CNWRA 95-021

# EXPERT-PANEL REVIEW OF CNWRA COUPLED THERMAL-MECHANICAL-HYDROLOGICAL PROCESSES RESEARCH PROJECT

*Prepared for*

**Nuclear Regulatory Commission**
**Contract NRC-02-93-005**

*Prepared by*

**Center for Nuclear Waste Regulatory Analyses**
**San Antonio, Texas**

**September 1995**

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**Mikko P. Ahola**

**Center for Nuclear Waste Regulatory Analyses**
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# ABSTRACT

An independent panel of five experts reviewed the ongoing research on coupled thermal-mechanical-hydrological (TMH) processes at the Center for Nuclear Waste Regulatory Analyses (CNWRA). The goals of the review were to (i) critically review the objectives and approaches of CNWRA coupled TMH research and its application to licensing issues at the proposed Yucca Mountain high-level waste repository site, (ii) recommend improvements to the research scope and methodologies, and (iii) investigate new issues that may not be part of the original research plans. The panel members reviewed relevant CNWRA reports, NUREGs, and other publications related to coupled TMH processes and attended a two-day meeting in San Antonio during which additional presentations and discussions took place. The discussions during the meeting and subsequent individual written summary prepared by each of the peer reviewers were constructive and are likely to improve future work. While the individual summaries have common thoughts and recommendations for improving certain areas of the coupled TMH processes work, they vary widely on the scope and priority of ongoing or potential future research. This report includes the individual summary reports, and attempts to assimilate and respond to the reviewer's comments and recommendations. However, additional work will be necessary in the modification of existing research project plans and preparation of future project plans to best implement the recommendations made by the peer reviewers. The peer reviewers believe that resolving the key issues related to TMH processes can be effectively performed in a decoupled fashion, namely by studying thermal-mechanical (TM) and thermal-hydrological (TH) processes, where the mechanical and TM effects are weakly coupled into the TH processes. Most of the reviewers agree that the TH processes involving vaporization, vapor transport, recondensation, and condensate dripping/wicking in the fractures represent the most crucial issue with the potential of highest impact on waste package performance. Consequently, the reviewers recommend that this issue be given the highest priority for future research.

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# ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications. This report is an independent product of the CNWRA and does not necessarily reflect the views or the regulatory position of the NRC.

The author would like to thank W. Patrick and B. Sagar for their review of the report. The author is thankful to Yolanda Lozano for her skillful typing of the report and to J. Pryor, who provided a full range of expert editorial services in preparing the final document.

# 1 INTRODUCTION

## 1.1 BACKGROUND

Significant coupled thermal, mechanical, and hydrological (TMH) interactions are anticipated in the perturbed zone at the proposed high-level waste (HLW) repository site at Yucca Mountain (YM) (Ghosh et al., 1993; 1994; Ofoegbu et al., 1995a; Buscheck and Nitao, 1994). The emplaced waste will generate heat that will cause the temperature of the rock mass around the emplacement areas to rise. If the temperature in the rock mass approaches or exceeds the boiling point, the pore water in the partially saturated rock matrix is likely to vaporize and flow away from the emplacement areas, condensing in regions where the temperatures are below boiling conditions. Thus, a dry-out zone may be created (Buscheck and Nitao, 1993). The condensate in the zones above the emplacement areas would tend to drain back toward the emplacement areas due to gravity and capillary effects. The extent of this moisture redistribution depends on the amount of heat generated from the waste. Key questions that need to be answered in order to reliably assess the performance of waste packages include: (i) can the reflux of condensate reach the waste packages; (ii) if so, when and what is the rate of condensate-flow toward the waste package; and (iii) what is the chemical content of the condensate that may contact the waste packages. It has been argued (Buscheck and Nitao, 1993) that, at YM, fracture flow may be the most likely means for condensate to flow back toward the heat source (waste packages) since the matrix permeability of the Topopah Spring welded unit (TSw2) in which the proposed repository is located is so small that the matrix flow in the near-field is of lesser concern to repository performance. Because the matrix permeability is small, the fracture-flow of condensate may persist for a long distance before being arrested by re-vaporization or matrix-imbibition, or both. It would, therefore, appear that the extent of the dry-out zone, amount of water available above the emplacement areas (which may be enhanced by both condensation and rainfall infiltration), and the hydrological properties of fractures are the predominant factors that will determine the answers to the first two questions.

The performance issues are complicated further by the possibility that the hydrological properties of fractures may not remain constant throughout the life of the repository. These properties will be perturbed in several ways. First, construction of the repository will change the state of stress, which, in turn, will cause mechanical deformation of the rock mass. It is believed that most of the rock-mass deformation will arise from normal and shear displacements on fractures (Kana et al., 1995; Hsiung et al., 1992a, b; Ghosh et al., 1995; Zimmerman and Finley, 1987). Fracture normal and shear deformations will not only have implications regarding the stability of excavations but will also affect fluid flow and solute transport in the rock mass through changes in fracture aperture. It should be noted that excavation stability is an important issue related to the waste retrievability period (possibly up to 150 yr after excavation). Excessive falls of large rock blocks may affect the performance of the waste packages during the operational and post-closure periods.

Second, the heating of the rock mass by the emplaced waste is expected to be active over an extended period of time. This thermal load induces rock expansion. The rock expansion may also cause dilation, closure, and shear displacement of fractures, thus leading to changes in the hydrological properties of fractures. Third, dynamic ground motions due to earthquakes, nearby underground weapons testing, etc., will take place in the environment of *in situ* stresses and thermally induced phenomena in the repository. The dynamic ground motions, including the cumulative effect of repetitive seismic motions (Hsiung et al., 1992a, b; Kana et al., 1995), will cause further dilation, closure, and shear of fractures. A typical example of the effect of earthquakes on hydrology occurred in California during the Loma

Prieta earthquake (Rojstaczer and Wolf, 1992). In the case of the Loma Prieta earthquake, it was inferred that the increased fracture permeability allowed the water table in the mountains to drop more than 21 m while greatly increasing the flow of springs and streams in the foothills. Hydrologic changes due to earthquakes have also been observed in connection with several other earthquakes (e.g., Ofoegbu et al., 1995b). At YM, the change of fracture permeability may occur due to the ground motion from earthquakes and underground nuclear explosions at the Nevada Test Site (NTS). Recent observations (Hill et al., 1993) that a large earthquake can induce smaller earthquakes at great distances from its epicenter makes this issue much more significant than previously thought. The cumulative effects of repetitive seismic loads may form preferential pathways connecting the emplacement area with the condensation zones above the emplacement area, perched water zones, or neighboring steep hydraulic gradient zone. Thus, the possibility that water would contact waste packages could increase significantly.

In addition to these three processes that may induce changes in fracture hydrological properties, it is well recognized that rock strength properties are a function of time (or stress), that is, rock masses deteriorate as time passes. Deterioration of the rock mass surrounding the repository is possible because the potential backfill for the emplacement drifts is not expected to be sufficient to support the rock mass and thus prevent such deterioration. The rate and extent of the deterioration depend primarily on the strength properties of fractures. All these factors are likely to increase the capability of fractures to conduct flow. Furthermore, pore water or vapor in the rock matrix tends to expand as temperature increases, causing the development of excess pore pressure. Since the rock matrix permeability at YM is low, the excess pore pressure may not dissipate quickly. Laboratory data presented by Althaus et al. (1994) suggest that such increased pressure in the rock matrix may weaken the rock enough to increase the likelihood of microfracturing. The occurrence of microfracturing may considerably increase the rock-mass permeability. However, it is not yet clear how such changes in rock-mass permeability may affect the performance of the proposed repository.

Research activities at the Center for Nuclear Waste Regulatory Analyses (CNWRA) related to TMH processes are motivated by the need to enhance the technical capability of the Nuclear Regulatory Commission (NRC) and CNWRA staffs to review Department of Energy (DOE) license application and to assess performance of underground facilities subjected to thermal stress along with repetitive seismic loads. More specifically, the ultimate goal is to develop capabilities in experimental and numerical modeling of the coupled TMH interactions discussed previously so that the DOE design assumptions and performance predictions can be independently examined.

## 1.2 OBJECTIVES OF COUPLED TMH PROCESSES RESEARCH

The overall objective of this research is to address Key Technical Uncertainties (KTUs) related to the effects of coupled TMH processes on the engineered barrier system (EBS) and surrounding host rock. More specific research objectives are primarily twofold:

(i) *To study the stability of underground excavations, primarily the emplacement drifts, considering long-term deterioration of jointed rock under heated, partially saturated, and stressed conditions.*

The stability of underground openings, including emplacement drifts, will primarily depend on *in situ* stresses; the excavation-induced stresses; dynamic motions, including the cumulative effect of repetitive seismic motions; and the thermally induced stresses and deformations. All these stresses will gradually degrade the rock surrounding the excavations and ground support system. Movement along the joints of the disturbed jointed rock mass is the primary mode of deformation of the near-field rock mass (Kana et al., 1991; Hsiung et al., 1992 a, b; Ghosh et al., 1995). Excessive slippage of a rock block along failed joints may affect the performance of the waste canisters inside emplacement drifts. In addition to the thermal-mechanical (TM) effects, the behavior of the joints is also influenced by the presence of water in the joints (Jaeger and Cook, 1979; Hoek and Brown, 1980).

(ii) *To study mechanically induced changes in hydraulic characteristics of the rock mass surrounding waste packages, as functions of time and space, for input to subsystem and total system performance assessment.*

Mechanically induced changes in the hydraulic characteristics of the near-field unsaturated region of the proposed repository can potentially impact the fluid flux to the waste canister from perched water or condensation zones as well as radionuclide transport from the degraded canister to the surround rock. Buscheck and Nitao (1993) have shown, through numerical calculations, that matrix-dominated flow will not likely result in significant vertical transport of radionuclides and that fracture-dominated flow may be the only credible mechanism for bringing water to the waste package and transporting radionuclides to the water table. During radioactive decay of the HLW, the resulting temperature field will generate thermal stresses that will induce displacement along fractures and change hydraulic characteristics of the fracture network. Another source that could significantly change joint hydraulic properties is ground motions from severe earthquakes and underground nuclear explosions at the NTS. In addition, cumulative effects of repetitive seismic loads may create preferential pathways for groundwater.

In addressing the above-mentioned research objectives, a number of specific research needs (topics) have been identified. Some of these topics are being addressed by current coupled processes research activities, and some would potentially be addressed in future research activities. These topics include:

- Study of time-dependent degradation (including constitutive laws) of rock properties (matrix and fracture) under heated, partially saturated, and stressed (including dynamic loads) conditions
- Extrapolation of laboratory-measured intact rock, rock joint, and fracture flow properties for field-scale application
- Development of a methodology for bounding spatial variation of rock and joint properties using stochastic approaches
- Interaction of rock and support systems under heated conditions (long-term effectiveness of ground supports under thermal environment)
- Evaluation of mechanical and thermomechanical effects on permeability changes in unsaturated fractured rock masses (noting that localized regions having saturated conditions may exist in recondensation zones, perched water zones, etc.)

- Development of an understanding of formation of dryout regions, recondensation of vapor, and condensate dripping through fractures in siting a repository in the unsaturated zone

- Evaluation of dynamic effect on jointed rock mass under heated conditions

- Evaluation of mechanical-effect (including repetitive seismic load) dependent fracture flow in unsaturated fractured rocks

- Evaluation of the performance of seals (including backfill materials) and the impact of repository-generated thermal loads and repeated seismic loads on the long-term performance of seals [including long-term TM effects, long-term thermal-hydrological (TH) effects on the chemical properties of seal materials, long-term TM (including repetitive seismic load) effects on the surrounding rock mass and seal-rock interface]

- Development of a methodology to identify and characterize important design parameters for underground excavations—a total system approach

## 1.3 PEER-REVIEW OBJECTIVES

Due to the wide range and complexity of issues related to coupled TMH processes at the potential YM repository site, it was recognized by both the CNWRA and NRC that an independent peer-review would help to better focus and improve ongoing research programs in view of time and resource constraints. Thus, the primary goals of this peer-review were to:

- Critically review the objectives and approaches of CNWRA coupled TMH processes research and its application to licensing issues at the proposed YM HLW repository site.

- Provide recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original plans.

As part of the second goal above, the peer-review panel members were to provide their thoughts and suggestions concerning the potential topics of future research identified in Section 1.2 of this report.

The overall emphasis of the review was to provide individual recommendations on the CNWRA coupled TMH research. The review was not intended to arrive at a panel consensus to resolve YM scientific issues.

# 2 REVIEW METHODS

For the CNWRA coupled TMH processes research project review, an initial letter soliciting nominations for review panel membership (Appendix A) was sent to 95 researchers and university professors active in various aspects of two- and three-component coupled processes in February 1995. The nomination letters were sent to individuals in the United States and abroad. The only restrictions placed on the nominations were that persons working either presently or in the past as employees or consultants to the DOE on the YM HLW disposal program were ineligible for panel membership, due to possible conflict of interest (COI). Five to ten nominations in the field related to coupled TMH processes were requested. Based on responses to these letters, additional solicitation letters were sent to researchers and professors nominated by the first group. There was a 67-percent response rate to the solicitation letters, which resulted in the nomination of 177 potential review-panel candidates. The number of nominations received by each candidate was as follows: (i) 1 candidate received nine nominations, (ii) 1 candidate received seven nominations, (iii) 3 candidates received six nominations, (iv) 3 candidates received four nominations, (v) 11 candidates received three nominations, (vi) 21 candidates received two nominations, and (vii) 137 candidates received one nomination.

The selection process started from the candidate with the highest number of nominations and proceeded down the list, eliminating those who were not available, had clear COIs, had qualifications and backgrounds very similar to a candidate already selected, or had qualifications and backgrounds that the six-member CNWRA selection team felt were not directly applicable in reviewing the coupled TMH processes research. For instance, a number of candidates that received a high number of nominations had backgrounds primarily in the area of geophysics, and it was felt that they would not be appropriate as peer-review panel members. Based on these selection criteria, the final panel member list was composed of the one candidate that received nine nominations, one candidate that received five nominations, one candidate that received four nominations, and two candidates that received two nominations.

The five candidates for the review panel were sent letters of invitation (Appendix B) and an outline of the proposed review (Appendix C). All the candidates accepted the invitation to participate on the review panel and were hired as CNWRA consultants for this review. The expert-panel members were:

- Dr. Nick Barton, Norwegian Geotechnical Institute (NGI), Oslo, Norway. Dr. Barton has more than 25 yr of experience working on a variety of rock mechanics projects such as design, analysis, and investigation of tunnels and rock caverns for the hydropower and transportation industry, nuclear waste repositories, caverns for storage of oil and gas, studies of joints in reservoirs, and evaluation of reservoir subsidence. He has devised the Q-system for rock mass classification. He is also the author of the Barton-Bandis rock joint model and is an acknowledged international expert in rock engineering. His other activities include mechanical-hydrological (MH) experimental studies, working internationally on tasks such as expert missions, panels, and trouble-shooting on projects, and teaching and lecturing.

- Dr. Emmanuel Detournay, Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minnesota. Dr. Detournay has more than 18 yr of teaching, research, and industrial experience in MH coupled analysis (poroelasticity), hydraulic fracturing, and rock mechanics (e.g., borehole stability, fracture mechanics, and plasticity). He has received several distinguished awards for his work in poroelasticity and has given many invited lectures and presentations at workshops and conferences on rock mechanics. He also serves on many editorial and peer review boards.

- Dr. Derek Elsworth, Department of Mineral Engineering, Pennsylvania State University, University Park, Pennsylvania. Dr. Elsworth has more than 15 years of teaching, research, and consulting experience in MH coupled processes investigations, including fracture flow and numerical modeling. He has authored or coauthored over 90 publications and serves on the editorial peer review boards of several journals.

- Dr. John Gale, Memorial University of Newfoundland, St. John's, Newfoundland, Canada. Dr. Gale has over 20 yr of experience in conducting and supervising both small- and large-scale projects covering a broad spectrum of environmental and geological engineering. His expertise is in the hydrogeology of fractured-rock systems, contaminant hydrogeology, flow system analysis, rock mass characterization, and rock mechanics. He has authored or coauthored over 150 scientific and engineering publications and he serves as chairperson on several university and other technical committees.

- Dr. Antony P.S. Selvadurai, Department of Civil Engineering, McGill University, Montreal, Quebec, Canada. Dr. Selvadurai has more than 20 yr of teaching, research, and consulting experience. His research covers a diversity of areas including theoretical and applied mechanics, geomechanics, experimental mechanics, and computational mechanics. Particular aspects of his research focus on soil-structure interaction, hydro-thermal mechanics, fracture mechanics, nonlinear elasticity, viscoelasticity, viscoplasticity, and damage mechanics. He has served on numerous review committees and currently serves on several journal advisory and editorial boards. He recently chaired an international workshop on TMH behavior of clay barriers.

In preparation for the review, expert-panel members were sent a scope of work (Appendix D), the annotated outline for the review (Appendix C), and copies of background reports contained in the annotated outline.

The review meeting was held in San Antonio, Texas, on July 10–11, 1995. Staff from the CNWRA, NRC Office of Nuclear Regulatory Research, Division of Regulatory Applications (NRC-RES), and the NRC Office of Nuclear Material Safety and Safeguards (NRC-NMSS), Division of Waste Management also attended and participated in the meeting. The meeting agenda is given in Appendix E.

# 3 EXPERT-PANEL REVIEW RESULTS

The individual expert-panel member reports submitted to the CNWRA are provided in full in Appendix F. The panel members were asked to give their independent judgment and, thus were not required to reach a consensus with the other panel members. Section 3.1 of this report summarizes each individual's report on the CNWRA coupled TMH processes research.

## 3.1 SUMMARY OF INDIVIDUAL REPORTS

Comments in this section are presented alphabetically by reviewer. Each section begins with a direct quote of the reviewer providing, to some extent, his general opinion on the coupled TMH processes research at the CNWRA. Annotated summaries of the reviewer's comments are provided as bulleted items. The full text of the original comments by each panel member is provided in Appendix F.

### 3.1.1 Comments by Dr. Nick Barton

"During the course of the CNWRA presentations, the panellists were made aware of the large discrepancy in resources between NRC/CNWRA HLW scientific activities and those of DOE and its contractors. In view of the discrepancy, the standard and extent of CNWRA activities are commendable and remarkable. However, in the opinion of this reviewer, the complexity and gravity of the Yucca Mountain HLW repository project warrant a far higher level of resourcing for the regulatory body if NRC is to continue to be assisted by experienced staff at CNWRA on the wide ranging list of issues that have yet to be addressed. Strengthening NRC response will strengthen DOE's activities and, in the long run reduce the risk of costly errors of judgement, which have a tendency to mar the economics and long-term benefits of major projects."

- The excessive gouge production in the CNWRA direct shear tests may be partly due to the usual nonuniform, edge-enhanced normal stress (and possible rotation effects). The nonconventional shear box design in which the top block specimen is smaller than the bottom block specimen may create unrealistic gouge as a result of the "ploughing" into "new" joint surface at the front and back of the top sample. Such a ploughing or "chisel-edge" effect is very unlikely *in situ* behind a tunnel wall or rock slope. It is likely that the shear strength, dilation, gouge production, and permeability have been affected by this design aspect, and therefore, the various conclusions drawn from the MH tests on rock joints should be reexamined and, if necessary, modified.

- The range of joint shear displacements (i.e., up to 25 mm) conducted for the MH experiments is viewed to be excessive. Scoping studies with either UDEC-BB or 3DEC based on realistic YM parameters should be conducted to verify that these magnitude shear displacements are indeed representative, and if not, a more realistic experimental philosophy established.

- Conclusions drawn by the Swedish Nuclear Power Inspectorate, NRC, and other funding organizations in the rock joint modeling under DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments) regarding the need to develop new constitutive models may not be appropriate due to the fact that these conclusions were based on single experimental test results with somewhat spurious experimental setups.

- The DECOVALEX project should continue to focus on some potential real problems of numerical modeling (avoidance of rotations that may not occur experimentally due to different restraint) and potential real problems of constitutive modeling (improvement of gouge-flow reduction modeling).

- Much of the CNWRA research in coupled TMH processes has been generic and fundamental in nature. In order to be able to respond to and suggest modification of DOE site characterization and design methods at YM in a timely fashion as site data now rapidly emerges, it is recommended that research (both experimental and numerical) be made more site specific. For instance, dynamic scoping studies using relevant velocity time histories in UDEC-BB and 3DEC should help to delineate the likely ranges of appropriate joint shearing and shear reversal phenomena for incorporation into future experimental test plans.

- The NRC/CNWRA should strive through whatever means to have access to relevant joint samples from YM Exploratory Studies Facility (ESF) excavations, since other experimental results can be misleading for site-specific application, unless used purely for verification of numerical (constitutive) models.

- Mechanical and TM modeling studies should be conducted regarding the consequences of tunnel-boring machine (TBM) tunneling (for emplacement safety, retrievability, and subsequent containment safety) in view of the DOE present choice of TBM excavation and late placement of nonconservative support (i.e., steel sets), to give better guidance to the DOE regarding the excavation and support of future disposal tunnels.

- Scoping studies using codes such as UDEC-BB or 3DEC should be conducted to assess the impact of lithophysal cavities on creating nonuniform stress and displacement distributions in the mechanical and TM phases in the vicinity of disposal tunnels or in the pillar between tunnels.

- With regard to dry-out, recondensation, and condensate dripping in joints, it is believed that research into rock engineering solutions to minimize its consequences might be more fruitful than very limited investigations on these complex phenomena. Such research might include the investigation of properties of micro cement-bentonite mixtures injected into joints when subjected to extended periods of intermediate-level thermal loading in a laboratory biaxial apparatus.

### 3.1.2 Comments by Dr. Emmanuel Detournay

"To perform its mission of assessing and reviewing the DOE design assumptions and performance predictions of the planned YM repository, the CNWRA group is developing state-of-the-art expertise in THM coupled processes and capabilities in computational modeling. Indeed, it appears that a significant portion of the activity of the Rock Mechanics group has been spent in reviewing the scientific and technical literature—as evidenced by the comprehensive review of the THMC processes (NUREG/CR-6021) and the evaluation of the computer codes for compliance determination (CNWRA 93-005 and CNWRA 94-001)—and in validating existing computer codes within the framework of the international cooperation program DECOVALEX (documented in CNWRA 92-005, CNWRA 93-002, CNWRA 94-021, and others). The work on THM coupled processes that has been reviewed is generally judged to be of very high quality. Also the staff at the CNWRA is found to be very competent and highly dedicated. Despite limited financial resources, it is apparent that a center of expertise in THM processes has been developed at the CNWRA."

- Although the laboratory studies on the MH behavior of rock joints have been useful from the standpoint of showing evidence of channelling fluid flow and permeability change due to gouge production and shear-dilatant response of the joint, the appropriateness in performing direct shear tests that involve the continued shearing of new surfaces (as the upper block is smaller than the lower block) is unclear.

- The modeling efforts have been very valuable, not only in the selection of computer codes (e.g., UDEC and ABAQUS), but also in providing information about areas of applicability, limitations, and implementation problems in these two codes.

- The DECOVALEX project provides a means to validate numerical codes, and it also gives the opportunity to evaluate the consequences of various modeling assumptions. However, some of the problems in DECOVALEX do not appear to have been judiciously selected. For example, it is doubtful that any useful conclusions can be reached on the basis of the near-field repository model, BMT3, which involves thousands of degrees of freedom used to define the geometry and many *ad hoc* assumptions. Such models defeat the very purpose of building models, which is to develop an intellectual tool to understand the processes under study.

- In view of limited resources, the research activities should focus as much as possible on integrating existing knowledge [which would include previous in-depth literature surveys as well as establishing contacts (or cooperation) with scientists at other institutions engaged in research of relevant processes]. In addition, the focus should be on developing expertise in a system approach, whereby emphasis is placed on classifying processes in regimes and mapping the regimes in terms of dimensionless groups. Models should be manageable (i.e., limited number of parameters) and exercised to answer specific questions and to provide upper bounds to the solutions.

- The planned experimental activities should be significantly downsized or completely stopped considering the costly and time consuming nature of experimental research and the limited resources available. Critical experiments needed to assess the relevance of proposed scenarios or to measure parameters needed in theoretical models should be performed by the DOE or its contractors, and duplicated by the CNWRA only if there is lack of consensus on the validity of an experiment (either about the methodology used or results that are obtained).

- Future research is encouraged to develop "simple" manageable (i.e., characterized by only a few degrees of freedom) models that can be used either to investigate the importance or relevance of a particular process or to provide plausible lower and upper bounds to the solutions. Efforts should be made to reach fairly general conclusions by expressing the results in terms of appropriate dimensionless numbers and showing the dependence of the solutions over the relevant (expected) range of variation of these controlling numbers (scoping analysis).

- In addressing the issue of stability of the underground openings, scoping analyses are recommended to assess the extent of the damaged rock region and magnitude of the support load for various plausible assumptions of thermal loading and rock degradation. The results of such analyses will provide information on whether or not the stability issue should be a major concern, and if so, the basis to direct the DOE to perform additional long-term testing of the repository tuff at the maximum expected temperature.

- The proposed future research topics regarding extrapolating laboratory measurements to field-scale application or determining the methodology for bounding spatial variation of rock mass properties should be addressed by performing scoping analyses. These analyses would reveal the sensitivity of the solution to estimated variation of the input parameters and would provide the basis for conservative predictions.

- The possible reflux of condensate toward the waste emplacement region is viewed as the most crucial KTU and should be given the highest priority in future activities. Modeling should focus on the TH coupling aspects and be aimed at providing bounds for the water inflow into the emplacement drifts by investigating various scenarios involving vaporization, vapor transport, condensation, and condensate flow. Since it is not possible to predict the actual flow path, evaluation of the TH effects must ensure that a conservative scenario is adopted involving, for example, circulation in a limited set of fractures. Estimation of the magnitude of the condensate reflux should be performed for two limiting cases of "high" and "low" fracture conductivity.

### 3.1.3 Comments by Dr. Derek Elsworth

"Overall review of the CNWRA program indicates substantial positive progress in the tasks. Indeed, the accomplishments are impressive, given that the stated time commitment to the full range of activities comprises only 1-1/2 full-time equivalents. In light of the relatively limited manpower commitment, it is recommended that future effort is placed in commissioning scoping studies and assimilating HLW research results, with laboratory and field studies completed mainly in support of apparent data gaps."

- The TM behavior is concluded as being the best defined of the processes included within this study and that TH processes are the least well constrained and understood. Because of the higher level of uncertainty within the anticipated TH behavior, it is recommended that the greatest emphasis be placed in this general task area.

- The assumption that conductive thermal effects are dominant should be verified via computational modeling in view of the fact that for unsaturated repository conditions, although the thermal capacity of the vapor will be low, the effects of phase change and subsequent vapor transport on the anticipated thermal regime may not be negligible. This confirmation is especially important for analyses of intermediate and far-field behavior of the system.

- The anticipated behavior of the TH system may be decoupled from the TM system to enable confirmation of anticipated TH behavior. The relative importance of pressure-driven versus buoyancy-driven vapor transport, the potential for capillary wicking and heat-pipe formation, and the anticipated dimensions of the dry-out zone may be evaluated by decoupling these effects from the mechanical effects.

- In addition to the laboratory experiments and numerical modeling, consideration should be given to field investigation studies (e.g., participation in proposed heater test at the Peña Blanca natural analog site in Mexico, and evaluation of alterations and processes around hot dry rock geothermal reservoirs and magmatic intrusions).

With regard to future research activity, the seven research topics defined by the CNWRA and one additional topic are presented below in their ranked order of importance:

(i) Vaporization, condensation, and mass migration around waste packages

(ii) TH effects on permeability changes

(iii) TM effects on permeability changes in partially saturated rock

(iv) Bounding spatial variation of rock mass properties

(v) Time-dependent degradation of rock properties

(vi) Parameter scaling to field scale

(vii) Long-term performance of repository seals

(viii) Rock-support interaction under heated conditions

Suggested approaches and anticipated results are given for each of these potential future research topics in the individual summary report in Appendix F.

### 3.1.4 Comments by Dr. John Gale

"CNWRA, with the limited resources available to its research staff, has made an impressive start in developing a very credible research program that is notable for its open-minded approach, objectivity, and lack of advocacy for any particular research position. The research program is well focused on the KTU and the need to assist NRC in developing its capability to interact with and respond to any future repository licensing application from DOE for the YM site."

- The current CNWRA research program appears to be a good balance between experimental and numerical work, with the possibility that the numerical work has been somewhat over-emphasized with respect to the experimental work. With regard to the experimental work, the CNWRA has made considerable progress in studying the problem of coupled stress-flow in a single fracture as a function of both normal and shear stress. Much more work still remains to be done in this area, since at present there is no basic mechanistic model available to predict the MH behavior of discrete fractures. Plans to extend this MH work to study TMH processes in single fractures are appropriate and consistent with the overall project needs.

- The direct shear apparatus should be reexamined, specifically with regard to how the mechanical loading is applied, to ensure that it is consistent with the way fracture planes are loaded *in situ*. In other words, to the extent possible, the resultant normal load during shearing should pass through the centroid of the sample to minimize tilting of the sample or wedging, thus creating unrealistic gouge formation, increased shear strength of the fracture surface, and misleading interpretation of results. It is recommended that the CNWRA researchers examine the designs of other shear-permeability test frames as well as justify the need for shear displacements of more than 5 to 10 mm before proceeding with additional tests. Other recommendations include: (i) drilling and installing manometer ports into each fracture plane to monitor the degree of wedging or tilting of the fracture plane during shear; (ii) utilizing a higher strength grout to hold the sample in the shear box and an epoxy grout for the TMH tests at moderate temperatures, which would promote less cracking than a cement-based grout; and (iii) making the top half and bottom half of the sample the same size.

- As a result of the difficulties with obtaining the pore structure from the profilometer measurements, it is recommended that additional tests be conducted to determine the pore structure by injecting the fracture plane with epoxy under the loads at which the hydraulic and mechanical tests were conducted.

- It is recommended that tracer tests be added to both the single-phase and two-phase flow experiments to constrain the data interpretation. Consideration should be given to conducting a simple vapor-condensation experiment on a single fracture to provide basic data for numerical simulation. Such an experiment would require heating on one end to produce vapor, or the introduction of steam, and cooling on the other end to produce condensation. Given the YM site conditions, this experiment would be considered crucial.

- The addition of thermal loads to the ongoing MH studies is considered essential, which would include determining the fracture response at different temperatures as well as monitoring effects of changes in temperature. In addition, these studies need to incorporate basic fracture-matrix interaction studies that include both single-phase and two-phase flows under both normal and shear displacement.

With regard to future research activity, the seven research topics presented during the peer-review meeting are ranked in order of decreasing priority as follows:

(i) Methodology for bounding spatial variation of rock mass properties

(ii) Mechanical and thermal-mechanical effects on permeability changes in an unsaturated fractured rock mass

(iii) Formation of dryout regions, recondensation of vapor, and condensate dripping through fractures in heated and partially saturated fractured media

(iv) Extrapolation of laboratory measurements to field-scale application

(v) Interaction of rock and support systems under heated conditions

(vi) Time-dependent degradation of rock properties under heated conditions

(vii) Evaluation of long-term performance of repository seals

A more detailed discussion on each of these topics is given in Dr. Gale's full individual summary report in Appendix F.

### 3.1.5 Comments by Dr. Antony P.S. Selvadurai

"The involvement of the CNWRA in addressing technical issues of TMH processes of importance to the YM Repository project is relatively new. Within this two and a half year involvement, the scientists and engineers at CNWRA have done a highly commendable job of becoming familiar with the overall importance of TMH processes to the proper engineering evaluation of the condition of a waste repository. There has been a concerted effort to develop a balanced research program which emphasizes both computational modeling and laboratory modeling that is geared to small-scale testing of jointed rock structures."

- More precise detail of the repository is needed in terms of its location, geometry of the drifts, the construction procedure, the nature of support of the heat-emitting containers, the degree of ventilation of the waste emplacement drifts, the presence or absence of an overpack or backfill surrounding the waste container, nature of the backfill and the method of placement of the backfill, its physical and mechanical characteristics, aspects related to its longevity, and thermal interaction with the container material.

- Better definition of the *in situ* or natural geological condition is needed in terms of the joint orientations, the classes of joints, fractures, inclusions and other defects, *in situ* stress state, as well as mechanical properties (i.e., elastic, failure, creep, and fracture properties) of the intact tuff within the various geologic horizons.

- Hydrological features and hydraulic conductivity characteristics of the repository location should be adequately mapped in terms of degree of saturation of the intact tuff, its porosity, hydraulic conductivity of the joints as inferred from joint roughness characteristics, the near-surface versus at-depth porosity, permeability, matrix hydraulic conductivity, and joint hydraulic conductivity at the repository locations. The exact nature of perched water at the site also needs to be defined.

- Computational modeling should be carried out to assess first the impact of the construction of the repository on the near-field and far-field response of the geological medium and the hydrogeological regime, particularly with respect to the behavior of the joint response and the impact of such joint responses on the stability of the perched water regimes.

- The direct shearing apparatus should be configured to examine the behavior of rock joints subjected to heating over a range of stress states at salient locations within the proposed repository where the effects of joints are expected to be of importance. The temperature ranges should correspond to those anticipated as a result of the radiogenic heating. The experiments should attempt to examine the influence of thermal loads and associated mechanical effects that could introduce enhanced degradation of the joints and possible enhancement of the hydraulic conductivity of the joint through localized thermal damage at the contacting surfaces.

- Simplified experimental procedures should be developed that can study processes associated with heat transfer, vaporization, vapor transport, and condensation that are expected to be of critical interest in the moisture regime around the repository. This aspect of the work can be restricted to only TH processes, and the effects of mechanical interactions could be accommodated via aperture control of the joint.

- The computational modeling should continue, using both UDEC and ABAQUS (or similar codes) in order to develop well-documented examples of TMH behavior involving intact and jointed rock types, for later use in inter-code comparisons of analyses conducted by organizations such as the DOE for evaluation of identical phenomena. Also, a concerted effort should be made to utilize the computational codes to predict the response of experiments that are in progress at CNWRA and elsewhere.

- Because of the identified limitations with the ABAQUS and UDEC codes, separate exercises in TH modeling should be conducted in partially saturated media with two-phase flow in both the rock matrix and joints. The TH model should be used to conduct scoping calculations that address the extent of the dry-out regime and condensate plume as well as its long term configuration with radiogenic decay. Such a TH model could be weakly coupled to the TM analyses using UDEC or ABAQUS to account for associated alterations in the hydraulic conductivity of the rock matrix and fractures with time.

- With regard to strength deterioration of rock joints and long-term stability of the jointed rock in the vicinity of openings, computational modeling should be conducted to ascertain the short-term or end-of-construction condition of the repository, and subsequent condition upon radiogenic heating to establish whether the devices used to provide support to the jointed rock mass in the exposed regions of the repository can continue to provide such support in the long term. Such simulations should include nonlinear time dependent movements such as creep of the intact rock and joints due to thermal and seismic loadings and their potential influences on additional loads imposed on rock support devices.

## 3.2 SUMMARY AND RESPONSE TO MAIN PEER REVIEW COMMENTS AND RECOMMENDATIONS

Many of the individual comments provided by the reviewers are considered thoughtful, constructive, and likely to significantly improve future CNWRA work, both in the experimental and computational modeling aspects. In reviewing the individual reports, it is clear that, while a good consensus exists on the future scope and direction of certain research activities, the individual peer review recommendations vary widely. In some cases, they are in direct conflict with one another. Also, several recommendations that relate to obtaining additional site characterization data are clearly the DOE charter and not that of NRC. This section of the report addresses the major comments and recommendations provided by the reviewers and synthesizes aspects in which the reviewers are either in agreement or disagreement. The more detailed comments provided by the reviewers will not be addressed in this report, but will be taken into consideration in the future coupled TMH processes work.

### 3.2.1 General Aspects of Thermal-Mechanical-Hydrological Coupled Processes Research

Comment: The individual reviewers appear to be in agreement that the TMH processes research can be decoupled because TM effects are considered for analysis of drift stability in the fractured medium, and TH effects are considered for analysis of processes related to vaporization, vapor transport, recondensation, and wicking or condensate dripping in fractures. With regard to the latter, both E. Detournay and D. Elsworth state that analysis of condensate reflux can be performed using two limiting cases of "high" and "low" fracture conductivity, which, in essence, would indirectly incorporate the mechanical effects on hydraulic fracture conductivity.

Response: We agree that due to the complexity of simulating all three coupled TMH processes in an unsaturated, fractured media, and, given the present limitations identified with the UDEC and ABAQUS computer codes, that this decoupling would be appropriate.

Comment: Both E. Detournay and D. Elsworth state that the TH processes involving the vaporization-migration-condensation-capillary wicking/dripping process are the least clearly defined and understood processes and the most crucial KTU (i.e., having potentially the greatest impact on waste package performance). D. Elsworth has given this topic the highest priority in the ranked list of future research topics. J. Gale and A. Selvadurai also rank this topic as a higher priority research topic. They recommend that modeling focus on the TH coupling aspects, aim at determining the extent of dry-out and recondensation zones, and provide bounds for the water inflow into the emplacement drifts by investigating various scenarios involving vaporization, vapor transport, condensation, and condensate flow. D. Elsworth depicts several such scenarios for dry-out and condensation zones graphically in his individual report. N. Barton, however, believes that dry-out, recondensation, and condensate dripping in the joints represent extremely complex and parameter-sensitive processes. Since it will be extremely difficult to obtain meaningful experimental results, he recommends focusing research on engineering solutions to minimize the consequence, such as TM studies of micro-cement-bentonite pre-grouting.

Response: We agree that more emphasis should be placed on identifying, at least in a general sense, the degree to which dry-out, recondensation, and condensate dripping would affect overall waste package performance based on the amounts of reflux and chemistry of the fluid flowing into the waste emplacement drifts. Research on TH processes (both experimental and modeling) has been conducted under the CNWRA thermohydrology project for over six years, and is expected to continue. If, through numerical parametric studies, it is found that condensate dripping is important for the range of thermal loadings and geologic conditions present, then the focus should be on engineered solutions to mitigate the effect as suggested by N. Barton. It should be noted that computational modeling studies would need cooperation with other CNWRA elements (e.g., thermohydrology), namely in utilizing their expertise and codes for simulating such TH processes as evaporation, vapor transport, and recondensation, that currently cannot be simulated using UDEC or ABAQUS. Based on the recent ABAQUS code evaluation study (Ofoegbu et al., 1995b), it was decided not to incorporate two-phase flow and phase change within ABAQUS. ABAQUS or UDEC could possibly utilize the results of a thermohydrology code such as

CTOUGH for calculating the amount of reflux from a condensation zone to the emplacement drift through fractures.

### 3.2.2 Modeling Studies

All the reviewers agree that computational modeling studies are extremely useful and should be continued in understanding key parameters associated with impacts of coupled TMH processes on waste package performance. This section focuses on responses to individual or combined comments related to the modeling aspects.

Comment: D. Elsworth stated that all computational analyses have assumed that conductive thermal effects are dominant. The significant temperatures anticipated around the proposed YM packages that may reach 230 °C and the resultant vaporization of matrix water may require reconsideration of this assumption. The reason is that for unsaturated repository conditions, although the thermal capacity of the vapor will be low, phase change effects and subsequent vapor transport on the anticipated thermal regime may be significant. Additional TH analyses could confirm or discount the validity of this assumption.

Response: We agree that most TM studies have been conduction dominated and have neglected the impact of hydrologic flow, phase change, and vapor transport on the temperature field. Considering that the rock matrix apparently entraps a significant amount of water, it would be beneficial to revisit this assumption. Such computational studies would have to rely on support from the Geohydrology/Geochemistry element in use of such codes as CTOUGH. Recent study by the thermohydrology project at the CNWRA shows a significant impact of hydrologic flow through fractures on the distribution of heat in the rock surrounding the waste package (Green et al., 1995).

Comment: Modeling studies have been suggested by several peer reviewers as a means of addressing the future research topics. For instance, E. Detournay suggested using "simple" models to address thermal degradation of rock strength properties (via a model of a supported circular tunnel in a thermoelastoplastic rock mass subjected to given temperature or heat flux boundary conditions), interaction of rock and support systems under heated conditions (via a model to assess the minimum drop of rock strength required to overcome the support system), etc.

Response: We agree that simple numerical models would be the best approach to gain a basic understanding of the impact of such processes on long-term stability and waste package performance in view of the difficulty in performing very long duration scale-model or field tests that would still require data extrapolation. In addition to performing some simple numerical scoping analysis on the thermal effects on tunnel stability, an extensive literature search will be initiated to gather information on thermal effects on rock degradation and rock/support interaction.

### 3.2.3 Experimental Testing

Comment: E. Detournay recommends that due to the limited resources, the experimental activities be significantly downsized or stopped, except for limited situations in which confirmatory experimental results are needed. However, the remaining reviewers favor the continuation of the experimental work, although in a more focused approach to assure that the KTUs are addressed.

Response: We disagree with E. Detournay's recommendation for conducting experimental research at universities as a presumedly more cost-effective approach, since this philosophy is contrary to the NRC reasons for creating the CNWRA and establishing a "Center of Excellence." With regard to significantly downsizing or eliminating future experimental studies, we agree with the philosophy stated in J. Gale's summary that numerical models only reflect the basic constitutive models, processes, and material properties that are used in the models. In the absence of a clear understanding of the basic coupled processes, relying solely on numerical models will likely provide little guidance or insight. In this regard, we opt to continue a limited focused experimental program on coupled processes in fractured rock.

Comment: Three of the reviewers (N. Barton, J. Gale, and E. Detournay) made similar comments that, prior to future experimental testing on single rock joints, both the results as well as the CNWRA direct-shear box design be critically reviewed. Their concern is that due to the differences in size between the top and bottom shear box specimens, there is a possibility for unrealistic gouge formation as a result of "ploughing" into new joint surfaces at the front and back of the top sample and rotating the top box. They also expressed concern that the range of shear displacements were perhaps unnecessarily large with no numerical scoping studies to confirm that such large shear displacements are representative of field conditions.

Response: Even though the CNWRA shear box design is slightly different from that used elsewhere, we disagree that the results are necessarily questionable in terms of excessive gouge formation at the leading edge of the top specimen block. Visual observations during the shearing did not indicate such "ploughing" phenomena at the leading edge as suggested by the reviewers. It is believed the large amount of gouge is a combination of factors including much weaker compressive strengths for the joint and the intact tuff rock, large normal applied loadings, and large range of shear displacements. The shear box design has the advantage of maintaining an average constant applied normal stress over the joint for both pseudostatic and dynamic tests under large joint shear displacements. Thus, adjustments to the normal load actuators which would be difficult in dynamic testing, are not necessary. We will, however, review the present shear box design and past results to determine whether undesired rotations, as a result of the resultant normal load shifting off center, are adversely affecting the results, and, if so, what corrective measures are needed. In addition, scoping calculations are being conducted to verify likely ranges of shear displacements due to seismic loading on a tunnel in fractured rock. However, we do not necessarily agree that conducting large shear displacement experiments in the laboratory represents a problem. We are evaluating the behavior of a joint under shear with the purpose to assess or develop a rock joint model. We may not know the full extent of shear on a joint in the underground repository environment, which will largely depend on the state of stress. If the resultant shear displacement is smaller than that used in the shear test, the rock joint model developed from the shear test results should be able to give a reasonable prediction within the range that occurs underground. In other words, the test results under large shear displacements should apply to potentially smaller joint shear displacements in the field.

Comment: Three of the reviewers (A. Selvadurai, J. Gale, and D. Elsworth) commented on continuation of the single fracture studies to better understand TM- and TH-type coupled processes in fractured rock. A. Selvadurai stated that since little experimental research exists regarding behavior of joints at elevated temperatures, heating should be incorporated into the single joint tests over a range of expected stress states to examine the influence of thermal loads and associated mechanical effects on localized degradation of joint contacts and possible enhancement of hydraulic conductivity. He also suggested TH-type tests that take into account two-phase flow in the fractures and associated matrix/fracture interactions with or without gravity effects. J. Gale also states that adding thermal loads to the ongoing MH experiments is essential, including the determination of fracture response at different temperatures and incorporation of basic fracture-matrix interaction studies including both single- and two-phase flow under both normal and shear displacement. Such tests should consider buoyancy effects in single vertical fractures. Finally, D. Elsworth states that it is important to evaluate the relative importance of TH processes in fractured and intact materials in the laboratory to determine the parametric controls on field scale TH processes, such as the vaporization, migration, condensation, capillary recirculation process. In his summary, he suggests possible courses of action.

Response: We agree with the comments and suggestions provided by these three reviewers about the need to extend beyond purely MH testing, giving high priority to conducting focused experiments on TH processes and lower priority on TM processes experiments in addressing key issues. It should be noted that a considerable amount of experimental work was conducted under the CNWRA thermohydrology project to investigate TH coupled processes within a simulated rock matrix with and without the presence of a single fracture (Green et al., 1995). Future experiments will build upon the knowledge gained under this project.

### 3.2.4 Field Studies

Comment: D. Elsworth commented that despite limited resources in the research area, field studies are important in (i) defining behavior at the scale closer to that of the prototype than the laboratory and (ii) incorporating processes that may inadvertently be missed in modeling efforts. He suggests that, in addition to proceeding with a full-scale heater test at the natural analog site in Mexico, reevaluations be done of the performance of existing large-scale/field-heater tests, as well as evaluation of active geothermal analogs including geothermal reservoirs and volcanically active regions.

Response: We agree. If the future budget and resources allow, selective field scale work should be done in combination with ongoing modeling studies either with regard to new field studies such as that proposed at the Peña Blanca natural analog site in Mexico, or review and further evaluation of existing field studies (e.g., hot dry rock geothermal reservoirs with significant vapor phase components) or other paleo-analogs (such as intrusions and haloes around magmatic dikes).

### 3.2.5 Ranking of Future Research Topics

As discussed in Section 3.2.1, the majority of the reviewers agree that high priority be given to better understanding of the TH processes (i.e., formation of dryout regions, recondensation of vapor, and condensate dripping through fractures in partially saturated, fractured media) and their potential consequences. Comments on the prioritization of other research topics are given below.

Comment: Both J. Gale and D. Elsworth suggest high priority be given to understanding the TM effects on permeability changes in partially saturated rock. J. Gale suggests that this understanding might be accomplished by experiments on single joints using tracers. D. Elsworth appears to suggest more of a modeling approach, where one can take into account TM effects on fractures by analyzing systems containing low fracture permeabilities and high fracture permeabilities, which may require support from laboratory evaluations. D. Elsworth also suggests that high priority be given to analyzing the TH effects on permeability changes as a result of alterations of the fracture walls and clogging by precipitation, dissolution, and reaction.

Response: We agree that one of the main goals in the rock mechanics research project is to establish both the mechanical and TM effects on fracture permeability in the near-field through numerical modeling studies with UDEC and ABAQUS and ongoing single jointed MH experiments. With regard to analyzing the TH effects on permeability, we believe that it is important in the long-term waste isolation period (Manteufel et al., 1993). However, it may be best to complete the work on the TM effects on permeability before addressing this issue.

Comment: The reviewers disagree widely on the research subject of bounding spatial variation of rock mass properties. This topic is given highest priority by J. Gale, who states that confidence in the approach taken to define spatial variability of the key parameters within the rock mass is essential for site assessment and incorporation of basic TMH processes into models in order to assess rock mass and drift/EBS response to thermal and mechanical loads. D. Elsworth gives this topic a medium priority ranking. However, E. Detournay states that this topic, along with the extrapolation of laboratory measurements to field-scale application arise in any rock engineering projects and should not be topics of future research. He states that, with the present state of knowledge, they should be addressed by performing scoping analyses, which would reveal the sensitivity of the solution to estimated variation of input parameters and would provide a basis for conservative predictions. N. Barton suggests using state-of-the-art graphical methods as a way of obtaining a better understanding of this issue rather than more difficult to interpret tabular presentations.

Response: There is no present or near-future research planned in the area of bounding spatial variation of rock mass properties. We believe that there will always be some uncertainty in the characterization of geologic and rock mass properties, especially as one extends away from the tunnel boundaries. The use of scoping studies to bound the likely response, we feel, would be an acceptable approach. Similarly, the adoption of more advanced extrapolation techniques developed in the fields of hydrology and geophysics may also provide a reasonable approach to estimating the rock mass properties. As several of the reviewers have suggested, perhaps either no additional research or only a minimal amount is necessary.

Comment: Research topics such as time degradation of rock properties, rock-support interaction under heated conditions, parameter scaling to field scale (to some degree), and long-term performance of repository seals were given lower priority by most to all of the reviewers for reasons discussed in the individual summary reports.

Response: We, as well as the DOE and NRC, believe that time-dependent degradation of the rock and rock support is a potentially important issue during the waste retrieval and isolation periods. During FY96, we plan to conduct a literature search on the topic, and, if it is determined that sufficient information on thermal rock degradation exists on evaluating the impact at YM, no further work will be initiated. With regard to scale effects, we believe that it is necessary to understand and to take into account the effect of scale on the measured values of the parameters necessary in analyzing the stability of underground openings and the flow of fluids through the fractures. Consequently, a literature review will be initiated in FY96. We agree with the reviewers that research on performance of repository seals is not necessary at this time, since the DOE will have a long period of time prior to closure to evaluate their design and performance.

### 3.2.6 General Comments

Comment: A. Selvadurai made some initial comments related to the need to arrive at more precise details of the repository in terms of its location, the geometry of the drifts, construction nature, etc., as well as the need for more detailed characterization of the *in situ* or natural geological and hydrological conditions and thermal loading strategy.

Response: These issues are clearly the responsibility of the DOE and not the NRC. We can only base our analyses, etc., on the most current site characterization and design information. Not having the final design parameters, such as thermal, loading creates less of a problem for the modeling activities than experimental work, since ranges of thermal loadings and other parameters can easily be simulated.

# 4 CONCLUSIONS

The expert-panel review of the CNWRA coupled TMH process research program met all the objectives of the review and provided constructive comments and recommendations that will significantly improve the future work in this area. Five independent experts in various aspects of TMH coupling examined the research program in detail. The reviewers concluded that the CNWRA research program has made significant progress, particularly in view of resource constraints.

Some of the major points and recommendations that arose from the review are that the research should:

- Progress from MH laboratory testing of single-rock joints to TM and TH testing on rock joints to address key issues associated with these processes in fractured rock.

- Focus more research effort on TH processes (i.e., vaporization, migration, condensation, capillary recirculation) because they are the least well constrained and understood with a potentially large impact on waste package performance.

- Consider simple numerical parametric studies to address several of the identified research topics (e.g., parameter scaling to field scale, bounding spatial variation of rock mass properties, and time-dependent degradation of rock properties).

- Confirm assumptions that the primary mode of heat transfer within the repository region is conduction, given that phase changes and vapor transport may have significant effects on the thermal regime.

- Re-evaluate the design of the CNWRA direct shear box to assure that it is not artificially influencing the results obtained, specifically with regard to rotation of the upper shear box, shifting of resultant normal load, and excessive gouge formation. The large range of shear displacements should also be verified to assure that they are indeed representative of site conditions.

- Consider conducting selective field scale work such as the proposed heater test at the Peña Blanca natural analog site in Mexico, or evaluation of existing field studies (e.g., hot dry rock geothermal reservoirs).

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# APPENDIX A

# NOMINATION SOLICITATION LETTER

# Center for Nuclear Waste Regulatory Analyses

6220 CULEBRA ROAD •P.O. DRAWER 28510 •SAN ANTONIO, TEXAS, U.S.A. 78228-0510
(210) 522-5160 •FAX (210) 522-5184

Contract No. NRC-02-93-005
Account No. 20-5704-036

Address

Dear :

The Center for Nuclear Waste Regulatory Analyses (CNWRA) is a federally funded research and development center that supports the Nuclear Regulatory Commission High-Level Nuclear Waste Repository Licensing Program. A candidate repository site at Yucca Mountain, Nevada, is currently under evaluation. In evaluating design and performance of this proposed repository, it is expected that coupling between thermal (T), mechanical (M), and hydrological (H) processes over a variety of spatial and temporal scales will have to be considered. The NRC's intention is to obtain an adequate understanding of T-M-H coupling so that an acceptable method can be developed to comprehensively, systematically, and logically evaluate DOE's T-M-H response calculations for the design and performance of the geological repository.

The CNWRA research efforts related to coupled T-M-H processes were initiated about two years ago. I am organizing an independent peer-review of this program in order to evaluate the initial research results and further refine proposed research strategies and goals. The current research program is scheduled to continue into 1998. The first step in this review is to select a peer-review group composed of experts in the field of T-M-H coupled processes. Because you are well known in one or more fields related to T-M-H coupled processes, I need your assistance in identifying candidates for the five-member review group.

We are seeking recognized experts in the fields of T-M, M-H, T-H, and T-M-H coupling, as well as those experienced in long-term degradation of rock and engineered materials under repository loading conditions to assist in this review. The general goals of this review are to (i) examine the overall objectives and approaches of current and planned CNWRA studies related to T-M-H coupling and long-term degradation of rock and engineered materials; (ii) recommend improvements and possible expansion of the research scope and methodologies; and (iii) evaluate interpretations of the available data and explore alternative hypotheses. Reviewers are expected to focus and lead discussions on issues that they deem important to repository design and performance. I anticipate holding a 2-day review meeting in San Antonio, Texas during June 1995; individual review recommendations will need to be submitted by August 10, 1995. The selected experts will be contracted by the CNWRA as consultants and will be paid for their time and associated expenses. I anticipate a total time commitment of about 120 hours, of which about 40 hours will be for the meeting and travel.

I would like to know if you would be interested in participating in this peer-review panel. If so, or if you would like more information on this review, please contact me directly at your earliest convenience. In any event, I would greatly appreciate the names of 8-10 people that you would regard as experts in the above fields related to T-M-H processes. I will, of course, keep these names confidential, and am only using this information to compile a list of potential candidates for the group. After this general solicitation is complete, I will then contact the potential panel members directly to further explore their interest and availability. Due to possible conflicts-of-interest, we unfortunately are unable to have employees of the U.S. Department of Energy and associated national laboratories (e.g., Los Alamos, Sandia, Lawrence Livermore) as members of this review group. We need to finalize the panel membership by the end of April, 1995, and thus hope that you are able to respond to this request within the next couple of weeks. I can be reached by phone at (210) 522-5799 and by e-mail at mahola@sleepy.cnwra.swri.edu.

Sincerely,

Mikko P. Ahola

# APPENDIX B

# FORMAL LETTER OF SOLICITATION FOR PEER-REVIEW PANEL

# Center for Nuclear Waste Regulatory Analyses

6220 CULEBRA ROAD •P.O. DRAWER 28510 •SAN ANTONIO, TEXAS, U.S.A. 78228-0510
(210) 522-5160 •FAX (210) 522-5184


Contract No. NRC-20-93-005
Account No. 20-5704-036

Address

Dear :

Recently Mr. Mikko P. Ahola of the Center for Nuclear Waste Regulatory Analyses (CNWRA) contacted you about participating on a peer-review panel for coupled thermal-mechanical-hydrological (TMH) processes research at the CNWRA. Having received your preliminary indication of interest, we are initiating formalities to acquire your services as a consultant to the CNWRA for this purpose. A brief introduction to the CNWRA and an outline of the review we desire is included in this letter, along with a request for information from you to permit us to initiate a contract.

The CNWRA is a Federally Funded Research and Development Center that has been established with a mission to provide quality research and technical assistance to the U.S. Nuclear Regulatory Commission (NRC) toward licensing the first national high-level nuclear waste (HLW) repository. The CNWRA is situated at Southwest Research Institute (SwRI) in San Antonio, Texas, and is operated by SwRI. The CNWRA currently has professional staff spanning all areas of geosciences and engineering relevant to HLW geologic disposal.

As the licensing authority, the NRC has a strong interest in coupled processes that are associated with the emplacement of heat generating nuclear waste in the potential HLW repository at Yucca Mountain, Nevada. The focus of this review is coupled TMH processes. Changes in chemistry of the rock as well as fracture surfaces over long periods of time may also likely effect the coupling mechanisms, however, the chemistry aspects are being investigated under other research projects and will not be a part of this particular peer review. Although Yucca Mountain is a partially saturated site, there exists a considerable amount of water within the geologic formations as well as in the identified perched water zones. Depending on the areal thermal loading scheme adopted by DOE, there has been preliminary calculations performed showing the potential for strong heat driven vaporization followed by recondensation in cooler regions above the repository. The subsequent flow of fluid from these hypothesized condensation zones downward through fractures towards the repository horizon and the potential impact on waste package performance is yet unclear. Yucca Mountain is also located in a seismically active area. The effect of repeated shearing along joints due to the regional seismicity as well as due to heating/cooling within the repository on the permeability of the fractured rock and long-term stability of openings is not fully known. Finally, the effect of the thermal stresses and long-term degradation of the rock under heating on the stability of the emplacement openings is an area of uncertainty. The present performance standard for the HLW repository requires that no significant release of HLW to the accessible environment occurs during the next 10,000 years. Specific criteria relevant to coupled TMH processes include: i) the requirement that openings be designed to reduce the potential for deleterious movement or fracturing of surrounding rock, ii) the requirement that seals be designed such that they do not become preferential pathways after permanent closure, and iii) the requirement that the underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system. The goal of the coupled TMH research at the CNWRA is to better understand some of these issues as well as to develop an independent review capability in assessing DOE's license application especially on those phenomena identified to have a strong impact of meeting performance objectives. This research is summarized in the enclosed outline.

Both the NRC and CNWRA recognize that peer-review will improve ongoing research programs significantly. The intended goals of the current review are to (i) examine the overall objectives and approaches of CNWRA coupled TMH processes research; (ii) improve and possibly expand the research scope and methodologies; and (iii) evaluate CNWRA's interpretations of the available data and hypotheses. The review panel will consist of five senior scientists such as yourself, with expertise in individual and coupled TMH processes. The CNWRA has developed and implemented a formal quality assurance program, which includes procedures for the performance of peer reviews. A copy of this procedure, CNWRA Quality Assurance Procedure QAP-002, is enclosed for your information.

We anticipate holding the review at the CNWRA in San Antonio, Texas, beginning on Monday June 26, 1995. The principal investigators on various activities of the coupled TMH processes research will present a synopsis of CNWRA research activities. These presentations will supplement the study plans and reports which will be sent for you to review in early May. The review-panel members will elect a chairman, who will preside over the meeting. The chairman will then lead discussions on the research program in general, followed by specific topics from the panel members's areas of expertise. During the two day meeting, the panel members will be shown the laboratory facilities used for conducting the research activities. The meeting will adjourn at the end of the day on Tuesday June 27, 1995. The reviewers will be ordered to provide written comments to the chairman who will provide them to the CNWRA. Later, these comments may be made public as a part of a CNWRA report.

We expect that the review of the background material and preparation for the panel meeting will require about 48 hours of your time. Participation in the meeting and associated travel will require an additional 32 hours. Following the meeting, panel members are expected to produce a written report of about 10 pages, which provides their evaluation of the CNWRA research program and recommendations for improvement. We expect that the preparation of this report will require about 40 hours of your time, and that the report will be completed by the 15th of August, 1995.

To meet CNWRA Conflict of Interest requirements, and to assist us in setting up a consulting agreement, we must receive from you the following items:

- Conflict of Interest Statement (form and a sample copy of a letter enclosed)
- Your fee schedule

We would appreciate your attention and quick response in supplying these items. Please send them to CNWRA, attention Anna Lopez. On execution of the consulting agreement, we will send you the following background materials to review: vitae for the CNWRA principal investigators, research project plans, CNWRA reports, journal articles, and abstracts related to these projects.

We greatly appreciate your interest in helping the NRC and the CNWRA in this matter of national importance. If you have any questions about the review during that time, please contact Mr. Mikko P. Ahola (210-522-5799) or Dr. Asadul H. Chowdhury (210-522-5151) at the CNWRA.

Sincerely,

Budhi Sagar
Technical Director

Enclosures

cc: W. Patrick
CNWRA Directors
CNWRA Element Managers
M. Ahola
S. Hsiung
S. Mohanty
G. Ofoegbu
A. Ghosh
R. Manteufel
A. Lopez

# APPENDIX C

## OUTLINE FOR THE EXPERT-PANEL REVIEW OF COUPLED THERMAL, MECHANICAL, AND HYDROLOGICAL PROCESSES RESEARCH AT THE CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

## I. Goal of Review

The peer review will focus on the following:

- A critical review of the objectives and approaches of CNWRA coupled TMH processes research and its application to licensing issues at the proposed Yucca Mountain high-level (HLW) repository site

- Recommendation to improve research scope and methodologies, and investigate new issues that may not be part of the original research plans

## II. CNWRA TMH Coupled Processes Research

### A. *Synopsis of the Regulatory Basis for Doing Coupled TMH Processes Research:*

10 CFR 60.1: Nuclear Waste Policy Act (1982) and amendments task the DOE to receive and store high-level nuclear waste in a geologic repository.

10 CFR 60.3: DOE is required to obtain a license for the repository from the NRC.

10 CFR 60.133(e)(2): Openings in the underground facility shall be designed to reduce the potential for deleterious rock movement or fracturing of overlying or surrounding rock.

10 CFR 60.133(i): The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, surrounding strata, and groundwater system.

10 CFR 60.134(a): Seals for shafts and boreholes shall be designed so that following permanent closure they do not become pathways that compromise the geologic repository's ability to meet the performance objectives for the period following permanent closure.

In essence, the NRC will have 3 years to evaluate the DOE license application and determine whether the proposed site could result in significant radiological health risks to the population. This evaluation process is expected to be highly contentious and subject to intense scrutiny by numerous groups with extremely divergent views on nuclear waste in general and the proposed repository site at Yucca Mountain in particular. Early peer review of the CNWRA coupled TMH processes research is thus prudent and will enhance the overall quality of the program.

### B. *CNWRA TMH Processes Research Developed Around 3 Key Technical Uncertainties:*

Key Technical Uncertainties (KTUs) were developed by the NRC to guide the research needed to effectively evaluate the DOE license application. With regard to coupled TMH processes effects on the engineered barrier system and surrounding host rock, three KTUs exist:

1. Uncertainty in the prediction of thermal-mechanical (including repetitive seismic load) effects on stability of emplacement drifts and engineered barrier system.

2. Uncertainty in the prediction of thermal-mechanical-hydrological (including repetitive seismic load) effects on the host rock surrounding the engineered barrier system.

3. Uncertainty in the prediction of the long-term performance of seals for shafts, ramps, and surface and subsurface boreholes.

C. *General CNWRA TMH Research Project Objectives:*

1. Develop a better understanding of the effect of normal and shear deformation along natural welded tuff joints on changes in joint permeability for both saturated and partially saturated flows.

2. Develop knowledge of TMH processes through experiments and numerical modeling conducted under the international cooperative project DECOVALEX (DEvelopment of COupled models and their VALidation against EXperiments)

3. Develop an understanding of the constitutive laws of time-dependent rock properties under heated, variably saturated, and stressed conditions.

4. Develop a technique to extrapolate laboratory-measured fracture flow data for field-scale application.

5. Assess the long-term TM effects on the performance of seals, surrounding rock mass, and seal-rock interface.

D. *Research Program Results and Products to Date:*

1. Intermediate/Major Milestones:

   - Literature review of coupled thermal-hydrologic-mechanical-chemical processes pertinent to HLW repository at Yucca Mountain.

   - Experimental results of single fracture flow behavior of welded tuff joints under normal and shear loadings.

   - Numerical modeling using the distinct element code UDEC and finite element code ABAQUS for the following experimental test cases and benchmark tests under DECOVALEX project:

     — Norwegian Geotechnical Institute (NGI) coupled shear deformation-flow experiment on single rock joints

     — Canadian benchmark test involving coupled TMH response of a multiply fractured rock block.

     — French benchmark test involving near-field coupled TMH response of a heated tunnel in a randomly, highly fractured rock mass.

— Japanese field scale test case experiment involving coupled TMH response of a simulated engineered barrier system consisting of a waste package, unsaturated clay buffer, and surrounding concrete block.

**III. What is required from reviewers:**

A. Background Material:

1. Detailed review:

   a. Project Plan for Rock Mechanics research project (TMH related research work, 10 p.

   b. Operations Plans for the Division of Waste Management (Investigation of issues related to repository design, construction, and operations, Subtask 2.3, 8 p.)

   c. Experimental assessment of fracture permeability changes under normal and shear loading and saturated flow. CNWRA 94-024 (65 p.)

   d. Key Technical Uncertainties (KTUs) identified with regard to effect of coupled TMH on host rock and engineered barrier system at proposed repository site (16 p.)

2. Skim for familiarization:

   a. CNWRA semi-annual research reports: January–June 1993 (Chapt. 4, 17 p.); July–December 1993 (Chapt. 3, 23 p.); January-June 1994 (Chapt. 2, 33 p.); July–December, 1994 (Chapt. 2, 28 p.).

   b. Assessment of coupled thermal-hydrologic-mechanical-chemical processes. NUREG/CR-6021, 125 p or 1993 Int. High Level Radioactive Waste Management Conference paper, 8 p.

   c. Numerical modeling of TMH benchmark tests and test cases under the DECOVALEX project. CNWRA 92-005 (58 p.); CNWRA 93-002 (44 p.); CNWRA 94-021 (43 p.).

   d. Evaluation of ABAQUS for compliance determination in the area of coupled TMH processes. 1994 Progress Report (75 p.)

B. Detailed Review of Project Scope: Discussions will be led by panel members and will focus on the main goals:

1. Critically review the objectives and approaches of CNWRA coupled TMH processes research and its application to licensing issues at the proposed Yucca Mountain HLW repository site.

2. Recommend improvements to the research scope and methodologies, and investigate new issues that may not be part of the original research plans

3. Evaluate interpretations of the available data, and explore alternative hypotheses

Reviews will consist of discussions in San Antonio and a short (about 10 pages) independent written report from each panel member.

**IV. Schedule and Plan for Peer Review:**

1) Recruit the experts. Solicitations from approximately 100 people including USGS, U.S. DOE, domestic and international companies and academic institutions, appropriate professional societies, and journal editors. Formal selection of 5 individuals, with expertise in various aspects of coupled TMH processes in fractured rock masses and long-term degradation of rock.

2) Prepare documentation and information for expert review. Determine format and detailed instructions to reviewers for initial review, mid/late May 1995.

3) Provide initial information and instructions to reviewers. Allow about 6 days (48h) billable for initial overview and preparation.

4) Meet in San Antonio, TX for overview and presentations by CNWRA technical staff, June 26-27, 1995. Four days (32h) including travel time.

5) Peer reviewers prepare detailed report, addressing major goals of review, by August 15, 1995. Arrive at individual recommendations for improvement of research approaches. Allow about 5 days (40h) billable.

6) Synthesize the 5 individual reports into a Major Milestone for NRC-RES. Delivery date at the end of September, 1995. Modify project plans or research strategies as appropriate.

# APPENDIX D

# SCOPE OF WORK FOR CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES THERMAL, MECHANICAL, AND HYDROLOGICAL COUPLED PROCESSES EXPERT-PANEL REVIEW

The work will be encompassed in one primary task with three subtasks, as follows:

The primary task is to provide an expert review of the CNWRA coupled TMH processes research being conducted as a subpart of the overall CNWRA Rock Mechanics Research Project. The objectives of the review are to:

- Critically review the objectives and approaches of CNWRA coupled TMH processes research and its application to licensing issues at the proposed Yucca Mountain HLW repository site.

- Provide recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original research plans.

The expert-panel review will be accomplished by the following subtasks:

1) Review the literature produced under the CNWRA coupled TMH processes research project, to become familiar with programmatic and technical goals. Detailed reviews will be conducted on study plans, description of associated Key Technical Uncertainties (KTUs), and critical reports (about 100 pages). Semi-annual research reports (about 100 pages) will be provided for familiarization , as well as other principal milestones (about 400 pages). A total of 48 hours is allotted for this subtask.

2) Attend a 2-day meeting in San Antonio, Texas, beginning June 26, 1995, to discuss the principal objectives of the review with CNWRA and U.S. Nuclear Regulatory Commission (NRC) staff and other expert-panel members. A total of 32 hours, including travel time, is allotted for this subtask.

3) Prepare a written report of recommendations to achieve the primary goals of the expert-panel review. Report will be due by August 15, 1995. A total of 40 hours is allotted for this subtask.

# APPENDIX E

# AGENDA FOR PEER REVIEW OF CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES COUPLED THERMAL, MECHANICAL, AND HYDROLOGICAL PROCESSES RESEARCH

**Monday July 10, 1995**

| | | |
|---|---|---|
| 9:00 - 9:30 | Introductions for Panel, CNWRA, and NRC attendees<br><br>Management overview of the CNWRA and relationship to SwRI and NRC<br><br>Focus of the review:<br><br>- Review objectives of CNWRA TMH coupled processes research<br>- Improve CNWRA research scope and methodologies | **- Budhi Sagar** |
| 9:30 - 10:00 | NRC perspective | **- Banad Jagannath**<br>**Jake Philip** |
| 10:00 - 10:15 | Break | |
| 10:15 - 11:00 | Overview of TMH technical/regulatory issues at Yucca Mtn site:<br><br>- Regulatory basis for research<br>- KTU's and their translation | **- Asad Chowdhury** |
| 11:00 - 11:30 | Expert-panel caucus. Panel members:<br><br>- Elect a Chair for the meeting, who will ensure that sufficient time is allotted to address the review goals for the project. Chair will recognize questions from the audience and limit discussions if necessary to remain on schedule. Individual reports in August will be sent to the Chair, who will ensure that the reports are complete and add a summary statement if so desired.<br><br>- Panel members will decide the agenda for the rest of the meeting. The review panel will lead the discussions, focusing on what has been accomplished in the TMH research program. | |
| 11:30 - 12:30 | Lunch | |
| 12:30 - 13:30 | Visit of CNWRA Laboratories | |
| 13:30 - 17:00 | General discussions/presentations on CNWRA ongoing TMH processes work<br><br>*Ongoing Research:* (Short presentations to be given by CNWRA personnel on following subjects followed by general discussions) | |

Coupled TMH modeling

- CNWRA computer code evaluation studies for TMH processes — **- Goodluck Ofoegbu**

- DECOVALEX — **- Mikko Ahola**

Laboratory experimentation on coupled MH behavior of single, natural rock joints under joint normal and shear deformation. — **- Sitakanta Mohanty**

**Tuesday July 11, 1995**

| | | |
|---|---|---|
| 9:00 - 11:30 | General discussions/presentations on topics of future CNWRA TMH processes research | **- Amit Ghosh** |

*Potential topics of future research:*

- time dependent degradation of rock properties under heated conditions
- extrapolation of laboratory measurements to field scale application
- methodology for bounding spatial variation of rock mass properties
- interaction of rock and support systems under heated conditions
- mechanical and thermomechanical effects on permeability changes in unsaturated fractured rock
- formation of dryout regions, recondensation of vapor, and condensate dripping through fractures in heated, partially saturated fractured media

| | |
|---|---|
| 11:30 - 13:00 | Lunch |
| 13:00 - 16:00 | Continue discussions from morning session |
| 16:00 - 16:30 | Review panel caucus to discuss preliminary issues raised in the review. |
| 16:30 - 17:00 | Wrap-up (Review panel members to provide preliminary evaluation/findings). |

# APPENDIX F

# INDIVIDUAL EXPERT-PANEL MEMBER REPORTS

**Dr. Nick Barton**

# Review of Center for Nuclear Waste Regulatory Analyses' Coupled Thermal-Mechanical-Hydrologic Process Research

# for assisting Nuclear Regulatory Commission in The Yucca Mountain High Level Waste Repository Assessments


by Dr Nick Barton
Rock Engineering Consultant
Oslo, Norway


31st July 1995

# Executive Summary

The report is based on a review of twelve documents concerning regulatory and research work connected with HLW geologic repositories. Documents reviewed in detail concern CNWRA research in thermal-mechanical-hydraulic (TMH) coupled processes, and international DECOVALEX coupled process validation modelling. Two days of CNWRA and Nuclear Regulatory Commission presentations and discussions in San Antonio and inspection of laboratory equipment and joint samples, completed the background information for the reviewers.

In respect of the big discrepancy in funding between NRC and DOE HLW research, the level and extent of experimental and numerical work at CNWRA is commendable and has surprised all the reviewers. Nevertheless, the function of a peer review is constructive criticism, and certain aspects of CNWRA and DECOVALEX work is highlighted for possible improvement in techniques and in the correctness of conclusions drawn from the work. Since the present reviewer has had responsibility for the development of a constitutive rock joint model used by CNWRA and by some DECOVALEX teams, several of the points made relate to assessment of this model and the needs for its improvement.

The CNWRA shear box design is believed to have been responsible for some of the unexpected gouge production and marked reduction in permeability with shear, despite dilation. Recommendations are made for improving the design so that it is more in line with conventional lay-outs despite the added levels of sophistication already achieved for dynamic and reversed shearing. An important error in the computer coding of the BB constitutive model in UDEC-BB was identified by CNWRA as a result of their work with reversed shear. This error was rectified during early 1995.

The international DECOVALEX coupled process modelling test cases that were modelled by CNWRA and other international teams addressed, among several models, two coupled stress flow tests (CSFT). The value of this work is evaluated, since it highlights both constitutive modelling problems and experimental design problems. It is recommended that greater care is taken by DECOVALEX in drawing the right conclusions from the very mixed results obtained by the different groups. Single, atypical experimental results should not be used to develop new constitutive models.

Recommendations for future research studies at CNWRA from this reviewer are focused on more site specific work. It is believed that this will help to put CNWRA in a stronger position to assist NRC in assessing DOE activities and design studies for the Yucca Mountain HLW repository. Up to now research activities have been specific to tuff but nevertheless somewhat generic in nature. It is recommended that numerical scoping studies are performed with UDEC-BB and 3DEC for studying the potential range of thermal, mechanical and dynamic response for a range of site specific potential joint structures to excavation, heating and dynamic (earthquake) loading. With likely magnitudes of joint shearing and reversed shearing modes better delineated, appropriate modifications can be made to the direct shear CSFT apparatus at CNWRA.

Dr Nick Barton
Rock Engineering Consultant
Tel/Fax: (47) 67 53 15 06

Langoddveien 122
N-1335 SNARØYA
Norway

DOE's choice of TBM excavation with its late placement of steel rings in place of rock bolts, has serious implications if carried through from the ESF to the HLW repository. Characterisation is hindered by TBM, boundary stresses are maximised, and thermal spalling may be expected to overload steel ring support which is located in the hottest possible location, and to compromise retrievability due to derailment, *etc.* Numerical scoping studies are recommended in order to understand the potential implications of TBM excavation and related late support.

It is believed that some form of corrosion and heat resistant, fully grouted rock bolting, applied (with mechanical anchorage) early in the excavation cycle, is the only viable rock mass reinforcement. It will help to minimise rock excavation disturbed zone apertures. Research in this area is therefore recommended, utilising laboratory bench scale tests with relevant Topopah Spring tuff samples.

Lithophysal cavities, which may be laterally continuous and are said to occur with cavity contents up to about 10% in Topopah Spring W2 unit, pose a challenge to tunnel excavation, and will be capable of seriously influencing stability and the response to thermal loading. In the first instance numerical scoping studies are recommended. Major grouting programmes may be called for.

Spatial variation of numerous rock mass parameters, and scaling of the usual small scale measurements to field scale application in computer and analytical studies, poses a challenge to designer and regulator. Depending on DOE thoroughness in this area, suggestions could be developed by CNWRA for clear, unambiguous graphical presentation of vertical and lateral variation of parameters, preferably far different from the cumbersome tabulations of data seen so far. Graphical methods used for tuff at the Sellafield site in the UK could be used as a starting point.

Dry-out, recondensation and condensate dripping in the joints represents an extremely complex and parameter-sensitive process, in which it will be extremely difficult to obtain meaningful experimental results. As an alternative to possibly doing thankless research in this area, an engineering solution to minimise the consequence of recondensation is recommended, involving T-M studies of micro-cement-bentonite pre-grouting.

The latter half of this review provides short comments to individual aspects of some of the key reports that have been reviewed. Special attention is paid to the experimental CSFT testing, to constitutive modelling of rock joints and to the attempts to verify computer codes against unexpectedly complex test cases within the DECOVALEX project.

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# 1 INTRODUCTION

This review of NRC funded CNWRA reports and suggestions for future research topics was requested by CNWRA on 13th June 1995.

During the panel review on 10th and 11th July 1995, presentations were given by CNWRA and NRC representatives, which helped clarify the main thrust of CNWRA activity to date. Laboratory visits were also helpful in visualising some details of the experimental work.

During the course of the CNWRA presentations, the panellists were made aware of the large discrepancy in resources between NRC/CNWRA-HLW scientific activities and those of DOE and its contractors. In view of the discrepancy, the standard and extent of CNWRA activities is commendable and remarkable. However, in the opinion of this reviewer, the complexity and gravity of the Yucca Mountain HLW repository project warrant a far higher level of resourcing for the regulatory body if NRC is to continue to be assisted by experienced staff at CNWRA on the wide ranging list of issues that have yet to be addressed. Strengthening NRC response will strengthen DOE's activities and in the long run reduce the risk of costly errors of judgement, which have a tendency to mar the economics and long term benefits of major projects.

# 2 GENERAL COMMENTARY ON TWO OF CNWRA ACTIVITY AREAS

In view of the resources made available in the past, and those expected for the future activities of the Center, the following comments are offered in the spirit of technical advice and should not be construed as criticism. The following technical areas will be discussed:

- CNWRA shear box for coupled MH investigations
- International joint modelling in DECOVALEX

## 2.1 CNWRA Shear Box for Coupled MH Investigations

The CNWRA shear box was designed with ambitious goals for MH coupling and large displacement (± 25 mm) forward and reverse shearing under sealed conditions. Out of a presumed desire to avoid correction for changing (reducing) area of contact under shear, the top box was designed for shorter samples of the joint surface than the bottom (a discrepancy of approximately 50 mm on each side).

Shearing has produced excessive amounts of gouge. It is believed that this is partly due to the usual non-uniform, edge-enhanced normal stress distribution (and possible rotational effects caused by line of action of forces). The main gouge producing mechanism however is considered to be the "ploughing" into "new" joint surface at the back and front of the top sample. *In situ*, behind a tunnel wall (or rock slope) such a ploughing "chisel-edge" effect is very unlikely since the "chisel-edge" is replaced by more joint surface. Furthermore, constitutive models for joint

Dr Nick Barton
Rock Engineering Consultant
Tel/Fax: (47) 67 53 15 06

Langoddveien 122
N-1335 SNARØYA
Norway

performance (*i.e.*, Barton, Bandis and Bakhtar, 1985) were not developed from this type of shear box result.

It is extremely likely that shear strength, dilation, gouge production and permeability (or effective aperture changes) have each been affected by this design aspect. Conclusions should therefore be modified. Despite what are considered to be experimental peculiarities, CNWRA should be commended for their discovery of incorrect implementation of the Barton-Bandis reverse shear behaviour in UDEC-BB. This error has already been corrected by NGI (Gutierrez, 1995) and Itasca (Christianson, 1995), and a corrected and improved version of UDEC-BB is now available, which shows reduced shear strength and reversed dilation as described by Barton (1982) and as deduced by CNWRA, the latter possibly of exaggerated extent due to "ploughing" in the first forward (and post-origin reverse) shearing.

The CNWRA desire to conduct reversed shear studies to as much as ± 25 mm magnitude is considered by this reviewer to be excessive. Scoping studies with UDEC-BB and 3DEC (discussed later) may well indicate much smaller levels of shear and shear reversal. An improved, more realistic experimental philosophy might prove to be ± 1, ± 2, ± 4, ± 8 mm, *etc.*, shearing, since roughness is unlikely to be removed immediately due to the normal stress increase. Alternatively, +2-1, +4-2, +8-3, *etc.*, shearing might better mimic the possible accumulation of shear in one direction, due to existing (one-way) shear stresses on the joint *in situ*. (See Barton, 1988 for a full discussion of this aspect.)

## 2.2 International Joint Modelling in DECOVALEX

Performance of CSFT Test Case 1 and 2 (TC1 and 2) models in the DECOVALEX modelling exercise produced in several respects, less than satisfactory performance. It was presumed at the outset that the CSFT was a fundamental, and relatively straightforward experiment. This proved not to be the case for various reasons such as actual stress level, actual geometry and peculiarities in the chosen test (TC2 in particular). The latter was clearly a poorly interlocked sample, requiring more than 1 mm of closure until some semblance of stiffening normal closure behaviour was experienced. This is very unusual. The conducting aperture under stress (at least 100 μm) was quite different from the other Borrowdale Volcanic Group specimens from Sellafield, which gave hydraulic apertures under stress in the range 5 to 15 μm, and more "classic" closure behaviour (*i.e.*, following Bandis *et al.*, 1983). Probably for the above reasons, the shear-dilation-aperture behaviour was very unusual. The modellers results were in this case more "correct" (*i.e.*, typical of most tests) than the chosen experiment.

It would be unwise and very unfortunate for future numerical modelling capabilities if SKI (and NRC and other funding agencies) continue to conclude that new constitutive models should be developed to match what are sometimes spurious experimental set-ups. Single test results are no basis either for developing or modifying existing codes, since, in the case of for example the BB model, some aspects of the code have been based on direct shear tests of as many as 600 joint samples (multiple testing under various normal loads excluded). That there is considerable scatter is obvious.

The DECOVALEX project has nevertheless focused attention on some potential real problems of numerical modelling (avoidance of rotations that may not occur experimentally due to different restraint) and potential real problems of constitutive modelling, which need further attention. Of particular importance, as identified extra strongly by CNWRA, is the improvement of gouge-flow-reduction modelling. Information at various laboratories (St John's, NGI, *etc.*) from numerous CSFT tests need synthesis in this respect, if confidentiality clauses do not hinder general release of such data.

## 3 RECOMMENDATIONS FOR FUTURE RESEARCH STUDIES AT CNWRA

It appears to be correct to conclude that up to now, CNWRA research has been generic and fundamental in nature, which has served a very useful purpose in giving staff hands-on experience through laboratory (*i.e.*, CSFT) and numerical modelling (*i.e.*, DECOVALEX).

### 3.1 Site Specific Scoping Studies with Numerical Models

In order to be able to respond to and suggest possible modification of DOE characterisation and design methods at Yucca Mountain in a timely fashion as site data now rapidly emerges, it is recommended that research (both experimental and numerical) is made more site specific in the near future.

Site specific joint data (geometric and strength data) should be incorporated in both simplified and more detailed UDEC-BB and 3DEC models to address, in the first instance, mechanical, dynamic, thermal and then TM-Dyn. performance as they impact 10 CFR 60 111b (retrievability) and 112 (post closure system performance).

Scoping (parametric) studies should be performed of tunnel orientation effects (in relation to structure and stress variations) in order to understand the implications of DOE's presently envisaged disposal tunnel layout, where for TBM excavation efficiency, tunnel axes may be chosen to parallel the long axes of perceived repository limits having regard for overburden and avoidance of major faulting. The general trend of the closely spaced sub-vertical NE and NW trending jointing and of the more widely spaced NE dipping sub-horizontal jointing, (Chapter 5, B 0000 0000-01717-5705-00015 Rev. 00, 08/29/94 !) in relation to present tunnel lay-out, may or may not be optimal from the point of view of the EDZ and the boil-off-return-dripping of moisture phenomenon. The consequences of alternative lay-outs should be investigated unless NRC are confident that an optimal choice has already been made.

Depending on tunnel orientation, 3DEC may prove the only viable code for present TMH-Dyn. studies. However, the 3D joint structure can be constructed in 3DEC and "end-faces" of 3D blocks can be generated perpendicular and parallel to major

Dr Nick Barton
Rock Engineering Consultant
Tel/Fax: (47) 67 53 15 06

Langoddveien 122
N-1335 SNARØYA
Norway

joint trends if 2D UDEC-BB modelling is seen to be viable for certain relevant tunnel orientations.

Dynamic scoping studies using relevant velocity-time histories in UDEC-BB and 3DEC should help to delineate the likely ranges of appropriate joint shearing and shear reversal phenomena. Correct modelling of dilation in the corrected BB sub-routine of UDEC-BB, and ***realistic*** ranges of roughness ($JRC_0$, $JRC_n$) and wall strength ($JCS_0$, $JCS_n$) for the joints concerned are seen as key items for obtaining a realistic range of experimental design data for possible modification of the CNWRA CSFT direct shear machine, and of CNWRA's opinions on this topic.

### 3.2 Modification of CSFT Apparatus and Site Specific Testing

Modifications to the CSFT direct shear machine have been discussed in Section 2.1 of this review. Relevant modifications will depend on the result of the above numerical scoping studies. It is expected that even multiple dynamic loading modelling will show lower shear reversals and possibly also much lower shearing than previously assumed. This is not to say that shear induced dilation, gouge production and increase or decrease of permeability are irrelevant. As shown from increased flows in mines (*e.g.*, Barton, 1984), enhancement of flows can occur when driving forces (*i.e.*, imbalanced shear stresses) are present.

However, the "conjugate" idealised joint models used by CNWRA as illustration of post closure phenomena and as laboratory physical models are too conservative, both from the point of view of joint orientation and relative lack of roughness-dilation phenomena between the cast blocks. More site specific modelling (physical and numerical) is needed if NRC's arguments are to have increased weight in discussions with DOE.

It is to be hoped that CNWRA will have access to relevant joint samples from Yucca Mountain ESF excavations, since other experimental results can be misleading for site specific application, unless used purely for verification of numerical (constitutive) models, as already achieved with success. In the opinion of this reviewer, NRC should insist, through whatever legislative means are available, on extensive site and sample accessibility, if this is presently perceived to be limited for their contractor, CNWRA.

### 3.3 Assessing the Consequences of TBM Tunnelling

Mechanical and thermo-mechanical modelling of the consequences of TBM tunnelling (for emplacement safety, retrievability and subsequent containment safety) is believed to be important in view of DOE's present choice of TBM excavation methods and rock support sequencing. It will obviously be convenient (but for certain reasons inappropriate) for DOE to follow similar principles of excavation and rock support when excavating disposal tunnels. CNWRA and NRC should be well prepared in case (when) they are presented in the future with DOE plans to do similar disposal tunnel excavation and support as that practised in the ESF (*i.e.*, TBM excavation and late placement of non-conservative support, *i.e.*, steel sets).

In the opinion of this reviewer there are several real and potential disadvantages of TBM excavation both under characterisation (ESF) and construction phases and because of effects on subsequent performance during the thermal loading phase. These should be investigated by appropriate 2D and 3D M-T modelling. These potential disadvantages can be listed as follows:

1) It is very difficult to characterise a jointed rock mass in a TBM tunnel due to the general lack of overbreak to predominant joint sets as compared to drill-and-blast tunnels. If, for geological reasons, such "overbreak" Does tend to occur behind the TBM hood, trailing fingers or shield, the contractor will usually apply heavier support (*i.e.*, pre-cast concrete rings) or closely spaced steel rings to "maintain" the circular profile. In other cases the overbreak occurs above the cutters and is essentially void space above the subsequent "supporting" rings. Characterisation is equally difficult and loosening is allowed in the primary containment, *i.e.*, the rock mass EDZ is maximised. (Disallowance of the EDZ in containment calculations is surely not justification for poor EDZ practice?)

2) The TBM as currently designed/used appears to have only two narrow "springline" slots (at approximately 10 and 2 o'clock) for potential rock bolt application. Based on the assumption that DOE do not believe that large area gripper pads prevent rock mass displacement, it must be concluded that full elastic and a lot of non-elastic (joint related) displacement has been allowed to occur before placement of a "soft" after-the-event tunnel support system some two (or more?) diameters behind the tunnel face. Use of such a system would be extremely unfavourable for disposal tunnel excavation support.

3) The "soft" after-the-event steel ring tunnel support system must not be used for disposal tunnels because
   a) the TBM circular excavation attracts maximum thermal stresses closest to the excavation,
   b) the steel rings are closest to the heat source and would be even less stiff as a result and would be very unlikely to provide support against thermal spalling.
   c) Steel ring support is outmoded and contrary to modern rock mechanics principles of reinforcing the rock mass to "support itself". (The rock usually has more resistance than our support methods if helped just a little.) Rock bolts can be placed 4-5 metres behind the head of modern well-designed TBM machines in most (angular) locations without delaying the 2 to 3 m per hour advance, and have the added advantage of being mostly many metres further away from the heat source, *i.e.*, they will continue to provide stiff reinforcement. Five-component corrosion resistant bolts are now available (CT bolts).
   d) The rail and rail car retrievability option requires careful T-M-Dyn modelling since maximum thermal spalling can be expected in the floor, and resulting non-symmetric (non-vertical) movement would prejudice performance under earthquake loading (retrievability might locally be impossible with a combination of unfavourable and feasible circumstances).

### 3.4 Thermal and Longevity Studies of Grouted Bolts

Dr Nick Barton
Rock Engineering Consultant
Tel/Fax: (47) 67 53 15 06
Langoddveien 122
N-1335 SNARØYA
Norway

Based on the assumption that some form of fully-grouted, sleeved, corrosion protected rock bolt represents the optimal solution for

a) minimising elastic and non-elastic tunnel deformation,
b) minimising thermo-elastic and thermo non-elastic tunnel deformation,
c) minimising the deleterious effects of heating on performance, *i.e.*, stiffness of the steel,

then CNWRA would be foresighted in conducting independent studies (or quality assurance studies of existing designs) for developing the necessary experience to assess suitable rock bolts.

The practical issues to be resolved appear to be the following:

a) Development of compatible, heat resistant grouts and corrosion protection sleeves (*e.g.*, Norwegian CT bolt-type)
b) Investigation of thermal loading and relative thermal expansion effects on the anchoring capability of various designs.

It is probably logical for CNWRA to initiate such studies with DOE candidate bolts (if such exist) and move on to advanced sleeved bolts (which can be used for initial mechanical anchoring and subsequent grouting) as required. Hollow cylinder hydraulic jacks with load cells calibrated over a 20-200°C approximate temperature range and a large oven are required. A good supply of, for example, 40 cm diameter, 50 cm long cylinders of site specific welded tuff with centrally drilled bolt holes would be the starting point for such a study.

### 3.5 Assessment of Consequences of Lithophysal Cavities

Lithophysal cavities, although not described in documents to be reviewed, nor listed as potential research topics, appear to warrant serious study, despite the obvious difficulties involved. Chapter 5 "Site Description" (B 0000 0000-01717-5705-00015 Rev. 00) describe cavity content as 5 to 30%, 0 to 11% and 0 to 16% respectively for Topopah Spring W1 unit, and "rarely more than 10%" for the target W2 unit.

Numerous lithophysal cavities greater than 100 mm in size were nevertheless observed in down-hole video of NRG-6 between 141 and 150 m and geophysical measurements suggest possible lateral continuity. More drilling and site investigation, and potential problems with the ESF TBM drivages should assist in further evaluation of these phenomena, which locally could seriously compromise the integrity of disposal tunnels (*i.e.*, constructability, stability during emplacement, stability during retrieval and thermal performance).

The simplest way to form an initial understanding of the potential consequences on non-uniform stress and displacement distributions in the M and MT phases would be the performance of UDEC-BB and 3DEC scoping studies with random distribution of sub-horizontal hollow lens-shaped voids within the blocks and/or concurrent with sub-horizontal jointing (or consistent with other current geological interpretation). A series of lenses in the neighbourhood of a disposal tunnel or in the pillar between tunnels will obviously have the potential for quite dramatic modification of behaviour. The need for extensive cross-hole tomography (seismic and radar) to delineate and thereby avoid (minimise) location near such features is clear.

### 3.6 Spatial Variation and Field Scale Application of Properties

Chapter 5 "Site Description" (B 0000 0000-01717-5705-00015 Rev. 00) emphasises the parameter RQD as being central to the "Q" and "RMR" systems of rock classification. While RQD histograms or drill core logs are a useful starting point, they can be quite misleading on their own, and are inadequate for engineering description. (Even the originator of RQD has admitted the possibility of being killed by an RQD = 100% block fall - *i.e.,* the case of massive rock with thin planar clay filled discontinuities and sufficient joint sets for block release.) The above qualifying statements imply the need for rock mass descriptors such as $J_r$, $J_a$ and $J_n$ respectively (from the Q-system).

Statistics for the six Q-system parameters (and for the RMR parameters) will greatly improve the presentation of logging data and CNWRA's lead in this area (if not already a feature of DOE presentation) would be valuable. Spatial variation of these parameters both vertically and horizontally can be correlated with VSP and cross-hole seismic data, and with $V_p$, n%, $\sigma_c$ and E data from laboratory tests (Figures provided to peer reviewers closely resemble the equivalent data sets obtained in the Borrowdale Volcanic Group - mostly tuff and ignimbrite - at Sellafield).

While classification data such as the above are useful aids in presentation of spatial variability, the "only" engineering data they provide may be rock reinforcement and support recommendations for specific rock classes, and "full-scale" deformation moduli estimates for modelling (*e.g.,* Barton, 1995). Other methods of evaluating the core (and borehole and tunnel walls) must be utilised in order to obtain the standard suite of input data (and its spatial variability) needed for DEM-style numerical modelling.

The Lotus spread sheet "geotechnical logging chart" developed in 1990 for the Sellafield project and used extensively since that date (see Barton *et al.,* 1992) may be found useful in this respect, as it combines the statistics of rock mass classification data and input data for numerical modelling in one chart, and can be utilised for individual core runs, for whole boreholes, and for logged tunnel walls. Charts can be combined at will for lateral correlations of spatial variability. The chart, which was developed for Sellafield and for other documentation-demanding projects, is based at present exclusively on the Q-system parameters and on the BB constitutive model parameters for the purpose of performing UDEC-BB modelling. Geometric data for "constructing" the joint geometry is also presented on the same chart. The data is collected and presented with due regard for the scaling of input parameters to full scale values, and would appear to satisfy some of the second and third topics for CNWRA's future research.

### 3.7 Dry-out, Recondensation and Condensate Dripping in Joints

If this complex topic ***is*** critical to the long term containment as often assumed (*e.g.*, 10 CFR 111a - protection against radiation releases and 10 CFR 112 - post closure system performance) then rock engineering to minimise its consequences might be worth considering. This could include micro cement-bentonite pre-injection in funnel shaped fans at regular (*i.e.*, 25 m) intervals ahead of all tunnels (whether TBM or drill-and-blast) so that tight joints are more tightly closed and open joints well injected with a material that is designed to swell outside the high temperature dry-out zone. In view of the remarkable site characteristics (lithophysal cavities), this pre-treatment may soon be seen as a local necessity (?) for other reasons than protection against radiation releases.

Necessary research would be in the investigation of the properties of micro cement-bentonite mixtures within tight, stressed joints when subjected to extended periods of intermediate level thermal loading in a laboratory biaxial apparatus. It is believed that research into engineering solutions to minimise the consequences and extent of dry-out recondensation and condensate dripping are more likely to bear fruit than necessarily very limited investigations of these complex phenomena.

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**Dr. Emmanuel Detournay**

**External Peer Review**
**of**

# Coupled THM Processes Research at CNWRA

**Submitted to:**

**Center for Nuclear Waste Regulatory Analyses**
**Southwest Research Institute**
**6220 Culebra Road**
**San Antonio**
**Texas 78238-5166**

**(Tel: 210-522 5160)**

**Submitted by:**


**Emmanuel Detournay**
**Panel Member**
**Department of Civil Engineering**
**University of Minnesota**
**500 Pillsbury Drive S.E.**
**Minneapolis, MN 55455-0220**

**Tel: 612-625 3043**
**Fax: 612-626 7750**
**E-mail: detou001@maroon.tc.umn.edu**


**August 14, 1995**

# Executive Summary

This report documents a review of the CNWRA research activities in THM coupled processes. This review is based on documents provided to the Peer Review Committee, and on presentations made by staff scientists during a two-day meeting held in the offices of CNWRA at the Southwest Research Institute in San Antonio, Texas. This document contains an evaluation of ongoing activities and research methodologies and lists a series of recommendations pertaining to future topics of investigation and research approaches.

# 1 Introduction

The host rock at the Yucca Mountain considered repository site is partially saturated and highly fractured. These characteristics of the site, together with the high thermal loading expected to be generated by the waste and the active seismicity of the region, pose very challenging problems for the design of the repository which has to satisfy various criteria and performance objectives established by the NRC. In order to develop the necessary expertise and capabilities to assist the NRC in its review of the DOE license application, an active research program in THM coupled processes has been put in place at CNWRA.

A 5 member peer-review panel has been assembled with instructions to

- review the research program of coupled THM coupled processes and its application to licensing issues at the proposed Yucca Mountain HLW repository site;
- provide recommendations to improve the research scope and methodologies, including the identification of new issues;
- evaluate interpretations of the available data, and explore alternative hypotheses.

Evaluations and recommendations contained in this report are based on a series of documents submitted to the Peer Review Committee, and on presentations made by staff scientists during a meeting held on July 10-11, 1995 in the offices of CNWRA at the Southwest Research Institute in San Antonio, Texas.

# 2 Research Activities at CNWRA

## 2.1 Mission of the CNWRA Research Group

To perform its mission of assessing and reviewing the DOE design assumptions and performance predictions of the planned Yucca Mountain repository, the CNWRA group is developing state-of-the-art expertise in THM coupled processes and capabilities in computational modelling. Indeed it appears that a significant portion of the activity of the Rock Mechanics group has been spent in reviewing the scientific and technical literature — as evidenced by the comprehensive review of the THMC processes (NUREG/CR-6021) and the evaluation of computer codes for compliance determination (CNWRA 93-005 and CNWRA 94–001)— and in validating existing computer codes within the framework of the international cooperation program DECOVALEX (documented in CNWRA 92–005, CNWRA 93-002, CNWRA 94-021, and others).

**Recommendations.** *In view of the limited resources, the research activities of the group should focus on integrating existing knowledge (which includes know-how in using existing numerical codes) and on developing expertise in a system approach.*

*The "knowledge integration" activity should build on previous in-depth literature reviews and could be enhanced by establishing contacts (or cooperation) with scientists at other institutions, who are engaged in research of relevant processes. Building such a network of contacts would require increased participation in conferences and visits to universities.*

*The system approach is essential in the evaluation of the performance of the planned repository. In a system approach, emphasis is placed in the identification of all possible relevant processes, their classification in terms of (dimensionless) controlling parameters and the ranking of these processes in light of specific knowledge and results of scoping analysis. Only a global analysis of the system can identify which parameters or components of the system are* *crucial in the evaluation of its performance. This particular recommendation will be made more explicit and will be amplified in the sections.*

## 2.2 Laboratory Studies

Various laboratory studies have been performed over the years at CNWRA: dynamic scale-model experiment of a jointed rock mass, shearing of a single natural joint of Apache Leap tuff in a direct shear test apparatus under cyclic pseudostatic and dynamic loads, linear and radial one phase flow experiment in the (modified) direct shear test apparatus under controlled normal and shear load. Other experiments, such as isothermal unsaturated flow experiments to measure air and water permeability and a scale experiment of a jointed rock mass under THM loading are under way or are being planned. This experimental program has certainly been valuable in showing evidence of channelling of fluid flow and permeability change due to gauge production and shear-dilatant response of the joint, but it raises also some questions. For example, how appropriate is it to perform a direct shear test that involve the continued shearing of new surfaces (as the upper block is smaller than the lower one) and what is the implication of this particular experimental set-up in regard to the conclusion that there is substantial reduced mobilized shear strength upon reversal of the motion. Also, how relevant to the field situation are the results of the dynamic scale-model experiment involving a regular block structure and (presumably) smooth joint surfaces.

**Recommendations.** *Despite the recognized values of the laboratory program, it is recommended that the planned experimental activities be significantly curtailed or completely stopped. The reasons behind this recommendation are several.*

- *First, it became apparent during the review meeting that the CNWRA research activities in rock mechanics operate under very limited resources (estimated at 1.5 man/year). Any experimental program is costly and time consuming and is likely to consume a* *significant portion of the resources allocated to research.*

- *Critical experiments that are needed to assess the relevance of proposed scenarios or to measure parameters needed in theoretical models should be performed by DOE or its contractors ("the burden of proof is on DOE"). As these experiments are expected to satisfy established scientific standards and to be published in the open literature, they would be open to scrutiny. Unless there is lack of consensus on the validity of an experiment (either about the methodology used, or the results that are obtained), there are no compelling reasons why these experiments should be duplicated.*
- *If an experiment is deemed essential, it should be subcontracted to a University with ongoing research in that area. Such sub-contracting is cost effective.*
- *As stated earlier, the research group at CNWRA should focus on the study of the "system" by studying various possible scenarios and performing scoping calculations to investigate the impact of particular modelling assumptions or the uncertainty in the magnitude of key parameters. Experimental research, being by nature component-oriented is distracting effort from this mission.*

*It is recognized that an experimental program provides, beyond the objectives it aims to achieve, healthy feedbacks to researchers. Such broader benefits could however be accomplished by establishing contacts with colleagues involved in (non DOE sponsored) experiments at other institutions. This point illustrates again the importance of establishing a network of scientific contacts.*

## 2.3 Modelling Efforts

Significant efforts have been expended by the CNWRA staff in examining, selecting, and validating numerical models and associated computer codes to be used for evaluating the repository design and for assessing the performance of underground facilities. These efforts which have led to the selection of two codes: (1) UDEC for assessing the stability of underground excavations in a fractured rock mass subjected to thermal and seismic loading (TM coupling in the near-field); and (2) ABAQUS for analyzing problems involving unsaturated fluid flow, vaporization of water and recondensation of vapor, and condensate dripping along fractures (THM coupling). The validation effort has been carried out, for the most part, under the auspices of the DECOVALEX project.

The modelling effort has been very valuable. Not only has it led to the selection of computer codes and joint cooperation in the DECOVALEX program, but it has also provided information about the areas of applicability, limitations, and implementation problems in these two codes. In particular, ABAQUS has presently serious limitations regarding the modeling of two-phase flow (the code tracks only the equations of the wetting fluid) and thus the formation of the dry-out and condensation regions, that are expected to develop at the repository, cannot be investigated.

The problems analyzed within the DECOVALEX project consist of both benchmark and test cases problems. The objective of this cooperative project is to evaluate the methodologies for modeling THM processes in fractured media by comparing the outcome of several simulations (performed by different teams and different codes) of the same problem. Such an approach provides not only a means to validate numerical codes, but it also gives the opportunity to evaluate the consequences of various modeling assumptions. Some of the problems do not appear, however, to have been judiciously selected. For example, it is doubtful that any useful conclusions can be reached on the basis of the near field repository model, BMT3. The definition of this problem involves thousands of discontinuities which are modelled explicitly. With thousands degrees of freedom used to define the geometry of the problem and many ad hoc assumptions it is unlikely that any robust conclusions can be reached in exercising this model. Actually, models such as BMT3 defeat the very reason of building models, which is to develop an intellectual tool to understand the processes under study.

**Recommendations.** *The research group at CNWRA is encouraged to develop "simple" manageable (i.e. characterized by only a few degrees of freedom) models that can be used either to investigate the importance or relevance of a particular process or to provide plausible lower and upper bounds to the solutions. Effort should be made to reach fairly general conclusions by expressing the results in terms of appropriate dimensionless numbers and showing the dependance of the solutions over the relevant (expected) range of variation of these controlling numbers (scoping analysis). This is believed to be the appropriate strategy for modelling THM processes around the repository. Indeed, in reviewing DOE's license application and in assessing the performance predictions of the proposed design, the following questions will need to be addressed: (i) have all the relevant processes been accounted for; (ii) are the modelling assumptions legitimate in view of the uncertainties in the material properties, and geometry of the discontinuities, and loading; and (iii) are the predictions robust, i.e. are they fairly insensitive to the expected range of variations of the controlling parameters or are they based on provable conservative assumptions. If the modelling predictions are not robust, the questions that modelling were addressing must be bypassed by an engineering solution.*

*"Simple" models could be used to answer well defined questions. For example the conditions under which thermal degradation of rock strength properties need to be examined could be addressed by studying the model of a supported circular tunnel in a thermoelastoplastic rock mass subjected to given temperature or heat flux boundary conditions. Similarly, a "simple" model could be used to assess the minimum drop of rock strength required to overcome the support system. Also the issue of whether or not water inflow by condensate dripping could be arrested by imbibition of fluid by the rock matrix could be explored using the model of a fracture in an infinite partially saturated rock mass.*

# 3 Key Technical Uncertainties (KTU)

## 3.1 TM Effects on stability of Emplacement Drifts and Engineered Barrier System (EBS)

Prediction of the stability of the emplacement drifts and the EBS under combined thermal and (repetitive) seismic loading has been identified has a KTU by the NRC. Excavation stability is an especially important issue during the operational period when nuclear waste will be stored in the repository (with possibility also of retrieving the waste) but also during the containment period which could last up to 1000 years after closure of the site. Various factors and processes have been identified that could contribute to uncertainty in predicting the long-term performance of the underground facility, such as the long-term degradation of rock under high temperature, or the performance of bolts or other support systems under heated conditions.

**Evaluation and Recommendations.** *Under the (assumed) conditions that heat is essentially transported by conduction, temperature change in the rock mass and thermally induced stress can be predicted with a high degree of confidence (since the thermal properties vary only in narrow bands). There is however uncertainty about the magnitude of the thermal loading (i.e. the heat rate density that will be generated by the packaged waste and which is conditioning the maximum temperature at the emplacement drift walls) and the long-term reduction of rock strength under elevated temperatures. The first step towards addressing the issue of stability of the underground openings is to perform scoping analysis to assess the extent of the damaged rock region and magnitude of the support load for various plausible assumptions of thermal loading and rock degradation. The results of such analyses will provide information on whether or not the stability issue should be a major concern. If it is a concern, DOE should be directed to perform additional long-term testing of the repository Tuff at the maximum expected temperature. Note that the proposed scenario of microfracturation of the* *rock triggered by pore pressure increase due to rise in temperature is believed to be unlikely in the unsaturated rock region. Indeed the increase of pore pressure will be more than offset by increase of the total stress.*

*Other issues have been raised, such as the problem of extrapolating laboratory measurements to field scale application or what should be the methodology for bounding the spatial variation of rock mass properties. Those issues, which arise in any rock engineering projects, should not be topics for future research at CNWRA. In the present state of knowledge, they should be addressed by performing scoping analyses. Such studies would reveal the sensitivity of the solution to estimated variation of the input parameters and would provide the basis for conservative predictions.*

*Stability of underground openings due to repetitive seismic loading is not perceived to be a KTU, provided that a compliant support system is selected and provided that the support system is expected to retain most of its load carrying capacity during the operational and containment period. DOE should, however, be directed to undertake engineering tests on the anchoring system of rock bolts to provide assurance that they will have acceptable performance over a period of hundreds of years.*

## 3.2 THM Effects on the Host Rock Surrounding the EBS

Condensate reflux towards the emplacement drifts is believed to be the most important KTU. The scenario by which water could come into contact with the waste package (thus possibly accelerating release of radionuclides by corrosion of the package) involves vaporization of water in the near-field region of the drifts, vapor condensation, and condensate flow back towards the waste emplacement areas along fractures by capillary and/or gravity effects. Estimation of the magnitude of water inflow in the emplacement drifts is a key issue.

**Evaluations and Recommendations.** *The numerical code ABAQUS was initially selected to analyze THM effects on the host rock but the current version was later found to have limitations in regard to modelling of the above issues. One of the criterion used in the selection of ABAQUS is its ability to account for the mechanical coupling on the hydrologic properties (for example, permeability). However, the mechanical coupling is not judged to be important here in view of the major uncertainties affecting the two factors controlling fluid flow in fractured media, namely the connectivity of the fluid flow domain and the aperture distribution of the fractures. Thus only TH coupling is believed to be relevant and ABAQUS should either be upgraded or an alternate code should be selected to perform analysis of the TH effects.*

*Since it will not be possible to predict the actual flow path, evaluation of the TH effects must ensure that the most conservative scenario is adopted (for example circulation in a limited set of fractures). In other words, the modelling effort should identify the maximum possible water inflow compatible with the (known) heat production rate and the amount of water that could be released by the rock mass (either water retained by capillary effects in the unsaturated rock, or perched water). Estimation of the magnitude of the condensate reflux should be performed for two limiting cases of "high" and "low" fracture conductivity. Indeed, the conductivity of the fractures is expected to control the mechanism of vapor transport and the processes that could reduce or eliminate water inflow ( imbibition by the rock and revaporization).*

*If condensate reflux is shown to be possibly significant, the EBS should be designed to mitigate the risk of the condensate reaching the waste packages.*

## 3.3 Long-Term Performance of Seals

The long-term performance of seals and backfill materials for shaft, ramps, and boreholes has been classified as a KTU. There is indeed little experience on how sealing materials perform under thermal loads and repeated seismic load.

**Evaluations and Recommendations.** *This issue should not be given high priority for reasons that have already been stated in the summary paper prepared for the external review. Firstly, the importance of the role of seals depends to a large extent to the amount of condensate flowing towards the emplacement drifts, and this particular process has not yet been quantified. Secondly, the installation of seals is not expected to be completed until the repository is ready for closure, thus giving ample time to perform in-situ testing under field conditions and for long periods of time.*

# 4 Conclusions

The work on THM coupled processes that has been reviewed is generally judged to be of very high quality. Also the staff at CNWRA is found to very competent and highly dedicated. Despite limited financial resources, it is apparent that a center of expertise in THM processes has been developed at CNWRA.

The following summarizes the main recommendations that have been expressed in this report and which recognize the very limited resources that are allocated to research activities.

- *Role of CNWRA.* The institute should mainly be a center of knowledge with expertise to review DOE license application and assess the performance prediction of the repository. The group should therefore maintain a state-of-the-art knowledge of all aspects of THM coupled processes that are relevant to the Yucca Mountain Repository project. Scientists and engineers are encouraged to develop a network of scientific contacts that would help them in this mission.

- *Experimental program.* Performing laboratory studies at CNWRA is not cost-effective and it is recommended that the experimental program be downsized. Also being necessarily very focused, these studies are not compatible with the recommended mission of the group.

- *Modelling methodology.* A system approach should be followed with emphasis placed on classifying processes into regimes and mapping the regimes in terms of dimensionless groups. Models should be manageable (i.e. limited number of parameters) and exercised to answer specific questions and provide bounds to the solution.

- *Key technical uncertainty.* Possible reflux of condensate towards the waste emplacement is viewed as the most crucial KTU, and should be given the highest priority in future activity. Modelling should be aimed at providing bounds for the water inflow by investigating various scenarios involving vaporization, vapor transport, condensation, and condensate flow.

**Dr. Derek Elsworth**

# PEER REVIEW REPORT
of
ONGOING AND FUTURE CNWRA
COUPLED THERMAL-MECHANICAL-HYDROLOGICAL
PROCESSES RESEARCH

Submitted to:

Center for Nuclear Waste Regulatory Analyses
Southwest Research Institute
6220 Culebra Road
P.O. Drawer 28510
San Antonio
Texas 78228-0510

By:

Derek Elsworth
Consultant & Panel Member

Department of Mineral Engineering
Pennsylvania State University
University Park
PA 16802-5000
USA

August 7, 1995

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## 1 EXECUTIVE SUMMARY

This report documents a review of CNWRA objectives, approaches and progress in ongoing TMH process research, together with a critical evaluation of *key technical uncertainties* (KTUs), recommendations to reduce these uncertainties, and a definition of potential gaps in addressing the KTUs.

Terms of reference for the review are included in Section 2.

A review of CNWRA *objectives and approaches* is completed in Section 3, together with recommendations, where appropriate. It is concluded that thermal-mechanical (TM) behavior is perhaps best defined of the processes included within this study and that thermal-hydrological (TH) processes are the least well constrained and understood. Dealing with TM and TH processes in essentially decoupled format is appropriate if the general sense of the cross coupling is represented, in essence. This approach enables commercially available computer models to be applied directly in scoping calculations, where quality assurance (QA) requirements are jointly accommodated.

Because of the higher level of uncertainty within the anticipated TH behavior, it is recommended that greatest emphasis is placed in this general task area. Correspondingly, confirmatory studies are suggested to define the interaction of processes in formation of the dry-out zone around the emplaced waste packages. These evaluations are prioritized in terms of:

1. Scoping calculations to define critical parameters and interaction of processes (Section 4.2) in formation of the dry-out zone with particular reference to zone size, and liquid and vapor circulation rates for broad ranges in near- and intermediate-field hydraulic parameters.

2. The use of previous heater experiments and field scale analogs to both condition and confirm the behavior defined from the scoping calculations.

3. The estimation of critical parameters and parameter ranges from available test data, and the commissioning of additional laboratory experiments, where necessary (Section 4.3).

4. The execution of new field tests (Section 4.4) in a variety of hydrogeologic environments to exercise new processes observed in the previously itemized tasks.

These activities are ranked to maximize the potential benefit in addressing KTUs given the limitations on available resources.

Recommendations to improve research scope specifically suggest *focusing* the evaluation to the critical areas defined in Section 5. These areas are ranked, placing TH processes as most critical in the performance assessment studies, with appropriate influence of TM effects being of secondary importance. This proposed emphasis is based on the observation that TH processes are least well defined in terms of available data describing both processes and the physical parameters that control TH response of the fractured medium.

Overall review of the CNWRA program indicates substantial positive progress in the tasks. Indeed, the accomplishments are impressive, given that the stated time commitment to the full range of activities comprises only $1\frac{1}{2}$ FTEs. In light of the relatively limited manpower commitment, it is recommended that future effort is placed in the commissioning of scoping studies and assimilation of HLW research results, with laboratory and field studies completed mainly in support of apparent data gaps.

## 2 Preamble

A review meeting was convened to evaluate current progress of CNWRA research tasks and to supply recommendations for future work in the rock mechanics tasks with reference to coupled Thermal-Mechanical-Hydrologic (TMH) processes, and specifically to:

- Critically review the objectives and approaches of CNWRA coupled TMH processes research and its applicability to licensing issues at the proposed Yucca Mountain HLW repository site.
- Provide recommendations to improve the research scope and methodologies, and investigate new issues that may not be part of the original research plans.
- Evaluate interpretations of the available data, and explore alternative hypotheses.

The panel members were supplied with an overview of current CNWRA research objectives,[1] appropriate CNWRA reports and details defining the legal basis for civilian HLW repository licensing (Code of Federal Regulations, 1995), the role of the Nuclear Regulatory Commission in this process (Johnson, 1994), and proposed methods for ensuring compliance within the licensing process (Nataraja and Brandshaug, 1992).

[1]Introduction of the Coupled Thermal-Mechanical-Hydrologic Processes Research at CNWRA, prepared for the Peer Review, by CNWRA Staff.

The meeting was convened July 10-11, 1995 at CNWRA, in San Antonio, Texas, with verbal summary comments provided by panel members at meeting close. The following expands on these comments and represents the final report.

# 3 Evaluation of CNWRA Objectives and Approaches

## 3.1 Objectives

The two primary objectives in the evaluation of coupled TMH processes (relevant to this review) are to define potential impact on the performance assessment of the repository with respect to:

- Determining the stability of adits, emplacement holes (if used) and drifts to prevent puncturing of the waste cannisters and breaching of the engineered barrier system (EBS). 10-CFR-60, §60.111(b); §60.1 §60.113.
- Determining the potential for release of the inventory from the near-field zone, through the potential for recirculation within, and migration from the dry-out zone, with the potential for: 10-CFR-60, §60.111(a); §60.11
  1. Cannister corrosion through contact with condensed hydrothermal vapors,
  2. Hydraulic transport of radionuclides away from the dry-out region, and,
  3. Hydrothermal alteration and weakening of the near-field strata.

## 3.2 Approaches

The Center (CNWRA) provides an independent evaluation of research appropriate to evaluating the performance of the civilian high level radioactive waste repository at Yucca Mountain, including critical commentary on DoE contracted research. Time allocations are $\frac{2}{3}$ : $\frac{1}{3}$ for technical assessment (TA) and independent exploratory and confirmatory research, respectively. To date, studies have covered the spectrum of field, laboratory and modeling investigations, including: evaluation of important coupled THMC processes impacting repository performance (Manteufel et al., 1992), modeling studies of coupled TM (Ghosh et al., 1994), TH (Ghosh et al., 1994) and

TMH (Ahola et al., 1994) processes; participation in DECOVALEX (Jing et al., 1993; Jing et al., 1994); permeability testing of fractures under large shear displacements, including gouge formation (Mohanty et al., 1994); field evaluation of mining induced seismicity (Ofoegbu et al., 1994), and; studies of hydrothermal processes including the potential for heat pipe formation. [2]

The assessment and research tasks have been accomplished through a variety of studies addressing the perceived key technical uncertainties (KTUs). These are documented as follows.

### 3.2.1 TM Effects on Drift Stability and EBS

Anticipated loads include the excavation induced stresses, thermal loads applied by the waste inventory and repetitive seismic loads applied by earthquakes to a peak anticipated acceleration of approximately $0.4g$.

**Accomplishments:** Uncertainties in defining the thermal field surrounding the repository have been shown to be small in comparison with other unknowns, provided the assumption of dominant conductive effects prevails. This engenders considerable confidence in defining the near-field stress and displacement regimes, in aggregate, but leaves some unknowns in defining small-scale variability. The relative importance of this uncertainty will be discussed in the later sections. Individual studies undertaken include:

- Evaluation of the influence of seismicity on the hydraulic behavior of the repository using an analog to mining-induced seismicity (Ofoegbu et al., 1994).
- Evaluation of the applicability of the UDEC and ABAQUS codes (Ghosh et al., 1994) to evaluate the TMH coupling processes of importance around a repository.
- Application of the ABAQUS code to evaluate the DECOVALEX problem representing the Big-Ben (TC3) experiment for THM behavior of buffer materials surrounding a waste package (Ahola et al., 1994).

**Evaluation:** The use of field analogs (Ofoegbu et al., 1994) in defining the anticipated influence of groundwater systems to undrained seismic re-

[2] Ron Green, personal communication, July 1995, report under review.

sponse, drained long term behavior, and modification to the conductivity field is considered excellent. The analog problem importantly includes processes represented at field scale. Benchmarking with phenomenological models, provides a reasonable indication of the severity of groundwater changes anticipated from seismic loading.

Exploratory analyses with UDEC and ABAQUS have identified the strengths and weaknesses of each code. UDEC will be used to evaluate discontinuum response of the rock mass to TM effects, and ABAQUS will be used in the evaluation of coupled TH processes. This decoupling is considered warranted and appropriate, particularly since the anticipated verification studies should concentrate on processes and process interaction, rather than determining site specific behavior, *per se*. Inadequacies in the models representing specific aspects of the coupling, especially for ABAQUS in defining TH behavior, may be addressed by incremental adjustments to the code.

**Recommendation:** All analyses have assumed that conductive thermal effects are dominant, with this assumption being driven by the saturated, and relatively low temperature waste package environments selected by other countries. The significant temperatures anticipated around the proposed YM packages (thermal loading still uncertain) that may reach 230°C, and the resultant vaporization of matrix water, may require reconsideration of this assumption. Some TH analyses could confirm or discount the validity of this assumption.

Although the anticipated thermal regime varies little with moderate changes in the conductive parameters, local failure and the development of preferential flow pathways will remain difficult to determine. Predictability of the influence of these effects will decrease with increased spatial and temporal scales. Drift stability will likely be readily predictable in the short-term but not in the long term. The development of preferential pathways for vapor transport are not readily predictable since initial structure will be poorly defined away from the excavated drifts, and time dependent effects cannot be reliably predicted.

These ill-defined factors are not considered a grave limitation in conducting confirmatory analyses to define behavior. Bounding behaviors may be readily examined through scoping calculations for reasonable parameter magnitudes and distributions. Correspondingly, the progression of gross processes should be evaluated in these calculations.

### 3.2.2 TMH Effects on Host Rock Surrounding the EBS

**Accomplishments:** The anticipated form of 2-way, 3-way and 4-way coupling of THMC processes has been documented and the important forms influencing the performance of a proposed repository in unsaturated rock defined (Manteufel et al., 1992). This includes exposition of the heat pipe phenomenon for mass and energy migration adjacent to the waste packages. This phenomenon has been evaluated in laboratory studies[3] and review of field heater tests. These data have been used to define new laboratory heater tests, within a fracture, that are currently in progress, and represent TH processes. A suite of field heater tests is proposed.

Laboratory studies of the shear-permeability behavior of a single fracture under large deformation (Mohanty et al., 1994) and with the formation of gouge infilling have been completed. The DECOVALEX participation has included analysis of the AECL block test (Jing et al., 1993, TMH; BMT2), the repository far-field in heated rock (Jing et al., 1994, TMH; BMT3), the NGI shear-conductivity test (Jing et al., 1994, MH; TC1:1 & TC1:2), and the Big-Ben experiment (Ahola et al., 1994, TMH; TC3).

**Evaluation:** From these studies, and the combined experience from DECOVALEX (Jing et al., 1993; Jing et al., 1994), a variety of conclusions are apparent:

- The thermal regime is reliably evaluated where conduction is the primary mechanism. Thermal conductivity, density and heat capacity of both the rock and rock mass show only second-order variation in magnitude and may be reliably estimated.

  The certainty that advective transport will <u>not</u> be important has not been demonstrated, but is assumed based on the assumption of relatively low thermal loading. For unsaturated repository conditions the thermal capacity of the vapor will be low, but phase change effects may be significant. The effects of phase change and subsequent vapor transport on the anticipated thermal regime should be confirmed.

- The influence of the thermal regime on deformation modulus, and strength is small in the short term and not well defined in the long term.

[3] Ron Green, Personal Communication, July 1995.

- The absolute behavior of the flow system is potentially unknowable in fine detail, due to the uncertain location of the initial fracture distribution, and the uncertainty in development of flow paths due to mechanical effects. These factors include uncertainty in defining stress paths, mass dilation and the potential formation of gouge. As a result of these uncertainties, it is reasonable to assume generalized behavior of the TM system and use these *lumped parameter* distributions to evaluate the TH response.

  For this reason it is important to evaluate the relative importance of TH processes in fractured and intact materials in the laboratory to determine the parametric controls on field scale TH processes, such as the vaporization→migration→condensation→capillary recirculation process. The individual parameters controlling behavior are considered to include saturated and partially saturated permeability relationships, capillary pressure - saturation relationships, reactive surface area or heat transfer area of discontinuities, thermal characteristics of the discontinuity wall rock and interior, and interconnectedness of porosity comprising the system.

**Recommendation:** It is suggested that TM behavior of the rock mass response is currently well understood with little uncertainty in parametric relationships and inter-relationships. This is true especially in comparison with the expected lack of certainty in defining geologic structure, in a deterministic sense, in the intermediate- and far-field around the repository (i.e. fracture system connectedness and permeability distribution, and change in these with thermal loading).

The anticipated behavior of the TH system may be decoupled from the TM system to enable confirmation of anticipated TH behavior. The relative importance of pressure drive versus buoyancy driven vapor transport, the potential for capillary wicking and heat-pipe formation, and the anticipated dimensions of the dry-out zone may be evaluated by substantially decoupling from the mechanical effects. Further details for suggested analyses in this task area are given in Section 4.2.

In developing an understanding of the complex TH processes that may operate around a *hot* repository, the importance in correlating the anticipated behavior with field scale analogs cannot be understated. Suitable analogs may include:

- Studies of palaeo-circulation around magma intrusions to define relic processes, estimate alteration zone magnitudes and define controlling parameters.
- Reevaluation of the performance of existing heater tests, including revisiting, where possible, to confirm or evaluate missing parameters in the data set.
- Evaluation of active geothermal analogs, including geothermal reservoirs and volcanically active regions.

### 3.2.3 Long-Term Performance of Repository Seals

**Accomplishments:** The performance of repository seals has been evaluated, in part, through participation in the Big-Ben (TC3) simulation experiment completed under DECOVALEX (Ahola et al., 1994). This has provided benchmarking of the ABAQUS code for the evaluation of TMH processes in unfractured media.

**Evaluation:** The predictions from the Big-Ben simulation provide adequate evaluation of anticipated thermal fields, despite uncertainties in parameters specified in the problem description. The Big-Ben experiment is not an ideal calibration example as cannister temperatures are elevated only to 65°C, and not the potential 230°C skin temperature possible for some of the proposed DoE disposal configurations.

Correspondingly, the modeling calibration does not include the potential for strong drying of the medium including phase changes, and parameterization for hydrochemical and mechanical changes in the buffer materials, especially those including chemical alteration and desiccation. These processes may result in breaching of the seals (backfill around the cannisters) in the near-field, depending on the specifics of the backfill configuration.

**Recommendation:** Long-term performance of the backfill seals will be strongly conditioned by anticipated maximum thermal loads. High thermal loads will desiccate backfill clays leaving them hydraulically breached and behaving only as a sorptive barrier. Rewetting by returning condensate may not heal the existing fractures. The fractured seals are then prone to migration of cannister inventory, if breached, particularly the migration of colloids (Sharland et al., 1993) that are not readily retarded by normal processes of sorption, but may be bound at meniscus boundaries in partially saturated fractures (Wan and Wilson, 1994). The rapid migration (days) of colloid-size particles at the scale of meters, in desiccated clay tills, has been clearly demonstrated (McKay et al., 1993). If, as a result of the proposed DoE seal design, these considerations are important, the potential for breaching of the seal may be investigated by:

- Evaluation of the potential for desiccation of clays by "baking" within an autoclave using temperatures and pressures representative of the repository environment.
- Evaluation of isothermal relative permeability, capillary pressure versus saturation relationships (Fredlund et al., 1994; Fredlund and Xing, 1994) and particulate transport behavior from tests or by estimation (Bear, 1988, see, for example, p. 448). Care should be taken in noting that laboratory tests and field behavior are not directly scalable when evaluating transport and attenuation of particulates such as viruses, microbeads or colloids (Sims et al., 1994). For this reason, unsaturated flow and transport processes may be approached through *estimation* of material parameters, potentially without the need for a suite of complex laboratory evaluations.
- Modeling studies to evaluate migration potential with realistic thermal loadings, evaluation of drying and desiccation, and incorporation of vaporization, gas-phase transport, condensation, and capillary wicking.

These studies may be used to evaluate potential for breaching of the near-field seals and backfill materials. Effects on intermediate-field seals, such as the use of grouts are not included in this evaluation, but are discussed in Section 5.7.

# 4 Potential Gaps in Addressing KTUs

## 4.1 Defining Missing Processes

The omission of a single significant process in the evaluation of repository performance is considered more important than the uncertainties involved in accurately bounding parameters describing known and understood processes. For this reason, the vaporization→migration→condensation→capillary wicking/dripping process is considered least clearly defined and understood of all the CNWRA objectives, and with potentially the largest impact on waste package survival. This is considered to be a predominantly TH process with possible hydrochemical effects influencing cannister corrosion. Correspondingly, the analyses may be completed largely decoupled from, but incorporating the general sense of, the TM behavior.

An evaluation of the importance of these effects could incorporate estimated material parameters in sensitivity analyses conducted through use of the ABAQUS code, and verified against available laboratory and field prototypes. The primary aim would be to *develop an understanding of the process, determine the controlling parameters, and determine the sensitivity of the process to variation in these parameters.* This may include:

- An evaluation of controlling parameter groups that might include:
  - Relative permeabilities and capillary relationships for fractures and gouge filled fractures to define dripping and wicking potential mechanisms.
  - Evaluation of the connectedness of fractures in defining network permeability with implications for the relative importance of pressure driven, versus buoyancy driven, vapor flows.
  - Evaluation of heat transfer mechanisms in condensing vapors and the relation to effective heat transfer area at the fracture walls, and imbibition characteristics of the matrix blocks.
  - Simplified evaluation of the potential geochemistry of the return fluids and the impact of this geochemistry on corrosion potential of the waste packages.
- Collection of required data sets, especially those that are not readily estimated or available in the literature. These might include:

  - Evaluating relative permeabilities and capillary relationships for fractures from laboratory tests with both closed (high stress) and open (low stress) fractures to bound parameter ranges and fit to Brooks-Corey or van Genuchten type relations.
  - Parameters may alternatively be determined from consideration of approximate aperture distributions (Tsang and Pruess, 1990) or characterizations available in the literature (Reitsma and Kueper, 1994, eg. entry pressures).
  - Gaining access to ongoing large scale laboratory flow and transport characterizations, such as LABROCK, currently underway at the PNC Entry Facility at Tokai, Japan.

- Provide scoping calculations to determine the sensitivity of the dry-out zone to both variability in parameter magnitudes and spatial heterogeneity in the material parameters. This may include evaluation of the relative potential for capillary wicking versus fracture dripping in the return of fluids to the repository, or in recirculation to the deep groundwater table (see details in Section 4.2).

- Reevaluate field scale processes and check concurrence of the predictions available from the above with:

  - Completed laboratory heat-pipe prototype tests.
  - Reevaluation of field heater tests to examine controlling parametric groups and their influence on the resulting processes. This may include retrieving additional field data, if both necessary and possible.
  - Potential commissioning of field heater tests, including that proposed at the Mexico field site, and evaluating long-term palaeocirculation around the intrusion from geochemical signatures, and corroboration with anticipated behavior.

## 4.2 Modeling Studies and Sensitivity Analyses

Modeling studies of importance in confirming DoE predictions within their performance assessment may be divided between near-field and intermediate-to far-field processes:

**Near-field:** Local evaluation of stability of the drifts and emplacement holes (if used) may be evaluated through use of current models, *viz.* UDEC. Geological structure in the near-field will be relatively well defined by drift mapping and the potential for local failure may, in all likelihood be engineered-out, to minimize the potential for rupturing of cannisters and the local EBS. The major unknowns in this task are considered the changes in long-term strength that might affect the reliability of predictions. Lower priority

**Intermediate- and far-field:** The intermediate- and far-field behavior is influenced by the induced thermal field and resulting changes in permeability precipitated by induced thermal strains. In the absence of significant convective transport and phase change effects, the prediction of the thermal regime is considered relatively well defined. The assumption that convective effects are small needs to be confirmed, as does evaluation of the vapor transport process that is assumed to propagate from the near-field to the intermediate-field with the development of dry-out and condensation zones. Higher priority

The raw processes governing vapor transport behavior appear well documented (Manteufel et al., 1992) although the constraints on behavior in heterogeneous fractured geologic media seem less certain. This is considered a crucial KTU. A modeling study to evaluate the sensitivity of the resulting behavior to variability in the geological environment is, correspondingly, suggested. The evaluation might include evaluation of behavior for geological environments conceptualized in Figure 1 and characterized by three alternate configurations, namely:

- **Low gas permeability system** where pressure gradient comprises the primary driving mechanism for the vapor.
- **High gas permeability system** where buoyancy flow is the predominant transport mechanism for the vapor, and,
- **High gas permeability with gouge wicks** where buoyant transport is the principal vapor escape mechanism and capillary wicking is the principal return mechanism.

Care needs to be taken in the assumption of local thermal equilibrium between the rock and fluid as this may not be appropriate. The analysis would provide some bounds on:

- The anticipated size of the dry-out zone,

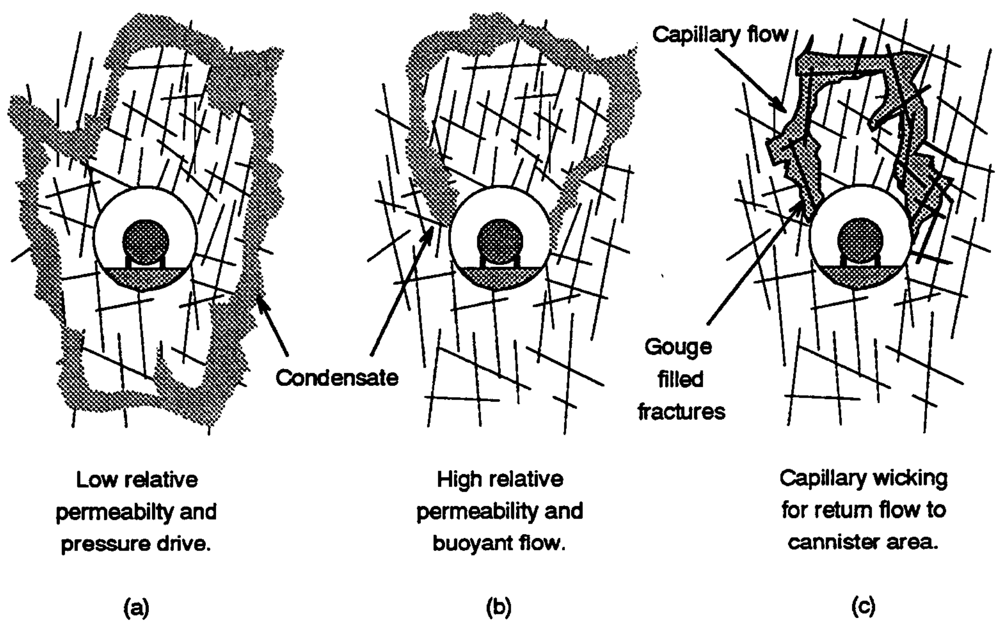


Figure 1: Relative behavior for TH migration from a heated drift or repository with transport by (a) pressure drive in low permeability materials, (b) buoyancy effects in high relative permeability materials, and (c) buoyant escape from the heated region with return flow by capillary wicking.

- Circulation rates of the fluids,
- The potential for migration of fluids, aqueous solutions and colloids from the near-field zone,

and allow corroboration with (see Section 3.2.2):

- Previous laboratory scale tests,
- Previous heater tests, complete with revisitation to determine missing required parameters, and
- Appropriate geological analogs and their observed performance.

## 4.3 Laboratory Testing

Migration away from the repository appears controlled by the relationship between vaporization in the near-field and condensation, block imbibition and return flow in the intermediate-field. Parameters needed to support quantification of this process depend on the geologic situation. For example, if the fracture system is open and of corresponding high permeability, variation in fracture permeability may have little influence on the extent of the dry-out zone. Rather, zone extent may be controlled by the heat transfer area of the fractures and/or the nature of the conductive thermal field. Correspondingly, this task is viewed as a support task to that described in Section 4.2, depending on the critical data requirements.

Flow processes are viewed in a hierarchy where knowledge of the distribution of void space or interconnectivity of fractures becomes increasingly more important. This hierarchy transits isothermal flow → non-isothermal flow → non-reactive transport → reactive transport (analog to thermal transport) → particulate transport (colloids) → unsaturated flow including capillary relationships. Consequently, characterization for isothermal flow behavior will not provide reliable estimates of advective transport rates and sorption characteristics. Rather, tests that exercise these processes are needed to define behavior. Correspondingly, the following components may be of interest:

- Evaluation of order-of-magnitude effects of fluid-rock interaction on the development of clay minerals and precipitation and dissolution characteristics within fractures. Evaluation of the current state-of-the-art from searching of the fluid-rock interaction and ore deposits formation literature would be useful in confirming data gaps. For example, this may give some evaluation of the expected magnitude of alteration effects and corresponding estimation of anticipated strength loss with time and the form of alteration of discontinuities that may result from hydrothermal circulation.

- Evaluation of fluid-rock interaction through use of autoclaves to conduct long-term testing of fractures and intact material under geothermal and geochemical conditions anticipated within the repository. The experimental arrangement could incorporate circulation of hydrothermal fluids and vapors in a heated environment to monitor permeability changes and changes in the hydrochemistry of effluent fluids with time, under constant stress (creep) or constant displacement (relaxation) conditions.

- Evaluation of transport characteristics of fractures and the presence or absence of channelling within fractures through use of conservative or reactive tracers (Sims et al., 1994; Piggott and Elsworth, 1993b) and thermal tracers (see, for example, the PNC LABROCK experiment).

- Evaluation of relative permeabilities and capillary relationships under changing aperture distributions representing shear or normal relative displacements. These may be of relevance in defining the vaporization-migration-condensation and fracture dripping processes anticipated to be active within, and adjacent to, the dry-out zone. These characteristics may also be important for clay gouge, but may be estimated from similar soil materials using existing van Genuchten or Brooks-Corey relationships.

- Evaluation of colloid transport characteristics in the absence of attenuation mechanisms, and their potential for trapping within the desaturated zone (Wan and Wilson, 1994).

- Evaluation of the importance of fracture intersections as fast pathways in distributing fluid or vapor flows (channelized) where little heat transfer area is available for sorption or cooling (see, for example, the PNC LABROCK experiment).

**Recommendations** for use of the current testing apparatus, if additional tests are necessary are as follows:

- If tracer tests are used to define transport processes, or if unsaturated fluid parameters are to be determined from the current testing arrangement, it is important that inlet manifold volumes and measuring system volumes are reduced to a minimum. The volumes should ideally be only a fraction of the fracture volume, to avoid problems in defining arrival times, or fluid transmission volumes.

- The measurement of rotations in defining relative motions of the fracture surfaces is important in providing adequate constraint for single fracture tests. Accurate triangulation of rotations between sample halves is important in defining spatial changes in fracture void distributions (Jing et al., 1994, for example). The presence of rocking modes is likely an artifact of small-scale tests that will reduce with increased sample size.

- A variety of useful measurements for fracture void volume and its distribution in space may be identified through use of tracers, such as

NaCl solutions, and measurement of electrical resistivity distribution during saturation and tracer testing (Piggott and Elsworth, 1993b; Piggott and Elsworth, 1993a, among others).

Use of particulate tracers may be important in defining the susceptibility to breaching of the near-field barriers by colloids. It would be important to recognize the important trapping mechanisms provided by capillary effects (Wan and Wilson, 1994) and the difficulty in scaling results from the laboratory to field scale (McKay et al., 1993; Sims et al., 1994).

### 4.4 Field Testing

It is realized that the CNWRA budget is tightly constrained and the corresponding scope of the research effort cannot rival that of DoE. However, despite the expense, field testing is important in defining behavior at a scale closer to that of the prototype than the laboratory and of also incorporating processes that may be inadvertently missed in modeling efforts. For this reason, large scale testing is considered important in providing confirmation of the DoE design.

This mode of testing is especially important in evaluating the anticipated controls on vaporization-migration-condensation behavior in the dry-out region. The following approach, combined with modeling studies and sensitivity analyses is recommended for prioritizing investigations. The limitation of funds may require selections to be made from the following prioritized list, as:

1. Complete modeling (numerical) studies to conceptualize the interaction of physical processes and define important controlling parameters and parameter groups.

2. Match these studies with currently completed heater tests, both in the laboratory and at field scale, including *in situ* heater tests. Collect additional data as necessary.

3. Complete laboratory tests to fill data gaps, such as relative permeability magnitudes for air and water in fractures, capillary relationships and imbibition characteristics.

4. Use the Mexico field site as a natural analog to define relic hydrothermal processes.

5. Initiate the full scale test proposed at the Mexico field site with 4 heater assemblies traversing the metamorphic aureole.

6. Evaluate the utility of other palaeo-analogs (such as intrusions and haloes around exhumed dikes) and contemporary analogs, including geothermal fields, especially hot dry rock geothermal reservoirs and depleted geothermal fields with significant vapor phase components.

## 5 Ranked Topics of Future Research

A variety of potential topics of future research are detailed and ranked. Of these, 7 were previously defined by CNWRA, and 1 (Section 5.2) is added. The following details the performance assessment (PA) objective addressed by each, suggests a potential approach for compliance related studies, and comments on the anticipated utility of the results. Topics are addressed in ranked priority of importance.

### 5.1 Vaporization, Condensation and Mass Migration Around Waste Packages

High priority.

**PA Objective:** To define the potential for migration of the inventory to the intermediate- and far-field.

**Suggested Approach:** This is considered the most crucial KTU of the processes considered in the scope of this review. The importance of understanding the interaction of processes, in both the near-field and the far-field is evaluated in Section 4.2. Supporting studies to define important field scale processes and to provide necessary parameterizations are elucidated in Sections 4.4 and 4.3, respectively.

**Anticipated Results:** The purpose of this proposed task is to evaluate the likely form and dimension of the dry-out zone, together with estimates of the variability of the dimension with variation in parameters. The potential for rewetting of the waste cannisters and migration of aqueous solutions, vapors and colloids from the repository may also be estimated.

## 5.2 TH Effects on Permeability Changes

High priority.

**PA Objective:** To evaluate the mobilization and migration of vapors from the near-field to the far-field together with the potential for return circulation to the waste packages and subsequent package corrosion.

**Suggested Approach:** Circulation of liquid and vapors around the heated waste packages will potentially effect; (i) alteration of fracture wall rock with potential influence on condensate imbibition, through formation of a skin of alteration products, (ii) potential clogging or opening of the fractures by precipitation, dissolution and reaction, and (iii) potential reduction in strength.

These processes are strongly influenced by the hydrochemistry of the circulating fluids, and the prevailing thermal regime. An appreciation of the importance of these effects may be gauged by:

- A survey of analogous processes, including clogging in geothermal reservoirs, and mechanisms of ore deposit formation and hydrothermal alteration, and,
- Conducting long-term autoclave experiments including hydrothermal circulation under constant stress (creep) or constant displacement (relaxation) conditions, as bounding behaviors. Recording changes in permeability, effluent fluid chemistry and seismic (p-wave) velocity with time would provide useful indices of alteration. Final destructive testing would enable strength degradation of the samples to be directly determined.

**Anticipated Results:** The previous studies would enable order-of-magnitude estimates to be made for changes in permeability and strength, as a result of hydrothermal alteration, to be determined. These are potentially important parameters in evaluating the potential for the formation of heat-pipe circulation cells, as described in detail in Section 4.2.

## 5.3 TM Effects on Permeability Changes in Partially Saturated Rock

High priority.

**PA Objective:** To define the potential for migration of the inventory to the intermediate- and far-field.

**Suggested Approach:** Modulus, strength, thermal conductivity and thermal diffusivity of the rock mass all exhibit second order variability with thermal and mechanical loading. Permeability change with induced thermal strains is a first order effect, and may be large, and uncertain, where the system is fracture dominated. Because of the inherent uncertainty in evaluating permeability distributions, it is important to understand the relative behaviors of the prototype *low permeability* and prototype *high permeability* systems identified in Section 4.2 and Figure 1. These studies may require support from laboratory evaluations, as detailed in Sections 4.3 and 4.4.

**Anticipated Results:** These results will further refine understanding of the TM and TH processes influencing the form of the dry-out zone.

## 5.4 Bounding Spatial Variation of Rock Mass Properties

Medium priority.

**PA Objective:** To evaluate the potential for transport in the intermediate-to far-field, with the potential for migration of the repository inventory.

**Suggested Approach:** Performance of the proposed HLW repository at Yucca Mountain will be controlled by site specific properties, and their distribution. It is not clear whether these data will be available in a timely fashion to enable detailed confirmatory analyses (by CNWRA) in evaluation of the license application. Correspondingly, it is important to note that:

- Large scale features will control processes operating at a large scale (far-field) and these features must be reliably located, and characterized.
- Confidence in extrapolating absolute parameter magnitudes over large scales is low, but understanding process behavior is considerably better.
- Some processes, such as conductive thermal transport, are intrinsically *robust* and are marginally affected by parameter variability. It is important to identify if, for example, under all reasonable parametric conditions the vaporization→migration→condensation process retains thermal transport as conduction dominated. If convective transfer is significant, it is important to bound the anticipated influence this may exert on the integrity of the EBS. See Section 4.2.

**Anticipated Results:** Scoping calculations will define the uncertainties involved in describing vapor migration from the repository, and directly incorporate the influence of meso-scale features on the performance of the system.

## 5.5 Time Dependent Degradation of Rock Properties

Medium priority.

**PA Objective:** To determine the potential for puncturing of waste packages in the near-field through loss-of-strength and loss-of-interlock within the rock mass with time.

**Suggested Approach:** The primary problem in this task is the extended observational time scale needed for any experimental work. This makes laboratory testing infeasible, except the potential for relatively simple constant stress (creep) or constant displacement (relaxation) tests conducted in sealed autoclaves.

Alternative approaches are to:

- Accelerate the processes of time dependence by increasing the hostility of the testing environment. Correspondingly, if the primary mechanism of degradation is hydrothermal alteration, then elevated temperatures and accelerated circulation rates may be used, with samples ultimately retrieved for nondestructive evaluation or destructive strength testing.
- Obtain samples representative of the long-term aggressive environment, by sampling from analog environments subjected to long-term thermal or hydrothermal loads. These potential locations include the haloes around intrusions in tuff, with studies incorporating geothermometry by appropriate methods.
- Anecdotal evidence from the survey of abandoned drifts in aggressive heated environments, such as the South African goldfields, and, for example, the Homestake Mine in Lead, South Dakota.

**Anticipated Results:** Studies of this type would provide order-of-magnitude estimates of anticipated long term behavior for use in modeling studies of drift stability. Determination of the production of clay minerals may be important in evaluating the transport and sorptive characteristics of fractures and fracture zones, and defining the potential for capillary recirculation around the waste packages (see Figure 1).

### 5.6 Parameter Scaling to Field Scale

Low priority.

**PA Objective:** To determine the potential for breaching of waste packages in the near-field by failure in the drifts and to evaluate the potential for migration of the inventory to the far-field.

**Suggested Approach:** Spatial scaling approaches describing strength variation of rock joints and rock masses are reasonably well understood and quantified within relatively narrow bounds (low priority). Spatial scaling of the parameters controlling thermal transport are narrowly bounded if convective transport and phase change effects are considered of second order importance, only (low priority). However, spatial scaling approaches applicable to intermediate- to far-field convective transport are much less well understood. Little confidence may be applied to modeling exercises conducted without adequate field constraint, unless the transport processes may be shown invariant and benign for a broad range of potential parameters, and their spatial distribution.

Determining the sensitivity of field scale transport processes to the uncertainty in transport parameters is considered the most important uncertainty in this class. The use of sensitivity analyses (numerical analyses) to define the impact of low permeability and high permeability geologic regimes on the form and extent of fluid and vapor migration around the dry-out region, is suggested. These calculations may directly indicate the sensitivity to certain parameters, or parameter groups, and directly drive characterization studies. This approach is described in detail in Section 4.2, and further referenced in Section 5.1.

It is important to also recognize that some parameters scale only with difficulty from the laboratory scale to field scale, and these include, for example, the colloid transport processes and the capillary relationships detailed in Section 3.2.3.

**Anticipated Results:** The use of scoping calculations will define the robustness of the TH processes to spatial and temporal changes in parameter magnitudes, and determine the level of uncertainty in the behavior.

## 5.7 Long-Term Performance of Repository Seals

Low priority.

**PA Objective:** To evaluate the potential for near-field breaching of seals enabling loss of inventory.

**Suggested Approach:** Seals may include the use of low permeability backfills around the waste packages and in drifts, and low permeability grouts in boreholes and fractures. The severity of the thermal loading proposed in the near-field (230°C) suggests that clay seals (if used) may not retain their hydraulic integrity and would be breached by the formation of desiccation cracks. Under these conditions, behavioral modes of interest include:

- Creep behavior with the potential for healing of fractures due to thermal and hydrothermal effects.
- Change in sorption capacity with desiccation and the production of fast flow pathways.

The urgency for research elements in this area depends strongly on the precise form of the DoE design, including anticipated temperatures and backfill configurations. These factors will influence the form of appropriate testing but might include autoclave testing of samples under simulated repository temperatures, and under constant stress (creep) or constant displacement (relaxation) conditions. Care must be taken in interpreting the very different form of permeability changes that may occur under these two different loading conditions, and consideration of the strong scale dependence of the effects.

**Anticipated Results:** If high surface temperatures are used for the waste packages, it seems unlikely that the engineered barrier in the near-field will provide hydraulic isolation, but may merely act as a sorptive barrier. In this instance, the assumption of breaching is reasonable, and data uncertainties are low.

Grouting of the near- and intermediate-field is not considered likely, but if used, the integrity of the seal will be strongly conditioned by local deformations. These effects may be quantified through shear testing of filled discontinuities, as necessary.

## 5.8 Rock–Support Interaction Under Heated Conditions

Low priority.

**PA Objective:** To evaluate the potential for drift failure in the near-field and its effect on the integrity of the waste packages.

**Suggested Approach:** Little uncertainty exists in defining the near-field thermal regime and the near-field rock mass structure. Conversely, little data, over an extended time-frame, exists to represent rock support interaction, and the anticipated long-term strength of the rock remains poorly constrained. Despite this, the consequences of local instabilities are not unduly limited by the usual constraints of civil construction that must resist closure, and retain safety for human intrusion. Where backfill is used within the drifts, the adverse effects of local instability are further mitigated. Uncertainties in this behavior are not considered of large order, or to warrant onerous investigation. It is considered that most of the adverse effects possible within this task may be engineered out.

Observational studies of the long term behavior of deep mines in aggressive thermal environments may be useful in providing anecdotal evidence of anticipated behavior (see Section5.5).

**Anticipated Results:** No specific research tasks are suggested. Observation of long-term rock support interaction in deep drifts (Homestake Mine, South African mines) and the shorter term monitoring of heated drifts in the prototype repository experiment at the Åspö site (Papp, 1993) in Sweden (where HLW will be interred in adjacent drill-and-blast and machine cut drifts), may be useful in constraining this behavior.

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**Dr. John E. Gale**

# PEER-REVIEW REPORT

TO

CNWRA
SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

ON

# PEER-REVIEW OF CNWRA COUPLED THERMAL-MECHANICAL-HYDROGEOLOGICAL (TMH) RESEARCH

August 15, 1995


JOHN E. GALE
DEPARTMENT OF EARTH SCIENCES
MEMORIAL UNIVERSITY
ST.JOHN'S, NEWFOUNDLAND, CANADA, A1B 3X5

**SUMMARY**

CNWRA, with the limited resources available to its research staff, has made an impressive start in developing a very credible research program that is notable for its open-minded approach, objectivity and lack of advocacy for any particular research position. The research program is well focused on the KTU's and the need to assist NRC in developing its capability to interact with and respond to any future repository licensing application from DOE for the Yucca Mountain site. However, while recognizing the existing and future budgetary constraints at both NRC and CNWRA, it is clear that the complexity of the issues and the limited time, in which to prepare for and respond to a repository application, requires that additional resources be made available to the CNWRA research effort.

Central to understanding TMH processes on the field scale is the need to develop within CNWRA expertise in the areas of rock mass characterization, especially in the statistical analysis and interpretation of fracture geometry and joint properties. The existing work on MH processes in single fractures needs to be continued. The method of loading the discrete fracture samples in the existing shear frame needs to be reevaluated to ensure consistency with in-situ loading. The approach used to test the discrete fracture samples should be compared to that used in other laboratories. Future tests on single fractures should be extended to include both single phase and two phase experiments on the same fracture under the same stress and temperature conditions. Tracer tests must be added to both the single phase and two-phase flow experiments to constrain the data interpretation. Consideration should be given to conducting a simple vapor-condensation experiment on a single fracture to provide basic data for numerical simulations. Given the Yucca Mountain site conditions, this would be considered a crucial experiment.

There is a continuing need for networking with other research groups in both the field and laboratory activities such as is already underway in the numerical modelling area through DECOVALEX. The topics for future research are quite broad and need to be more focused. This can be accomplished by grouping four of the topics under one heading and defining sub-topics to cover the essential areas of TMH research. The four main areas that should be addressed, in order of priority, are (A) Methodology for bounding spatial variation of rock mass properties, (B) Mechanical and thermal-mechanical effects on permeability changes in unsaturated fractured rock mass, (C) Formation of dryout regions, recondensation of vapour, and condensate dripping through fractures in heated and partially saturated fractured media and (D) Extrapolation of laboratory measurements to field scale application. Completion of key elements of this research program, based on these four areas, will provide the basic TMH constitutive and empirical relationships needed to formulate a first order performance model from the rock mechanics perspective.

# 1 INTRODUCTION

The Department of Energy is proposing to construct a mined repository for high level nuclear waste at Yucca Mountain, Nevada. The Center for Nuclear Waste Regulatory Analysis (CNWRA) is conducting basic and applied research to support the Nuclear Regulatory Commission's (NRC) High-Level Nuclear Waste Repository Licensing Program for the proposed repository at Yucca Mountain. CNWRA has requested a peer-review of the coupled thermal-mechanical-hydrological (TMH) research that it is conducting for NRC as part of its overall Rock Mechanics Research Project. The objectives of this review are to (i) critically review the objectives and approaches of CNWRA coupled TMH processes research and its application to licensing issues at the proposed Yucca Mountain HLW repository site, (ii) provide recommendations to improve the research scope and methodologies, and investigate new issues that may not be a part of the original research programs and, (iii) evaluate interpretations of the available data, and explore alternative hypotheses. In meeting the first objective, the reviewers are expected to assess whether the current approach is adequate to resolve key technical uncertainties, to assess whether the appropriate emphasis is being given to understanding those coupled processes that are expected to have an impact on repository performance as well as provide a ranking of the proposed research activities, consistent with the time and resources available to both CNWRA and NRC. The resources available to CNWRA for this rock mechanics coupled processes research is approximately 1.5 full time equivalents (FTEs) representing an average of five researchers spending about 1/3 of their time on research and about 2/3 of their time on technical assistance. Some additional numerical modelling is included under the technical assistance category. In order to place these review comments in a site specific context, the following summary of the relevant site characteristics has been extracted from the literature provided for this review and the presentation material provided during the peer review meeting.

The bedrock units at the proposed site consists of a shallow dipping (approximately 80 to 130 m per km), layered, sequence of volcanic tuffs. Based on the topographic maps in the reports, the surface topography is rugged with about 1000 ft of relief on the surface over the area of the proposed repository. The rock mass appears to be normally loaded, with the maximum principal stress oriented in the vertical direction and averaging 7.0 MPa at the level of the planned repository. The horizontal stresses are assumed to average from 3.5 to 4.2 MPa with a ratio of minimum to maximum horizontal stress that may range from 1.2:1 to 2:1. This stress field will produce relatively low stresses in the roof and floor and higher stresses in the walls, at the springline. As pointed out in the site reports, drift failures will be controlled by the discontinuities in the rock mass.

The degree of vitrification varies within the bedrock units. Basic rock strength properties, presented by Martin et al., 1995, for the TSw2 unit in borehole NRG-7/7A are highly variable with the overlying TSw1 unit being significantly weaker. The RQD data presented by Langkopf and Gnirk (1986) show significant variations in rock quality both vertically and horizontally within the TSw2 unit. Surface mapping (Scott and Bonk, 1984) shows a significant number of faults and long fracture traces. The through-going nature of the faults, especially the Ghost Dance Fault, is confirmed by the structural offsets of the potential repository horizon as evidenced by the differences in dip between adjoining structural blocks. Surface mapping and borehole logs have identified four fracture sets, of which at least two and possibly three are classified as significant in terms of frequency and/or size. It is important to note that three of the joint sets have steep to vertical dips.

The groundwater table is located about 300 to 500 m below the potential repository level. Based on the water levels in a number of deep boreholes, there are significant variations in the local hydraulic gradient across the site. Boreholes have encountered perched water above the potential repository horizon. Both observations suggest significant vertical and horizontal variations in the rock mass transmissivity. Porosities in the TSw2 unit generally cluster around 10 to 13 percent, with the overlying units having sections with porosities that are 50 percent or greater. Some of the bedrock units above the level of the proposed repository contain lithophysal zones with cavities that make up from 10 to 30 percent of the rock mass volume. Even in the bedrock unit that has been designated as the potential repository horizon, these cavities can represent up to 10 percent of the rock mass volume.

Hence the rock mass, in which the repository will be located, is a highly fractured tuff that is partially saturated above and below the level in which the repository would be located, but contains zones (perched water) in which the rock mass is fully saturated. Hydrogeologically, the rock mass can be considered as a fractured porous media in which the matrix provides significant storage but the fractures are the primary conduits. The role of the fractures versus the matrix in terms of unsaturated flow under both isothermal and nonisothermal conditions is unclear. However, the displacements and stresses induced by drift excavation, thermal and seismic loads will be reflected in changes in the hydraulic and mechanical properties of the fractures, more so than in the matrix, because of the non-linear behaviour of most natural and induced fractures over the range of in-situ stresses that exist at the proposed repository level.

# 2 ASSESSMENT OF KEY TECHNICAL UNCERTAINTIES

Key technical uncertainties, defined as technical uncertainties that pose a high risk of noncompliance with a performance objective, include (a) predicting thermal-mechanical effects on stability of emplacement drifts and the engineering barrier system, (b) prediction of the thermal-mechanical-hydrological effects on the host rock surrounding the engineered barrier system, (c) predicting the long-term performance of seals for shafts, ramps, and surface and subsurface boreholes and (d) demonstration of compliance with the requirement to maintain the ability to safely retrieve high-level nuclear waste. In this review, I have focused on (a) and (b) above, since the importance of (c) and (d) as discussed below is determined by the design of the engineered barrier system.

If the emplacement drifts are backfilled, it is accepted that it will be very difficult to demonstrate retrievability of the waste as specified in (d). However, it is quite clear that if the emplacement drifts are not backfilled and if steel sets are used to support the drift walls without rock bolt reinforcement, then (c) as well as (d) could become quite important. In this case, given the highly fractured nature of the site, it should be possible to use the weakest link approach to assess the importance of (c) as a KTU and demonstrate that the shaft and borehole seals will occupy the lower range of fracture permeabilities that are known to exist at the site. In addition, one would expect the excavation induced stresses plus the thermal stresses, produced by the thermal pulse, to induce failure in the steel sets. The resulting drift closure will produce significant fracture deformations over a large volume of rock in the near-field that will alter the fracture permeabilities. Collapse of the emplacement drifts, due to failure of the steel sets, would make it very difficult to ensure retrievability. Even in the absence of backfill, the use of rock bolts to reinforce the rock mass would reduce room collapse and hence reduce the volume of the rock mass over which the in-situ stresses would be perturbed and within which the fracture properties would be altered.

Technical uncertainty, as it relates to the above effects and performance issues, from the NRC/CNWRA perspective consists of lack of certitude about: (I) methods for obtaining information, (II) methods for analyzing information, or (III) the understanding of conditions or processes. In this respect, the NRC/CNWRA program is not intended to contribute to the site specific database but is designed to permit NRC/CNWRA staff to assess compliance. Both the TM and the TMH effects constitute KTU's whether or not the drifts will be backfilled, but they will be more important if the drifts are not backfilled and the drift walls are not reinforced since a bigger volume of the fractured rock mass will be disturbed as the drift deforms. Critical to predicting both TM and TMH effects on a drift scale will be the degree of confidence that exists in the rock mass characterization over the volume that is expected to be perturbed around each drift. Confidence in the rock mass models will require that both fracture geometry, in terms of both size and orientation, as well as the mechanical properties of the fractures, primarily in terms of fracture type and stiffness, depending on the scale of the fracture, be described in an appropriate statistical or deterministic manner. While methods for collecting the required information are available, excessive site intrusive work is required and will most likely not be permitted in the rock mass around the drift walls. In addition, the current statistical approaches to analyzing the data in 3D are not sufficiently robust, and they do not reflect the basic genetic models of the fracture system or identify the relevant size parameters. Thus, in addition to developing a methodology for bounding spatial variability, there is an implicit need to recognize and quantify the spatial variability in the controlling parameters over the domain of interest. If this work is not already being pursued at CNWRA, or by some other sub-contractor of either CNWRA or NRC, then this area of research should be given priority because of its over-riding control on the predicted response of the fractured rock mass to TM loadings effects.

This priority is increased when one recognizes the need, during the repository application review stage, to have at least one or more researchers who are committed to developing hands-on experience with these data analysis and data interpretation procedures.

One should be able to assume that the repository licensing process will result in the acceptance of a combined drift support and rock mass reinforcement system that will maximize drift stability. Thus, in terms of uncertainty, the thermal-mechanical-hydrological effects on the rock mass becomes the major KTU. Also, unless there are programmatic reasons, the TMH and TM KTU's should be combined since commonality of the problems and similarity of the research required to address each KTU produces unnecessary repetition and confusion. Thus, I agree that the appropriate emphasis should be on the first two KTU's as they relate to the "prediction of thermal-mechanical-hydrological effects on the host rock and their impacts on emplacement drift stability and the engineered barrier system".

# 3 RESEARCH SCOPE, METHODOLOGIES AND DATA INTERPRETATION

The proposed research topics are much too broad given the resources available to CNWRA. Mounting a full fledged program in any one area would consume all of the resources that NRC provides to CNWRA, especially if the program included laboratory and field components. Restricting the research program to literature reviews and numerical modelling would permit most of the topics to be addressed. However, numerical models only reflect the basic constitutive models, processes and material properties that are used in the models. In the absence of a clear understanding of the basic coupled processes, numerical models will provide little guidance or insight.

In the current CNWRA research program, there does appear to be a good balance between experimental and numerical work, with the possibility that the numerical work has been over-emphasized relative to the experimental work. The field work at the Mexican site that is proposed by R. Green will be a welcome and much needed addition to building an application review capability within CNWRA since the repository application from DOE will be based on an actual field site and will contain a large volume of field data. The challenge to the CNWRA researchers, as well as the peer review group, is to identify the critical components of the research program that will enhance the review capability at NRC's disposal within the available time and resources. The prudent course of action is to continue with a well balanced program and build on the accomplishments that have already been achieved. Thus, I have reviewed selected components of the current TMH research program and provided comments and suggestions that may help focus those areas that need focusing as well as strengthen those areas that are making good progress.

- Research on Single Fractures

CNWRA researchers have made considerable progress in studying the problem of coupled stress-flow in single fracture as a function of both normal and shear stress. These researchers have encountered many of the problems associated with such coupled stress-flow work and have formulated reasonable and practical solutions to these experimental problems. Plans to extend this MH work to study TMH processes in single fractures are appropriate and consistent with the overall project needs.

Before continuing their work with the existing direct shear apparatus, the researchers should examine how the fracture plane is being loaded. In most direct shear frames, it is accepted that under normal loading with zero shear stress, the resultant force passes through the centroid of the sample. However, if one considers a simple vector diagram, it can be shown that as the shear force is applied the resultant force moves from the centroid of the sample towards the end of the sample. This action, if it is pronounced enough, produces a tilting of the sample or a wedging effect that is not consistent with the way fracture planes are loaded in-situ. Manometer ports should be drilled into each fracture plane to enable one to monitor the degree of wedging or tilting of the fracture plane during shear displacement. Without a clear understanding of how the sample is being loaded, the results could be misleading, especially if one tries to back-fit to field data.

I recommend that the CNWRA researchers examine the design of other shear-permeability frames before proceeding with tests on additional samples. Also, a higher strength grout should be used to hold the sample in the shear box. For TMH testing at moderate temperatures, an epoxy grout, with its higher tensile strengths, would be more effective than cement grouts and much less prone to cracking. The top half and the bottom half of the sample should be the same size. In the current configuration, the top half is continually ploughing into a fresh section of the fracture surface and this, coupled with the movement of the resultant force toward the edge of the sample, may produce an artificial increase in the shear strength of the fracture plane. Given the recent field data that shows the close correlation between nearby blasting and changes in the permeability of a fractured rock mass, the capacity of the shear frame to apply dynamic loads should be assessed.

The profilemeter approach to characterizing the roughness of the fracture surface as well as the aperture distribution has encountered difficulty, in matching the opposite surfaces, similar to that encountered by other researchers. I recommend that pore structure results obtained from the profilometer be compared to the results obtained from the pore structure determined by injecting the fracture plane with epoxy under the loads at which the hydraulic and mechanical tests were conducted.

It is very important that the researchers not lose sight of the basic premise in the KTU. That is, to predict the TMH behaviour of discrete fractures from simple index or field tests prior to doing the TMH experiments. While considerable work has been done on the MH response of single fractures, much more remains to be done. At present there is no basic mechanistic model available to predict the MH behaviour of discrete fractures. All of the models are based on curve fitting techniques or, as in the case of the Barton-Bandis (BB) model, are matched to parameters derived from existing databases. The BB model comes the closest to providing a predictive tool for discrete joints, based on simple index parameters. However, the BB model consistently underpredicts the shear strength and modifications to the basic algorithm are required before consistent results will be produced. (Care should be taken in using the UDEC code since it incorporates the BB model).

Basic models that predict the TMH response of discrete fractures must be able to predict the fluid velocity or tracer breakthrough curve as well as predict the total volume of flow or flowrate, since prediction of both quantities is based on the same basic flow and transport equation. No model currently has this basic predictive capability even for single phase flow. However, a large number of models can be calibrated to existing experimental data but they usually require a significant adjustment of the basic model to match both the flux and the velocity. Such changes show that we do not understand the basic processes and constitute bad science. I recommend that tracer tests be added as a matter of routine to the single fracture laboratory experiments.

Based on our experience, the sample size that is being used in the single fracture experiments is appropriate. The applied stresses are also consistent with the isothermal stress levels expected at the Yucca Mountain site. Care should be taken to distinguish between classical size effects and normal variability. Many of the problems encountered in trying to extrapolate laboratory measurements to the field are related to the differences in boundary conditions that are imposed on the fractures in the field versus in the laboratory. If possible, a minimum of three to four samples should be collected from the same fracture plane or fractures of the same set. Samples should be collected and tested from each of the three to four main fracture sets. While it is important to conduct the hydraulic tests at high water pressures such as the water pressures that would de required to produce the high pressure drop of 690 kPa that is proposed, the hydraulic gradients should not be greater than 10 or 20. Higher water pressures may require a significant change in the flow boundary controls that may be very difficult to implement. Also, since part of the problem with leaks during shear tests is related to the large shear displacements that were applied, the need for shear displacements of more than 5 to 10 mm should be justified.

- Coupled TMH Studies on Single Fractures

Adding thermal loads to the ongoing MH studies is essential. This includes determining the fracture response at different temperatures as well as monitoring effects of changes in temperature. In addition, these studies need to incorporate basic fracture-matrix interaction studies that include both single phase and two phase flow under both normal and shear displacement. The current experimental apparatus should be evaluated to determine if a vapour-condensation experiment can be conducted on a single fracture. This would require heating on one end to produce vapor, or the introduction of steam, and cooling on the other end to produce condensation. Such an experiment would provide an effective test of the predictive capabilities of the non-linear codes that are currently being evaluated. In designing the experiment, care should be taken to consider buoyancy effects in single vertical fractures.

# 4 RANKING OF RESEARCH TOPICS

CNWRA has provided a list of seven potential topics or areas for future research. The peer review group was asked to rank these proposed activities and/or propose other priority areas of research. The seven topics are fairly broad and can be presumed to cover a wide range of sub-topics. I have arranged the seven topics in the order of decreasing priority. While I have made specific comments on the last three topics, I consider the first four topics to be highly interrelated and I have discussed them as a group throughout this review. A few limited comments are provided on each of the first four topics and should be read in the context of the above discussion.

A. Methodology for bounding spatial variation of rock mass properties. As discussed above, confidence in the approach taken to define the spatial variability of the key parameters within the rock mass is essential for site assessment and the incorporation of basic TMH processes into models in order to assess the rock mass and drift/engineered barrier system response to thermal and mechanical loads. CNWRA researchers need to have an hands-on familiarity with the basic approaches used to analyze and interpret the field data, especially the data on fracture geometry and rock mass characteristics.

B. Mechanical and thermal-mechanical effects on permeability changes in unsaturated fractured rock mass. Despite the work that has been done on this topic it is still a key area of research. Also, this topic should include mechanical and thermal-mechanical effects on saturated flow and partially saturated flow in the same fractures under the same stress and temperature conditions. All tests on single fractures must be referenced to tracer tests and both the single and two-phase flux must be compatible with the fluid velocity measurements. The flux and transport models must be based on the same pore structure model. Emphasis in this program must be on predicting the TMH response, from basic fracture characterization data, before the tests are conducted. Successful predictions, based on acceptable criteria, should be the basis for considering that the TMH processes are reasonably well understood.

C. Formation of dryout regions, recondensation of vapour, and condensate dripping through fractures in heated and partially saturated fractured media. This process is best assessed by a well defined 3D numerical model. However, consideration should be given to conducting an experiment, using the existing shear frame, to investigate vapor migration and condensation in a single fracture as a function of normal displacement and shear displacement, in which significant gouge is developed.

D. Extrapolation of laboratory measurements to field scale application. Successful extrapolation of the laboratory results to the field is essential, but depends on the completion of a well defined laboratory program. Numerical models provide the essential tools with which to integrate the field and laboratory data. Because of the cost and time involved, the field experiments will have to be a shared activity.

E. Interaction of rock and support systems under heated conditions. This is much more of an applied engineering problem than an area of research. The problem can be assessed with existing numerical models. From a compliance perspective, the study should be changed to "Comparison of the interaction of rock and support systems versus the interaction of combined rock, support and reinforcement (fully grouted rock bolts) systems under heated conditions to minimize THM effects on rock mass performance and overall waste retrievability". Or more simply, "Comparison of the interaction of rock, support and reinforcement systems under heated conditions". The 3D nature of the rock reinforcement problem would require a 3D modelling approach using codes such as 3DEC. If necessary, the model results could be validated against a shared in-situ drift experiment that is conducted at depth on a scale that is equal to 5 to 10 times the average fracture spacing. However, I do believe that in relative terms the computer modelling would be sufficient.

F. Time dependent degradation of rock properties under heated conditions. I am assuming that the term "rock properties" refers to both the matrix and fracture properties. In the case of the matrix properties, the procedures for studying temperature effects, both steady state and transient, on basic mechanical properties are well established in the geophysical and rock mechanics fields and on basic transport properties in the petroleum fields. A significant volume of experimental data exists on a range of intact rock samples that is sufficient for performance assessment as it relates to what is a second order effect in terms of the intact material. The procedures for interpreting these data are well established and the processes are reasonably well understood. There is certainly a need for more site specific data, but this should be a requirement that is placed on the proponent. CNWRA research staff will need to have access to the existing data base for modelling purposes, but this is best achieved by having the CNWRA research staff network with researchers and laboratories that have been or are currently active in the field. Combined TMHC effects may be the exception here as well as the time dependent effects of temperature on two-phase flow. However, both of these topics should be studied in the context of combined fracture-matrix TMH effects as outlined in A, B and C above.

G. Evaluation of long-term performance of repository seals. Considerable work has been done on this topic in a number of countries, including research on both materials and emplacement procedures. A considerable volume of practical experience in drift sealing exists in the mining industry, especially in coal and evaporite mines. In a repository that has not been backfilled, and which contains some fairly conductive fractures, undue emphasis on drift and borehole sealing is equivalent to worrying about the effectiveness of a cork in a bottle neck with the bottom missing. From a compliance perspective, and recognizing the limited resources available to CNWRA, the capability to address this problem for licensing purposes can be developed by evaluating the existing literature, networking with researchers from other countries and using the weakest link approach to perform sensitivity analysis as outlined in the proposed research program. In order to obtain a "hands-on" feel for the problem, researchers can continue to use the existing data in various modelling exercises such as is currently being done through the DECOVALEX program.

**Dr. A.P.S. Selvadurai**

External Peer Review

of

# COUPLED TMH PROCESSES RESEARCH

conducted by

**The Center for Nuclear Waste Regulatory Analyses**
**Southwest Research Institute**
**6220 Culebra Road**
**San Antonio**
**TEXAS 78238-5166**
**U.S.A.**

Review by Panel Member

**A.P.S. Selvadurai**
**Professor and Chair**
**Department of Civil Engineering and Applied Mechanics**
**McGill University**
**817 Sherbrooke Street West**
**Montreal**
**QC, Canada H3A 2K6**

Telephone: (514) 398-6857
Fax: (514) 398-7361
e-mail: apss @ civil.lan.mcgill.ca

25 July 1995

# EXECUTIVE SUMMARY

This report contains the recommendations resulting from an External Peer Review of the Coupled Thermo-Mechanical-Hydraulic (TMH) Processes Research conducted by the Center for Nuclear Waste Regulatory Analyses (CNWRA) at the Southwest Research Institute, San Antonio, TX. The recommendations result from a review of documents and summary positions of the research submitted to the Peer Review Committee and from discussions and observations of a two-day meeting with scientists, engineers and administrators of CNWRA. In keeping with the terms of reference of the External Peer Review, this document critically evaluates the current status of the TMH research effort at CNWRA and provides recommendations for research directions which are intended to address, within a stated time frame, items of critical importance to the better understanding of TMH processes which are likely to occur and are of particular importance to the current concepts proposed for the Yucca Mountain Repository.

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## 1. BACKGROUND

The basic disposal concept associated with the Yucca Mountain Project falls within the general area of deep geological disposal concepts for high level, heat emitting nuclear fuel wastes. The majority of such concepts advocate the siting of the repositories, by and large, in relatively intact geological formations where the defects, fractures and fissures which are either naturally present in the region or created as a result of the construction of the repository and associated thermal loads are sparse and restricted to identifiable locations. Also, in such deep geological repositories, proposed by countries including Canada and Sweden, the groundwater movements within the geological medium are expected to be dominated by flows which occur within the hydraulically active joints and fracture zones. This assumption is largely substantiated by the competent, dense and relatively low permeability character of the intact geological medium. In the context of the Yucca Mountain Repository, the intact geological medium is considered to be a porous volcanic and volcanoclastic material and the formation itself is known to be highly jointed. A further essential departure of the Yucca Mountain Repository concept relates to the reference temperatures imposed by the stored waste. The anticipated reference drift wall temperature of approximately 250°C is considerably higher than the reference temperatures associated with other deep geological disposal concepts, notably those in Canada (reference temperature in the range of 80°C) and Sweden (reference temperature lower than 100°C). This places a considerable burden on the development of a research effort and technical support which could have taken advantage of the research and development programs conducted by other countries. Furthermore, the heat generation is expected to be active over an extended period of time, the duration and decay rate of which is not clearly defined (documents indicate a period between 1000 to 5000 years). A further complication arises from the fact that the repository itself is located in a region which is considered to be seismically active and scenarios have to be developed to assess the impact of fluid migration into the waste storage regions as a result of the development of conduit type features which can connect the repository with perched water bodies.

It is understood that the role of the CNWRA is to develop a range of expertise, both in terms of computational efforts and experimental concepts, which will enable the NRC to critically evaluate the license application of DOE. To this end, the CNWRA has identified certain Key Technical Uncertainties with a view to focussing attention on an effective utilization of its resources, both within the time frame of the activity and the resources allocated over the next three years.

## 2. REMARKS AND RECOMMENDATIONS

The basis for the development of these remarks and recommendations relies on the following:

(i) a summary document submitted to the Peer Review Panel describing the achievements of the Center with regard to the experimental and computational research and the key technical uncertainties as identified by the NRC and research groups at CNWRA;

(ii) reports on the individual research programs initiated by the Center, and

(iii) the observations made at the 2-day meeting convened at SwRI where scientists from both NRC and CNWRA made presentations summarizing the objectives and deliverables sought by the NRC and the progress made by the TMH research group at the Center in addressing such objectives.

The recommendations made in this section are grouped into five parts covering general aspects, the experimental research program, computational modelling, engineering issues and international cooperation and linkages.

### 2.1 General Aspects

During the course of the discussions at the Panel meeting and in reviewing the documents submitted to the Peer Review Panel, it became clear that the configuration of the repository and the precise nature of the thermal loadings are left relatively unspecified. While this is meant to leave some flexibility in the range of options available for the repository design, and to allow for modifications as and when new and pertinent information becomes available on the overall project, it makes the task of organizing a focused research effort much more difficult. The time frame envisaged is certainly insufficient to embark on any topic which is identified as being of marginal importance to the anticipated range of temperatures induced by the radiogenic heating and the tentative engineered configuration of the repository.

***Recommendation 1***

*The NRC together with CNWRA should, at this stage, attempt to arrive at a more precise detail of the repository in terms of its location, the geometry of the drifts, the construction procedure, the nature of the support of the heat emitting waste containers, the degree of ventilation of the galleries, the presence* *or absence of an overpack or backfill surrounding the waste container, the nature of the backfill and the method of placement of the backfill, its physical and mechanical characteristics and aspects related to its longevity and thermal interaction with the container material.*

*The rationale for this recommendation is that all other activities related to the study of TMH processes will be influenced, to a large extent, by the thermal loads imposed by the stored waste on the surrounding geological media. The TMH processes which are activated in the geological media , within the 0 – 100 ℃ temperature range, will be substantially different from those processes which will be present when the temperatures are expected to be in excess of 250 ℃ at the drift walls. Furthermore, the rationale for the specification of this upper limit for the temperature is not entirely clear: In reality, the only quantity that can be specified at the outset is the heat output per unit surface area of the waste container. The temperature induced at the rock surface will be consistent with the actual configuration of the waste emplacement mode and the presence or absence of backfill or the possible effects of venting of the disposal adits.*

***Recommendation 2***

*The in situ or natural geological condition in the vicinity of the proposed location of the repository should be adequately mapped and defined in terms of joint orientations, the classes of joints, fractures, inclusions and other defects. These typical geological features should be amenable to interpretation in terms of acceptable measures of rock joint characteristics which can be used in the quantification of the joints through computational models, The typical mechanical properties of the intact tuff in all horizons should also be characterized in terms of elastic, failure, fracture, creep and other characteristics. The in situ stress state within the various horizons of tuff should also be determined or inferred from back calculation exercises applicable to similar situations.*

***Recommendation 3***

*The hydrogeological features and hydraulic conductivity characteristics of the repository location should be adequately mapped in terms of degree of* *saturation of the intact tuff, its porosity, hydraulic conductivity of the joints as inferred from joint roughness characteristics, the near surface vs. at depth porosity, permeability, matrix hydraulic conductivity and joint hydraulic conductivity of the repository locations. The exact nature of the perched water regimes should be assessed in order to determine the extent of such features and to determine whether pathways can be established between the perched water and the repository by the activation of existing joints during both the construction of the repository and subsequent thermal loadings. Attempts should also be made to establish the changes in these initial conditions due to major water infiltration scenarios (e.g., long term hydrological data).*

***Recommendation 4***

*Computational modelling should be carried out to assess firstly the impact of the construction of the repository on the near field and far field response of the geological medium and the hydrogeological regime, particularly with respect to the behaviour of the joint response and the impact of such joint responses on the stability of the perched water regimes. These computational models can take into consideration purely mechanical effects or at most the coupling of the hydrological effects through flow in regions of the geological medium containing perched water. There are a number of well established 2D and 3D codes which can handle the H-M coupling effects by taking into consideration non-linear effects in the joint regions. The modelling should also have the capability to introduce the creation of new fractures or new discontinuities which could be initiated as a result of the stress relief. The computational modelling should take into consideration the effects of the in situ stress state within the various geological features. A fundamental deficiency in the computational modelling is expected to arise from lack of precise knowledge of the stress/deformation state of the joints and fissures immediately prior to the construction of the repository. The computational modelling should attempt to arrive at plausible bounds for the stress state by considering the mapped condition of the discontinuities in terms of their deterioration.*

The evaluation of the mechanical and hydraulic/hydrogeological state of the geological media prior to construction of the repository and immediately following the excavation of the repository is considered to be an essential prelude for the study of TMH couplings that may be induced subsequent to the emplacement of the waste which emits radiogenic heating.

The objectives of Recommendations 1 to 4 are to clearly identify the *in situ* conditions of the repository location and to establish whether these conditions could persist at the end of construction of the repository firstly in the absence of the radiogenic heating.

## 2.2 Experimental Research Program

The experimental modelling that is currently in progress at CNWRA involves, primarily, the isothermal study of rock joint behaviour in natural geological materials similar to the tuff that could be encountered in the Yucca Mountain site and the study of heating induced performance of geological and cementaceous materials with thermo-hydraulic characteristics similar to the cemented tuff. A further aspect of the program involves the small scale simulation of the jointed rock features with a view to examining the extent of earthquake induced rock joint movements. All experimental research programs appear to have received adequate support for development of novel experimental concepts which have intrinsic merit, although the reliability of small scale dynamic simulations of the jointed rock mass is open to question. However, in view of the very narrow time frame involved in preparations for the evaluation of the DOE documents and in view of the rather limited funding available for the overall research effort, the experimental research program has to have very specific goals in terms of addressing, at least in a ranked order of priority, problem areas identified as the key technical uncertainties. At this stage of the program it is not entirely clear whether the experimental research is geared to providing answers to fundamental TMH processes associated with both joint and intact materials consisting of all the horizons of geological media located at the Yucca Mountain site.

The work on the isothermal H-M behaviour of rock joints made on the Apache Leap tuff is a useful exercise in terms of identifying the natural condition of the geological formation both prior and subsequent to the construction of the repository galleries. The experimental configuration is a departure from the conventional schemes involving equi-areal upper and lower joint surfaces at the start of the experiment. Also, the mode of application of the normal and shear loads appear to be load-controlled, although the system can be adapted to perform under stroke control, thereby considering the possibility of stiffness control at the interface. A main objective of the experiment is to duplicate the kinds of relative motions that can be experienced by a rock joint during an earthquake. There are no scoping calculations that are available to narrow down the range of relative movements that can occur along joints for typical earthquakes that can occur in the repository region. It is likely that large differential displacements can occur along major fault zones and there are differences of opinion that relative displacements of similar magnitude are unlikely to occur along joints. The magnitude of typical joint movements needs to be assessed accurately in order that the results of shearing experiments can be made more relevant to the assessment of TMH processes in joints.

The small scale laboratory experimentation of the response of a jointed rock mass is useful from the point of view of obtaining qualitative measures of the performance of a complete discontinuum type jointed rock mass. The extrapolation of the results to prediction of prototype behaviour is beset with a number of uncertainties, particularly with regard to similitude of non-linear effects in joints and the process is complicated even more when dynamic loadings are encountered. The experimental configuration involving base shear of the laboratory model can only duplicate vertically propagating shear waves and the boundary constraints may not be truly representative of the mass of rock in a repository region and radiation damping effects associated with media of large extent. The experiments as they stand may be of limited use unless they are used to validate some computational modelling of <u>static</u> performances of a jointed rock mass. These experiments, however, have not yet focused on the influences of the temperatures which are of significance to the post emplacement scenarios. In terms of the rock joint behaviour, several questions have been posed which can be summarized by the following:

(1) Will the anticipated temperatures have an influence in altering the contact conditions at the rock joint, i.e. will the application of thermal loadings on already stressed samples of the joint cause further alterations in its hydraulic conductivity characteristics?

(2) Are such processes reversible, i.e. will the rock joint achieve its original state at the end of the radiogenic heating cycle? Are the strength and stiffness characteristics of the joint influenced by the thermal loadings?

(3) Will thermal loadings enhance the fluid transport characteristics within the intact tuff in the vicinity of the joint apertures?

(4) Can the thermal experiments be conducted on samples which are saturated to the *in situ* saturation conditions?

(5) Are stress and thermally activated creep phenomena at the joint contact surfaces an important issue?

(6) Can hydraulic conductivity of the joint be defined for two phase flow of water and vapour at the anticipated elevated temperature ranges?

Clearly, the critical experimental evaluation of many of these aspects will require a great deal of time and resources which apparently will not be available within the scope of the current research initiatives. It is also clear that the experimental research program over the past few years has devoted a great deal of resources to the development of experimental facilities associated with the shearing of rock joints and the study of thermal effects on tuff-like materials. The following recommendations are proposed with a view to utilizing existing experimental facilities more effectively in addressing input to the key technical uncertainties and to the identification of similar experimental configurations of benefit in any validation and verification exercise.

***Recommendation 5***

*The shearing device or a modified version thereof should be configured to examine the behaviour of the rock joints which are subjected to heating over a range of stress states at salient locations of the proposed repository where the effects of joints are expected to be of importance. The temperatures ranges should correspond to those anticipated as a result of the radiogenic heating. The research group should consider this recommendation rather carefully since the anticipated range of high temperatures testing could involve a complete modification of the experimental device. The experiments should attempt to examine the influence of thermal loads and associated mechanical effects which could introduce enhanced degradation of the joints and possible enhancement of the hydraulic conductivity of the joint through localized thermal damage at the contacting surfaces. Since experimental research involving behaviour of joints at elevated temperatures appears to be scarce, this avenue of enquiry may be an effective way of utilizing the shear device. The reservations concerning the unconventional nature of the shear test needs to be resolved in any future work associated with the joint testing (i.e. large joint movements which allow new contact regions to develop). When dealing with high temperature effects, some* *account has to be made for thermal deformations of the support on load and/or stroke control.*

***Recommendation 6***

*The research group should focus some attention on the development of simplified experimental processes which can model the processes associated with heat transfer, vaporization, vapour transport and condensation which are expected to be of critical interest to the moisture regime around a repository. The simplified configurations could involve large, partially saturated specimens of the tuff containing a single fracture and the experiment can be configured to examine both orientation of fractures and gravity effects. This aspect of the work can be restricted to only H-T processes and the effects of the mechanical interactions could be accommodated via aperture control of the joint. There should be an attempt to develop an experimental configuration which is amenable to modelling, through specification of the basic classes of processes that can be encountered in the Yucca Mountain Repository environment, i.e. coupled heat and moisture (vapour and water) transport in the matrix; vaporization and condensation induced two-phase transport in the fracture, either with or without gravity effects. Such an experimental configuration should be able to address certain key issues which are raised as technical uncertainties.*

## 2.3 Computational Modelling

The TMH processes that could be encountered at the Yucca Mountain Repository are highly complex and such complications arise from a number of specific features of the geologic setting and the anticipated thermal loadings associated with the radiogenic heating. The geological setting of the medium requires that the computational modelling should address modelling issues related to a rock matrix which in certain zones can be unsaturated and a rock mass which is heavily jointed with highly non-linear processes present in the joint system. The question of effects on the repository is also considered a key technical uncertainty, especially in the light of the activation of dormant joints or the creation of new fractures. The level of the thermal loading associated with the radiogenic heating will introduce heat transfer effects which can conceivably involve coupled heat and moisture movement in the rock matrix and two phase transport in the joints due to vaporization and condensation in the presence of gravity forces. To the reviewer's knowledge, there is no known computational code which can address all the issues associated with coupled TMH processes at elevated temperatures in both intact geological media and fractured geological media.

The CNWRA Report 92-011 (Manteufel et al., 1992) is a valuable document which summarizes the state of the art in research in the area and it compliments well the SAND 88-7145 (Updegraff, 1989), which documents the heat driven flow codes for unsaturated media. The codes such as TOUGH, PORFLOW, FEHMN, NORIA, PETROS, SAGUARO, etc., appear to focus on heat and mass transport (either single or two phase flow) and the effects of fractures and pores are interpreted through dual permeability models which are passive in their relationship to the thermal and hydrological couplings. These codes clearly do not consider non-linear processes in jointed media. The capabilities for dealing with temperature ranges where effects of vaporization dominate is an advantage of these codes. Other codes, such as FRAC-UNIX, ROCMAS, GENESYS, ABAQUS, FEHMS, UDEC, FRACON, etc., are capable of dealing with mainly saturated flow in fractures (which exhibit non-linear effects) and within the pore matrix of the intact rock, but fall short when dealing with two-phase flows that are present at elevated temperatures such as those associated with the Yucca Mountain Repository concept. Neither group of codes appear to have capabilities for the modelling of creation of new joints which could accompany the TMH processes.

Any computational modelling exercise that would be carried out by the CNWRA should exercise a certain degree of independence from codes that may originate from work sponsored by the DOE if objectivity is to be upheld and conflict of interests are to be avoided. Furthermore, within the framework of time and the resources allocated, it is certainly not feasible to consider the development of a code where complete coupling between TMH processes are achieved in both intact rock matrix and rock joints and fractures to accommodate the two phase flow effects associated with temperatures in excess of 250°C which could be encountered at the drift wall.

In the light of the above comments, the general approach currently adopted by the CNWRA group responsible for computational modelling appears to be a reasonable alternative. This involves the use of separate codes for the study of TMH processes in media with either isolated joints (ABAQUS) or ubiquitous joint systems (UDEC/3DEC). Both these codes are also capable of modelling influences of in situ stress state, the alteration of such stress states as a result of construction of a repository and the consideration of possible influences of seismic loadings. Both codes in the forms indicated in the documentation do not address the issue of two phase transport at temperatures in excess of 250°C. These codes will therefore be incapable of providing information related to the development of dryout regions, extent of condensation and saturation beyond the dryout zones, stability of the dryout front during decay of the radiogenic heating or major water infiltration from the surface, condensation plumes and their long term movements. The possible interactions between the lower water table and the moisture regime created by the dryout zone could be important from the point of view of radionuclide transport due to premature breach of a waste container .

***Recommendation 7***

*The computational modelling research group at CNWRA should continue with the exercises in computational modelling which involves both the UDEC and ABAQUS (or similar codes) in order to develop well documented examples of TMH behaviour involving intact and jointed rock types. The purpose of such an exercise would be primarily to test the validity of any alternative code that could be advocated by organizations such as DOE for evaluation of identical phenomena, through an inter-code comparison. In instances when the alternative code can be identified a priori (e.g. TOUGH, FEHMN, etc.) the calibrations should be done by recourse to the alternative code. When discrepancies occur the factors contributing to such discrepancies should be well documented. There should be a concerted effort to utilize the computational codes to predict the response of experiments that are in progress both at CNWRA and elsewhere.*

***Recommendation 8***

*The deficiencies with respect to the capabilities of the UDEC and ABAQUS codes in addressing TMH processes associated with temperature regimes in excess of 250°C should be rectified by considering separate exercises in TH modelling of partially saturated media with two phase transport processes in both the rock matrix and in the rock joints. The results concerning changes in the stress state in the vicinity of the repository due to thermal loading and associated alterations in the hydraulic conductivity characteristics of both* *the matrix and the joints could be deduced from results derived from studies involving both UDEC and ABAQUS codes. The extent of the dryout regime and the condensate movement should be established from this TH model which is weakly coupled to the mechanical effects. The TH model should also be used to conduct scoping calculations which should address the issue of the decay of the radiogenic heating and the anticipated long term configuration of the condensation plume.*

## 2.4 Engineering Issues

The main considerations of an engineering nature relate to the short term and long term stability of the vault with specific reference to the investigation of the effects of stress relief caused by the construction procedure, thermal loading and effects of earthquakes. In particular, the area of prime concern appears to be the possible consequences of long term strength deterioration of rock joints and the stability of the jointed rock especially in the vicinity of the opening. In many waste disposal concepts, an engineered barrier, such as an overpack or backfill is provided to minimize the detrimental influences of rock movements and rock falls on the waste container. Since, in the concepts that are being investigated there are no definite plans to include a backfill component to isolate the waste container from the detrimental effects of the highly jointed rock, the techniques adopted for ensuring stability of the excavated galleries need to be investigated. The reviewer is, however, of the opinion that the progress in tunnelling technology is such that the repository could be created with the minimum of disturbance and that currently available computational tools can be used effectively in examining the post construction state of the gallery. Such investigations could include consideration of rock anchoring techniques that can be adopted to enhance the stability of blocks which could be dislodged either during or after construction or during earthquakes.

***Recommendation 9***

*The computational modelling group should conduct simulations of the construction procedure to ascertain the short term or end of construction condition of the repository. This should take into consideration H-M processes associated with existing perched water domains, the in situ stress states, the non-linear effects in the jointed rock and effects of rock reinforcement. If the excavation is to be made by blasting techniques, this issue should be addressed* *via the dynamic computational modelling. The radiogenic heating should be imposed on the constructed repository to establish, through T-M modelling, the influence of additional time dependent movements associated with thermal loading. These studies should also attempt to include creep effects that can be activated in both the intact rock and rock joints due to the elevated temperatures. The objective of the computational exercise is to establish whether the devices used to provide support to the jointed rock mass in the exposed regions of the repository can continue to provide such support in the long term. Long term relative displacements of joints and their potential influences on additional loads imposed on rock support devices should be investigated. Such analyses should also include a study of earthquake induced movements of the jointed rock mass in the presence of thermal effects and their impact on the rock support system. The initiation of new laboratory experimental work to examine any of these effects is not strongly advocated.*

## 2.5 International Cooperation and Linkage

Participation of CNWRA in DECOVALEX is through the auspices of the NRC and this involvement constitutes the main international linkage which provides valuable input to the experimental and computational research groups at the CNWRA. Many of the scientists and engineers participate in the validation exercises and this involvement enhances their exposure to work conducted in other countries to address technical issues of interest to the various disposal concepts.

At present, the goals and objectives of DECOVALEX appear to be focused on topics such as TMH processes in engineered buffer materials and predictive TMH exercises involving flow in fractures conducted both on a laboratory scale and on a field scale. The disposal concepts that come under the purview of DECOVALEX are largely influenced by the deep rock disposal concepts currently being developed by countries such as Canada, Sweden, Japan and France. The reference temperatures associated with the disposal concepts put forward by these countries are substantially lower than the drift wall temperatures that are specified for the Yucca Mountain Repository concept. This does place a limitation on the direct relevance of DECOVALEX as a vehicle for investigating problems of immediate importance to the proposed Yucca Mountain Repository scheme.

***Recommendation 10***

*The NRC and the CNWRA should maintain its involvement in activities of DECOVALEX and its subsequent developments primarily for the purposes of keeping up to date with developments in other countries with respect to concepts, methodologies and research programs being considered for the deep geological disposal of heat emitting, high level nuclear fuel waste. If the participation in DECOVALEX is on the basis of a funding partner, the management of DECOVALEX should be encouraged to address, in at least a limited sense, the validation concepts that are applicable to unique situations such as the Yucca Mountain Waste Repository concept. Such attention should mainly focus on the TMH modelling applicable to the range of temperatures that are envisaged in the Yucca Mountain Waste Repository.*

## 3. CONCLUSIONS

The involvement of the CNWRA in addressing technical issues of TMH processes of importance to the Yucca Mountain Repository project is relatively new. Within this two and a half year involvement, the scientists and engineers at CNWRA have done a highly commendable job of becoming familiar with the overall importance of TMH processes to the proper engineering evaluation of the condition of a waste repository. There has been a concerted effort to develop a balanced research program which emphasizes both computational modelling and laboratory modelling which is geared to small scale testing of jointed rock structures. There are also initiatives to develop certain *in situ* heater experiments in geological settings approaching that of the *in situ* conditions at the Yucca Mountain Repository location The developments to date have primarily focused on the experimental modelling and computational modelling of TMH processes which are present at temperatures substantially lower than the temperatures that are prescribed for the Yucca Mountain Repository concept. This could be viewed either as a deficiency or an advantage of the research effort. The deficiency stems from the lack of consideration of realistic temperatures and the resulting TMH processes of direct importance to the Yucca Mountain Repository concept. The advantage of the effort is in the focus on a manageable scope of research activity which has intrinsic merit and allows the researchers to gain confidence in their abilities to undertake further work. The limitations of time and resources would imply that if the issues related to TMH processes of interest to the Yucca Mountain Repository concept are to be examined critically, the computational and experimental research program should now be refocussed to examine the issues of major importance to the current concept of the repository. The review advocates certain research directions where the temperature ranges are to reflect the critical range of values that will be encountered in the Yucca Mountain Repository. The objective of these recommendations is also to present CNWRA with guidance as to the topics that should be addressed and solved by DOE if any complete review of a license application by DOE is to be approved. It is hoped that the research group at CNWRA will be given the opportunity and resources to address, at least, some of these issues. The group has the background, interest and leadership to achieve some degree of success in addressing difficult technical issues related to TMH processes of special relevance to the current proposals for the Yucca Mountain Repository concept.