresponds both to the peak rock mass shear strength and the peak deformation resistance of the support (Egger, 1980). For the optimum use of the method, proper timing of support installation is essential. While the deformation of the support can be fairly readily evaluated, it is seldom possible to predict the ground characteristic from basic geomechanics data. Field measurements of rock mass behavior are necessary, and preliminary estimates can be obtained from underground test facilities within the horizon of interest. During construction, detailed geologic studies coupled with field measurements in the rock mass of interest, can result in enhanced capability for predicting the ground characteristic in virgin ground.

2.3.2 Numerical Modeling

There are a variety of numerical modeling approaches available for use in the design of stable underground openings (St. John and Hardy, 1982). For a geologic repository, modeling appears at present to be the best way to address the following specific design issues.

1. Rock mass deformation around openings
2. Time-dependent behavior
3. Effect of hydrologic regime
4. Deviations from simple rock mass behavior due to thermal effects
5. Repository layout
6. Geologic variations: stress field, rock mass competence, and water conditions

The proper use of numerical modeling schemes requires a considerable base of reliable, in-situ data as well as remotely-gained data. Hence, these methods are most useful when such data are available from underground test excavations. Also, some codes are quite complex and costly to use, and their use should be limited to the most favorable repository scenarios.

The U. S. National Committee on Rock Mechanics (1981) has summarized recent modeling schemes. These require the following types of data.

1. Geometry of opening and rock mass discontinuities
2. Heat transfer and fluid flow parameters
3. Assumptions of finite or infinite strain
4. Nature and properties of the rock mass and its mode of deformation
5. In-situ stress
6. Excavation methods
7. Support-rock interaction

Computer modeling schemes fall into the two categories of differential methods and integral methods. Desai and Christian (1977) discuss the theory behind numerical modeling schemes.

Differential methods (finite element and finite difference) permit the introduction of interfaces (slide lines or element boundaries) within a continuum. The finite element method (FEM) (Zienkiewicz, 1971) has the advantages of handling complex geometries, inhomogeneties, nonlinearity, and support-rock interaction. In problems involving repository excavations, several nonlinear phenomena may need to be considered. These involve plasticity, creep, nonlinear behavior of joints, and other complex constitutive relations including coupled thermal-mechanical response of rock mass.

Elastic-plastic methods hold significant potential in their ability to model the complexities of repository design concepts, and the ability to handle inhomogeneities. One important aspect of the elastic-plastic model is the definition of a damaged zone in the rock where yielding has propagated, away from the opening and into the rock mass, according to the selected yield criterion (Goodman, 1980). Certain associated aspects of the conceptual elastic-plastic model, which need to be considered in applications to design of repository openings are: the change in both stiffness and strength of the damaged rock, the influence of time (and distance from the face) before installation of supports, and the support-rock interaction.

Integral or boundary-element methods are based on the solution of integral equations that connect the boundary tractions to boundary displacements (Crouch, 1976; Cruse and Rizzo, 1975). The boundary of the opening is discretized and defines the solution for the interior. Thus these methods are most applicable when conditions at the boundary are of most concern.

Thermomechanical behavior can be modeled by the principle of superposition, in which stresses due to thermal and excavation effects are added. Thermomechanical modeling develops thermal stress values for this purpose; an example is ADINA/ADINAT (Bathe, 1978) which has been used to model the repository environment. Two-dimensional models can be useful for preliminary design. Coupled models assess the interaction of thermomechanical and hydrological conditions. Three-dimensional models avoid the simplifying assumptions inherent in a two-dimensional approach, but are more complex and costly. They do, however, allow for anisotropic rock behavior.

2.3.3 Observations During Construction

During the construction of any underground facility, in-situ monitoring of the rock mass is essential for verification that design objectives are being achieved.

In conformance with the provisions of 10CFR60.141 and 60.142, a full monitoring program should be implemented. This should include measurements of relative and absolute ground movements, support load response, visual performance of support, geologic mapping, hydrologic monitoring, and records maintenance. Specific plans will depend on the design of the repository, but should be complete and at a level of accuracy that affords prediction of rock mass behavior.

Analysis of these data may lead to redesign of some construction elements. Since prediction of geologic conditions is not an exact science. some redesign is anticipated in even the most thoroughly investigated underground construction projects.

The process of design based on instrumentation and construction monitoring is the basis of the New Austrian Tunneling Method (NATM). The NATM is widely accepted in Europe and requires a high degree of interaction between the construction contractor and the owner/designer. Elements of the NATM approach may be suitable for repository construction, and should be carefully considered.

3.0 APPLICABILITY OF THE DESIGN.APPROACH

The design logic presented in Section 2.0 can be applied successfully to a jointed rock such as basalt. The data collected to-date at the Hanford site can be analyzed to provide the following design input parameters:

- Rock mass strength and elastic properties
- In-situ stress magnitude and direction
- Groundwater pressure and flow
- Rock mass thermal properties

These parameters would be estimates obtained on the basis of laboratory test results scaled down to in-situ values using geological, hydrological and geomechanical data resulting from core logging, pump testing, and Near Surface Test Facility (NSTF) testing. The geomechanics classification systems mentioned in Section 2.0 can be used in estimating rock mass strength.

The excavation induced stresses can be obtained using analytical approaches and the 2-D numerical modeling method mentioned in Section 2.0. The loosened zone around the opening can be included in the 2-D numerical model by assuming a lower modulus value than the rock mass. Thermally induced stresses can be computed using the thermomechanical analyses mentioned in Section 2.0. The principle of superposition can be used to superimpose the thermal stresses on the excavation induced stresses. Stresses around the openings can then be compared to the rock mass strength estimates to determine the stability of the openings. Deformation resulting from the stresses can be determined using the finite element technique.

The conceptual design obtained by the above mentioned techniques should have sufficient flexibility to accommodate the improvements that can be incorporated by using in-situ data from the exploratory shaft testing. The estimates that were used for the design input parameters can be verified and/or refined as in-situ data on rock mass strength, modulus of deformation, rock mass thermal properties, in-situ stresses, and groundwater is obtained from the underground testing program. The spatial variability of the in-situ data in the repository horizon can be estimated, and sensitivity analyses carried out using a range of expected design input parameters. These analyses will determine the effect of geologic variability on repository design.

The support system behavior under the expected temperature and moisture conditions should be analyzed using the data from in-situ monitoring in the underground test excavations. Design refinements

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can be constantly made as the data base from underground observations accumulates and provides greater confidence in the predictability of rock mass behavior.

4.0 AREAS OF CONCERN

There are several areas of concern in the BWIP Site Characterization Report (SCR) that have to be addressed in future SCR updates. These are related to in-situ stresses, rock mass strength, rock mass deformation, and repository design.

4.1 In-situ Stress

The in-situ stress measurements by the hydraulic fracturing method have to be verified by conducting overcoring (or other stress relief techniques) tests at the bottom of the exploratory shaft. The spatial variability of in-situ stresses in the reference repository location (RRL) has to be established by conducting hydraulic fracturing tests in other boreholes in the RRL. The constuctability of openings, both waste emplacement rooms and holes, in the high horizontal stress field should be established in the exploratory shaft testing program. Monitoring of deformation of the underground openings as they are excavated will provide an indication of the global rock mass stress conditions. The effect of the uncertainties in the assessment of the in-situ stress field on repository design should be evaluated.

4.2 Rock Mass Strength

Rock mass strength should be estimated on the basis of geological data collected to date, data from the NSTF, and laboratory test results. Estimates arrived at independently by the NRC using the BWIP laboratory data and core log information indicate that the rock mass strength may be about one-half of the 200 MPa used in the BWIP conceptual design. Rock mass strength should be determined using the heated block test, and other appropriate tests in the exploratory shaft bottom. Detailed mapping of underground exposures should be done, especially in the areas where rock mass strength tests are to be conducted. This will permit correlation of rock mass strength with the discontinuity characteristics of the rock. Derived correlations can then be used to predict the rock mass strength throughout the repository. Rock mass strength assessment should include the effect of moisture (various degrees of saturation), temperature and time.

4.3 Rock Mass Deformation

Rock Mass deformation modulus should be measured in the bottom of the exploratory shaft by conducting the Rocha Slot test or other appropriate tests. In addition, monitoring of all underground drifts will provide an estimate of rock mass deformation and support requirements in the repository. Deformations should be carefully measured in heater tests to determine the effect of temperature increase on rock mass deformation. In essence, the rock mass constitutive relationship under expected repository conditions should be established.

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4.4 Repository Design

The waste emplacement rooms have been designed as ovaloids to accommodate the high horizontal stress; however, the reaming rooms are designed in a horseshoe shape. This might cause overstressing and instability. The sensitivity of the various input parameters, especially rock mass strength and modulus, thermal properties, and geologic structure, have not been considered in the design. Sensitivity analyses are important because they provide valuable guidance in data gathering efforts at the bottom of the exploratory shaft.

The effects of moisture, temperature and time on the performance of the support system have not been fully considered. These effects and the effect of thermal loading on the stability of waste emplacement holes are major factors in providing for local retrieval from portions of the repository which are deemed unsuitable from a geologic standpoint.

The basis for orientation of the rooms and waste emplacement holes seems to be the in-situ stress field; however, the effect of groundwater flow seems to have been neglected. The justification for selecting the maximum design stress and the maximum design temperature is not clear and seems to be based on laboratory derived values. The manner in which the conceptual design will be changed to accommodate the geologic, geohydrologic, and geomechanics data obtained from the exploratory shaft testing program is not described in the SCR. In addition, the effect of geologic variability within the repository horizon on repository design is not discussed.

5.0 CLOSURE

A design logic for stable openings is presented in this appendix which can accommodate the improving nature of the data base inherent in geologic exploration. The need for flexibility in the conceptual design is emphasized since this will allow for design improvements based on in-situ data to be obtained from the exploratory shaft. A phased design approach, which is applicable to a fractured hard rock such as basalt, is presented. Critical design input parameters are discussed since they define the information needs for resolving several issues affecting repository design.

The applicability of the design approach to the BWIP subsurface design is discussed. Several techniques are available to satisfy this design approach, the key elements of which are the determination of rock mass characteristics and the stresses and deformations resulting from excavation and thermal loading. The importance of monitoring subsurface openings and using the monitored data to improve the design are emphasized.

Areas of concern in the conceptual design presented in the BWIP Site Characterization Report are briefly discussed. Ongoing site characterization and design efforts could resolve these areas of concern.

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