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Informal Report

Rock Mechanics Methods and In Situ Heater Tests for Design of a Nuclear Waste Repository in Basalt

M. P. Board

June 1978

Prepared for the United States
Department of Energy
Under Contract EY-77-C-06-1030

Rockwell International

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**Rockwell Hanford Operations
Energy Systems Group
Richland, WA 99352**

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PRELIMINARY REPORT

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Informal Report

ROCK MECHANICS METHODS AND IN SITU HEATER TESTS
FOR DESIGN OF A NUCLEAR WASTE REPOSITORY IN BASALT

M. P. Board

Basalt Technology Unit
Waste Isolation Program

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1.0 INTRODUCTION

This paper discusses how in situ data from the Near-Surface Test Facility will be integrated into the overall Waste Isolation Program. It also discusses the rock mechanics methods used for the design of a repository in hard jointed rock and places the Near-Surface Test Facility heater tests into the context of the total picture of the repository design.

The following discussion deals primarily with the application of numerical models to the design of a waste repository. First, the various types of models currently available are discussed with reference to design in basalt. Next, the breakdown of the problem of repository design is given. It is seen that the most efficient method for analyzing repository design is to break the problem down into several problems which are based on physical scale. These include the area directly surrounding a single waste canister (the very near field), the area including many canisters and canister emplacement rooms (the near field), and the area including the entire repository and the rock mass to the free surface (the far field). The methods by which numerical models are used for design are discussed. Flow charts are used to show the basic input data required, the calculational processes used, and the preliminary criteria for judgment of suitable repository performance. It is seen through the preceding discussion that the ultimate design of the allowable gross thermal loading density, and, thus, the layout of the underground workings is highly dependent upon the rock mass properties supplied as base line input data to the numerical models. Of the many input properties required, the thermal conductivity, the thermal expansion coefficient, and elastic moduli of the rock mass have, perhaps, the greatest effect on the calculation of induced temperatures, stresses, and displacements and, thus, repository design. To ensure that the design continues with confidence, actual field (in situ) values of input data must be obtained. Finally, the role of the Near-Surface Test Facility in situ testing in obtaining these basic required data is discussed.

2.0 ROCK MECHANICS METHODS IN REPOSITORY DESIGN

2.1 INTRODUCTION

In most branches of engineering, the engineering designer can choose the structural materials with which he plans construction. These materials generally have known physical properties, and the ambient conditions of temperature, stress, and moisture under which this structure must operate are well known. The designer of structures in rock, however, must perform design on materials which are at hand. In the case of a nuclear waste repository in hard, jointed rock, the design must be able to proceed with the confidence that the underground structure will be stable and perform as predicted over time spans not presently considered in normal engineering design. Numerical models which simulate the heat transfer as well as elastic behavior of the rock mass will be used for repository design. In order that the design proceed with confidence, the models which are used must be:

- Based on realistic input data which take into consideration the gross mechanical and thermal characteristics of the jointed rock mass; and,
- Field verified with actual in situ rock testing data.

2.2 NUMERICAL MODELING AND CONCEPTUAL REPOSITORY DESIGN

Underground structures in rock are normally designed by a combination of various computer modeling methods and practical experience. In the case of the design of a deep nuclear waste repository in hard rock, computer models will largely be used, since there is little practical experience in the behavior of rock when subjected to thermal loads. The following is a basic description of the models currently being used in the Waste Isolation Program, the basic equations describing the calculation of the induced rock mass temperatures, stresses, and displacements, the input data required, and, finally, the factors and criteria required for structural repository design.

2.2.1 Numerical Methods

There are several different numerical methods which can be used for the design of a nuclear waste repository in hard rock. These methods must take into account both the thermal and the mechanical effects of waste emplacement. The type of method used depends on the type of material behavior expected, as well as the scale of the problem to be analyzed. Basically, the functions which these methods must perform are: ⁽¹⁾

- Thermal Analysis - The analysis should include non-homogeneous materials and temperature-dependent materials;
- Stress Analysis - The analysis should include the calculation of both thermal- and mining-induced stress for non-homogeneous materials;
- Sequential Excavation and Waste Emplacement - Simulation of the time sequence of waste emplacement is important, since the sequencing will control the stress history of the repository;
- Interaction of Excavations - Interactions of thermally loaded excavation horizons are complex and important in the determination of stress-loading history;
- Stability Analysis - Analysis of the stability of underground openings is required to examine the proper design of the underground workings;
- Simulation of Discontinuities - Should have the ability to simulate at least major discontinuities such as faults; small-scale discontinuities directly around the mine openings could be analyzed by assumed non-linear material behavior;
- Simulation of Heat - Stress - Ground Water Flow Interaction - Codes must be developed which couple these phenomenon.

The above functions can be accomplished through the use of individual or by a combination of computer codes. The basic types of computer codes currently being utilized are:

- Analytical solution model;
- Differential model;
- Integral model.

2.2.1.1 Analytical Solution Models

Models utilizing analytical solutions are, perhaps, the simplest thermomechanical models. They consist primarily of

closed form solutions to well-known problems, such as the stresses and temperatures around a point heat source in an infinite medium. Analytical solutions are used to study such problems as the temperatures around a single canister over short time periods, or the regional rock mass behavior where geometric detail and non-linear rock behavior are not important. Examples of analytical solutions can be found in much of the literature on repository design.^(1,2,3)

2.2.1.2 Numerical Methods

It is not possible to obtain analytical mathematical solutions for many problems encountered in engineering. For complex systems (such as rock masses), numerical methods are required which yield approximate (within acceptable limits) solutions. Numerical methods currently available for solving thermomechanical problems can be classed as differential or boundary-integral. In the differential methods, the entire region of study is modeled; whereas in the integral methods, only the boundaries of the region need be defined. The differential methods are better suited to modeling problems of complex, non-linear behavior and the integral methods are better for simpler problems of large areal extent.

Differential Methods

Differential methods include both the finite difference and finite element methods. In the finite element method, the actual continuous structure is replaced by an equivalent idealized structure composed of discrete elements referred to as finite elements. By assuming displacement or temperature fields within an element, it is possible to satisfy equilibrium conditions and solve the actual temperatures, stresses, and displacements within the body. In the finite difference method, the governing mathematical equations describing the physical behavior of the body are approximated directly at points throughout the structure. The approximation is, therefore, mathematical rather than physical, as in the finite element method. The following discussion on integral and differential methods and problem breakdown is from Hardy, et al.⁽³⁾

Differential methods may be used to solve both boundary value and initial value problems (Figure 2.2-1). The governing differential equations in the former case are of the elliptic type, while those for initial value problems are hyperbolic or parabolic. Initial value problems include stress wave propagation and transient heat and fluid flow processes. Solution of this latter group of problems involves some sort of time stepping algorithm, which could be one of two fundamentally different formulations. The solutions at any time may be expressed in terms of values at the previous time step only, or values at the current time step. In the first case, the solution procedure would be termed fully explicit and, in the second case, fully implicit. Practical advantages of the explicit schemes include that no equations need to be solved and that any type of material behavior can be readily defined within the computational process. A disadvantage lies in the necessity to meet a numerical stability criterion which limits the maximum time step size. In contrast, implicit schemes are unconditionally stable (numerically). The choice between the two schemes must depend largely on the rate of the physical process which is being modeled. When changes are slow, then an implicit technique might be used so that time intervals between calculations may be large. When the changes are rapid, and it is important to obtain the detailed history for any parameter, the explicit formulation would be more economical. Additionally, explicit schemes are particularly well suited to solving large problems, because, since they do not involve handling large sets of equations, they need not make excessive demands on computer storage.

Both finite element methods and finite difference methods may be used to solve initial value problems in the manners discussed above (Figure 2.2-2). Several powerful computer codes based on explicit formulations of the finite difference method are available and have been widely used, particularly in weapons research.⁽⁴⁾ There are fewer examples of explicitly formulated finite element models, perhaps because of the obvious simplicity of the alternative finite difference approach. Although all of

FIGURE 2.2-1

DIFFERENTIAL METHODS

FIGURE 2.2-2
SOLUTION OF INITIAL VALUE PROBLEMS

these models solve initial value problems, they may also be used to solve boundary value problems if the dynamic effects are appropriately damped (Figure 2.2-1). Such an approach may be particularly useful when conditions are indeed time varying and wherever the history of events may affect the final solution. Non-linear material behavior around an exponentially decaying source of heat would be a good example of such a problem.

Boundary-Integral Methods

The boundary-integral methods have been less widely used than the differential methods; their historical development having been more heavily dependent upon the availability of computers. However, there are now three distinct groups of methods: the boundary element; the displacement discontinuity; and, the boundary-integral equation, or reciprocal. When applied to solve problems in elasticity, the boundary element method and the displacement discontinuity method make use of elementary solutions from the theory of elasticity. In the boundary element method, a set of fictitious forces is applied to the boundary to produce a stress state satisfying all the boundary conditions. In the displacement discontinuity method, an equivalent set of fictitious displacements is obtained. The stress at any point is then known in terms of the fictitious forces or displacements. The boundary-integral equation method is currently the most versatile of the boundary-integral methods. It is conceptually similar to the boundary element method, but the reciprocal theorem from the theory of elasticity is used to eliminate fictitious forces for the analysis. The solution is then expressed in terms of real displacements or stresses at the boundaries. Developments of the boundary-integral equation method include treatment of non-homogeneous materials by a method of substructuring, treatment of elastoplastic behavior, and solution of dynamic problems.⁽⁵⁾

There are examples of the use of the boundary-integral equation and boundary element methods in geomechanical modeling, and special developments of the latter to handle joint opening

and slip have been made. At the present time, the displacement discontinuity method has been particularly developed for this purpose. Models incorporating material discontinuities, such as faults and joints which have non-linear deformational properties, have been developed. In addition, displacement discontinuities have also been used to represent, in both two- and three-dimensional space, tabular or vein-like mining, or extraction systems. For these applications, each displacement discontinuity assumes properties that reflect the physical properties of the material on the extraction horizon; these being linear or non-linear, as appropriate.

2.2.2 Problem Breakdown for Design Analysis

To model in one step the complete repository, including the detail required around the excavations and the canister, is impossible at this time. Therefore, the problem has to be broken down into a number of parts in order to model the thermomechanical behavior of a repository effectively. An ideal subdivision of the problem is in terms of scale; for example:

- The immediate vicinity of a canister or a number of canister rooms (canister-scale);
- The canister room interaction or number of rooms, a number of excavations (room-scale); and,
- The complete repository without the detail of the canisters (repository-scale).

A diagram indicating these three study areas is illustrated in Figure 2.2-3.

Within each scaled subdivision for the problem, breakdown into individual studies might be used to consider differing time scales or to investigate the influence of various phenomena.

Canister-Scale Studies

The thermomechanical interaction of waste canisters within a borehole will be modeled in detail to evaluate alternate canister borehole configurations. These studies will be described toward two primary objectives:

CANISTER-SCALE STUDIES

REPOSITORY-SCALE STUDIES

ROOM-SCALE STUDIES

FIGURE 2.2-3

PROBLEM BREAKDOWN INTO THREE DIFFERENT STUDIES DEPENDING ON SCALE

- Establish the maximum allowable power input per canister; and,
- Determine borehole lining configurations that will allow ease of canister retrieval.

Studies are currently being undertaken to achieve these objectives.

- Study of Canister Design and Rock Interaction - The mechanics of heat transfer from canister to rock could include radiation, conduction, and convection within the air gap between the canister and rock, or rock lining. In addition, the internal design of the canister, which could consist of up to three spent fuel rods arranged in a sealed canister, is important to studies of the maximum canister and canister/rock interface temperatures.
- Study of Rock Lining Interaction - Lining of the borehole in the basalt could be required to guarantee retrievability. The interaction of this lining and the basalt under the thermally induced stresses is somewhat unusual to normal rock mechanics experience. Hence, in selecting a suitable lining material and lining dimensions, a very detailed analysis, including non-linear rock behavior, phase change in the interstitial water, and influence of blasting and earthquakes, will be required.
- Thermal Analysis of Various Borehole Sealing Alternatives - These studies will assess thermal loading to cavern and, hence, ventilation requirements.
- Interaction of Thermal Stresses from Adjacent Canisters Within Retrievability Period - Canisters could be spaced in a single row down the center of rooms or in multiple rows per room. The interaction of the canisters will influence allowable thermal power inputs per hole and lining requirements. Two approximate geometrical subdivisions of this problem are noted below.
 - (1) Model single canister detail by axisymmetrical analysis about the canister (see Figure 2.2-4). The outer boundaries of the model are assumed to be flux-free and radial displacements-fixed. This type of analysis is appropriate for very short times when the temperatures and stresses are relatively independent of the neighboring heat sources and, hence, symmetrical about the vertical axis. The canister/rock lining/rock failure interaction and the heat transfer from within the canister to the rock can be modeled on this scale.
 - (2) Plane strain model, where a line of canisters is merged as a strip of heat sources. Clearly, for this model (two dimensions), the temperature distribution and stresses between individual canisters cannot be determined;

FIGURE 2.2-4

AXISYMMETRIC MODEL ABOUT THE CANISTER FOR SHORT-TERM ANALYSIS

but, such things as influence of multiple rows of canisters per room and the influence of a single row of canisters on room stability can be studied.

In some circumstances, full three-dimensional analysis, as shown in Figure 2.2-5 is required. The symmetry for the problem shown in Figure 2.2-5 is for four planes; that is, two vertical planes through the center of the canister (one parallel and the other perpendicular to the axis of the excavation), one vertical plane through the excavation centerline, and one vertical plane through the pillar centerline. The problem is three-dimensional and, because of the strong interaction between the borehole and excavation for stress analysis, it is difficult to simplify the geometry. A three-dimensional finite difference mesh of the geometry illustrated in Figure 2.2-5 is given in Figure 2.2-6. This mesh consists of five parallel sections perpendicular to the excavation axis. In this case, the canister borehole is modeled as square in cross section, rather than circular as is the real case. Illustrations of results from the finite difference calculations are given in the section entitled: Room-Scale Studies.

Room-Scale Studies

Room-scale studies involve the geomechanical modeling of the interaction of the thermal stress generated by canister placement and the excavation. The primary objective of these studies is to establish acceptable waste disposal densities per room and to design and size the shape and support requirements for the rooms. Some important areas related to these studies include:

- Short-Term

- (1) Stability of rooms for the retrievability of canisters and the backfilling of rooms;
- (2) What support is required to assure stability;
- (3) Effects of earthquakes and blasting on room performance;
- (4) Short-term cooling from ventilation;
- (5) Problems with water inflow;
- (6) Extraction ratio;
- (7) Backfilling;

FIGURE 2.2-5

GEOMETRICAL ARRANGEMENT FOR CANISTER EMPLACEMENT
OF A SINGLE ROW OF CANISTERS IN A WASTE CORRIDOR

FIGURE 2.2-6

THREE-DIMENSIONAL FINITE DIFFERENCE MESH.

- (8) Establish acceptable pattern of canister holes per room.

• Long-Term

- (1) Collapse of excavations, whether connection between individual rooms occurs and associated changes in permeability or piping occurs above individual rooms, causing low-permeability paths for water flow;
- (2) Water flow;
- (3) Weathering giving rise to increases in permeability.

The geometry of a series of parallel excavations with canisters down the centerline of the rooms, as shown in Figure 2.2-7, is also applicable for analysis of the room-scale studies. This geometry is for immediate placement of all canisters. However, for periods greater than approximately 3 years after canister placement, the thermal output of the canisters can be considered as two-dimensional. This is illustrated in Figure 2.2-8. In Figure 2.2-8, isotherms on vertical planes perpendicular to the excavation Axis A through the center of a canister and Axis B through the point midway between two canisters respectively are shown. The spacing of the canisters in this thermal analysis was 13 feet with a thermal loading of 200 kilowatts per acre at an elapsed time of 5 years. Isotherms at 3 years, although not shown here, are similar for the two sections. Therefore, thermomechanical analysis can be undertaken of a series of two-dimensional excavations as indicated in Figure 2.2-7.

The canister boreholes are not modeled, but, if the boreholes are well spaced, then the calculation of the temperatures, stresses, and displacements around the excavation will not be in error. Also, the modeling of the placement sequence of the canisters, as illustrated in Figure 2.2-7, can be considered by this two-dimensional simplification of geometry.

Repository-Scale Studies

The objective of the repository-scale studies is to establish the overall waste disposal density and to provide

FIGURE 2.2-7

TWO-DIMENSIONAL IDEALIZATION OF EXCAVATION GEOMETRY

FIGURE 2.2-8

ISOTHERMS AT SECTIONS THROUGH THE CANISTER
AND MIDWAY BETWEEN THE CANISTERS
AFTER 5 YEARS FOR THE 200 KILOWATTS PER ACRE CASE

analysis to assist in the overall layout planning and sequencing of the repository. Repository-scale studies will include the interaction of the repository with regional geological, hydrological, and surface features.

Studies will be required to determine:

- Interaction of repository with shaft, determination of location and lining requirements;
- Changes in permeability due to stress changes above and below the repository;
- Temperature rise in aquifers and near the surface;
- Uplift/subsidence of the surface;
- Thermal gradients giving rise to ground water flow;
- Overall stability of the repository in the short- and long-term;
- Acceptable room spacing and overall initial gross thermal loads (waste disposal per acre of repository);
- Influence of geological features, such as faults, and lithology on repository design.

In some cases of the regional analysis, details such as canister boreholes and excavation geometry will not be modeled directly, but simplifying assumptions will have to be made. For example, Figure 2.2-9 shows a repository layout for which a two-dimensional analysis would be quite misleading. For such a repository, a regional analysis would not include the influence of the excavations, but would correctly distribute the heat sources throughout the rock, as would be the case in the repository.

2.2.3 The Process of Repository Design Utilizing Numerical Methods

Figure 2.2-10 is a flow chart which shows the basic thought processes for the use of numerical models for repository design. The basic flow of the design is from very near field (canister-scale) studies to near field (room-scale) studies to regional-scale (repository-scale) studies. The maximum power per borehole is determined in the very near field analysis; the spacing of boreholes (and, thus, the gross thermal loading) is determined

FIGURE 2.2-9

SCHEMATIC OF TYPICAL UNDERGROUND WASTE REPOSITORY

*K = Permeability
 k = Thermal Conductivity
 α = Thermal Expansion Coefficient
 ρ = Density
 C_p = Specific Heat
 E = Young's Modulus
 ν = Poisson's Ratio
 σ_c = Compressive Strength

ϕ = Internal Angle of Friction
 S_c = Cohesion
 T_o = Tensile Strength

** Circled letters indicate additional flow charts for detail on those criteria.

FIGURE 2.2-10

FLOW CHART FOR REPOSITORY DESIGN

from the near field analysis; and, finally, the effects of the gross thermal load on the regional repository field is checked in the regional or far field analysis. The initial input data required of the models include the following.

- Site Conditions
 - (1) Depth of overburden
 - (2) Stratigraphy of site
 - (3) In situ state of stress
 - (4) Ambient rock temperature
 - (5) Ground water system
- Rock Properties
 - (1) Thermal conductivity, k
 - (2) Specific heat, C_p
 - (3) Thermal expansion coefficient, α
 - (4) Young's Modulus, E
 - (5) Poisson's Ratio, ν
 - (6) Compressive strength, σ_c
 - (7) Permeability, K
 - (8) Internal angle of friction, ϕ
 - (9) Cohesion, S_c
 - (10) Density, ρ
 - (11) Tensile strength, T_o
- Mine Geometry
 - (1) Room dimensions
 - (2) Pillar dimensions
 - (3) Sequence of waste emplacement
- Nuclear Fuel Properties
 - (1) Initial heat load per canister

- (2) Decay of heat over time
- (3) Physical dimensions of heat source
- (4) Canister dimensions
- (5) Liner geometry
- (6) Geometry of canisters (i.e., borehole geometry)

2.2.3.1 Very Near Field (Canister-Scale) Studies

The process of repository design is started by choosing an initial canister spacing and heat load and inputting to the very near field analysis. As described in the section entitled: Problem Breakdown for Design Analysis, the very near field analysis is normally undertaken by an analytical or differential model. Examples of the types of equations which are utilized for this analysis are given below.⁽⁶⁾ The equations are typical exact solutions for the temperatures and stresses induced by an instantaneous line heat source in an infinite medium. Other equations of thermoelasticity are similar and these are given only to demonstrate how the basic input data are used.

- Temperature

$$T = Q_o \frac{e^{-r^2/4\kappa t}}{4\pi\kappa t c_p} \quad (1)$$

- Stress

- (1) Radial

$$\sigma_{rr} = \frac{Q_o E \alpha (1 - e^{-r^2/4\kappa t})}{2\pi(1-\nu) r^2 c_p} \quad (2)$$

- (2) Tangential

$$\sigma_{\theta\theta} = Q_o \frac{E \alpha}{2\pi(1-\nu)} \left(\left[1 + \frac{r^2}{2\kappa t} \right] e^{-r^2/4\kappa t} - 1 \right) / (r^2 c_p) \quad (3)$$

- Displacement
 - (1) Radial

$$U_r = Q_o \frac{(1+\nu)\alpha}{(1-\nu)} \frac{(1-e^{-r^2/4\kappa t})}{2\pi r C_p} \quad (4)$$

where;

- ν = Poisson's Ratio,
- α = Coefficient of linear thermal expansion,
- κ = Diffusivity,
- t = Time,
- E = Young's Modulus,
- r = Radial distance from center of heat source,
- C_p = Specific heat,
- Q_o = Initial power output heat source,
- T = Temperature,
- $\sigma_{\theta\theta}$ = Tangential Stress,
- σ_{rr} = Radial Stress;
- U_r = Radial Displacement.

The model will output the parameters of temperature, stress, and displacement. The thermally induced stress and displacement are superimposed upon the mining-induced values to obtain the total temperature, stress, and displacement behavior of the very near field. As seen in Figure 2.2-10, the stresses and temperatures are compared to the criteria established for maximum waste temperature, maximum canister temperature, allowable rock mass temperature, and allowable rock mass stress. The maximum waste and canister temperatures are given in Figure 2.2-11. The allowable limits for the rock mass are not currently known (see Figure 2.2-12); however, it appears that these are not the controlling factors, unless borehole decrepitation seriously alters basalt thermal conductivity at low temperatures. This will be determined from in situ heater tests.

FLOW CHART A

TOTAL RECYCLE*	GLASS	500°C
	CALCINE	700°C
	STAINLESS STEEL	
	CANISTER	375°C
URANIUM ONLY RECYCLE*	GLASS	500°C
	CALCINE	700°C
	STAINLESS STEEL	
	CANISTER	375°C
SPENT UNREPROCESSED FUEL**	ZIRCALOY CLADDING	375°C

*Source: Reference 7.

**Final determination not made to date.

FIGURE 2.2-11

MAXIMUM WASTE AND CANISTER TEMPERATURE LIMITS

FLOW CHART B

Source: Reference 3.

FIGURE 2.2-12

DETERMINATION OF MAXIMUM ALLOWABLE NEAR FIELD ROCK TEMPERATURES AND STRESSES

If any of the criteria from Flow Chart A are exceeded, the estimated canister spacing is increased and/or the heat load per canister is reduced, and the models are run again. If it is found that the estimated canister geometry results in temperatures and stresses far below the criteria in Flow Chart A, the canister spacing is reduced and/or the heat load per canister is increased.

2.2.3.2 Near Field Analysis (Room-Scale)

When the maximum heat load per canister and optimum canister spacing are determined, they are then used as input parameters to the near field analysis. The near field analysis (as described earlier) is normally conducted by either two- or three-dimensional differential or integral models. In addition to the canister heat loading parameters, the room and pillar shapes and dimensions, as well as the base line rock properties, are required input data. The shape and size of rooms and pillars are derived from two basic sources:

- From previous work in the size of openings required for ease of canister handling and transport; and,
- From practical mining experience.

With this basic input, the numerical models are run and the temperatures, stresses, and displacements around the mine openings are determined. It is noted here that the calculation of induced rock stress is highly dependent upon the assigned rock mass values of Young's Modulus, thermal conductivity, and the thermal expansion coefficients. The following equation for the thermally induced radial stress around a line heat source illustrates the importance of these factors. ⁽³⁾

$$\sigma_r = \frac{\alpha E}{(1-\nu)} \frac{\bar{T}}{2} \times 10^3 \text{ Megapascals} \quad (5)$$

where,

α = Thermal expansion coefficient,

E = Young's Modulus,

$\bar{T}$ = Mean temperature within a radius, r,

ν = Poisson's Ratio.

The temperature in this case is approximately inversely proportional to the thermal conductivity of the rock mass. It is seen that the stress is directly proportional to modulus, expansion, and temperature. A poor knowledge of the in situ values of these constants can, therefore, have a great effect upon the calculated induced stresses and, thus, the room and pillar dimensions and the allowable maximum heat loading of the repository.

After calculation of the induced stresses, they are compared with an appropriate rock mass strength or stability criterion to determine the suitability of the mine geometry. The determination of stability criteria for the in situ rock mass is, perhaps, the least well-developed area of the field of rock mechanics. There is little definitive field experience in the determination of in situ strength values of rock, and, therefore, high safety factors are often assigned. Several methods are used for the determination of the structural stability of the rock mass. The primary idea behind these stability criteria is that, during the life of the mine and the retrievability period, failure of the rooms or pillars should not exceed that which can be economically supported or easily cleaned up (i.e., no more than very local failures such as small block slippage around the room periphery). After repository decommissioning, the failure around the repository should not be progressive in nature and must be limited in extent. A stability or failure criterion essentially defines the relationship among the principal stresses ($\sigma_1, \sigma_2, \sigma_3$) within the rock mass to a postulated rock mass strength. The stresses are determined from the near field numerical models. Methods used to determine the rock mass strength values include the following.

- Reduction Factors

Reduction factors are often applied to the rock mass elastic and strength properties as determined from laboratory rock tests in an attempt to take into account the effects of fractures and joints as the "specimen" size increases. The reduction factor can be expressed as:

$$R = \frac{\text{Rock Mass Value (Strength, Modulus, etc.)}}{\text{Laboratory Value (Strength, Modulus, etc.)}}. \quad (6)$$

Reduction factors are derived primarily from personal experience. Without confirming field testing, such values are highly subject to criticism. If the calculated stress overcomes the strength of the material, failure is assumed to occur, and pillar dimensions must be increased to reduce stress.

• Mohr-Coulomb Criterion

The Mohr-Coulomb Criterion is often used to determine the susceptibility of the rock mass to shear failure. This method is particularly useful in the study of room stability, since a likely failure mode is by shear failure in jointing surrounding the room. A recent example of this type of analysis was presented by Mahtab, et al.⁽⁸⁾ The Mohr-Coulomb Criterion is given by the equation:

$$T = S_c + (\sigma_n - p) \tan \phi \quad (7)$$

where;

T = Shear stress associated with the plane of failure,

σ_n = Normal stress associated with the plane of failure,

p = Pore water pressure,

ϕ = Internal friction angle of the material (either intact or jointed),

S_c = Cohesion of the rock mass.

The internal angle of friction is a laboratory-determined parameter. The cohesion can be expressed as:

$$S_c = (1/2) C_o \tan (\pi/4 - \phi/2) \quad (8)$$

where;

C_o = Uniaxial compressive strength of the rock.

Models are run and the stresses determined at points in the rock mass. The stresses for planes of varying attitudes are determined and inserted into Equation 7 above. If the shear stress existing along this plane is greater than the strength,

the rock is assumed to have failed and residual strength parameters are assigned to the rock mass at that point. In this manner, iterations can be made with the computer model, and progressive failure simulated. Figure 2.2-13 illustrates the influence of the in situ stresses, joint cohesion, and angle of friction upon the progressive failure of a jointed rock mass. Contour lines indicate zones in which the rock mass has overcome the Mohr-Coulomb Criterion indicating slippage along joints. It is seen that, in all cases, failure is highly localized and within one radius of the tunnel.

- Slabbing Failure

Criteria have been established for "slabbing" of brittle rock walls around underground excavations based upon the work of Fairhurst and Cook.⁽⁹⁾ This criterion relates the principal stresses and the rock mass strengths under triaxial loading conditions. The criterion is given by the equation:

$$\sigma_1 = C_o + \frac{1-\mu}{\mu} \sigma_3 \quad (9)$$

where,

σ_1, σ_3 = Principal stresses (calculated),

C_o = Uniaxial compressive strength,

μ = Ratio of the uniaxial compressive strength to uniaxial tensile strength (i.e., $\mu = \frac{C_o}{T_o}$).

This criterion is not often used, since the behavior of the room periphery is primarily controlled by the joints, and, therefore, the Mohr-Coulomb Criterion is preferable.

- Thermal Spalling

Studies to date by Mahtab, et al.,⁽⁸⁾ and Thirmulai⁽¹⁰⁾ indicate that thermal spalling around the room periphery will not present a problem; however, definitive field experience is required with thermally loaded in situ rock. No criteria are currently available.

Flow Chart C (Figure 2.2-14) illustrates the process of determination of optimum room and pillar dimensions. If criteria are exceeded, either the pillar dimensions must be increased or the thermal loading decreased.

Legend: --- $k=2$ k =Ratio of the principal stresses.
 — $k=1$

INFLUENCE OF IN SITU
 STRESS ON PROGRESSIVE
 FAILURE OF JOINTED ROCK

Legend: — $C=2.9$ MPa
 --- $C=.69$ MPa

INFLUENCE OF JOINT CO-
 HESION ON PROGRESSIVE
 FAILURE OF JOINTED ROCK

Legend: — $B=45^\circ$
 --- $B=30^\circ$

INFLUENCE OF ANGLE OF
 FRICTION OF JOINTS ON
 PROGRESSIVE JOINTED ROCK

FIGURE 2.2-13

THE INFLUENCE OF IN SITU STRESS, JOINT COHESION, AND
 JOINT FRICTION ANGLE ON THE PROGRESSIVE FAILURE OF THE ROCK MASS

FLOW CHART C

FIGURE 2.2-14

DETERMINATION OF OPTIMUM ROOM AND PILLAR GEOMETRY

Far Field Analysis (Repository-Scale)

The local thermal loading (as determined from the near field analysis) is used as input to the regional studies. The local thermal loading can also be referred to as the gross thermal loading in kilowatts per square meter. The regional models are primarily of the integral type. The present methods include the boundary element and displacement discontinuity models. Stresses, displacements, and temperatures are calculated in the area surrounding the repository and to the ground surface. These parameters are then compared to criteria which determine if the gross thermal loading, which was acceptable in the near field and very near field cases, is acceptable for the regional case. The Union Carbide Corporation, Nuclear Division, Office of Waste Isolation recently considered the following criteria. (11, 12)

- Surface Uplift/Subsidence

Surface uplift might have to be limited if it gives rise to several disturbances of the rock mass (i.e., change in surface runoff, effects upon surface structures, fracturing of rock mass due to uplift, and subsidence). Limits have not been set; however, for a basalt repository at greater than 2,500 feet, less than 1 foot of displacement occurs for high gross thermal loadings.

- Ground Surface Temperature Rise

A temperature rise of the ground surface might affect flora and fauna. A preliminary limit of 1 degree Fahrenheit was set; however, this appears premature until further work has been completed. All calculations thus far show temperature rises of less than 1 degree Fahrenheit.

- Aquifer Temperature Rise

Rise in ground water temperature levels should be limited at the point of their removal, so that they can be used without cooling.

- Ground Water Flow and Radionuclide Transport

Ground water flow is directly related to the induced temperatures and stresses of the repository region. The least flow could tend to increase the flow rate of ground water above the repository horizon through the development of circulation cells. Induced tensile stresses above the plane of the repository could reduce the normal stress along joints and,

thus, increase the rock mass permeability. Limits have not been set on temperature or stress levels around the repository horizon.

If the regional field criteria have not been overcome, the maximum allowable overall thermal loading has been developed. The models have, thus, provided the:

- Maximum power per borehole;
- Maximum gross thermal loading;
- Optimum room shape;
- Maximum room dimensions;
- Minimum pillar dimensions;
- Preliminary layout of the repository.

An architect/engineering firm can now develop the model designs into actual construction design.

3.0 THE ROLE OF IN SITU HEATER AND MECHANICAL TESTS IN REPOSITORY DESIGN

The previous discussion on the process of repository design through the use of numerical models pointed out some shortcomings. The statement has been made that no numerical model is any better than the input data with which it is fed. This is particularly true with design in rock. The basic thermoelastic equations were given to point out the great dependency of the outcome of repository design on the initial input of rock properties. Unless the input data and the model itself can be used with confidence, the design is highly subject to criticism.

3.1 BASIC ROCK PROPERTY DATA

The basic rock mass properties required as input parameters to design were given in the section entitled: The Process of Repository Design Utilizing Numerical Methods. It was shown that, of these parameters, the Young's Modulus, thermal conductivity, and thermal expansion coefficient have probably the greatest effect on the eventual structural design of the

repository. It is, therefore, required that a better knowledge of these in situ parameters be obtained.

3.1.1 Elastic Moduli

In addition to the basic heater experiments in the Near-Surface Test Facility, several relatively inexpensive mechanical tests will be run, primarily to characterize the rock mass prior to testing. In particular, a large jointed block test will be performed, as well as downhole measurements of the deformation modulus.

3.1.1.1 Jointed Block Test

One method of determining the static elastic properties of in situ, jointed rock is to subject an in-place block of rock to compressive forces and monitor the subsequent displacements, seismic velocity, stress, electrical resistivity, and permeability of the rock mass. An example of such an experiment was reported by Pratt, et al.,⁽¹³⁾ in a cube of massive, jointed granite near Laramie, Wyoming. A block of granite is freed on five sides by line drilling, and flatjacks inserted into the drilled slots to provide both uniaxial and biaxial block compression (see Figure 3.1-1).

FIGURE 3.1-1

SCHEMATIC DIAGRAM OF THE EXPERIMENTAL BLOCK
AND THE POSITIONS OF THE FLATJACKS USED TO LOAD THE SPECIMEN⁽¹³⁾

Holes are drilled in the block for insertion of jacks which are inflated and measurement of the rock mass and joint displacements, seismic velocity, electrical resistivity, and permeability is made. Figure 3.1-2 illustrates the effect of

FIGURE 3.1-2

COMPARISON OF LABORATORY AND IN SITU STRESS-STRAIN
BEHAVIOR UNDER UNIAXIAL STRESS (13)

(The stress direction is indicated on each curve. These are average values. The spread is given by the set of error bars shown. Note the approximate agreement of elastic moduli of laboratory and field values at high stress; at low stress, the laboratory samples are much more compliant.)

loading on the in situ modulus and how it varies from the laboratory-determined value. It is seen that the variance of the laboratory to in situ value is quite significant until a load of approximately 1,000 pounds per square inch is obtained. It is, therefore, highly important that accurate modulus values are known, since the rock mass surrounding the excavations will be "de-stressed." In addition, the change in permeability with stress will provide very important information for the coupled

stress-heat-ground water flow models, since the rock mass permeability is a direct coupling between stress and fluid flow.

3.1.1.2 Colorado School of Mines Dilatometer

The Colorado School of Mines Dilatometer is a device for measuring the deformability (modulus) of a rock mass from within boreholes. The device is merely a cylindrical cell which supplies a radial "jacking" against a borehole wall from which the modulus of the material can be determined. It has been utilized successfully in many rock types. The device will be inserted into many of the Near-Surface Test Facility instrumentation holes prior to installation to determine the in situ modulus along the extent of the borehole.

3.1.2 Thermal Properties

As stated earlier, the thermal properties of conductivity and expansion are very important in the calculation of the thermally induced stress. It is quite possible that joints and fractures, particularly those which are filled, will have a significant influence on the thermal properties of the rock mass. For this reason, a measurement of the "gross" thermal properties is very important for inclusion to numerical models.

3.1.2.1 Conductivity

The in situ conductivity can be determined in several ways. First, arrays of thermocouples will measure temperatures at radii of approximately 6 inches to greater than 13 feet from the heater borehole wall. At several times during the full-scale testing, the heat flux will be increased by a rise in heater power level. By measuring the temperature rise in the thermocouple arrays and by knowing the heat flux and temperature rise time, the thermal conductivity of the rock mass can be calculated.

Less direct methods can be used to qualitatively determine the conductivity, such as numerically modeling the heat transfer around the simulated heater tests. The model input values can be altered to produce the field-measured results and the conductivity

thus inferred. It is noted here that the pre-test geologic characterization is very important for the analysis of the test results. To completely interpret the measurements of in situ properties, they must be correlated to the geologic features in the test near field.

3.1.2.2 Expansion

The thermal expansion coefficient, as well as rock mass temperature, determines the induced thermal stress within the rock mass (see Equation 5). The Near-Surface Test Facility heater near field will be instrumented with two types of stress measurement devices. First, the U. S. Bureau of Mines borehole deformation gauge measures the displacement of the borehole walls, and the local stress field existing around the borehole can be calculated. Each U. S. Bureau of Mines gauge is equipped with a thermocouple for temperature measurement. Second, The IRAD Company vibrating wire gauge indirectly measures the displacement of the walls of a borehole and determines the change in stress existing across the borehole diameter. Again, each IRAD Company vibrating wire gauge is equipped with a thermocouple for temperature measurement. As shown in Equation 10, the radial stress is a function of the temperature and what is called the thermomechanical factor, F :⁽¹⁴⁾

$$F = \frac{\alpha E}{1-\nu} \quad (10)$$

where,

α = The coefficient of thermal expansion;

E = Young's Modulus;

ν = Poisson's Ratio.

The temperature changes are known from the thermocouple reading and Young's Modulus have been determined from the jointed block test described earlier. Since the stresses can be calculated from the gauge readings, the value of the expansion coefficient can, therefore, be "back calculated."

It is obvious that the relation of the orientation of joints and fractures to the position of the gauges is important. For example, a joint set which is perpendicular to the radius connecting the heater centerline and the stress-measuring device could close under radial expansion without affecting the gauge measurement. It is felt, however, that the fractures in the Near-Surface Test Facility will be "tight" and most (as seen from the exploration drilling) are re-healed. In addition, in the basalt flow entablature, there appears to be no significant orientation pattern of joints and, thus, will probably have little effect on stress measurements at varying locations around the heater array.

In addition, the expansion coefficient could be determined in the same qualitative manner as discussed for the conductivity. Predicted stress distributions will be compared to the measured values and, by utilizing the field-measured temperature distributions, the expansion coefficient required to produce the measured stresses can be "back calculated." Such techniques as these have been used to successfully determine in situ salt creep coefficients for the results obtained in the Project Salt Vault. Again, a complete geological characterization of the rock comprising the test area must be completed prior to testing, so that rock mass characteristics can be correlated to testing results.

3.1.3 Numerical Model Verification

As was stated earlier, the structural design of the repository will largely be accomplished through the use of numerical models. Models which are based solely upon laboratory data and have not been verified by actual field testing are highly subject to criticism. For example, recent modeling studies of the prediction of mining-induced stress in stopes in a deep mine indicated that, for a purely elastic analysis, the Young's Modulus had to be reduced by 30 times from the laboratory value before stresses which were comparable to field-measured values could be obtained.⁽¹⁵⁾ Because of this basic problem, the numerical models must be field-verified, so that repository design can proceed with confidence.

Figure 3.1-3 illustrates the data flow from the Near-Surface Test Facility tests. The basic data of temperature, displacement, and stress will be analyzed and coordinated with the geologic characterization. We will then issue data reports leading to the qualification of basalt as a capable heat transfer medium. Data will also be used in preconceptual repository design studies utilizing the numerical models described earlier. We will be performing a complete pre-analysis of the heater tests prior to their start. When the tests have begun, predicted results will be compared to actual field results and the models either verified or modified.

The activity networks shown in Figures 3.1-4 and 3.1-5 show the process of data transference from the heater tests to the mine modeling effort. It is seen that the verified and/or modified computer models are used directly for repository conceptual and Title I design. Initial code development will be completed by the time that Near-Surface Test Facility data are available for analysis.

3.1.4 Other Engineering Data Obtained from Near-Surface Test Facility Tests

In addition to the basic rock mass properties and numerical model verification studies, the Near-Surface Test Facility heater tests will provide some basic engineering design parameters as given in the Near-Surface Test Facility Test Plan. Of these, the following are most important:

- Response of a storage borehole to a heat source simulating a spent fuel canister;
- Decrepitation response of a storage borehole to thermal loading;
- Performance of a borehole liner;
- Measurement of the closure behavior of the testing room and adits, as well as determination of support adequacy.

Some experiments have been performed to study the decrepitation behavior of basalt. The studies show the decrepitation is very low. Even under very high thermal gradients

FIGURE 3.1-3

BASIC NEAR-SURFACE TEST FACILITY
DATA ACQUISITION AND UTILIZATION

FIGURE 3.1-4

ACTIVITY DIAGRAM SHOWING THE PROGRESS OF THE IN SITU TESTS AND THE
POINTS OF DATA FLOW TO THE MINE MODELING EFFORT

FIGURE 3.1-5

ACTIVITY DIAGRAM SHOWING THE PROGRESS OF THE MINE MODELING EFFORT AND THE INTERFACES WITH THE IN SITU TESTING PROGRAM

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and repeated thermal cycling, there is no spalling and little reduction in compressive strength. There are no data, however, on the decrepitation behavior of a jointed and fractured borehole. The results of the in situ response of the borehole to high thermal loads could have far-reaching implications to repository design, such as:

- How do borehole walls (including both intact and jointed rock) perform under thermal loading;
- Does a borehole liner provide adequate support to ensure retrievability under thermal loads;
- What effect do the air gaps between the canister and the basalt have upon the transfer of heat into the rock mass; i.e., are convection and radiation modes important;
- What is the maximum power which basalt can structurally store;
- Are borehole liners required to ensure retrievability?

The testing room and entries will be equipped with extensometers and closure points to monitor the displacement response of the openings over the testing period. There will be little, if any, effects due to the heater experiments over this time frame. This will allow the study of the closure behavior of the rock mass over time, thus supplying valuable information on joint behavior and suitability of the rock support methods.

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