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**Fractured Rock Modeling in the
National Waste Terminal Storage Program:
A Review of Requirements and Status**

Technical Report

May 1983

**Christopher St. John
J.F.T. Agapito and Associates, Inc.
715 Horizon Drive, Suite 340
Grand Junction, CO 81501**

**in collaboration
with**

**Alan Krug—Basalt Waste Isolation Project
Sam Key—RE/SPEC Inc.
James Monsees—Lachel Hansen and Associates**

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Office of NWTIS Integration

BATTELLE Project Management Division

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Christopher St. John¹
J.F.T. Agapito and Associates, Inc.
715 Horizon Drive, Suite 340
Grand Junction, CO 81501

in collaboration
with

Alan Krug—Basalt Waste Isolation Project
Sam Key²—RE/SPEC Inc.
James Monsees³—Lachel Hansen and Associates

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1. Presently with Agbabian Associates
2. Previously with Sandia National Laboratories
3. Previously with Office of Nuclear Waste Isolation, BPMD.

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ABSTRACT

Generalized computer codes capable of forming the basis for numerical models of fractured rock masses are being used within the NWTs program. Little additional development of these codes is considered justifiable, except in the area of representation of discrete fractures. On the other hand, model preparation requires definition of medium-specific constitutive descriptions and site characteristics and is therefore legitimately conducted by each of the media-oriented projects within the National Waste Terminal Storage program. However, it is essential that a uniform approach to the role of numerical modeling be adopted, including agreement upon the contribution of modeling to the design and licensing process and the need for, and means of, model qualification for particular purposes. This report discusses the role of numerical modeling, reviews the capabilities of several computer codes that are being used to support design or performance assessment, and proposes a framework for future numerical modeling activities within the NWTs program.

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1 EXECUTIVE SUMMARY

This report summarizes the need for geotechnical numerical models to support repository development in fractured media and proposes a formalized approach to predictive modeling within the NWTS program. Part of this approach consists of a definition of verification and qualification activities considered essential if computer models are to be used in the licensing environment. This definition, which is summarized in Table 6-1, could be used to provide a basis for developing an investigative effort that would assure that the necessary predictive capability is available to meet the needs of the NWTS program in an economic and timely manner.

The report initially draws a distinction between computer codes and numerical models - the former being described as generalized mathematical and computational tools capable of being applied to a wide range of problems, while the latter are considered to consist of simulations of a particular medium and geologic setting. Computer modeling, therefore, involves a set of activities that includes site characterization, prototype idealization, and interpretation of results as well as mathematical computation. Such modeling activities have a role that extends through all stages of development of a repository, from conceptual design to decommissioning.

In addition to proposing an approach and a tentative set of standards for modeling activities, this report addresses the adequacy of the current modeling effort and the need for communication among the various medium-specific projects within the NWTS program. It concludes that currently available computer codes are largely adequate to support most modeling activities for fractured rock. Weaknesses exist, however, in the capability to model discrete fractures and in treatment of systems in which fluid flow, heat transfer and mechanical deformation, and geochemical processes interact. Hence, relatively limited code development is considered necessary. On the other hand, each project must continue development and qualification of medium-specific numerical models so that the necessary predictive capability is available to meet all projects' needs.

2 INTRODUCTION

The Interface Working Group (IWG) on Fractured Rock Modeling was established in November, 1980, by the Repository Interface Coordination Group (R-ICG) to review the status of fractured rock modeling within the National Waste Terminal Storage (NWTs) program. Specific objectives of the IWG included identification of areas of weakness, areas of overlap between the several groups within the NWTs program, and ways to provide direction for future work in this area. This report summarizes the discussions of the IWG and makes recommendations that should be incorporated in their present form, or some modified form, within the NWTs program strategy for reaching the objectives of licensing and operating geologic, nuclear waste isolation facilities.

Early in the discussions of the IWG, it was apparent that several definitions are required before any rational discussion of fractured rock modeling can take place. The first of these definitions referred to the modeling activity itself. This activity has several components, but broadly consists of simulating some aspect of the behavior of a specific geologic setting or host rock mass. Necessary activities that contribute to the modeling process, therefore, include site characterization, site idealization, numerical analysis, and interpretation of the results of analysis. The numerical analysis is performed using a computer code to construct a model with a particular geometry, constitutive behavior, and set of initial and boundary conditions.

Following this first definition, it is clear that modeling is quite different from preparing computer codes or programs. Modeling will, therefore, be an important function of each medium-specific project within the overall NWTs program, as models must be medium- and site-specific. On the other hand, codes are simply computational tools and can therefore be common to all parts of the NWTs program. This report focuses mainly on modeling but also indicates where some computer code development may be necessary.

The second definition, or set of definitions, refers to the need to provide some assurance that the results of any modeling activity are adequate for a given purpose. Provision of such assurance is divided into Verification and Qualification. Verification is used to mean demonstration that a computer code, or program, is computationally correct. Numerical calculations should be undertaken using only verified codes.

However, the mathematical precision of the code does not in itself ensure that the calculation is adequate, since the model used during the analysis incorporates a description of the geologic setting and the specific constitutive models that govern material behavior. The assurance process for models has been termed "qualification". Models must be qualified for particular application by means of demonstration, validation, and field confirmation. Specific activities necessary to accomplish each of these levels of qualification are discussed later in this report.

Modeling needs of the NWTS program must be established within the framework of the wider objective of the program, which is terminal isolation of nuclear waste. Critical steps within this program are the design and licensing of the underground facility. These steps are supported by several activities including site characterization, laboratory investigation, field testing, and modeling. Estimation of the need for each of these supporting activities requires that their contribution to design and licensing be understood. This report is concerned with the role of modeling and therefore discusses its relationship to other key activities of the NWTS program. These discussions provide a basis for proposing subjective estimates of the required accuracy of modeling results, and degrees of model qualification required as the program progresses from conceptual design through eventual decommissioning and license termination.

In order to assess the adequacy of existing computer codes and of geotechnical modeling within the NWTS program, it is necessary to appreciate the different physical phenomena that must be represented. Four different classes of phenomena are identified: mechanical, thermal, fluid, and chemical. These may be treated independently in some circumstances, while in others the interactions or coupling among the phenomena must be considered. In this report, some existing codes that may be used to support the development of geotechnical models for various programmatic functions are tabulated in terms of the phenomena they represent and the constitutive models that they incorporate. This tabulation is used primarily to provide a basis for assessing the adequacy of existing code capability, but it may also assist in selecting appropriate codes for a particular purpose.

Finally, it should be recalled that the purpose of the Interface Working Group was to assess the NWTS effort in the area of geotechnical modeling of fractured rock masses. While this original objective should be satisfied by this report, the substance of the report extends to the general topic of geotechnical

modeling, whether for fractured or unfractured rock masses. This is inevitable because the activities involved in geotechnical modeling are the same whether the rock mass is so sparsely fractured that individual fractures need be modeled, or so pervasively fractured that individual fractures are unimportant, or whether the rock mass is unfractured and exhibits plastic or viscous behavior. Many computer codes have been used during modeling investigations of several different aspects of nuclear waste isolation in more than one of the potential geologic settings.

3 THE FUNCTION OF MODELING

Although there are many examples of civil engineering structures and even underground excavations that have performed satisfactorily for several hundreds and even thousands of years (Monsees and Munson, 1982), there are many aspects of a nuclear waste isolation facility that are unique. For example, an underground repository will consist of an extensive network of large excavations that must remain completely stable for perhaps as long as 100 years or more (U.S. Nuclear Regulatory Commission (NRC), 1981a). The analogy to mining excavations is good, but ignores the fact that most large underground mining excavations are made for the purpose of extracting ore; long-term stability of the excavations is seldom of direct concern. Indeed, many mining methods, such as longwall caving, are planned in such a manner that failure of the rock mass around the excavation occurs in a controlled manner. Underground excavations for civil engineering purposes frequently have much longer planned lives, but these usually are rather shallow and are not subject to the thermomechanical loading that will be typical of a repository (Raines et al, 1980). Hence, mining and civil engineering provide relevant experience but not direct historical precedent.

Another unusual aspect of a commercial underground waste isolation facility is that it will be the subject of a licensing process (U.S. NRC, 1981a, b) intended to ensure that radioactive releases to the accessible environment meet specific standards both during the operational period of the facility and any time thereafter. This requirement places unusual demands on the site investigation and design activities, particularly in respect to the quality of prediction of system performance.

Because there is no direct historical precedent for an underground repository and because any such facility will be subject to a strict licensing process, there will be a requirement for extensive predictive modeling. Such modeling will be supported by, and complementary to, laboratory and field testing. This section of the report briefly reviews the several programmatic activities that will be supported by modeling and draws particular attention to the several steps in the licensing process that must be completed before eventual geologic isolation of any high-level nuclear waste.

3.1 LABORATORY AND FIELD INVESTIGATIONS

In the absence of direct historical precedent, it is necessary to undertake laboratory and field experimentation to support design. Such experimentation serves three purposes. These might be termed phenomenological, quantitative, and demonstrative. Phenomenological testing is completed to identify the physical processes of concern, quantitative testing to provide direct measurement of parameters or system response, and demonstration tests to provide direct experience of system performance or some aspects of operational procedures. The logical sequence of events would be phenomenological testing, quantitative testing, system design, and then demonstration of system performance. However, careful planning will allow experimentation to serve several functions simultaneously.

Modeling is required to support planning of experimental activities in two ways. Scoping studies using rather simple models provide approximate predictions of system response, thereby establishing bounds for experimental testing. For example, preliminary calculation of temperatures around a possible waste canister establishes the temperature range over which important physical properties should be determined. As the physical properties are described more precisely, the models can be refined and testing then has as its objectives the resolution of residual uncertainties in material behavior and demonstration of the adequacy of the constitutive model used to describe that behavior.

Modeling is used not only to establish ranges for investigation but also to plan experiments so that maximum benefit is gained from their execution. This is particularly the case for in situ testing, where instrumentation is necessarily selective. Such instrumentation must be placed so as to monitor the response effectively and should be selected to have the appropriate range and accuracy. Obviously the level of modeling will depend upon the type of experimentation, but simple models will generally support phenomenological testing, whereas detailed modeling should be undertaken during the planning of quantitative field tests. The most detailed predictive modeling is required when demonstration of model adequacy is an important purpose of the experiment.

3.2 LICENSING

An underground commercial nuclear waste repository is required to be licensed to receive and possess radioactive materials. Licensing requirements and associated technical criteria will be defined in the appropriate Code of Federal Regulations (U.S. NRC, 1981a, 1981b) . The criteria are, for the most part, qualitative and it is clear that, during the licensing process, the applicant will be responsible for providing acceptable evidence of the adequacy of the facility.

Several distinct steps in the licensing process may be identified. As a preliminary step, at least three sites will be characterized and considered for further development. The U.S. Nuclear Regulatory Commission (NRC) will review and comment upon the site characterization report prior to initiation of detailed site characterization, and will be informed of its progress. These steps constitute a preapplication review and are not a part of the formal licensing process. However, failure to comply could lead to denial of any subsequent application.

The formal licensing process starts with submission of an application consisting of general information, a Safety Analysis Report, and an environmental report. Several parts of the Safety Analysis Report are relevant to the current discussion of modeling requirements and are worth highlighting at this point. However, before doing so it should be noted that the requirements, as defined in 10CFR Part 60 60.21 (U.S. NRC, 1981a and 1981b) refer to the final form of the Safety Analysis Report. At the time of preparing the Preliminary Safety Analysis Report (PSAR), the only direct access to the potential repository horizon will have been at the site of the Exploratory Test Facility, with its single exploratory shaft. (McIntosh, 1981). However, it is presumed that the PSAR will have to meet the requirements of the Safety Analysis Report as far as is possible in view of the relatively limited data base and limited opportunities for in situ observation and testing.

The Safety Analysis Report, and by implication the PSAR, will contain a description and assessment of the site at which proposed geologic repository operations are to be located. The description must include:

- The anticipated response of the bulk geomechanical, hydrogeologic, and geochemical systems to the maximum design thermal loading.

And the site assesment must include:

- An assesment of the expected performance of the proposed geologic repository, noting the rates and quantities of expected releases of radionuclides;
- An analysis of the expected performance of the major design structures, systems, and components that bear significantly on the suitability of the geologic repository; and
- An explanation of the measures used to confirm the models used to perform the above assesments.

Further, it is required that analyses and models used to predict future conditions and changes in the geologic setting must be confirmed by using field tests, in situ tests, field-verified laboratory tests, monitoring data, or natural analog studies.

Following review and consideration of the application and environmental report, the NRC can authorize construction of the repository. During the construction period, the application will be updated on the basis of construction experience and the results of research and testing programs carried out to confirm the adequacy of design.

Once construction is substantially complete, the NRC can issue a license to receive radioactive waste. Unless unexpected conditions or performance are encountered, or design changes or operating procedures are modified, the operating license will remain in effect until an amendment authorizing the decommissioning is sought. The necessary application for this step will consist of an update of the original license application and will include the results of tests, experiments, and any analyses relating to repository sealing and long-term isolation of emplaced wastes. Following decommissioning, the DOE can apply to the NRC for an amendment to terminate the license. It is anticipated that the time period between issuance and termination of the license will be approximately 110 years (NRC, 1981b).

From this summary of licensing requirements, it should be clear that licensing is a continuing process in which each step leads towards eventual geologic isolation of the waste. The process allows for progressive updating of the design and improvement of understanding of the behavior of the repository system. However, adequate assurance of successful completion must be demonstrated in advance. The initial application will need, therefore, to be

supported by predictive analysis of both short- and long-term responses. It is particularly important that short-term modeling be well developed by the time of the initial application, because comparison between predicted and observed response during construction will be used to support subsequent steps in the licensing process.

3.3 DESIGN

The licensing process requires that the design procedure for a repository be subject to close scrutiny by the NRC. The design of the underground excavations is a very important part of the overall system design. Traditionally, historical precedent has played a very significant part in the design of underground openings, whether they are for civil engineering purposes or for mineral extraction. The historical precedent may often be informal, to the extent that a demonstrably adequate design is copied or modified to suit local conditions, or formalized, to the extent that generalized empirical design relationships are established. Either approach is practical only when departures from the precedent are minor and when remedial action can be taken to correct any design inadequacies. In the case of a repository, departure from existing experience is quite marked, in terms of both thermomechanical loading of the rock mass and the design objectives. Because of obvious similarities between a repository and civil and mining excavations, there is a tendency to use a conventional, relatively empirical, approach to repository design. While such an approach may be expected to result in an acceptable design, the design may be far from optimum, and it may not be sufficiently rational to satisfy the pertinent licensing requirements. Accordingly, it is important that the framework for geotechnical design be clearly defined. Furthermore, there will be obvious advantages if this framework is used by each of the medium-oriented projects within the NWTS program.

Numerical modeling must be used to provide a framework for rational development of the geotechnical design of a repository facility. It should contribute to this development throughout the design process, starting with development of design guidelines which provide a rational basis for design decisions. Development of design guidelines can be undertaken using relatively simple models. For example, studies might provide evidence that some excavation shapes are better than others, or that some waste emplacement layouts are preferable to others. Preliminary predictions of performance establish the feasibility of

different disposal alternatives and system constraints. The same studies can provide guidance for site investigations through determination of the site parameters that will most strongly affect the system performance.

Preliminary analyses have already been performed within the NWTs program. While these analyses have undoubtedly contributed to an increased understanding of the general behavior of the rock mass, they have not been closely related to the design process. Until a close relationship between modeling and design is established, design objectives cannot be formally defined and the design process will continue to appear rather arbitrary.

Modeling is important throughout the design process because it is necessary to account for the particular characteristics of the geologic setting. In practice, several design steps must take place before the site characteristics are well defined. At an early stage, generic data are available and provide a general description of the geologic characteristics and preliminary ranges of site parameters. Modeling must be adequate to support selection of design alternatives; it can incorporate significant approximations since the emphasis of design, at this stage, is to formulate concepts that define the engineering and scientific work required to support later steps in design and licensing.

The design activities that occur prior to site selection are all referred to as conceptual. Conceptual designs must be completed well before license application (see Section 3.2), since they must provide details for the site characterization program that the DOE will submit to the NRC during the Pre-application Review (10 CFR Part 60, 60.10). The conceptual design should also be adequate for reliable cost estimates to be made and realistic schedules to be defined.

Title I and Title II design can be initiated after submission of the license application. Title I, which is also referred to as Preliminary Design, uses the Conceptual Design and design criteria as a basis for defining the features and characteristics of the final design and for determining costs and schedules. Title II is the definitive design stage which results in final working drawings and specifications. As part of Title I, any additional field work necessary for final design will be undertaken. Information resulting from this field work, as well as design upgrades, would be supplied to the NRC by the DOE as part of updates to the license application (10 CFR Part 60, 60.24). However, detailed construction drawings will have to be completed before construction authorization is issued because the NRC must be satisfied that the site and design comply with the technical criteria of 10 CFR Part 60.

4 QUANTIFIED NEEDS

The previous section of this report provides a general discussion of the requirement for numerical modeling of repositories. In this section, the repository responses at different scales that need to be considered for geotechnical modeling are reviewed. This discussion provides a background for assessing the adequacy of the existing code and model developments that have formed a part of the rock mechanics activities of the NWTs program. Such an assessment requires a more quantitative evaluation of needs. Unfortunately, such an evaluation has not been completed and there remains considerable uncertainty as to the standards that reasonably should be expected of numerical modeling. A set of standards is proposed in this section and will be used as a basis for a qualitative assessment of the adequacy of available computer codes to be used for particular applications. It should be noted, however, that the proposed standards are tentative. At the moment they are completely subjective. If standards of this type are to be adopted, they must be substantiated in a rational and quantitative manner.

4.1 QUANTIFIABLE MEASURES OF RESPONSE

In order to reduce the information to a reasonable level, the responses that should be represented within numerical models are considered only in their broadest possible sense. This leads to the use of four major headings in the assessment table (Table 4-1): temperature, displacement, induced stresses, and fluid flow.

4.1.1 Temperature

Heat transfer processes include conduction, convection, radiation, and mass transfer at rock/air interfaces. They result in some temperature field that may be recorded using temperature-measuring instrumentation (e.g., thermocouples) within the rock mass, in the designed components of the repository, or in the ventilation airstream of the underground facility.

TABLE 4-1. PROPOSED ACCURACIES REQUIRED OF PREDICTIVE MODELING

Programmatic Needs	Response	Temperature				Displacement				Induced Stress				Fluid Flow								
		VNF	NF	FF	R	VNF	NF		FF	R	VNF	NF	FF	R	VNF		NF		FF		R	
		Rel	Abs	Rel	Abs	Abs	Abs	Abs	Abs	Vol(b)	Vel(c)	Vol	Vel	Vol	Vel	Vol	Vel	Vol	Vel			
Experiment Design		0.8-1.2	0.8-1.2	(a)	—	0.5-2.0	0.5-2.0	0.5-2.0	—	—	0.5-2.0	0.5-2.0	—	—	0.25-4.0	—	0.25-4.0	—	—	—	—	—
Repository Design Criteria, Conceptual Design		0.8-1.2	0.8-1.2	0.7-1.5	0.7-1.5	0.7-1.5	0.5-2.0	0.7-1.5	0.7-1.5	0.7-1.5	0.7-1.5	0.5-2.0	0.5-2.0	0.25-4.0	—	0.5-2.0	—	0.5-2.0	0.5-2.0	0.5-2.0	0.25-4.0	0.25-4.0
License Application (Construction Authorization) Title I, II Design		0.8-1.2	0.8-1.2	0.7-1.5	0.7-1.5	0.7-1.5	0.5-2.0	0.7-1.5	0.7-1.5	0.7-1.5	0.7-1.5	0.5-2.0	0.5-2.0	0.25-4.0	—	0.5-2.0	—	0.5-2.0	0.5-2.0	0.5-2.0	0.25-4.0	0.25-4.0
License Application Upgrade for Operation		0.8-1.2	0.8-1.2	0.8-1.2	0.7-1.5	0.7-1.25	0.5-2.0	0.7-1.25	0.7-1.25	0.7-1.25	0.7-1.5	0.7-1.5	0.5-2.0	0.5-2.0	0.25-4.0	—	0.5-2.0	—	0.5-2.0	0.5-2.0	0.5-2.0	0.25-4.0
Decommissioning and License Termination Applications		0.9-1.1	0.9-1.1	0.8-1.2	0.8-1.2	0.75-1.25	0.5-2.0	0.75-1.25	0.75-1.25	0.75-1.25	0.7-1.25	0.7-1.25	0.75-1.5	0.7-1.5	0.5-2.0	—	0.7-1.5	—	0.7-1.5	0.5-2.0	0.7-1.5	0.5-2.0

(a) A null entry implies that the response need not be predicted to support particular programmatic objectives

(b) Volumetric flow

(c) Ground-water flow velocity

Note This table contains a set of proposed "acceptable" ranges of inaccuracy or uncertainty. Ranges are given for the four scales: very near field (VNF), near field (NF), far field (FF), and regional (R). The ranges may be interpreted as either the degree to which measured response might depart from predicted response, or the degree of certainty with which a prediction is made. For example, the range of 0.8-1.2 for the very-near-field temperature prediction is intended to indicate that the actual temperature, if measured in the field, should be expected to lie in the range of 80 to 120 percent of that predicted. Similarly a range of 0.25-4.0 for prediction of regional ground-water flow velocities is intended to indicate that there would be every reason to expect that the actual, average velocity would lie somewhere between one quarter and four times that predicted by numerical modeling. Obviously, these ranges include an assessment of the quality of site characterization, since the numerical model must incorporate site and material descriptions.

4.1.2 Displacement

Displacements occur in the rock mass in response to a change in the original stress field caused by excavation of the underground openings and by temperature changes resulting from heat generated by the waste and the cooling effect of underground ventilation. These displacements are all absolute in the sense that they can, in principle, be related to some stationary point. In practice, however, the relative displacement of two proximate points can be measured with greater ease than the absolute displacement of either point. Relative displacements are typically measured using an extensometer or a laser interferometer, while precise surveying techniques, such as leveling, triangulation, or trilateration, provide a means of measuring absolute displacements.

4.1.3 Induced Stress

Absolute stress may be measured using several techniques, including overcoring and hydrofracturing. These measurements are made during site characterization and will provide important initial conditions for numerical modeling of the rock mass. The function of modeling is to predict the induced stress, or the stress change from the initial state, in the geologic system. There remain significant practical problems in measuring stress changes in the field. It is anticipated, therefore, that such measurements would be made primarily to provide evidence of the validity of the predictions of system performance, rather than for routine monitoring.

4.1.4 Fluid Flow

The ultimate measure of the performance of the repository is its ability to isolate radionuclides for the accessible environment. Several scenarios have been studied, but the major concern is that of release via natural or thermally induced ground-water flow. Such flow may be expressed in two important ways that relate to release. First, the volume of contaminated flow is of concern, since it is required to predict radiation dose in the event of release of radionuclides. The volume of flow, which can be determined from the average flow velocity, is also required to design systems to handle ground water flowing into

the repository during the construction and operation phases. Second, the local flow velocity is of concern so the transit time of ground water from the repository to the accessible environment may be determined. For fractured rock masses, predicting the flow velocity is complicated by the presence of the fractures, since the flow velocity in the fractures may be much higher than that through the intact rock matrix.

For many radionuclide species the actual transit time for radionuclides, which will decay during travel to the accessible environment, may be much longer than the fluid transit time because of the natural retardation characteristics of the geologic formation. Uncertainties in the sorption characteristics of the rock and in dispersion of the contaminants within the ground water as it flows through the rock mass make it more convenient to consider ground-water transit time rather than nuclide transit time. The emphasis on prediction of the water transit time, rather than nuclide transit time, is consistent with the position of the NRC, as stated in 10 CFR Part 60.

4.2 SCALES OF ANALYSIS

Four scales of analysis are recognized. Generally, the small scales refer to design details, while the larger scales affect performance assessment of the entire system.

4.2.1 Very Near Field

The very near field, or canister scale, is related to the waste package and its immediate host environment. Since the waste package is likely to be approximately 3 m in length, and will be separated by approximately 2 m from adjacent canisters, the very near field may be restricted to as little as 25 m³ of rock. Problems on this scale include those relating to liner design, backfill selection, and canister retrieval.

4.2.2 Near Field

The near field, or room scale, is related to a single emplacement room, with the adjacent pillars and the rock mass immediately influenced by the excavation of rock and the emplacement of waste. Since emplacement rooms are

likely to be some 6 to 7 m² and separated by pillars 20 to 30 m wide, the cross section of concern for modeling on this scale will be of the order of 1,000 m². Analyses will generally be two-dimensional, since the axial dimension of an emplacement room will be much greater than either the room width or the room spacing. Problems on this scale include roof support, pillar performance, and estimation of the effect of rock mass movements upon the local permeability.

4.2.3 Far Field

The far field, or repository scale, is related to large parts of the repository such as a complete panel or the entire facility. As an upper limit this scale includes the rock mass to a depth of approximately 2 km and extending 1 km horizontally beyond the limits of excavation of the facility. It therefore involves up to 50 km³ of rock. Typical problems are modification of the permeability of the host rock due to thermomechanical loading and prediction of ground-water flow volumes and velocities through the facility.

4.2.4 Regional

The regional scale is the geologic system that may ultimately be perturbed by the presence of the repository and may extend up to 100 km from the site. This scale is predominantly of concern in connection with predicting ground-water movements that could result in nuclide transport to the biosphere, and subsequent dose to man. Regional and far-field modeling must be coupled to the extent that regional and far-field models define boundary conditions for each other.

4.3 ACCURACY

The necessary accuracy of prediction is extremely difficult to quantify for three reasons. First, with the exception of ground-water transit times, there is not likely to be any single regulatory criterion for any of the phenomena or processes discussed above. Second, the inherent variability of the geologic system makes adequate characterization difficult. (Assessment of necessary accuracy must take into account the difficulties of characterization as well as

the approximation introduced by the numerical simulation.) Third, any assessment of accuracy must be tempered by considerations of the precision with which phenomena or processes can reasonably be expected to be measured.

Discussion of accuracy may benefit by reference to specific examples of predictions of performance. Two very simple cases are considered in the discussion that follows. The first is that of stresses and displacements around a circular hole, and the second is the temperature, displacement, and stress field around a point heat source. Both cases assume linear behavior - a reasonable assumption for the purposes of this simplified discussion since the loading of the rock mass is likely to be sufficiently low that the behavior is substantially linear over most of the region considered.

In the case of the circular hole created in a stressed material, the analytical solution (Jaeger and Cook, 1969) indicates that:

- The displacement field depends upon the initial stress and the constants E and α (elastic modulus and Poisson's ratio); and,
- The stress field depends upon the initial stress state.

In the case of the point heat source, the analytical solution (Nowacki, 1962) indicates that, for a given thermal loading:

- The temperature field depends upon the thermal diffusivity (which is directly related to the thermal conductivity and inversely related to the density and specific heat of the material);
- The displacement field depends upon the temperature field, the coefficient of thermal expansion, and Poisson's ratio; and,
- The induced stress field depends upon the temperature field, the coefficient of thermal expansion, the elastic modulus, and Poisson's ratio.

A similar discussion of fluid flow is difficult because of the significant dependence of the flow field on the thermal and mechanical fields. However, both the velocity and the volumetric flow rates are directly dependent upon the hydraulic conductivity of the rock. The hydraulic conductivity may be defined from the intrinsic permeability of the rock mass and the kinematic viscosity of the fluid. The former is approximately a cubic function of induced stress (Scheidegger, 1963; Witherspoon et al, 1981), while the latter is a similar function of temperature. The volumetric flow rates are also strongly dependent upon the geometry of the hydrogeologic units affected.

4.3.1 Accuracy of Temperature Prediction

It should be clear from the above that the temperature field is most critical because it directly influences the deformation, induced stress, and fluid flow. Fortunately, the thermal conductivity upon which the temperature predictions are based can be relatively well described. Indeed, relatively good agreement between observed and predicted temperature distribution has been reported for the large-scale field tests in which emplacement of nuclear waste has been simulated using electric heaters (Gregory and Kim, 1981). Based on the importance of temperature and the fact that it can be measured with relative ease, the accuracy of prediction required for the temperature field should be relatively high.

4.3.2 Accuracy of Displacement Prediction

The displacement field around a heat source has been shown to be dependent upon the temperature field, the coefficient of thermal expansion, and the Poisson's ratio for the simple thermal problem discussed. The temperature field can be reasonably well established, the coefficient of thermal expansion is relatively insensitive to temperature and stress changes likely to be experienced (Hocking et al, 1981), and the sensitivity to Poisson's ratio is relatively low for expected ranges of this parameter. One would therefore expect to achieve good accuracy in predicting the displacement field. This is certainly true in the far field, but on a smaller scale discontinuities and local inhomogeneities lead to difficulties in precise prediction. Also, in the vicinity of excavations, the rock mass deformability and the initial stress field - two parameters difficult to measure with accuracy - influence the displacement field more strongly. Accordingly, one may expect more accurate displacement predictions away from the immediate influence of repository excavation and less accurate predictions in the very near field and near field. The accuracy of prediction also corresponds to the accuracy of measurement, as far-field absolute displacements can be measured with some precision using precise surveying techniques, while relative displacements in the near and very near fields may be quite small in comparison with the precision of measurements on that scale.

4.3.3 Accuracy of Stress Prediction

Induced stress in very near and near fields will depend on the initial stress field and the thermal loading and will be locally influenced by discontinuities and inhomogeneities in the rock mass. Since neither the initial stress field nor the rock structure can be very accurately determined, the accuracy of prediction of stress change or absolute stress will be relatively low. Further afield, the thermal effect will dominate and the quality of the prediction will then depend upon the adequacy of the characterization of the host environment, and in particular upon estimates of the rock mass deformability.

4.3.4 Accuracy of Fluid Flow Prediction

The accuracy of prediction of fluid flow will also vary significantly with scale, particularly in rock masses in which flow through fissures dominates flow through the intact material. On any scale at which the influence of individual discontinuities, and hence fissure flow, becomes insignificant, the pressure distribution can probably be predicted within 10 to 20 percent, even though permeability may be estimated at best to an order of magnitude. Prediction of the local fluid flow velocity, which depends upon the permeability and the effective porosity, will be poorer because of the uncertainties in characterizing fissures. However, prediction of the volumetric flow rate through the mass depends primarily on the bulk permeability and will be rather better than that for the local fluid flow velocity. Coupling of fluid flow models to nuclide transport models requires that the dispersivity of the medium be estimated. Since measurement of this property (a second-rank tensor) of a fractured rock mass is difficult, any predictions of transit times for nuclides, even ignoring difficulties associated with estimating the retardation characteristics of the host medium for each species, will always be significantly poorer than those for the fluid velocity only.

4.4 PROPOSED MODELING ACCURACY TO MEET PROGRAMMATIC NEEDS

The role of numerical models of fractured rock masses in the design and licensing process of a repository was reviewed in the previous section. Applications

of models will occur over a time period extending from conceptual design during early site investigation, through the operational period, to eventual application for license termination. Throughout this period the data base upon which modeling studies are based will increase, and a progressively better predictive capability should be attained. This progressive improvement is also required because the highest level of assurance will be needed at the time when the decision is made to terminally isolate the nuclear waste.

For the purpose of discussing accuracy, the programmatic needs are divided into five groups:

- Experiment design,
- Repository design criteria development and conceptual design,
- License application (construction authorization) and Title I, II design,
- License application upgrade for operation,
- Decommissioning and license termination applications.

While it is desirable to define the accuracy of any modeling required to support each of these programmatic functions, there are several fundamental objections to such an endeavor. Here are the more serious of these objections:

- The ultimate objective of modeling is to obtain adequate prediction of the system performance rather than precise prediction of particular responses.
- Accuracy requirements should only be established for much more specific cases, probably when the site and design are already defined.
- Accuracy requirements cannot be established without careful assessment of the consequences of modeling accuracies.
- There is no means of establishing whether required accuracies have been achieved, because it is impractical to measure the actual response.

These objections are legitimate and can only be countered by the argument that some standard is required by which the geotechnical modeling effect within the NWTs program can be assessed. It is also important that investigators outside the modeling community, and persons responsible for program direction, have a reasonable expectation of the results of any modeling activity.

To avoid some of the difficulties associated with defining accuracy, it is proposed that standards of acceptable ranges of uncertainty be adopted. Uncertainties arise because of limitations in the ability to characterize the original system, approximations introduced by the constitutive models adopted, and practical limitations on the scope of any modeling activity. However, it should be possible to demonstrate that there is a reasonable expectation that the actual response might lie within a given range. If the necessary assurance cannot be given, then it should be demonstrated that the large uncertainties in response do not invalidate performance predictions of the entire system.

Ranges of uncertainty are proposed in Table 4-1. These ranges decrease with improvement of the data base and with use of computer models with more precise constitutive descriptions of the geologic media. Acceptable ranges are expressed as proportions of the best estimate of the predicted response. Local variations may be much greater than those suggested because of the inherent inhomogeneity of any geologic system, so the ranges should be regarded only as average objectives. Further, these objectives really only apply to predictions of the response at locations where it is a maximum, and therefore of most concern. Remote from the area of most concern, the response will be reduced and of less significance so increased uncertainty would be acceptable.

5 COMPUTER CODES FOR FRACTURED ROCK MODELING

This section of the report reviews a number of codes that have been used by various investigators within the NWTs program and attempts to indicate the applicability of each code to the five programmatic functions identified earlier. The task of summarizing the capabilities of codes is relatively straightforward, even though it is often difficult to define the true capabilities until one has rather extensive personal experience as a user. In the present case the task is more difficult as the tabulations presented involve an assessment of specific features required to support particular programmatic functions, as well as the extent to which these can be adequately treated by a particular code. The former component of the task, the assessment of necessary features, will be discussed so that any ambiguity in the meaning of the terms used will be minimized.

5.1 REQUIRED CODE CAPABILITIES

The capabilities required to support all geotechnical aspects of the NWTs program have been divided into four groups: geometry, phenomena, kinematics, and constitutive behavior. Each group and the features which it embraces will be discussed separately.

5.1.1 Geometry

One-, two-, and three-dimensional geometries are possible, with reductions from the real three-dimensional case permissible whenever there is translational or rotational symmetry for all phenomena of concern. The important geometries in this case are generally referred to as plane, axisymmetric, and fully three-dimensional. Plane geometry is appropriate in situations, such as an emplacement corridor, where there is no change of cross section over a considerable length. There is then a significant volume of material that is remote from three-dimensional end effects. Axisymmetric geometry has rather limited application in repository design, since the necessary rotational symmetry is generally absent. The main use of axisymmetric analysis is in connection with prediction of the short-term, very-near-field response of the rock mass and any hole liner around the waste package. Fully three-dimensional analysis is required when symmetry is absent. Such conditions occur on all scales, but the

effect of the three dimensionality may be of less significance than uncertainties in the prototype description, or inconsequential to the results of a particular analysis.

5.1.2 Phenomena

Three phenomena are of concern in this investigation: thermal, mechanical, and fluid flow. In almost all cases, the processes that occur may be treated as quasistatic because the inertial components of deformation or fluid flow are insignificant. Some cases of the repository subjected to dynamic loading, such as resulting from an earthquake or rock burst, might be considered during analysis of possible highly unusual events. Such a requirement should be identified but would hardly constitute a major programmatic need. The extent to which coupling between phenomena is treated is of more immediate concern. Four couplings are identified: thermal-mechanical (T-M), thermal-hydraulic (T-H), mechanical-hydraulic (M-H), and thermal-mechanical-hydraulic (T-M-H).

5.1.3 Kinematics

Three types of behavior are identified. In most cases of analysis of hard rock, even when fractures are present, it will be acceptable to use codes based on small, or infinitesimal, strain and small displacement theory. In some cases, displacements may be large but strains may still be small. In cases involving large plastic or time-dependent deformation, formulations that correctly treat large strains will be required. Cases in which large displacements must be considered may be encountered when simulating the behavior of relatively weak rock masses or backfill emplaced in canister emplacement holes or underground excavations.

5.1.4 Constitutive Models

Constitutive models, or descriptions, are taken to include all mathematical descriptions of the thermal, mechanical, and fluid flow behavior of the geologic system. The computer code used to build a model of the physical system of concern must have the necessary general description of the particular constitutive behavior in which site-specific parameters may be used. Particular classes of behavior are considered below.

Linear Thermal. The thermal properties of the material are independent of temperature, stress, fluid pressure, or moisture content.

Nonlinear Thermal. One or more of the thermal properties of the material are dependent on temperature, stress, fluid pressure, or moisture content.

Thermal Anisotropy. The thermal properties of the material are direction-dependent. Treatment of anisotropy is generally restricted to the case of transversely isotropic, or orthotropic, materials.

Linear Elastic. There is a unique and linear relationship between stress and strain. The necessary parameters to describe this relationship are independent of temperature, stress, fluid pressure, or moisture content.

Nonlinear Elastic. The relationship between stress and strain is nonlinear, and the material properties may be dependent on temperature, stress, fluid pressure, or moisture content. However, deformation is recoverable.

Plastic. Deformation has an irreversible component that occurs instantaneously. This deformation is described by a yield function, a plastic potential, and a flow rule.

Creep. Time-dependent deformation occurs. For particular classes of material, this deformation may be partially recoverable.

Mechanical Anisotropy. The mechanical properties of the material are direction-dependent. Again, treatment of anisotropy is generally restricted to the case of transverse isotropy.

Ubiquitous Joints. Ubiquitous jointing, or systematic fracturing that has a definite orientation in space but not a specific location, may be described as a mechanical anisotropy up to the point that the shear strength of the fracture surfaces is exceeded. Beyond that point, slip parallel to the direction of the fracture set will occur. The relationship between stress and deformation will then be described as some type of anisotropic plastic or creep behavior.

Slip Surfaces. In some instances, the location and orientation of fractures, whether joints, faults, or bedding planes, must be specifically represented in the model. These surfaces, or interfaces, may behave elastically until the shear strength of the surface is exceeded. Sliding will generally be accompanied by dilatation due to the roughness of the sliding surfaces. Again, slip may be time-dependent.

Cracking. Plasticity is used to describe yield of the material and occurs without formation of new fractures. Rock failure is associated with coalescence of material flaws and the generation of new fracture surfaces. The direction of

the new surfaces will be dependent upon the loading conditions at the time of failure. The necessary logic for determining fracture growth must therefore be included within the code.

Block Movement. A rock mass is usually discontinuous. It is typically transversed by fractures or fissures that divide it into a number of units. For certain classes of problems the interaction of these units must be specifically modeled. This generally occurs when the kinematic constraints are insufficient to prevent block rotations. In the context of the NWTs program, block movement may only need to be considered in respect to design of support systems for underground excavations, specifically during development of design methodology.

Work Softening. Rocks typically exhibit decreasing load-bearing capacity during failure. This may occur rapidly if locally stored energy can be released suddenly.

Equivalent Porous Medium. Flow within a fractured rock mass occurs through both pores of the intact rock and fractures. The simplest models of flow recognize neither the pore flow nor the fissure flow independently, but ascribe to the rock mass equivalent porosity and permeability values.

Double Porosity. The rock pores and the fracture systems are characterized independently. Each is ascribed its own porosity and permeability, and the contributions of each to the flow system are determined.

Hydraulic Anisotropy. Permeability can be direction-dependent. This occurs either as a consequence of the characteristics of the intact rock or because of systematic fracturing. The treatment of hydraulic anisotropy is generally restricted to the case of transverse isotropy.

Fracture Flow. Treatment of a fractured system as an equivalent porous material is practical only when the spacing of fractures is small with respect to the scale of the problem of concern. In some cases it is necessary to model flow through specific fractures. This would occur on the repository scale when a few major features, such as faults, pass through a relatively impermeable matrix, or around underground excavations if the fracture spacing is similar to the excavation dimensions.

It should be observed that fluid dispersion that occurs within a fracture system may be quite different from that of the equivalent porous medium. There may be, therefore, circumstances in which it is desirable to model fracture flow even though the fracture spacing might be regarded as relatively close.

Unsaturated Flow. In some geologic settings, flow may occur through material that is unsaturated. This would certainly be the case in arid regions where the repository could be sited above the ground-water table.

Two-Phase Flow. Two-phase flow may occur in the very near field as ground water or contained water within the host medium is heated beyond its boiling point. It is likely that this would occur only in the short term as the very-near-field temperatures are expected to peak within the first few years following waste emplacement.

5.2 TABULATION OF APPLICABLE CODES

Table 5.1 lists the current characteristics of a number of computer codes offering capabilities for thermal, mechanical, and fluid flow analyses. This information updates previous tabulations of codes being used in the NWTS program (Tsang, 1980 and Wang, 1981) and is similar in form to a recent tabulation prepared by the U.S. National Committee for Rock Mechanics (1981). The table also identifies code capabilities that are considered to be necessary for development of models to be used to support particular programmatic functions, and it indicates whether such characteristics are offered by current versions of each code.

Two types of entry appear in the tables. Under code characteristics, the features of each code are identified as available (A) if the bases for problem-specific model development are already contained within the code. Some modifications may be required, but these would not be classed as major code development activities. In some instances, development of necessary capabilities is known to be in progress and is denoted (D).

The final entries in the table are an assessment of the possible application of each code for each of the programmatic functions identified in Section 4.4. These entries identify the type of modeling that may be undertaken with the code. For example, the entry T indicates that the code is considered suitable for thermal modeling for the identified function. Of course, the same code might not be suited to supporting another function. It might be too simplistic or unjustifiably complex.

Many of the codes are considered capable of treating two phenomena or processes. Few treat the more general problems involving more than one coupling. Even when it is marked that a code can be used to simulate two phenomena,

TABLE 5-1. CODES AND THEIR POTENTIAL APPLICATIONS IN THE NWTs PROGRAM

Code Providing Basis for Model		Geometry		Phenomena Treated								Constitutive Models																			Potential Applications							
		Plane	Axymmetric 3 Dimensional	Thermal (T)	Mechanical (M)	Fluid Flow (F)	Inertial	T M	T F	M F	T M F	Small Strain Sm Displ	Small Strain-Lq Displ	Large Strain Lq Displ	Linear Thermal	Nonlinear Thermal	Thermal Anisotropy	Linear Elastic	Nonlinear Elastic	Plastic	Creep	Mechanical Anisotropy	Ubiquitous Joints	Slip Surfaces	Cracking	Block Movement	Work Softening	Equivalent Porosity	Double Porosity	Hydraulic Anisotropy	Fracture Flow	Unsaturated Flow	Two-Phase Flow	Experiment Design	Design Criteria Development and Conceptual Design	License Application Title I, II Design	License Application Upgrade for Operation	Decommissioning and License Termination Applications
ADINA & ADINAT	3,4,5,6	A	A A A	A A A	A A	A A					A A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A D		A		A								T-M	T-M	T-M	T-M	T-M
ANSYS	2	A	A A A	A A A	A A	A A					A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A										T-M	T-M	T-M	T-M	T-M	
DAMSWEL	2,9	A	A A		A A						A A					A A						A A										M	M	M	M	M		
DBLOCK	2	A			A A		A A				A A A					A A								A								-	M	M	-	-		
FINEL	2	A	A A A	A A A	A A	A A					A A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A									T-M	T-M	T-M	T-M	T-M		
HONDO II	4,5	A	A A		A A		A A				A A A					A A																-	M	M	M	M		
HEFF	2	A			A A			A A			A A					A A																T-M	T-M	-	-	-		
MARC	4	A	A A A	A A A	A A						A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A		A A								T-M	T-M	T-M	T-M	T-M		
MINAQ (SALTY)	2(1)	A			A A A		A A				A A			A A		A A				(A)			A A									-	T-M	-	-	-		
STRESS3D	2		A		A A A		A A				A A					A A																T-M	T-M	-	-	-		
SANCHO	3,4,5	A	A A		A A						A A A					A A				A A A	A A A	A A A	A A A									-	M	M	M	M		
SPECTROM 11 + 21 + 41	1,3	A	A A D		A A A		A A				A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A									T-M	T-M	T-M	T-M	T-M		
STEALTH	1,4	A	A A D		A A A		A A A		A A A		A A A			A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A	A A A					A				T-M,M,F,T-F	T-M,T,F	T-M,M,F,T-F	T-M	T-M		
UTAH2	9	A			A A						A A					A A				A A		A A										M	M	-	-	-		
VISCOT	9	A	A A		A A						A A								A A		A A											M	M	M	M	M		
FTRANS	9	A	A A				A A																									F	F	F	F	F		
NETFLO	9	A	A A				A A																									F	F	-	-	-		
CCC	7	A	A A A		A A A				A A					A A A	A A A																	T-F	T-F	T-F	T-F	T-F		
CFAST	8	A		A A A	A A A			A A						A A																		T-F	T-F	T-F	-	-		
GEOETHER	9	A	A A A		A A A				A A					A A																		T-F	T-F	T-F	-	-		
MAGNUM	2	A			A A A		A A A							A A																		T-F	T-F	T-F	T-F	T-F		
PORFLOW	2	A	A A		A A A		A A A							A A																		T-F	T-F	T-F	-	-		
SHAFT79	7	A	A A A		A A A		A A A							A A A	A A A																	T-F	T-F	T-F	T-F	T-F		
SPECTROM 55	1	A	A A		A A A		A A A							A A A																		T-F	T-F	-	-	-		
SWENT (SWIFT)	9	A	A A A		A A A		A A A							A A A	A A A																	T-F	T-F	T-F	T-F	T-F		
ROCMASS	7	A	A A		A A A		A A A		A A A					A A A		A A A																T-M,M-F,T-F	T-M,T,F	T-F	T-F	T-F		
STAFAN	9	A	A A		A A A		A A A							A A A	A A A		A A A															T-M,M-F,T-F	T-M,T,F	T-M,M,F,T,F	T-M,M,F,T,F	T-M,M,F,T,F		
REFERENCE NEEDS																															KEY TO USERS							
Experiment Design		X X X		X X X X X X X X								X																			1 ONWI 6 LLNL							
Design Criteria Dev & Concept Des		X X X		X X X X X X X X								X X																			2 BWIP 7 LBL							
License Applic Title I & II		X X X		X X X X X X X X								X X X																			3 NNSWI 8 BPNL							
License Applic for Operation		X X X		X X X X X X X X								X X X																			4 WIPP 9 ONWI (SCEPTER Program)							
Decommissioning & License Term		X X X		X X X X X X X X								X X X																			5 SNL							

it may not really solve the coupled response, because the solution for each phenomenon is obtained during an independent, although related, calculation. For example, it is common in thermal-mechanical analyses for thermal calculations to be completed before mechanical calculations. Hence the thermal calculation is strictly an input to the mechanical calculation, rather than the two responses being calculated simultaneously. Such partial coupling is acceptable for many cases encountered in repository analysis because some of the interactions between phenomena are weak (Tsang, 1980).

6 CODE VERIFICATION AND MODEL QUALIFICATION

It is clear that a policy in respect to the role of modeling within the NWTS program is required. Such a policy would provide a basis for consistent development of a modeling capability within each medium-specific project and, hence, input to planning of rock mechanics activities within the NWTS program. This section of the report proposes definitions of several levels of assurance of the adequacy of any predictive capability. The first level of assurance is gained through verification of the code, or codes. This is followed by a series of steps leading to qualification of a model for a particular purpose. The means of achieving such qualifications are discussed, and a timetable for achieving each step of the qualification process is proposed.

6.1 CODE VERIFICATION

Code verification consists of demonstrating that a code is mathematically correct and internally consistent. It is achieved by comparison with analytical solutions whenever they are available, and comparison with other codes when the problems are too complex to be solved using a closed-form analytical solution. The latter comparative activity, which is often referred to as bench-marking (Morgan et al, 1981), should be completed for problems that are representative of those for which the code will be used for completing calculations in support of repository design or licensing. Codes should not be used in any part of the formal design or licensing process until they have been thoroughly tested and the theoretical background, use, and accuracy have been adequately documented in readily available, public reports. Many so-called proprietary codes and the more widely used public domain codes would satisfy these requirements.

6.2 MODEL QUALIFICATION

A model is used to perform simulations of the behavior of a particular geologic setting or structure within a geologic setting. It therefore includes a definition of geometry and the constitutive equations governing the behavior of the geologic medium. A general model may be developed for each potential host medium, but the constitutive description used may vary depending on the particular analysis undertaken.

Three levels of qualification are proposed: model demonstration, model

validation, and field confirmation.

Model Demonstration. It must be demonstrated that the model is in qualitative agreement with relevant engineering experience. Monitoring of underground construction in similar geologic materials, generic field testing, and medium-specific testing all contribute to the data base that supports this level of qualification.

Model Validation. Validation is achieved by successful prediction of the outcome of field experimentation specifically designed to test the validity of a particular constitutive relationship and modeling methodology used to describe medium behavior.

The methodology includes the steps taken to characterize the rock mass tested and the extent of idealization used during preparation of the model. Specifically, the methodology is the formal link between data collection in the laboratory or in the field and definition of the model geometry, boundary conditions, and controlling parameters. Initial validation, for any given host rock, may be medium-specific before being site-specific. For most problems, validation is possible only for the near-field and very-near-field scales and over short time periods because of practical limitations on field experimentation. Whether "a priori" prediction is required in order to validate a model is a critical issue, affecting scheduling of field testing.

Field Confirmation. Field confirmation of the adequacy of the model relies upon observation during the construction and operation of a repository. Since such observations extend over a rather brief period in comparison to the design life of the system, additional field confirmation must be sought by observation and interpretive modeling of natural geologic processes.

6.3 ACHIEVING MODEL QUALIFICATION

Model qualification will be achieved through field studies and related laboratory investigations. Opportunities for qualification arise throughout the program, but in the following discussions they have been subdivided into those that occur during site evaluation, site characterization, demonstration tests, validation tests, and field confirmation.

6.3.1 Site Evaluation

Site evaluation is the investigation that occurs prior to the selection of a specific site for repository construction. It therefore includes exploration

from the surface, construction of an exploratory shaft, and any preliminary exploratory development and testing within the potential host unit. Throughout this process, every opportunity should be taken to provide data that can be used to support the model qualification process. For example, construction of any exploratory shaft and any associated underground excavations will provide useful data with minimal effort, provided monitoring and instrumentation requirements are considered at an early stage in the planning process. Four specific measurements or observations should be considered in this regard:

- Permeability measurements made at several depths down an exploratory shaft and at various distances into the host rock would provide information on the effect of shaft construction on the permeability of the rock mass and also the relationship between rock stresses and permeability. Successful measurements of this type require that the effects of any mud or grout used during sinking be clearly understood and separated from the stress effect.
- Stress measurements made at several depths down an exploratory shaft would provide useful data on the inhomogeneity of the stress field within the geologic setting. This is of particular interest when the setting consists of a succession of stratigraphic units.
- Records of construction practice, including design of blasting rounds and support procedures, should be correlated with rock damage and local modification of permeability. Data on support should include the timing at which the support was installed as well as the load carried with respect to time.
- Permeability of the undisturbed rock mass can be evaluated by macropermeability testing achieved by maintaining a record of the water balance for any underground excavation. This would require monitoring water supplied and water pumped out, as well as changes in humidity of the air stream.

6.3.2 Site Characterization

Site characterization is achieved by a number of activities, including detailed mapping of lithological units and structural features. Samples are

collected for laboratory testing, and initial conditions, such as rock temperature and stress state, are determined by in situ measurement. Some, large-scale, in situ material property tests should be carried out because they can provide an unambiguous link between laboratory measurements and field behavior. Jointed block tests (Voegele et al, 1981; Edwards et al, 1981) are of particular value for model development as the effect of scale is only poorly understood at the present time.

Thorough characterization is essential if field observations of rock mass performance are to be used subsequently in the model qualification process. Thorough characterization of candidate sites in the various geologic settings should be undertaken at the earliest opportunity so that the similarities and dissimilarities between the various settings can be clearly identified. Model qualification activities for one site may contribute to qualification for another if the medium and site characteristics can be demonstrated to be similar.

6.3.3 Demonstration Tests

Demonstration tests are required to support aspects of the design which depart from the current practice or experience. Qualitative, or phenomenological, tests are also required to support selection of necessary constitutive descriptions. Very-near-field demonstration tests have been performed for all potential media (Bradshaw and McClain, 1973; Witherspoon et al, 1980; Ramspott and Ballou, 1980; Gregory and Kim, 1981; and Stickney and Wagner, 1981). No additional tests of this type are required, although similar tests may be undertaken at potential repository locations in support of model validation. Demonstration tests involving the use of spent fuel are largely unjustified from a modeling standpoint as there is no evidence that the rock mass will respond significantly differently to a radioactive heat source than to an electrical heat source. However, if such tests are undertaken, thorough site characterization should be undertaken and adequate instrumentation should be installed to ensure that any opportunities for model qualification are not missed.

The majority of field testing has been restricted to evaluation of very-near-field performance. There are aspects of design that need to be studied on a larger scale. Specifically, room-scale testing in stress and temperature environments representative of a repository is required. The purpose of such tests is to evaluate alternative excavation techniques and rock support systems for different host media. It is expected that such testing will be carried out

prior to completion of Title I design so that design uncertainties may be addressed. This is probably earlier than essential for the model qualification process.

6.3.4 Validation Tests

Validation tests are designed to demonstrate the adequacy of a particular model, or group of models, incorporating a particular constitutive description of the geologic medium. These may be generic, medium-specific, or site-specific. Heater tests should provide the necessary validation in the very near field. Such tests have been completed in several of the host media. Whether these are considered as validation tests depends on whether it is considered essential that completely satisfactory predictions be completed prior to test performance. Similar, but not necessarily identical, tests will have to be performed at the repository horizon as part of the model qualification process. Room-scale, or near-field, validation tests will also be required because of the scale effects typical of jointed rock. It is assumed that these must be completed for each rock type before an operating license is granted. For practical reasons validation tests may be completed sooner than is essential for licensing, perhaps in conjunction with design demonstration studies.

6.3.5 Field Confirmation

Validation tests will inevitably be restricted to the very near field and near field and will generally be of relatively short duration. The final phase of model qualification must therefore rely upon monitoring the performance of the repository system. For behavior over much larger time frames than can practically be observed in a repository, study of naturally occurring geologic events must be used to demonstrate that there is qualitative agreement between predictions made using numerical models and the behavior observed in the field.

6.4 PROPOSED MODEL QUALIFICATION REQUIREMENTS

Various levels of qualification of models have been proposed in this section, and requirements for the accuracy of predictive modeling were proposed in Section 4.3. A relationship between programmatic function and the levels of qualification is proposed in Table 6-1. This relationship provides a schedule

TABLE 6-1. CODE AND MODEL REQUIREMENTS TO SUPPORT REPOSITORY DESIGN AND LICENSING

Function or Activity	Code Verification	Model Qualification		
		Model Demonstration	Model Validation	Field Confirmation
Experiment Design	Required			
Design Criteria Development and Conceptual Design	Required			
License Application (Construction Author- ization) and Title I, II Design	Required	Required		
License Application Upgrade for Operation	Required	Required	Required Medium-Specific	Required - Obtain From Construction Data Base
Decommissioning and License Termination Application	Required	Required	Required Site-Specific	Required - Obtain From Repository and Natural Processes Data Bases

for completion of model development and qualification. It identifies the latest time at which each level of model qualification must be achieved in order to satisfy specific programmatic requirements. For example, it is proposed that the minimum requirement for construction authorization by the NRC will be demonstration that behavior predicted by the models used to support the license application is consistent with that observed during field tests and in related engineering structures. Of course, a higher level of qualification is desirable, but it is not considered essential.

It is proposed that a major increase in levels of model qualification will be necessary before an operating license is issued. This level of qualification can be achieved during the construction period, but necessary testing must be initiated sufficiently early so that the original license application can be updated to include all necessary model qualification well in advance of when an operating license is required.

7 CONCLUSIONS AND RECOMMENDATIONS

The preceding sections of this report have summarized the current needs for, and status of, modeling of fractured rock masses within the NWTs program. Conclusions regarding the adequacy of the current effort and recommendations for future work can only be made providing these earlier statements are considered reasonable positions to adopt. The first recommendation is, therefore, that the position stated is reviewed and considered for adoption by the NWTs program. Subsequent conclusions and recommendations would have to be modified if the defined objectives of modeling could not be agreed upon.

7.1 MODELS IN THE DESIGN AND LICENSING PROCESS

In Section 4 of this report, the accuracy required of predictive modeling at various stages of the design and licensing processes of a nuclear waste repository is proposed. These proposals should be reviewed and adopted as they are or, in some modified form, as the stated objectives of the geotechnical numerical modeling effort within the NWTs Rock Mechanics Program. Of course, any such standards should be subject to continuing review as their pertinence to repository performance is investigated via modeling studies or field studies. The means of assuring that the necessary predictive capability is achieved has been discussed as consisting of a process involving code verification and model qualification. The definition of these activities should also be reviewed and become part of the stated objectives of the NWTs program. This would provide a basis for design of laboratory and field-testing programs necessary to support development and qualification of models to be used during repository design and performance prediction. In summary, it is recommended that steps are taken to ensure that modeling requirements are clearly defined, and that acceptable levels of quality assurance and means of achieving them are agreed upon. Such issues as the need for a priori predictive modeling as part of the model qualification process need to be resolved, as they have an important impact on long-term plans for laboratory, field, and modeling activities.

7.2 ADEQUACY OF CODES

As indicated in Section 5, the available selection of codes is quite large

and the range of constitutive models available is extensive. At the present time there are practical limitations on the size of problems that can be solved, particularly when all three spatial dimensions are represented. Resolution of these practical limitations should not be a major objective of code development work undertaken within the NWTIS program. Instead, emphasis should be placed on developments that are specifically required to support modeling activities peculiar to repository performance prediction.

Two areas identified for development are improvements of the representations of discrete fractures within a rock mass and complete coupling of all phenomena or processes of concern for a fractured rock mass. The first development is considered to be critical to performance assessment of repositories in fractured rock. The second development may not be explicitly required to support the design and licensing processes but is required to support model verification and qualification and to resolve uncertainties that may arise if the interactions between phenomena are not thoroughly investigated.

7.3 ADEQUACY OF MODELS

Available constitutive models of a rock mass are adequate when fractures are either totally absent or so pervasive, or ubiquitous, that they need not be considered individually. In such circumstances, it is possible to build satisfactory models of a system, providing the rock mass can be adequately characterized. The main limitation is obtaining estimates of the rock mass parameters - such as thermal conductivity, strength, deformability, or permeability - when measurements can only be done on a small scale, either in the laboratory or in the field. Similar problems of characterization of the system exist in cases when fractures must be explicitly represented in the model. In this case, there are also deficiencies in the constitutive models of fracture deformation and fracture flow and, as noted in the previous section, inadequacies in existing computer codes upon which models may be based.

In summary, the major deficiency in the modeling capability of fractured rock masses is characterization of the rock mass itself. The difficulty must be resolved by studying the relationship between measured parameters and system behavior during large-scale field testing. Although the general principles of characterization will be similar for all fractured rock types, there are sufficient differences to make medium-specific investigation necessary.

7.4 LABORATORY AND FIELD INVESTIGATIONS

Preparation and qualification of a site-specific model require detailed site characterization and measurement of parameters defining the initial conditions of the host rock and the constitutive descriptions. In practice, a limited amount of large-scale field testing can be completed, so reliance must be placed upon measurements of material properties made in the laboratory. The relationship between these laboratory measurements and field parameters must be clearly defined. The relationship is an important part of the medium-specific model.

There will be a continuing need for laboratory investigations to provide support for modeling activities and also to investigate processes or relationships that need to be quantified to resolve uncertainties in performance prediction. The testing needs will vary significantly between the medium-oriented projects because of the particular characteristics of the potential host medium being investigated. In every case the needs and priorities should be established on the basis of the potential effect upon repository performance prediction. Such effects can be evaluated using available modeling capabilities.

Field tests are essential for the preparation of medium-specific models and are required as part of the model qualification process. Existing testing within the NWTS program has been restricted to the very near field and very short time periods. There are a number of issues, such as rock support and rock mass damage, that must be addressed by field tests conducted on a larger scale and over longer time periods. These needs can be satisfied by room-scale testing that extends over a period of five to ten years. Such testing should be initiated at the earliest opportunity so that results are available to support the license application. It is recommended that provision for room-scale testing be included within plans for engineering testing at the base of exploratory shafts, if not sooner.

All field tests conducted for demonstration or site investigation purposes should be carefully evaluated so that opportunities for obtaining engineering data or for providing additional model qualification are not lost. Personnel responsible for model development should therefore be given an opportunity to propose specific engineering tests or observations whenever such field tests are being planned.

8 REFERENCES

- Bradshaw, R. L., and W. C. McClain, 1973. Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines, ORNL-4555, Oak Ridge National Laboratory, Oak Ridge, TN.
- Edwards, R. C., E. C. Gregory, W. H. Heneveld, and K. Thirumalai, 1981. "Results From the Near-Surface Test Facility Heater Tests and Block Tests", Proceedings of the 1981 National Waste Terminal Storage Program Information Meeting, DOE/NWTS-15, Office of NWTS Integration, Battelle Memorial Institute, Columbus, OH, November, p. 156.
- Gregory, E. C., and K. Kim, 1981. "Preliminary Results From the Full Scale Heater Tests at the Near-Surface Test Facility", Proceedings of the 22nd U. S. Symposium on Rock Mechanics, Boston, MA, June 28 - July 2.
- Hocking, G., J. Williams, P. Boonlualohr, I. Mathews, and G. Mustoe, 1981. "Numerical Modeling of the Near Surface Test Facility #1 and #2 Heater Tests", Proceedings of the 22nd U.S. Symposium on Rock Mechanics, Boston, MA, June 28 - July 2.
- Jaeger, K., and N.G.W. Cook, 1969. Fundamentals of Rock Mechanics, Methuen and Company, London.
- McIntosh, W., 1981. "Introduction to Session II-A. Site Characterization", Proceedings of the 1981 National Waste Terminal Storage Program Information Meeting, DOE/NWTS-15, Office of NWTS Integration, Battelle Memorial Institute, Columbus, OH, November, p.9.
- Monsees, J. E., and D. E. Munson, 1982. "Design Considerations for a Nuclear Waste Repository in Salt", Tunneling Technology Newsletter, U.S. National Committee on Tunneling Technology, Number 37, March.
- Morgan, H. S., R. D. Krieg, and R. V. Matalucci, 1981. Comparative Analysis of Nine Structural Codes Used in the Second WIPP Benchmark Problem, SAND81-1389, Sandia National Laboratories, Albuquerque, NM, November.

Nowacki, W., 1962. Thermoelasticity, Addison-Wesley, New York, NY.

Raines, G. E., et al, 1980. "Development of Reference Repository Conditions for Nuclear Waste in the U.S.A.", International Symposium on Scientific Basis for Nuclear Waste Management, 1980 Annual Meeting of Materials Research Society, Boston, MA, November 16-20.

Ramspott, L. D., and L. B. Ballou, 1980. "Test Storage of Spent Reactor Fuel in the Climax Granite at the Nevada Test Site", paper presented at the Tuscon Waste Management Conference, Tuscon, AZ, March.

Scheidegger, A. E., 1963. Handbuch der Physik, VIII/2, Springer, Berlin.

Stickney, R. G., and R. A. Wagner, 1981. "Avery Island Studies: Comparison of Numerical Simulations and Field Measurements", Proceedings of the 1981 National Waste Terminal Storage Program Information Meeting, DOE/NWTS-15, Office of NWTS Integration, Battelle Memorial Institute, Columbus, OH, November, p. 173.

Tsang, C. F., 1980. "A Review of the State-of-the-Art of Thermomechanical-Hydrochemical Modeling of a Hardrock Waste Repository", Proceedings of the Workshop on Thermomechanical-Hydrochemical Modeling for a Hardrock Waste Repository, ONWI-164, LBL-11204, prepared by Lawrence Berkeley Laboratory for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH, July 29-31, p. 16.

U. S. National Committee for Rock Mechanics, 1981. "Numerical Modeling", Chapter 9, Rock Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction, National Academy Press, Washington, DC.

U. S. Nuclear Regulatory Commission, 1981a. "Disposal of High-Level Radioactive Wastes in Geologic Repositories", Federal Register, 46 FR 3280, July 8.

U. S. Nuclear Regulatory Commission, 1981b. "Disposal of High-Level Radioactive Wastes in Geologic Repositories", Federal Register, 46 FR 13971, February 25.

Voegele, M., E. Hardin, D. Lingle, M. Board, and N. Barton, 1981. "Site Characterization of Joint Permeability Using the Heated Block Test", Proceedings of the 22nd U. S. Symposium on Rock Mechanics, Boston, MA, June 28 - July 2.

Wang, J. S. Y., 1981. "Introduction to Numerical Modeling of Thermohydrologic Flow in Fractured Rock Masses", Proceedings of the Workshop on Numerical Modeling of Thermohydrological Flow in Fractured Rock Masses, ONWI-240, LBL-11566, prepared by Lawrence Berkeley Laboratory for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH, September.

Witherspoon, P. A., N. G. W. Cook, and J. E. Gale, 1980. Progress with Field Investigations at Stripa, LBL-10559, Lawrence Berkeley Laboratory, Berkeley, CA.

Witherspoon, P. A., Y. W. Tsang, J. C. S. Long, and J. Noorishad, 1981. "New Approaches to Problems of Fluid Flow in Fractured Rock Masses", Proceedings of the 22nd U. S. Symposium on Rock Mechanics, Boston, MA, June 28 - July 2.

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