Dr. B. John Garrick, Chairman
Advisory Committee on Nuclear Waste
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

SUBJECT: COMMENTS ON THE U.S. DEPARTMENT OF ENERGY'S LICENSE APPLICATION DESIGN SELECTION PROCESS AND RECOMMENDED REPOSITORY DESIGN

Dear Dr. Garrick:

I am responding to your August 9, 1999, letter to Chairman Dicus conveying your observations and recommendations on the U.S. Department of Energy's (DOE's) License Application Design Selection (LADS) process, and the Management and Operating Contractor's recommended repository design for the site recommendation and license application. I would like to thank you for sharing your observations on the LADS process, and for providing the recommendations in Dr. Fairhurst's white paper, "Engineered Barriers at Yucca Mountain - Some Impressions and Suggestions," presenting an innovative design concept for the repository and suggestions on geotechnical aspects of the design.

Our responses to the Advisory Committee on Nuclear Waste's (ACNW's) observations and recommendations are enclosed. As discussed in this enclosure, the Commission has layed out the regulatory responsibilities of the U.S. Nuclear Regulatory Commission (NRC). One important aspect of the Commission's regulatory philosophy is that the NRC does not become involved in the selection of sites or the development of designs. Consistent with this Commission position, the staff did not review the white paper in detail. Instead, consistent with the independent regulatory role of the NRC, the staff will evaluate the design proposed by the DOE as part of its license application.

Because the DOE is currently in the process of considering what design it will ultimately select for the repository, the ACNW may want to consider providing the white paper directly to DOE. I trust this letter responds to your concerns.

Sincerely,

William D. Travers
Executive Director
for Operations

WM-11

Enclosure: As stated
cc: Chairman Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield
SECY

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

September 30, 1999

Dr. B. John Garrick, Chairman
Advisory Committee on Nuclear Waste
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

SUBJECT: COMMENTS ON THE U.S. DEPARTMENT OF ENERGY'S LICENSE APPLICATION DESIGN SELECTION PROCESS AND RECOMMENDED REPOSITORY DESIGN

Dear Dr. Garrick:

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Our responses to the Advisory Committee on Nuclear Waste's (ACNW's) observations and recommendations are presented in Enclosure 1. As discussed in Enclosure 1, the Commission has set forth the regulatory responsibilities of the U.S. Nuclear Regulatory Commission (NRC) with respect to the consideration of alternative sites or designs (see Enclosure 2). Consistent with this Commission position, the staff did not review the white paper in detail. Instead, consistent with the NRC's independent regulatory role, the staff proposes to evaluate the design the DOE will propose as part of its license application.

Because the DOE is currently considering what design it will ultimately select for the repository, the ACNW may want to consider providing the white paper directly to the DOE. I trust this letter responds to your concerns.

Sincerely,

Frank J. Miraglia for
William D. Travers
Executive Director
for Operations

Enclosures:
1. NRC Staff Response to ACNW Observations and Recommendations
2. Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions and Related Conforming Amendments 49 FR 9352, March 12, 1984

cc: Chairman Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield
Office of the Secretary

U.S. NUCLEAR REGULATORY COMMISSION STAFF RESPONSE TO THE ADVISORY COMMITTEE ON NUCLEAR WASTE OBSERVATIONS AND RECOMMENDATIONS

Observation 1: The License Application Design Selection (LADS) process is not transparent enough to support selection of the EDA-II design.

Response: The U.S. Nuclear Regulatory Commission (NRC) staff agrees that the basis for the Management and Operating Contractor's (M&O's) recommendation of the EDA-II design is not totally transparent. We are aware that the M&O recommended the EDA-II design for the site recommendation (SR) and license application (LA), and that the U.S. Department of Energy (DOE) has not yet made a decision on accepting the M&O's recommended design. The NRC staff has attended the DOE's briefings on the LADS, and is aware of the Advisory Committee on Nuclear Waste's (ACNW's) and the Nuclear Waste Technical Review Board's (NWTRB's) concerns about the process used in selecting the recommended design (EDA-II) among the five alternate designs considered in the LADS. Because the DOE has not yet accepted the M&O's recommendation, it is possible that the DOE may address the NWTRB's and the ACNW's concerns in the LADS report that will be submitted to the NRC. We will know that when the DOE determines how it will address the M&O's recommendation, and submits a design to the NRC as part of the SR or in the LA.

Independent of the DOE's efforts on the design, the staff is currently developing the Yucca Mountain Review Plan (YMRP). In the YMRP, the staff will include criteria it will use to determine if DOE has acceptably demonstrated compliance with the applicable regulatory requirements. The development of the YMRP will be essential in allowing the staff to conduct an efficient and sound review of any design that the DOE ultimately selects. Thus, regardless of what process the DOE undergoes today to select a design, the staff, by having the YMRP ready, will be in a position to judge the acceptability of that design.

Recommendation 1A: The NRC should expect the repository design to change until the LA and, if needed, in the Preclosure period. The NRC should develop a license review strategy that allows the DOE maximum flexibility to implement beneficial design changes during the preclosure period.

Response: The staff clearly recognizes that the repository design may evolve until the LA. As part of the pre-licensing consultation process, the NRC reviews and comments on design documents that the DOE submits. However, as noted above, independent of any DOE activities, the staff is developing the YMRP which will contain the guidance staff will use to determine the acceptability of the DOE design. Because of this guidance, the DOE will have available to it a level of information the Department can use for a final design as the repository evolves. This process of having the YMRP available allows the staff to conduct pre-licensing consultation with the DOE with a focus on what ultimately will be acceptable in a final LA design for the repository. Thus, the NRC staff's initiative of developing the YMRP today for use in both pre-licensing consultation, and during the LA review, will provide the flexibility the ACNW recommends. The YMRP could be changed by the staff as it also gains experience from DOE repository operations.

During the pre-closure phase of the repository, the staff fully expects that the DOE will propose design changes as it gains operational experience. This is not inconsistent with what happens at all types of facilities that the NRC regulates such as reactors and fuel-cycle facilities. The process requires the licensee for the facility to determine whether it needs to file an application for an amendment to its license in order to make the change. As part of the amendment process, the staff would evaluate the proposed design change, and if the change were found acceptable, modify the license accordingly.

Recommendation 1B: The NRC should not constrain the DOE from proposing revisions to the approved design during the pre-closure period of the repository, and the NRC should conduct independent evaluations of alternate, cost-effective, and innovative designs.

Response: The NRC staff agrees with the first part of the recommendation that it should not constrain the DOE from proposing revisions to any repository design found acceptable. As discussed in the response to Recommendation 1A, there is a process in place that allows the DOE to propose changes to the repository during pre-closure activities, both construction and operation. If the DOE finds that repository-horizon conditions or operational experience justify changes, the Department has the flexibility to propose such changes. For those changes requiring an NRC review, the NRC staff will evaluate the merits of the changes, and determine if they are acceptable. The options available to the staff in conducting such reviews, or for the entire LA, are discussed later.

It is important to note, however, that the NRC will not advocate nor work with the DOE to develop any design changes. Rather, as reflected in the "Statement of Considerations" (SOC) for revisions for 10 CFR Part 51, the Commission has stated that as an independent regulatory agency, the NRC does not select designs nor participate with an applicant in selecting proposed designs. Relevant portions of the SOC are provided in an Appendix for the convenience of the Advisory Committee on Nuclear Waste (ACNW). Consistent with this Commission policy, the staff would not recommend any design changes that the DOE could make. Rather, the staff would review those design changes proposed by the DOE to determine if they meet the applicable regulatory requirements.

The options available to the NRC in conducting reviews of the DOE LA or any proposed changes once the site is licensed are to either: (1) accept the proposal; (2) accept the proposal with conditions; or (3) deny the proposal. These options were identified by the Commission in the SOC for the Part 51 revisions. Given this Commission direction, the NRC staff cannot develop any independent design or propose any solutions to applicants/licensees as that would compromise the Agency's ability to perform its independent regulatory mission. To this end, the NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA) staffs are developing the review capabilities in the YMRP needed to independently evaluate the DOE application. However, the NRC staff, working within the framework established by the Commission for all NRC, cannot conduct independent evaluations of alternative, cost-effective, and innovative designs for the repository. It is the DOE's responsibility to propose a design in the LA. The NRC can only evaluate the proposal made by the DOE, and determine if it complies with the applicable regulations, and adequately protects public health and safety.

Observation 2: The preclosure period is likely to be 50 to 300 years, and it presents an opportunity to establish the validity of the design assumptions via performance confirmation (PC) monitoring. In the design option suggested in the white paper, it is suggested that the PC monitoring drifts may be used for diverting infiltration in the post-closure phase.

Response: The NRC staff is aware of the possibility that the preclosure period may extend 50 to 300 years, and agrees that it presents an opportunity to collect data to confirm the design assumptions made by the DOE in the LA. The PC monitoring during preclosure was seen as an important way for verifying design parameters and design assumptions, and for comparing the monitored performance with the assessed performance of the design. The current regulations as well as those in the proposed 10 CFR Part 63 include requirements for a PC program. This requirement was intended to ensure that the data available from the operating repository would be collected, and used to confirm the LA design. In the YMRP, the staff is developing criteria to review a DOE license application which will include the DOE's PC program. These criteria will allow the NRC staff to determine if the DOE's PC monitoring will obtain the data needed to verify the design assumptions, and thus comply with the applicable regulations.

With respect to the second part of the recommendation, the NRC is not in a position to propose the design concepts recommended in the white paper; namely that the design option suggested in the white paper would use PC monitoring drifts for diverting infiltration in the post-closure phase. As noted in the response to Recommendation 1B, the Commission's view of the NRC's role is that of an independent regulatory Agency that is not involved in the selection or development of designs. Rather, if the DOE LA design or subsequent design change contained a design incorporating the white paper recommendation, the NRC staff would evaluate that design, to determine its acceptability, using the YMRP.

Recommendation 2: The ACNW endorses the U.S. Geological Survey's (USGS's) view that monitoring program details should be carefully developed, and suggests that the NRC staff consider how long-term monitoring may be factored into the design.

Response: The NRC staff agrees with the USGS views on PC monitoring. As mentioned above, the NRC staff is currently developing a review plan for reviewing the LA, including the PC program. In developing the review plan for the DOE's PC program, the staff will consider the USGS's views and will prepare a plan that ensures an adequate review of DOE's PC program. The NRC will also enforce any PC commitments that are in the license as individual conditions.

Observation 3: Reiterate the NWTRB's comments on the DOE's LADS process.

Response: The NRC staff is aware of, and agrees with, the NWTRB's and the ACNW's concerns about the lack of quantitative evaluation of the several alternate designs considered in the LADS process. The NRC staff will review the LADS report when the DOE submits it to NRC. In conducting its review of the LADS report, the staff will use to the extent practical, those portions of the YMRP that are avaiable.

Recommendation 3: Encourage the NRC to make sure that the rationale, approach, and assumptions used in the evaluations and in comparisons of alternatives are appropriate. It recommends that the NRC and the CNWRA conduct their own independent evaluations of alternative, cost-effective designs similar to the innovative design described in the white paper.

Response: The staff will consider the ACNW's concerns during review of the LADS report as well as other DOE design documents up to and including the LA. The development of the YMRP is an essential component in establishing the criteria the NRC staff will use to judge the acceptability of the DOE's analysis of alternatives. With respect to the NRC and the CNWRA staff conducting independent evaluations of alternative designs, the Commission has stated that the NRC, as an independent regulatory Agency, does not become involved in the selection or development of designs. As such, the NRC staff's role would be to evaluate whether the DOE has proposed an acceptable design. However, the NRC does not undertake the development nor evaluation of innovative, cost-effective designs similar to the one presented in the white paper.

be considered in operating license proceedings for nuclear power plants, and need not be addressed by operating license applicants in environmental reports submitted to the NRC nor by the staff in environmental impact statements (EIS's), at the operating license stage. An exception to or waiver of the rule will be permitted in particular cases if special circumstances are shown in accordance with 10 CFR 2.758 of the Commission's regulations, "Consideration of Commission rules and regulations in adjudicatory proceedings." The rule will be applied to ongoing licensing proceedings then pending on its effective date and to issues or contentions therein.

Pursuant to the Atomic Energy Act of 1954, as amended, the National Environmental Policy Act, of 1969, as amended, the Energy Reorganization Act of 1974, as amended, and section 553 of Title 5 of the United States Code, notice is hereby given of the adoption of the following amendments to 10 CFR Part 51.

47 FR 57446
Published 12/27/82
Effective dates:
10 CFR 20.311 of Part 20 effective date is 12/27/83; 10 CFR Part 61 and all other changes effective 1/26/83.

Licensing Requirements for Land Disposal of Radioactive Waste

See Part 61 Statements of Consideration

49 FR 9352
Published 3/12/84
Effective: Upon approval of the information collection requirements by the OMB or 6/7/84.

10 CFR Parts 2, 30, 40, 50, 51, 61, 70, 72, and 110

Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions and Related Conforming Amendments

AGENCY: Nuclear Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Nuclear Regulatory Commission is revising Part 51 of its regulations to implement section 102(2) of the National Environmental Policy Act of 1969, as amended (NEPA) in a manner which is consistent with the NRC's domestic licensing and related regulatory authority. Related conforming amendments are being made to Parts 2, 30, 40, 50, 61, 70, and 110. This rule reflects the Commission's policy to develop regulations to take account of the regulations of the Council on Environmental Quality (CEQ) implementing the procedural provisions of NEPA voluntarily, subject to certain conditions.

EFFECTIVE DATE: Upon approval of the information collection requirements by the Office of Management and Budget or June 7, 1984, whichever is later. NRC will announce the date of approval of information collection requirements by OMB in a future document.

FOR FURTHER INFORMATION CONTACT: Jane R. Mapes, Senior Regulations Attorney, Regulations Division, Office of the Executive Legal Director, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Telephone: (301) 492-8695.

SUPPLEMENTARY INFORMATION: On March 3, 1980, the Nuclear Regulatory Commission published in the Federal Register (45 FR 13739-13766) a proposed revision of 10 CFR Part 51 and related conforming amendments to 10 CFR Parts 2, 30, 40, 50, 61, 70, and 110 of its regulations. Interested persons were invited to submit written comments and suggestions on the proposed amendments during the sixty day comment period which expired May 2, 1980. Comments were also solicited on several provisions of the CEQ regulations which the Commission had identified as requiring further study before implementing regulations could be prepared.

In addition to the preliminary views of the Council on Environmental Quality as set out in CEQ's letters of September 26, 1979 and October 29, 1979 which were published in Appendix B to the proposed rule, the Commission received twenty-one letters of comment, expressing the views of interested Federal agencies, state and local governments, industry, including electric utilities, vendors and architect-engineers, professional organizations and individual members of the public. The letters contained more than 100 individual comments and in some instances represented the views of several commenters. Comments were also received from interested members of the NRC staff.

As requested in the Commission's notice of proposed rulemaking, several commenters expressed views on the following sections of the CEQ regulations: 40 CFR 1502.14(b), 1502.22 (a) and (b) and 1508.18. A brief description of each of these provisions, accompanied by a summary of the relevant comments and a statement of the Commission's present views on the issues raised, is set out below. The views of the commenters are fully set out in the individual letters of comment and in a subject matter compendium which has been placed with the letters in the Commission's Public Document Room at 1717 H Street, N.W., Washington, D.C. where they are available for inspection and copying. Since the topics addressed by §§ 1502.14(b) and 1502.22(a) of CEQ's regulations are interrelated, these sections will be discussed together.

By way of preface, the Commission restates its view that, as a matter of law, the NRC as an independent regulatory agency can be bound by CEQ's NEPA regulations only insofar as those regulations are procedural or ministerial in nature. NRC is not bound by those portions of CEQ's NEPA regulations which have a substantive impact on the way in which the Commission performs its regulatory functions.

Consideration of Alternatives

1. *40 CFR 1502.14(b).* This section provides that the environmental impact statement "[d]evote substantial treatment to each alternative considered in detail including the proposed action so that reviewers may evaluate their comparative merits."

In addition to the Council on Environmental Quality, eleven commenters responded to the Commission's request for views on this provision of the CEQ regulations. Of these eleven commenters, four provided brief statements expressing general support for 40 CFR 1502.14(b). Seven commenters voiced the opinion that § 1502.14(b) does not accurately reflect the statutory mandate of NEPA with respect to the consideration of alternatives. Relying on judicial decisions handed down since the enactment of NEPA, these commenters stated that consideration of alternatives in an environmental impact statement is subject to a rule of reason, that neither the number of alternatives considered nor the amount of information furnished concerning each alternative need be exhaustive. According to the commenters, consideration need only be given to *reasonable alternatives* to the proposed federal action; the detail and amount of information furnished concerning the environmental consequences of each of those alternatives, including the proposed action, need only be sufficient to permit the decisionmaking agency to make a reasoned choice among those alternatives so far as environmental consequences are concerned. The commenters noted that the courts have recognized that Federal agencies have a responsibility to reach meaningful decisions respecting environmental consequences if the objectives of NEPA are to be achieved. The commenters pointed out, however, that although the courts have taken a close look at the adequacy of the information on which those decisions are based, the courts have not required agencies, under the rule of reason, to supply or obtain more detailed information when the information needed for a meaningful decision is adequate.

2. *40 CFR 1502.22(a)*. This section provides that "[i]f the information relevant to adverse impacts is essential to a reasoned choice among alternatives and is not known and the overall costs of obtaining it are not exorbitant, the agency shall include the information in the environmental impact statement."

Seven commenters, including the Council on Environmental Quality, submitted views on 40 CFR 1502.22(a). Two commenters expressed general agreement with the CEQ position that the standard set forth in 40 CFR 1502.22(a) merely restates existing NEPA law, is subject to a rule of reason, and therefore should be adopted by the Commission. One of these commenters also expressed concern that failure to obtain the requisite information as mandated by 40 CFR 1502.22(a) would preclude the Commission from carrying out its NEPA responsibilities to make a rigorous comparison of the proposed action with available alternatives.

Several commenters expressed the view that the standard imposed by 40 CFR 1502.22(a) should not be automatically applied in every case because it would place "a burden on the NRC in preparing an EIS that is not required by NEPA." These commenters noted that "NEPA cannot be read as a requirement that complete information concerning the environmental impact of a project must be obtained before action may be taken," and that this CEQ provision could have the practical effect of "requir[ing] that the EIS not be used as a decision-making document, *i.e.*, does not satisfy the mandate of NEPA, until all 'relevant' information is available so long as the costs of obtaining such information are not 'exhorbitant'."

One commenter emphasized the importance of care and restraint in determining when costly information is essential to a reasoned choice among alternatives. The commenter suggested that requests for data involving large costs should "be justified on the basis that the magnitude of the benefits to be derived from the information clearly exceed the costs associated with obtaining and analyzing this information * * *" and that requirements for data involving large costs "should be limited to matters that speak to the basic license ability [*sic* licensability] of the perferred site/plant combination."

Several commenters stated that NEPA does not require that all relevant information regarding the adverse impact of alternatives, including information which is not readily available because it is expensive or otherwise difficult to obtain, be known before a decision is reached. According to these commenters, NEPA merely requires that the decisionmaker be informed of any uncertain or unknown environmental effects. In each case, responsibility for evaluating the sufficiency of the information rests with the decisionmaker who must determine first, whether it is possible to make a reasoned decision on the basis of the information provided, and second, whether in the absence of adequate information, more information should be obtained or a decision should be made not to proceed with the proposed action. In the opinion of the commenters, strict application of the standard in 40 CFR 1502.22(a) would not only eliminate this element of flexibility in agency decisionmaking, it would also lengthen the time needed to complete NRC environmental reviews. The commenters expressed the view that application of the rule is unlikely to result in better decisionmaking and could have a severe and detrimental effect on the ability of the NRC, as an independent regulatory agency, to carry out its substantive licensing and related regulatory functions in a responsible and objective manner.

The primary mission of the Nuclear Regulatory Commission is to regulate civilian nuclear energy activities to ensure that they are conducted in a manner which will protect the public from the standpoint of radiological health and safety, maintain national security, comply with the antitrust laws and, since the passage of the National Environmental Policy Act of 1969, protect the environment. Charged with carrying out the licensing and related regulatory functions of the former Atomic Energy Commission,[1] the NRC has no authority to encourage and promote the development of atomic energy for peaceful purposes. Nor does it bear any responsibility for the development or regulation of other energy sources.

Within this framework, the possible actions which the Commission itself may take are limited. Their scope is determined in the first instance by the nature of the application or petition presented to the Commission for action. So far as Commission action is concerned, the available alternatives are to grant the application, grant the application subject to certain conditions, or deny the application, either with or without prejudice. Although the Commission has an obligation to determine the accuracy and relevance of the safety-related and environmental information presented and to perform the requisite safety and environmental analyses, the Commission has no power to compel an applicant to come forward or to require an applicant, once having come forward, to prepare and submit a totally different proposal, for example to construct and build a different type of nuclear power reactor pursuant to detailed specifications furnished by the Commission on a site identified by the Commission but not chosen by the applicant. As an independent regulatory agency, the NRC does not select sites or designs or participate with the applicant in selecting proposed sites or designs.

In preparing this revision of 10 CFR Part 51 in final form, the Commission has reviewed its regulatory experience under NEPA, both from the standpoint of the kinds of alternatives which are considered in making evironmentally sound regulatory decisions and the kinds and amounts of information needed to evaluate the comparative merits of those alternatives. In the usual case, these alternatives include the alternative of no action (denial of the application) and reasonable alternatives outside the jurisdiction of the NRC.

The types of alternative actions which the Commission itself is able to take reflect the Commission's functional role—the role of an independent regulatory agency authorized to perform quasi-judicial and quasi-legislative functions. The decisions which the Commission is required to make in carrying out its responsibilities as an independent regulatory agency play an equally important role in determining whether, from the standpoint of NEPA, all reasonable alternatives have received substantial treatment and whether the information submitted with respect to each alternative is sufficiently detailed. In developing these regulations, the Commission has tried to ensure that, at the respective points of decision, sufficient information will be available for meaningful consideration and comparison of a reasonable spectrum of alternatives, leading, in turn, to a reasoned decision. The Commission believes that the provisions of subpart A of Part 51 are consistent with the standard in 40 CFR 1502.14(b), that alternatives selected for detailed consideration be accorded substantial treatment. The Commission is also of the opinion that the way in which the NRC conducts its evironmental reviews implements this standard in a responsible and meaningful manner. This includes the practice of handling generic matters (for example, those

[1] The Atomic Energy Act of 1954, as amended, Pub. L. 83–703, as amended, 42 U.S.C. 2011 et seq.; the Energy Reorganization Act of 1974, as amended, Pub. L. 93–438, as amended, 88 Stat. 1233–1254, see especially 42 U.S.C. 5841 et seq.

which are common to all power reactor licensing proceedings and which may relate to environmental as well as safety issues) in generic rulemaking proceedings and generic environmental impact statements. Generic environmental issues which have received this kind of analysis and review need not be accorded the same kind of detailed consideration as that given to issues arising solely in the context of a specific licensing proceeding.

The Commission intends to follow the standard in 40 CFR 1502.22(a), though it notes that implementation of § 1502.22(a) may present substantive issues, specifically whether information which is not known is (a) relevant to adverse impacts, (b) essential to a reasoned choice among alternatives, and (c) obtainable at a cost which is not exorbitant. Based upon its past experience, the Commission believes that it will seldom, if ever, be called upon to determine whether the cost of obtaining unknown information deemed relevant to adverse impacts and essential to a reasoned choice among alternatives is or is not exorbitant. In the unlikely event that the issue is presented, the Commission reserves the right to resolve the matter in a manner which is consistent with the Commission's reponsibilities as an independent regulatory agency.

As illustrated in the following description of the manner in which NRC considers alternatives in connection with its environmental review of license applications for nuclear power plants, the amount of detailed information needed to make a reasoned decision on each of the many issues presented varies substantially among issues but is in each case commensurate with the nature of the issue addressed. With respect to most issues, with the possible exception of those relating to radiological matters, information need not be presented in the same degree of detail as that furnished in support of the applicant's proposal. In the review of alternative sites, for example, the Commission has found that reconnaissance-level information is adequate to assure that these alternatives are accorded substantial treatment.

Consideration of Alternatives in NRC Environmental Review and Analysis of License Applications for Nuclear Power Plants

In the customary NRC environmental review, detailed descriptions are prepared of the proposed plant, of the site on which the plant is proposed to be located, of the need for the plant, and of the environmental impacts likely to result from construction of the plant and from station operation. The following alternatives to the project are then addressed:

1. *Alternative energy sources and systems*, including alternatives which do not require new generating capacity and alternatives which do require new generating capacity. The former include such alternatives as power purchases, reactivation of retired plants, extension of the service life of existing plants and conservation measures. The latter include other alternative energy sources uniquely available to the applicant. In each case, consideration is given to the following types of energy sources: solar and wind, geothermal, petroleum liquids, natural gas, hydrodynamic, advanced nuclear, municipal solid wastes, biomass and coal. After the available alternative energy sources have been identified, they are categorized as competitive or non-competitive.

The amount and type of information needed to make a determination that a particular energy source is not available, or that a particular energy source, although available, is not competitive, is less extensive than that required to evaluate the comparative advantages and disadvantages from the standpoint of the environment between the proposed plant which is the subject of the license application and an alternative energy source which is both available and competitive. Once it is readily apparent that an alternative is non-competitive, either because of its technological status or lack of availability, the only data and information required with respect to that alternative is that needed to explain why the alternative is no longer being considered. Similarly, it is possible to reach a meaningful decision on the issues presented at subsequent levels of review (for example, classification of alternatives as environmentally preferable, environmentally equivalent, or environmentally inferior to the applicant's proposed plant, and comparison of the applicant's proposed plant with environmentally preferable or environmentally equivalent alternatives) without insisting that the amount and type of information presented respecting the alternative energy source be as extensive and detailed as that provided concerning the facility sought to be licensed.

2. *Alternative sites*. The Commission uses a two-stage decision standard to assure that adequate consideration has been given to alternative locations for constructing power generation facilities to meet the demonstrated need. The first part of this standard requires that the applicant submit a slate of alternative sites which are "among the best that could reasonably be found" inside a region in which it is reasonable to construct a plant to meet the projected need for power. The second part of the standard requires that the proposed site be approved only if no obviously superior alternative site has been identified.

The reason for considering alternative sites is that many environmental impacts can be avoided or significantly reduced through proper selection of the location for a new generating facility. These significant impacts which can be avoided or reduced are also readily detected at the planning stage of a power plant. For this reason alternative site reviews are encouraged as early as possible in the process of licensing a power plant and the use of reconnaissance-level information for making the comparative analyses is urged. The use of reconnaissance-level information to identify potentially significant environmental impacts has been extensively used and while it may not be possible to optimize design or make detailed impact predictions based on such information it is still sufficient to make decisions at the pre-design stage to determine which site should be chosen. It is highly unlikely that detailed examination of the site selected would reveal a significant environmental impact that had escaped the reconnaissance-level investigations. Based on its past experience, the Commission has found reconnaissance-level information adequate for informed environmental decisionmaking on alternative sites.

3. *Alternative plant systems*. These systems include alternative heat dissipation systems, alternative circulating water systems and alternative non-radioactive waste-treatment systems.

Several levels of review, each requiring differing amounts and types of information, are used in evaluating alternatives to the heat dissipation systems and circulating water systems of the proposed plant. An initial screening is performed to eliminate alternative systems or system components which are obviously unsuitable for use at the proposed site, or are obviously incompatible with the types of systems expected to be used in the proposed plant. The remaining alternatives are screened again for the purpose of identifying those which are environmentally preferable, environmentally equivalent or environmentally inferior to the systems which the applicant is proposing to use in the proposed plant. The baseline systems against which the alternative systems are compared are those proposed by the applicant with any verified mitigation schemes to limit adverse impacts. The information needed to make this determination varies among alternatives and from case to case according to the type and

Because the DOE is currently considering what design it will ultimately select for the repository, the ACNW may want to consider providing the white paper directly to the DOE. I trust this letter responds to your concerns.

Sincerely,

Original signed by
Frank J. Miraglia

William D. Travers
Executive Director
for Operations

Enclosures:
1. NRC Staff Response to ACNW Observations and Recommendations
2. Environmental Protection Regulations for Domestic Licensing and Related Regulatory Functions and Related Conforming Amendments 49 FR 9352, March 12, 1984

cc: Chairman Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield
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Dr. B. John Garrick, Chairman
Advisory Committee on Nuclear Waste
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

SUBJECT: COMMENTS ON THE U.S. DEPARTMENT OF ENERGY'S LICENSE APPLICATION DESIGN SELECTION PROCESS AND RECOMMENDED REPOSITORY DESIGN

Dear Dr. Garrick:

I am responding to your August 9, 1999, letter to Chairman Dicus conveying your observations and recommendations on the U.S. Department of Energy's (DOE's) License Application Design Selection (LADS) process, and the Management and Operating Contractor's recommended repository design for the site recommendation and license application. I would like to thank you for sharing your observations on the LADS process, and for providing the recommendations in Dr. Fairhurst's white paper, "Engineered Barriers at Yucca Mountain - Some Impressions and Suggestions," presenting an innovative design concept for the repository and suggestions on geotechnical aspects of the design.

Our responses to the Advisory Committee on the Nuclear Waste's (ACNW's) observations and recommendations are enclosed. As discussed in this enclosure, the Commission has set forth the regulatory responsibilities of the U.S. Nuclear Regulatory Commission (NRC) with respect to the consideration of alternative sites or designs. Consistent with this Commission position, the staff did not review the white paper in detail. Instead, consistent with the NRC's independent regulatory role, the staff proposes to evaluate the design the DOE will propose as part of its license application.

Because the DOE is currently considering what design it will ultimately select for the repository, the ACNW may want to consider providing the white paper directly to the DOE. I trust this letter responds to your concerns.

Sincerely,

William D. Travers
Executive Director
for Operations

Enclosure: As stated
cc: Chairman Dicus
Commissioner Diaz
Commissioner McGaffigan
Commissioner Merrifield
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Dr. B. John Garrick, Chairman
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Our responses to the Advisory Committee on the Nuclear Waste's (ACNW's) observations and recommendations are enclosed. As discussed in this enclosure, the Commission has set forth the regulatory responsibilities of the U.S. Nuclear Regulatory Commission (NRC) with respect to the consideration of alternative sites or designs. One important aspect of the Commission's regulatory philosophy is that the NRC does not become involved in the selection of sites or the development of designs. Consistent with this Commission position, the staff did not review the white paper in detail. Instead, consistent with the NRC's independent regulatory role, the staff will evaluate the design the DOE proposed as part of its license application.

Because the DOE is currently considering what design it will ultimately select for the repository, the ACNW may want to consider providing the white paper directly to the DOE. I trust this letter responds to your concerns.

Sincerely,

William D. Travers
Executive Director
for Operations

Enclosure: As stated
cc: Chairman Dicus
Commissioner Diaz
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Chairman Dicus

FOR SIGNATURE OF : ** GRN ** CRC NO: 99-0730

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cc: Greeves
Holonich
Santiago

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AFFILIATION: ADVISORY COMMITTEE ON NUCLEAR WASTE

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON NUCLEAR WASTE
WASHINGTON, D.C. 20555-0001

August 9, 1999

The Honorable Greta Joy Dicus
Chairman
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

Dear Chairman Dicus:

SUBJECT: COMMENTS ON DOE'S LICENSE APPLICATION DESIGN SELECTION PROCESS (LADS) AND RECOMMENDED REPOSITORY DESIGN

This letter conveys our observations and recommendations regarding the Department of Energy's (DOE's) License Application Design Selection (LADS) process and the Management and Operations Contractor (M&Os) recommended repository design for the site recommendation (SR) and license application (LA). The letter also transmits the attached "white paper" by Charles Fairhurst titled, "Engineered Barriers at Yucca Mountain -- Some Impressions and Suggestions." In his white paper, Dr. Fairhurst examines some geotechnical aspects of the repository design in the setting of Yucca Mountain with particular attention to two issues - (i) reduction of water inflow to the waste emplacement drifts and (ii) pre- and post-closure stability of the drifts. A concept of an innovative repository design not presently being considered by the DOE is described, together with some impressions of the currently favored repository design. We hope that the paper will help the NRC as it prepares to conduct a thorough and critical safety review of the final repository design and the projected overall performance of the Yucca Mountain high level waste (HLW) disposal facility.

The observations and recommendations we make here are based on briefings we heard on July 20, 1999 on DOE's license application design selection, during the 111th ACNW meeting in Rockville, Maryland. The basis for the attached white paper is derived from a variety of sources, including the DOE's viability assessment, and interactions with the NRC and DOE staffs, the Center for Nuclear Waste Regulatory Analyses (CNWRA), the M&O, the ACNW, and others.

White Paper on Engineered Barriers at Yucca Mountain

In the attached paper, Dr. Fairhurst examines a repository shield concept that appears to have the potential to greatly reduce water infiltration into repository drifts. The shield acts like an umbrella above the repository to divert water around drifts by taking advantage of the vertical fractures and predominantly vertical flow system in the vicinity of the repository horizon. The shield system may also help reduce near-field flow uncertainties in designs such as the Enhanced Design Alternative-II (EDA-II) currently recommended by the M&O to the DOE. The shield concept is shown to be most effective when used in conjunction with a multi-layered repository to minimize the surface area contacted by infiltration. Dr. Fairhurst suggests that if the shield can be demonstrated to be effective with high confidence, it may be possible to avoid the need for the very costly ($4.6 billion) titanium drip shield used in the EDA-II.

The purpose of the paper is not to promote or endorse a specific design. Rather, the paper is intended to demonstrate that there may be innovative ways to engineer the natural setting such that the overall performance of the repository is improved. Current DOE designs appear to concentrate exclusively on engineering options within the drift itself. We believe that exploration of such ideas supports the NRC in its mission and in its vision of "enabling the safe and efficient use of nuclear materials." Consideration of the repository shield and a multiple level repository and other design concepts can provide insights into approaches for reducing critical uncertainties and for modifying the degree of reliance placed on natural versus engineered barriers. Exploration of alternative design concepts may also provide insights to help the NRC avoid placing constraints on DOE's repository design that might inadvertently limit possible future beneficial design changes and innovations, that would lead to greater confidence in the safe disposal of HLW at Yucca Mountain.

In its July 9, 1999, letter to Lake Barrett (DOE)[1], the Nuclear Waste Technical Review Board (NWTRB) expresses concern about the uncertainties associated with the above-boiling-temperature EDA-II design recommended by the M&O, and the lack of transparency in the process and rationale used to select this design. The EDA-II design is a "high temperature" design having a peak drift-wall temperature (160°C) above the local boiling point of water (96°C), with the space between drifts below boiling. To reduce uncertainties, the NWTRB urges DOE to consider modifying the EDA-II design to achieve below- boiling temperatures everywhere in the rock by increasing the rate or duration, or both, of ventilation before repository closure.

The ACNW believes that further analyses must be done before a determination can be made on a choice between a "totally below boiling" temperature repository and one in which some boiling takes place. Dr. Fairhurst points out that the recommended EDA-II design has some merits but also some disadvantages. Although a cooler repository design may simplify modeling of water redistribution, the potential for a higher temperature repository design to reduce the quantity of water reaching the drifts should not be abandoned without further assessment. It is possible that the existing EDA-II design, possibly modified to include multi-layered emplacement drifts, in conjunction with the infiltration shield concept, can be shown to reduce the uncertainties of water refluxing associated with a hot repository while maintaining the advantage of the hot repository to drive moisture away from the canisters.

We hope that you find Dr. Fairhurst's white paper to be of interest.

---

[1]July 9, 1999 letter from Jared L. Cohen, Chairman, Nuclear Waste Technical Review Board, to Lake H. Barrett, Acting Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy.

Observations and Recommendations Regarding the DOE's Design Selection Process and the Recommended Repository Design

Observation 1

Over the past 10 months, the M&O contractor has been conducting a study of alternative repository designs for the proposed Yucca Mountain repository. As noted earlier, the M&O recently recommended that DOE select the EDA-II. The DOE has not yet made a decision about adopting the M&O's recommendation. The recommended EDA-II design differs significantly from the repository design presented in the DOE's viability assessment. As noted above, the NWTRB has expressed its dissatisfaction with the design selection process as well as with the recommended EDA-II design. Such recent and rapid changes suggest that the fundamental design and the many design-related details are likely to continue to change until such time as DOE submits its LA to the NRC. DOE's repository design must be regarded as a work in progress.

Recommendation 1A:

The NRC should plan for continued change in the repository design up until the time the LA is submitted. It follows that the NRC staff should adopt realistic expectations about the turnaround time that may be required to conduct a thorough review of the SR or LA design. The NRC should also develop a license review strategy that allows the DOE maximum flexibility to implement beneficial design changes and other innovations before its submittal of the LA as well as times throughout the preclosure period of the repository.

Recommendation 1B

As noted in the attached white paper, the preclosure period of the repository could last as long as 300 years, and, because of this, the NRC staff must be careful to avoid placing constraints on the design that might preclude future beneficial design changes or innovation. The NRC staff must ensure that it is prepared to recognize such innovation during its review of the LA. Further, as part of a strategy to develop review capability and insights into repository systems, the NRC and the CNWRA staffs should conduct independent evaluations of alternative, cost-effective designs. In evaluating such innovative designs as part of its preparation to review the LA, the NRC staff would gain insights into the relative importance of various design features, alternative strategies to reduce critical uncertainties, and alternative strategies for demonstrating defense in depth. The insights gained through the evaluation of alternative design concepts will enhance the NRC staff's capability to assess repository safety.

Observation 2

NRC's proposed rule governing HLW disposal (10 CFR Part 63) requires monitoring of repository performance. The 50- to 300-year repository preclosure period presents a major opportunity to establish the validity of design assumptions. Monitoring will require "performance confirmation drifts"[2]. Such drifts, appropriately located, could also serve as part of the flow diversion system proposed in the white paper.

Recommendation 2

The ACNW endorses the sentiment expressed recently by the U.S. Geological Survey (USGS), "that a careful description of the proposed monitoring strategy, as well as a detailed and complete list of what is to be monitored—and why, where, how, and for how long—should be developed expeditiously."[3] We encourage the NRC staff to consider long-term monitoring needs and strategies for how DOE may factor performance confirmation monitoring into its final design.

Observation 3

As noted above, in its July 9, 1999, letter to L. Barrett, the NWTRB expresses concern over the lack of transparency in the assumptions and value judgments made in the design selection process as well as the recommended design. Implicit in the NWTRB's letter is that the Board is uncomfortable with the M&O's selection of the EDA-II repository design because of the current uncertainties associated with high repository temperatures. It is not clear to the ACNW how the uncertainty associated with the various design concepts and features has been quantified and factored into the M&O's process for selecting a preferred design. The M&O's identified evaluation criteria do not include uncertainty as a criterion for making a selection. The conceptual model and assumptions for the various design concepts and features will drive the results of the evaluation and comparison of alternatives.

Recommendation 3

The ACNW believes that the M&O's approach used to evaluate and compare quantitatively the various EDAs has not been made transparent. We encourage the NRC to ensure that the rationale, approach, and assumptions used in the evaluations and in comparisons of alternatives are appropriate. In addition, as noted in recommendation 1B, the NRC and CNWRA staffs should conduct their own independent evaluations of alternative, cost-effective designs, similar to the evaluation of the innovative design described in the attached white paper.

Sincerely,

B. John Garrick
Chairman

---

[2]Viability Assessment of a Repository at Yucca Mountain, Preliminary Design Concept for the Repository and Waste Package, USDOE, Volume 2, 1998, p. 4-111

[3]USGS Circular 1184, 1999, "Yucca Mountain as a Radioactive Waste Repository."

Summary

Yucca Mountain was initially recommended as a potentially suitable site for a high-level waste repository because it was anticipated that it would be dry. The repository would be situated in the unsaturated zone at a depth of 300 m below the surface and approximately 300 m above the current water table. It was also proposed as a "hot repository," in which rock temperatures would rise above 200 °C and would remain above the boiling point of water for several thousands of years. The intent was to prevent any liquid water from reaching the waste packages during that period.

Recent studies suggest that infiltration rates in the unsaturated zone may be higher than originally anticipated, and may increase substantially 20,000 years or so into the future. This information has prompted a redesign of the repository placing greater emphasis on engineered barriers within the waste emplacement drifts, e.g., a drip diversion (Richards) barrier; corrosion-resistant waste package; titanium drip shield (cost $4.6 billion); active ventilation during the 100- to 300-year preclosure period; and lower repository temperatures.

The viability assessment (VA) published by the U.S. Department of Energy (DOE) in December 1998 indicates that these engineering measures should suffice to meet the 10 CFR Part 63 requirements of the U.S. Nuclear Regulatory Commission (NRC) over the 10,000-year regulatory period, although doses are predicted to rise considerably beyond 10,000 years.

These notes, prepared after review of the VA, focus on geotechnical aspects of the repository design. The author has profited from discussions with colleagues of the Advisory Committee for Nuclear Waste (ACNW) and NRC, as well as from participation in numerous meetings and discussions with staff of DOE and its Management and Operating (M&O) contractors. The notes emphasize (1) a repository shield concept and (2) prediction of drift stability during both the (100 yr ~ 300 yr) preclosure and postclosure periods.

This paper does not promote or endorse any specific repository design. Rather, its purpose is to stimulate the NRC's thinking as it prepares to conduct a thorough and critical review of the repository design used in DOE's license application. The paper attempts to demonstrate that consideration of such innovative ideas as the repository shield concept and triple-layer repository can redefine the problem by reducing or eliminating critical uncertainties, or altering the degree of reliance placed on natural versus engineered barriers..

Given that decisions regarding final closure will not be made until the end of the operational period of the repository, the NRC must be careful to avoid placing constraints on the project now that would inadvertently limit possible future advantageous design changes and innovation. It is incumbent on the NRC to have the capability and be prepared to recognize the possibilities for such innovation during its evaluation of the license application.

The repository shield acts as an *umbrella* above the repository, taking advantage of the (dominantly vertical) fracture and flow system of the site to divert water away from the

repository drifts. The shield uses natural material (rock) only, augments an existing design, can be developed at any time during the preclosure period, and can serve to house a remote-monitoring network for the repository.

For a repository shield to be most cost effective, the repository should be a multi-level (three-tier or two-tier) design. (Figure 2 shows a three-tier design.) The shield appears to have the potential of greatly reducing water infiltration to the repository drifts —with attendant reduction of doses and simplification of performance assessment calculations. Construction of a flow diversion barrier in the (radiation-free) slot excavations above the drifts would be simpler than remote placement around the unshielded waste packages in the repository drifts —as currently proposed by DOE. If water infiltration is reduced to the extent predicted by analysis to date (see Appendix I), the expensive titanium drip shield (see Figure 4) may not be required. The presence of the drainage slots directly above the emplacement drifts may also simplify near-field fluid-flow and reflux processes during the thermal cycle. The concept deserves serious examination by DOE and its contractors.

With respect to drift stability, the repository environment is unique in that substantial thermo-mechanical stresses may be generated in both the reinforcement support and the rock. From information available on the mechanical properties of the Topopah Springs formations, it appears that stable excavations can be designed in both the lithophysal and the non-lithophysal units. It is believed that rock reinforcement using fully grouted bolts, mesh, and (if possible) shotcrete is preferable to the use of concrete or steel set supports for the repository drifts. Attention will need to be given to pH control of the cement used, but this problem does not appear to be an insuperable problem.

For the postclosure period, it must be assumed that any rock reinforcement or support system will no longer be effective. Recent developments in the numerical modeling of long-term progressive degradation of the mechanical properties of rock masses can provide more realistic assessment and prediction of the behavior of rock around excavations that are not back-filled than were possible in the past. Progressive disintegration and collapse of the rock may, in fact, result in a "natural back-filling" process that could be as effective, eventually, as standard back-fill. Of course, this does not preclude the use of a "chemically tailored" back-fill in the drift section below the waste packages, which could provide significant radionuclide "capture" benefits.

Introduction

The goal of geological isolation of highly radioactive waste is fundamentally simple — to place the waste at depth in the subsurface such that the radioactive elements or *radionuclides* in the waste will never return to the biosphere in concentrations sufficient to pose a significant health risk to humans.

Given the very long half-life of some radionuclides, the times for which isolation is required may be on the order of several hundreds of thousands of years.[1]

The primary vehicle for transport of the radionuclides from the initial underground location or repository is moving water that comes into contact with the waste. Radionuclides become entrained in the water (by dissolution or by colloidal suspension) and move to the biosphere, either directly or in water that is pumped from the aquifer and used for drinking and/or irrigation.

Thus, one of the main criteria in repository siting is to minimize the probability of radionuclide uptake by water and transport to the biosphere. Some radionuclides have very low solubility in the groundwater, others may be very soluble. The physical and chemical characteristics of the rock may also greatly retard the overall rate of movement of particular radionuclides in relation to the rate of groundwater movement. The concentration may also be reduced by dilution (e.g., in water or air) so that release to the biosphere via large bodies of water (i.e., seas or oceans) can also provide an added measure of safety.

The first formal report on the feasibility of geological disposal was published by the U.S. National Academy of Sciences/National Research Council in 1957 (NAS/NRC, 1957). The report noted that:

> *Wastes may be disposed of safely at many sites in the United States, but, conversely, there are many large areas in which it is unlikely that disposal sites can be found, for example, the Atlantic Seaboard. The research to ascertain feasibility of disposal has for the most part not yet been done . . . .*

The report concludes with the following two *General Recommendations on Corollary Problems:*

> 1. *The movement of gross quantities of fluids through porous media is reasonably well understood by hydrologists and geologists, but whether this is accomplished by forward movement of the whole fluid mass at low velocity or whether the transfer is accomplished by rapid flow in "ribbons" is not known. In deep disposal of waste in porous media it will in many cases be*

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[1] The "half-life" of plutonium 239, for example, is 24,000 years, i.e., the specific radioactivity will decline to $(\frac{1}{2})^{10}$ (i.e., 0.001 or 0.1%) of its initial activity in 24,000 × 10 = 240,000 years, and to (0.001)(0.001) or 0.0001% in 480,000 years. Other very long-lived radionuclides that contribute to the potential dose at various (long) times at Yucca Mountain are technetium 99 (half-life of 212,000 years), uranium 234 (245,000 years), neptunium 237 (2.14 million years), and iodine 129 (17 million years).

essential to know which of these conditions exists. This will be a difficult problem to solve.

2. *The education of a considerable number of geologists and hydrologists in the characteristics of radioactive wastes and its disposal problems is going to be necessary.*

Today, more than 40 years later, there are many hydrologists and colleagues in related disciplines worldwide who have studied groundwater flow in considerable detail. Significant advances have been made, but characterization of water flow still involves large uncertainties, especially in fractured rock masses. It remains "a difficult problem to solve."

Geological repository siting and evaluation programs are currently underway in approximately 30 countries. Of these, all but the Yucca Mountain project in the USA are sites below the groundwater table. For these, the host rock is usually of low intrinsic permeability with a low regional hydraulic gradient (i.e., the overall rate of water movement from the repository is expected to be very low). A number of countries are considering repositories in crystalline rock. Characterizing groundwater flow in fractures is frequently a serious issue for these sites.

In addition to understanding the natural system at Yucca Mountain, i.e., groundwater flow and radionuclide transport, NRC's proposed high level waste (HLW) disposal regulation, 10 CFR Part 63, indicates that *an engineered barrier system (EBS) consisting of one or more distinct barriers is required in addition to natural barriers.* The proposed rule states that *the Commission continues to beleive that multiple barriers, as required in the Nuclear Waste Policy Act of 1982 (NWPA), must each make a definite contribution to isolation of waste at Yucca Mountain.* Thus, DOE must design and demonstrate quantitatively that the total repository system relies upon and balances the contributions of both natural and engineered barriers to isolate waste.

The preclosure period of the proposed Yucca Mountain repository is expected to range from 50 to 300 years. Given that final repository closure will not occur until the end of the preclosure period, the NRC must be careful to avoid placing constraints on the project now that would inadvertently limit possible future beneficial design changes and innovations. It is incumbent on the NRC to have the capability (and be prepared) to recognize the possibilities for such innovation during its evaluation of the license application. One way to develop such capability is for the NRC to conduct an independent evaluation of viable, cost-effective designs. To conduct such evaluations, the NRC needs to have competent scientific and engineering expertise available over the broad spectrum of disciplines involved in repository design and long-term performance assessment. With the much larger complement of technical staff available to DOE and the recent and rapid changes in repository designs proposed by the DOE, the NRC faces a formidable challenge.

This report focuses on geotechnical aspects of the proposed Yucca Mountain repository. A design concept consisting of a repository shield used in conjunction with a multi-tiered repository is outlined. Particular attention is given to two issues: (1) diversion of groundwater before it reaches the waste-filled drifts and (2) drift stability. The paper then considers prediction of drift stability during the preclosure and postclosure repository periods. The paper compares the respository shield concept to the DOE's current, preferred repository design, which has changed significantly from the design presented in the DOE VA. The purpose of the paper is to stimulate the NRC's thinking as it prepares to conduct a thorough and critical review of the repository design used in DOE's license application. The ACNW may also use the ideas in the paper in preparing its specific comments on the DOE site recommendation and license application. The paper attempts to demonstrate that consideration of alternative, innovative design concepts, such as the repository shield/multiple-layer repository, may take better advantage of the geological characteristics of the proposed repository site at Yucca Mountain. Critical, persistent uncertainties may possibly be reduced substantially and the degree of reliance placed on natural and engineered barriers can be varied. The proposed "shield drifts" can also serve the role of performance-confirmation monitoring drifts (see VA, Vol. 2, p. 4-111).

Groundwater Flow at Yucca Mountain

At Yucca Mountain, the proposed repository horizon is in the unsaturated zone, approximately 250—300 m below the surface of the Amargosa Desert and 300 m above the water table. Tectonically, the region is currently undergoing extension (i.e., the rock mass is tending to extend horizontally). This implies that, at least near the surface (i.e., within the region of concern with respect to the repository), the lateral stresses in the rock are less (~3 MPa) than the vertical (gravitational or *overburden)* stresses (~7 MPa at a depth of 300 m). This situation has given rise to high-angle (i.e., almost vertical) fracturing (see VA, Vol. 2, Figure 2-9, p. 2-17). As a result of this situation, the fractures tend to be highly transmissive, so that rainfall and surface waters drain rapidly through the fractured mass into the groundwater. However, these fractures are generally not single, continuous planar features. Individual fractures are of limited extent, so that connected pathways, allowing flow through the fracture network, will be considerably less frequent than the individual fractures.

In initial planning for the repository (Roseboom, 1983), it was felt that the annual percolation flux (i.e., precipitation less the amount of surface evapo-transpiration) was very small (on the order of 1 mm/yr) and that little or no moisture would drain into the repository (i.e., the repository would be "dry"). In addition, it was decided to adopt a "hot repository" design (i.e., such a disposal layout that the rock temperature in the vicinity of the repository would remain well above 96 °C, the local boiling point of water, for hundreds or thousands of years, so that no liquid water could reach the waste canisters[2]).

More recent studies indicate that the total infiltration may be higher, and that a considerable portion of this may flow through the interconnected fracture pathways. As noted in the VA:

> *Estimates of average percolation flux from these various studies range from about 0.1—18 mm (0.004—0.7 in) per year. Because of Paintbrush attenuation most of the flux probably requires hundreds to thousands of years to reach the repository horizon. However, isotopic (chlorine-36) data suggest that at least a fraction of the flux reaches the repository level in ten years or less. Thus, while some of the*

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[2] The high-temperature design is feasible in an unsaturated high permeability zone, such as exists at Yucca Mountain, where the pressurized water vapor in the rock in the vicinity of the excavations can "leakoff" readily toward the surface.

water moves downward quickly, much of it travels more slowly. (VA, Vol. 1, p. 2-38).

Studies of long-term climate change in the Yucca Mountain region over the past 500,000 years (see Figure 1) indicate that the climate in the region will very likely become colder *within the next few hundreds or thousands of years* (VA , Vol. 1, p. 2-30). Annual precipitation and infiltration are then likely to increase considerably. DOE performance assessment calculations consider a mix of dry and wetter climates extending up to several hundreds of thousands of years into the future (VA, Vol. 3, Sect 3.1.2.1, p. 3-15). These periods include dry climate conditions, as now, with an assumed base infiltration rate of 8 mm/yr, a long-term average period with a base infiltration rate of 42 mm/yr; and *superpluvial* periods with a base infiltration rate of 110 mm/yr (VA, Vol. 3, Table 3-5, p. 3-15). Increased infiltration rates will increase the proportion of total flow through fractures.

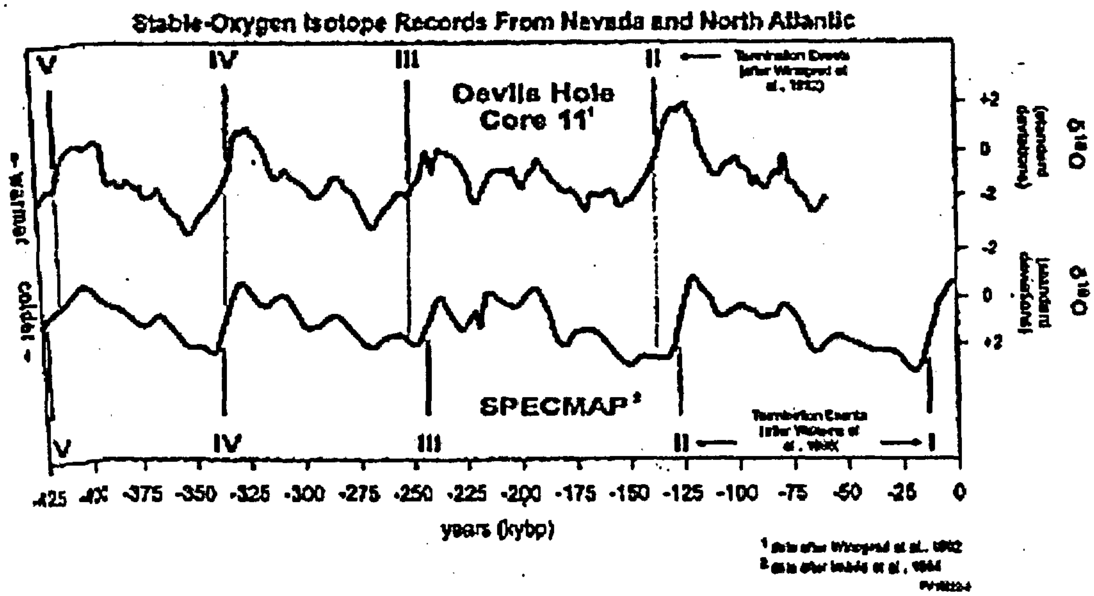

Figure 1 Stable-Oxygen Isotope Records from Nevada and North Atlantic as Indicators of Past Climate Variation in the Vicinity of Yucca Mountain

The overall conclusion with respect to repository design at Yucca Mountain is that a significant fraction of the total infiltration through the unsaturated zone will be by flow through interconnected fracture pathways. The precise location of these pathways cannot be predicted, and the amount of flow may vary considerably from place to place in the repository. The rates of flow in these fracture pathways can be high, on the order of tens of meters per year.

A fraction of the flux arriving at the drift horizon is assumed to drip onto the waste packages, causing corrosion of the package and, eventually, contact with and dissolution of some of the waste. Details of the calculation procedure are outlined in the viability assessment (VA, Vol. 3, Sec. 4.1.3, p. 4-4 et seq.).

Repository Design and Yucca Mountain

Waste isolation poses unique problems for both geoengineering and geoscience. These problems center around the time frames involved, with at least semi-quantitative answers needed over times on the order of 10^4 or 10^6 years — far longer than the 10^1 or 10^2 years for which engineers are accustomed to provide quantitative solutions. The geoscience issues have received more attention to date, so there is a good awareness of the uncertainties associated with predictions presented with respect to waste isolation over such times. With engineering design now receiving more attention, it is important not to overlook the time element. Repository design considerations place severe constraints on the use of "engineering experience" and require an unprecedented reliance on predictive (often numerical) analysis.

Development of a convincing prediction of the performance of a waste package alloy thousands of years into the future, when that material may have been known for less than 100 years or so, is an example of the challenges involved.

Time Frames of Concern in Repository Design

The following three periods of interest can be distinguished in the design and assessment of long-term performance of a repository at Yucca Mountain:

Preclosure[3] — Between 100 and 300 years (i.e., the period from the start of repository excavation until the decision is made to "close" the filled repository). Although it would not be impossible to retrieve waste from the closed repository, retrievability at Yucca Mountain is currently envisaged to be accomplished only during the preclosure period. The drift support system should be designed for the preclosure period.

10,000 years beyond closure — This is the regulatory period specified in 10 CFR Part 63. If the total system performance assessment (TSPA) computations presented in the license application submitted by DOE are deemed by NRC to provide reasonable assurance that individual doses to a reference *critical group* located 20 km from the

[3] The 300-year upper limit was apparently chosen because it corresponds to ten half-lives of radioactive decay for cesium 137 and strontium 90.

repository do not exceed allowable limits at the end of 10,000 years after closure, the repository can be licensed.

Beyond 10,000 years — Although this period is strictly not part of 10 CFR Part 63, DOE acknowledges in the VA that doses will continue to increase significantly beyond 10,000 years, approaching the order of natural background radiation (Fig. 4.12 in VA, Vol. 3 shows a peak dose of 0.2 rem, at 200,000~300,000 years), almost an order of magnitude greater than the 25-mrem maxmimum dose allowed during the 10,000-year NRC regulatory period.

The U.S. National Academy of Sciences/National Research Council 1995 report, *Technical Bases for a Yucca Mountain Standard* (TYMS, 1995), recommended that the regulatory period be sufficient to cover the period of peak dose. As noted above, this period extends well beyond 100,000 years.

Some estimates indicate much higher doses than those given in the VA, as is illustrated in the following extract from a recent article by Carter and Pigford (1998)[4]:

> *Calculations by the project show that in 10,000 years the annual dose from drinking contaminated water from the repository will be about 0.02 rem per year. When the dose from eating food contaminated by irrigation water from these same wells is added, the total dose will be about 0.13 rem. This is 13 times the annual dose limit established by the U.S. Nuclear Regulatory Commission (NRC) two decades ago for persons living near a nuclear power plant. It is five times the*

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[4] Pigford, T. H., and E. D. Zwahlen, " Maximum Individual Dose and Vicinity-Average Dose for a Geologic Repository, "Scientific Basis for Nuclear Waste Management XX, W. J. Gray and J. R. Triay, Eds, Materials Research Society, Pittsburgh, PA, 1996, Vol. 465, pp. 1099-1108 .

Professor Pigford also recently provided the writer with the following details concerning the doses mentioned in the quotation:

> *For the dose calculations, we relied first on the dose calculations in TSPA-95 (Akins, J. E., J. H. Lee, S. Lingineni, S. Mishra, J. A. McNeish, D. C. Sassani, S. D. Secoughian, "Total System Performance Assessment — 1995: An Evaluation of the Potential Yucca Mountain Repository," TRW, November 1995.) These doses were calculated only for drinking contaminated well water. Additional doses from food chains were not included in TSPA-95. We utilized the graphs showing the cumulative complementary distribution functions for 1,000,000 years and for 10,000 years. We selected the drinking-water doses at a CCDF of 0.05, corresponding to a 95% confidence level. The 95% confidence level is commonly used in engineering practice, it has been recommended by Britain's NRPB, it was recommended in my dissent appearing in the National Research Council's TYMS (1995) report, and it was incorporated in draft legislation proposed by Congress for Yucca Mountain.*
>
> *From other graphs in TSPA-95 we identified which radionuclides were the principal contributors to these doses. From EPRI data (Smith, G.M., B. M. Watkins, R. H. Little, H. M. Jones, A. M. Mortimerk, "Biosphere Modeling and Dose Assessment for Yucca Mountain," EPRI Report TR-107190, 1996) we derived the ratio of total individual dose to drinking-water dose for each of the principal radionuclide contributors. Multiplying the drinking-water doses derived from TSPA-95 by the appropriate ratios yielded the doses reported in our article in the Bulletin of Atomic Scientists.*

> *two decades ago for persons living near a nuclear power plant. It is five times the annual dose the NRC allows for persons making unrestricted use of a nuclear facility whose license has terminated. (The dose calculations allow a 5 percent probability of doses higher than those cited here.)*
>
> *After 10,000 years, the calculated annual dose at a well three miles distant rises rapidly. Indeed, after 30,000 years, the annual dose from iodine 129 and technetium 99 will have increased about 80-fold, to 10 rems. Then the longer-term annual dose from neptunium 237 appears and rises to about 50 rem by about 100,000 years, amounting in less than a decade to an exceedingly high, life-shortening cumulative dose.*
>
> *The energy department recognizes that these doses exceed reasonable standards for public health protection — hence the pressing need for deeper analysis and a search for a more promising strategy.*

It is likely that a license application showing a dose that is in compliance over a 10,000-year regulatory period, but that indicates significantly increasing doses beyond that time, will be subject to legal challenge even if considered acceptable by NRC. A repository design that could avoid this difficulty, if such a design is feasible, should be given serious consideration.

Engineering design considerations will differ depending on the period of concern. The pre-closure period, although considerable, is comparable to the usual time for which engineered structures (e.g., bridges, tunnels) are designed to perform. Primary concern will likely be occupational exposure of workers involved in construction and maintenance of the open repository and its contents.

As noted earlier, the much longer postclosure period (to 10,000 years and beyond) requires a less traditional engineering design approach. However, it is worth recalling that the decision to use underground *(geological)* settings for waste repositories was made, at least in part, because rock is a natural material that is known to have existed in stable form for *many millions* of years. Prediction of performance for a small fraction of this time into the future involves much less uncertainty than is the case for fabricated materials that have been available on the order of 100 years only. (The Swedish [SKB] decision to select copper as their waste-package material was based in large part on the fact that native copper deposits are known to have survived for millions of years in groundwater environments similar to those proposed for their waste repository.)

Primary Attributes of a Yucca Mountain Repository Design

DOE's viability assessment (VA) lists the following four main attributes of a repository at Yucca Mountain that can influence the release of radionuclides to the biosphere:

- water contacting the waste package;
- waste-package lifetime;
- mobilization rate of radionuclides; and
- concentration of radionuclides in water.

These attributes serve as primary guides for DOE in establishing its repository safety strategy (RSS). *Each attribute has been further subdivided into principal factors of the so-called reference design.* Alternative design features have also been defined as possible contributors to an enhanced design (i.e., to improve the overall safety of the repository). The inter-relationships among these elements are all contributors to the RSS (see VA, Vol. 2, Table 8-3, p. 8-5).

Clearly, if water percolation into the waste-filled drifts could be avoided (i.e., if no water contacted any waste package), then the remaining three attributes become of little or no significance. All are dependent, in large measure, on contact of the groundwater with the waste package.

As noted by Shoesmith and Kolar (1998) in summarizing their study of the corrosion resistance of metallic alloys and the possibility of long-lived waste packages:

> *If the contact of seepage drips with the waste package is avoided, then extremely long lifetimes, in excess of 10^6 years, are predicted. This would suggest that the adoption of any engineering option to avoid contact between drips and waste packages would be a good idea.*

Given the potential benefits of elimination of water contact with the waste package, it is surprising that little consideration has been given in the VA to:

(1) diversion of inflowing water *before* it reaches the repository horizon, and

(2) use of a multi-level design (i.e., to reduce the repository plan area, or *footprint*, in order to minimize the potential for dripping into the drifts.

If, as appears to be the case at Yucca Mountain, flow through the unsaturated zone is predominantly vertical, at least in the southern portion of the proposed repository location, then elimination, or at least major reduction, of infiltration to the drifts seems technically feasible.

If net infiltration could be eliminated, major TSPA uncertainties would be removed, and doses would be reduced dramatically, especially beyond 10,000 years.

Elimination of Water Infiltration

The following two engineering options are within current technology and offer the possibility of eliminating water inflow to the repository:

(1) Surface modification (i.e., engineered fill), and

(2) Underground repository infiltration shield.

Surface modification is mentioned briefly in DOE's viability assessment (VA, Vol. 2, Sec. 8.2.2, p. 8-7). The repository shield concept is not considered.

Surface Modification

> *Net infiltration into the mountain could be significantly decreased if the surface of the mountain were modified. . . . Likewise, facilities for drainage of water to enhance runoff could be designed. Because these effects could potentially eliminate net infiltration at the site, the potential importance to performance could be high* (VA, Vol. 2, p. 8-7, emphasis added).

Standard procedures of surface mining and site rehabilitation could be used to cover the repository site with an impermeable cap and drainage. As noted in the viability assessment:

> *Surface modifications and near-field rock treatment can be independently evaluated* [i.e., without affecting other features of the design] *so this alternative concept was not retained for further consideration as an alternative design concept. However, the merits of these features will be evaluated in a separate study (VA, Vol.2, Sec 8.2.4.2, p. 8-12).*

Surface modification treatments (e.g., several meters of thickness of an impermeable barrier, such as clay, overlain by a drainage layer of large river gravel covered by, say, 10—15 m of alluvium) are well within current surface mining technology. However, the surface topography above the proposed repository is variable, so that this surface treatment could be costly and environmentally objectionable.

One of the potential shortcomings of surface modifications alluded to in the viability assessment (VA, Vol. 2, Table 8.5, p. 8-30), is the questionable longevity of such a barrier, due to erosion. However, erosion rates at Yucca Mountain are estimated (VA, Vol. 1, p. 2-26) to be less than 1.1 cm per 1000 years, or 11 m in 1 million years. DOE has given preliminary consideration to a more limited treatment of the surface, including a cover of alluvium over the existing surface (E. L. Hardin, personal communication, 1999), but this has not been pursued to date. Lack of permanence of the cover was one of the concerns cited.

Underground Repository Infiltration Shield, with Multi-Level Repository

An underground infiltration shield is particularly well suited to a repository in the unsaturated zone in fractured rock. where groundwater flow is predominantly vertical and the rock mass is anisotropic, both hydrologically and mechanically. At Yucca Mountain, fracturing (subvertical) is such that the vertical hydraulic conductivity is significantly larger than the horizontal conductivity. Similarly, the modulus of deformation of the rock mass is larger in the vertical direction than in the horizontal direction.

The infiltration shield concept is illustrated in Figure 2. In the example shown, the repository is laid out as a three-level system.[5] This alone, by reducing the plan area *(footprint)* of the

[5]Note that this would also reduce the probability of penetration of a vertical igneous dike intrusion by a similar factor, e.g., from a probability of 1×10^{-7}/yr as currently estimated by NRC scientists to 3.3×10^{-8}/yr.

repository to one-third of a single-level design, reduces the exposure of the drifts to vertical infiltration by a factor of three. Although the shield principle can be applied to a single-level repository design, it is obviously more cost effective to use a multi-level design.

A numerical analysis of the effect of placing a fourth row of drifts (left open, for example, as ventilated observation and performance confirmation drifts (see VA, Vol. 2, p. 4-45) above the three repository levels was carried out by Professor Pierre Perrochet, University of Neuchatel, Switzerland, using the numerical (hydrological) code FEFLOW. The analysis, with assumptions and results, is outlined in Appendix I to this paper.

A single typical column of drifts was analyzed. This corresponded to the central column shown in the upper diagram in Figure 2, but with the upper slot replaced by a circular drift (see diagram in Appendix I). The flow conditions and rock mass properties were considered to be representative of those in the unsaturated zone at Yucca Mountain. It was assumed that the rock mass could be considered to behave as an anisotropic continuum (i.e., discrete fractures were not considered). A uniform vertical infiltration of 50 mm/yr (1096 x 10^{-5} m^3/d over the 80 m^2 potential capture area (per meter of drift) was assumed to occur 30 m above the top row of drifts. A wide range of hydraulic anisotropy was examined. For all anisotropies considered, at least 94% of the top infiltration bypasses the lower three (rows of) drifts. The fluid pressure head above the lower drifts is reduced because of the proximity of the overlying drift, thus enhancing the potential for diversion of water around the lower drifts.

This calculation can be criticized in that it assumes the drifts to be circular and smooth, thus enhancing flow deviation around the drifts — as indicated in Figure 3 (after Philip et al., 1989; Philip, 1990). The presence of discrete fractures in the roof would increase the potential for water to drip into the drifts compared to the case analyzed — viz. that of a smooth opening in a continuum.

This criticism can be circumvented if the upper drift is replaced by a slot, say, 2 m high and ~10 m—20 m wide. Each such slot could be inclined slightly, as shown in Figure 2, and backfilled so as to establish a *flow diversion barrier*, to ensure that any infiltration from above the slot would drain into the rock mass outside the perimeter of the repository. Excavation of the 15 m—20 m slot would serve a dual purpose. A zone of enhanced fracturing would tend to develop above the slot (this would be further enhanced during the thermal cycle after the repository is filled with waste.) Any water infiltrating into the zone would drain into the slot; any remaining flow would be directed into the rock mass away from the drifts. Thus, both mechanisms (capillary diversion around and fracture flow into the slot) act to prevent flow into the drifts.

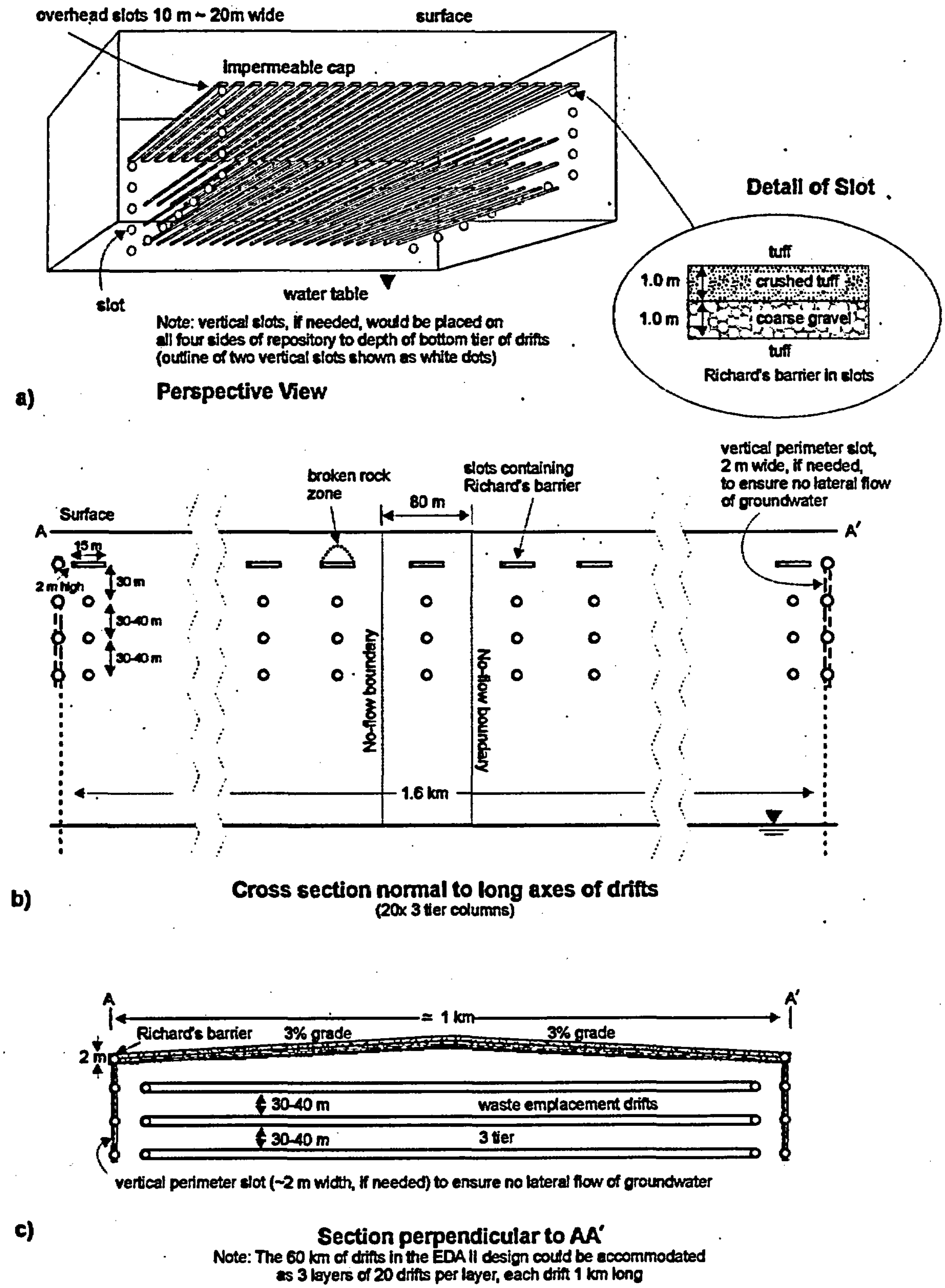

Figure 2. Underground Repository Infiltration Shield

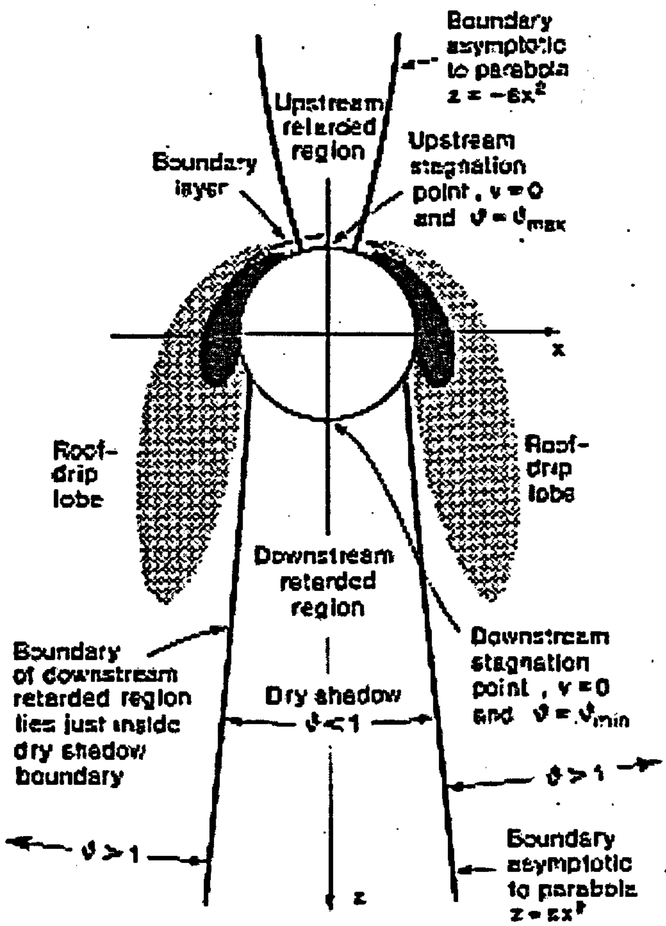

Figure 3. Seepage around cylindrical cavities (schematic diagram illustrating critical points and regions of the flow field)

Richards Barrier

This flow-diversion system incorporates two layers of material with contrasting hydraulic conductivities — a fine-grained porous layer overlying a coarser-grained layer, also porous (see EPRI (1996), pp. 1—2 et seq. for details). The capillary pressure established within the pore space in the upper layer material at the interface with the lower layer acts to prevent flow into the lower layer and promote flow laterally in the upper layer. Currently, the DOE is engaged in considerable study of the Richards barrier. The intention is to cover the waste packages with a "tailored backfill" possibly designed as a Richards barrier to divert water drips from the roof of the drift away from the packages (see Figure 4)[6]. Figure 2 shows a similar two-layer arrangement of backfill for the slots in the proposed repository shield.

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[6]It may be that the behavior of a Richards barrier over very long times (i.e., 10,000 years and longer) could be considered doubtful. It is believed that a simple drain, consisting of graded, more or lessuniformly sized granite boulder (river gravel) would suffice to establish free draining of the slots.

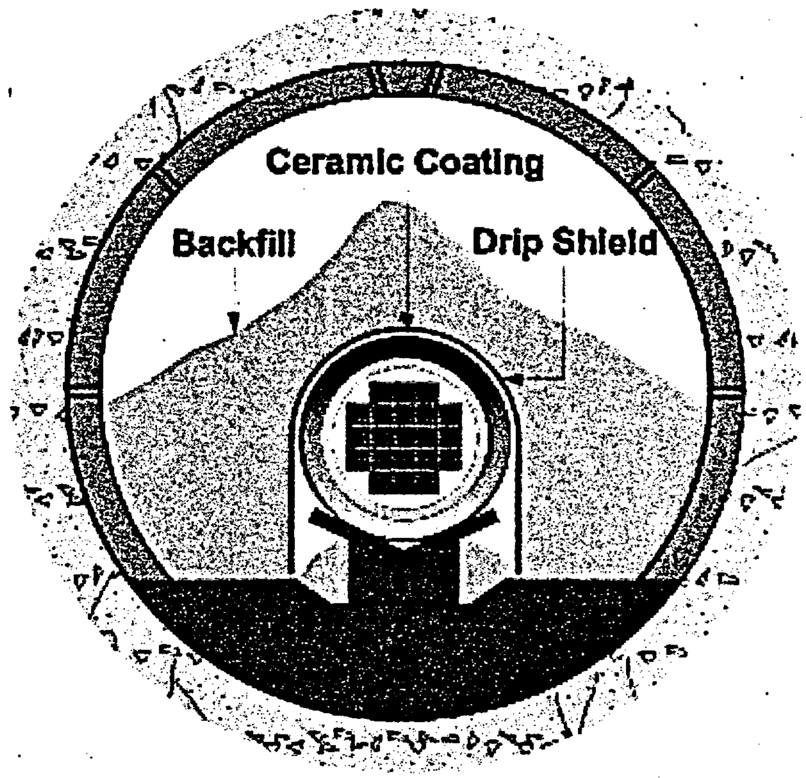

Figure 4. ***Near-Field Engineering Measures to Prevent Dripping on to Waste Packages (It is planned to place the backfill in two layers as a Richards Barrier, with fine-grained rock material overlying a coarser-grained rock material.)***

Potential for Lateral Flow at the Repository Horizon

The repository shield design described above is designed to be effective against vertical infiltration. It will fail if there is significant lateral flow across the repository. Lateral flow is possible, and is known to occur both above and below the proposed repository horizon. Within the proposed horizon (particularly, the southern region), flow appears to be dominantly vertical. As noted in the DOE viability assessment (VA, Vol. 1, p. 2-38),

> *. . . evidence indicates that surface infiltration generally moves downward rapidly in fractures through the Tiva Canyon tuff until it encounters the non-welded Paintbrush tuff. Flow in the non-welded unit appears to be predominantly in the rock matrix although fast flow paths along faults, fractures and other high permeability zones are present locally. In general, it appears that the Paintbrush non-welded unit attenuates (slows) and distributes flow downward, perhaps for periods of up to thousands of years. After migrating through the Paintbrush tuff, water moves into the welded Topopah Spring tuff* [Note: The proposed repository horizon is in the Topopah Springs formations] *where flow again appears to be dominantly in the fractures. The distribution of flow is heterogeneous; in some areas characterized by widely dispersed or poorly connected fracture systems, percolation fluxes may be very low. In areas with highly transmissive features*

such as faults or dense fracture networks, significant volumes of water may move downward rapidly.

This discussion suggests that lateral flow across the repository is likely to be minimal, so that (horizontal) slots above the waste-filled drifts will eliminate most, if not all, of the potential infiltration into the repository. It is entirely feasible technically, if deemed advisable to further reduce uncertainty, to construct a vertical perimeter shield around the entire repository, as shown in Figure 2. This would require a single vertical column of four 5-m-diameter drifts, located on the same level as the repository drifts and slots, along each side of the repository periphery. A narrow vertical zone of enhanced permeability could then established by blasting, using the VCR (vertical crater retreat) method (or a similar stopping procedure). Blasting would be conducted in vertical holes drilled downward from each overlying drift. The blasted rock would fill the underlying drift such that little, if any, of the broken rock would need to be removed. The aim is to establish a highly transmissive vertical flow pathway around the periphery of the repository; it is not necessary or desirable to create a vertical excavation. Alternate, less expensive techniques (e.g., creation and propping of hydraulic fractures from vertical holes along the drifts) could also be considered.

The horizontal slots and perimeter drifts could be used for monitoring (e.g., by microseismic and other geophysical techniques) repository performance during the preclosure period and beyond, if necessary. Since these openings would be ventilated during this period, any infiltration would be carried out as vapor in the air stream.

Additional Excavation Required for the Repository Shield

Horizontal Slots Only — The total excavation to develop 20 m-wide x 2 m-high slots would be the equivalent of 40 km of 5 m-diameter drifts. The EDA II repository design envisages a total of 60 km of waste-filled drifts. Thus, addition of the 20 m excavation slots would result in a total excavated volume less than the 110 km of drift excavation contemplated in the VA repository design.

"Full" Shield — The four drifts along the entire repository perimeter, if needed, would add a further 21 km of excavation (i.e., 4 x 2(1.6 + 1.0) km). It may be possible, in view of the reduced concern over reflux pathways between the (columns of) drifts, to reduce the spacing between drifts (currently 81 m). This would reduce the extent of the repository footprint plus the cost of generating the high-permeability vertical fracture zone between the drifts.

However, it is considered unlikely that construction of these vertical high-permability zones will be needed provided the repository horizon is selected appropriately, i.e., where the two sub-vertical joint sets are both well developed. They are orthogonal to each other, thus forming an effective barrier to lateral flow across the repository.

The preceding discussion suggests that it is technically feasible to ensure that essentially no infiltration into the repository ever occurs, for a cost that would not significantly exceed that of the VA repository design. This does not consider the added cost of a three -level repository compared to the VA single-level repository. DOE has considered a two-tier or split-level repository option, but did not examine the potential for water diversion. An increased cost of construction of 19% compared to the VA reference design was indicated (CWRMS/M&O Report

Design Feature Evaluation #25, Repository Horizon Elevation, April 2, 1999). It is also worth noting that the repository shield requires no reliance on the long-term performance of manmade materials. It should be relatively easy to establish the very long-time reliability of the repository shield.

The distinct possibility that the repository shield concept could reduce drift infiltration sufficiently to make the titanium drip shield (Figure 4) unnecessary — for a cost saving of $4.6 billion — strongly suggests that the repository shield concept deserves detailed study by DOE. Such a study should examine the implications of the multi-level arrangement (with overlying slots) on the optimum repository design.

Location of a Multi-level Repository at Yucca Mountain

A three-tier repository, as shown in Figure 2, would occupy a vertical interval of approximately 60 m~80 m in the Topopah Springs formation. Since the horizon proposed currently for the single-level repository is approximately at elevation 1080 m it appears that a three-tier interval from 1,040 m to 1,120 m in the central third of the current repository (see VA, Vol. 2, Fig. 4.21, p. 4-40) will remain well within the "groundwater surface plus 100 m" lower limit and within the "200 m cover" upper limit. The slot horizon would be some 30 m or so above the upper row of drifts, but this too will have almost 200 m of rock cover. Since the slot would contain no waste, a cover slightly less than 200 m is considered adequate.

Optimum Repository Layout

The VA reference design was a "hot repository" in which rock temperatures in excess of 200 °C were envisaged. A main intent was to prevent access of liquid water to the waste packages, at least for much of the regulatory period. Concern over the uncertainties associated with two-phase fluid flow behavior in the near-field of the repository and associated complexity of coupled (thermo-hydrological-mechanical-chemical) effects, especially in the near-field around the drifts, led to calls to revise the design to one in which the rock temperature was lower, preferably below the boiling point of water for much of the duration of the thermal cycle. The EDA II "lower temperature" design responds to these concerns.

The two designs are compared in Table 1 (from the presentation "Current Status of Repository Design," by Daniel G. McKenzie III, to the Drift Stability Panel, April 13, 1999).

The EDA II design has some merits, but also some disadvantages. Although the lower temperature system may be simpler *(perhaps!)* for purposes of analysis of near-field fluid (liquid water and water vapor) movement, the possibility that the high-temperature design may inhibit access of liquid water to the drifts is a feature that should not be abandoned lightly. Center for Nuclear Waste Regulatory Anslysis (CNWRA) staff (R. Green, personal communications, 1999) suggests that some counter-current flow may occur, -whereby water vapor may ascend within a fracture while liquid water may descend into the drift via the same fracture. The importance of this possibility in the context of a repository shield design would need to be assessed.) Also, as noted in the EPRI report (EPRI, 1996, p. 1-2):

> *The proposed DOE schemes for lower thermal loadings would not eliminate completely any of the coupled thermal effects causing concern at Yucca Mountain, although the proposed schemes would reduce the magnitude of at least some of these effects. For example, lowering peak temperatures below the boiling point does not eliminate the potential for evaporation of liquid water from the rock followed by buoyant convection and subsequent condensation farther afield. In order to reduce dramatically thermal effects in the very near field around the containers, the amount of spent fuel contained in an individual container would have to be dramatically reduced or the decay time of the spent fuel would have to be significantly extended (well beyond 100 years). Neither of these approaches seems so practical since both would dramatically increase disposal costs.*

Table 1. Comparison Between the EDA II and VA Repository Design Options

EDA II Design	**DOE VA Design**
60 MTU/acre	**85 MTU/acre**
1,050 acre-layout	**741 acre-layout**
60,000 m of emplacement drifting for statutory waste capacity	**117,000 m of emplacement drifting for statutory waste capacity**
2-5 m^3 /s/drift airflow	**0.1 m^3/s/drift airflow**
81 m drift spacing	**28 m drift spacing**
Line load	**Point load (3 m between packages)**

It is instructive, in this regard, to consider the performance of a multi-level EDA II design, as illustrated in Figure 2. The switch to a "line load" of waste packages (i.e., with the packages placed essentially adjacent to each other along the drift) compared to a "point load" (packages separated by several meters along the drift) and a much increased spacing between drifts (81 m for EDA II; 28 m for the VA Reference Design), together with some (low) velocity ventilation of the EDA II drifts, was intended to simplify the convective flow paths with reflux via the cool region in the center of each pillar.

With the multi-level design, the rock temperatures are likely to be increased, principally along the vertical axis between the drifts. The region between the pillars will be less affected, although raised somewhat. Convection cells of heated water and water vapor would form, driving the fluids upward into the slots, where it would tend to condense on the coarser rock in the lower portion of the Richards barrier, flowing along the inclined drifts to drain outside the repository. Continued heating would eventually dry out the rock between each column of drifts. This pathway provided by the slots would tend to eliminate the need for a pathway for the condensed reflux between the pillars, although concentration of the overburden stress through the pillars would induce a small tension tangential to the central vertical axis of the pillar, thereby tending to open the reflux pathway. In this regard, it should be noted that the intensity of the vertical stress concentrations in the pillars will persist to a greater depth than in the case of isotropic and unjointed rock (i.e., the "aperture opening" effect may be more significant in the jointed rock (see Goodman, 1989, Figs. 9.10 and 9.11 pp. 352—361). Shears induced at the corners of the slots could also cause fracture dilation, especially during thermal cycles.

It should be possible to reduce the 80-m drift spacing of EDA II somewhat (say, to 50 m). This would increase the temperature along the center-pillar axis, but the stress concentration in the now narrower pillar between the slots would increase, which may increase shear and dilation of fractures. The reduced pillar size would reduce the plan area of the repository, thereby either reducing the extent of any vertical perimeter shield or increasing the capacity of the repository. Chemical dissolution of minerals species (e.g., silicates) in the rock by the hotter fluids in the near field, with condensation upon reaching the slots would tend to develop a low-permeability "skin" along the slot floor during the thermal period. This would be beneficial to drainage of condensate along the drift.

Obviously, more detailed analysis and optimization studies are needed to establish the merits of the multi-level design with the repository shield in order to establish the merits of this concept vis-à-vis the proposed single-level designs.

Control of Repository Temperature

Reference has already been made to the perceived benefits of reduced repository temperatures in order to simplify the near-field fluid flow regime. Low temperatures are also desirable to reduce corrosion of the waste packages. The EDA II waste package involves a 2-cm-thick outer cylinder of C-22 alloy steel, with a 5-cm-thick inner cylinder of stainless steel (316NG).

Shoesmith and Kolar (1998) argue that pitting and crevice corrosion of C-22 are unlikely to occur at temperatures below 150 °C and 102 °C, respectively. The authors present detailed discussion of the corrosion processes, but conclude that a conservative design limit is to take 80 °C as the temperature below which crevice corrosion of C-22 can not occur (Shoesmith and Kolar, 1998, p. 5-8, para. 1). Also, it is noted that water must be present for significant waste package corrosion to occur. A relative humidity less than 70% and a temperature below 80 °C are sufficient to reduce the possibilities of corrosion of the C-22 alloy to insignificant values, i.e., yielding estimates of waste-package lifetimes considerably longer than the 10,000 years of the regulatory period.

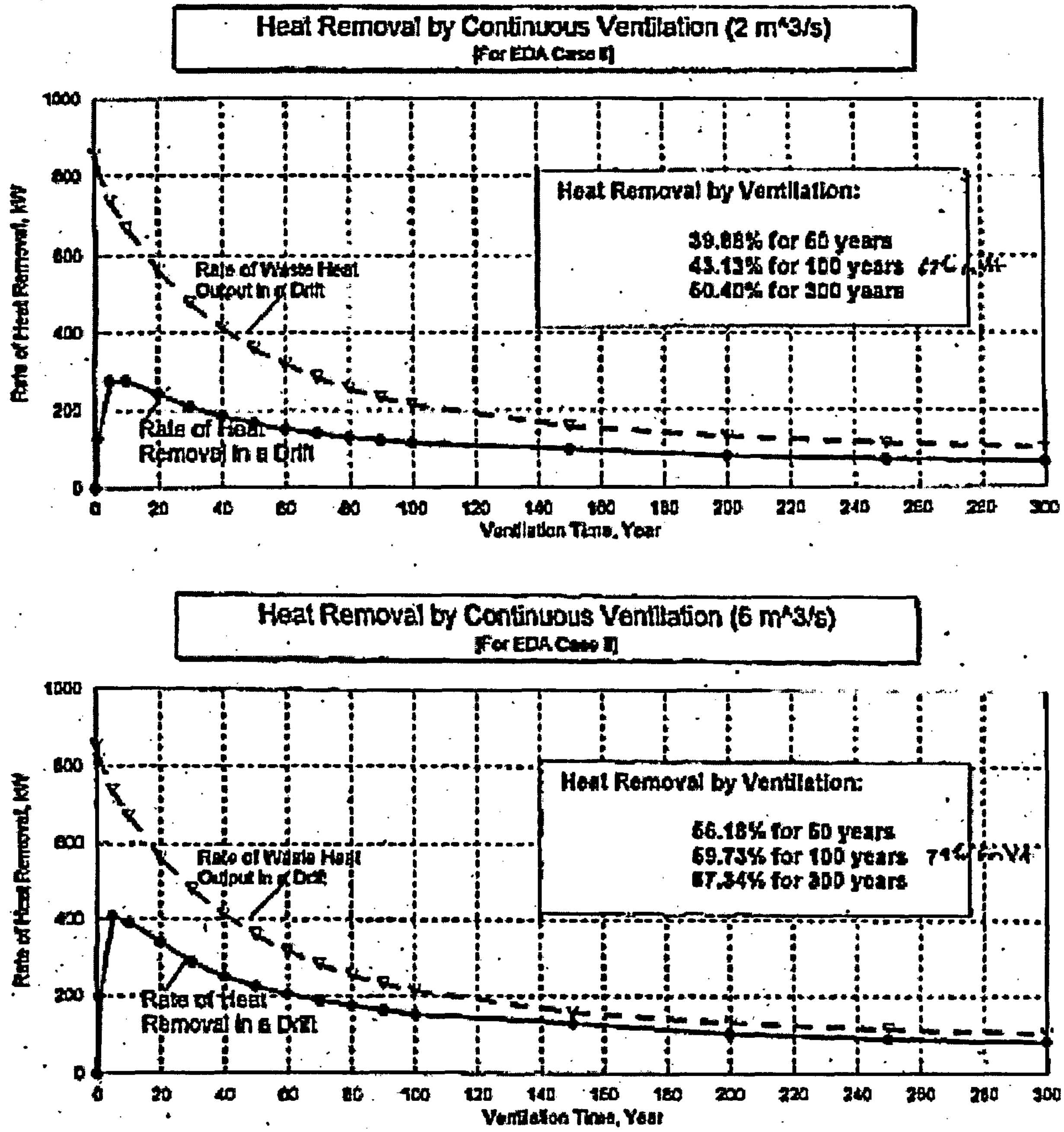

Figure 5. ***Heat removed by continuous ventilation of waste-filled drifts during the pre-closure period ($2 m^3/s$ air flow in a 5-m diameter drift corresponds to an air velocity of 20 ft/min, or 0.23 mph)***

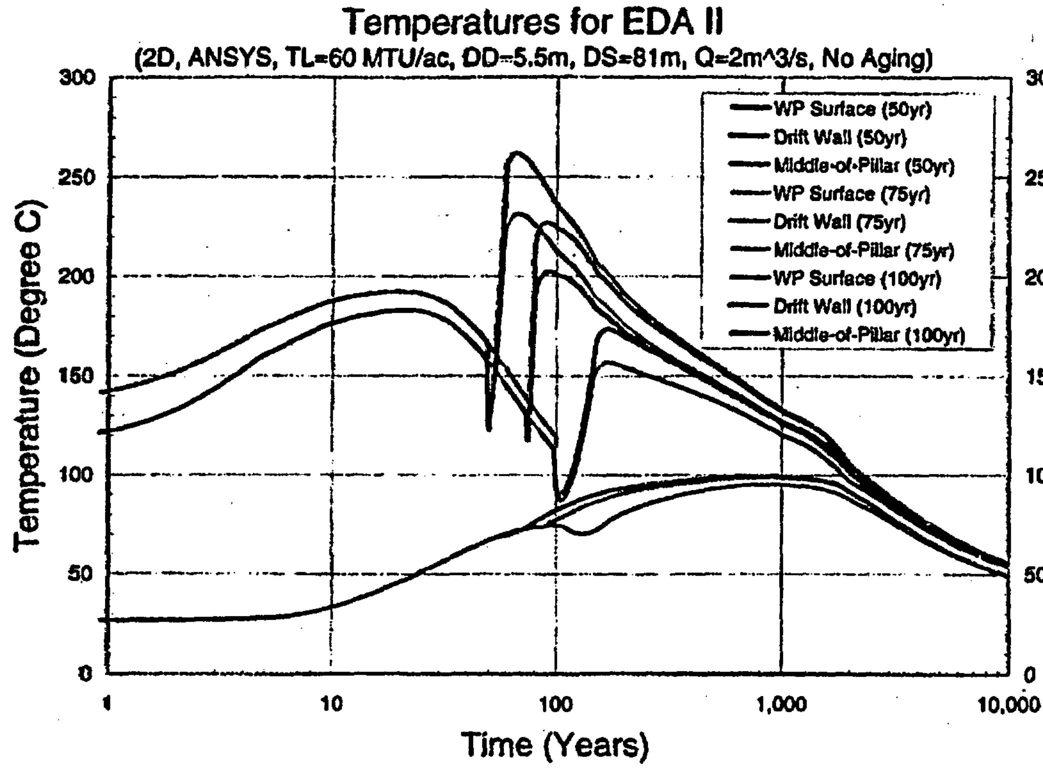

Figure 6. ***Effect of backfill on the evolution of temperature in the repository drifts (EDA II design)***

Figure 5 (kindly provided by the DOE, courtesy of R. Craun, 1999) indicates that drift ventilation can remove significant quantities of heat from the waste packages, especially during the first 50~100 years, when heat generation is most intense. Figure 6 (courtesy of D.G. McKenzie, April 1999) indicates that, with the EDA II design, drift ventilation of 2 m^3/s, and no aging of the waste:

(1) The waste package surface and the drift wall both exceed 150 °C for several years after installation, and

(2) Active ventilation of the drifts, either natural or forced, can also reduce the humidity. Stellavato and Montazer (1996, pp. 25—26) have used the atmospheric/hydrologic code ATOUGH to model heat removal from a ventilated repository.

They advocate design of the repository to allow air to flow continuously and indefinitely through the waste-filled drifts driven by natural ventilation. In their report, the authors conclude that:

> *By considering a naturally ventilated repository (after construction) and taking advantage of the thermal drive of the waste package, the repository may be kept dry during at least the first 10,000 years if not longer. The amount of moisture removed from the rocks during this time will create a thick low-saturation skin*

> *around the drifts that will require thousands of years to re-saturate. Ventilation can also remove large amounts of heat generated by the waste canisters.*

The authors' analysis indicates that the rock temperature never exceeds 25 °C during the ventilation period. The topography and surface layout of the proposed repository at Yucca Mountain is favorable to natural ventilation (and ventilation produced by waste heat generation), but it seems likely that the drifts will collapse over time, increasing the resistance to ventilation. Partial filling of the drifts with "moderately large" boulders to ensure some air access to the packages could be considered, but the resultant overall resistance to flow would be considerable.

Clearly, there is merit in preclosure ventilation of the repository with respect to limiting temperatures. Ventilation also tends to develop a "dryout" zone in the rock. Measurements over the past several years suggest that a region of approximately 100-mm radial thickness is dried out annually. Although the radial extent may not increase linearly with time, it appears that a region not greater than 10 m from the drift excavation will be "dried" over 100 years. With interruption of ventilation, this region will resaturate, probably at a comparable rate, so that the drift will be resaturated (i.e., partially) after the order of 200 years from installation of the waste. Thus, for almost all of the 10,000 years of the regulatory period, the waste packages (and backfill?) would be subject to a humid environment. With the C-22 alloy outer cover of the packages, and a package temperature not significantly above 100 °C, the alloy will corrode very slowly, if at all. This resaturation rate would be slowed considerably if the repository shield concept was used.

The preceding calculations suggest that, if one would hold the temperature of the C-22 waste package below 80 °C , some combination of waste form "blending" in the drifts, aging of the waste in surface facilities before emplacement in the repository, and active *vigorous* ventilation of the packages for at least 50—100 years may be necessary in open drifts. An *open drift* implies that the waste package will not be covered. —i.e., the waste package surfaces should be accessible to the ventilation. Tailored or "getter" backfill in the drift invert below the waste package could still be used.

Design considerations such as those outlined above suggest that it is entirely possible to engineer the natural setting of the unsaturated zone at Yucca Mountain to ensure that a high-level waste repository will be demonstrably safe for an indefinite period into the future. The *umbrella principle* of the repository shield is simple and can be comprehended easily by the general public.

Drift Stability

It is planned to locate the repository in the Topopah Springs tuff formations. For purposes of drift support/reinforcement and stability analyses, the formations can be divided into two general categories:

(1) *Non-lithophysal tuff.* - These formations contain three relatively well-developed joint sets. (Two are subvertical: joint set No. 1 has a dip of 77° and a dip direction of 40° ; joint set No. 2 has a dip of 80° and a dip direction of 130°. One is sub-horizontal: joint set No. 3 has a dip of 25° and a dip direction of 300°); and

(2) *Lithophysal tuff.* -These formations contain three-dimensional voids — approximating spheres or ellipsoids in most cases — or *lithophysae* generated as gas pockets during the

period of deposition of the volcanic tuff. Some of the lithophysae can approach 0.5 m in diameter, although most are smaller (predominantly 7—15 cm in diameter). Also, fractures in the lithophysal rock are shorter and less persistent than in the other units, and often terminate (or originate?) at the lithophysae.

> It seems likely that the lithopyhsal zones will be stronger and stiffer (i.e., higher rock mass modulus) than the non-lithophysal zones because of the lesser influence of through-going joints. The higher modulus would result in higher thermally induced stresses for a given temperature, so that the extent of *damage* during the thermal cycle could be comparable for both lithophysal and non-lithophysal tuffs.

It seems to the writer that excavations with rock reinforcement should be stable in both formations. The following discussion will examine the likely mechanical response of the two types of formation to loads generated in a repository. The stability of the repository drifts is of particular importance for the preclosure period, and can have consequences for the long-term performance of the repository, especially if the drifts are not backfilled.

Preclosure Stability

Although there is a wealth of experience in designing and constructing tunnels of the general dimensions of the repository drifts, and there are examples of tunnels that have remained stable for much longer than 100—300 years, design of a repository is unique in that a major thermal cycle is involved. For the case of a hot repository, this heating imposes substantial additional stresses on the rock and any rock lining. The likelihood that a concrete lining would be seriously and adversely affected by the high temperatures is — in part, at least — the reason why an Expert Panel on Drift Stability has recently recommended the use of rock bolts and wire mesh as being a more suitable support system than a concrete liner.

Postclosure Stability

DOE lists the following information needed with respect to performance assessment (PA) for ground support/drift stability (R. Howard, Yucca Mountain Drift Stability Panel, April 13, 1999):

Ground Support/Drift Stability Information Needs for PA (FEPs)[7]

- masses and spatial distribution of ground support materials
- nature and rates of continuous degradation processes
- nature and probability of disruption by rock fall
- nature and probability of disruption by seismic motion

Of these, the first can be answered as soon as a support system is selected. The remaining three require an understanding of the long-term, time-dependent behavior of the rock mass ***only if the drifts are not backfilled***. If the drifts are backfilled, then these issues are no longer of concern.

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[7] FEPs are features, events, and processes that are considered to influence repository performance.

No firm decision has yet been made concerning whether to backfill the drifts after waste emplacement.

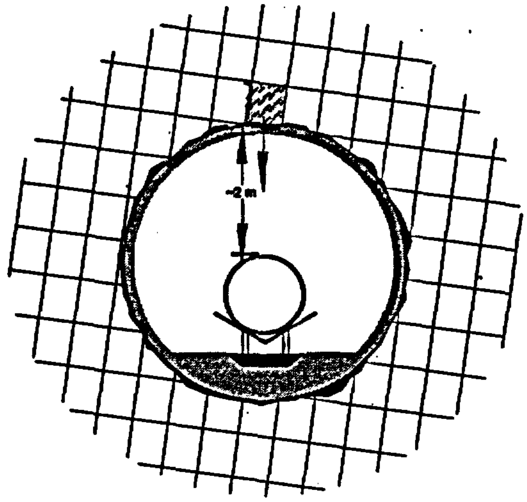
Numerical (discrete element) models currently in use to assess drift stability at Yucca Mountain have a significant limitation in that the rock blocks in these models, although deformable, are assumed to have infinite strength (i.e., they cannot break). This results in significant over-estimation of the consequences of rock falls on to waste packages. Considerable improvement in prediction of both (1) the consequences of heating on spalling of the drift walls and (2) the behavior of falling blocks can be obtained using a code such as the micro-mechanics numerical code PFC (Potyondy and Cundall, 1999) that allows the blocks to break under applied loading. Some indication of the difference that may be expected is demonstrated by the simple example of a rock block falling 2 m from the roof of the drift onto a waste package, as shown in Figure 7. The resultant force-versus-time history during the impact is shown in Figures 7(b) and 7(c) for the two cases in which (b) the block has infinite strength, and (c) a similar block has the (finite) strength of Yucca Mountain tuff. Fragmentation of the block (Figure 7(c)) traps a substantial proportion of the kinetic energy and momentum of the block with the result that, in this case, the peak force on the waste package is reduced to approximately one-third of the value indicated with the infinitely strong block.

Thermal loading and seismic effects can be considered in the PFC code. The rate of degradation over a long time can also be estimated, but this would require laboratory data on the strength of tuff (and joints in tuff) as a function of applied loading conditions (and possibly thermal conditions). Such data may not be available. The *pattern* of collapse with time can be examined for various *assumed* strength-degradation models. If this indicates that the pattern is relatively independent of rate of degradation, knowledge of the degradation pattern may suffice for PA purposes. Another approximate approach is to assume that the joint cohesion declines progressively in time toward zero. Frictional properties may decline somewhat, but are likely to remain significant.

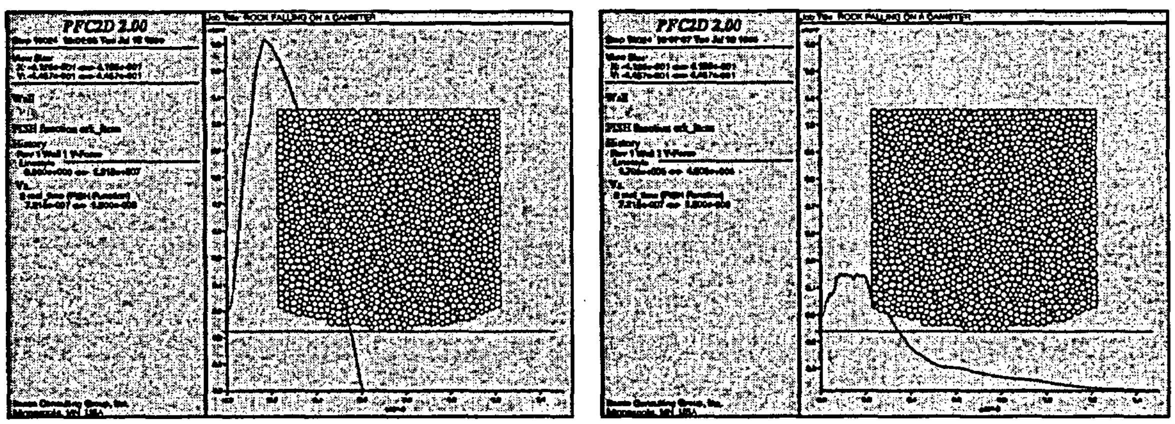
It is anticipated that an analysis using PFC would indicate progressive spalling of the drift wall and collapse of *relatively small* rock blocks on to the packages. This would further reduce the severity of any rockfalls on to the waste packages.

Time-dependent deterioration of rock strength (and possible collapse) can occur whenever rock is loaded in compression beyond 40% to 50% of its ultimate compression strength. Stresses significantly above this level could be generated in the rock during the thermal pulse period of repository operation. (In the case of Yucca Mountain, the stress induced in the rock by temperature increase is approximately 0.5MPa/°C for an assumed modulus of deformation of the rock mass of $E = 6$ GPa.)

Recognition of the limited value of classical geotechnical engineering design approaches in prediction of rock mass behavior for repository design has stimulated studies to obtain a more fundamental understanding of the physical principles that control time-dependent failure in rock. The report by Potyondy and Cundall (1999), describing studies being conducted for the Canadian nuclear-waste isolation program (and including the influence of heat in degrading rock strength with time) outlines valuable developments on this topic.



(a)



(b) *(c)*

Figure 7. ***Effect of finite rock strength on the impulse generated by free fall of a rock block onto a waste package (PFC model) (The block in Fig. 6(c) has the same deformability as the (infinite strength) block of Fig. 6(b), but a strength corresponding to that of Yucca Mountain tuff)***

Effect of Heating on Drift Stability

Figure 8 illustrates the change in stresses produced in the periphery of an unsupported drift as the result of heating, in this case to 145 °C, assuming that the rock mass has properties almost equal to those of intact tuff (i.e., RMQ 5). The initial insitu stresses were assumed to be approximately 10 MPa vertical. (This is equivalent to a depth approaching 400 m and 3 MPa horizontally). Under these stress conditions, the tangential stresses around the drift preceding heating would reach a maximum compression of approximately 26 MPa acting vertically across the central horizontal axis. Assuming a rock mass modulus of 32 GPa (i.e., RMQ5 rock properties), the effect of heating to 145 °C is to add compression on the order of 120 MPa more or less uniformly around the tunnel wall if the rock retains the RMQ5 properties and remains elastic.

If the rock properties are *degraded* to those of rock of RMQ1 quality, the stresses shown by the solid lines in Figure 8 are developed. The effect of a total of 50 years of heating, after which high temperatures (and stresses) have penetrated further into the rock, is shown by the dotted stress distribution. This results in a zone of inelastic deformation such as indicated in Figures 8 and 9. It is seen that the stress distribution and extent of inelastic deformation depend heavily on the rock properties. Recent results of insitu modulus measurements in the heated drift experiment indicate that the rock mass modulus (of deformation) increases from the order of 6~7 GPa at ambient temperature to higher values at higher temperatures. This is due, very likely, to expansion of the rock and consequent closure of the rock joints with increase in rock temperature. It is unlikely that the rock mass modulus in the jointed rock will reach the laboratory value for intact rock (32 GPa). In the lithophysal tuff, however, the modulus can be expected to be higher than in the non-lithophysal jointed tuff.

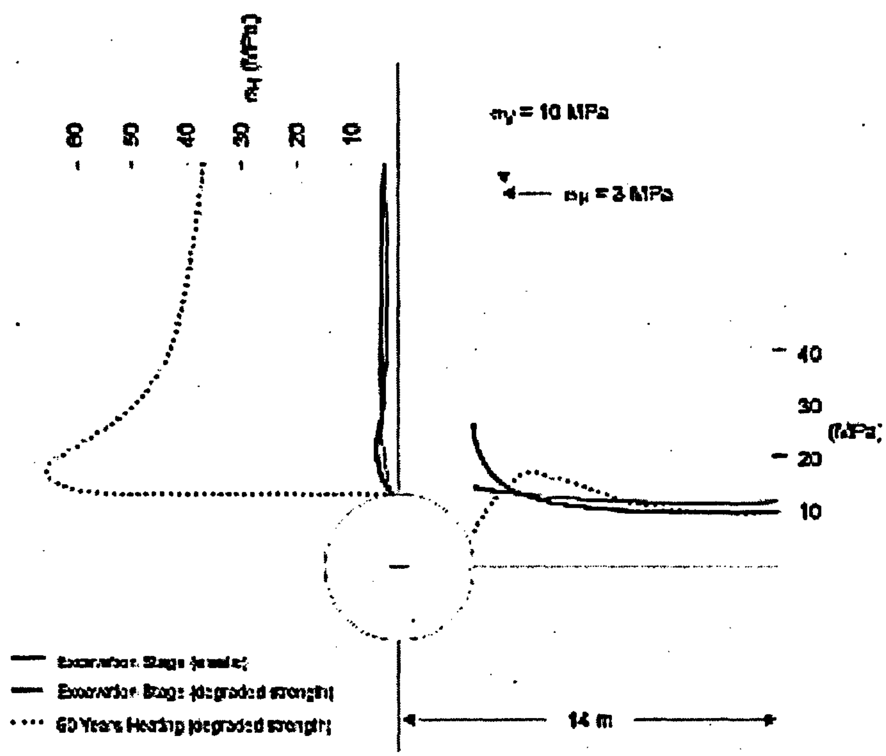


Figure 8. Effect of Heating on Stresses Around One of a Series of Excavations

Figure 9 shows the extent of joint slip that occurs before (Figure 9(a)) and after (Figure 9(b)) heating when a PMQ5-quality jointed rock mass is subject to heating as described for Figure 8.

Figures 9(c) and 9(d) show the results of numerical modeling in which a 5-m-diameter unsupported open drift is subjected to two identical seismic events, one that occurs before heating (Figure 8(c)); the other (Figure 8(d)) that occurs after 50 years of heating of the rock to a maximum temperature of 145 °C at the tunnel wall. The regions of joint slip are shown in Figures 9(a) and 9(b), and the rockfall due to the two seismic events in Figures 9(c)and 9(d). It is seen that the rock fall is considerably reduced for the heated rock. This is because the increased temperature superimposes a high compression all around the tunnel, tending to "clamp" the rock blocks together, and preventing fallout.

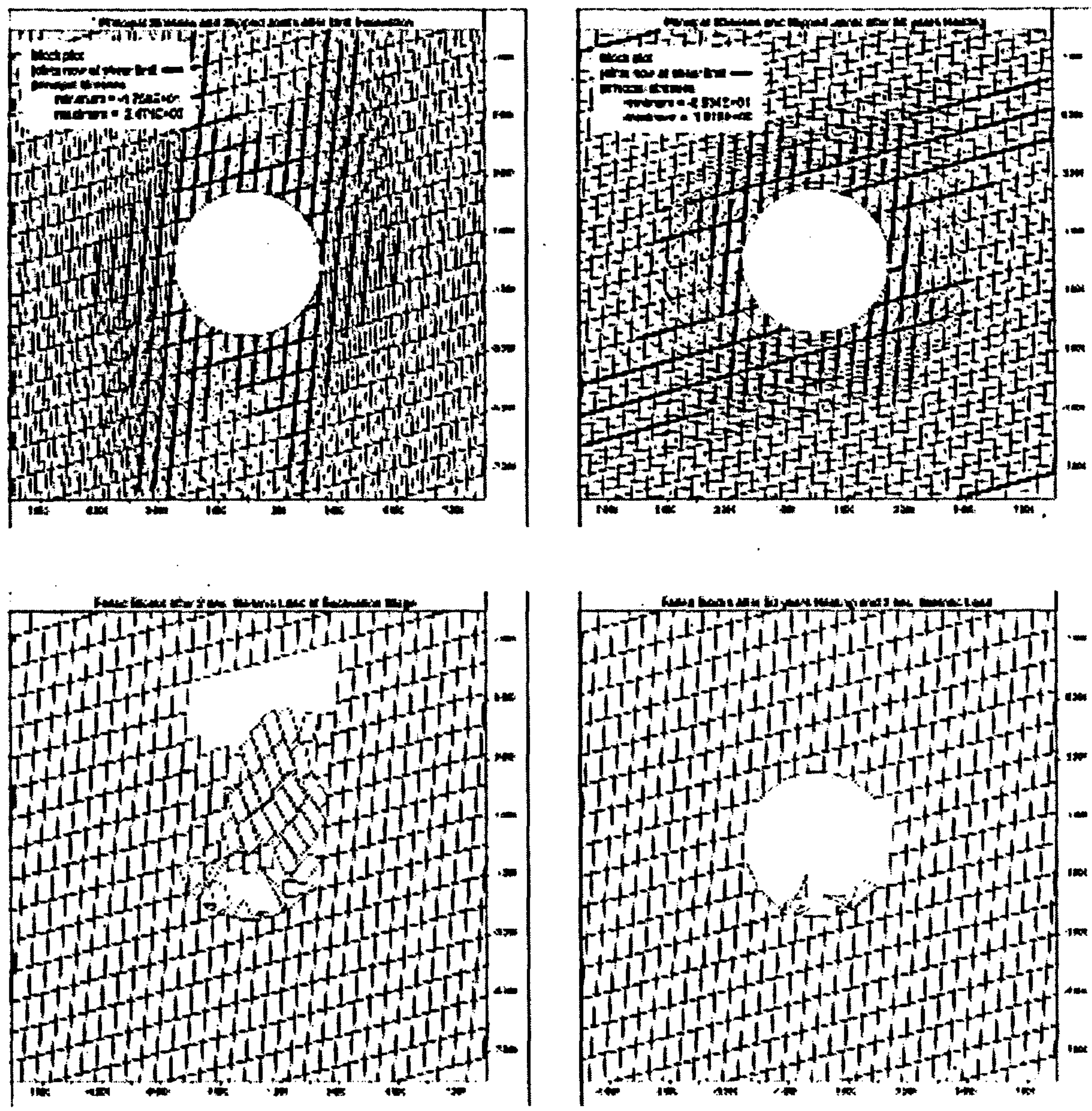


Figure 9. Effect of Heating (a,c) on Drift Stability and Seismic Event Before (b) and During (d) Heating

Thus, the consequences of a seismic event will depend very much on when the event occurs with respect to the thermal loading produced by the waste package. Upon cooling, the induced thermal stresses will disappear, and some additional collapse could occur. It was found, during the study of seismic effects mentioned above, that the second seismic event in each case caused little additional rockfall. However, the effect of time-dependent weakening of the rock mass was not considered. It seems probable that additional collapse would occur if this factor were added.

Figures 10(a)—10(d) show the results of numerical modeling to simulate various support options and assumed rock conditions.

The rock joints are assumed to have an initial (high) friction angle of 56° and a cohesion of 0.07 MPa. Other properties are those for RMQ5 rock (as defined by the M&O contractor). The reinforcement [grouted bolts (c)],or support [concrete (d)] is then installed, or the drift is left unsupported [(a), (b)] depending on the case considered. The rock is then heated to 100 °C. Joint slip and rock failure occur. Then, in order to simulate time-dependent degradation of the rock joints, the joint friction angle is reduced to 35°. Except for case (b), the joints are all assumed to be continuous. In case (c), the joints are *non-persistent*, consisting of alternate l-m-long segments of intact rock and joint, for which the friction angle is degraded to 35°.

Results indicate that the extent of the damage zone depends primarily on the frictional properties of the joints. Non-persistent joints (case (b)) behave essentially as intact rock, so that the extent of the damage zone is significantly reduced compared to that produced with continuous joints (case (a)); see the discussion of the lithophysal rock zone, below. Grouted rock bolts (case (c)) reduce considerably both the slippage on joints and the extent of the damaged region. Case (d) indicates that the elastic liner installed with a gap between the crown of the drift and the top of the liner to simulate a noncontinuous liner/rock contact does little to reduce the extent of damage compared to the case in which there is no support (case (a)), although the liner does, of course, prevent the rock fallout that would be very likely to occur in case (a).[8]

Lower Lithophysal Rock Zone

A brief analysis of the mechanical properties of lithophysal tuff (see Figure 11 and related discussion) suggests that the overall mechanical response to stresses (including thermal stresses) in these zones may be less influenced by joints and joint slip than is the case in the non-lithophysal zones. Thus, the rock mass strength in the lithophysal tuff may be somewhat higher, but the modulus of deformation will also be higher. Because the induced thermal stresses are directly related to this modulus, the *ratio* of stress:strength will change less. It seems, therefore, that from the mechanical stability perspective, drifts (e.g., for a multi-level repository) may be located in either or both lithophysal and non-lithophysal regions.

Both the Nuclear Waste Technical Review Board (NWTRB) and the NRC have criticized DOE for its failure to determine the insitu mechanical properties of the lower lithophysal rock, in which approximately 70% of the repository will be located. (Most of the rock properties have been determined for other, non-lithophysal units.)

An analysis was conducted to assess the influence of the lithophysae (assumed to be spheres) on the strength of the rock mass. Since, as noted in the discussion of Figure 10 case (b), non-persistent joints tend to exhibit the same strength as the intact rock in which they are found, the analysis assumed that the rock around the lithhophysae had the same properties as those defined by RMQ5. As stresses are increased (in this case, due to heating) on the rock, the lithophysae behave essentially as interior (spherical) excavations, i.e., stress concentrations occur around the

[8] These analyses were made available, courtesy of Dr. R. Hart of Itasca Consulting Group Inc. Dr. Hart is a member of the Drift Stability Panel, for which the analyses were conducted.

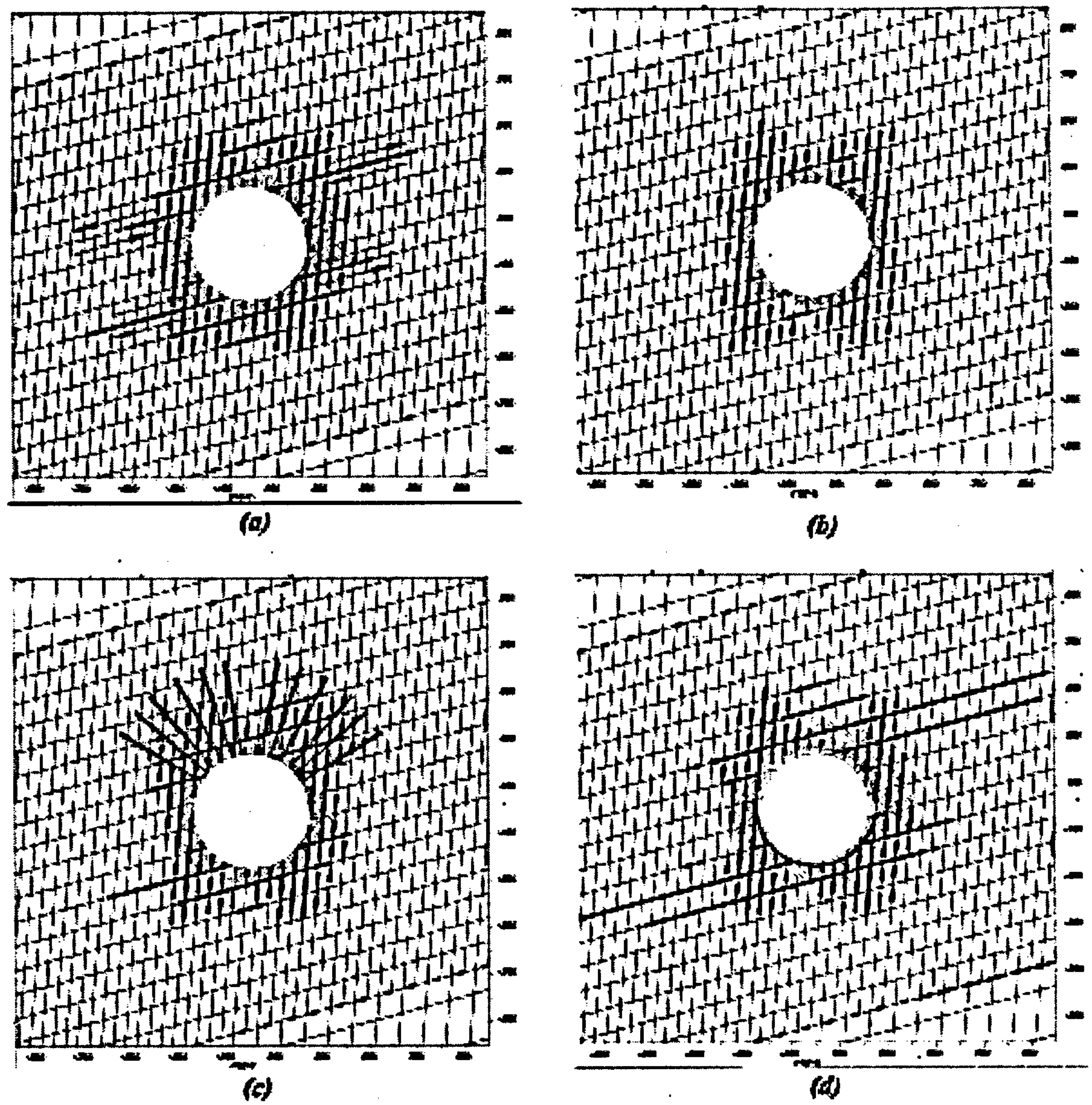
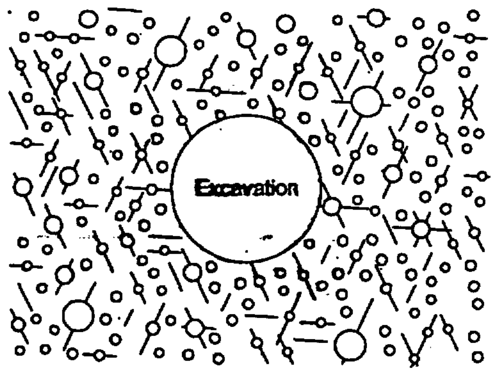
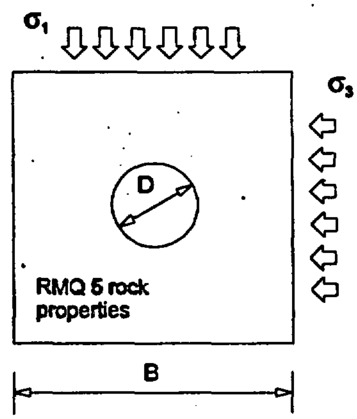


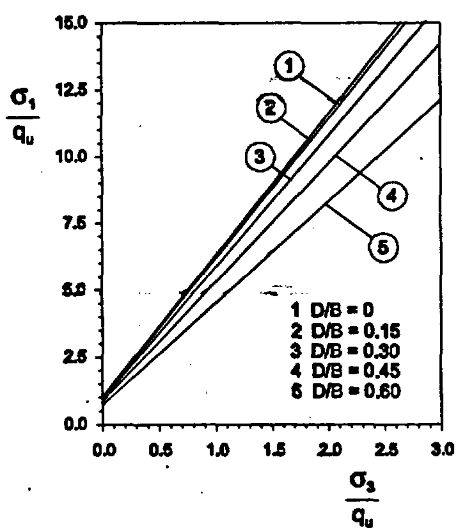
Figure 10. Effect of Long-term Degradation of Rock Joints Properties on Extension of Inelastic Failed Rock Zone for (a) Unsupported, Regularly Jointed Rock; (b) Unsupported, Non-persistent Jointing; (c) Reinforced by Jointed Rock Bolts; and (d) Supported by Elastic Concrete Support



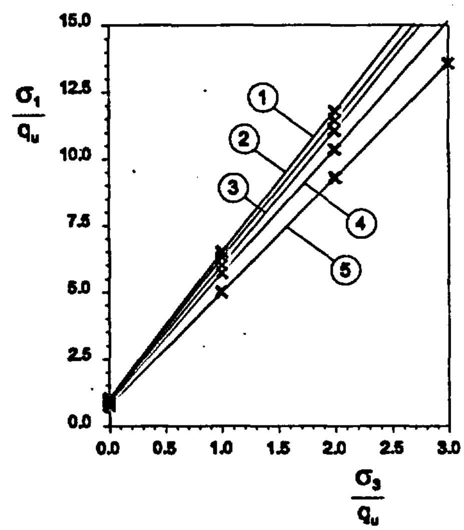
(a) Idealized representation of excavation in Lithophysae Tuff.



(b) Model analyzed in calculations.



(c) 'Tributary area' yield envelopes..



(d) FLAC^{3D} yield envelopes.

Note. Tributary area strength in (c) is calculated from the expressions,

$$\frac{\sigma_1}{q_u} = \left[1-\frac{\pi}{4}\left(\frac{D}{B}\right)^2\right]K_p\frac{\sigma_3}{q_u} + \left[1-\frac{\pi}{4}\left(\frac{D}{B}\right)^2\right] \qquad K_p = \frac{1+\sin\phi}{1-\sin\phi}$$

where q_u is the unconfined compressive strength and ϕ is the friction angle [with these intact rock properties, the yield envelope is given by line 1 in (c) and (d)].

The FLAC3D analysis also yielded the following results for the influence of the lithophysae on the overall modulus of deformation (E) of the lithophysae rock compared to the modulus of the rock without the lithopysae (E').

D/B	0.0	0.3	0.45	0.6
E/E'	1.0	0.96	0.89	0.78

Note E' in the FLAC3D analysis was 7.76GPa.

Figure 11. Predicted Rock Mass Strength (Mohr-Coulomb) Envelopes and Modulii of Deformation for Lithophysal Tuff (Intact rock between lithophysae is assumed to have RGM 5 mechanical properties.)

lithophysae and, eventually, the rock around the spherical periphery will begin to "collapse" into the lithophysal cavity.

The model analyzed is shown in Figure 11(b). B is assumed to be the width of a cubical region containing one cavity, diameter D. Various ratios of B:D were considered. The reduction in strength of the cube of rock containing the cavity, compared to the strength of a cube without a cavity (B/D = 0) is shown in Figures 11(c) and11 (d).

Two approaches are taken. In the so-called *tributary area* method (frequently used for room and pillar design in mines), it is assumed simply that the strength is reduced in proportion to the reduction in cross-sectional area of the center section of the cube containing the spherical cavity. In the second approach, a three-dimensional numerical analysis (FLAC3D) was carried out. The strength limit was assumed to be reached when inelastic deformation started at the wall of the sphere. Results are shown in Figures 11(c) and 11(d). Although the FLAC3D results indicate slightly higher strengths for a given cavity size, the difference between the two approaches is small (maximum about 18% for D/B = 0.6), and the tributary area approach is conservative (i.e., it underestimates the strength of the rock). Thus, it seems sufficient to use the tributary area method in calculations involving the rock-mass strength of the lithophysal zone.

The FLAC3D analysis also yielded results for the influence of the lithophysae on the overall modulus of deformation (E) of the lithophysal rock compared to the modulus of the rock without the lithophysae (E*). Results (tabulated in Figure 11) indicate that the reduction in E is also small, and follows a similar trend to that of the strength reduction.

It is recommended that laboratory tests be carried out on intact samples (taken between lithophysae) to establish the envelope corresponding to D/B = 0, and then to estimate an average value of D/B from exposures in drift walls. This information can then be used, with Figure 10(c), to establish an envelope for the rock mass strength.

Actual lithophysal voids tend to be ellipsoidal rather than perfectly spherical. Although it is feasible to generate ellipsoidal cavities and analyze them numerically, the effect of such cavities will depend on their distribution in size and orientation with respect to each other and to the applied stress field. As a first approach, over-conservative but simple approximation, the voids could be assumed to be "replaced" by spheres of diameters equal to the major axis of the ellipsoid. (A less conservative option would be to assume spheres of diameter equal to the mean of the major and minor axes of the ellipsoids.) The approximate expressions presented in Figure 11 could then be used.

Use of Concrete for Excavation Support

Concern has been expressed that the use of concrete, as is popular, in concrete and "shotcrete" linings and in the cement grouting of rock bolts[9] would result in a high pH of water entering the drift. This could have numerous adverse consequences (for example, on the radionuclide retardation capability of materials that may be placed below the waste packages, or

[9] Note that resin grouts are not favored, as they are organic compounds.

that exist below the repository, e.g., zeolites) in order to retard the movement of radionuclides e.g., neptunium.

Discussions with concrete technologists reveal that it is possible to avoid high-pH water (e.g., by carbonating the cement, using carbon dioxide). The carbonation reaction has been studied extensively (it occurs naturally in concrete due to the effects of carbon dioxide in the atmosphere), and it appears possible to engineer a solution to avoid high-pH water. Also, the strength (and ductility) of concrete can be increased considerably compared to standard concretes traditionally used in construction. Although care should be taken to ensure that adverse effects are avoided, it is recommended that drift support designers not be prevented from taking advantage of the merits of shotcrete and grouted bolts, both of which could play a valuable role in drift support at Yucca Mountain.

Most of the designs showing precast concrete lining or steel sets in the (circular) drifts (admittedly idealized) indicate that the linings/sets are in intimate uniform contact with the drift wall. In reality, of course, there will be irregularities in the wall profile. Normally, these would be filled with cement grout to ensure that the lining is uniformly loaded. Sand *backpacking* can be substituted, but it is important that analysis of the lining support include consideration of the influence of such irregularities and fill methods on the bending stresses generated in the support during the thermal cycle.

The writer believes that a well-designed system of grouted rock bolts, mesh, and shotcrete will be sufficient to ensure stable openings during the preclosure period. Precast concrete linings or steel set supports, which would be very expensive, will not be needed.

Upper-Bound to Collapse Region

A simple estimate of the maximum extent of collapse around an unsupported tunnel can be made as follows.

Consider a circular tunnel, of radius a, surrounded by a circular zone of damaged rock, radius V. When rock is damaged, slip along joints and dilation occur, rock may collapse into the tunnel, etc. (i.e., the damaged rock will occupy a greater volume than when it was intact and undisturbed; it is said to undergo "bulking"). Let us assume that the rock is damaged to a radius b ($b > a$). If we assume that the broken rock has a bulking factor (i.e., unit volume of unbroken rock occupies a volume $(1+k)$ in the broken state), we may determine the volume of unbroken rock in the annulus $(b - a)$ that, upon breaking, will fill the excavation. Thus, we have

$$\pi (b^2 - a^2)(1 + k) = \pi b^2$$

from which we obtain

$$\frac{b}{a} = \left(\frac{1+k}{k} \right)^{0.5}$$

For a value of $k = 10\%$ (10% to 25% is considered to cover most mining collapse situations), we find $b/a = 3.3$. For $k = 25\%$, $b = 2.2$.

Thus, the maximum possible extent of the damage zone around a repository tunnel will be of the order of three tunnel radii. Beyond this region, the rock will contain joints and fractures similar to those in the virgin rock mass. Hence, for calculation of post-thermal cycle water influx to the tunnel, such a model should suffice.

Heated drift experiments and niche tests are unlikely to resolve several important post-thermal cycle inflow issues. The effect of the thermal cycle on the mechanical properties of the rock mass, information that would have been very useful in drift stability analysis, appears to be a secondary consideration in these experiments compared to the hydrological issues. There has been no modeling of the effect of discrete jointing on rock mass behavior, for example. (Appendix II shows a preliminary study to illustrate what is possible.) Acoustic emission (micro-seismic) studies have only recently been added, and an opportunity to observe the rock-mass response from the onset of loading has been missed. Some microseismic equipment has now been installed, and data are being collected. Collection of such data can be very valuable in establishing which joints are slipping, and this information can be used to calibrate numerical models that contain such discrete features. (Figure 12 illustrates the microseismic network set up for the mine-by experiment at the Underground Research Laboratory in Canada, together with the locations of the microfracturing (detected by acoustic emission) induced by excavation. The network was installed before the mine-by excavation was started.)

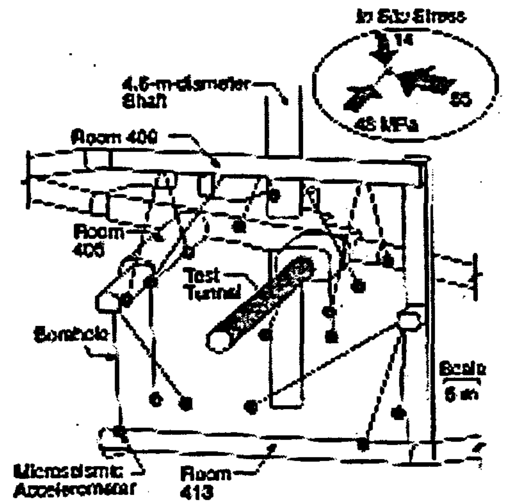


Figure 1: Layout of the 420 Level showing the location of the Mine-by test tunnel, the microseismic monitoring system and Room 405, the location of the borehole breakout study.

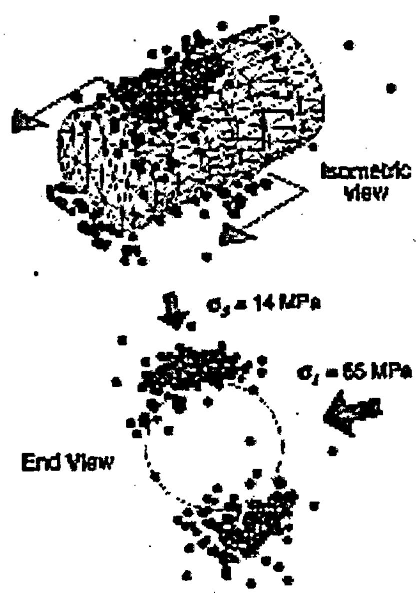


Figure 13: Location of microseismic events recorded after the excavation of a 1-m-long round in the test tunnel.

Figure 12. Mine-by Experiment, Underground Research Laboratory, Pinawa (Read and Martin, 1996)

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Appendix I

Steady Vertical Unsaturated Infiltration Through an Array of Horizontal Drifts

Assumptions

Validity of Richard's equation with equivalent unsaturated properties. Isothermal medium.

$$\nabla\cdot(\mathbf{K}K_r(\psi)\nabla(\psi+z)) = 0$$

ψ : relative pressure head ($\psi < 0$ unsaturated zone, $\psi > 0$ saturated zone) [m]
z : vertical coordinate [m]
K : hydraulic conductivity tensor [m/s]
$K_r(\psi)$: relative hydraulic conductivity ($K_r < 1$ unsaturated zone, $K_r = 1$ saturated zone) [-]

Parametric model for unsaturated conductivity

van Genuchten : $K_r(\psi) = \dfrac{1}{(1+|\alpha\psi|^n)^{m/2}}\left(1-\left(1-\dfrac{1}{1+|\alpha\psi|^n}\right)^m\right)^2$, $m = 1-\dfrac{1}{n}$

Exponential : $K_r(\psi) = e^{\alpha\psi}$

Assumed material properties

Matrix porosity : 0.1
Matrix permeability : $4\cdot10^{-18}$ m^2
Fracture frequency : 4.5 1/m
Fracture aperture : 54 µm

Matrix hydraulic conductivity (isotropic) K_{min} : $4\cdot10^{-11}$ m/s
Fracture hydraulic conductivity (cubic law) K_{max} : $5.85\cdot10^{-7}$ m/s
Homogeneous saturated and residual moisture θ_s, θ_r : 0.1, 0.01
van Genuchten model parameters α, n : 4 1/m, 2
Exponential model parameter α : 10 1/m

2D vertical equivalent hydraulic conductivity tensor (assuming vertical fractures)

$$\mathbf{K} = \begin{bmatrix} \beta K_{max} & 0 \\ 0 & K_{max} \end{bmatrix}$$

Anisotropy ratio β varied from 1 to K_{min}/K_{max}

Geometry

Drifts; diameter - 5 m ;spacing - 80 m (horizontal), 30 m (vertical)
Potential capture zone (per unit width) for a column of drifts : 80 m^2

Boundary conditions

Unsaturating infiltration rate at the surface (i): 50 mm/y ($1.37\cdot10^{-4}$ m/d , $1.59\cdot10^{-9}$ m/s)
Atmospheric seepage at the drifts
Static watertable level at – 200 m

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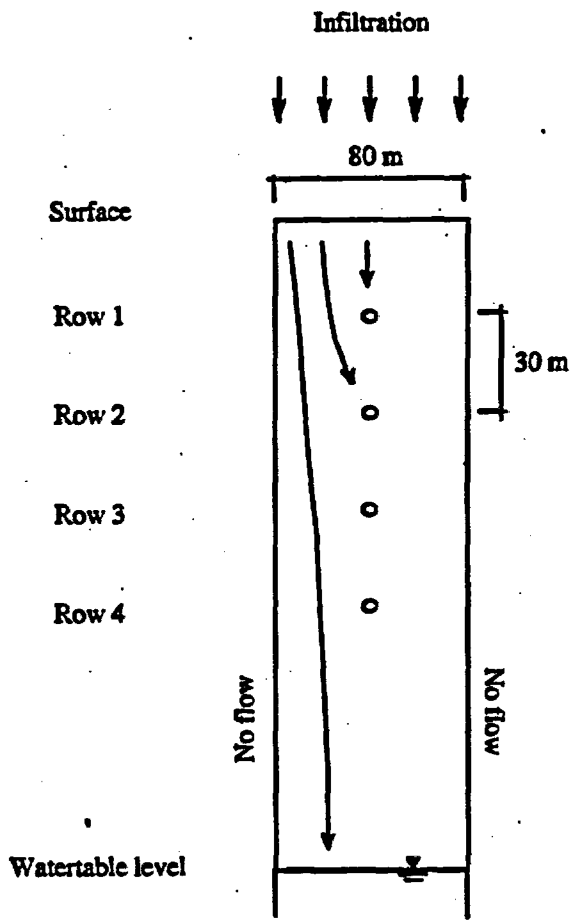
* i.e. 1096 x 10^{-5} m^3/d over the 80 m^2 potential capture area.

Sketch of the flow towards drifts in columns (with symetry conditions)



Discharge rates under steady state unsaturated conditions [10^{-5} m^3/d]

	Case 0 : $\beta = 1$ (isotropic)	Case 1 : $\beta = 10^{-1}$	Case 2 : $\beta = 10^{-2}$
Top infiltration	1096.0	1096.0	1096.0
Drifts at – 30 m	– 0.0	– 0.0	– 35.6
Drifts at – 60 m	– 0.0	– 0.0	– 0.0
Drifts at – 90 m	– 0.0	– 0.0	– 0.0
Drifts at – 120 m	– 0.0	– 0.0	– 0.0
Bottom drainage	– 1096.0	– 1096.0	– 1060.4

	Case 3 : $\beta = 10^{-3}$	Case 4 : $\beta = 10^{-4}$ ($\approx K_{min}/K_{max}$)	Case 5 : $\beta = 0$
Top infiltration	1096.0	1096.0	1096.0
Drifts at – 30 m	– 58.0	– 60.3	– 68.5
Drifts at – 60 m	– 6.1	– 7.0	– 0.0

Drifts at – 90 m	– 3.2	– 2.4	– 0.0
Drifts at – 120 m	– 2.9	– 2.0	– 0.0
Bottom drainage	– 1025.8	– 1024.3	– 1027.5

Remarks

Under unsaturating vertical infiltration, buried cavities may behave as obstacles to the flow and so increase water relative pressure head at parts of the cavity surface. Gravity dripping into the cavity occurs only at those points where the pressure head reaches the pressure inside the cavity (e.g., atmospheric pressure). Under uniform infiltration the first point reaching this pressure is the highest point of the cavity roof.

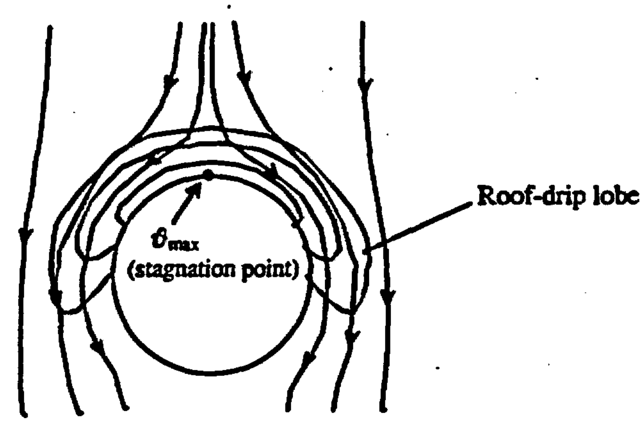
An analytical solution exists for horizontal cylindrical cavities in an isotropic medium (Philip and Knight, 1989, *Water Resources Research*, 25, 16-28). Assuming an infinite vertical medium submitted to constant, uniform unsaturated seepage, the question as to whether or not water drips into a circular section centered at the origin is answered in a straightforward manner with the following simple rule

$$\text{if} \quad i < \frac{K_{sat}}{\vartheta_{max}(s)} \quad \text{no dripping in the cavity, dripping otherwise}$$

In this (exact) formula i [m/s] is the specified uniform infiltration rate, K_{sat} [m/s] is the saturated isotropic hydraulic conductivity and ϑ_{max} is a normalized Kirchhoff potential. Its value is maximum at the top of the circular section and can be approximated with excellent practical accuracy by

$$\vartheta_{max}(s) \approx \begin{cases} 2s+1 \ , & \text{for small values of } s \\ 2(s+1) \ , & \text{for large values of } s \end{cases} \qquad , \qquad s = \frac{\alpha D}{2}$$

where s is a dimensionless quantity defined by the decay parameter (α) of the Exponential model for the relative conductivity, and by the cavity diameter (D). Small s indicate capillarity dominated seepage, tending to divert water around the cavity, whereas gravity is dominant for larger values. Moreover, the larger the cavity the more vulnerable it is to water entry.



Iso-ϑ around the cavity and seepage flow lines

In the present situation ($s = 10 \cdot 5/2$) no dripping occurs into the cavity since the above inequality is satisfied ($1.59 \cdot 10^{-8} < 5.58 \cdot 10^{-6} /52$). The infiltration rate could actually be increased by, roughly, a factor 10 before droplets form at the top of the cavity. Alternatively, the isotropic saturated hydraulic conductivity could be reduced, or the cavity diameter increased by the same factor, to produce dripping into the cavity.

These theoretical considerations explain why the drifts remain dry in Case 0 and to a certain extend in cases with mild anisotropy (i.e., Case 1). As anisotropy becomes larger, horizontal capillary flow becomes less significant and water cannot be diverted around the cavity surface with the same magnitude any more.

As a result, saturation increases and dripping starts in the first drift (Case 2), while the drifts below remain dry because the roof-drip lobes coming from above are too diffuse (capillarity is still active) to generate saturation conditions there.

At larger anisotropy ratios (Case 3 and Case 4) the lower drifts become gradually active, but in a manner that is not straightforward to understand. There are obviously highly non-linear effects (the decay coefficient α is rather large) combined to the anisotropy ratio. Numerical effects due, for instance, to mesh orientation and refinement around the drifts may also be present. However, several grid size were enforced (the finer with node spacing of the order of 0.2 m around the drifts) yielding the same type of results. More investigations (including analytical ones) are needed to understand the flow processes (e.g. use of finer meshes and various solution schemes, columns with more drifts, etc), particularly at high anisotropy ratios.

With zero horizontal conductivity (Case 5) the first drift theoretically captures the quantity of water given by iD (i.e., $68.5 \cdot 10^{-5}$ m^3/d in the present case) and by-passes the drifts vertically below.

Appendix II

Numerical Simulation of the Effects of Heating on the Permeability of a Jointed Rock Mass

B. Damjanac, C. Fairhurst and T. Brandshaug

Itasca Consulting Group, Inc.
708 South Third Street
Suite 310
Minneapolis, Minnesota 55415

To be presented at the 9th ISRM Conference (Paris, August 1999)

Numerical simulatic of the effects of heating on th permeability of a jointed rock mass

Simulation numérique des effets d'une augmentation de température sur la perméabilité d'une masse rocheuse fissurée

Numerische Simulation der Hitzeeinwirkung auf geklüftetes Gebirge

B.DAMJANAC, C.FAIRHURST & T.BRANDSHAUG, Itasca Consulting Group, Inc., Minneapolis, Minnesota, USA

ABSTRACT: One of the objectives of the Drift Scale Test (DST), currently underway at Yucca Mountain, USA, is to assess the effect of large-scale heating on the permeability of the rock mass. The DST is simulated using continuum and discontinuum models to predict the change in permeability in the rock mass surrounding the heated drift. The simulations show that heating will cause both reduction in permeability (in regions of increasing mean stress) and increase in permeability (in regions of non-linear shear deformation—slip). Although the elasto-plastic (ubiquitous joint) continuum model and the distinct element model (DEM) indicate similar regions of joint slip in the rock mass, the resulting change in permeability can be calculated much more easily from the DEM.

RÉSUMÉ: Un des objectifs de l'essai DST (Drift Scale Test), en cours au site de Yucca Mountain, Etats Unis, est l'évaluation de l'effet d'une variation thermique sur la perméabilité de la masse rocheuse, à l'échelle de la galerie. L'essai DST est simulé numériquement à l'aide de modèles continu et discontinu afin de prédire le changement de perméabilité de la masse rocheuse entourant la galerie lorsqu'elle est soumise à une augmentation de température. Les simulations numériques montrent que l'échauffement cause à la fois une réduction (dans les régions d'augmentation de la contrainte moyenne) et une augmentation de perméabilité (dans les régions de déformation non-linéaire en scisaillement–glissement). Bien que les modèles continu élastoplastique (ubiquitous joint) d'une part et d'élements distincts (DEM) d'autre part prédisent des zones similaires de glissement de joint dans la masse rocheuse, la méthode DEM se prête plus aisément au calcul des changements de perméabilité.

ZUSAMMENFASSUNG: Eine der Aufgabenstellungen des "Drift Scale Tests - DST", der gegenwärtig im Yucca Mountain Projekt in den USA durchgeführt wird, ist es, den Effekt von großräumiger Erhitzung auf die Permeabilität des Gebirges zu untersuchen. Der DST wurde durch Kontinuums- und Diskontinuumsmodelle simuliert, um die Änderungen der Permeabilität im Gebirge um den erhitzten Teil zu prognostizieren. Die Simulationen zeigen, daß die Erhitzung sowohl eine Reduzierung der Permeabilität (in Regionen erhöhter mittlerer Spannungen) als auch eine Erhöhung der Permeabilität (in Regionen nicht-linearer Scherdeformationen - "slip") bewirkt. Obwohl das elasto-plastische (verschmierte Klüfte) kontinuumsmechanische Modell und das Distinkt-Element-Modell (DEM) ähnliche Bereiche von Scherbewegungen auf Klüften ausweisen, kann die resultierende Änderung der Permeabilität über die DEM wesentlich einfacher bestimmt werden.

1 INTRODUCTION

A main objective of the ongoing Drift Scale Test (DST) at Yucca Mountain, Nevada, USA, is to assess the effect of large-scale heating (intended to simulate the heating produced by stored high level nuclear waste) on the permeability of the rock mass. The DST is conducted in fractured, densely welded, ash-flow tuff at the proposed repository horizon in Yucca Mountain. The permeability of this rock mass is controlled primarily by natural fractures in the rock; the matrix permeability is very small.

This paper discusses the results of numerical analyses carried out to examine the effect of heating around the DST on the change of permeability in the surrounding rock. Continuum models of a fractured medium (e.g. the ubiquitous joint model) provide reasonable approximation of the rock mass when: (1) the joint spacing is small relative to the characteristic dimensions of the problem, and (2) the joint properties are uniform (i.e. there are no joints in the set that have an aperture and transmissivity substantially greater than that of other joints). Determination of the constitutive relations needed to allow accurate prediction of the change in permeability of such a rock mass when deformed is especially difficult with continuum models. The relationship between deformation and permeability can be represented much more directly in models (such as the distinct element method), that simulate explicitly the effect of joints on deformation and fluid transport.

Given the actual geometry of the excavations and joints, rigorous interpretation of the effect of heating on joint aperture and permeability changes and flow in the drift experiment requires a three dimensional model. *3DEC* (Itasca Consulting Group, Inc. 1998a) was used to consider this influence. However, since a coupled thermo-mechanical-hydrological analysis of a fractured rock mass is computationally intensive, the main part of the analysis in this study has been carried out using the two-dimensional Universal Distinct Element Code, *UDEC* (Itasca Consulting Group, Inc. 1996). The continuum code *FLAC* (Itasca Consulting Group, Inc. 1998b) was also used to estimate the regions of non-linear deformation (i.e. the regions where the rock permeability changes) induced in the rock mass by heating. Comparison of results obtained using different models and codes (continuum; discontinuum, two-dimensional; three-dimensional) has proven to be very valuable in verifying the assumptions used in development of the analyses and may guide the use of particular models in further analysis.

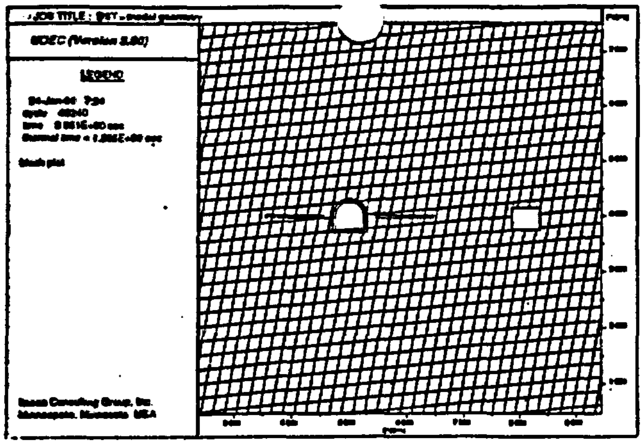


Figure 1. Geometry of the two-dimensional discontinuum model

2 DESCRIPTION OF THE MODELS

The heated drift is a 5 m × 5 m excavation of "horse-shoe" cross-section (see Fig. 1). The observation drift is rectangular, 5 m × 4 m in cross-section. A three-dimensional model of the DST was generated using *3DEC*. Figure 2 shows the lower half of this model (i.e. from the drift horizon downward). Three joint sets are represented. Joint set 1 has a dip of 77° and dip direction of 40°; set 2 has a dip of 80° and dip direction of 130°; set 3 has a dip of 25° and dip direction of 300° (Wagner 1996a). The joint spacing in each set is 10 m. The vertical cross-section, perpendicular to the axes of the drifts (from the *3DEC* model), coincides with the plane of the two-dimensional models used for simulation of the DST.

Figure 1 shows the joint sets 1 and 3 in the two-dimensional *UDEC* model. The joints in the two-dimensional model are spaced 2 m apart—i.e. much closer than the 10-m spacing in the three-dimensional model. (The coarser spacing in the *3DEC* model is dictated by the heavy computational demands of three-dimensional analysis.)

The rock was considered to be linearly elastic and isotropic, and to have the properties (Birkholzer & Tsang 1996) shown in Table 1. The response of the joints to deformation normal to the joint plane is assumed to be linearly elastic for compressive stresses (Joints can not sustain tension.); the response to shear deformation is assumed to be linearly elastic-perfectly plastic according to the Mohr-Coulomb slip condition. Slip of the joints is associated with

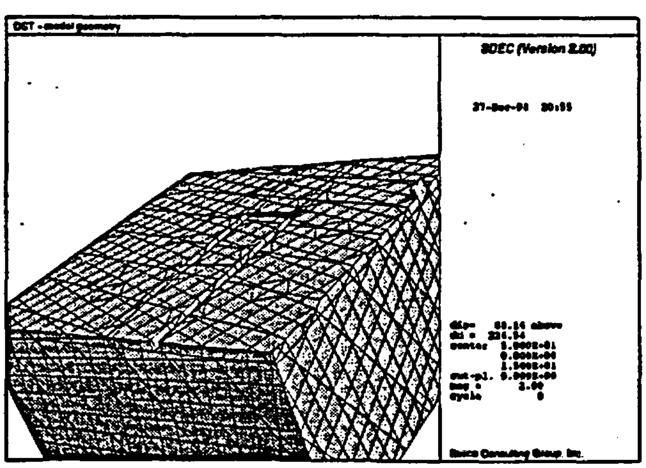


Figure 2. View of three-dimensional model (blocks above the drifts are hidden)

dilation—i.e. joint [illegible]ing.

Table 1. Properties of the rock

Density, ρ	2540	kg/m^3
Young's modulus, E	32.4	GPa
Poisson's ratio, ν	0.17	
Thermal conductivity, k_t	1.67	W/m°K
Specific heat, c_t	928	J/kg°K
Coefficient of thermal expansion, α	10^{-5}	

"Fast paths", joints or fracture zones with much higher initial permeability (i.e. initial hydraulic aperture) than the other joints, are known to occur at Yucca Mountain. It is also expected that fast paths will be more compliant and weaker than the other joints. Two cases were considered in the discontinuum models: (1) all joints have the same properties, and (2) "fast-paths" are assumed to exist at several different locations relative to the heated drift. The properties of "typical" rock joints (Olsson & Brown 1997) used in the analysis are shown in Table 2.

Table 2. Properties of the rock joints

Normal stiffness, k_n	200	MPa/mm
Shear stiffness, k_s	150	MPa/mm
Cohesion, c	0.23	MPa
Friction angle, ϕ	42°	

For this analysis, the mechanical properties of the fast paths (shown in Tab. 3) are simulated by reducing the properties of "typical" joints—as can be seen by a comparison of Tables 3 and 2.

Table 3. Properties of fast paths

Normal stiffness, k_n	50	MPa/mm
Shear stiffness, k_s	50	MPa/mm
Cohesion, c	0.05	MPa
Friction angle, ϕ	25°	

The initial state of stress in the rock mass was assumed to be $\sigma_h = -5$ MPa, $\sigma_v = -10$ MPa at the drift level. The initial stresses vary as a function of elevation due to gravity, with a constant ratio maintained between the horizontal and vertical normal stresses. The initial temperature in the rock mass was taken to be constant, at 25°C throughout the model.

Thermal analysis of conductive heat transport was carried out for 4 years. An 800-W/m heat source, provided by heaters located in the square block at the floor of the heated drift, was simulated as a heat flux uniformly distributed along the boundary of the heated drift. The wing heaters are located symmetrically relative to the axis of the heated drift: a planar source of 125 W/m^2 is distributed between 4 m and 9 m from the drift axis, and a planar source of 175 W/m^2 is distributed between 9 m and 14 m distance from the drift axis (Wagner 1996b).

3 JOINT DILATANCY

Joint (normal and shear) stiffness and strength (cohesion and friction angle) are properties that affect the dependency of the permeability (of the joints and rock mass) on the imposed mechanical loading. However, the joint dilation angle ψ has the most profound effect on the dependence of the per[illegible]bility to shear deformation of a rock joint.

The joint dilation angle, the measure of joint opening as a result of joint slip, is a function of:

1. shear deformation (Dilation is usually large during the initial slip deformation, decreasing with slip accumulation.); and
2. stress normal to the joint plane (confinement). (Dilation is a consequence of joint roughness. The relative movement of rock blocks cannot be strictly parallel to the plane of the joint between them, since joint roughness enforces some displacement normal to the joint plane. At very high normal stresses, the joint asperities can be sheared-off, resulting in a reduced or zero dilation angle.)

Olsson & Brown (1997) reported joint dilation angles measured on samples taken from the TSw2 geological unit at Yucca Mountain for different confinements. (TSw2 is the repository unit.) The measured dilation angles show large dispersion, varying between 1.11° and 33.4°. As a result, the relationship between confinement and dilation angle is unclear. Therefore, the first-order analyses were conducted using an upper value, $\psi = 30°$, and an average value, $\psi = 14°$, for the dilation angle. It was further assumed in these analyses that the dilation angle was constant, independent of the shear deformation or normal stress. The dilation angle for the fast paths was assumed to be equal to the dilation angle of "typical" joints.

3.1 Numerical Experiment

In order to establish a clearer understanding of the dependence of dilation to shear deformation and confinement for the range of values expected to occur in the model, numerical experiments were conducted to simulate shearing of a rough joint using a shear box—in a manner similar to that described by Cundall (1999). The results from the numerical experiments (i.e. the relationship between peak dilation angle; joint shear displacement, and normal stress) for TSw2 rock and joint conditions were then used in the *UDEC* simulation of the DST.

The micro-mechanical model of the shear box experiment using the Particle Flow Code—PFC^{2D} (Itasca Consulting Group, Inc. 1999), is shown in Figure 3. The bonded assembly of particles (Particles are bonded at contact points.) can be envisioned as a synthetic rock. By adjusting the contact stiffness (shear and normal) and strength (shear and tensile), this "rock" was made mechanically similar to the TSw2 rock. The length of the specimen in Figure 3 is 0.10 m, and the height is 0.04 m. The joint trace is indicated by the continuous black lines transecting the specimen from left to right. The particles at or adjacent to this line are left unbonded. The black particles along the boundary of the specimen are designated as the shear box. The shear box particles below the joint trace are fixed, while those above the trace are assigned a constant horizontal velocity. The joint trace was produced using the following decreasing power law power spectrum (Brown 1995):

$$G(k) = Ck^{\alpha} \tag{1}$$

where C is a constant; $k = 2\pi/\lambda$;λ is the wavelength; $\alpha = 5 + 2D$; and D is the fractal dimension of joint surface. Joint topography data provided by Olsson & Brown (1997) for specimen YM30 taken from the repository unit TSw2 were used. Numerical

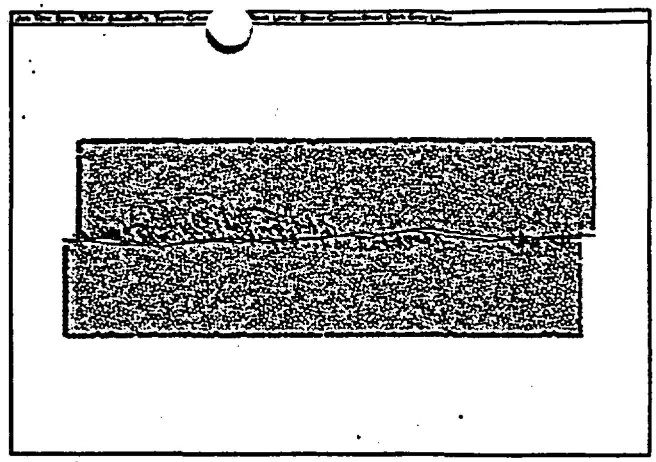


Figure 3. PFC model of a shear box test

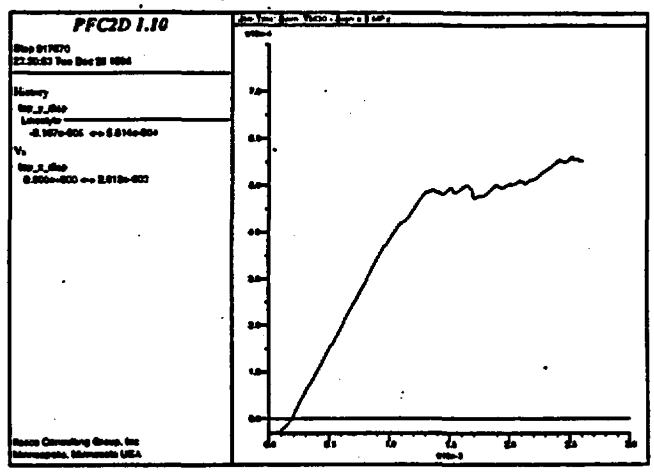


Figure 4. Vertical (m) versus shear displacements (m)

tests were conducted for normal stresses of 2.5, 5, 10, 15, 20, and 25 MPa. Figure 3 shows the specimen after a significant amount of shear for a normal stress of 5 MPa. The short black lines indicate locations of tensile cracks in the specimen, while the dark gray lines indicate shear cracks. Note that a significant amount of damage can be attributed to tensile cracking (i.e. particle contacts failing in tension). The test in Figure 3 predicted a peak shear strength of 6 MPa after 0.2 mm of shear displacement. Figure 4 shows normal displacement (m) (i.e. dilation) versus shear displacement (m) for the test in Figure 3. (Figure 4 suggests a peak dilation angle of 28°.)

The results from the numerical experiments were simplified as a bi-linear relationship between dilation and joint shear displacement. (This relationship is defined by a constant dilation angle and a shear displacement at which dilation becomes zero.) The dependence of the dilation angle and the zero dilation shear displacement on the confinement, as obtained from the numerical experiments (shown in Table 4), was implemented in the *UDEC* model of DST to provide a better approximation of the dilation behavior of the joints.

Table 4. Approximate relationship between joint dilation, zero dilation shear displacement, and normal stress for YM30

Normal stress (MPa)	2.5	5.0	2.5	10.0	15.0	25.0
Dilation angle (°)	42	28	16	15.5	13.0	12.0
Displacement (mm)	1.0	1.5	2.5	2.5	2.5	2.5

4 . MODELING RESULTS

4.1 Temperature fields

It was assumed in all simulations (*FLAC*, *UDEC* and *3DEC*) that conduction is the only mode of heat transfer in the rock mass. In fact, boiling of pore water is likely to occur in the rock around the heated drift because of the high temperatures. This effect has been analyzed in models of heat and fluid transport by Buscheck (1998).

The temperature distributions due to heat conduction are almost identical for the continuum and discontinuum models. The contours (°C) after 4 years of heating are shown in Figure 5.

4.2 Deformation in the two-dimensional continuum models

The ubiquitous joint model is a continuum, elasto-plastic model in which an anisotropic strength of the rock mass is taken into account—i.e. there are predefined planes of weakness. The strength in the planes of weakness was assumed to be equal to the joint strength as given in Table 2. The markers shown in Figure 6 indicate slipping along the planes of weakness corresponding to sub-vertical joint set from Figure 1.

The ubiquitous joint model predicts the deformation and the region of joint slip in the rock mass. To assess the change in permeability produced by this deformation and slip, it is necessary to establish a constitutive relation between deformation (volumetric and shear) and the change in permeability. In the case of the distinct element method, the joint deformation is calculated, and it is usually assumed that the change in the joint hydraulic aperture is equal to joint normal displacement (i.e. closing and opening).

4.3 Deformation in the two-dimensional discontinuum models

The discontinuous model of the rock mass in which the joint properties are taken to be uniform shows a complex response to the perturbation induced by heating (Fig. 7). In general, it is possible to identify two regions exhibiting significantly different responses. In the immediate vicinity of the drift, the joints tend to close as a consequence of an increase in the compressive stress normal to the joint planes. Both the maximum closure and the region over which the joints close increase with the duration of heating. Joints from both sets (sub-vertical and sub-horizontal) tend to close, but the sub-vertical joints close more. Above and below the region of joint closure, the sub-vertical joint set dilates (opens) as a result of shear slip. Both the extent of the region where joints are opening and the value of the maximum opening increase as a function of the duration of heating. The maximum opening is more than twice as large as the maximum closure. The effect of dilation angle is significant. The maximum opening in the model with a 30° constant dilation angle (1.5 mm) is two to three times larger than in the model with a 14° dilation angle (0.6 mm). The maximum opening in Figure 7, which shows results for variable dilation angle calculated from the *PFC* model, is 1.2 mm. The regions of slip along joint set 1, as calculated in *UDEC*, agree remarkably well with the regions of plastic deformation indicated by the *FLAC* ubiquitous joint model.

The actual position of possible fast paths relative to the heated drift is unknown. However, the effect of the fast path was assessed by performing a series of simulations for three different assumed locations of the fast paths:

Case 1. The fast path passes through the heated drift.

Case 2. The fast path is offset approximately 15 m to the left of the axis of the heated drift.

Case 3. The fast path is offset approximately 15 m to the right of the axis of the heated drift.

The analysis shows that the effect of the fast path in case 1 is insignificant. The effects of the fast paths in cases 2 and 3 are dramatic. The joint opening and closure for case 3, after four years of heating, is shown in Figure 8. The maximum joint opening caused by slip in cases 2 and 3 is about 6 mm, compared to 1.5 mm in the model with uniform joint properties.

4.4 Deformation in the three-dimensional discontinuum model

The results of the three-dimensional model show that the two-dimensional model is an acceptable approximation of the deformation in the middle of the heated drift. However, deformation of joint set 2, which is neglected in the two-dimensional model, becomes important in the region close to the drift ends, where the temperature field is also three-dimensional.

5 CONCLUSIONS

Comparison of the results of different computational models used to predict the thermo-mechanical response of a jointed rock mass

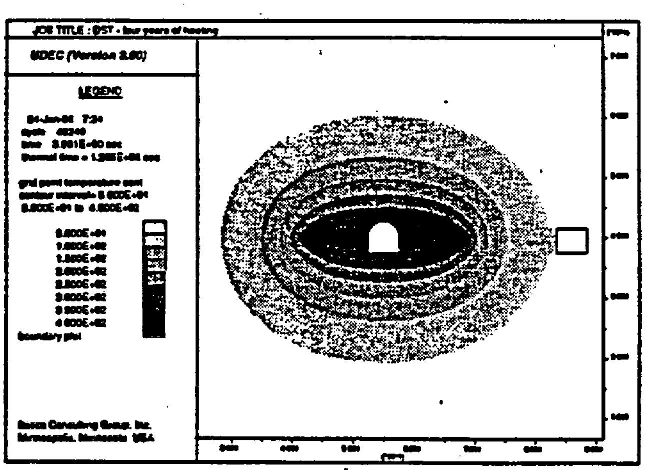


Figure 5. Temperature contours (°C) after 4 years of heating

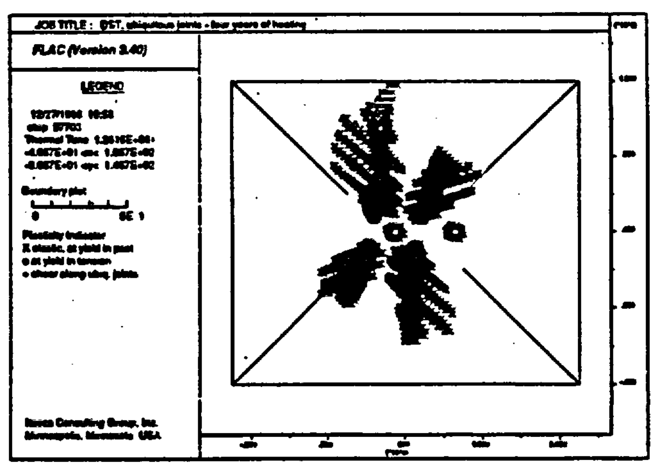


Figure 6. Indicators of slip in the ubiquitous joint model after 4 years of heating

in the vicinity of the DST, indicate following.

1. Continuum, elasto-plastic ubiquitous joint models give a good prediction of the regions in the rock mass over which the joints slip. However, to calculate permeability change as a result of calculated deformation, a constitutive model that relates both volumetric and shear (elastic and plastic) strains to permeability change is required.
2. Discontinuum models are the most effective way to simulate the effects of heating (or any mechanical deformation) on change in permeability of a jointed rock mass. Constitutive relations are also required, but they are more straightforward than in the case of the equivalent continuum. Joint dilation angle and its dependence on accumulated slip and normal stress are important parameters that define the change in permeability produced by joint slip.
3. The two-dimensional model is an acceptable approximation of the deformation in the middle of the drift, even for the case in which orientation of the joints relative to the drifts' axes is slightly oblique.
4. Three-dimensional effects (particularly the deformation of the joint set neglected in the two-dimensional model) become important close to the end of the drift.

The various analyses described above have been used to illustrate the effects of large-scale heating on the hydrological conditions in the rock mass around the drifts in the DST. Increase in temperature produces different effects on the deformation of the rock joints (i.e. both closure and separation) in different regions of the rock mass. In general, shear stresses cause slip on the sub-vertical joints away from the drift, while increase in confinement causes closure of the joints (The sub-vertical joints close more.) in the vicinity of the heated drift. Both regions of opening and closure, and the maximum values of opening and closure in these regions are functions of several parameters, including: (1) intensity of thermal loading, and (2) properties of the rock mass and rock joints (e.g. stiffness, strength, dilation angle, orientation and spacing of joints). The effect of the deformation on the permeability of the rock mass is even stronger in the case when a fast path crosses the regions of large shear stresses induced by heating. The shear deformation and slip localize along the fast path. If a constant (independent of the magnitude of slip and the confinement)

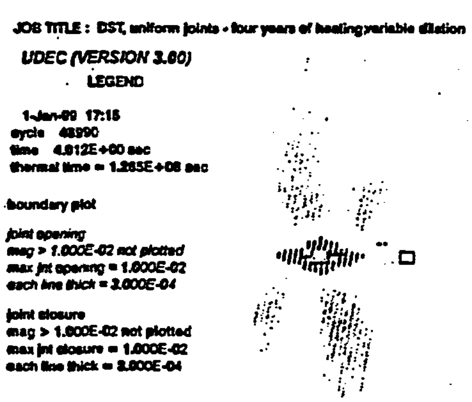


Figure 7. Uniform joint properties, variable dilation angle – opening and closure (m) of joints after 4 years of heating

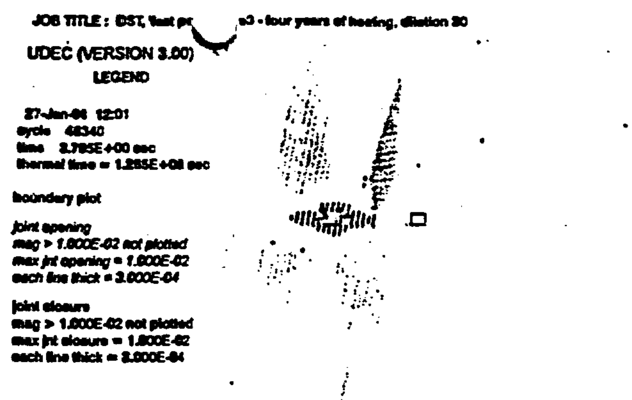


Figure 8. Fast path, case 3, dilation angle 30° – opening and closure (m) of joints after 4 years of heating

dilation angle of 30° is assumed, the opening of the fast path is of the order of six millimeters.

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