ISSUE RESOLUTION STATUS REPORT

KEY TECHNICAL ISSUE: REPOSITORY DESIGN AND THERMAL-MECHANICAL EFFECTS

Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission

Revision 3

September 2000

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Change History of "Issue Resolution Status Report, Key Technical Issue: Repository Design and Thermal-Mechanical Effects"

Revision	Section	Date	Modification
Rev 0	All	September 1997	None. Initial issue
Rev 1	All	September 1998	General editorial and citation format changes
Rev 1	3.1		Table 1 revised to be consistent with repository safety strategy
Rev 1	3.3		Figure 1 replaces the four corresponding figures from Rev 0 Text made consistent with Figure 1
Rev 1	4.1.2		Review methods added
Rev 1	4.1.5		Section added to include GROA design control process review
Rev 1	4.2.2		Review methods added and subsection numbers revised
Rev 1	4.2.3		Acceptance criteria reworded for clarity, and two previous criteria were combined
Rev 1	4.3		Entire section expanded
Rev 1	5.0		Section expanded and renumbered
Rev 1	6.0		References added and changed as necessary
Rev 2	3.3.3	September 1999	Revised
Rev 2	3.3.4		Revised
Rev 2	4.3.3.1		Minor modification to acceptance criteria
Rev 2	4.3.3.2		Technical bases revised
Rev 2	4.3.4.2		Part of technical bases modified and section expanded
Rev 2	5.3		Section expanded and renumbered
Rev 2	5.4		Section revised
Rev 2	6.0		New references added

Change History of "Issue Resolution Status Report, Key Technical Issue: Repository Design and Thermal-Mechanical Effects", Cont'd

Revision	Section	Date	Modification
Rev 3		September 2000	Executive Summary added
Rev 3			Minor format modification
Rev 3	1.0		Discussion added on issue resolution status definition
Rev 3	3.0		Revised to reflect the most current DOE repository safety strategy
Rev 3	4.0		Review methods and acceptance criteria removed
Rev 3	5.0		Major revision (Major addition and some deletion)
Rev 3	6.0		New references added

EXECUTIVE SUMMARY

The focus of the Repository Design and Thermal Mechanical Effects Key Technical Issue (RDTME KTI) is the review of design, construction, and operation of the geologic repository operations area with respect to the preclosure and postclosure performance objectives, taking into consideration the long-term thermal-mechanical processes. Revision 3 of the Issue Resolution Status Report documents the progress made in closing several components of subissues under RDTME KTI. The status of the RDTME KTI subissues is summarized in the following table.

Subissue	Closed	Open	Comment
Design Control Process	Closed		Staff conclusions are based on DOE's simplified document hierarchy; transparency and traceability of flowdown of requirements; and successful resolution of questions raised by NRC during interactions.
Seismic Design Methodology	Closed Pending		Awaiting DOE Seismic Topical Report No. 3 for review by NRC.
Thermal-Mechanical Effects		Open	Concerns on adequacy of data, data reduction approach, modeling approaches, and assumptions for ventilation model are noted. DOE has committed to address concerns related to modeling rockfall impact on drip shield and WPs. Concerns related to rock size calculation and earthquake effects on rockfall are yet to be addressed. Concerns related to thermal-mechanical effect on change in hydrologic properties still remain. Concerns related to screening out drift geometry change from model abstractions need to be addressed.
Repository Seals	Closed		10 CFR Part 63 does not have specific requirements for repository seals.

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ACKNOWLEDGMENTS FOR REVISION 0

Revision 0 of the Issue Resolution Status Report (IRSR) was prepared by M.S. Nataraja, Senior Geotechnical Engineer, Division of Waste Management (DWM), Engineering and Geosciences Branch (ENGB). The author acknowledges the supervision provided by R. Weller (Section Leader), N.K. Stablein (Acting Branch Chief), and the guidance provided by the High-Level Waste (HLW) Review Board. E. Barbely provided her usual enthusiastic secretarial support. A number of key technical issue leads have provided inputs at various stages of completion of this IRSR. The Performance Assessment (PA) and Integration Section of the PA and HLW Integration Branch reviewed the drafts and assisted the author in making this IRSR uniform with the other current IRSRs. Lastly, C.W. Reamer, in the Office of the General Counsel, reviewed the draft for any legal objections.

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Revision 1 of the IRSR was prepared by U.S. Nuclear Regulatory Commission (NRC) staff M.S. Nataraja, DWM/ENGB, and S.M. Hsiung, G.I. Ofoegbu, R. Chen, A. Ghosh, and A.H. Chowdhury, Center for Nuclear Waste Regulatory Analyses (CNWRA). D. Rom, DWM, Uranium Recovery Branch, conducted the necessary NRC/U.S. Department of Energy (DOE) interactions and documented the progress made by the DOE under the subissue of design control process. P. Chaput, a summer intern with DWM, helped synthesize the inputs from several contributors. The authors thank W. Patrick for his technical review, B. Sagar for his programmatic review, and N.K. Stablein and R. Weller for their management reviews. Inputs and review comments provided by various Key Technical Issues (KTI) teams are greatly appreciated. Thanks also go to J. Wike for assisting with the word processing and to B. Long and B. Ford, Southwest Research Institute (SwRI), Publications Services, for editorial reviews.

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1 INTRODUCTION

One of the primary objectives of the U.S. Nuclear Regulatory Commission (NRC) refocused prelicensing program was to direct its activities toward resolving the 10 key technical issues (KTIs) it considered to be most important to repository performance. This approach is summarized in Chapter 1 of NRC's High-Level Radioactive Waste Program Annual Progress Report: Fiscal Year 1996 (Center for Nuclear Waste Regulatory Analyses, 1997). Other chapters of this document address each of the 10 KTIs by describing the scope of the issue and subissues, path to resolution, and progress achieved during fiscal year (FY) 1996.

Consistent with NRC regulations on prelicensing consultations and a 1992 agreement with DOE, staff-level resolution can be achieved during prelicensing consultation. The purpose of issue resolution is to assure that sufficient information is available on an issue to enable the NRC to docket a license application (LA). Resolution at the staff level does not preclude an issue being raised and considered during the licensing proceedings, nor does it prejudge what the NRC staff evaluation of that issue will be after its licensing review. Issue resolution at the staff level during prelicensing is achieved when the staff has no further questions or comments at a point in time regarding how the DOE is addressing an issue. Pertinent additional information could raise new questions or comments regarding a previously resolved issue.

Issues are "closed" if the DOE approach and available information acceptably address staff questions such that no information beyond what is currently available will likely be required for regulatory decision making at the time of initial LA. Issues are "closed-pending" if the NRC staff has confidence that the DOE proposed approach, together with the DOE agreement to provide the NRC with additional information (through specified testing, analysis, etc.) acceptably addresses the NRC's questions such that no information beyond that provided, or agreed to, will likely be required at the time of a potential LA. Issues are "open" if the NRC has identified questions regarding the DOE approach or information, and the DOE has not yet acceptably addressed the questions or agreed to provide the necessary additional information.

An important interim objective of the staff efforts toward issue resolution is to provide DOE with feedback regarding issue resolution before the forthcoming Site Recommendation (SR) and LA. Issue Resolution Status Reports (IRSRs) are the primary mechanism that the staff will use to provide timely feedback to DOE regarding progress toward resolving the subissues comprising the KTIs. This report is the third revision of the IRSR on RDTME. This revision supersedes previous revisions of the IRSR. IRSRs include (i) acceptance criteria (ACs) for use in issue resolution and regulatory review, (ii) technical bases for the RDTME KTI, and (iii) status of resolution including where the staff currently has no comments or questions, as well as where it does. Additional information is also contained in the technical documents prepared by staff, which summarize the significant technical work toward resolution of all KTIs during each reporting period. Finally, open meetings and technical exchanges with DOE provide opportunities to discuss issue resolution, identify areas of agreement and disagreement, and develop plans to resolve such disagreements.

Revision 3 of the IRSR contains six chapters, including this Introduction in Chapter 1. Chapter 2 defines the KTI, all the related subissues, and the scope of the particular subissue or subissues addressed in the IRSR. Chapter 3 discusses the importance of the subissues to repository performance, including: (i) qualitative descriptions; (ii) reference to a Total System Performance Assessment (TSPA) flowdown diagram; (iii) results of any available sensitivity analyses; and (iv) relationship to DOE's repository safety strategy (RSS) (i.e., DOE's approach to its safety case). Chapter 4 provides the technical basis for review of DOE's work related to this KTI. Note that the review methods and acceptance criteria (ACs) previously listed in Chapter 4 of the RDTME KTI IRSR Revision 2 are being used to develop the Yucca Mountain Review Plan. In the process, these ACs are continuing to undergo modifications. The ACs listed in Chapter 5 reflect the current status of the review criteria under development. Chapter 5 concludes the report with the status of resolution of various subissues. The open items documented in the IRSR will be tracked by the staff, and resolution will be documented in a future document. Finally, Chapter 6 includes a list of pertinent references.

2 KEY TECHNICAL ISSUE AND SUBISSUES

2.1 PRIMARY ISSUE

The primary focus of the RDTME KTI is the review of design, construction, and operation of the geologic repository operations area (GROA) with respect to the preclosure and postclosure performance objectives, taking into consideration the long-term thermal-mechanical (TM) processes. Consideration of the time-dependent TM coupled response of a jointed rock mass is central to repository design and necessary for performance assessment (PA) at the Yucca Mountain (YM) site and consequently, the focus of both the preclosure and postclosure subissues of this KTI. Design for adequate postclosure performance requires an understanding of the TM response of the jointed rock mass during an anticipated compliance period of 10,000 years. Long-term TM response is anticipated to influence hydrological properties in the vicinity of the emplacement drifts, waste package (WP) degradation, radionuclide release within the engineered barrier system (EBS), performance of seals, and flow into and out of the emplacement drifts. Design for keeping the repository open for approximately 50–125 years (U.S. Department of Energy, 2000) requires an understanding of TM response of the jointed rock mass as it influences drift, shaft, and ramp stability, and waste retrievability. There are additional technical and regulatory topics of interest related strictly to preclosure performance; for example, the design, construction, and operations of surface facilities and preclosure safety analysis. Such topics will be dealt with separately.

2.2 SUBISSUES

The RDTME KTI has been divided into subissues to facilitate addressing the breadth of technical concerns comprising the issue. It is expected that resolution of the subissues will lead to resolution of the primary issue. These subissues address topics that are of regulatory concern because they are, in general, at the limit of or beyond conventional engineering experience, and may jeopardize the safe preclosure operations or effective postclosure performance of the GROA, or both. Although clearly interrelated, the subissues have been formulated to minimize redundancy. Alternatives, such as organizing the subissues by repository subsystem, would require, for example, seismic effects to be considered separately for the drifts, the seals, and the WPs, thus introducing extensive duplication. The four main subissues are stated in the next paragraph, with important considerations in each subissue noted parenthetically, as appropriate:

Design Control Process—Implementation of an Effective Design Control Process Within the Overall Quality Assurance Program (QAP).

Seismic Design Methodology—Design of the GROA for the Effects of Seismic Events and Direct Fault Disruption [including implications for drift stability, key aspects of emplacement configuration (i.e., fault offset distance, retrievability, and WP damage)].

Thermal-Mechanical Effects—Consideration of TM Effects on Underground Facility Design and Performance (including implications for drift stability, key aspects of emplacement configuration that may influence thermal loads and associated thermomechanical effects, retrievability, the change in geometry and flow into and out of emplacement drifts, and fault setback distance).

Design and Long-Term Contribution of Seals to Performance—Design and Long-Term Contribution of Repository Seals in Meeting the Postclosure Performance Objectives (including implications for inflow of water and release of radionuclides to the environment).

Each of the four subissues may, in turn, be addressed in terms of its principal components. For example, Although implementation of an effective design control process permeates the entire DOE's high-level waste (HLW) repository program, it may be addressed in two components: the design control process employed for the design, construction, and operation of the exploratory studies facility (ESF) and the design control process used for the design, construction, and operation of the GROA. Each component must be consistent with DOE's QAP. Furthermore, to the extent that the ESF is incorporated into the repository, its design must fulfill the requirements for preclosure safety and postclosure performance.

Similarly, the following three components have been identified for the second subissue: (i) DOE's methodology to assess seismic and fault displacement hazard, (ii) DOE's seismic design methodology, and (iii) seismic and fault displacement inputs to the design and PAs. Note that DOE has elected to consider preclosure aspects of seismic design separate from those for postclosure, although the repository design eventually must be shown to meet both sets of requirements. While this IRSR deals with the second component (i.e., design methodology) and parts of the third component (i.e., design inputs), a companion IRSR within the Structural Deformation and Seismicity (SDS) KTI addresses the remaining components.

The third subissue—consideration of TM effects in underground facility design and PAs—has three components: (i) stability of the underground excavations with regard to safety during the preclosure period, waste retrievability, and potential adverse effects on emplaced wastes; (ii) effect of seismically induced rockfall with respect to WP performance; and (iii) changes of emplacement drift geometries and hydrological properties surrounding emplacement drifts due to TM perturbation of the rock mass. All of these components have broad design and performance implications.

The fourth subissue deals primarily with postclosure performance concerned with three main topics: (i) design and construction of seals (including material selection), (ii) long-term stability of seals and their components, and (iii) importance of seals in meeting the postclosure performance objectives. This subissue was considered important because of a specific regulatory requirement under 10 CFR 60.134. However, this subissue is now considered closed because the proposed 10 CFR Part 63 provides no specific performance requirements for borehole, shaft, and ramp seals.

3 IMPORTANCE OF ISSUE TO REPOSITORY PERFORMANCE

3.1 RELATIONSHIP OF THE ISSUE WITH U.S. DEPARTMENT OF ENERGY REPOSITORY SAFETY STRATEGY

DOE identified several principal factors for the postclosure safety case in its repository safety strategy (RSS). The factors are considered to be the most important factors affecting performance at the proposed YM site for long periods of time (U.S. Department of Energy, 2000). These principal factors include:

(1) Seepage into drifts,

(2) Solubility limits of dissolved radionuclide,

(3) Dilution of radionuclide concentration,

(4) Retardation of radionuclide migration in the unsaturated zone,

(5) Retardation of radionuclide migration in the saturated zone,

(6) Performance of the drip shield, and

(7) Performance of the WP barriers.

Addressing these principal factors and design assumptions requires an understanding of DOE's design and the effects of time-dependent TM coupled processes occurring in the jointed rock mass on the GROA, including WPs. The relationships between the RDTME subissues and DOE's RSS are indicated in Table 1.

In addition to the principal factors noted, DOE assumed that the preclosure facilities (both surface and underground) can be designed to withstand the effects of vibratory ground-motion and fault displacements, and these facilities can be built and operated with minimal maintenance for a period of 125 years. DOE expects that the design actually provides for the repository to remain open for as long as 300 years after initial waste emplacement, if necessary (U.S. Department of Energy, 2000).

3.2 IMPORTANCE TO PRECLOSURE PERFORMANCE

3.2.1 Design Control Process

The Quality Assurance (QA) requirements for the GROA are specified in the proposed YM site-specific regulation 10 CFR Part 63 (Subpart G). The QA requirements are based on the criteria of Appendix B of 10 CFR Part 50, and are applied to activities such as site characterization and repository design, construction, operations, decommissioning, and closure.

Appendix B includes 18 criteria that comprise an effective Quality Assurance Procedure (QAP). The application of criterion III for "design control" of repository structures, systems, and components (SSCs) is of particular interest here.

Table 1. Relationship Between Repository Design and Thermal-Mechanical Effects Key Technical Issue and the U.S. Department of Energy Repository Safety Strategy

	Hypotheses from Repository Safety Strategy						
	Seepage into Drifts	Solubility Limits	Dilution	Retardation in Unsaturated zone	Retardation in Saturated Zone	Drip Shield	Waste Package
Design Control Process	X	X	X	X	X	X	X
Seismic Design Methodology				X	X	X	X
Thermal-Mechanical Effects	X					X	X

Design control is one of the most important of the 18 criteria because it defines the means by which the design organization will establish a design baseline, track changes with respect to the baseline, and document that regulatory requirements (RRs) related to design have been fulfilled. Meeting the QA requirements is an important aspect of demonstrating compliance with preclosure design criteria during the licensing review. Prelicensing reviews by NRC staff identified several weaknesses in DOE's QAP and design control process (Bernero, 1989). Also, in its own audit activities conducted in the past few years, many deficiencies were identified in areas such as data traceability, data management, software control, data qualification, and planning for scientific investigations (U.S. Department of Energy, 1998b,c,d,e; 1999). To address these deficiencies, DOE and its Management and Operating (M&O) contractor office developed new administrative procedures to replace the existing QAP.

The staff considers implementation of an effective design control process by DOE to be an important programmatic issue with major preclosure performance implications. Consequently, NRC staff will continue to monitor the DOE's progress on implementing an effective design control process.

3.2.2 Seismic Design Methodology

The major preclosure performance objectives in the proposed 10 CFR Part 63 include (i) 10 CFR Part 20 requirements, (ii) numerical guides for design requirements, (iii) integrated safety analysis (ISA), (iv) retrievability, and (v) performance confirmation. DOE's designs for both the surface and underground facility SSCs must adequately address seismic effects and direct fault disruption to demonstrate compliance with these four performance objectives. Failure of any of the SSCs important to safety due to vibratory ground-motion or direct fault displacement could severely affect GROA performance during the preclosure period of 100 to 150 years. Because of this long period for which there is no regulatory experience for meeting public and worker radiation safety requirements and because of the unusual requirements associated with retrievability of HLW, the seismic design is considered one of the most important factors affecting preclosure performance.

3.2.3 Thermal-Mechanical Effects

Consideration of TM effects on the underground facility is important in the design of an effective and efficient ventilation system, which, in turn, is important to meeting radiological safety objectives during the operational period. Thermal loads also have considerable effect on stability of the underground openings (Ahola, et al., 1996), which, in turn, affect ongoing access and monitoring, as well as waste retrievability, should that become necessary.

Furthermore, seismic effects will take place during the prolonged thermal environment. Depending on waste loading and other design features, the combined effect of thermal loads and seismic events may degrade the rock mass surrounding emplacement drifts. The rock mass may need to be reinforced with ground supports to ensure operational and radiological safety of workers during the preclosure period. The condition of the rock mass will also influence retrievability, if support systems are not designed adequately to maintain stable openings. Consequently, the evaluation of TM effects is considered important to preclosure performance.

3.3 IMPORTANCE TO POSTCLOSURE PERFORMANCE

Figure 1 highlights the inputs provided by the four subissues of the RDTME KTI to postclosure PA. Subsections 3.3.1–3.3.4 describe the importance of the four subissues to postclosure performance.

3.3.1 Design Control Process

DOE's design control process plays a major role in demonstrating compliance with the design requirements and performance objectives. Although it may appear that the design requirements in the proposed rule are focused mainly on preclosure performance, many (especially for the underground facility) play a significant role in meeting postclosure performance requirements as well. Thus, the design control subissue dealing with traceability of design changes and flowdown from RRs is equally important to postclosure performance. The design control process subissue directly or indirectly affects all the Integrated Subissues (ISIs) under the engineered system shown in the flowdown diagram of TSPA (Figure 1).

3.3.2 Seismic Design Methodology

Design of the GROA for the effects of seismic events and direct fault disruption has several postclosure implications. The particular effects of seismic events and direct fault disruption, and consequently their importance to long-term performance, are design dependent. In general, the GROA design and the methodology used to develop that design must consider seismic effects on the WPs and other EBs and key aspects of the emplacement configuration, particularly fault offset distance.

The WPs, backfill, drip shields, and other elements of the EBS that DOE may choose to deploy, as well as the surrounding rock mass, will all be subjected to repeated episodes of seismic loading during the postclosure period. The potential effects on these engineered and natural components are complex functions of the presence and properties of the various barriers. For example, degradation of rock mass strength and consequent rockfall could be quite important if backfill is absent, but have relatively little effect if backfill is present. In contrast, the absence of backfill could tend to mitigate the effects of direct fault displacement because of the large free space available around the WP. Depending on design, backfill could act to more directly transfer load to the WPs, thus having a potentially adverse effect with respect to direct disruption by unidentified or random faults. The DOE design concept for backfill involves a partial filling with uncompacted material. The backfill constructed using this design could eliminate the concern that it may allow for load transfer to the WPs during faulting. These examples highlight the complexity of design considerations related to seismic effects and direct fault disruption. Furthermore, they point to the need for the PA methodology to be sufficiently flexible to address the performance implications of a range of possible designs.

In subsequent revisions of the IRSR, sensitivity studies employing the Total-system Performance Assessment (TPA) code (Mohanty and McCartin, 1998) will be used to evaluate the effects of these phenomena on repository performance. Processes such as rockfall and mechanical disruptions to WPs and other EBS components will be evaluated. The seismic design methodology subissue provides inputs to the "mechanical disruption of WP" ISI of the flowdown diagram for TSPA (Figure 1).

3.3.3 Thermal-Mechanical Effects

The potential influences of TM processes on underground design and performance during the postclosure period come into play with the early stages of construction. Construction methods employed for the underground facility, geometry of underground openings (shape, size, orientation, slopes, and waste emplacement configuration), distribution of thermal load, presence or absence of backfill, and quality and quantity of roof support are some of the parameters that may have a significant effect on the long-term performance of the repository (Ahola, et al., 1996). With the new Enhanced Design Alternative No. II (EDA-II) option, the temperature experienced in the rock-mass surrounding the emplacement drifts may decrease somewhat due to the design option of a continuous ventilation for about 50 years. Consequently, deterioration of the emplacement drifts may be reduced. However, the effect of such change needs to be examined. As waste emplacement proceeds, TM effects begin to manifest in the EBS and surrounding rock mass. TM stresses resulting from excavation-induced changes and heat produced by the WPs will be superimposed on the existing *in situ* lithologic stresses throughout the postclosure period. TM effects combined with seismic loads may affect drift stability, particularly with unbackfilled designs. The effects may also cause rock to fall from the rock mass surrounding the emplacement drifts. Potential rockfall is a concern that could affect WP and drip shield performance.

In addition, the effect of TM interactions on the hydrologic properties of the surrounding rock mass must be considered in design and PA, given that ground supports (including concrete liners) are currently designed to meet the requirements for only preclosure performance. In assessing the postclosure total system performance, DOE made it clear that the effectiveness of the ground support system will not be considered in the assessment. In other words, the ground support system is assumed to lose its function after closure. This approach is clearly conservative. However, by taking this approach, the potential effects on postclosure performance of deterioration of the rock mass surrounding emplacement drifts will need to be evaluated.

Current understanding is that, after the emplacement of waste, the drifts will be subjected to a sustained high state of stress for a long time (Ahola, et al., 1996). This high state of stress results mainly from thermal loading and may lead to significant deterioration of the rock mass surrounding the emplacement drifts. Subsequent collapse of the rock mass may eventually occur due to either long-term deterioration or seismic activities. Such collapse will obviously change the geometry of the emplacement drifts and, consequently, change the capture area for seepage in the vicinity of the emplacement drifts. The collapse will also affect the hydrologic properties in the vicinity, and local changes in hydrologic properties are likely to be large. It is obvious that these changes will affect the WP environment. Accordingly, an understanding of TM effects is important to the staff's independent evaluation of DOE's PA. Thus, the TM effects subissue provides direct inputs to all ISIs included in the EBS (Figure 1).

3.3.4 Design and Long-Term Contribution of Seals to Performance

The discussions related to this subissue have been removed because of a change in the proposed 10 CFR Part 63.

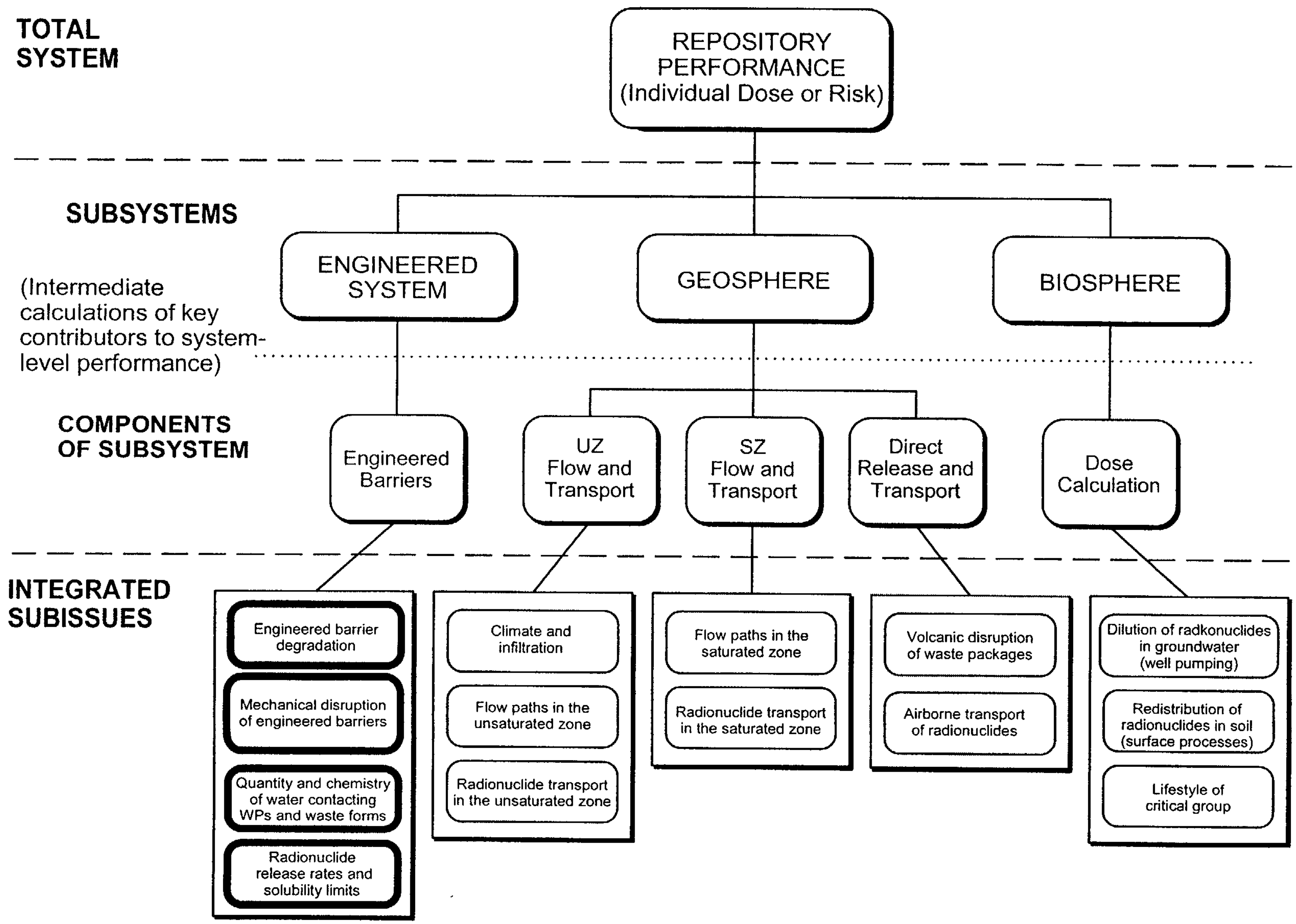


Figure 1. Inputs from repository design thermal-mechanical engineering subissues to postclosure performance

4 TECHNICAL BASES FOR SUBISSUES

In this revision (Revision 3), the ACs and review methods for evaluating DOE's approach to abstracting RDTME KTI, and evaluating DOE's analysis of RDTME KTI in a TSPA have been removed. They are being used to develop the Yucca Mountain Review Plan. In the process, they have undergone some modifications. This section contains only a discussion of the technical bases for the subissues that are related to the RDTME KTI. The discussions related to concrete behavior are deleted since the use of concrete liners as the primary means for ground support is no longer an option in the design. Otherwise, the discussions regarding technical bases are essentially the same as those presented in the RDTME KTI IRSR Revision 2.

4.1 IMPLEMENTATION OF AN EFFECTIVE DESIGN CONTROL PROCESS WITHIN THE OVERALL QUALITY ASSURANCE PROGRAM

4.1.1 Background

The focus of this component of the RDTME IRSR is on the staff evaluation of DOE's implementation of design control process for design, construction, and operation of the ESF. According to the proposed 10 CFR Part 63 (Subpart G) QAP requirement, QA comprises all those planned and systematic actions necessary to provide adequate confidence that the geologic repository and its subsystems or components will perform satisfactorily in service. Section 63.143 requires DOE to implement a QAP based on the criteria of Appendix B of 10 CFR Part 50. The YM-specific regulation currently under development is anticipated to retain these or similar QA provisions. As a result of past DOE NRC interactions in the area of ESF/GROA design and associated QA concerns, NRC had identified serious deficiencies in DOE's design control process (Bernero, 1989).

It has long been recognized by NRC that it is impractical for the staff to conduct a thorough review of all DOE's design documents given the limited resources at NRC's disposal. Consequently, NRC has utilized a "vertical slice" (audit) approach in which the staff selectively reviews some important aspects of DOE's ESF/GROA design packages and observes DOE's internal reviews, looking for trends that can be used as examples to provide feedback and guidance to DOE. NRC has paid particular attention to the design of the ESF because it will eventually become a part of the GROA if the YM site is found to be suitable. Therefore, many RRs applicable to GROA would also be applicable to the ESF. In the past, DOE found it difficult to demonstrate to NRC the traceability of RRs and to provide the necessary documentary evidence to clearly show that all applicable requirements were indeed being applied to various design components. In order to thoroughly examine this issue, NRC conducted a phased in-field verification in 1995 to evaluate DOE's design control process.

There were a number of open items that resulted from this in-field verification and the past NRC-DOE interactions and from NRC's review of ESF-GROA design documents related to this subissue. All these open items are being monitored under the RDTME KTI, and a number of them were closed during FY1996 as a result of staff reviews and interactions with DOE. Some of the main FY1996 activities conducted to help resolve the remaining open items and subissues were reported under Section 7.3.2 of "NRC's High-Level Radioactive Waste Program Annual Progress Report for Fiscal Year 1996" (Center for Nuclear Waste Regulatory Analyses, 1997).

Past DOE audits identified severe deficiencies regarding the design control process (U.S. Department of Energy, 1998a,b,c,d,e; 1999). An extensive effort is currently being made to correct these deficiencies. It is clear that to ensure an effective implementation of the design control process, constant monitoring by DOE of the progress will be required.

4.1.2 Technical Bases for Review: Design Control Process

The review of DOE's design control process has been molded by a number of past and continuing review activities, interactions, and correspondence on this subissue. It is important to keep in mind the historical background drawn from repository prelicensing interactions and regulations of similar nuclear facilities that has provided additional technical and review bases to the staff. Some of the important reviews, activities, interactions, and correspondence are described below.

4.1.2.1 ESF—GROA Relationship

The overall premise of staff reviews of DOE's design control process for the ESF is that the ESF will eventually become a part of the GROA if the YM site is found to be suitable for the disposal of HLW. Therefore, it is important that all site characterization activities, including the design, construction, and operation of the ESF be carried out in such a way that all RRs applicable to the GROA be considered applicable to ESF, unless it can be shown to be otherwise. The staff has used two main bases for judging the ESF construction and other testing activities: (i) design, construction, and operation of the ESF should not result in unmitigable impacts adversely affecting long-term waste containment of the EBS and isolation capabilities of the site; and (ii) design, construction, and operation of the ESF should not preclude gathering necessary site characterization information. In addition, the staff specifically looks for site characterization activities that might have a potential for test-to-test, construction-to-test, or construction-to-construction interference and, thus, adversely affect containment and isolation or DOE's ability to gather crucial data.

The staff has effectively applied these criteria to judge the adequacy of DOE's Site Characterization Plan (SCP) and various study plans (SPs) at different stages of the program and raised a number of objections, comments, and questions that have significantly affected DOE's program over the years. In response, DOE has developed a process that requires a "Determination-of-Importance-Evaluation" (DIE) at important stages of ESF construction and testing. Each DIE consists of a "Test-Interference-Evaluation" and a "Waste-Isolation-Evaluation," the results of which are used to make crucial decisions before major site activities are initiated. The staff may use the results of DIE reviews as bases for selecting certain design/site characterization activities for focused review.

4.1.2.2 Regulatory Basis

As mentioned earlier, Appendix B to 10 CFR Part 50 (Quality Assurance Criteria for Nuclear Power Plants adopted by the proposed 10 CFR Part 63) provides the underpinning technical/regulatory basis for the staff review methods and AC. Specifically, Criterion III of the 18 criteria described in Appendix B has been restructured into the specific criteria (listed under Section 4.1.3) for reviewing DOE's design control process. These criteria will continue to be used to review DOE's design control process employed during the GROA design, construction, and operation.

4.1.2.3 Staff Technical Positions

Additional bases are found in the staff technical positions (STPs) on: (i) Items and activities in the "HLW Geologic Repository Program Subject to QA Requirements" (NUREG–1318, Duncan, et al., 1988); and (ii) "Regulatory Considerations in the Design and Construction of the Exploratory Shaft Facility" [NUREG–1439 (Gupta, et al., 1991)].

NUREG–1318 (Duncan et al., 1988) provides guidance on approaches acceptable to the staff for identifying items and activities subject to QA in the HLW repository program for preclosure and postclosure phases. NUREG–1439 (Gupta et al., 1991) provides guidance on identifying RRs applicable to the ESF and describes an approach acceptable to the staff for implementation of proposed applicable 10 CFR Part 63 RRs. [Note: NUREG–1318 (Duncan et al., 1988) was developed using 10 CFR Part 60 and thus needs updating. However, the underlying principles of the STP still apply.]

4.1.2.4 QA Audits and Surveillances

From time to time, DOE conducts QA audits and surveillance of its contractors and subcontractors. The staff is invited to observe such audits and provide feedback. Over the years, the staff has chosen to observe numerous DOE audits and written Audit Observation Reports in which the staff has documented either its satisfaction or concerns related to particular issues. The staff has also conducted a limited number of independent audits of DOE and/or its supporting organizations and documented the results of such audits in trip/audit reports. Such reports and reviews are used as the bases for making generalized observations on the overall effectiveness of DOE's QAP.

4.1.2.5 Site Characterization Review

The staff has conducted detailed technical and programmatic reviews of DOE's SCP and several associated SPs. Review comments have been documented in NRC's documents, such as the Site Characterization Analysis (SCA) and SP reviews. The results of such reviews have been used by the staff as bases for identifying concerns related to DOE's QA and technical programs.

4.1.2.6 Design Reviews

The staff has participated as observers during DOE's design reviews in which the participating design organizations coordinate their individual efforts and integrate different aspects of ESF and GROA design. Such design reviews used to take place at approximately the middle of a major effort (known as 50-percent design review) and toward the end (termed 90-percent design review). Depending on the design topic and the availability of resources, the staff has participated as observers and provided feedback to DOE on various aspects of ESF design. The staff has also, on a limited basis, conducted independent design reviews of specific design packages and documented the results of each review. For example, in accordance with NRC's "vertical slice approach," the staff has reviewed selected portions of ESF Design Requirements (ESFDRs), and various ESF Design Packages, such as Packages 2b and 2c, and DOE's Regulatory Compliance Review Report (RCRR). The results of the RCRR were transmitted to DOE on December 14, 1995 (Nataraja et al., 1995). The results of such observations and limited independent reviews have been used as technical bases for staff conclusions on the effectiveness of DOE's designs and design control process.

4.1.2.7 Meetings

DOE and NRC conduct several technical meetings on topics of mutual interest under the existing prelicensing agreement (Shelor, 1993). DOE makes presentations on several aspects of QA and design, and the staff provides feedback to DOE during or after such meetings. The meeting minutes document issues and concerns that are also used as bases for staff positions on the effectiveness of DOE's program. Appendix 7 meetings are effectively used by the staff to conduct free and open discussions on topics of mutual interest. Although no formal meeting minutes are kept of Appendix 7 meetings, the information is used as technical bases for staff conclusions regarding DOE's design control process.

4.1.2.8 On-Site Representatives' Inputs

NRC's on-site representatives (OSRs) attend a number of DOE's technical and management meetings and observe day-to-day proceedings at DOE and its M&O contractor offices. They also have access to site activities on a regular basis. They can acquire and review DOE's documents that are still under preparation and, thus, can provide feedback to DOE on a real-time basis. The OSRs reports are also used as bases for staff conclusions on DOE's design control process.

4.1.2.9 Site Visits and In-Field Verification

The staff visits the ESF periodically and observes construction and testing activities, reports on important matters, and provides written feedback in its trip reports. The staff has also developed a procedure for conducting in-field verification of DOE activities (such activities may include design, construction, or operation). These procedures are part of the HLW Division Manual, Chapter 0330 (U.S. Nuclear Regulatory Commission, 1995a). The primary objective of the in-field verification is to determine if DOE is acceptably implementing the site characterization program and constructing and operating the ESF. The first in-field verification of DOE's program was conducted in phases starting in April 1995, and the results were documented in the in-field verification report [NRC–VR–95–1, (U.S. Nuclear Regulatory Commission, 1995b)]. This report documents the objective evidence and technical bases for staff conclusions on the adequacy of ESF design and DOE's design control process.

4.1.2.10 Relevant U.S. Department of Energy/U.S. Nuclear Regulatory Commission Correspondence and Interactions

The staff has actively pursued the design control process subissue beginning with NRC's objection to DOE's SCP, specifically, the ESF Title-I design control process. The extensive correspondence and exchanges between NRC and DOE that have provided additional bases for the review methods and review criteria and positions taken by the staff on this subissue are listed in the appendix.

4.1.2.11 Summary of Technical Bases

The subissue regarding DOE's design control process is a very important and highly complex one that historically has played an important role in helping NRC staff monitor DOE's site characterization program. Staff activities at the management, programmatic, and technical levels have been used to evaluate the adequacy of the ESF design and the design control process in the context of the overall

GROA design and DOE's QAP. The staff will continue to monitor DOE's program by conducting focused reviews of selected vertical slices of GROA design documents prepared by DOE. The historical background that can be traced in the various DOE/NRC correspondences and interaction minutes will continue to serve as bases for future staff reviews.

4.1.3 U.S. Department of Energy's Design Control Process for the Geologic Repository Operations Area

4.1.3.1 Selective Review and Results

To evaluate DOE's progress in implementing the design control process for the GROA, an Appendix 7 meeting was held at the M&O contractor's office during the week of June 8, 1998. The purposes of the meeting were to examine a number of design documents at different stages of preparation, and to select a limited number of them for comparison with the AC listed in Section 4.1.3 of the RDTME KTI IRSR, Revision 2.

Six documents considered to be both adequately developed and sufficiently representative of those describing underground facility systems and surface facility systems were identified for further review. The six documents reviewed in detail were: (i) Overall Development and Emplacement Ventilation System, (ii) Repository Subsurface Layout Configuration Analysis, (iii) Repository Ventilation System, (iv) Waste Handling Systems Configuration Analysis, (v) Site Gas/Liquid Systems Technical Report, and (vi) Surface Nuclear Facilities HVAC Analysis. These documents were developed using the design baseline included in the TSPA-Viability Assessment (VA).

The M&O Contractor also provided the following additional documents to facilitate the review: (i) a current version of the Controlled Design Assumptions (CDA) Document; (ii) a matrix which interrelates VA product documents with the CDA; (iii) Repository Design Requirements Document (U.S. Department of Energy, 1994a); and (iv) Engineered Barrier Design Requirements Document (U.S. Department of Energy, 1994b). These documents were used for comparison with design control process criteria.

For each of the six systems designated for review, the relevant technical documents were examined against the AC in Section 4.1.3 of the IRSR Revision 2. Where specific design criteria and assumptions were cited, cross-checks between documents were made to verify source documentation. The document citations for sections dealing with design criteria and design assumptions were also verified to relate to the topic discussed therein. Each reference section was crosschecked for each individual use of a reference to verify that the appropriate document was cited.

Staff verified that the checking processes are autonomous, and that the individuals performing design system checks were both independent and technically qualified. The staff found and examined evidence that verification records were maintained by the M&O contractor. As a result of the Appendix 7 meeting and the document review by staff, it was concluded that DOE is currently maintaining adequate oversight of the design control process. However, there is one area of concern, that being the control of changes to an original design and proper documentation of such changes.

4.1.3.2 Comparison with Acceptance Criteria

During the June 1998 meeting, the 12 ACs discussed in Section 4.1.3 of the IRSR Revision 2 were used by NRC staff as the guide on which to base any conclusions. Each of the M&O sources was checked for discrepancies dealing with the 12 criteria. Results of comparison with each criterion are listed below to illustrate the review process used by the staff. The majority of the items reviewed showed general agreement with the review criteria. Total agreement with all the review criteria, however, could not be established because of the evolving nature of the GROA design.

As mentioned previously, the documents evaluated here were developed using the TSPA-VA baseline design. From the middle of 1998, the M&O contractor conducted an extensive evaluation of repository design alternatives. The objective of the evaluation was to develop an enhanced design for a potential LA. At the end of the process, an enhanced design alternative was identified and recommended by the M&O contractor for DOE consideration (CRWMS M&O, 1999a). If this alternative is selected by DOE as the baseline for a potential LA, the previously mentioned documents will have to be reevaluated.

AC1: The applicable RRs are identified: In every system document reviewed, the RRs were listed in Section 4.4 of the respective documents (CRWMS M&O, 1997b,c,d,e,f, 1998a).

AC2: The design bases associated with the RRs are defined: In Section 4.2.1 of the Surface Nuclear Facilities HVAC Analysis, "The WHB and WTB ventilation systems are to accomplish the following confinement functions in accordance with 10 CFR 60.131" [waste handling building (WHB) and waste treatment building (WTB)]. The analysis then describes the functions the ventilation system will accomplish (e.g., minimizing the spread of radioactive material in the air) (CRWMS M&O, 1997e).

AC3: The RRs of AC 1 and the design bases of AC2 are appropriately translated into specifications, drawings, procedures, and instructions: It should be noted that some of the data used in the design are yet to be confirmed, or are to be used only to determine space and size requirements. Some examples of what has been done to date for each category of interest include:

a. Specifications: Using the 85 metric ton of uranium (MTU) value for the spent nuclear fuel (SNF), the drift spacing value of 28 m was derived (CRWMS M&O, 1997c).

b. Drawings: In the Repository Subsurface Layout Configuration Analysis, Figure 7-2 shows the repository layout with respect to geological boundaries, and incorporates its Criterion 4.2.3 (Deleterious Rock Movement).

c. Procedures: Since the design is still in early stages, procedures are yet to be developed.

d. Instructions: Section 7.3 of the proposed wet waste handling system description of the Waste Handling Systems Configuration Analysis implements the need to minimize exposure to personnel.

AC4: Appropriate quality standards are specified in the design documents: Every design/technical document reviewed has a QA Section (Section 2) that lists the governing QA documents.

Section 4 of the system analyses lists the assumptions, criteria, design parameters, and codes and standards that will form the basis for the document (CRWMS M&O, 1997b,c,d,e,f, 1998a).

AC5: Any deviations from the standards specified under AC 4 are controlled properly: The use of the terms TBV (to be verified) and TBD (to be determined) is stated in Section 2 of all the technical documents; these are used when a specific value is unknown (i.e., cannot be measured at this time) or when the values are preliminary in nature (CRWMS M&O, 1997b,c,d,e,f, 1998a). There are instances where the (assumed) values differ from those listed in the standards, but this is because the current standards were revised after the design documents were finalized. The future revisions are expected to reconcile the differences.

AC6: Measures are established for selection of materials, parts, equipment, and processes that are essential to functions of SSCs that are important to safety and waste containment and isolation: Section 4.2.9 in Overall Development and Emplacement Ventilation Systems states, "Subsurface repository operation involves continuous ventilation of repository airways until closure. To provide radiological protection to repository workers, and to have a positive control on potential radiological exposure to as low as is reasonably achievable, the subsurface repository ventilation design will include isolated return airways, isolation barriers and separate ventilation between emplacement and development." In Section 7.4.8 of the document, the general equipment and processes which achieve compliance with Section 4.2.9 are described, including the maintenance of a pressure differential, the use of ventilation barriers, and the standards for a primary ventilation fan. Materials and specific parts and equipment are not discussed due to the early stages of the design.

AC7: Design interfaces are identified, controlled and appropriately coordinated among participating design organizations: DOE has developed QAP NLP–3–34, Mined Geological Disposal System (MGDS) Interface Control Documentation. DOE has defined four levels of MGDS interface, as described in its Configuration Management Plan. The four interface levels are designated A, B, C, and D. Levels A and B are *external* to a system, and levels C and D are *internal* (Ashlock, 1997):

Level A—Interfaces between the (CRWMS) and other external systems (e.g., waste producers).
Level B—Interfaces between the CRWMS elements (Repository, Transportation, Storage, and Waste Acceptance).
Level C—Interfaces within an element (MGDS) and between its systems (e.g., Surface Repository, Subsurface Repository, WP, and ESF configuration items).
Level D—Interfaces between subsystems internal to a MGDS system (Ashlock, 1997).

The interface control documents meet the standards of this criterion by maintaining guidelines for the interfacing organizations to follow.

AC8: Procedures are established for review, approval, release, distribution, and revision of documents involving design interfaces: M&O's QAP NLP–3–34 provides instructions for the management of Level C interfaces on the MGDS. During the Appendix 7 meeting, NRC staff were informed of the following: until such time as formal guidelines for the management of

Level A and B interfaces are approved by DOE, a procedure similar to that of NLP–3–34 is being used for Level A and B interfaces (it is expected that formal written procedures similar to NLP–3–34 will be in place in the near future for Level A and B interfaces); Level D interfaces, which do not follow management by procedure NLP–3–34, are controlled by a process which requires formal design review by the parties potentially affected by the design in question (Ashlock, 1997).

AC9: Measures are established for verifying or checking the accuracy of design calculations (e.g., performing design reviews using alternate or simplified calculational methods): The M&O established Product Checking Group (PCG) verifies the design calculations through independent reviewers. The PCG is discussed in-depth under AC 11.

AC10: If testing is employed for verification of design adequacy, the testing is conducted under the most adverse conditions anticipated: The application of this criterion cannot be verified at this time since the systems are in design stages only. Application of this criterion will be verified and documented in future revisions to this IRSR.

AC11: The design verification is conducted by independent and qualified professionals who did not participate in the original design efforts: To address the issue of reviewer independence, the M&O contractor established an independent PCG. The PCG verifies the independence of reviewers for: (i) drawings, (ii) specifications, (iii) analyses, (iv) system description documents, (v) interface documents, and (vi) reports. By maintaining a database for checking, confirmation of the independence of reviewers, receipt and return dates, and back check dates can now be confirmed with relative ease (CRWMS M&O, 1998b).

The product checking procedures are identified in the Design Guidelines Manual (DGM) Section 10 (CRWMS M&O, 1997g). The DGM identifies the following topics:

1. Assembly of Engineering Documents for Discipline Check
2. Selection of a Checker
3. Tracking Checked Engineering Documents
4. Discipline Check of Input Lists and Engineering Documents
5. Final Check
6. Checking and Internal Processing of Engineering Change Requests
7. Checklists

AC12: In addition to being applied to the original design, the design control process is also applied to design changes and to field changes, and the changes are documented properly: In Section 4.3.6 of IRSR Revision 2, Overall Development and Emplacement Ventilation Systems that was checked and approved on September 19, 1997, it is stated, "Backfill in emplacement drifts is not required." Yet in the referenced CDA Key 046, dated May 8, 1997, this assumption has been withdrawn (CRWMS M&O, 1998c). This indication that the design uses the earlier assumption (CRWMS M&O, 1996a) shows a potential loss of control with respect to changes in, and evaluation of, design inputs. Similar examples were found at least once in all of the design systems reviewed by the staff. The M&O staff explained that the lapse was due to revisions and Document Change Notices in the design input documents, specifically the CDA. The future revisions to GROA designs are expected to reconcile the differences.

4.2 DESIGN OF THE GEOLOGIC REPOSITORY OPERATIONS AREA FOR THE EFFECTS OF SEISMIC EVENTS AND DIRECT FAULT DISRUPTION

4.2.1 Background

This version of the RDTME IRSR focuses on design of the GROA for the effects of seismic events and direct fault disruption. To date, DOE has addressed the first two components of this subissue (i.e., hazard assessment methodology and seismic design methodology). Furthermore, DOE has limited the scope of its topical report (TR) on design methodology to preclosure aspects. Consequently, the following discussion is similarly limited to preclosure aspects. The third component of this subissue will be addressed in future revisions of the RDTME and other companion IRSRs.

4.2.2 Technical Bases for Review: Seismic Design Methodology

4.2.2.1 Seismic Design Topical Report Approach

Among several approaches to resolving potential licensing issues is the use of TRs. Historically, the purpose of NRC's TR program has been to provide a procedure whereby licensees may submit reports on specific important-to-safety subjects to NRC staff and have them reviewed independently of any construction permit or operating license review. The benefits resulting from this program are a minimization of duplication of time and effort that the applicants and NRC staff spend on these subjects and improved efficiencies in NRC's reviews.

NRC staff has documented in its TR Review Plan (RP) (U.S. Nuclear Regulatory Commission, 1994) the conditions under which DOE can prepare a TR on a given issue (such as a design or analytical method) and submit it for staff review. Under this TR process, DOE submits an annotated outline (AO) of the proposed TR to get agreement of the staff on the scope and content of the report before spending significant resources. Subsequently, the completed TR is submitted for staff review that takes place in two stages, namely, an acceptance review and a detailed, independent technical review by the staff. The acceptance review in which the staff checks the general adequacy of the TR using the four criteria listed under Section 4.2.3 of the RDTME KTI IRSR Revision 2. The detailed technical review is conducted using the nine criteria listed in the same section. Considerable discussion with DOE may be required before the staff finally documents the status of the resolution of a particular issue or a subissue.

4.2.2.2 U.S. Department of Energy/U.S. Nuclear Regulatory Commission Decision to Use the "Topical Report" Approach for Seismic Design

DOE decided and the staff agreed that the issue of seismicity and fault displacement is an appropriate one to be dealt through the TR process. The issue of seismic design has a long history of potential for litigation and high public interest during licensing hearings of nuclear power plants. The TR approach is expected to facilitate efficient reviews during the limited licensing review period available under the Nuclear Waste Policy Act.

After discussions with the staff, DOE decided that the issue of seismicity and fault displacement is too unwieldy to be covered under one TR. Therefore, DOE developed a plan to address the issue using three TRs. The first TR (TR–1) deals with the proposed DOE's methodology to assess seismic hazards. The second TR (TR–2), which is one subject of this IRSR, deals with the proposed DOE's seismic design methodology. The third TR (TR–3), which is slated for completion during FY2002, deals with vibratory ground-motion and fault displacement inputs that will be used in repository design and PAs. Further details on these three TRs are discussed in following sections.

TR–1 Seismic Hazard. In its TR–1 (U.S. Department of Energy, 1994a), DOE has developed a five-step process for assessing the vibratory ground-motion hazard at the YM site. First, the seismic sources are evaluated. Second, the maximum magnitude and rate of occurrence of each source are estimated. Third, ground-motion/attenuation relationships are developed for the site region. Fourth, a probabilistic hazard curve for vibratory ground-motion is generated. Finally, multiple seismic hazard curves are developed to incorporate the various uncertainties. After completing a detailed review of TR–1 in several stages, the staff documented the status of the resolution of the subissues covered under TR–1 in its letter to DOE (Bell, 1996a), which stated that the staff has no further questions on TR–1 at this time.

TR–2 Seismic Design Methodology. TR–2, mentioned above, addresses preclosure seismic design methodology, keeping in mind that SSCs important to safety must ultimately be built to a single design that meets all requirements, including those for postclosure performance. The seismic design methodology and criteria in Rev. 0 of TR–2 (U.S. Department of Energy, 1995) were based on DOE's safety performance goals found in DOE Standard 1020-94 (U.S. Department of Energy, 1994c). Upon staff review and recommendation, DOE revised TR–2 [Rev. 1, (U.S. Department of Energy, 1996)] substantially to make it compatible with NRC's NUREG–0800 (U.S. Nuclear Regulatory Commission, 1987) for the repository design (as applicable to surface facilities) and design basis events (DBEs) as clarified in a 10 CFR Part 60 rulemaking (U.S. Nuclear Regulatory Commission, 1996).

TR–3 Design Inputs. TR–3, which will develop and document all the seismic and fault displacement inputs for repository design and PA, is scheduled for completion early FY2002. A review process similar to the one adopted for TR–1 and TR–2 will be used for the review of TR–3. Only after the completion of the review of TR–3 can the staff resolve the seismic issue and potentially adopt the set of three TRs as an acceptable reference to the repository LA.

4.2.2.3 Seismic Design Methodology Presented by the DOE

DOE's seismic design methodology and criteria are described in TR–2. If implemented properly, this methodology is expected to provide reasonable assurance that vibratory ground-motions and fault displacements will not compromise the preclosure safety functions of the SSCs important to safety. Although DOE emphasized preclosure aspects of seismic design in TR-2, staff's approach to review includes considerations of postclosure impacts.

The seismic design methodology and criteria implement the requirements of Part 60, including the latest amendments related to DBEs. Accordingly, the report summarizes DOE's approach to identifying categories-1 and -2 DBEs and establishes hazard probability levels that are appropriate for determining the two levels of design basis vibratory ground-motions and the two levels of design basis fault displacements.

DOE intends to use mean annual probabilities of 1×10^{-3} and 1×10^{-4}, respectively, as reference values in determining the frequency of the above two design basis vibratory ground-motions. Criteria for defining DBEs for both surface and underground facilities are provided for vibratory ground-motion and fault displacement design. In addition, the report provides criteria for fault avoidance, which is DOE's preferred approach for mitigating fault displacement hazards. Seismic design considerations for WPs are also discussed in TR–2.

After reviewing NUREG–0800 for potential use in repository design, DOE considers that specific criteria and guidance contained therein are appropriate for use in surface facility preclosure seismic design. TR-2 identifies several NUREG–0800 RPs, such as Standard RPs 3.7.1–3.7.3 and 3.8–3.10, along with specific exceptions, as applicable to the surface facility design.

Many of the standard seismic design methods that are applicable to the surface SSCs are also applicable to SSCs underground except that the vibratory ground-motions are appropriately attenuated to account for the depth below surface. Therefore, many of the RPs mentioned above for the surface facilities are also considered applicable at the repository level. However, the design of underground openings requires a combination of empirical and analytical approaches to account for the interaction of excavation-induced and thermally generated stresses superimposed on the *in situ* stresses. TR-2 describes the empirical methods, such as Dowding and Rozen's observational method (Dowding and Rozen, 1978), Rock Mass Quality Index Method (Barton, et al., 1974), and analytical methods, including the Quasi Static Method and Dynamic Analysis Method (Hardy, 1992) that will be employed by DOE in the design of the underground facilities.

In general, the TR-2 approach to fault displacement design is to avoid major faults, and whenever possible, to provide sufficient standoff distance between SSCs and faults. TR-2 adopts the guidance provided in NUREG–1494 (McConnell and Lee, 1994) in establishing design criteria.

4.2.2.4 Staff Review of Seismic Design TR–2

DOE requested a scoping review of the AO of TR–2 in August 1994 (Milner, 1994). The staff reviewed and transmitted its comments on the AO to DOE in November 1994 (Bell, 1994). DOE submitted a revised AO in January 1995 (Milner, 1995) that was considered acceptable. The staff notified its acceptance to DOE in its letter of February 14, 1995 (Bell, 1995a). DOE submitted Rev. 0 of TR–2 for NRC's review in October 1995 (U.S. Department of Energy, 1995).

Using the criteria given in Section 4.2.3, the staff concluded that the TR–2 contained sufficient information with sufficient detail to be considered for a detailed technical review. Staff acceptance of TR–2 for a detailed review was transmitted to DOE in their letter of December 1995 (Bell, 1995b).

A detailed technical review of Rev. 0 of TR–2 was conducted using the generic guidance available in the TR RP. In addition, the review criteria delineated in Section 4.2.3 were developed especially for this TR that deals with a specific design methodology.

After a detailed technical review of Rev. 0 of TR-2 and two Appendix 7 meetings with DOE (March 13–14, 1996, in Las Vegas and April 23, 1996, in San Antonio), the staff concluded that the TR-2 (Rev. 0) would not meet most of the criteria stated in Section 4.2.3 of RDTME KTI IRSR Revision 2. In addition, there were other major concerns with TR-2, Rev. 0, such as:

(1) A lack of adequate consideration of postclosure performance issues that might affect design;

(2) Incompatibility of DOE's proposed design methodology based on its Standard 1020 with the DBE definition provided in the amendments to 10 CFR Part 60;

(3) Inadequate consideration of existing models and codes for conducting dynamic analyses of jointed rock behavior for the design of underground facilities; and

(4) Lack of a clear rationale for the choice of criteria that will be used to deal with uncertainties in the DBEs for ground-motion and fault displacements.

These and other concerns were conveyed to DOE in the staff letter of May 1996 (Bell, 1996b).

As a result of the staff review and recommendations, DOE revised TR–2 and submitted the report to NRC in October 1996 (Brocoum, 1996). The most substantive change to the TR was that DOE dropped its proposed "performance-goal- based design" approach (derived from DOE Standard 1020) and adopted an approach that: (i) complies with the new definition of DBE provided in 10 CFR Part 60; (ii) adopts the existing review criteria from NUREG–0800 for the design of surface facilities and some of the SSCs underground; and finally, (iii) addresses the significant concerns raised during the review of TR-2, Rev. 0.

The staff completed a detailed technical review of TR-2, Rev. 1 using the same criteria that were used for the review of Rev. 0 and found Rev. 1 to be a significant improvement. The staff transmitted its review results along with several recommendations for clarifications in a letter in March 1997 (Bell, 1997).

DOE finalized TR-2 in its third version (Rev. 2), and submitted the report for staff acceptance on August 27, 1997 (Brocoum, 1997). Based on a verification review to check if all clarifications sought in the March 21, 1997, letter were provided, the staff concluded that all concerns raised by the staff have been addressed satisfactorily by DOE. After a detailed technical review, the staff concluded that DOE's methodology was acceptable based on the following:

(1) The methodology proposed by DOE utilizes the AC found in NUREG–0800 that have been used repeatedly and tested many times during the licensing hearings for many nuclear power plants. The technical bases for the criteria in NUREG–0800 and its references have been clearly documented. TR-2 identifies the appropriate sections of the particular RPs that will be used as guides for the seismic design of surface facilities and certain SSCs of the underground facility.

(2) TR-2 adopts staff guidance from appropriate STPs, namely NUREG–1451 (McConnell et al., 1992) and NUREG–1494 (McConnell and Lee, 1994). NUREG–1494 describes a methodology acceptable to the staff for investigating seismic and fault displacement hazards at the YM site. It also establishes criteria for defining the region of interest and the types of faults to be investigated. The STP emphasizes those faults that might have an effect on design and performance. NUREG–1494 (McConnell and Lee, 1994) provides additional guidance and clarification on avoiding faults within the preclosure controlled area of the repository.

(3) The empirical design methods and analytical/numerical methods that are proposed in TR-2 for the seismic design of the underground facility and the associated uncertainties are found acceptable to the staff.

(4) The approach for the fault displacement design and the technical bases for the criteria chosen are acceptable to the staff.

(5) Finally, all the comments made and concerns raised by the staff during Appendix 7 meetings and several rounds of reviews have been addressed in the revisions to TR-2 including the final set of clarifications sought by the staff on Rev. 1.

In summary, the staff accepted DOE's seismic design methodology proposed in TR–2; the staff is awaiting submittal of the DOE's TR–3 currently scheduled for completion by DOE in early FY2002.

4.3 THERMAL-MECHANICAL EFFECTS ON UNDERGROUND FACILITY DESIGN AND PERFORMANCE

4.3.1 Background

The subissue of the TM effects on underground facility design and performance consists of three major components. One is related to repository design while the other two areas focus on performance. More specifically, these three components include: (i) TM effects on underground facility design; (ii) effect of seismically induced rockfall on EBS performance; and (iii) postclosure TM effects on flow into the emplacement drifts.

4.3.2 Technical Bases For Review: Thermal-Mechanical Effects on Design of Underground Facility

4.3.2.1 Thermal Properties Characterization

The thermal properties required for TM analyses of the repository rock mass are:

(1) Thermal conductivity;
(2) Specific heat capacity; and
(3) Density.

The values of these properties provided by the YM Project (YMP) (i.e., DOE) are typically derived from laboratory tests on intact rock specimens (e.g., CRWMS M&O, 1998d, Table 4-3; Hardin, 1998, Table 3-5). One set of values is given for conduction-only analyses (CRWMS M&O, 1998d, Table 4-3), in which the effects of vaporization and water saturation are approximately accounted for through a dependence of thermal conductivity and specific heat on temperature near the boiling point of water. A different set of values is given for thermal-hydrological analyses (Hardin, 1998, Table 3-5) that explicitly account for vaporization and water-saturation changes. Comparison of predicted and measured temperatures in field-scale experiments, such as the DOE single heater test (Blair et al., 1999) and the DECOVALEX Bench Mark Test 3 (Stephansson, 1999), indicate that intact-rock thermal properties are adequate for characterizing the thermal response of a rock mass. Therefore, using intact-rock thermal properties to characterize the thermal response of the YM rock mass would be considered adequate.

4.3.2.2 Mechanical Properties Characterization: Continuum Rock-Mass Model

The mechanical properties required for TM analyses depend on whether the rock mass is modeled as a continuum assigned composite rock-mass properties or as a discontinuous medium consisting of a network of intact-rock blocks separated by fractures. The following rock-mass properties are required in a continuum rock-mass model:

(1) Poisson's ratio;
(2) Thermal expansivity;
(3) Young's modulus; and
(4) Strength parameters, such as friction angle and cohesion.

Characterization of the rock mass for the purpose of obtaining mechanical properties required to implement a continuum rock-mass model should address the following four features:

(1) Spatial variation of rock-mass mechanical properties from differences in intact-rock properties between the various stratigraphic units;

(2) Spatial variation of rock-mass mechanical properties from changes in the frequency, surface characteristics, and continuity of fractures;

(3) Spatial variation of rock-mass mechanical properties from changes in the nature and volume fraction of lithophysae; and

(4) Variation of mechanical properties with time as a result of degradation of the rock mass through a variety of processes such as progressive fracturing caused by sustained TM loading; alteration of fracture-wall rock from extended exposure to heat and moisture; and other appropriate thermal-hydrologic-mechanical-chemical (TMHC) processes within the rock mass.

Intact-Rock Mechanical Properties

Intact-rock mechanical properties for the YMP are given in CRWMS M&O (1997h) where the data are classified following the YM stratigraphy introduced by Buesch et al. (1995). Earlier compilations of YM intact-rock data such as Lin et al. (1993a) and Brechtel et al. (1995) present the data in terms of the TM stratigraphy of Ortiz et al. (1985), which recognizes five TM-stratigraphic units at YM. A difference between the Ortiz et al. (1985) stratigraphy and the more detailed Buesch, et al. (1995) stratigraphy that may be of most significance is the division of the repository host horizon (RHH) in the latter into four units: upper lithophysal unit (Tptpul), middle nonlithophysal unit (Tptpmn), lower lithophysal unit (Tptpll), and lower nonlithophysal unit (Tptpln). There may be significant differences in intact-rock properties among the four units (e.g., Peters and Datta, 1999). As a result, the TM behavior will be different for these four units, especially with the presence and absence of lithophysaes. In order to account for the different behavior, the intact-rock data for the four units need to be improved. In this regard, it may be more appropriate to follow the Buesch et al. (1995) stratigraphy in presenting intact-rock data for YM since it includes more representative data.

Effects of Fractures on Rock-Mass Properties for the Continuum Analysis

Mechanical characterization of the rock mass has followed the traditional approach (e.g., Barton, et al., 1974; Bieniawski, 1979) in which intact-rock and fracture characteristics are combined using empirical rules to obtain an index value that represents the quality of the rock mass. Rock-mass quality variations at YM were initially described following a probabilistic approach that assigned statistically calculated quality-index values to each of five quality categories within each of the TM stratigraphic units (e.g., Lin et al., 1993a). The percentage occurrence of each quality category was initially estimated through statistical analyses of borehole data. Subsequently, data obtained through fracture mapping of the ESF were used to develop a rock-mass quality (Q) profile along the ESF (Figure 2), which was, in turn, used to obtain better estimates of the percentage occurrence of the five quality categories within the stratigraphic units intersected by the ESF (CRWMS M&O, 1997a). The ESF Q data give the north-south variation of Q along the eastern boundary of the repository footprint (approximately between ESF stations 28+00 and 55+00 in Figure 2) within the Tptpmn stratigraphic unit. These data will likely be augmented with results from a recently completed cross drift that traverses the repository footprint in an approximately NW-SE direction and intersects all four RHH stratigraphic units (Beason, 1999).

The value of a rock-mass quality index, such as Q or the rock-mass rating (RMR) index of Bieniawski (1979), in mechanical analyses relies on the availability of empirical correlation functions that relate values of the index to values of mechanical parameters. For example, Serafim and Pereira (1983) present an exponential relationship between RMR and rock-mass Young's modulus (E) derived through analyses of measured deformations at a dam site. Also, Hoek (1994) and Hoek and Brown (1997) present empirical relationships for the estimation of E and the rock-mass strength parameters (friction angle, ϕ, and cohesion, c) from Q, RMR, or the Geological Strength Index (GSI).

Two sets of empirical E-vs-RMR data available from the literature (Bieniawski, 1978; Serafim and Pereira, 1983) are presented in Figure 3 along with similar data for YM presented at a recent DOE drift stability workshop (Lin, 1998). The figure also shows the Serafim and Pereira (1983) E-vs-RMR curve and a curve suggested for YM in the Lin (1998) presentation. It is important to note that the YMP data in Figure 3 have not been formally published by the DOE. The most recent E data for YM published by the DOE (CRWMS M&O, 1997a), which was used in the ground-support design analyses for the VA (CRWMS M&O, 1998d), were derived using the Serafim and Pereira (1983) relationship. An observation that stands out clearly from Figure 3 is that the YM data are sparse (six data points from ESF convergence analyses and one data point each from the plate-loading and Goodman-jack tests). The available YM data indicate that the Serafim and Pereira relationship may be inappropriate for the YM rock mass, but the data are insufficient to support a determination whether the difference between the YMP and the other two datasets in Figure 3 should be interpreted as a real difference in behavior between different rock masses or as the expected spread of E values [around the Serafim and Pereira (1983) predictions] at low to medium RMR values. The approach of attempting to fit the YMP data to a curve anchored at the intact-rock modulus (i.e., at RMR of 100), as illustrated in Figure 3, may not be appropriate. The shape of the E-vs-RMR curve for rock-mass qualities close to intact rock may significantly differ from the shape at low to medium qualities. In fact, laboratory data on the effect of microcracks on intact-rock stiffness (e.g., Ofoegbu and Curran, 1992) suggest that the stiffness of a rock mass would approach the intact-rock stiffness asymptotically as the rock-mass quality approaches intact rock. Therefore, because the shape of the *E*-vs-RMR curve may change significantly within the full range of rock-mass quality from lowest qualities to intact rock, it would be misleading to extend an *E*-vs-RMR curve beyond the range of the available rock-mass quality data. The YMP should develop a sufficient number of data points to firmly establish the *E*-vs-RMR (or *Q*) relationship at YM over the range of rock-mass quality values encountered at the site, if it intends to use this approach in the design.

The values for the rock-mass strength parameters c and ϕ currently proposed for YM (CRWMS M&O, 1997a) were estimated by fitting straight lines to sets of σ_1-vs-σ_3 values (where σ_1 and σ_3 are maximum and minimum principal stresses) calculated using the Hoek-Brown failure criterion (e.g., Hoek, 1994; Hoek and Brown, 1997). This approach led to values for ϕ that are too high compared to the values suggested based on the rock-mass classification systems. For example, CRWMS M&O (1997a, Table 6) gives $\phi = 57°$ and $\phi = 58°$ for the lowest and highest quality categories of the TSw2 stratigraphic unit. On the other hand, the highest ϕ value from Hoek and Brown (1997, Figure 8) for the highest rock-mass quality (approaching intact-rock) is less than 53°.

The procedure presented by Hoek and Brown (1997) for estimating c and ϕ is based on the GS. The values of this index can be determined through geologic mapping of the rock mass following guidelines described by Hoek and Brown (1997) or estimated through correlations with *Q* or RMR. The values of c and ϕ obtained using this procedure (Ofoegbu, 1999) with the TSw2 section of the ESF *Q* data (Figure 2) are given as functions of *Q* in Figure 4. The figure shows ϕ varying from about 28° to about 35° as *Q* varies from about 0.73 to about 13.6. These values of ϕ are much smaller than the DOE values presented previously. The difference between the CRWMS M&O (1997a) ϕ values of 57–58° and the values in Figure 4 (28–25°) for the same range of *Q* values is quite significant in predicting the mechanical behavior of the rock mass in the vicinity of the proposed waste-emplacement openings (e.g., see the numerical-model results discussed presently).

Degradation of Mechanical Properties with Time

Rock-mass mechanical properties may degrade with time because of a decrease in the strength of intact rock under sustained long-term loading and a decrease in the shear strength of fracture surfaces due to wall-rock alteration caused by extended exposure to heat and moisture. Laboratory data (e.g., Lajtai and Schmidtke, 1986) indicate that the strength of hard intact rocks (e.g., granite, sandstone, or welded tuff) under slow or sustained loading may be much smaller than the strength obtained through conventional (usually rapid) laboratory-loading conditions. Under sustained loading, slow-growing fractures, such as may be driven by stress corrosion at crack tips, are able to extend and coalesce sufficiently to cause eventual rupture of the specimen. On the other hand, such fractures do not have sufficient time to grow under rapid-loading conditions. For example, Lajtai and Schmidtke (1986) presented unconfined compressive strength of crystalline igneous rocks from sustained-loading tests as low as 60 percent of the conventional unconfined compressive strength. Because the repository environment will be subjected to mechanical loading arising mainly from thermal expansion of rock under high temperatures that may be sustained for a few hundred years, at least, the strength of intact rock within the environment should be governed by behavior under sustained loading. As a result, the value of intact-rock unconfined compressive strength used in the repository design analyses should be a fraction of the value obtained from conventional laboratory testing. There is currently no data on the behavior of YM intact rocks under sustained-loading conditions.

Although widespread chemical weathering of the rock mass is not likely considering the ambient climatic conditions at YM, alteration of fracture-wall rocks at and near the repository horizon is considered likely because of possible exposure of such fractures to moisture under elevated temperatures for an extended period (Hardin, 1998). Alteration of fracture-wall rock could result in fracture apertures widening in some areas due to dissolution of minerals along the fracture surface. In addition, fracture apertures could be reduced due to precipitation of minerals (such as clay and calcite) that are much weaker than the surrounding rock. Such changes in fracture characteristics could weaken the rock mass, resulting in values for the rock-mass strength parameters c and ϕ significantly smaller than their values under current conditions. The effects of fracture-wall rock alteration on rock-mass properties may be expressed through a reduction of Q following the guidelines of Barton et al. (1974) for accounting for fracture skins that are different from the parent rock. However, the guideline requires a knowledge of the potential thickness of the altered fracture-wall rock and the surface-area fraction of the fracture surface that is covered by the altered rock. The difficulty of predicting such quantities raises doubts on the possibility of quantifying possible reductions of Q following the Barton et al. guideline. As an illustration, the effects of an order-of-magnitude reduction of Q on mechanical properties are presented in Figure 4, which shows the values of E, c, and ϕ estimated from the degraded Q values (by placing Q with 0.1 Q in the empirical equations identified in the figure). It should be noted that one order-of-magnitude reduction in Q is approximately equivalent to an 8-point reduction in RMR [using an empirical RMR-vs-Q relationship such as presented in Hoek (1994)]. The analyses results discussed presently indicate that such a reduction in the Q value would significantly affect drift-stability predictions. Consequently, the mechanical characteristics of the degraded rock mass should be accounted for in predicting future stability of the emplacement drifts.

Results from a Two-Dimensional Site-Scale Continuum Model

Finite element (FE) analyses of the emplacement drift area of the proposed repository conducted by NRC used a plane-strain model to examine the effects of the following on drift stability: (i) spatial variation of mechanical properties; (ii) mechanical degradation of the rock mass caused by sustained loading and fracture-wall alteration from extended exposure to heat and moisture, and (iii) mechanical degradation of the ground support. Input data for the analyses were derived from the ESF Q profile (Figures 2 and 5). Drift spacing was set at 28-m center to center for a thermal-loading equivalent of 85 MTU/acre following the emplacement-drift layout in CRWMS M&O (1997a). Drifts were modeled as 5 × 5-m squares, and concrete-lining support was simulated using beam elements placed at the edges of the openings. The model used for the analyses is discussed in detail in Ofoegbu (1999).

The results of the analyses and conclusions drawn based on such results are presented next.

(1) Analyses performed using nondegraded rock-mass properties (curves Y1, F1, and C1 in Figure 4) did not produce significant inelastic response. Also, analyses performed using curves Y2 or Y3 with any of the strength-parameter curves did not indicate significant inelastic response. These results indicate that stress-induced instability of the emplacement drifts (different from structure-induced instability that may result from loose-rock fall, for example) would be insignificant under the simulated thermal loading if: (i) mechanical

degradation of the rock mass does not occur, or (ii) the rock-mass modulus followed the curve labeled YMP in Figures 3 and 4. Significant inelastic response (Figures 6 and 7) was obtained from analyses performed using nondegraded Young's modulus (curve Y1 in Figure 4) with degraded strength parameters (curves F2 and C2 in Figure 4). This parameter combination represents a simulation of an initial period of stress buildup in nondegraded rock mass followed by a period of mechanical degradation. The results illustrate the important roles of mechanical degradation of the rock mass and ground support in controlling the intensity and distribution of potential stress-induced ground movement. Therefore, for these reasons, the possibility of rock-mass degradation needs to be addressed. Inelastic response is most intense in the pillar centers and in the roof and floor areas of the openings. With stiff drift support (Figure 6), inelastic response is most intense in the pillar centers in areas of higher rock-mass stiffness because of the occurrence of high horizontal stress and low vertical stress in the pillars as will be illustrated. On the other hand, loss of confinement caused by the simulated degradation of ground support causes increased inelastic response in the roof and floor, with higher intensity of the response occurring in lower-*Q* areas (Figure 7).

(2) The results in item (1) also illustrate the strong effects of Young's modulus on the calculated response, which occur because the magnitude of thermal stress is controlled by Young's modulus. Consequently, there is a strong need to establish the range of the *in situ* E data for YM site. The role of Young's modulus is emphasized further (Figure 8) through the results of a set of homogenous-medium models in which E, ϕ, and c were varied between the minimum and maximum *Q* values on curves Y1, F2, and C2 in Figure 4. With stiff drift support, the higher thermal stresses developed in the higher-*Q* model dominate the response, resulting in more intense inelastic straining in the higher-*Q* model. On the other hand, deactivation of the support system under constant temperature (which is a purely mechanical change) to simulate support degradation causes increased inelastic strain intensity in the lower-*Q* model. The response of the lower-*Q* model to support degradation is governed by the effect of loss of confinement on low-strength (i.e., low c and ϕ) rock mass.

(3) Thermal loading from the emplacement-drift pattern results in horizontal compression and vertical extension, which cause an increase in horizontal stress from an initial value of about 2 MPa and a decrease in vertical stress from an initial value of about 7.5 MPa (Figures 9 and 10). The largest decrease in vertical stress occurs in the pillar centers and roof and floor. As a result, the maximum principal stress would be horizontal and the minimum would be vertical, under the thermal regime. The orientation of the maximum principal stress would shift from approximately north-south in the pillars to approximately east-west in the roof and floor (Figure 10). Regardless the drift orientation, these stress orientations would favor slip on gently ($\leq 30°$) dipping fractures that strike parallel to the drifts in the pillars or normal to the drifts in the roof and floor. Consequently, inelastic response in the roof and floor would be controlled by slip on a gently dipping dominant fracture set that strikes approximately normal to the proposed drift orientation. It should be noted that two-dimensional models oriented normal to the drifts will not be able to capture the effects of slip on such fractures. Therefore, other modeling approaches [e.g., three-dimensional model (3D)] should be considered to assess such effects.

4.3.2.3 Mechanical Properties Characterization: Discontinuum Rock-Mass Model

TM analyses using a discontinuum model require two groups of mechanical properties:

(1) Mechanical properties for rock blocks: Rock-block properties include mass density, elastic or deformability properties, strength parameters, and post-failure parameters. Two basic elastic properties for an isotropic material behavior are Young's modulus and Poisson's ratio [sometimes bulk modulus and shear modulus are used (e.g., in UDEC)]. Strength parameters depend on the failure criterion chosen. For the Mohr-Coulomb failure criterion, the strength parameters are cohesion, friction angle, and tensile strength. Post-failure properties depend on the type of post-failure responses chosen. For the Mohr-Coulomb model, shear dilatancy (dilation angle) is required to describe post-failure behavior. In a discontinuum model, however, the presence of discontinuities will account for a good portion of the scaling effect on properties. Even so, some adjustment of block properties may still be required to represent the influence of heterogeneities and micro-fractures, fissures, and other small discontinuities on the rock-mass response (Itasca Consultant Group, Inc., 1996).

(2) Mechanical properties for fractures: Mechanical properties for fractures include basic elastic parameters (normal stiffness and shear stiffness), strength parameters (fracture friction angle, fracture cohesion, and fracture tensile strength), and post-failure properties (fracture dilation angle). Similar to block properties, fracture properties measured in the laboratory typically are not representative of those for real fractures in the field, and choices of appropriate parameters need to be guided by fracture properties derived from available field tests.

As discussed previously, there are several versions of intact-rock mechanical properties reported by DOE, and the latest are those of CRWMS M&O (1997h). Rock-mass mechanical properties were estimated for the five rock-mass quality categories using, mainly, an empirical approach (CRWMS M&O, 1997a).

Fracture strength parameters (cohesion and friction angle) were initially estimated and used in the ESF ground support design analysis (CRWMS M&O, 1996b). The estimate was based on an empirical relation for friction of rock joints proposed by Barton (1973). These parameters were further analyzed using the same empirical approach based on qualified field mapping data (CRWMS M&O, 1997a) and used in subsequent ground support analyses for the VA (CRWMS M&O, 1998d). Fracture tensile strength was assumed to be half of the fracture cohesion according to Lin et al. (1993b) in ESF ground support analyses (CRWMS M&O, 1996b) and assumed to be zero for conservatism in ground support analysis for the VA (CRWMS M&O, 1998d). Fracture shear stiffness was estimated in Lin et al. (1993b). Fracture normal stiffness is often assumed to be the same as fracture shear stiffness (e.g., CRWMS M&O, 1998d). It should be noted that the approaches used by DOE for estimating fracture mechanical properties (strength and stiffness) have considerable uncertainties. In order to conduct the discontinuum analysis with reasonable confidence, these approaches need to be tested. Furthermore, the associated uncertainties need to be quantified.

Temperature and Time Effects on Concrete

Because of changes in DOE design, concrete material is no longer used for ground support or inverts. Consequently, the discussions on temperature and time effects on concrete have been deleted.

Thermal Properties of Concrete at Elevated Temperature

Because of changes in DOE design, concrete material is no longer used for ground support or inverts. Consequently, the discussions on thermal properties of concrete at elevated temperature have been deleted.

Temperature Impact on Material Properties of Concrete

Because of changes in DOE design, concrete material is no longer used for ground support or inverts. Consequently, the discussions related to temperature effects on concrete material properties have been deleted.

Degradation of Concrete

Because of changes in DOE design, concrete material is no longer used for ground support or inverts. Consequently, the discussions on degradation of concrete have been deleted.

4.3.3 Technical Bases For Effects of Seismically Induced Rockfall on Engineered Barrier System Performance

Seismicity is a disruptive event that needs adequate consideration in both repository design and PA. Seismicity could affect WP performance by producing rockfall that may damage WPs. The potential effects on the performance of WPs are twofold. The first possible effect of rockfall is to rupture WPs by the impact produced by the falling rock. The second aspect is that rockfall may cause damage to the container outer pack in a manner that corrosion of the WPs will accelerate and thus reduce the intended service life of WPs. In order to perform an adequate assessment of the effect of rockfall due to either TM load or seismicity, a number of factors will need to be understood better, such as the design of WPs, repository design (ground supports and backfills), and potential size of rockfall. Equally important is the availability of a reasonable model/approach that can be used to perform such an assessment.

The analyses of rockfall should explicitly account for four basic aspects: (i) size distribution of individual block that can potentially fall, (ii) possibility of multiple blocks falling onto a WP simultaneously; (iii) vertical and lateral extent of the region undergoing rockfall, and (iv) effects of repeated rockfall on the (corroded) canister due to repeated seismic events. These aspects of rockfall analyses are discussed in this section, with emphasis on specific needs for analyses, appropriateness of methodologies, and sufficiency of input considerations and associated uncertainties. The discussion is based mainly on data from YM site characterization activities, current DOE approaches, and ongoing modeling efforts at NRC/Center for Nuclear Waste Regulatory Analyses (CNWRA). The ultimate goal of these analyses is to give technically adequate estimation of the volume range and quantity of rock blocks that have the potential to fall onto the WPs so as to evaluate the effects of such rockfall on the integrity of the WPs. Because characterizing rockfall is a recently initiated ongoing effort, the technical bases provided in this section of the IRSR are not completely developed and, therefore, should be considered preliminary.

4.3.3.1 Size Distribution of Individual Blocks and the Probability of Rockfall

The size distribution of individual rock blocks is controlled by geometrical characteristics of the fracture network. In characterizing a fracture network, fractures are often grouped into primary sets, and each fracture set is modeled by parameters such as orientation, spacing, dimension, location, and persistence. These geometric parameters of the discontinuities are statistical in nature. Besides primary fracture sets, a random fracture set is often simulated to account for fractures that are random in nature and could not be accounted for in the primary sets. It is through fracture network modeling that the size distributions of individual rock blocks are estimated. Some examples of fracture network modeling in the recent geological engineering practice include the commercial code FRACMAN (Dershowitz et al., 1993), analyses based on Key Block theory (Goodman and Shi, 1985; Shi, 1996), and some other commercial and noncommercial software such as FRACNTWK (Kulatilake, 1998), Stereoblock (Hadjigeorgiou et al., 1998), and DRKBA (Stone Mineral Ventures, Inc., 1998).

At YM, an earlier attempt to estimate size distribution of rock blocks was made by Gauthier et al. (1995) using a modified (log-space) version of the Topopah Spring fracture spacing distribution developed by Schenker et al. (1995). It is a two-dimensional analysis based on the North Ramp Geotechnical (NRG) core hole, the ESF data, and the assumption of cubic and parallelepiped blocks. Assumptions of cubic or parallelepiped block shape may distort the estimation of size distribution of *in situ* blocks due to various assumptions with regard to the extent of fractures in the third dimension. Recently, DOE[1] conducted Key Block analyses in three dimensions using DRKBA (Stone Mineral Ventures, Inc., 1998). In this software, fracture sets are identified based on clustering of fracture poles projected on stereonets, and probabilistic distributions of fracture parameters (Fisher constant, orientation, spacing, and trace length) are determined for each set. Fracture planes are then simulated by a Monte Carlo technique from probability distributions of fracture parameters. Finally, volume distributions of the key blocks per unit drift length are determined for various lithologic units (Tptpul, Tptpmn, Tptpll, and Tptpln) and for different drift orientations.

Volume distributions of the key blocks are used in estimating the probability of various sized rock blocks that may fall into the emplacement drifts.[2] In this preliminary analysis, key block failure as a function of time is estimated based on an underground rockfall database compiled by Smith and Tsai (CRWMS M&O, 1995a) and an approach used by Gauthier et al. (1995) that relates the effect of seismic and tectonic events to the incidence of rockfall. The study considered rockfall frequencies obtained by Smith and Tsai (CRWMS M&O, 1995a). Gauthier et al. (1995) adopted the CRWMS M&O (1997i) approach for treating the uncertainties and selected the high-, best-, and low-estimates for rockfall frequency as 9.4×10^{-3}, 9.4×10^{-4}, 9.4×10^{-5} per year per km, respectively. The study further estimated numbers of rockfalls and predicted occurrence rate (or return period) for rockfall

[1]CRWMS M&O, *Key Block Analysis—Preliminary Results,* Las Vegas, Nevada, Civilian Radioactive Waste Management System Management and Operating Contractor, 1999.

[2]Ibid.

greater than a certain block size using the following equation and volume distribution of the key blocks obtained from DRKBA analyses.

$$\text{OccRate} = (100\% - \text{cum}\%) * f\xi_i * L \tag{1}$$

where

OccRate	—	occurrence rate for rockfall greater than the block size
cum%	—	cumulative percentage of the block size
$f\xi_i$	—	unit length rockfall frequency
L	—	drift length

There are some inherent assumptions in this latest DOE approach to rockfall estimation that do not appear to be technically defensible and thus, limit the practical application of this study. First, in the study, rockfall frequency determined by Gauthier et al. (1995) is based on the frequency of earthquake occurrence. This assumes that rockfall is induced by seismic events, which are dynamic processes. However, the Key Block method is a purely static geometric approach. It does not consider dynamic processes of seismic activity, nor does it consider failure mechanisms such as the possibility of failure propagation (or falling of multiple rock blocks) due to falling of one particular key block. In fact, results from recent dynamic modeling show that, in most cases, multiple rock blocks will fall instead of a single key block during a ground-motion event (see section 4.3.3.2). In the staff's opinion, the Key Block analyses can be used to estimate rockfalls that are random in nature and occur under gravity, as well as the likely failure initiation location of a rockfall event. Rockfalls due to thermal load and/or earthquake ground-motion events need to be determined through thermal and dynamic analyses. In the case of earthquake-induced rockfall, rockfall frequency depends on the frequency of ground-motion events. In thermal-load induced rockfall, frequency may be a time function of the evolution of the thermal load and the degradation of rock properties.

Second, the DRKBA Key Block analysis assumes that the likelihood of a rockfall event and the number of key blocks are equal everywhere along emplacement drifts. This analysis further assumes that the same volume distribution of the key blocks applies everywhere in the repository located in the same lithologic units. These assumptions do not appear to be realistic because fracture network characteristics vary significantly from place to place. Modeling of the fracture network should be more detailed and should distinguish regions with different fracture network characteristics that affect mechanical behavior. Furthermore, in DOE Key Block analyses, the amount of rockfall does not depend on the level of ground-motion, characteristics of ground-motion (such as frequency content, spectrum characteristics, etc.), rock block and fracture TM properties.

4.3.3.2 Possibility of Simultaneous Rockfall and Vertical Extent of Potential Rockfall

TM analyses at the drift scale up to 100 years (Ahola et al., 1996, Chen, et al., 1998) show that thermal loading causes significant stress redistribution around the drift. These studies considered a single drift in a rock mass that had a regular joint pattern with two joint sets (subhorizontal and subvertical). The analyses were conducted using the computer code UDEC (Itasca Consulting Group, Inc., 1996). Figures 11 and 12 compare the distribution of principal stresses following drift excavation and after 100 years of heating under a 100 MTU/acre thermal loading density. The thermal load increased the maximum compressive stress, and rotated its direction from vertical to horizontal. The location of the highest compressive stress region shifted from the side walls to roof and floor areas of the drift. Failure along side walls due to concentration of compressive stresses and lack of lateral support in underground mines and tunnels is a frequently observed phenomenon. When such compressive stress is rotated and shifted to the roof area, a similar phenomenon could occur and thus cause rockfall.

These studies also reveal that thermal load could increase failure of intact rock blocks. Other studies have observed this phenomenon (Tsai, 1996; CRWMS M&O, 1995b). Although failure zones in most cases were localized to the immediate areas around the drift, in some cases they extended to the middle of the pillar in rock masses that are weaker and have a higher thermal expansion coefficient (Figures 13 and 14). Although failure of intact rock in discontinuum analysis may not be the direct evidence of explicit rockfall, it represents a failure or damage state and indicates the need to establish a criterion for determining the vertical extent of potential rockfall with appropriate modeling methodologies and input parameters (e.g., joint patterns representative of the site).

Rockfall phenomena were analyzed by simulating the behavior of an unsupported emplacement drift undergoing repeated seismic ground-motion after subjecting it to *in situ* stress and, in some cases, a time-decaying thermal load generated by the emplaced wastes (Chen, 1998; 1999). These analyses used the distinct element computer code UDEC (Itasca Consulting Group, Inc., 1996). Modeling results show that, in most cases, multiple rock blocks (rather than a single rock block) fall simultaneously under seismic ground-motion. Fracture patterns have controlling effects on the amount of simulated rockfall. In these analyses, a regular fracture pattern refers to a fracture network with two or more sets of fractures of infinite length and constant orientation and spacing (Figure 15a). An irregular fracture pattern refers to a fracture network defined by certain statistical distributions of fracture parameters such as orientation, spacing, trace length, and gap length (Figure 15b). The complexity of fracture patterns increases with increasing number of fracture sets, decreasing spacing, and increasing variations of parameters. Modeling results show that with increasing complexity of fracture patterns, the number of rock blocks falling, the extent of the rockfall region, and the overall drift instability increase. Figure 16 compares simulated rockfalls for two slightly different irregular fracture patterns. Case A contains two fracture sets, whereas Case C has an additional fracture set with relatively large spacing. This figure shows that adding the third fracture set increases the amount of simulated rockfall significantly. In general, the amount of simulated rockfall for a heated drift is less than that of an unheated drift with the same fracture pattern because the thermal compressive stress tends to reduce fracture normal displacement. A similar phenomenon was observed by Fairhurst (1999). A second ground-motion event usually produces little additional rockfall.

Dynamic modeling results (Chen, 1998; 1999) also show that the stress distribution is altered significantly by thermal load and, to a lesser degree, by dynamic load. As mentioned previously, the superposition of thermal stresses on excavation-induced mechanical stresses changes the location of the maximum principal stress from drift sidewalls (nearly vertical) to roof and floor (nearly horizontal). In most cases, a zone of tensile minimum principal stress occurs in the roof and floor. Figure 17 shows that the extent of the region with tensile minimum principal stress (positive stress) is greater for an irregular fracture pattern (lower plot) than that for a regular fracture pattern (upper plot), causing more extensive rockfall in the case of an irregular fracture pattern.

It is desirable to establish a criterion that could be used to determine the maximum vertical extent of potential rockfall. The extent of rockfall will depend on factors such as level of ground-motion, joint pattern, individual block sizes, thermal and mechanical properties of the rock mass, joint shear and normal displacements, joint shear and normal stresses, and joint strength.

Dynamic modeling results (Chen, 1998; 1999) show that of all these factors, fracture pattern may have the most significant effect on rockfall. Therefore, analyses using a regular fracture pattern such as the one shown in Figure 16 may not be conservative. An ongoing effort at CNWRA is to simulate fracture network patterns representative of the *in situ* conditions based on mapping and scanline data from the ESF and Cross Drift. Future dynamic analyses will incorporate more realistic fracture patterns and recent changes in DOE repository design.

4.3.3.3 Approach for Assessing Effects of Rockfall on Waste Package Performance

In the following, an approach to evaluating the effects of rockfalls on WP performance that was implemented in the SEISMO module of the TPA code is discussed (Manteufel et al., 1997; Mohanty and McCartin, 1998). This approach represents the first attempt by NRC to address rockfall and is used to assess the number of WPs ruptured due to rockfall induced by seismicity in the repository thermal environment. Rockfall due to instability of emplacement drifts caused by TM load can also be evaluated in a similar manner. It is recognized that the rockfall conceptual model developed using this approach is based on a series of assumptions. Some of these assumptions may be conservative and some not. A systematic effort is ongoing to quantify rockfall due to seismicity and its effect on WP and drip shield performance using site representative data and the most current design (Hsiung et al, 2000; Gute et al., 2000). The results of the investigation will be used to develop a more representative rockfall model.

Conceptual Model

The SEISMO module adapted in NRC's TPA code (Version 3.2) evaluates the potential for direct rupture of WPs due to rockfall induced by seismicity in the repository thermal environment. The code takes the volume of rockfall as input to perform impact analysis to determine integrity of WPs. The magnitude of the impact load is essentially a function of the size of the falling rock block and the distance of this rock block from the WPs. The volume of rockfall is in turn a function of rock conditions, *in situ* stress, thermal load, and magnitudes of seismic events. In the following paragraphs, discussions related to the conceptual model will be provided in the following sequence: (i) how variations of rock conditions are accounted for in the model, (ii) how falling rock size is related to the magnitude of seismicity, (iii) how the time dependency of the seismic events is accounted for; (iv) how impact load and impact stress are calculated, (v) how rupture of WPs is determined, and (vi) how the number of WPs ruptured is determined. A flowchart showing the steps of calculation in SEISMO is provided in Figure 18.

Joint Spacing and Rock Conditions in TSw2 Unit

It is recognized that not all rocks falling from the roof of the emplacement drifts will have an effect on WPs. The effective size of the rock falling on a WP is considered to be controlled by joint spacing (width and length) and height of the falling rock block and the falling distance of the rock block before it impacts the WPs. The falling distance is controlled by the diameters of emplacement drifts and

WPs. Another factor that affects the falling distance is the number of rockfalls taking place at the same location.

The falling distance for the second rockfall is no doubt longer than that for the first rockfall at the same location. Consequently, the associated energy will apparently be higher and impact will be greater if the WP is not already covered by rock debris. The ability for assessing the effect of repeated rockfalls at the same area is not currently provided in the SEISMO module. One can indirectly evaluate the effects of repeated rockfalls by changing the baseline falling distance provided in the input file for the TPA code. In the future revision of the SEISMO module, the capability of evaluating the effect of repeated rockfalls on WPs will be included.

The joint spacing information provided in a Sandia report (Brechtel et al., 1995), which summarizes data collected from NRG holes, is used to bound the five rock conditions. A range of joint spacing is assigned to each rock condition. Since each rock condition represents a range of joint spacings, a uniform distribution function covering the range of joint spacings is assumed for each rock condition.

As discussed earlier, dividing the TSw2 unit into five rock conditions as implemented in the current version of SEISMO based on joint distribution information using NRG hole data is arbitrary. As more information regarding joint distribution in the TSw2 unit becomes available, it may be possible to develop a continuous function to describe the rock condition in the TSw2 unit such that the assumption of five rock conditions can be removed from the SEISMO module.

Determination of Size of Rockfall

The size of a falling rock can be calculated by joint spacing (width) × joint spacing (length) × height of the rock block. At this time, the SEISMO module assumes, for simplicity, that the width of a falling rock is equal to its length, and the joint spacing is controlled by the rock condition. The maximum heights of the falling rock blocks are assumed to be equal to the heights of calculated yield zones induced by *in situ* stress, thermal load, and various levels of ground accelerations.

The height of the yield zone for each rock condition subjected to ground acceleration is estimated from the results of numerical modeling using the UDEC computer code (Ahola et al., 1996) based on three case studies. The height of the yield zone is a function of rock condition and magnitude of ground acceleration. Using the height of yield zone for calculation of the size of falling rock tends to give an upper bound value. Consequently, the determination of the vertical dimension of the rock that is falling in the SEISMO module is made through sampling a uniform function between the minimum vertical dimension and the maximum vertical dimension. The maximum vertical dimension is assumed to be equal to the height of yield zone while the minimum vertical dimension is assumed to be equal to the average joint spacing of a rock condition.

Investigation is currently under way to devise a more acceptable approach for determining the size of the falling rock using available joint information at the YM site.

Fractional Coverage of Rock Conditions and Determination of Number of Waste Packages Ruptured

Based on the Sandia report (Brechtel et al., 1995), rock condition 4 appears to contain a larger portion of the TSw2 Unit. About 62.9 percent of the area can be characterized as rock condition 4 and rock condition 5 occupies roughly 35.6 percent of the area. Rock conditions 1, 2, and 3 take up only 1.5 percent of the area in total. Due to a lack of specific information, the 1.5 percent is equally divided into the three rock conditions.

If a seismic event triggers rockfall for a particular rock condition, rockfalls are not expected to take place in the entire area of that rock condition. In fact, only a small fraction of the rock under that rock condition will fall in response to a seismic event because of the inherent variation associated with the rocks. Another fraction of the rock may fall at a later time when a separate seismic event, having the same or greater intensity, takes place. Rockfall could also take place at a relatively smaller magnitude event if the rock has been sufficiently weakened due to repeated seismic events. The size of the fraction may be related to the event magnitude, joint dip angles, and incidence angle of incoming seismic waves, etc. At this time, there is little information available to determine such a relationship. Consequently, CNWRA experts developed a continuous function relating the fractional area of rockfall to the magnitude of seismic ground accelerations based on experience in the field. This function is implemented in the SEISMO module for TPA Version 3.2. As currently implemented, this function is rock-condition-independent, that is, the same fraction is applied to all rock conditions in estimating WPs affected by rockfall. This function represents our current thinking. Modification to the function may be necessary at a later date when more technical information becomes available. Also, this function should be made rock-condition-dependent. It is intuitive that, for a particular seismic event, weaker rock should experience relatively larger area of rockfall compared to stronger rock conditions.

Seismic Hazard Parameters

The SEISMO module requires a history of seismic events over the time period of interest. The history of seismic events is generated by the TPA executive SAMPLER utility module. The input required for generating event history includes ground acceleration sampling points and the corresponding recurrence times. These two pieces of information form a prescribed seismic hazard curve.

In determining the recurrence of seismic events, the horizontal acceleration hazard curve provided in DOE's Seismic Design Methodology for a Geologic Repository at YM report (U.S. Department of Energy, 1995) for surface facilities is used. The effect of surface/depth attenuation can be investigated using the SEISMO module. At the time of preparing Revision 2 of this IRSR, new information generated through expert elicitation regarding potential seismic hazards at the YM site became available (U.S. Department of Energy, 1998e). This new information will be included as the base case in a subsequent version of the SEISMO module.

As noted earlier, the seismic recurrence sampling is handled by the SAMPLER utility module in the TPA code. Ten discrete sampling accelerations can be used to describe a seismic hazard and should provide a relatively good representation of that hazard curve. Evaluation of the sensitivity of results to various hazard curves is possible using SEISMO by giving the ground acceleration sampling points and corresponding recurrence times representative of the seismic hazard curves to be analyzed.

Impact Load and Stress Calculations

The approach used for dynamic or impact load determination in the SEISMO module is approximated based on the principle of conservation of energy. This approach assumes that the potential energy associated with freely falling rock is converted completely to strain energy imparted to the WPs during impact. Several other assumptions are also made: (i) a WP can be treated as an equivalent spring with a spring constant, *kwp*, (ii) the deformation of WPs is directly proportional to the magnitude of the dynamically applied force, (iii) no energy dissipation takes place at the point of impact due to local inelastic deformation of the WP material, and (iv) the inertia of the WP resisting an impact may be neglected.

Based on the previous assumptions, the impact load can be approximated using the following equation (Popov, 1970):

$$P_{\mathrm{dyn}} = W\left(1+\sqrt{\left(1+\frac{2hk_{\mathrm{wp}}}{W}\right)}\right) = W\left(1+\sqrt{\frac{2h}{\Delta_{\mathrm{st}}}}\right) \tag{2}$$

where

P_{dyn}	—	impact load
W	—	weight of the rock falling
h	—	falling distance of rocks to WPs
Δ_{st}	—	spring deformation
k_{wp}	—	stiffness of the WPs

k_{wp} of a WP is defined as the load necessary to produce a unit deflection at the center of a simply supported beam.

The WP supports are considered to be flexible in the SEISMO module. In the current conceptual design, a WP will be sitting on four equally spaced v-shaped thin beams with one vertical cylindrical bar on either side of the v-shaped beam. However, only the two supports at the ends of a WP are considered. Originally, Δ_{st} in Eq. (2) is the static deflection of the object impacted. In order to account for the deformability of WP support, Δ_{st} is made to be equal to

$$\Delta_{\mathrm{st}} = \frac{W}{k_{\mathrm{wp}}} + \frac{W}{2N_p k_b} \tag{3}$$

where k_{wp} is stiffness of the WP, $N_p = 2$, which is the number of the supports at the end of a WP, and k_b is stiffness of the vertical bars.

k_b can be calculated by

$$k_b = \frac{AE}{L} \tag{4}$$

and k_{wp} can be calculated by

$$k_{wp} = \frac{48EI}{L_{wp}^3} \tag{5}$$

where *A* and *L* are the cross-sectional area and height of the vertical bar.

L_{wp}	—	length of the WP
I	—	$\pi R_{avg}{}^3 t$
t	—	thickness of WP considering both inner and outer layers
R_{avg}	—	average of the outer and inner wall radius of the WP

No information regarding the shape and dimension of the bar is currently available.

From the impact load, the equivalent static stress resulting from the impact can be calculated by adopting a simple concept of two spheres in contact and assuming that the pressure is distributed over a small circle of contact with the sphere representing rock has an infinite radius (Timoshenko and Goodier, 1987), the impact pressure, *p*, can be obtained by

$$p = \frac{3}{2\pi}\left(\frac{16P_{dyn}}{9\pi^2}\frac{1}{\left(c_{wp} + c_{rock}\right)^2 R_{wp}^2}\right)^{\frac{1}{3}} \tag{6}$$

where

R_{wp}	—	radius of lower sphere or WP
c_{wp}	—	material constant for lower sphere or WP
c_{rock}	—	material constant for upper sphere or rockfall

$$c_{wp} = \frac{1-\mu_{wp}^2}{\pi E_{wp}} \tag{7}$$

$$c_{rock} = \frac{1-\mu_{wp}^2}{\pi E_{rock}} \tag{8}$$

where

E_{wp}	—	modulus of elasticity of lower sphere or WP
μ_{wp}	—	Poisson's ratio of lower sphere or WP
E_{rock}	—	modulus of elasticity of upper sphere or rockfall
μ_{rock}	—	Poisson's ratio of upper sphere or rockfall

The assumption made for the WPs, spherical in shape instead of a cylinder, is believed to give a conservative calculation of impact stress since the contact area calculated using this assumption is smaller than that from assuming a cylindrical shape.

Failure Criterion

To judge the failure of a WP, a maximum allowable strain failure criterion is adopted in the SEISMO module. If the impact stress calculated using Eq. (6) induces a total strain at the contact of impact exceeding 5 percent (Mohanty et al., 2000), the WPs are assumed to be ruptured. This assumption should provide a conservative approach for estimating failure of WPs. The potential damage that rockfall can cause to the SNF cladding is currently not accounted for in the SEISMO module.

Limitations of the SEISMO Approach

Although the current SEISMO module does not link seismicity with corrosion, over time, corrosion could weaken WPs and make them more susceptible to failure by seismically induced rockfall. Conversely, the damage resulting from rockfall could weaken WPs and make them more susceptible to corrosion over time. In the current SEISMO module, these conditions are not included. These conditions may be considered in the future revision of the SEISMO module.

For calculation of the rockfall impact load, the falling rocks are assumed to remain intact (that is, all energy generated through dynamic impact is transferred to the WP). If rock is allowed to break, the effective impact stress on the WP should be smaller since some impact energy will be absorbed by breaking the rock. Consequently, assuming that the falling rock blocks remain intact is conservative in assessing integrity of WPs.

The SEISMO module in its current form does not take into consideration cumulative damage due to repeated rockfalls. Some work will need to be done to address this limitation.

4.3.3.4 Review of U.S. Department of Energy Rockfall Analysis (Viability Assessment and Technical Basis Document)

The DOE completed the VA report (U.S. Department of Energy, 1998f) of the YM site in 1998 at the direction of the U.S. Congress. The VA "describes the strategies that DOE has developed to deal with uncertainties associated with estimates of long-term repository performance and to ensure that public health and safety will be protected before and after the repository is permanently closed" (U.S. Department of Energy, 1998f). This VA report also contains three key components of site characterization—testing, design, and TSPA.

From a technical perspective, the TSPA portion of the VA [Volume 3 of the VA (U.S. Department of Energy, 1998f), referred to as TSPA-VA] and the Technical Basis Document (TBD) (CRWMS M&O, 1998f), which contains supporting analyses used in the TSPA-VA, have the most relevance to the RDTME KTI. Of these two documents, the TBD contains greater detail. A summary review of the TBD and the referred documents related to RDTME is provided in the following section. The main focus of the review is placed on the TBD, Section 10.5.1, Rockfall.

Technical Basis Document, Section 10.5.1: Rockfall

Section 10.5.1 of the TBD addresses the rockfall model, which describes the likelihood of earthquake-induced rockfall, potential size of rockfall, and the consequence to WP integrity and radionuclide releases. The possible effects of seismic disturbance (vibratory ground-motion or fault displacement) include rockfall damage to WPs and change in flow pattern near the emplacement horizon. From DOE's perspective, rockfall is expected to be the primary source of WP disturbance (CRWMS M&O, 1998f).

Available Rock Block Size in the Exploratory Studies Facility

The distribution of rock block sizes determined in CRWMS M&O (1997a), which was based on the joint spacings obtained from the scanline mapping in the ESF, was used in the TBD to assess rockfall effects on WP disturbance. The rock block size was estimated using the approach suggested by Palmstrøm (1996)

$$V_b = \beta\, J_v^{-3} \tag{9}$$

where V_b is the block size (volume), β is the block shape factor, and J_v is the volumetric joint count. Separate equations are available for determining β and J_v (Palmstrøm, 1996). For simplicity, the joints are assumed to intersect at right angles to form a block (CRWMS M&O, 1997a). The rock size distribution was conveniently divided into four rock quality designations.

Estimation of Rockfall Due to Ground Motion

It is difficult to estimate the extent of damage and rockfall of underground excavations subjected to ground-motions. The level of damage and amount of rockfall as a result of vibratory ground-motions depend heavily on the related rock mass conditions (rock types), state of stresses, and ground supports. An empirical equation proposed by Kaiser et al. (1992) was used in the TBD to estimate the damage to underground excavations caused by shaking. This equation was developed for assessing rockburst-induced tunnel damage for underground mines in Sudbury, Ontario, Canada, and is qualitative in nature. This equation was modified in the TBD to account for the effect of rock mass conditions, as follows:

$$DL = \frac{\ln\left(\frac{PGV}{5}\right)}{\ln(2)} - 2.33 + 1.33\,IC \tag{10}$$

where DL is the damage level, a qualitative damage index; PGV is the peak ground velocity; and IC is the measure of rock condition related to rock wall quality, failure potential, local mining stiffness, support effectiveness, and temperature (CRWMS M&O, 1997a).

It is worth noting that Eq. (10) was developed for assessing tunnel damage caused by rockbursts. The ground shaking signals associated with rockbursts are of relatively short duration and high frequency (Hsiung et al., 1992), whereas earthquakes involve longer duration and relatively lower frequency ground-motions. Consequently, applicability of the damage level assessment empirical equation to the YM site needs to be verified.

The *IC* values in Eq. (10) were assigned to each of the four rock quality designations based on an assessment of ESF data (CRWMS M&O, 1997a). The technical basis for assigning these values is not provided in the TBD. Because the rock quality designations are related to rock block sizes as indicated in the previous section, *DL* can be related to the available rock block sizes through Eq. (10). (Note that the rock size referred to here and for the rest of this paragraph means rock mass.) However, this relationship did not seem to be used in Section 10.5.1.6, Development of Rockfall Model Source Term, to determine the rock size needed to assess damage to WPs. Instead, two additional terms were introduced: size of rock expected from *DL* and size of rock from a probability density function (PDF). The rock size from a PDF was compared with the critical rock size required to damage WPs. If the former is larger, the WP impacted is judged to be damaged. No discussion is provided in the TBD regarding how the size of rock expected from a given *DL* is determined, nor does it present clearly how the size of rock is determined from a PDF.

Furthermore, there appears to be a miscalculation of *DL*, for example, in Tables 10-28 and 10-30a where *DL* values are consistently underestimated. A close examination of the *DL* values provided in these tables indicate that they were determined using

$$DL = \ln\left(\frac{PGV}{5}\right) - 2.33 + 1.33\,IC \tag{11}$$

Figure 19 graphically shows the difference of *DL* values calculated for various peak ground velocity (PGVs) using these two equations. The calculated *DL* value is about 40 percent smaller for strong rock and about 30 percent smaller for the medium rock if Eq. (11) is used. It is not clear which equation was intended to be used in the TBD. If Eq. (11) is the correct equation, DOE needs to provide justification. If the use of Eq. (11) is a mistake, this mistake needs to be corrected and the rockfall effect on WP damage reevaluated.

Waste Package Damage Criteria

The TBD considered two forms of rockfall damage to WPs: through-wall cracks and crack initiation. The rock size necessary to cause these two types of damage was estimated by dynamically modeling the rockfall impact on WPs (CRWMS M&O, 1996c,d). The dynamic analysis conducted in the two reports published by CRWMS M&O (1996c,d) assumed that the rock was spherical in shape. The report stated, "This assumption provides a bounding approach to the problem since the most severe effect of impact on the WP will be determined without any failure on the rock surface." This assumption appears to be reasonable. In a CNWRA analysis, (Gute et al, 1999) the effects of several types of impact contacts were analyzed. The results indicate that a spherical rock would appear to cause the most damage to the WPs and thus would represent a bounding case. Work is continuing in this area, however, to determine whether the strain energy distribution through the thickness of the WP wall, at the point of impact, can provide additional information as to the relative significance of rock size and shape.

The FE analysis conducted in both reports models a section of the WP (in the middle span) about 1.5 m in length. This length is about the distance between two adjacent pedestal supports. Both reports (CRWMS M&O, 1996c,d) postulate that, "since the middle section of the WP provides a smaller length than the full WP length, the finite element model is conservative." This assertion is based on the understanding that the bending stress on a beam is directly proportional to the square root of the beam length (CRWMS M&O, 1996c,d). In both reports, the beam length is assumed to be the length of a WP. The assumption of conservativeness does not seem to be justifiable because the beam length used in calculating bending stress is the length between two adjacent supports (for a simply supported beam). In the case of the support configuration proposed for the WPs, the beam length is 1.5 m. Consequently, using the 1.5-m section for modeling is reasonable and not necessarily conservative as both reports have stated.

In determining the fall height of a rock, degradation (thinning as a result of corrosion) of WPs was considered (CRWMS M&O, 1996c,d). The fall height is the vertical distance between the bottom of a rock before it falls and the top of the WP. The bottom of the rock before it falls was fixed to coincide with the crown of the emplacement drift (CRWMS M&O, 1996c,d). While assuming a fixed full height appears to be a good first approximation, it does not allow for consideration of the increased height of fall for subsequent rockfalls at the same location. In that situation, the fall height will be greater and so will be the effect of the same size rock. In addition, the vertical velocity of the WP and the initial velocity of the rock when it becomes dislodged due to the seismic ground-motion have not been taken into consideration.

Another area of concern pertaining to the work documented in the reports (CRWMS M&O, 1996a,b) is the use of a maximum normal stress failure criterion to establish rupture of the WP outer barrier due to rockfall. Specifically, the M&O CRWMS 1996b report states, in assumption 4.3.15,

> "The materials are assumed to reach the ultimate tensile strength at the maximum percent elongation. The basis for this assumption is that the failure criteria are based on the ultimate tensile strength of the materials, and not on the path followed by the curve in the plastic region of the stress-strain diagram. Hence, the stress distribution results are conservative in this analysis."

Except under a very limited set of special conditions (e.g., extremely low temperature) a failed tensile test specimen of a ductile metal will exhibit failed surfaces that are at a 45° angle with respect to the specimen's cross section. This is clearly indicative of failure due to shearing. When subjected to more general types of three-dimensional model (3D) stress conditions, the appropriate failure criterion should be based on the same failure mode as was observed for the tensile test specimen. Moreover, it can be demonstrated by a simple Mohr's circle diagram that there are generalized 3D stress states that will fall within the acceptable bounds of the maximum-normal-stress-theory, but will fall well outside the bounds of an acceptable out-of-plane shear stress. Development of a generalized failure criterion for ductile metals is not a trivial matter and more work needs to be done in this area. However, it needs to be emphasized that the use of the maximum-normal-stress-theory as a failure criterion for predicting the rupture of the WP outer barrier is both inappropriate and nonconservative.

Damage to Fuel Rods

The TBD acknowledged that rockfall could cause mechanical failure of spent-fuel rods or shattering of a glass/ceramic waste form through shock and container-wall deformation even if a WP is not breached due to rockfall (CRWMS M&O, 1997a). The damaged fuel rods increase the probability of radionuclide releases when the WP is finally breached due to either rockfall or corrosion. The TBD also presented some results of an analysis of the effects of rock configurations on fuel rod damage. Rockfall effects on fuel rod damage and related dose calculation were discussed in Section 6 of the TBD. The evaluation of these effects will be included in the IRSR of the Container Life and Source Term KTI.

Time Periods for Waste Package Damage Assessment

The TBD calculated WP damage for four time periods: 0 to 1,000 years, 0 to 10,000 years, 0 to 100,000 years, and 0 to 1,000,000 years. In each time period, 500 event times were randomly drawn (CRWMS M&O, 1997a, Section 10.5.1.6). Consequently, the event frequency for each time period is 0.5 event/year, 0.05 event/year, 0.005 event/year, and 0.0005 event/year, respectively. It seems clear that more emphasis of rockfall effect was placed on early times of the repository performance because the event frequency considered is much higher. No discussion is provided in the TBD why the emphasis was placed on early time periods, especially from 0 to 1,000 years in which the WP experienced little degradation and rockfall was deemed to have no effect on WP damage.

In determining the rockfall model source term, "the fall of a single rock size (the largest possible for the PGV selected) per event" (CRWMS M&O, 1997a, Section 10.5.1.6) was modeled. This approach appears not to be conservative. CRWMS M&O recognizes this and stated in the TBD that, "clearly, many rocks fall during an earthquake. Future analyses will incorporate multiple rockfalls into the integrated corrosion-rockfall WP degradation model."

4.3.4 Technical Bases For Review: Thermal-Mechanical Effects on Flow into Emplacement Drifts

In the current DOE approach to repository design, the ground-support system for the emplacement drifts would be designed to maintain stability of the openings during the preclosure period only. That is, no credit would be taken for the effectiveness of the ground-support system, and no technical evaluation of such effectiveness would be provided for the post closure period. As a result, the support system is assumed to have completely lost its effectiveness in the analyses of the postclosure behavior of the emplacement openings (e.g., U.S. Department of Energy, 1998f, Section 2.2.6.1).

The expected behavior of unsupported underground openings under sustained rock mass degradation includes cave-in of the roof, collapse of the sidewalls, and progressive damage of the surrounding rock mass, resulting in an altered zone within, above, and below the repository horizon. The consequent changes in the geometry of the openings (gross shape and size and roughness of the drift surface) and in the fracture porosity and permeability within the altered zone are of interest in assessing the quantities of water flow that may contact the WPs. Change in the geometry of the openings could have significant effect on the potential water dripping into the emplacement drifts. For example, the threshold value of percolation flux at which dripping would begin decreases as the drift surface becomes irregular from rockfall (Hughson and Dodge, 1999). Also, an increase in fracture permeability within laterally discontinuous altered zones anticipated from TM effects would cause a redistribution of percolation flux through the repository horizon, such that areas at the downstream end of the altered zone experience elevated water fluxes (Ofoegbu, 2000; Ofoegbu et al., 2000).

Thermally induced ground movements (rock deformations, collapse, and other changes that may affect the integrity and geometrical configuration of underground openings) will affect inputs to hydrological flow assessment in two ways: changes in fracture permeability and porosity associated with rock deformation, and changes in geometry of underground openings. Both effects have been recognized within DOE's program. The assessment of the impact of thermal loading on the fracture porosity and permeability throughout the host rock, particularly near the emplacement drifts and within the intervening pillars is one of the issues that was presented to a panel of experts assembled by DOE to examine the role and assessment of near-field/altered-zone coupled effects (Geomatrix Consultants, Inc., 1998). Also, the fraction of WPs exposed to seepage, referred to as seepage fraction, f_s, is a key input into the assessment of WP degradation and, ultimately, dose to individuals in DOE's TSPA-VA code (Wilson, 1998). The parameter f_s depends on the distribution of seepage on the drift wall, for which the size and shape of the drift are key inputs because of their effects on the capture area for drift seepage (Wilson, 1998; Birkholzer, 1998).

Changes in size and shape of emplacement drifts may result from drift-wall collapse and consequent enlargement of the roof (e.g., Figures 7 and 16). Changes in fracture permeability and porosity may result from both elastic deformations (caused by reversible thermal expansion of rock) and inelastic deformations (associated with failure in shear or tension). Adequate assessment of thermally induced changes in porosity and permeability requires consideration of both elastic and inelastic processes, because the magnitude of thermally induced elastic deformations may be small relative to the potential magnitude of inelastic deformations that may result due to failure caused by rock-mass degradation. For example, the assessment of permeability changes suggested by Elsworth (1998), which is based purely on consideration of elastic deformations, is likely to give only a lower-bound estimate of the potential permeability change.

It is DOE's decision to design the ground supports to maintain stability of the emplacement drifts for the preclosure period only, therefore, the continuing function of the ground supports beyond permanent closure cannot be assured. Consequently, the underground openings must be assumed to be unsupported during the postclosure period. Postclosure response within the underground facility will be controlled by thermal stresses imposed on a rock mass that may be experiencing progressive degradation of strength and elastic properties caused by sustained loading and extended exposure to heat and moisture. The expected behavior around unsupported underground openings under such conditions includes collapse of the surrounding rock into the openings and consequent cave-in of the roof area, leading to changes in geometry (size and shape) of the openings and changes in hydrological properties (such as fracture porosity and permeability) in the vicinity of the openings (see Figure 16).

An assessment of such potential changes in porosity and permeability as well as changes in emplacement-drift geometry will be considered by other KTIs as appropriate.

4.4 DESIGN AND LONG-TERM CONTRIBUTION OF REPOSITORY SEALS IN MEETING POSTCLOSURE PERFORMANCE OBJECTIVES

This subissue is closed (see end of Chapter 2, Section 2.2).

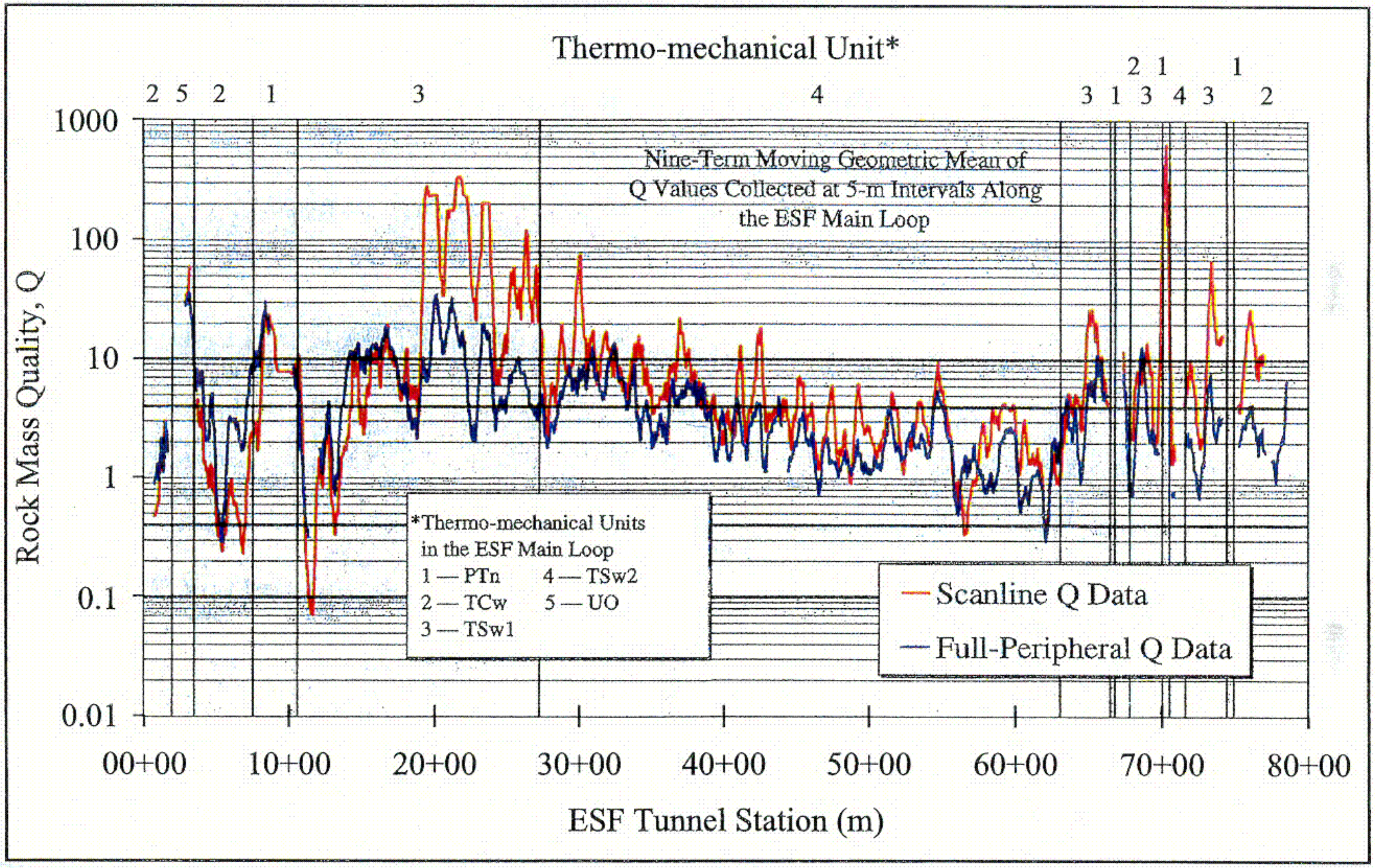


Figure 2. Profile of rock-mass quality, *Q*, along the Exploratory Studies Facility (CRWMS M&O, 1997a)

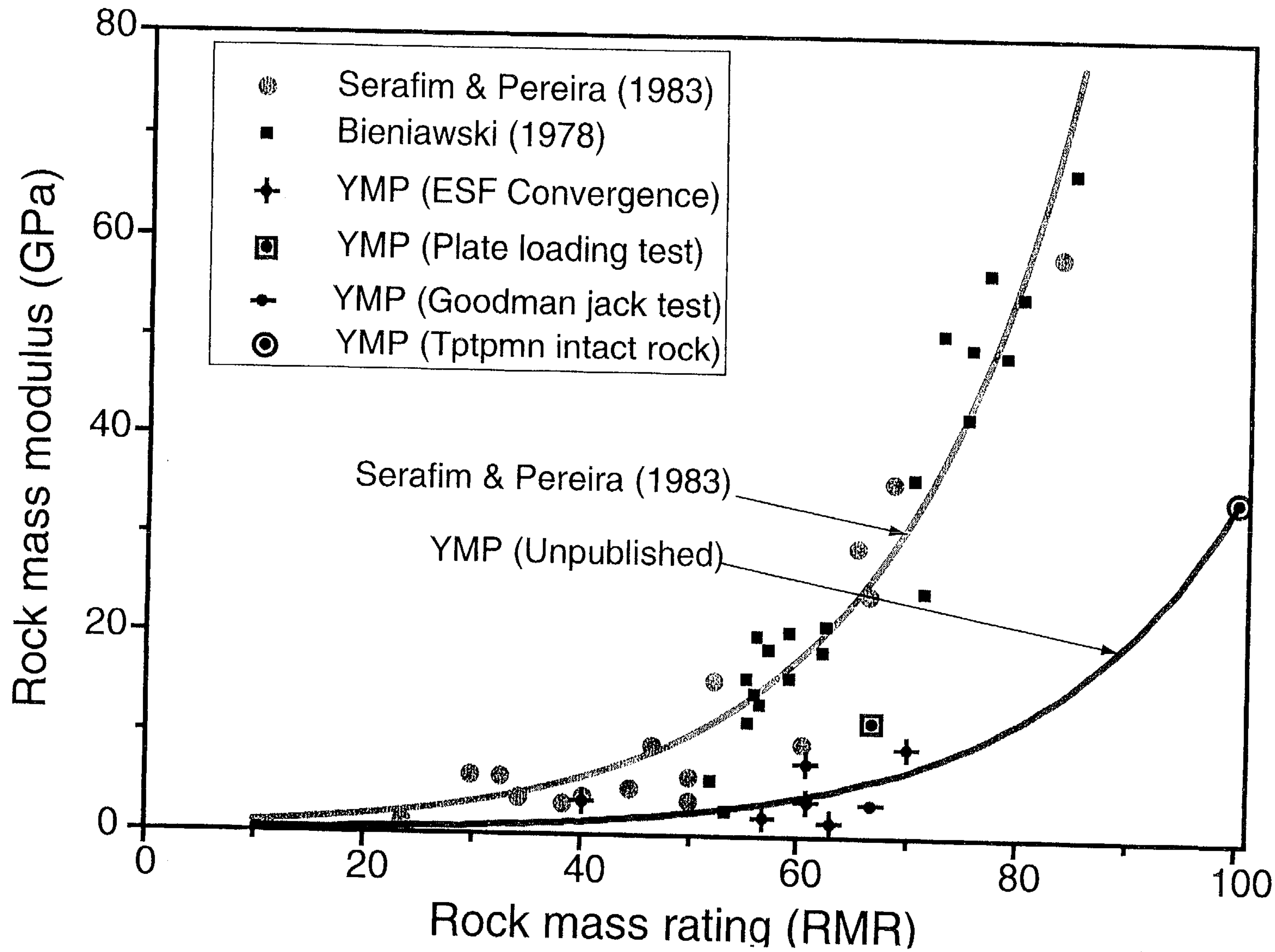


Figure 3. Variation of rock-mass modulus with rock-mass rating based on data available from the literature and the Yucca Mountain Project. The figure shows a curve suggested recently for YM tuff (Lin, 1998), the validity of which is questionable because the curve was derived by extrapolation of sparse rock-mass modulus data to intact rock.

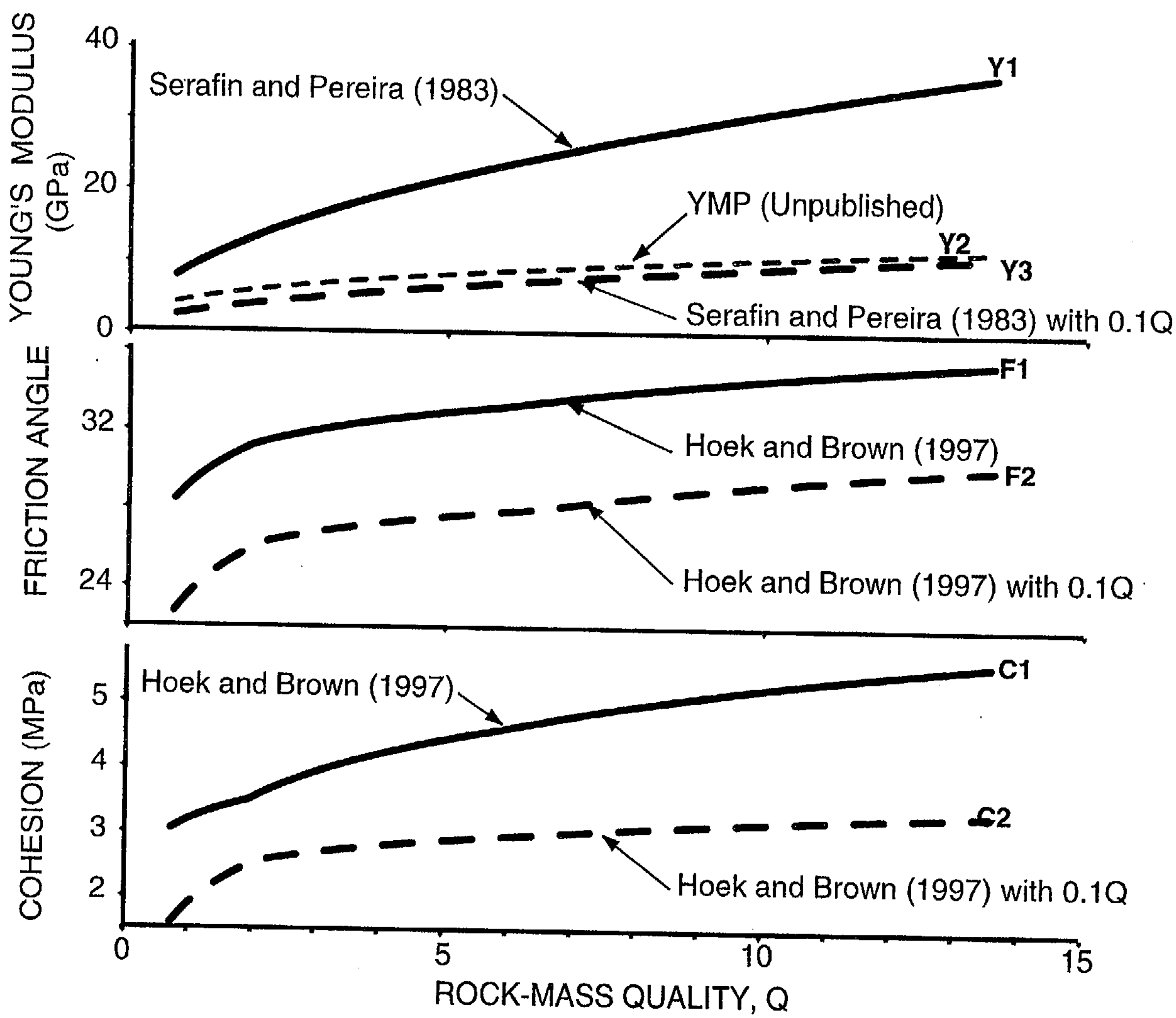


Figure 4. Mechanical parameters estimated from *Q* for the TSw2 stratigraphic unit using empirical relationships (Hoek, 1994; Hoek and Brown, 1997) for: (i) current rock-mass conditions (curves Y1, F1, and C1); and (ii) degraded rock-mass conditions (curves Y3, F2, and C2). The reduction of *Q* to 10 percent of its current value simulates the effects of fracture-wall alterations from extended exposure to heat and moisture. The curve Y2, which is of questionable validity as indicated in Figure 3, is shown here to emphasize its relationship with the other Young's-modulus curves.

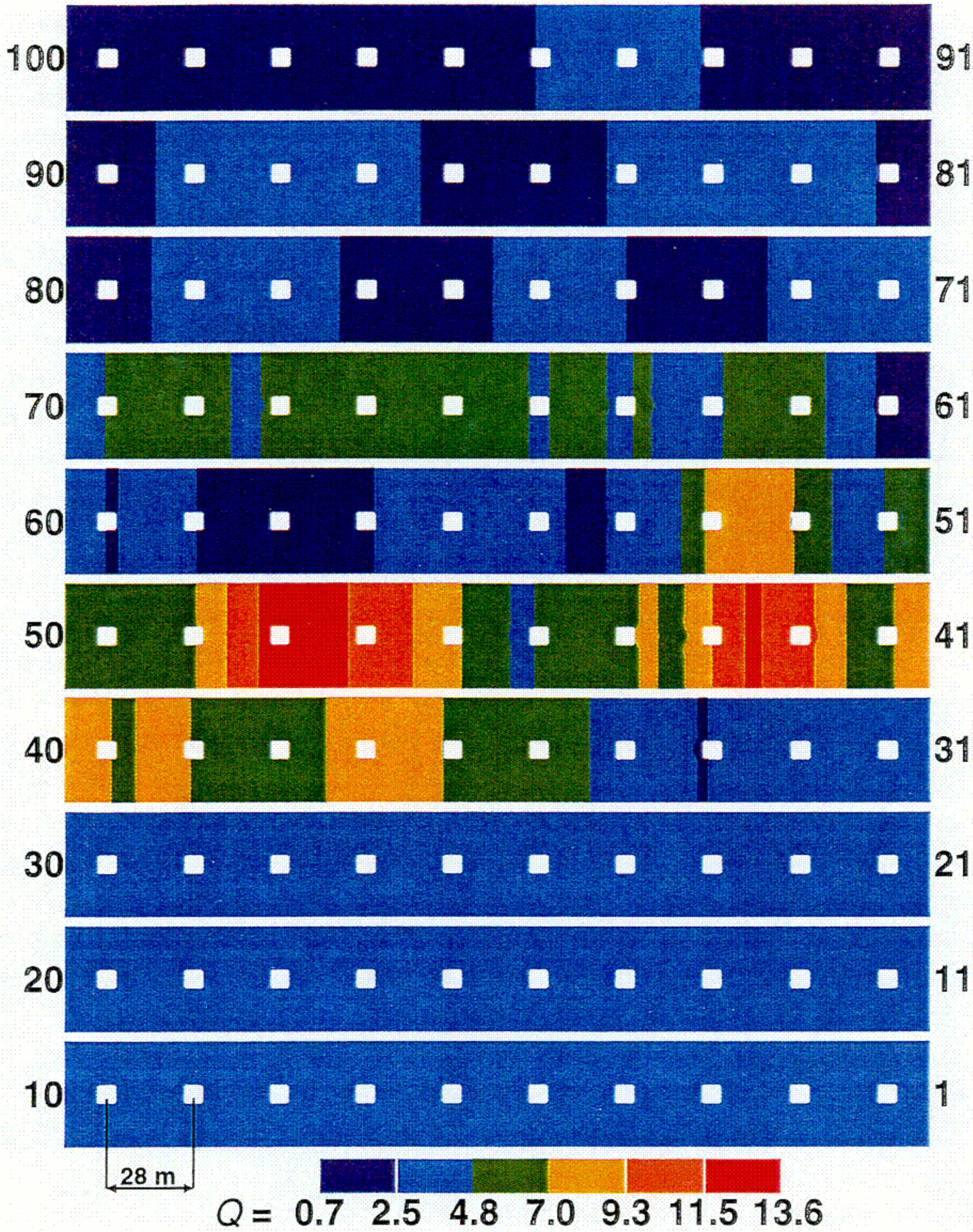


Figure 5. South-to-north profile of rock-mass quality, *Q*, adopted from the ESF main-drift profile. The profile is presented in ten 35-m high and 280-m long sections. Each section includes 10 drifts (end-drift numbers shown). Drifts #1 and #100 are at the north and south ends of the drift array. Areas between drifts #1 and #32, which fall outside of the ESF main-drift alignment, were assigned the *Q* value for #32.

C02

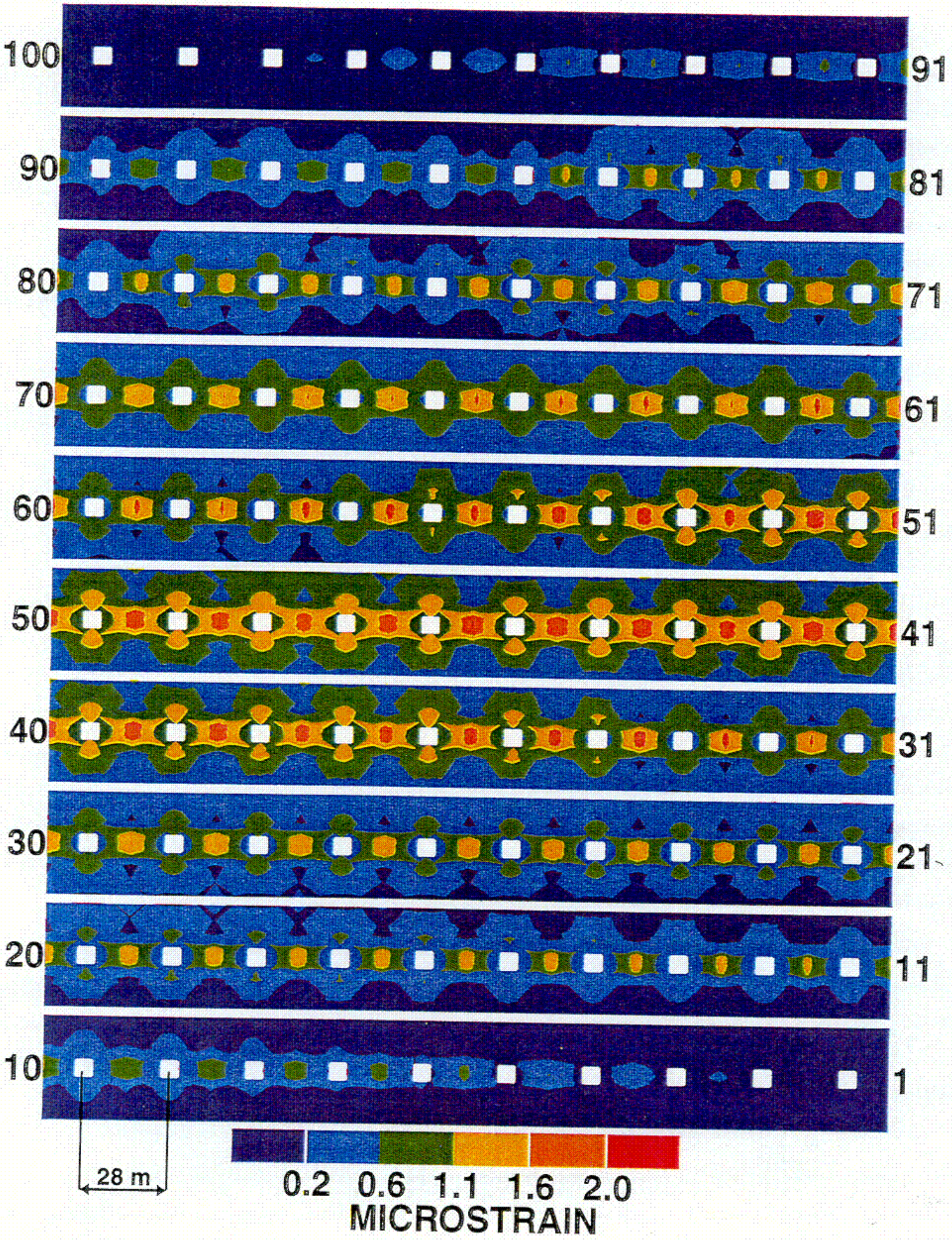


Figure 6. Inelastic strain distribution at 150 years with stiff drift support, shown in 10 sections as explained in Figure 5.

C03

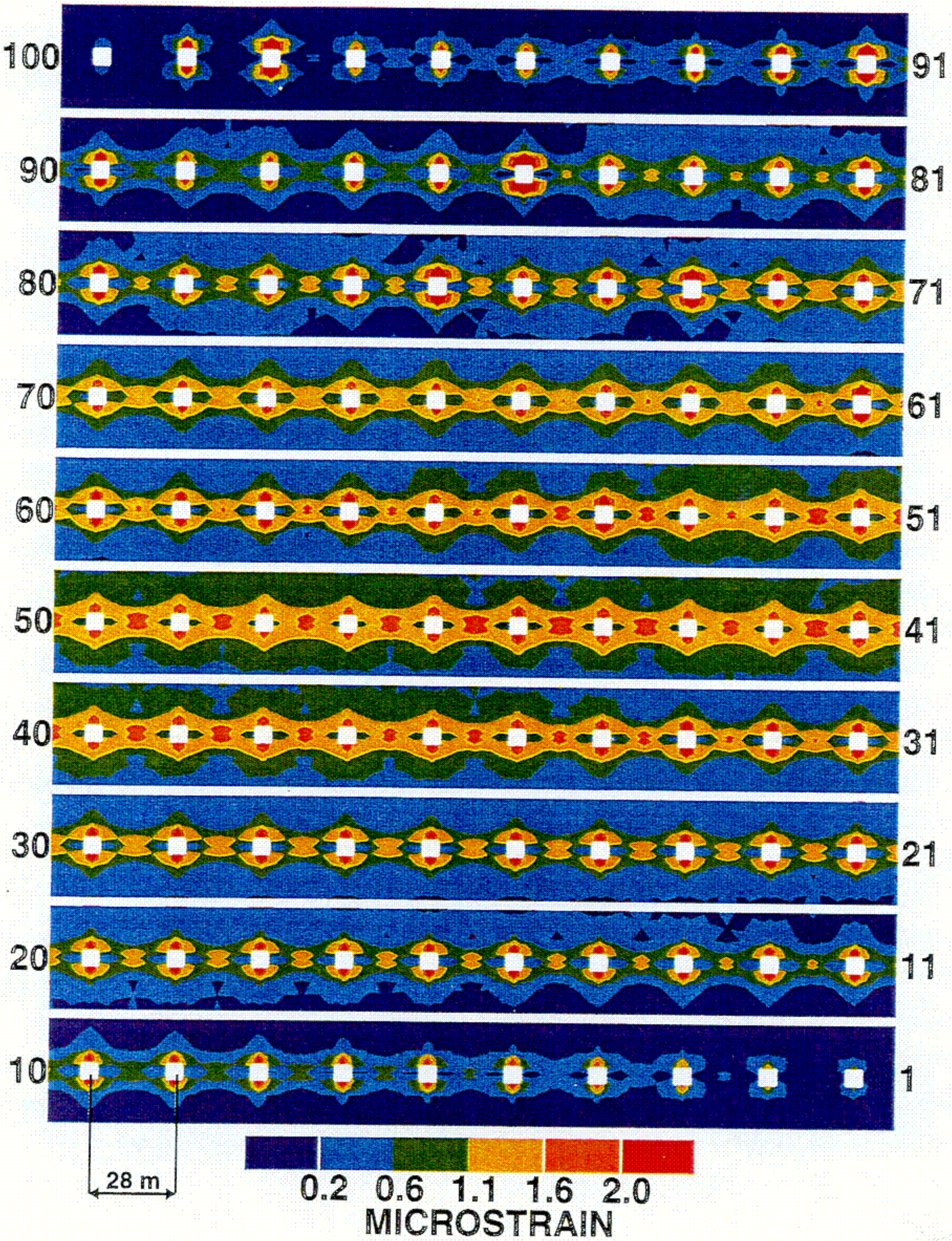


Figure 7. Inelastic strain distribution at 150 years with degraded drift support. Support degradation was simulated by deactivating the support system rapidly (over 1 year) after 150 years.

C04

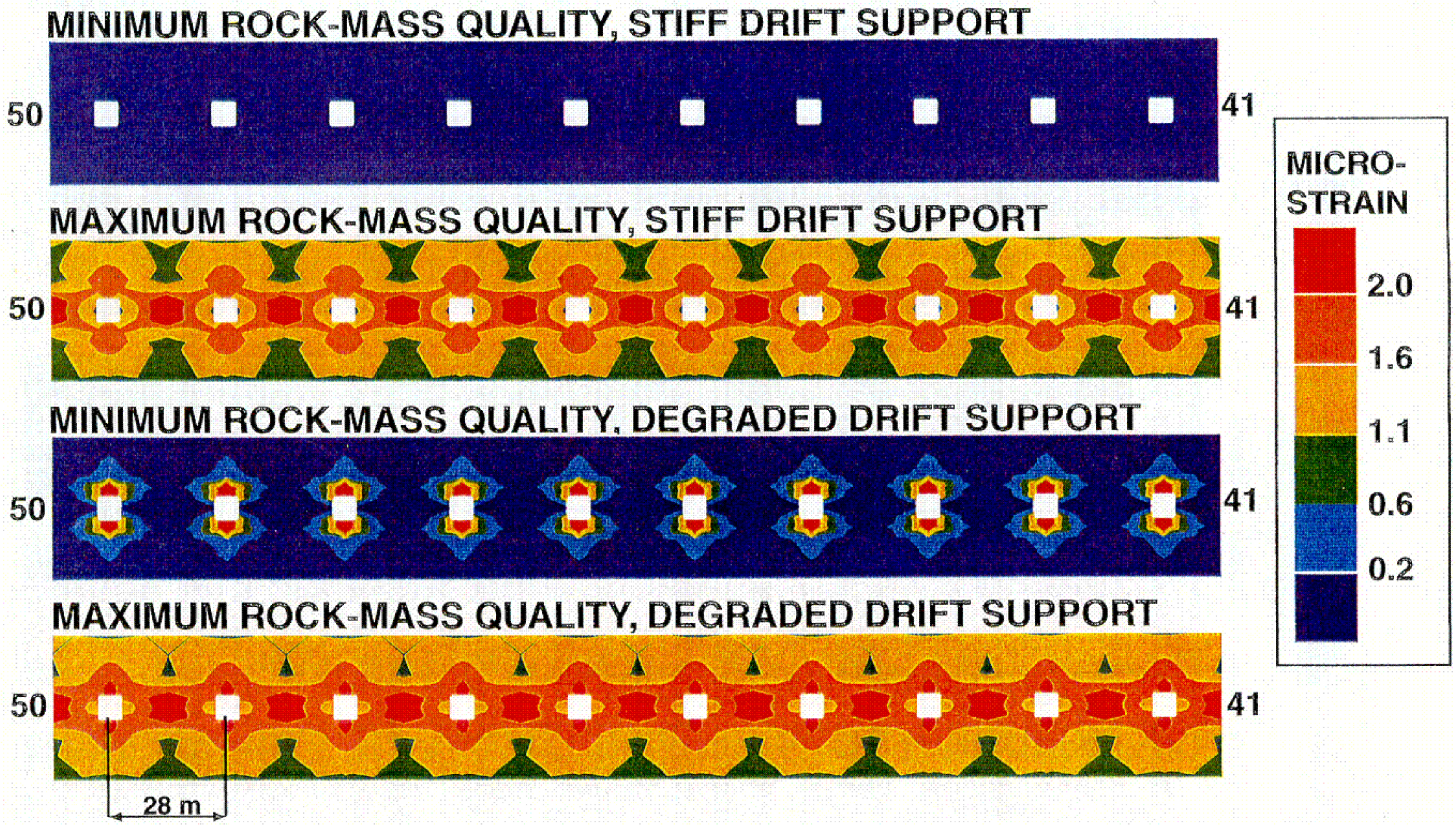


Figure 8. Inelastic strain distributions between drifts #41 and #50 at 150 years, from homogeneous models. Analyses were performed using the parameter values that correspond with the minimum and maximum *Q* values on curves Y1, F2, and C2 in Figure 4.

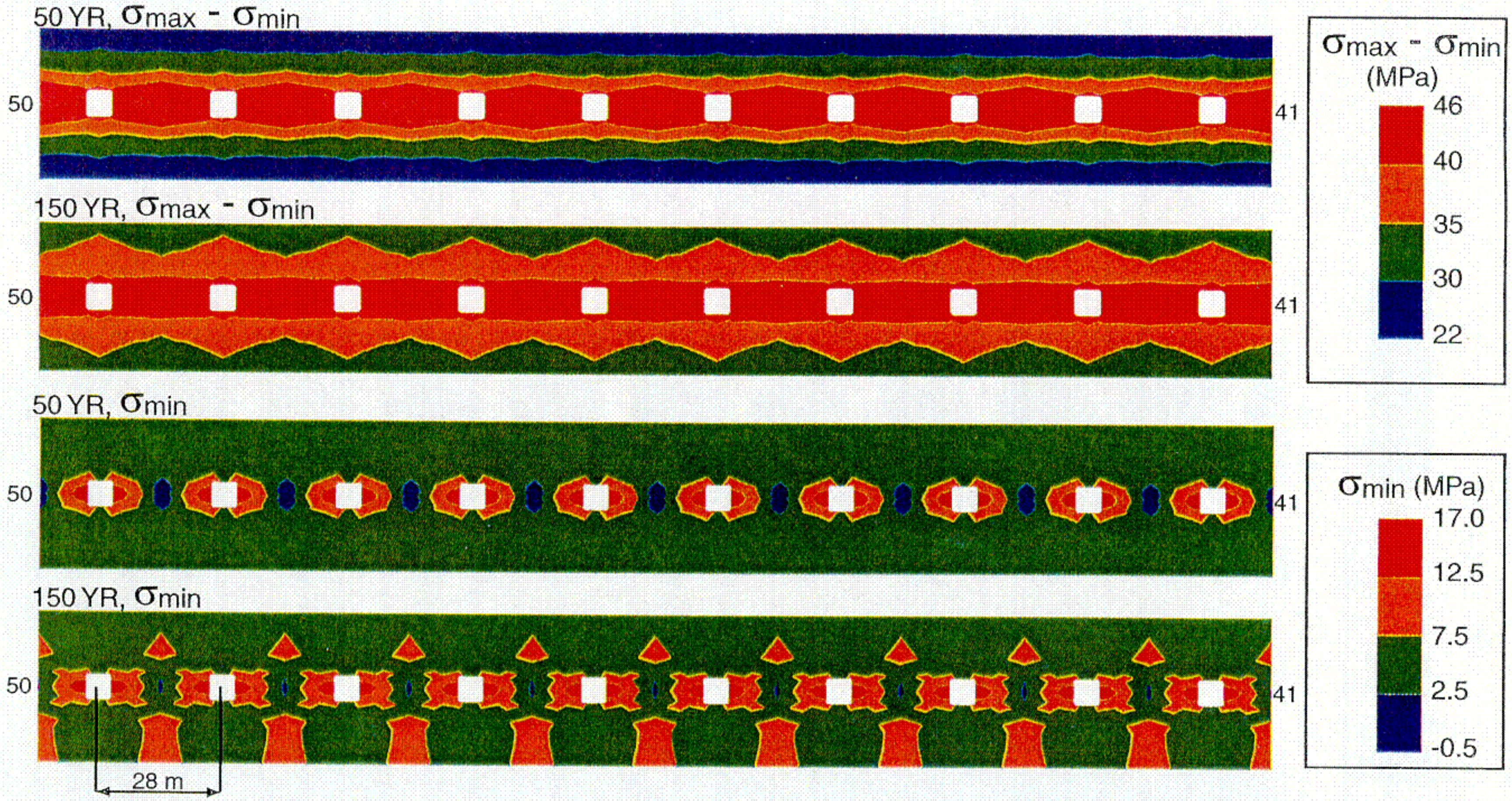


Figure 9. Distribution of principal stress difference ($\sigma_{max} - \sigma_{min}$) and minimum principal stress (σ_{min}) from a homogeneous, linear-elastic model with stiff drift support and Young's modulus corresponding to the maximum *Q* value on curve Y1 of Figure 4.

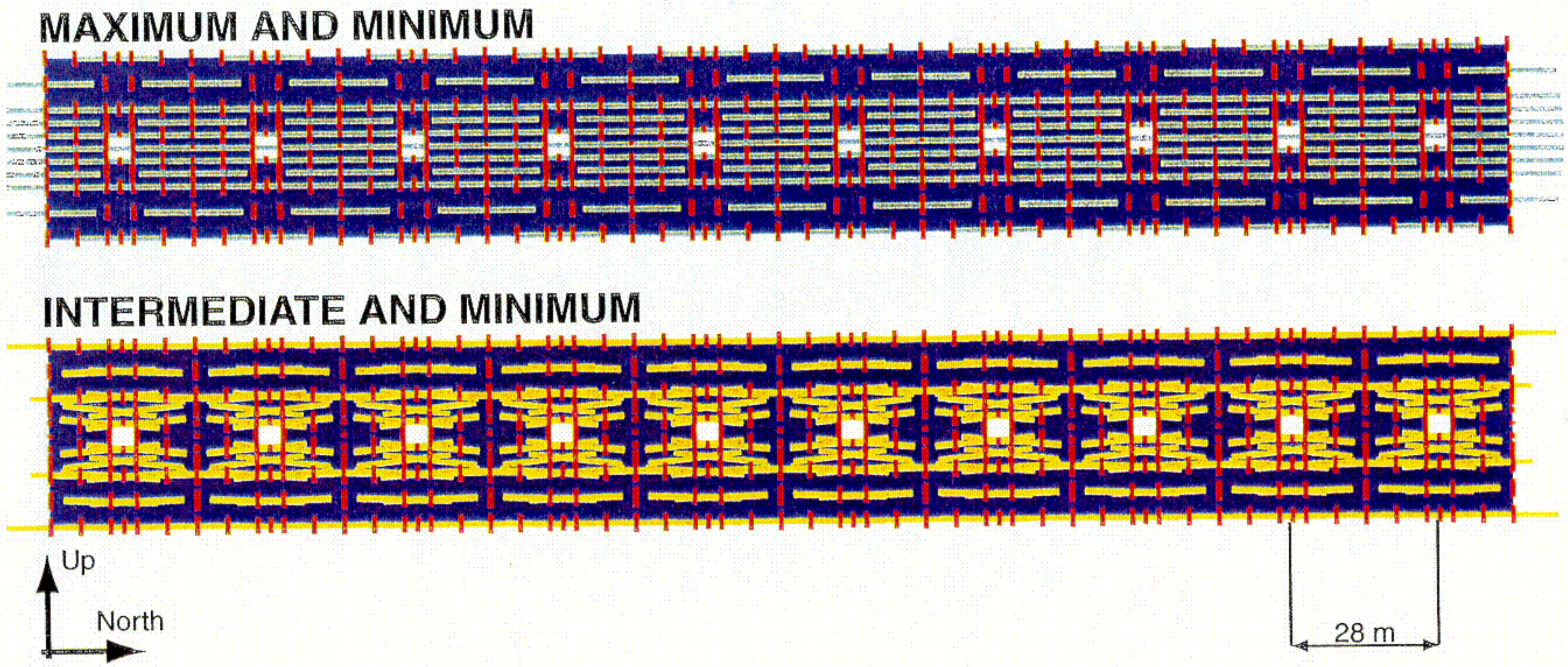


Figure 10. Principal stress orientations from a homogeneous, linear-elastic model with stiff drift support. Each plot shows the orientations of the in-plane principal stress components only, so the plots demonstrate that the maximum principal stress is in-plane (~north-south) in the pillars and out-of-plane (~east-west) in the roof and floor.

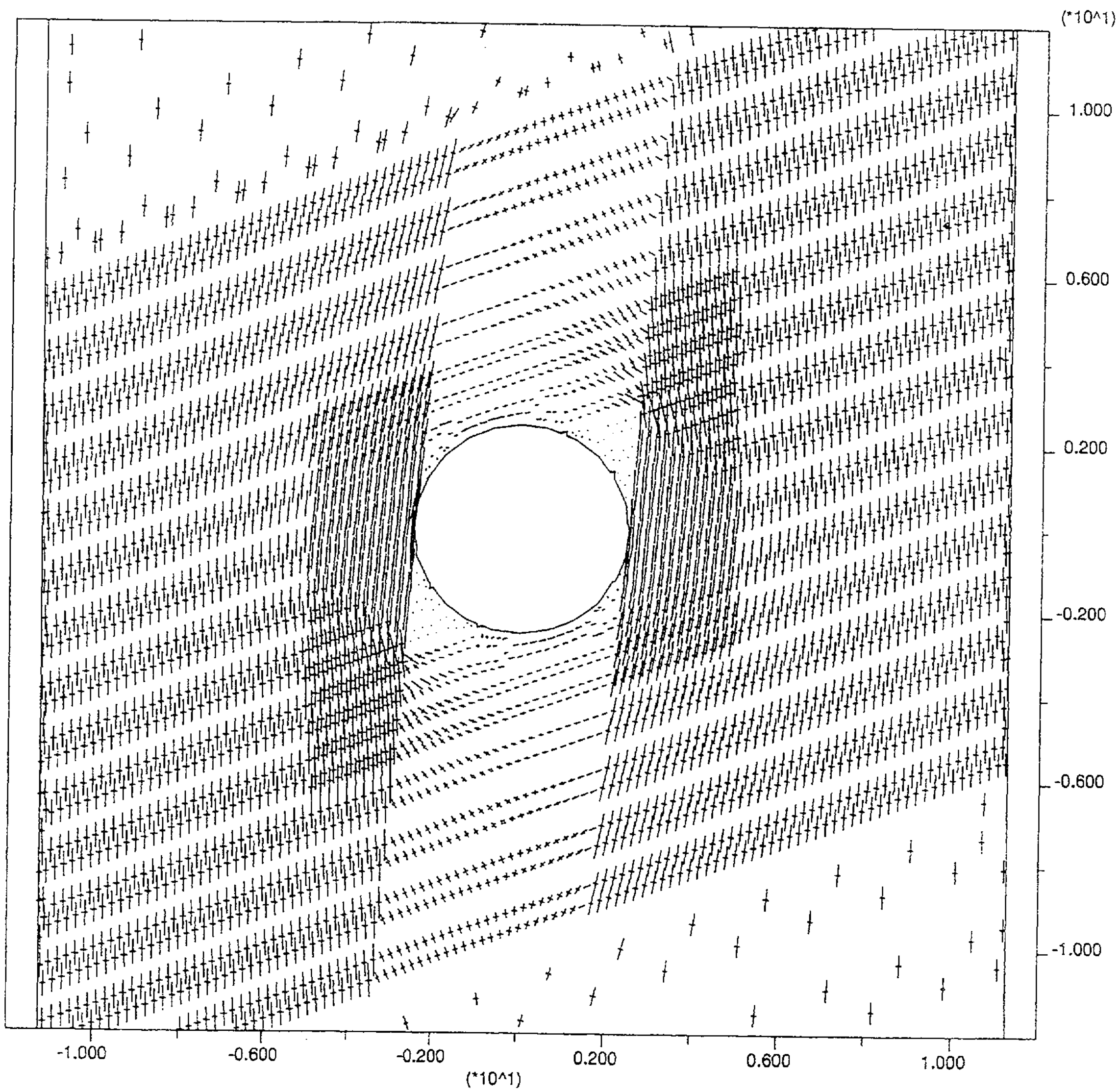


Figure 11. Distribution of principal stresses after drift excavation

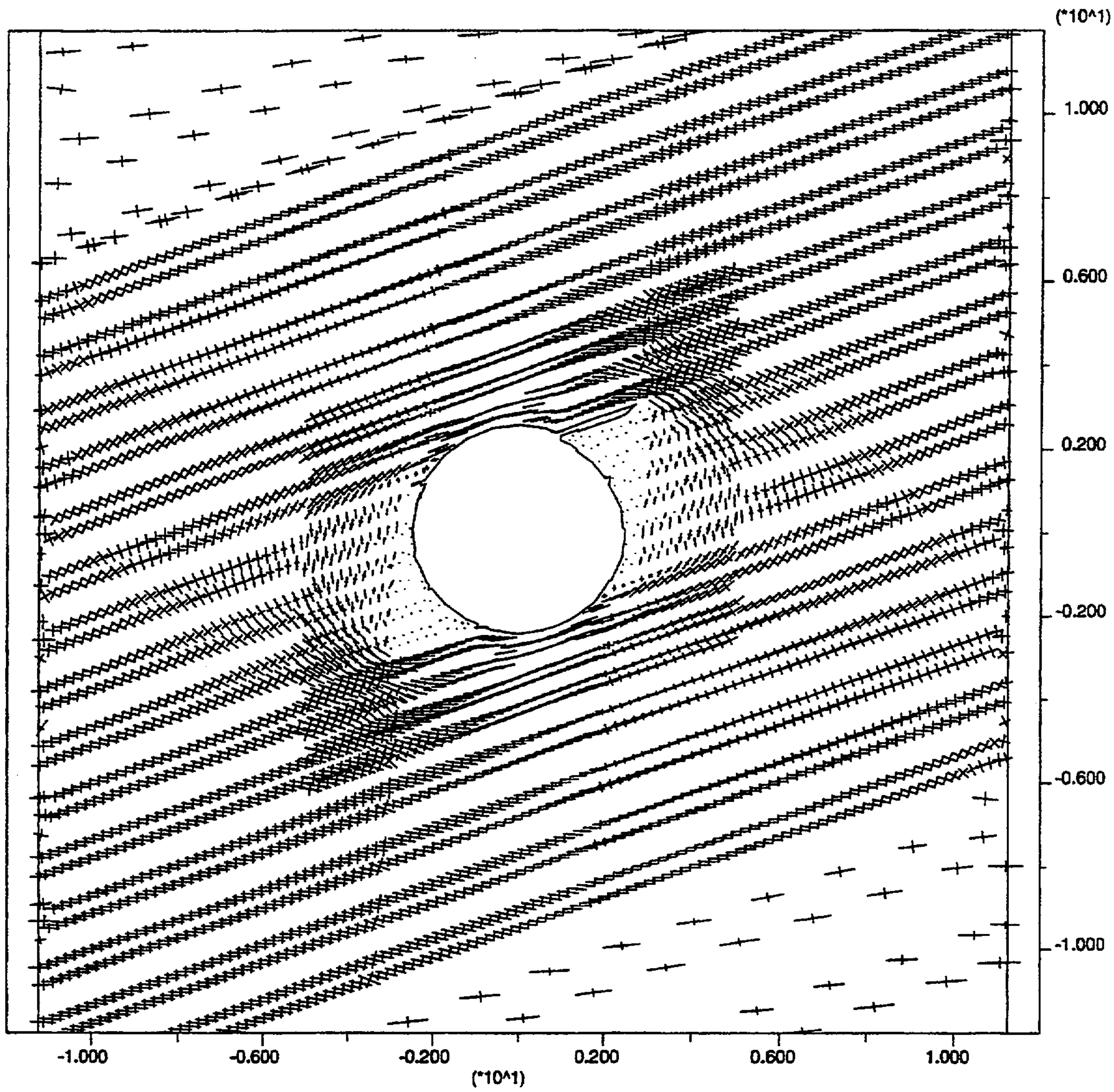
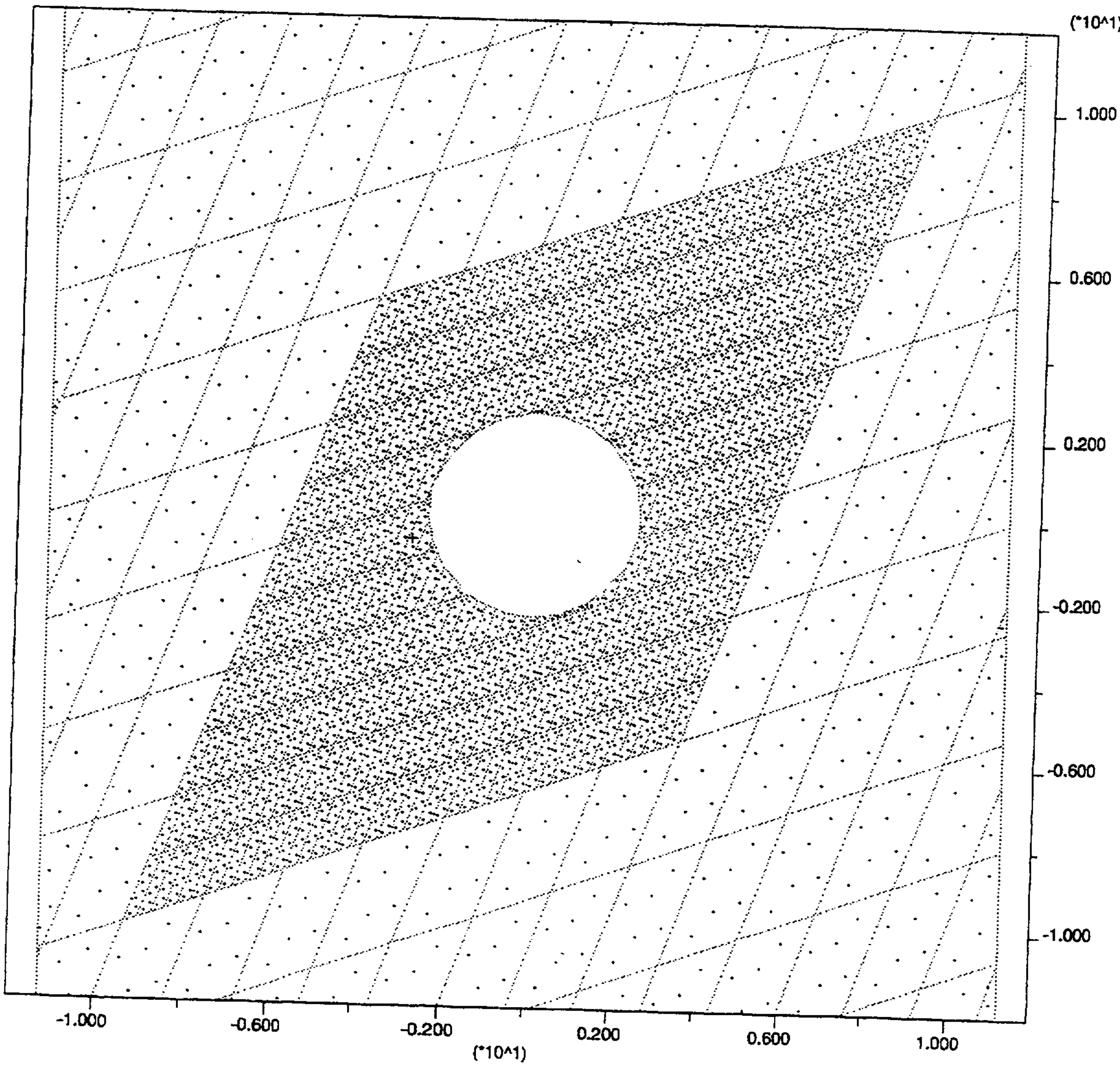
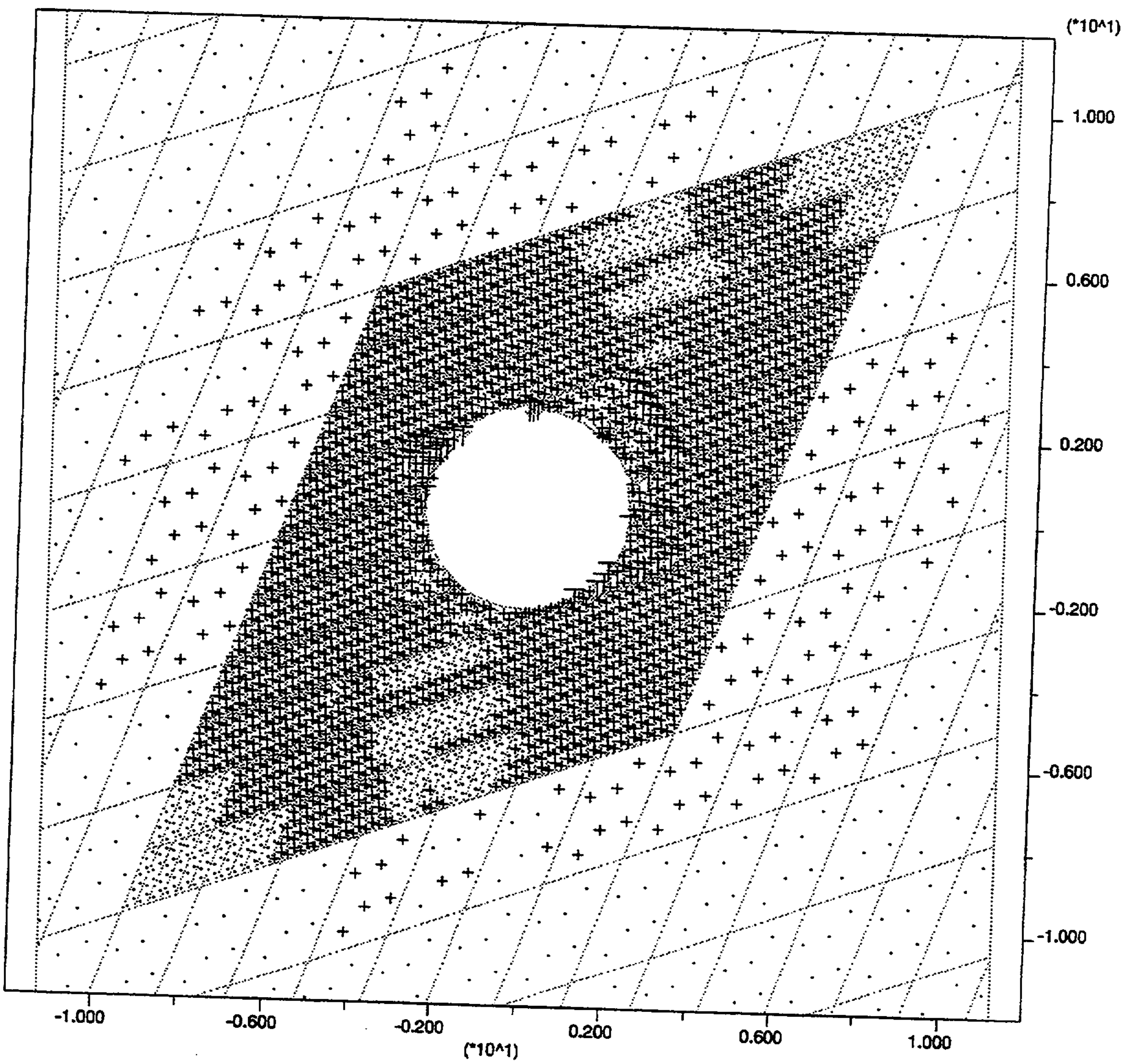


Figure 12. Distribution of principal stresses after 100 years of heating



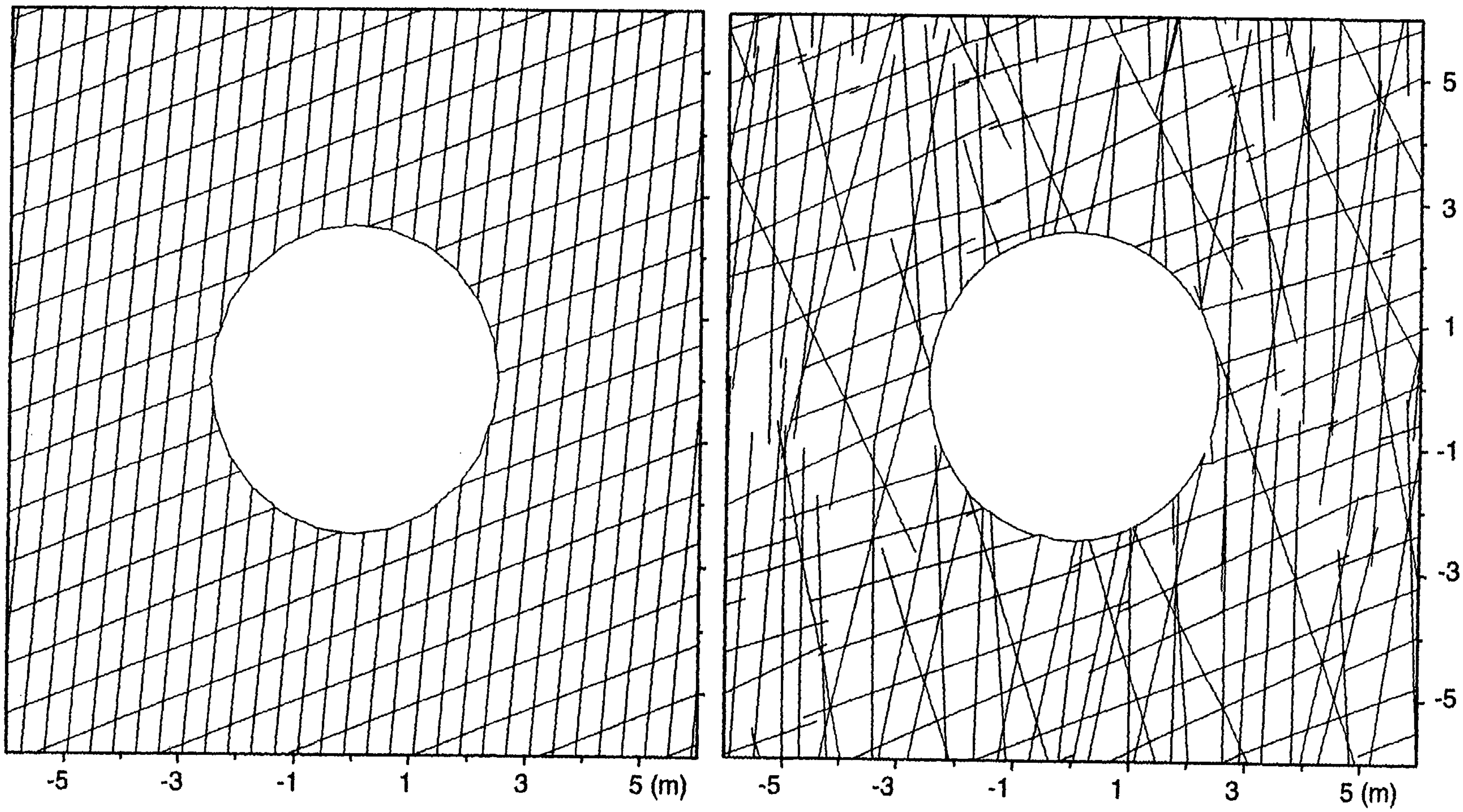
Note: Dots represent elastic state. Crosses represent yield zones. Dash lines represent joints.

Figure 13. Distribution of yielding after drift excavation



Note: Dots represent elastic state. Crosses represent yield zones. Dash lines represent joints.

Figure 14. Distribution of yielding after 100 years of heating



(a) Regular Fracture Pattern

(b) Irregular Fracture Pattern

Figure 15. Examples of (a) a regular fracture pattern and (b) an irregular fracture pattern

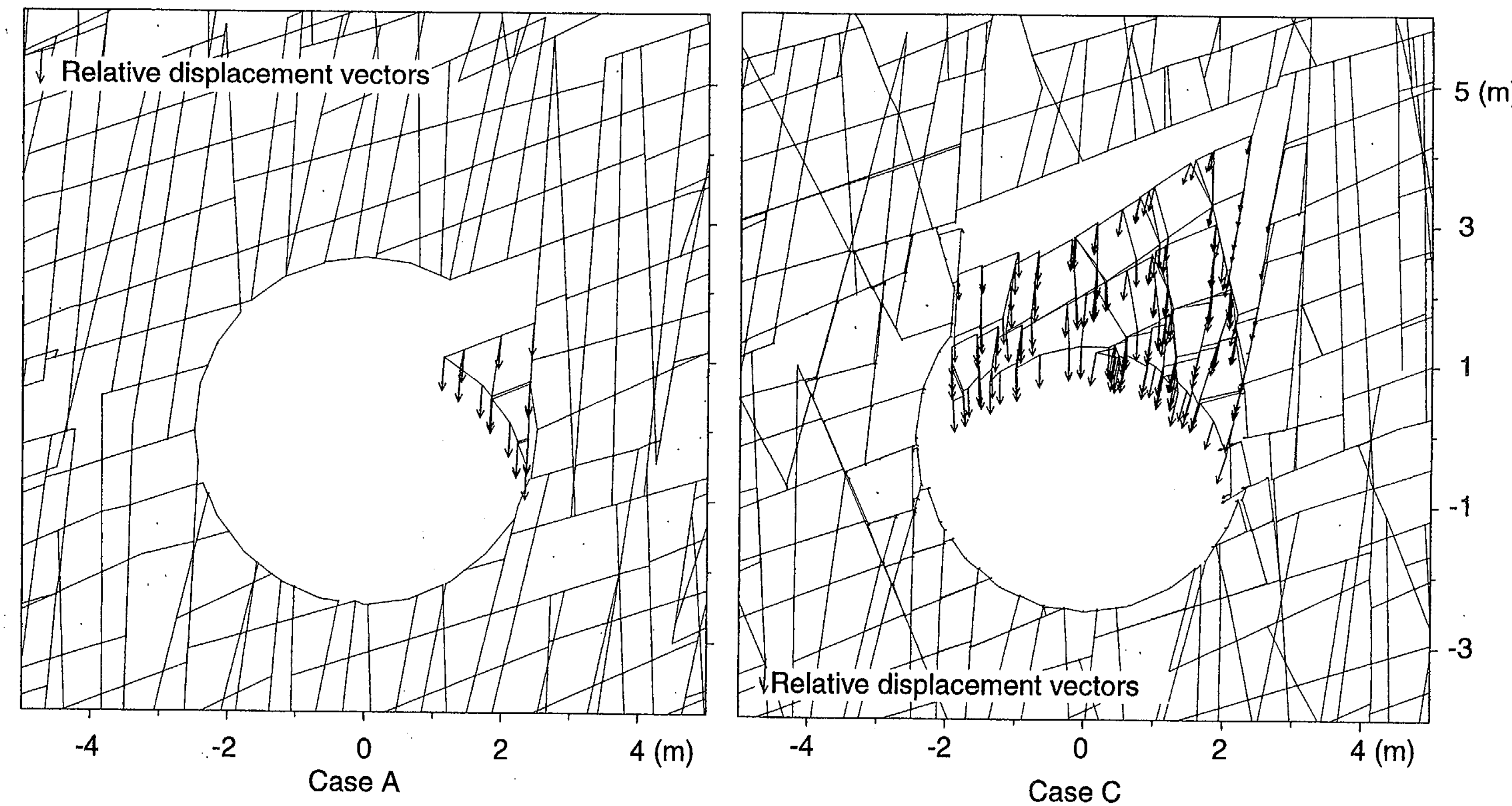


Figure 16. Simulated rockfall after 100 years of thermal loading and one episode of dynamic ground-motion for two slightly different fracture patterns

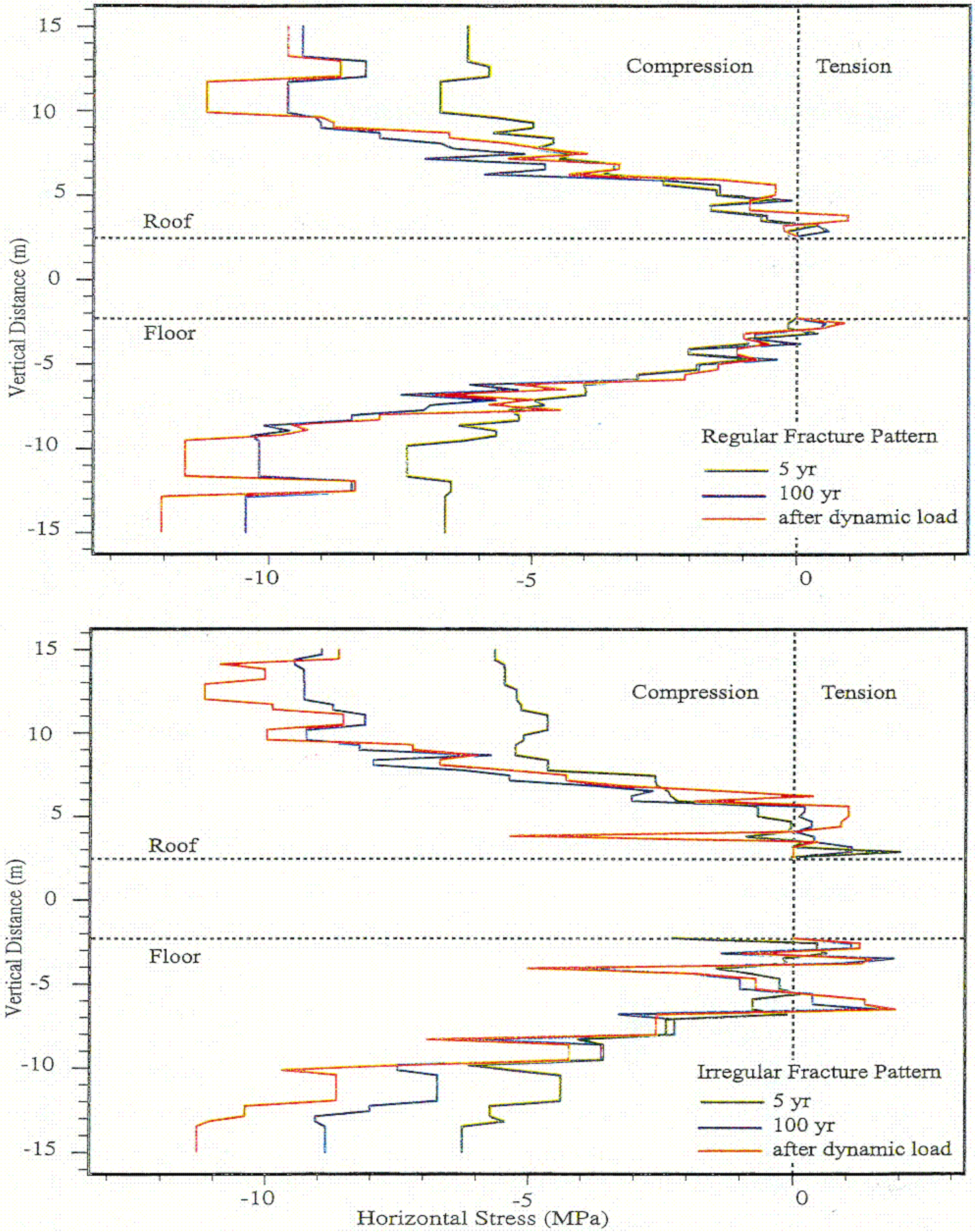


Figure 17. Comparison of vertical profile of minimum principal stresses for irregular and regular fracture patterns after 5 and 100 years of thermal and dynamic load

C08

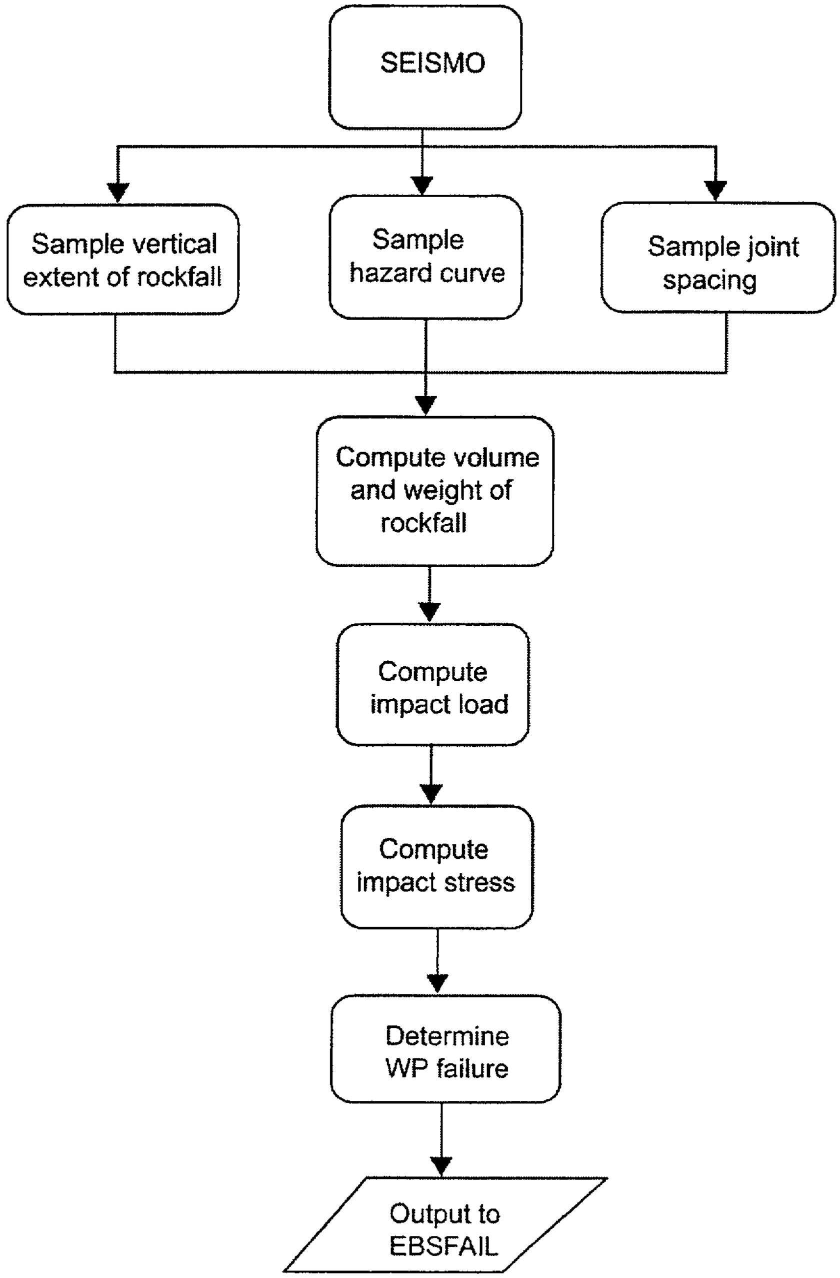


Figure 18. Flowchart highlights SEISMO calculation

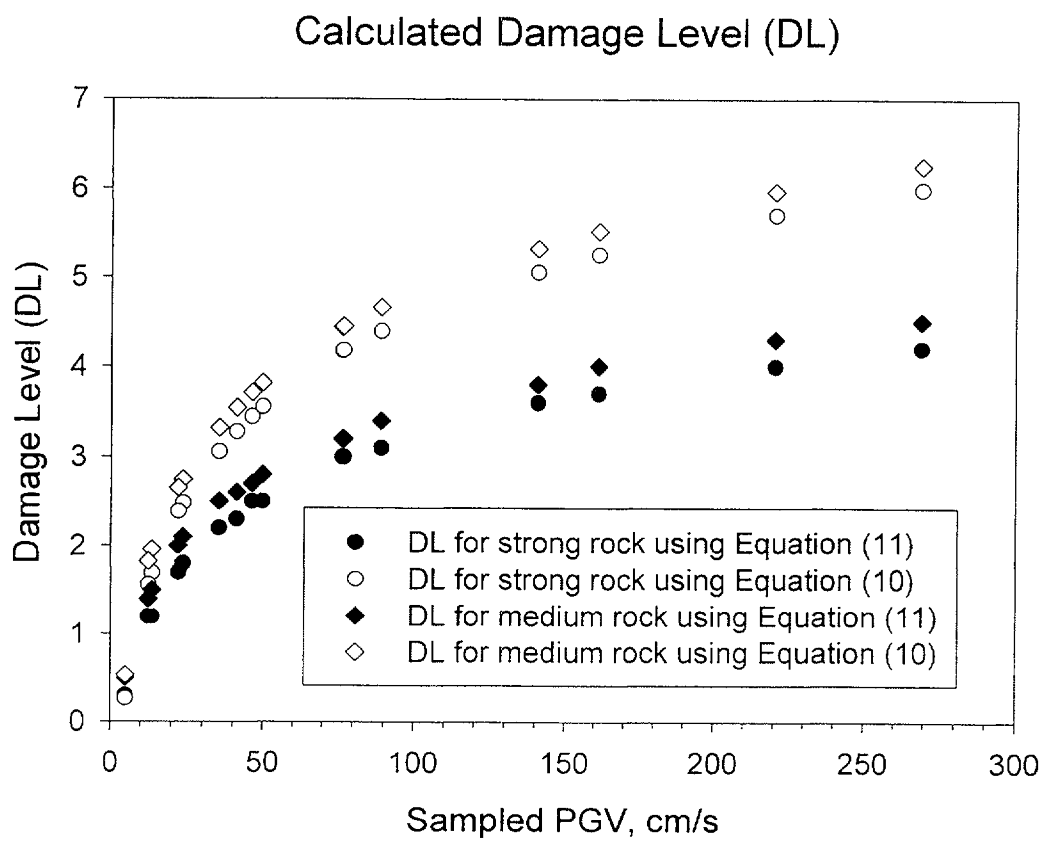


Figure 19. Damage level versus peak ground velocity

5 STATUS OF ISSUE RESOLUTION AT THE STAFF LEVEL

We have reviewed and commented on the DOE site characterization, design, and performance assessment programs in areas related to the RDTME KTI. The site characterization concerns were documented in the Staff Site Characterization Analysis of the DOE Site Characterization Plan, Yucca Mountain Site, Nevada (U.S. Nuclear Regulatory Commission, 1989). We have also reviewed a number of technical documents related to design and performance of the GROA including a limited number of Analysis and Model Reports (AMRs) and Process Model Reports (PMRs). The staff recognizes the preliminary nature of the draft AMRs and PMRs. Thus, the staff has not used the information contained in those draft documents to resolve any open subissues in this report. To aid the issue resolution process, however, the staff has reviewed and provided comments on the sufficiency of the information in the preliminary documents to address staff concerns. After a review of the final PMRs or other documents that indicate DOE's acceptance of the information in the preliminary documents, the staff will consider such additional information in the resolution of subissues or any portion of the subissues.

The status of issue resolution reported in this chapter reflects the current understanding of NRC staff based on the most recent information that is available to the staff. The format for documenting the status of resolution for the different subissues reflects the nature of the subissue, its complexity and history of NRC and DOE interactions. A summary of the resolution status on RDTME KTI subissues is provided in Table 2 and the status is discussed in detail in the following sections.

As discussed in Chapter 1, issues are "closed" if the DOE approach and available information acceptably address staff questions such that no information beyond what is currently available will likely be required for regulatory decision making at the time of initial license application. Issues are "closed-pending" if the NRC staff has confidence that the DOE proposed approach, together with the DOE agreement to provide the NRC with additional information (through specified testing, analysis, etc.) acceptably addresses the NRC's questions such that no information beyond that provided, or agreed to, will likely be required at the time of a potential LA. Issues are "open" if the NRC has identified questions regarding the DOE approach or information, and the DOE has not yet acceptably addressed the questions or agreed to provide the necessary additional information in the license application.

5.1 IMPLEMENTATION OF AN EFFECTIVE DESIGN CONTROL PROCESS WITHIN THE OVERALL QUALITY ASSURANCE PROGRAM

Historically, DOE's implementation of a design control process for design, construction, and operation of the GROA has been one of NRC's major concerns. The staff conducted a series of interactions, reviews, and an in-field verification to evaluate the effectiveness of DOE's design control process.

Exploratory Studies Facility: The staff considers DOE's design control process implemented for the ESF to be acceptable. This conclusion is based on the reviews of DOE's responses to staff queries; observation of DOE's internal QA audits and surveillances; and staff review of DOE's RCRR, observation of design reviews, selective reviews of design packages, site visits, meetings, and in-field verification. The staff has no major concerns or questions related to the ESF design or the design control process employed for the ESF design, construction, or operation at this time.

Table 2. Summary of Subissue Resolution Status

Subissue	Closed	Open	Comment
Design Control Process	Closed		Staff conclusions are based on DOE's simplified document hierarchy; transparency and traceability of flowdown of requirements; and successful resolution of questions raised by NRC during interactions.
Seismic Design Methodology	Closed Pending		Awaiting DOE Seismic Topical Report No. 3 for review by NRC.
Thermal-Mechanical Effects		Open	Concerns on adequacy of data, data reduction approach, modeling approaches, and assumptions for ventilation model are noted. DOE has committed to address concerns related to modeling rockfall impact on drip shield and WPs. Concerns related to rock size calculation and earthquake effects on rockfall are yet to be addressed. Concerns related to thermal-mechanical effect on change in hydrologic properties still remain. Concerns related to screening out drift geometry change from model abstractions need to be addressed.
Repository Seals	Closed		10 CFR Part 63 does not have specific requirements for repository seals

Geologic Repository Operations Area: During FY1998, the staff conducted a limited evaluation of the effectiveness of DOE's implementation of the design control process as a generic matter for all the SSCs that comprise the GROA. Specifically, the staff selected six systems of the GROA (three surface and three subsurface systems) for a detailed assessment on the effectiveness of DOE's design control process. While the staff recognized that the six systems represented only a small part of DOE's design activities for the entire GROA, the staff nevertheless concluded that, with one exception, DOE had an effective design control program for the GROA, based on this limited review. The one area in this program in need of improvement was in relation to control of design changes relative to an original design and proper documentation of such changes (Section 4.1.3.2).

Subsequent to staff review in 1998, DOE conducted several audits of M&O contractors during 1998 and 1999 with a focus on the implementation of the design control process. Several deficiencies have been found that cover a wide spectrum of the design control process, including data traceability, management, qualification, and software control (e.g., U.S. Department of Energy, 1998a,b,c,d,e; 1999). To address these deficiencies, the M&O contractor is developing new administrative procedures to replace the existing QAPs. The new administrative procedures will provide a wider coverage to apply to its subcontractors (e.g., National Laboratories). It is understood these new administrative procedures will be in effect in the near future.

Status: Closed.

Basis: Through several interactions with DOE, the staff found that DOE has greatly simplified its document hierarchy which controls the design activities. As a result, transparency and traceability of the flowdown from the RRs to design bases and criteria are greatly improved. The staff considers this simplified design control process to be acceptable. The implementation of this design control process will continue to be monitored through observation of DOE audits or NRC independent audit/inspection of DOE activities.

5.1.1 Open Items from Site Characterization Plan/Site Characterization Analysis, and Study Plans

Item ID: OSC0000001347C121 Comment 121 SCA
Title: Seismic design criteria for ESF
Status: **Closed**
Basis: Staff review of revised ESFDR submitted by DOE (YMP/CM-0019, Rev. 2), appendix-A. Design input values are subject to verification under TR–3 review.

Item ID: OSC0000001347C130 Comment 130 SCA
Title: Part 60 design criteria applicable to ESF
Status: **Closed**
Basis: Staff review of RCRR submitted by DOE in response to NRC's letter of October 13, 1994.

Item ID: OSC0000001347Q003 Question 003 SCA
Title: Rationale for selecting the total area for repository development
Status: **Closed**
Basis: Design concepts for the repository have changed. The question may be re-examined when DOE submits up-to-date design concepts.

Item ID: OSC0000001347Q020 Question 020 SCA
Title: Vertical versus horizontal emplacement orientation decision
Status: **Closed**
Basis: Vertical emplacement is no longer an option.

Item ID: OSC0000001347Q021 Question 021 SCA
Title: Radiation shielding of host rock
Status: **Closed**
Basis: Question based on outdated concepts of WP design and vertical emplacement that is no longer an option.

Item ID: OSC0000001347Q042 Question 041 SCA
Title: Regulatory basis for Issue Resolution Strategy 2.4 on waste retrieval
Status: **Closed**
Basis: Transferred and will be reviewed under a separate activity that focuses on preclosure topics.

Item ID: OSC0000001347Q042 Question 042 SCA
Title: Stability of vertical emplacement holes
Status: **Closed**

Basis: Vertical emplacement hole is no longer an option.

Item ID: OSC0000001347Q056 Question 056 SCA
Title: Fault displacement tolerance
Status: **Closed**
Basis: Question based on outdated vertical emplacement concept. Actual fault displacement design inputs are subject to verification during TR–3 review.

Item ID: OSC0000001347Q057 Question 057 SCA
Title: Borehole drilling and design flexibility
Status: **Closed**
Basis: Question based on outdated ESF design

Item ID: OSC0000001347Q058 Question 058 SCA
Title: Design to accommodate *in situ* WP testing
Status: **Closed**
Basis: Question based on two vertical shafts rather than the current ramps

Item ID: OSC0000001347Q062 Question 062 SCA
Title: Separation distance between ESF and waste emplacement panels
Status: **Closed**
Basis: Question based on SCP conceptual design that is outdated.

5.1.2 Open Items from U.S. Department of Energy–U.S. Nuclear Regulatory Commission Correspondence/Interactions

Item ID: OQA013OCT1994C00 Comment 001
Title: The M&O QAP is not being effectively implemented in a manner that will assure acceptability of the ESF (includes flowdown of RRs)
Status: **Closed**
Basis: See OQA013OCT1994Q00 Question 003

Item ID: OQA013OCT1994Q00 Question 001
Title: Phases of proposed design and construction of ESF
Status: **Closed**
Basis: See OQA013OCT1994Q00 Question 003

Item ID: OQA013OCT1994Q00 Question 002
Title: Potential of construction work to impact site characterization or the waste isolation capability of the site
Status: **Closed**
Basis: See OQA013OCT1994Q00 Question 003

Item ID: OQA013OCT1994Q00 Question 003
Title: Current conceptual design, testing strategy, and control mechanism
Status: **Closed**
Basis: The previous four items are closed based on staff review of DOE's responses of

October 17, 1994; November 14, 1994; January 27, 1995; March 14, 1995; May 1, 1995; staff observation of DOE's QA audit of January 9–13, 1995; and staff in-field verification of April 3–6, 1995 (see appendix for details).

5.1.3 Open Items from In-Field Verifications

Item ID: In-field Verification Recommendation-1
Title: Numerical modeling of rock bolts
Status: **Closed**
Basis: Review of Book #2, "Numerical Modeling of Rock Bolts," during Appendix 7 meeting at M&O office, June 11–12, 1997.

Item ID: In-field Verification Recommendation–2
Title: Reportable geologic condition
Status: **Closed**
Basis: Staff review of revised procedure, "YAP–30.27" (which superseded administrative procedures–6.14).

Item ID: In-field Verification Recommendation–3
Title: Quality classification of precast concrete inverts
Status: **Closed**
Basis: Precast concrete inverts are no longer a design option in the EDA-II.

Item ID: In-field Verification Open Item
Title: Document Hierarchy
Status: **Closed**
Basis: DOE has greatly simplified its document hierarchy. Consequently, the transparency and traceability of document hierarchy have been improved.

5.2 DESIGN OF THE GEOLOGIC REPOSITORY OPERATIONS AREA FOR THE EFFECTS OF SEISMIC EVENTS AND DIRECT FAULT DISRUPTION

To address this subissue, DOE developed three TRs. TR–1 and TR–2 were reviewed and accepted by NRC before the inception of the IRSRs. Consequently, the status of these two TRs is briefly summarized in the following sections without including discussion of compliance with specific AC used for the review. TR–3 will be reviewed during early FY2002. The status of resolution for the report will be documented in a combined safety evaluation report for all three TRs.

5.2.1 Methodology to Assess Fault Displacement and Vibratory Groundmotion Hazards at Yucca Mountain (Topical Report-1)

Status: Closed.

Basis: The details of status of open items for TR–1 have been documented in the SDS KTI IRSR.

5.2.2 Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain (Topical Report-2)

Status: Closed.

Basis: Based on the review of Rev. 2 of TR-2, the seismic design methodology presented by DOE is acceptable to the staff. The concerns related to repeated seismic loading for the preclosure design have been closed based on the rationale presented in TR-2. The staff has no further questions on this component of the subissue at the present time.

Although DOE's seismic design methodology is acceptable, it should be noted that the acceptability of DOE's seismic and fault displacement design of the GROA will be determined during a potential LA review. Furthermore, this methodology is intended for a minimal maintenance of the preclosure facilities for a period of 50–125 years.

5.2.3 Topical Report-3 (Yet to be Developed)

Status: Closed pending further information.

Basis: Consideration of repeated seismic loading for the (postclosure) design of the WP and TSPAs is expected to be covered during review of TR–3. (As stated earlier, the staff will review TR–3 on seismic and fault displacement inputs for design and PA and consider the set of three TRs in the context of how the TRs together will help simplify the licensing review.) TR–3 will be reviewed during FY2002 and review results will be documented in a combined safety evaluation report.

5.3 THERMAL-MECHANICAL EFFECTS ON UNDERGROUND FACILITY DESIGN AND PERFORMANCE

This subissue includes three components: (i) TM effects on design of the underground facility; (ii) effects of seismically induced rockfall on WP and drip shield performance; and (iii) TM effects on flow into emplacement drifts. The status of resolution for each component is presented in separate subsections. The basis for the status for each component is presented by first summarizing DOE approach and followed by NRC evaluation using ACs from the Yucca Mountain Review Plan that is currently under development. Status of evaluation against each AC is also provided as applicable.

5.3.1 Thermal-Mechanical Effects on Design of Underground Facility (Status: Open)

U.S. Department of Energy Approach

DOE load considerations for subsurface facilities include *in situ*, thermal, and seismic load (U.S. Department of Energy, 1997). Characterization of the *in situ* stress is rather straightforward. The vertical component of the *in situ* stress is calculated using overburden rock-mass density. The horizontal stress component is estimated from the vertical component. In most of the earlier DOE analyses (i.e., CRWMS M&O, 1998d; 1996b), the horizontal component of the *in situ* stress was calculated from the vertical component and rock mass Poisson's ratio. During the

DOE/NRC Appendix 7 Meeting on Ground Control[3], however, it was proposed that horizontal stress be calculated from vertical stress and an assumed horizontal to vertical stress ratio of 0.3–1.0, with 1.0 being the upper bound stress ratio.

Thermal load depends on repository design, and DOE repository design is still an evolving process. The EDA II design (CRWMS M&O, 1999a) is the most recent design concept. EDA-II is also most likely to be submitted by DOE in its SR and, eventually, in a potential LA (Barrett, 1999). In EDA-II, thermal load is designed to be an initial areal mass loading of 60 MTU/acre. This initial heat load will decay with time. The specific decay characteristics of thermal load are discussed in a CRWMS M&O report (CRWMS M&O, 1997c). No thermal load calculations (modeling) documented in the form of AMRs; PMRs; or Features, Events, and Processes (FEPs) are available for staff review at the time of preparation of this revision of IRSR. If designed appropriately, ventilation could reduce temperature around the emplacement drift significantly. DOE preliminary draft Ventilation Model AMR (CRWMS M&O, 1999c) documented numerical analyses conducted to predict the fraction of heat that would be removed from the repository during the preclosure period. The analyses used a combination of 2D models for heat transfer in drift-normal planes and spread-sheet calculation for along-drift heat transfer. The numerical stability of the explicit stepping algorithm applied in the analyses to advance the solution along the drifts was not investigated.

Design ground-motion parameters for the proposed repository have not been finalized. DOE will document them in its Seismic TR–3 to be submitted for staff review in FY2002. The design ground-motion parameters will be developed based on site-specific probabilistic seismic hazard analyses (PSHA) (CRWMS M&O, 1998e). Details of the DOE approaches in its site-specific PSHA and staff evaluation can be found in SDS IRSR (U.S. Nuclear Regulatory Commission, 1999). In a preliminary report dealing with the development of seismic design basis inputs for YM (CRWMS M&O, 1998h), DOE documented some preliminary design ground-motion inputs at the repository interface. These results include: (i) 1–2 Hz and 5–10 Hz design earthquake spectra at annual exceedence probability of 10^{-3} and 10^{-4}; (ii) representative vertical and horizontal time histories at an annual exceedence probability of 10^{-4} and 1–2 Hz; and (iii) vibratory motions, dynamic strains, and dynamic curvatures throughout the tuff overburden for the seismic design of inclined and vertical shafts, ventilation shafts, and associated structures. These input parameters, however, have not been finalized by DOE.

No details of ground support design or drift stability and ground support design analyses have been documented by the DOE in the form of AMRs, PMRs, FEPs, or any other forms that are available for staff review at the time of preparation of this revision of IRSR. The following summary of DOE approaches, therefore, is based mainly on information obtained during the Appendix 7 meeting on ground control. Previous DOE analyses used design configuration and thermal load that are very different from the EDA-II design concept. Previous analyses include ground support design analyses for ESF (CRWMS M&O, 1996b) and for VA (CRWMS M&O, 1998d). Although the results of these analyses will not be applicable to the final design, it is likely that the same analysis approaches could be used by DOE in its drift stability and ground support design analyses for a potential LA.

During the Appendix 7 meeting on ground control in November, 1999, it was proposed that ground support design analyses be conducted using continuum and discontinuum approaches using numerical codes FLAC and UDEC, respectively. Ground support modeling will include fully grouted

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[3]DOE/NRC Appendix 7 Meeting on Ground Control, 1999.

rock bolts and steel sets. In case steel sets are over-stressed due to thermal loads, stress-relief elements or additional contact gaps may be used. Rock-mass and fracture property values for lithophysal and nonlithophysal rock units were proposed at the Appendix 7 meeting. However, no bases for the selection of such property values were given and these property values are not consistent with previous values given by DOE (CRWMS M&O, 1997a,h; 1998d). No actual modeling results were presented during the Appendix 7 meeting.

U.S. Nuclear Regulatory Commission Staff Evaluation

AC1 Design assumptions, codes, and standards used for the design of subsurface facility SSCs important to safety are acceptable.

- Applicable design codes, standards, or other detailed criteria used for the design of the subsurface facility are specified. Codes and standards are equivalent to and consistent with those accepted by the NRC for design of nuclear facilities with similar hazards and functions. If nonstandard approaches are used, adequate technical bases are provided to justify why they are used.

- Assumptions made for the design of the subsurface facility are technically defensible.

- Designs for steel and concrete structures and components, air controlled systems, electrical power systems, and ventilation systems use applicable standards.

Status: Open.

Basis: At the time of preparing this revision (Rev. 3) of the RDTME KTI IRSR, the design codes, standards, and other applicable detailed criteria identified or determined by DOE for the design of the subsurface facility are not available for staff review. Neither are the assumptions made for the design of the subsurface facility. Consequently, the staff is unable to determine if codes and standards used for subsurface design are equivalent to and consistent with those accepted by the NRC for design of nuclear facilities with similar hazards and functions, if assumptions in subsurface design are technically defensible, and if the design of other components uses applicable standards.

AC3 Materials and material properties used for the subsurface facility design are appropriate.

- The selection of materials and the properties of these materials are appropriate for the anticipated subsurface environment.

- Materials and material properties are consistent with applicable design criteria, codes, standards, and specifications. If no standards are used, Appropriate technical bases are provided.

- Applicable American Society for Testing and Materials (ASTM) standard specifications are used.

- The selection of ground support materials accounts for degradation of such materials under elevated temperature and thermal loading. Plausible mechanisms for material degradation are identified and properly incorporated in assessments of subsystem SSC performance.

- Fire resistant materials are incorporated into the design of the subsurface ventilation systems (e.g., fire resistant filters) to protect against fires occurring inside or outside the systems. Ventilation equipment/components are designed to withstand prolonged high temperature conditions, effects of potential sudden blast cooling, and potentially wet and corrosive environments.

Status: Open.

Basis: Information related to this AC will be evaluated once it becomes available and results documented in subsequent revisions.

AC4 Design analyses use appropriate load combinations for normal and Category 1 and 2 event sequence conditions.

- The arrangement of WPs within the subsurface facility satisfies the thermal load design criteria.

- The magnitude and temporal history of the applied thermal loading are consistent with the anticipated characteristics of the proposed nuclear waste, repository design configurations, and design areal mass loading.

- Thermal analyses have an appropriate technical basis, use site-specific thermal property data, consider temperature dependency and uncertainties of thermal property data, and use thermal models and analyses that are properly documented. If credit is taken for use of ventilation, assessments of the effects of ventilation are adequate.

- Design analyses consider appropriate *in situ* stresses and potential running ground conditions.

- The dynamic loads used in design analyses are consistent with seismic design ground-motion parameters including any repeated seismic effects, consider faulting effects, and are consistent with accepted methodologies for assessing faulting hazards.

Status: Open.

Basis: No design analysis reports based on the current design concept (EDA-II) are available for staff review and evaluation, except information obtained from an Appendix 7 meeting on ground control held in November 1999. In considering *in situ* stresses, DOE proposed modeling horizontal to vertical stress with a ratio of 0.3 to 1.0 and considers the stress ratio of 1.0 as "bounding cases."[4] This range of stress ratio adequately covers the possible *in situ* stress ratio; however, as discussed in the

[4]U.S. Department of Energy/Nuclear Regulatory Commission Appendix 7 Meeting on Ground Control, November, 1999.

Appendix 7 meeting, they may not necessarily represent bounding cases after superimposing thermal load. A more realistic stress ratio should be used.

Thermal load calculations depend on details of repository design. As the repository design evolves, thermal load calculations need to be updated and the updated calculation needs to be considered in ground support design and drift stability analyses. In the cases where such analyses take credit for ventilation, the acceptability of thermal load calculation also depends on whether the ventilation model is acceptable.

Design values for seismic ground-motion are still to be developed. The evaluation of input seismic loads used for design depends on the acceptability of DOE seismic TR–3. The modeling approach, however, can be established in advance. Recent analyses conducted at the CNWRA indicate that it may be necessary to consider both velocity and acceleration as input ground-motion in seismic design analyses (Chen, 2000). It is also desirable to perform analyses in both the time domain and frequency domain, because the effect of frequency may be affected by the input wave form. Chen (2000) also shows that incorporating input ground-motion parameters into ground support design and drift stability analyses can be very difficult, depending on available software. The preliminary representative design ground-motion time histories developed by DOE (CRWMS M&O, 1998h) have over 60 s of strong motion. Using these time histories as input for ground support design and drift stability analyses using numerical modeling could be a challenging task. DOE should ensure that selected numerical design analyses tools are capable of handling these time histories. Design spectra should also be developed so that the engineers and designers can take them for frequency-domain analyses. In the final Seismic TR–3, design ground-motion time histories should be developed for all the frequency ranges of interest [instead of only 1–2 Hz presented in CRWMS M&O (1998h)].

The design seismic load proposed during the NRC/DOE Appendix 7 meeting on ground control held in November 1999 includes only PGV and peak ground acceleration. These may not be sufficient. The analyses conducted at the CNWRA (Chen, 2000) show that seismic wave form and other input ground-motion parameters affect the load acting on ground support. Such effects need to be analyzed using time domain and frequency domain analyses. Further evaluation will be conducted once the documents related to DOE methodologies for considering load and load combinations for design analyses become available to the staff.

AC5 Design analyses use appropriate models and site-specific properties of the host rock and consider spatial and temporal variation and uncertainties in such properties.

- Appropriate combinations of continuum and discontinuum modeling as well as 2D and 3D modeling are conducted to assess the behavior of a fractured rock mass under prolonged heated conditions and identified Category 1 and 2 event sequences. The bases for the choice of specific models and model combinations are adequate. Appropriate bases for the assumptions and limitations of the modeling approach are provided.

- Principles formulating the design analyses, the underlying assumptions, and the anticipated limitations are documented, are consistent with modeling objectives, and are technically sound.

- Values for the rock mass thermal expansion coefficient are consistent with properly interpreted site-specific data, and such interpretation accounts for likely scale effects and temperature dependency. The uncertainty in the thermal expansion coefficient is adequately assessed and considered in the thermal stress calculation.

- For continuum rock-mass modeling, the values for rock-mass elastic parameters (Young's modulus and Poisson's ratio) and strength parameters (friction angle and cohesion) are consistent with properly interpreted site-specific data. If the parameter values are obtained through empirical correlations with a rock-quality index, the empirical equations used are appropriate for the site and are applied correctly and the values of the index are consistent with site-specific data. If intact-rock-scale values are used, the bases for application of the values to the rock-mass scale are adequate.

- For discontinuum rock mass modeling, the selection of fracture patterns for numerical modeling is appropriate for the objectives of the design and analyses and the interpretation of modeling results adequately considers effects of simplification of the characteristics of the modeled fracture network compared to those of the *in situ* fracture network.

- For discontinuum modeling, the selection of stiffness and strength parameters for rock blocks between any fractures that are explicitly represented in the model are appropriate and account for fractures that are not explicitly represented.

- For discontinuum modeling, the values for fracture stiffness and strength parameters are consistent with properly interpreted site-specific data.

- For both continuum and discontinuum modeling, time-dependent mechanical degradation of the rock mass, fractures, and ground support that may occur following the emplacement of nuclear waste is adequately accounted for in thermal-mechanical analyses. The bases for the magnitude and rate of mechanical degradation applied in the analyses are appropriately established and are technically defensible.

- Uncertainties in rock mass and fracture mechanical properties are adequately estimated and considered in both continuum and discontinuum modeling.

Status: Open.

Basis: No design analyses based on the current design concept (EDA-II) are available for staff review and evaluation, except information obtained from an Appendix 7 meeting on ground control held in November 1999. Therefore, staff evaluation of design analyses is based on information from the Appendix 7 meeting, and ground support design analyses for VA (CRWMS M&O. 1998d). During the Appendix 7 meeting, it was announced that both continuum and discontinuum model analyses will be performed. It was proposed that such calculations will use FLAC and UDEC. No actual analyses or results, however, were presented.

Section 4.3.2 of this IRSR summarizes data needs and characterization for a continuum approach and demonstrates a 2D site-scale continuum analysis model. The analysis illustrated methodologies for considering spatial and temporal variations in rock mass properties and the effects of fractures on rock-mass properties for continuum analyses. Section 4.3.2 also summarizes rock mass and fracture property data required in discontinuum analyses. Chen, et al. (2000) and Chen (2000) further illustrated important factors, parameters, and modeling limitations that affect drift stability and ground support design analyses, using a discontinuum approach. Similar and more complete analyses should be performed and documented by DOE using well justified site-specific properties and models. In the evaluation of DOE approaches in drift stability and ground support design analyses, the staff has the following concerns:

(i) Input rock mass and fracture mechanical properties have not been consistent and may not be conservative (also see Section 4.3.2). Specifically, rock-mass friction angle ranging from 56 degrees for a RMQ1 rock mass to 58 degrees for a RMQ5 rock mass (as proposed for the TM analyses during the November, 1999 Appendix 7 meeting) is too high and not realistic. These values are even higher than DOE laboratory testing results on intact TSw2 rock (48 degrees, CRWMS M&O 1997a). Rock mass Young's moduli ranging from 9.22 MPa for a RMQ1 rock mass to 24.90 MPa for a RMQ5 rock mass, proposed at the Appendix 7 meeting, are not consistent with the previously used range of 7.76 for a RMQ1 rock mass to 32.61 for RMQ5 rock mass (CRWMS M&O 1998d). No bases for selecting these parameters were provided. DOE rock mass friction angles and Young's moduli deviate significantly from those obtained from CNWRA independent implementation of the same empirical procedure based on rock mass quality (Ofoegbu, 1999, 2000; Ofoegbu, et al., 2000). Also, a fracture friction angle of 41 degrees proposed at the Appendix 7 meeting is too high and not consistent with available laboratory testing data (e.g., Hsiung, et al., 1993).

(ii) Rock-mass properties for the lithophysal zone were proposed at the November 1999 Appendix 7 meeting. However, no bases for these parameter values are available for staff review. These parameter values need to be justified, particularly because a large portion of the repository will be in the lithophysal unit.

(iii) DOE has based its design analyses largely on approaches developed from mining and tunneling. Such design analyses may be appropriate for ambient conditions but they may not be appropriate for emplacement drifts in heated conditions. Recent analyses performed at the CNWRA show that rock mass responses in heated conditions expected at the proposed YM repository are different from their responses in ambient conditions (Chen, et al., 2000; Chen, 2000). Under thermal load, rock mass deformation and load acting on ground support may be much greater in a strong (RMQ5) rock mass than in a weak (RMQ1) rock mass. This phenomenon contradicts observations from conventional underground mining and tunneling in ambient conditions. These observations show that a weaker rock mass would experience greater deformation than a stronger rock mass under the same loading conditions. Consequently, design approaches, particularly empirical design approaches using rock mass classification, that have been developed from underground mining and tunneling in ambient conditions may not apply to the design of emplacement drifts and ground support in YM.

(iv) Analyses at the CNWRA also show that rock mass deformation under thermal load may be controlled by different mechanisms in different quality rock masses (Chen, et al., 2000; Chen, 2000). In a strong (RMQ5) rock mass, deformation is controlled mainly by high thermal stresses and failure occurs along subhorizontal fractures in roof and floor areas. In a weak (RMQ1) rock mass, deformation is controlled mainly by preexisting structures and failure occurs along subvertical fractures in sidewall areas.

(v) Rock mass thermal properties have been shown to have varying degrees of effect on the magnitude and distribution of thermal stresses and, consequently, drift stability. The effect of thermal expansivity is direct and significant because thermal stresses are directly proportional to rock mass thermal expansivity. Such an effect was illustrated by a simple numerical experiment (Chen, 2000). Future DOE drift stability and ground support design analyses need to use realistic and well based thermal expansivity values. Temperature-dependent thermal conductivity and specific heat capacity also affect thermal stresses (Ofoegbu, 2000). Inconsistent values have been reported and used in previous DOE analyses.

(vi) Previous DOE analyses often used very simplified fracture patterns consisting of two sets of through going fractures with constant orientation and spacing. The effect of *in situ* fracture network characteristics has not been addressed. CNWRA analyses show that fracture pattern has a controlling effect on drift stability, particularly in terms of rockfall and drift collapse (Chen, 1999). Fracture pattern also affects load acting on ground support. Whereas it is acknowledged that no currently exiting discontinuum tools could incorporate fracture network characteristics to the level of complexity observed at YM, the potential effect of fracture pattern on drift stability and ground support design analyses should be evaluated.

With regard to seismic design, the analyses conducted at the CNWRA (Chen, 2000) show that dynamic modeling using UDEC is difficult and, in some cases, impractical because it is time consuming. Modeling results show that dynamic load has various degrees of impact on drift stability and ground support performance. The extent of such effects depends on many factors, including fracture pattern, input ground-motion parameters (particularly frequency), and, to a lesser degree, rock mass properties. Such effects need to be evaluated in drift stability and ground support design analyses for preclosure design. DOE has proposed using UDEC and FLAC to conduct its seismic design analyses. UDEC and FLAC treat dynamic input in a similar fashion. The staff is skeptical of the capability of these numerical tools. There are problems with UDEC dynamic modeling which must be resolved before it could be used for ground support design:

(i) The form of input ground-motion that UDEC accepts is limited to stress history converted from velocity history based on rock-mass properties. A stress time history may not be appropriate for a highly prestressed model. If input acceleration is to be used rather than velocity, the acceleration needs to be converted to velocity, and frequency has a huge effect on such conversion. A factor of 10 difference is introduced in input stress amplitudes in the frequency range of 1 and 10 Hz ground-motions. These conversions make it difficult to interpret modeling results and distinguish true frequency effects from modeling artifacts.

(ii) Drift stability under dynamic load depends largely on simulated fracture pattern. When the fracture patterns are simplified, almost no response can be observed. For a more complicated fracture pattern, however, there are numerical problems such as numerical instability. A complicated fracture pattern also increases the size of the problem and often makes it impractical to do sensitivity analyses or to use a time history that is longer than a few seconds.

(iii) A time history is only a particular case in a spectrum of ground-motions. It may be necessary in ground support design to conduct frequency-domain analyses. UDEC is not capable of such analyses.

(iv) A geological model may respond differently to different forms of dynamic input. The differences in model responses to velocity, stress, or acceleration inputs need to be examined and UDEC is not capable of such examinations.

AC6 The design of ground support systems is based on appropriate design methodologies and interpretations of modeling results.

- Design methodologies or combinations of design methodologies are properly applied to the design of ground support systems. When used, the empirical design approach is consistent with accepted technology in the underground tunneling and mining industry. The evaluation and selection of ground support systems are supported by analyses that satisfy the previous two AC and that provide mechanical evaluation of ground support systems under thermal and dynamic loads.

- The ground support system responses are adequately evaluated, based on the results of model analyses. If the ground support system is explicitly modeled, the ground support responses include an adequate assessment of deformation and potential failure of the ground support systems. The interaction between the ground support system and the host rock units is adequately considered in the analysis. If the ground support system is not explicitly modeled, the anticipated ground support system responses from the modeling results are reasonably estimated and the technical bases for these estimates are adequate.

- The geometrical, thermal, and mechanical characteristics of the support system used in the TM analyses are consistent with design and construction specifications. The time-dependent mechanical degradation of the support system under heated conditions is adequately accounted for in the analyses.

- Stability of drifts, shafts, and ventilation tunnel is adequately assessed both with and without ground support. Such assessment includes identification of rock blocks that have potential to fall in the drift; the potential for cave-in, collapse, or closure of the emplacement drifts; and the extent and severity of rock-mass disturbance in the vicinity of the drift. The selection of a ground support system is consistent with the anticipated rock-mass responses and potential failure mechanisms of the rock mass in the vicinity of the drifts.

Status: Open.

Basis: DOE has proposed to use both empirical and numerical approaches for the design of ground support. The emphasis has been on empirical approaches based on rock mass classifications. Numerical approaches have been used for confirmation purposes. Empirical design approaches have been developed mainly from experiences gained from conventional underground mining and tunneling in ambient conditions. As mentioned in the evaluation of the previous acceptance criterion, rock mass response in a heated environment is different from that in an ambient thermal environment. Ground support analyses conducted at the CNWRA, using rock bolt and steel sets as examples, show that load acting on ground support is much greater in a strong (RMQ5) rock mass than in a weak (RMQ1) rock mass (Chen, 2000). This phenomenon appears to contradict with observations on rock mass deformation from conventional underground mining and tunneling in ambient conditions. It implies that a stronger rock mass in heated conditions needs more ground support than a weaker rock mass. The empirical design approach, on the other hand, states that a weaker rock mass needs more ground support. DOE needs to address this behavior and factor this into ground support design as appropriate.

Also, as indicated in the evaluation in previous acceptance criterion, the deformation and failure of different quality rock masses under thermal load may be controlled by different mechanisms. Consequently, different strategies in ground support design may need to be applied in different quality rock masses.

AC7 The subsurface ventilation systems are adequately designed.

- The design of subsurface ventilation system is consistent with accepted design criteria, codes, standards, and specifications or with those specifically developed by DOE.

- The subsurface ventilation systems including their power sources identified as important to radiological safety (reviewed using section 4.1.1.6 of the YMRP) are designed to continue functioning under normal subsurface operating conditions, as well as under Category 1 and 2 event sequences.

- Applicable ventilation design guidance is met for the subsurface ventilation design.

- Subsurface ventilation equipment important to safety has backup or standby equivalents and fail safe mechanisms, where required, or DOE's ventilation design and analysis adequately shows that such equipment is not required.

- There is an adequate periodic inspection, testing, and maintenance program to assure that concentrations of radioactive materials meet the limits specified in 10 CFR Part 20 and 10 CFR Part 63 as practicable.

- The subsurface ventilation design is adequate to seal off or isolate airborne radiation within areas that could have a potential release.

- The ventilation design analysis is based on accepted industry codes or methods, incorporates site specific data, and is based on an accurate representation of the subsurface drift structure. The ventilation design analysis shows that subsurface ventilation flows from the least contaminated areas to the most contaminated areas and meets all other specified design criteria.

Status: Open.

Basis: As described previously, the staff has questions on the methodology and, consequently, results of the DOE ventilation analyses model. The main concern is that the numerical stability of the explicit stepping algorithm applied in the analyses to advance the solution along the drifts was not investigated and, consequently, calculated air and drift-wall temperatures and the predicted amount of heat removal by ventilation may not be correct. Staff independent confirmatory analyses found inconsistency in DOE calculated drift-wall temperature and air temperature. The assumptions and methodology of the DOE ventilation model need to be further assessed and modeling results need to be supported. Also, the model needs to be reanalyzed as the repository design changes.

5.3.2 Effects of Seismically Induced Rockfall on the Engineered Barrier System Performance (Status: Open)

This component of the Subissue on TM Effects on Repository Design and Performance relates to the assessment of rockfall effect on WP integrity. Two aspects of the rockfall event that are addressed are: (i) probability of this event and (ii) the subsequent consequences to the EB components.

The following model abstraction applies to this subissue:
- Mechanical Disruption of EBS

U.S. Department of Energy Approach

DOE disruptive events FEPs screening analysis (CRWMS M&O, 2000b) has concluded that mechanical disruption of the WP due to rockfall will not be considered in the TSPA because of the presence of the drip shield and/or backfill. According to the preliminary draft *Engineered Barrier System Degradation, Flow, and Transport Process Model Report* (CRWMS M&O, 2000a), Table 3-47, however,

> "...a design change prompted by thermal considerations, was initiated to remove backfill and change the drift orientation to minimize the size of key blocks. Revision or ICN of the AMR and the EBS PMR will assess consequences of this change."

DOE used key block analysis to assess drift degradation due to seismicity, thermal load, and long-term rock mass degradation for the 10,000-year performance period (CRWMS&O, 2000k). DOE has concluded in its preliminary analysis (CRWMS M&O, 1999d) that about 1 percent of the total length of emplacement drifts to be located in the Topopah Spring Tuff (TSw2) Lower Lithophysal unit is expected to experience rockfall during the 10,000-year performance period and about 16 percent of the TSw2 nonlithophysal unit. About 75 percent to 80 percent of the WP will be emplaced in the TSw2 lower lithophysal unit.

The consequences of rockfall on various components of the EBS continue to be considered by DOE. Specifically, DOE is using FE based numerical analysis methods to assess the structural response of the drip shield and WP to rock block impacts. For example, a recent report (CRWMS M&O, 2000k) pertaining to rockfall describes the current drip shield design and the FE modeling methodology used to perform the rock block impact simulation. Areas of interest addressed in this report include: (i) the assumed sizes and shapes of the impacting rock blocks, (ii) modeling of the drip shield and rock block material behavior, (iii) the individual FE types used to model the drip shield and rock block, (iv) the load and displacement boundary conditions employed within the analysis, and (v) the failure criterion used to assess the ability of the drip shield to withstand rock block impacts.

The rock block sizes and shapes used to impact the drip shield in the FE analysis were derived from fracture geometry data obtained from tunnel mapping in the ESF located at YM (CRWMS M&O, 2000c). Using the software program entitled UNWEDGE (Version 2.3), the rock block geometry is calculated using input data representing three fracture sets. The fracture set data were defined in the context of an assumed repository tunnel azimuth of 75 degrees.

Only a 3-m length section of the drip shield was modeled in the FE analysis. The justification given for modeling the drip shield in this manner was that the largest partial volume of the rock block occurs over a 3-m length. The report further states that:

> "For sizes of rock up to 4 MT, entire rock volume is located above the 3-m partial length of the drip shield. ... the increase in rock mass is by increase in length of the rock geometry along the emplacement drift rather than any increase in the rock block apex height. For approximately the same apex height (1.3 m) ... a 4 MT rock" will have "a total length of 4 m along the emplacement drift whereas ... a 52 MT rock mass" will have "a length of 40 m. ... Using the concept of effective rock mass over a 3-m partial-length of drip shield, maximum rock mass is determined to be 10 MT per 3-m partial length of drip shield. In other words, an estimated maximum rock of 52 MT will load a 3-m partial-length of drip shield the same as a 10-MT rock, and for any rock mass over 52 MT a 3-m partial-length of drip shield will experience the same load as 10 MT."

The following table (table 3) delineates the relationship of the actual rock mass with the effective partial-volume rock mass for the different rock sizes addressed in the DOE analysis of rockfall on the drip shield.

Table 3. Relationship between actual rock mass and effective rock mass

Actual Rock Mass (MT)	Effective Rock Mass Over a 3-m Length of Drip Shield (MT)
2.0	2.0
4.0	4.0
6.0	5.7
8.0	6.7
52.0	10.0

In expectation of the drip shield experiencing loads from the rock block impact that would cause plastic deformations, the drip shield materials (i.e., Titanium Grades 7 and 24) were modeled using bi-linear stress-strain curves. The material properties required to construct a bi-linear stress-strain curve are the yield stress, ultimate strength, Young's modulus, and minimum elongation. The actual material properties used for the two materials to construct these curves were derived from empirical data obtained at room temperature (i.e., approximately 20 °C).

The rock block material was assumed to respond to the impact load in a purely elastic manner. The rationale for this assumption was that the stresses experienced by the drip shield would be bounded if potential energy dissipation mechanisms of the rock block were not accounted for. Shell and solid element formulations were used to model the drip shield and rock block, respectively.

Even though the drip shield is intended to be a free-standing structure (i.e., the base of the drip shield is not mechanically attached to the invert), the FE model employed boundary conditions that fixed the base of the drip shield to the invert. In other words, the base of the drip shield was not allowed to translate in any direction. No definitive information was provided regarding the constraints, if any, that were applied to the rotational degrees-of-freedom of the nodes at the base of the drip shield. The justification given for fixing the translational degrees-of-freedom was that the stresses experienced by the drip shield as a result of the rock block impact would be larger than the case of no constraints at all. No information was provided concerning the displacement boundary conditions applied at the ends of the 3-m section of the drip shield model.

The fall height of the rock block was estimated to be 2.3 m. Assuming no initial downward velocity for the rock block at the time it becomes dislodged, the velocity of the rock block at the time of impact with the drip shield was calculated to be 6.72 m/second.

A strain-based criterion was used to establish the structural failure of the drip shield. Specifically, "The failure of the drip shield is defined as the condition when the strain in the drip shield exceeds the failure strain (ductility), which results in rupturing of the material." No further information on the implementation of this failure criterion was provided.

Two different rock block and drip shield impact scenarios were investigated. In the first scenario, the rock block was centrally positioned above the drip shield such that impact would occur at the crest of the drip shield crown. The second scenario addressed the rock block impacting the side of the drip shield. Additional analyses considered the effects of increasing the drip shield side wall height by 0.2 m.

It was reported (CRWMS M&O, 2000k) that:

> "The results of the finite element solutions indicate that no crack develops in the drip shield due to the dynamic impact of a rock on the drip shield for any of the rock sizes .... This is based on the steady-state drip shield configuration after the impact. The failure of drip shield structural components were specified by failure strain values equal to the material elongation values .... When the failure strain value is reached during the simulation, the corresponding elements are automatically removed from the FER. Since none of the elements were removed throughout the simulation, the failure strain is not exceeded in any of the components, and the drip shield is deemed to remain intact after the rockfall event."

No discussion was provided in the report detailing which components or types of strain measure were used in making this assessment.

The FE analysis results were also used to assess the potential for the initiation of stress corrosion cracking (SCC) arising from the residual stresses developed as a consequence of the rock block impact. The results indicated that the drip shield may be susceptible to SCC. No discussion was provided in the report detailing which components or types of stress were used in making this assessment.

U.S. Nuclear Regulatory Commission Staff Evaluation

AC1 Important design features, physical phenomena and couplings, and consistent and appropriate assumptions have been identified and described sufficiently for incorporation into the abstraction of mechanical disruption of EB components (MDEB) and other related abstractions in the TSPA and the technical bases are provided. The TSPA abstraction in the DOE LA identifies and describes aspects of MDEB that are important to waste isolation and includes the technical bases for these descriptions.

- DOE identifies the EB components (e.g., backfill, drip shield) that may: (i) mitigate the effects of mechanically disruptive events on WP performance or (ii) adversely affect WP performance. DOE sufficiently describes these influences and the technical bases provided for their inclusion or exclusion in the MDEB abstraction.

- DOE identifies the materials used in the construction of the WP and other relevant EB components. DOE defends the technical basis for including or excluding various behavioral characteristics and properties (e.g., corrosion, SCC, hydrogen embrittlement, fracture toughness, ultimate strength, etc.) of these materials in the MDEB abstraction in the DOE LA.

- DOE justifies the environmental effects (e.g., temperature, water chemistry, humidity, radiation, etc.) included or excluded in the MDEB abstraction.

- DOE identifies pertinent design features and dimensions of the relevant EB components accounted for in the MDEB abstraction.

- DOE justifies the mechanically disruptive events considered in the development of the MDEB. DOE considers, at a minimum, seismicity, seismically induced rock fall, faulting, transient criticality, and igneous intrusion.

- DOE identifies the mechanical failure processes and concomitant failure criteria used for the individual EB components included in the MDEB abstraction. DOE defends the technical bases used to demonstrate that the failure processes and criteria are consistent with the material behavioral characteristics and anticipated loading conditions derived from the disruptive events.

- DOE justifies the TSPA models of seismicity, seismically induced rock fall, faulting, and igneous intrusion relies on consistent and appropriate assumptions throughout the TSPA abstraction process.

- DOE demonstrates the impact of internal pressure and temperature build-up on the integrity of the WP.

- DOE justifies the earthquake vibration effect on the EB and in particular the WP and its support (the invert).

- DOE considers appropriate components such as WP internal structures and WF (i.e., SNF matrix, cladding, structural support) that effect mechanical integrity under disruptive events.

Status: Open.

Basis: DOE disruptive events FEPs screening analysis (CRWMS M&O, 2000b) has concluded that mechanical disruption of the WP due to rockfall will not be considered in the TSPA because of the presence of the drip shield and/or backfill. According to the *Engineered Barrier System Degradation, Flow, and Transport* PMR (CRWMS M&O, 2000a), Table 3-47, however, "...a design change prompted by thermal considerations, was initiated to remove backfill ...." Consequently, backfill needs to be removed from the screening arguments used by DOE as an EB component that will mitigate the effects of rockfall on the WP. In addition, backfill should no longer be used as justification for excluding rockfall effects as they pertain to the drip shield. The NRC staff does recognize that the presence of the drip shield will play a significant role in protecting the WP from rockfall. In the absence of backfill, however, the drip shield will be susceptible to extensive damage potential because of rock block impacts. Of particular concern is the continued ability of the drip shield to act as a water infiltration barrier once it has been damaged by falling rock blocks.

The NRC staff is also concerned that the use of the *Drift Degradation Analysis* (CRWMS M&O, 1999d) as a screening argument for excluding seismically induced rockfall from the TSPA code is premature and misrepresents the significance of the analysis results presented. For example, the areal coverage and sizes of the key blocks are reportedly quite small when the emplacements drifts are oriented at an azimuth of 75 degrees. This result is being independently verified by the NRC staff. The preliminary results indicated that the key block trace area (projected on the emplacement drift wall) to the emplacement drift surface area is about 1.4 to 2.2 percent for the TSw2 lower lithophysal unit. Although the drift length affected by rockfall was not specifically calculated, the trace plots of the key blocks show a much higher percentage than the 1.0 percent reported in the DOE *Drift Degradation Analysis* report (e.g., Figure 21). Consequently, the 1.0 percent value does not appear to be appropriate or conservative. Furthermore, in determining block sizes, the *Drift Degradation Analysis* report assumes that a joint surface is represented by a circular disc with a radius equal to twice the mapped trace length. This assumption may potentially underestimate the block size. Shorter joint length indicates less persistency; thus, the rock blocks will be bigger and their shapes will become more irregular, as shown in Goodman and Shi (1985). Consequently, the pyramid shape will be much less dominant as suggested in the DOE *Possible Rock Block Geometry, Dimension, Orientation, Probability, and Masses* report (CRWMS M&O, 2000c). A preliminary analysis indicates that a reduction of joint length to half could cause the maximum rock block size to increase by as much as 30 to 40 percent. In the *Drift Degradation Analysis* report, Monte Carlo simulations were used to model a 24.4-m-long tunnel in 3D space to generate rock blocks for conducting key block analysis. The use of a 24.4-m-long tunnel for analysis is not justified in the report. The complete dimension of the model domain is not given. The potential "boundary effect" is not discussed, either.

The effects of thermal load and long-term degradation of rock-mass was considered in the *Drift Degradation Analysis* report by reducing joint cohesion. The report indicates that time-dependent and thermal effects have a minor impact on rockfall. This finding is intuitive since the value used to represent joint cohesion is very small to start with. The report neglected the potential effects of reduction in joint friction angle.

Furthermore, the thermal stress induced in the rock-mass surrounding the emplacements drift could potentially fracture the intact rock and consequently cause additional rockfalls due to rock fracturing and subsequently increase the possibility for other rock blocks to fall. The *Drift Degradation Analysis* report does not take this aspect into consideration. The rock block size and potential emplacement drift affected by rockfall could increase if mapped trace length is used, and long-term and thermal effects on joint friction angle and intact rocks are factored into consideration. The concern regarding use of a pseudostatic approach to address seismic effect on rockfall using the key block analysis is discussed *Change in Emplacement-Drift Geometry*, U.S. Department of Energy Approach subsection of this section.

It does not appear that the *Drift Degradation Analysis* report considered potential joint sampling biases. Accurate characterization of fracture networks at YM requires that several important sampling biases common to fracture analyses be accounted for. If left uncorrected, these sampling biases could potentially lead to under-representation of fracture intensity, porosity, permeability, and connectivity and an incorrect statistical determination of dominant and subordinate fracture distributions. A detailed examination of sampling biases in the YM fracture data sets is given in the SDS IRSR Revision 2.0 (U.S. Nuclear Regulatory Commission, 1999). Some of the pertinent points are summarized in the following paragraph.

First, the lengths of the longest fractures in a population are often unconstrained because the ends of the fracture are obscured (blind). This bias can lead to underestimation of fracture connectivity. Second, the orientation of a one-dimensional sampling line (e.g., borehole or detailed line survey scan line) or two-dimensional sampling surface (e.g., pavement or road cut) inherently biases sampling against discontinuities parallel to the sampling line or surface, and in favor of sampling discontinuities at a high angle to the sampling line or surface. Mathematical corrections (e.g., Terzaghi, 1965) can partially compensate for this sampling bias. Third, because measuring every fracture from microscale to megascale is impractical or impossible for large sample areas, fracture studies usually have a size (e.g., length) cutoff. Fractures smaller than a given dimension are not counted. Consequently, small fractures are under-represented in fracture characterization. Exclusion of fractures less than 1-m from the ESF data set may lead to an incorrect interpretation of fracture intensity. For example, interpretations near faults such as the Ghost Dance fault in the ESF, where the1-m cutoff for trace length was used, leads to extremely variable fracture intensity estimates over a wide zone (Sweetkind, et al., 1997a,b).

DOE has indicated that the drip shield will be fabricated using Titanium Grades 7 and 24. The WP, according to the EDA-II design, will employ Alloy 22 for the outer barrier and stainless steel 316NG for the inner barrier of the WP.

In anticipation of loads that would cause the drip shield materials to exceed their respective yield stress limits, the drip shield materials were modeled using bi-linear stress-strain curves in the preliminary DOE analysis of rockfall on the drip shield (CRWMS M&O, 2000k). The material properties required to construct a bi-linear stress-strain curve are the yield stress, ultimate strength, Young's modulus, and minimum elongation. The actual material properties used for the two materials to construct these curves were derived from empirical data obtained at room temperature (i.e., approximately 20 °C). As tables 4 and 5 indicate, however, the mechanical material properties for Titanium Grade 7 are strongly dependent on temperature. In addition, note that the yield stress values for Titanium Grade 7 published in the 1995 and 1998 versions of the ASME Boiler and Pressure Vessel (B&PV) Code, Section II, Part D–Properties (American Society of Mechanical Engineers, 1995; 1998) are not in agreement.

The temperature-dependent values for the yield stress, ultimate strength, and Young's modulus of Titanium Grades 5 or 24 are not provided in the ASME B&PV Code. Note that the composition of Titanium Grades 5 and 24 are the same except that Grade 24 contains 0.04 to 0.08 percent palladium. As a result, it is expected that these two grades will exhibit similar mechanical behavior (i.e., mechanical properties). The *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures* (U.S. Department of Defense, 1998) and *Material Properties Handbook: Titanium Alloys* (American Society for Metals International, 1994) provide extensive material data for Titanium Grade 5. As Table 6 illustrates, the values for the yield stress, ultimate strength, and Young's modulus that were extracted from graphical data provided in the *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures* (U.S. Department of Defense, 1998) are also strongly dependent on temperature. Even though Titanium Grade 5 exhibits much higher strengths than Titanium Grade 7, the relative effects of temperature are still significant and must be considered when assessing the ability of the drip shield to withstand rock block impacts.

Because the potential reductions in yield stress and ultimate strength for Titanium Grades 7 and 24 as a result of elevated emplacement drift temperatures are significant, there is some concern by the NRC staff that these materials will also be susceptible to creep related failures arising from the support of dead loads (e.g., backfill and/or fallen rock blocks). Further justification for the staff concerns pertaining to creep failure of the drip shield materials can be found in *Fracture Mechanism Maps for Titanium and its Alloys* (Rao et al., 1986) and *Material Properties Handbook: Titanium Alloys* (American Society for Metals International, 1994). Consequently, DOE should provide the technical basis for excluding creep as a potential failure mechanism from the MDEB abstraction within its TSPA code.

Table 4. Relevant mechanical properties of Titanium/Grade 7 as a function of temperature according to the 1995 American Society of Mechanical Engineers Boiler and Pressure Vessel Code

Temperature °F (°C)	Yield Stress* ksi (MPa)	Ultimate Tensile Strength† ksi (MPa)	Modulus of Elasticity‡ ksi (GPa)
-20 to 100 (-29 to 38)	40.0 (275.8)	—	15.5×10^3 (106.9)
200 (93)	32.2 (222.0)	—	15.0×10^3 (103.4)
300 (149)	25.2 (173.8)	—	14.6×10^3 (100.7)
400 (204)	18.6 (128.2)	—	14.0×10^3 (96.5)
500 (260)	14.1 (97.2)	—	13.3×10^3 (91.7)
600 (316)	11.4 (78.6)	—	12.6×10^3 (86.9)

* – 1995 American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section II, Part D, Table Y-1.
† – No values published.
‡ – 1995 American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section II, Part D, Table TM- 5.

Table 5. Relevant mechanical properties of Titanium/Grade 7 as a function of temperature according to the 1998 American Society of Mechanical Engineers Boiler and Pressure Vessel Code

Temperature °F (°C)	Yield Stress* ksi (MPa)	Ultimate Tensile Strength† ksi (MPa)	Modulus of Elasticity‡ ksi (GPa)
-20 to 100 (-29 to 38)	40.0 (275.8)	50.0 (344.8)	15.5×10^3 (106.9)
200 (93)	40.0 (275.8)	43.6 (300.6)	15.0×10^3 (103.4)
300 (149)	40.0 (275.8)	36.2 (249.6)	14.6×10^3 (100.7)
400 (204)	40.0 (275.8)	30.9 (213.1)	14.0×10^3 (96.5)
500 (260)	40.0 (275.8)	26.6 (183.4)	13.3×10^3 (91.7)
600 (316)	40.0 (275.8)	22.8 (157.2)	12.6×10^3 (86.9)

* - 1998 American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section II, Part D, Table Y-1.
† - 1998 American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section II, Part D, Table U.
‡ - 1998 American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section II, Part D, Table TM-5.

Table 6. Relevant mechanical properties of Titanium/Grade 5 as a function of temperature.

Temperature °F (°C)	Yield Stress* ksi (MPa)	Ultimate Tensile Strength* ksi (MPa)	Modulus of Elasticity† ksi (GPa)
Room Temperature	120.0 (828.0)	130.0 (895.0)	16.9×10^3 (116.5)
200 (93)	105.6 (728.6)	118.3 (814.5)	16.2×10^3 (111.8)
300 (149)	94.8 (654.1)	109.2 (751.8)	15.5×10^3 (107.2)
400 (204)	85.2 (587.9)	101.4 (698.1)	14.9×10^3 (102.5)
500 (260)	78.0 (538.2)	96.2 (662.3)	14.4×10^3 (99.0)
600 (316)	74.4 (513.4)	93.6 (644.4)	13.7×10^3 (94.4)

* Room temperature reference value obtained from American Society for Testing and Materials B 265-98. Temperature correction factor extracted from Figure 5.4.1.1.1 of the *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures.*
† Room temperature reference value obtained from Table 5.4.1.0(c_1) and the temperature correction factor extracted from Figure 5.4.1.1.4 of the *Military Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures.*

No DOE analyses pertaining to the assessment of the new EDA II design for the WP when subjected to rockfall were available at the time this report was prepared. Specific aspects of the new WP design of interest to the NRC staff are (i) the potential loss of material ductility in the immediate area of the closure lid welds; (ii) the design provisions made to account for the significant difference in thermal expansion between the inner and outer barriers of the WP; and (iii) the failure criteria used to assess the structural integrity of the WP. Potential failure mechanisms related to rockfall include breaching of the WP barriers and SCC potential arising from the residual stresses attributable to rock block impacts.

To address these and other potential concerns, DOE indicated during the Container Life and Source Term (CLST) KTI Technical Exchange (TE) held September 12-13, 2000, Las Vegas, Nevada, that in-progress rockfall calculations are: (i) using temperature dependent material properties; (ii) considering rock block impacts above the region of the WP closure welds; (iii) including the effects of seismic ground motion on the relative velocity between the EB component (i.e. drip shield and WP) and the impacting rock block; (iv) using a Tresca shear stress failure criterion; (v) coupling the mechanical stresses caused by rockfall to SCC and hydrogen embrittlement; and (vi) assessing the potential for water infiltration pathways being generated when rock block impacts occur on the interconnecting region between individual drip shield units. In addition, DOE also indicated during the aforementioned CLST TE that future rockfall calculations will assess the effects of: (i) potential embrittlement of the WP closure lid weld material and Alloy 22; (ii) drip shield wall thinning due to corrosion; (iii) hydrogen embrittlement of the titanium drip shield; (iv) multiple rock blocks falling on the drip shield and WP; and (v) dead loads (caused by emplacement drift collapse) on the drip shield during seismic events.

AC2 Sufficient data (e.g., field, laboratory, and natural analog data) pertaining to the EB materials, mechanical failure processes, and the characterization of potential disruptive events are available to adequately define relevant parameters and conceptual models necessary for developing the MDEB abstraction in the TSPA. The data are also sufficient to assess the degree to which FEPs related to MDEB and which affect compliance with 10 CFR 63.113(b) have been characterized and to determine whether the technical bases provided for inclusion or exclusion of these FEPs are adequate.

- DOE demonstrates that the data for mechanical failure models of the EB are based on laboratory measurements and tests designed to simulate or appropriately bound conditions that can be expected during a given mechanically disruptive event.

- DOE considers the effects of prolonged exposure to the expected emplacement drift environment (e.g., the effects of temperature, corrosion degradation, hydrogen embrittlement, radiation exposure, etc) in the constitutive models and their concomitant properties and failure criteria for the different EB component materials.

- DOE justifies that the use of material test results not specifically designed or performed for the YM repository program incorporates or appropriately bounds environmental conditions expected to prevail in the emplacement drift at the proposed YM repository.

- DOE demonstrates that sufficient data are presented to support the conceptual models, process-level models, and alternative conceptual models of mechanical disruption of MDEB.

- DOE identifies the data that support the technical bases for FEPs related to MDEB that have been included or excluded in the DOE LA.

- DOE demonstrates the effects design features and/or fabrication methods for the WP and other relevant EB components have on mechanical stresses and material properties. These effects may include, but are not limited to, residual stresses and/or structural flaws introduced during fabrication, stresses induced by differential thermal expansion, and material strain hardening.

- DOE adequately evaluates seismic source characterization, recurrence, and ground-motion attenuation. For example, DOE justifies seismic source data, including: (i) the geologic and tectonic settings of the site and region; (ii) local and regional faults (Type I faults); (iii) areal sources; (iv) the historic earthquake record; (v) fault slip rates, (vi) recurrence activity rates; (vii) clustered events; and (viii) earthquake and strong motion data used to develop ground-motion attenuation models, are geologically consistent and reasonable, compatible with current understanding of the YM tectonic framework, and adequate to support the TSPA abstraction of MDEB, such that reasonable projections can be made of future YM seismic activity.

- DOE adequately evaluates rock block sizes, contact surface geometry of the rock, and relative impact velocities between the rock block and EB components. For example, DOE's interpretations of rock block size from surficial and underground mapping and geophysical or analog investigations are geologically consistent and reasonable, are compatible with current understanding of the YM joint spacing and orientation framework, and are adequate to support conceptual models, attendant assumptions, and boundary conditions such that reasonable projections can be made on how future rock fall within the emplacement drifts will affect EB integrity.

Status: Open.

Basis: The mechanical properties of Titanium Grades 7 and 24 have a significant influence on the overall structural behavior of the drip shield. Specific mechanical properties of interest include yield stress, ultimate strength, Young's modulus, minimum elongation, and creep rate. These same mechanical properties are dependent on temperature and these temperature effects should be accounted for in the design analyses. Given the lack of consistency and/or absence of published data for Titanium Grades 7 and 24, independently qualified tests may have to be conducted to establish the variability of these mechanical properties over the temperature range expected to exist within the proposed repository emplacement drifts.

No discussion was provided in the *Rock Fall on Drip Shield* report detailing which components or types of strain measure were used in concluding that "... no crack develops in the drip shield due to the dynamic impact of a rock on the drip shield for any of the rock sizes ...." For generalized three-dimensional stress states, failure criteria are typically based on maximum shear stress, octahedral shear stress, Von Mises stress, or strain-energy density. These measures are used because they can be readily employed to discern failure when complex stress states exist using data derived from simple tension tests.

FE analysis results were used to assess the potential for the initiation of SCC in the drip shield arising from the residual stresses developed as a consequence of the rock block impact. The results indicated that the drip shield may be susceptible to SCC. No discussion was provided in the report detailing which components or types of stress were used in making this assessment. As pointed out in the *Threshold Stress Level for Initiation of Stress Corrosion Cracking (SCC) in Alloy 22, Ti Gr7 and Ti Gr24* (CRWMS, M&O, 2000d),

> "...no experimental test results on SCC initiation stress threshold (IST) values are available for any of the corrosion-resistant alloys selected for the drip shield (Ti Gr7 and Ti Gr 24) and for the waste package (Alloy 22 and 316NG) under expected bounding waste package/drip shield surface environments and temperatures. ...However, a review of the literature indicates that SCC IST evaluation test results obtained in boiling magnesium chloride solutions performed in accordance with ASTM G36 or similar test procedures are very likely lower bound values as compared to the range of IST values expected in bounding waste package/drip shield surface environments. Consequently, the lower bound IST values obtained in boiling magnesium chloride tests reported in the literature for similar classes of alloys should be conservatively used for design and PA [Performance Assessment] purposes until directly measured alloy/environment relevant IST values are generated in currently planned test programs. In particular, IST values of 20 to 30 percent of room temperature yield stress (reported for stainless steels Types 304, 304L, and 316) will be used for the subject drip shield alloys (Ti Grade 7 and Ti Gr24) and waste package

alloys (Alloy 22, 316NG) for design and PA purposes. This lower bound ITS range is assumed to be uniformly distributed between 20 and 30 percent of room temperature yield stress"

Although a literature search pertaining to IST values for SCC was apparently conducted, no supporting references were cited in the report to justify the assumption that the lower bound IST range is uniformly distributed between 20 and 30 percent of room temperature yield stress. Moreover, there was no information provided that addresses the recommended procedure for how generalized 3D stress states obtained from engineering analyses should be interpreted to properly determine whether the 20 to 30 percent of yield stress criterion for IST has been exceeded. In other words, should the Von Mises or first principle stress be used for comparison with the 20 to 30 percent of yield stress criterion. In addition, given the significant reduction in yield stress for Titanium Grades 7 and 24 at emplacement drift temperatures relative to the values at room temperature, the assumed IST criterion does not appear to be conservative or technically defendable.

AC3 Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the TSPA abstraction of MDEB are consistent with site characterization data, are technically defensible, and reasonably account for uncertainties and variabilities. The technical bases for the parameter values used in the TSPA abstraction are provided.

- DOE justifies the process-level models used to determine corrosion-dependent parameter values that define the relevant behavioral characteristics and properties (e.g., SCC, hydrogen embrittlement, fracture toughness, ultimate tensile strength, etc.) of the materials of the EB components considered important to waste isolation and susceptible to mechanical disruptions. DOE adequately defines a range of variations for these parameter values that accounts for the effects of and uncertainties associated with fabrication flaws, accumulated damage caused by multiple disruptive events, and the temporal and spatial changes in the emplacement drift environment (e.g., temperature, redox conditions, pH, chemical composition of water contacting the relevant EBs, etc.). These variations: (i) have been incorporated into the MDEB abstraction such that the model will not underestimate the failure of the relevant EB components subjected to mechanically disruptive events and (ii) are consistent with the requirements of the CLST KTI IRSR (U.S. Nuclear Regulatory Commission, 2000).

- DOE justifies, through appropriate methods for nondestructive examination of fabricated EB, the type, size, and location of fabrication defects that may lead to premature failure as a result of rapidly initiated EB degradation. The parameter values used in the analysis are consistent with the results of the nondestructive examination. DOE considers these defect when evaluating rock fall.

- DOE addresses, through appropriate sensitivity analyses or conservatively chosen bounds, uncertainty and variability in the relevant EB component corrosion models and their effects on the response of the EB component to mechanically disruptive events.

- DOE justifies the process-level models used to represent seismic conditions within the emplacement drifts at the proposed YM repository. DOE parameter values are adequately constrained by YM seismicity data such that the effects of seismicity on EB integrity are not underestimated. DOE identifies parameters within conceptual models for seismicity are consistent with the range of seismicity characteristics observed at YM.

- DOE's seismicity model parameters account for variability in data precision and accuracy. For example, DOE adequately accounts for uncertainty and verified parameter distributions of (i) maximum magnitude, (ii) depth of seismogenic crust, (iii) earthquake recurrence or activity rates, (iv) fault recurrence and dip, (v) wave propagation characteristics between earthquake sources and the YM site, and (vi) empirical and theoretical factors controlling directivity and other near-field effects.

- DOE identifies the seismic hazard inputs used to estimate rockfall potential are consistent with the inputs used in the repository design criteria and TSPA.

- DOE demonstrates with adequate consideration of associated uncertainties that the size distribution of rocks that may potentially fall on the WP and other relevant EB components is estimated from site-specific data (e.g., distribution of joint patterns, spacing, and orientation in three dimensions).

- DOE appropriately establishes that possible correlations between parameters are included in the TSPA abstraction.

- Where sufficient data do not exist, the definition of parameter values and conceptual models are based on appropriate use of other sources such as expert elicitation conducted in accordance with appropriate guidance such as NUREG–1563.

Status: Open.

Basis: Materials related to this AC will be reviewed and the results documented in subsequent revisions.

AC4 Alternative modeling approaches consistent with available data and current scientific understanding are investigated and results and limitations are appropriately factored into the abstraction of MDEB. DOE has provided sufficient evidence that ACMs of FEPs have been considered, that the models are consistent with available data (e.g., field, laboratory, and natural analog) and current scientific understanding, and that the effect of these ACMs on TSPA has been evaluated.

- DOE adequately considers the temporal and spatial variations of parameters relevant to the response of the EBs to mechanically disruptive events (e.g., fracture toughness, dimensional changes, residual stresses, and SCC).

- DOE investigates alternative modeling approaches for seismicity, such as recurrence relationships or ground-motion attenuation relationships. For example, DOE models adequately considers uncertainties in: (i) geologic and tectonic conditions, (ii) seismic activity of independent and clustered events, (iii) recurrence-magnitude models, or (iv) ground-motion attenuation models.

- DOE identifies alternative conceptual models for seismically induced rockfall on theWP and other relevant EBs. DOE demonstrates that the analytical models used in the estimation of impact load due to rock fall on the WP and other relevant EB components are: (i) based on reasonable assumptions and site data, (ii) consistent with the underground facility (e.g., emplacement drift geometry and backfill) and EB component designs, and (iii) defensible with respect to providing realistic or bounding estimates of impact loads and stresses. DOE considers the rock fall analyses, as functions of ground-motions: (i) the possibility of multiple blocks falling onto the EBs simultaneously and (ii) the extent of the potential rock-fall area around the individual emplacement drifts and the entire repository. Within the rockfall dynamic analyses, DOE considers the TM effect and time-dependent jointed rock behavior and provides the background conditions on which seismic loads are superimposed.

Status: Open.

Basis: Materials related to this AC will be reviewed and the results documented in subsequent revisions. For evaluation of the last item of this AC, refer to the discussion provided for AC1.

AC5 Output from the TSPA abstraction of the degradation of EB is justified through comparison with output from detailed process-level models and empirical observations arising from laboratory tests and field measurements.

- DOE defends modeling results for MDEB by seismicity by comparison to output from detailed process-level models, empirical observations, or both. DOE demonstrates that results of assessments of the seismic disruption of the WP and other relevant EB components used in TSPA models were verified against results from empirical observations (including appropriate analogs). DOE appropriately adopts acceptable and documented procedures to construct and test empirical and physical models used to estimate the seismic hazard. DOE defends the effectiveness of proposed models in quantifying ground-motion at YM as it relates to earthquake-induced rock fall and repository performance.

- DOE justifies the output from the abstraction of the effect of seismically induced rock fall on the WP and other relevant EB components, and compares the results with a combination of corrosion degradation, rock block size and shape, impact velocities, and temperature adjusted EB component material characterizations. DOE identifies detailed models of mechanical failure to evaluate the PA abstractions of MDEBs.

Status: Open.

Basis: Materials related to this AC will be reviewed and the results documented in subsequent revisions.

5.3.3 Thermal-Mechanical Effects on Flow into Emplacement Drifts (Status: Open)

With respect to DOE's PA abstractions, TM Effects on Flow into Emplacement Drifts address three aspects: changes in (i) emplacement-drift geometry, (ii) rock-mass hydrological properties owing to geomechanical response to thermal and seismic loading, and (iii) the characterization of repository thermal loading and ventilation. The following PA abstractions are affected by these three concerns:

- Degradation of EBs
- Quantity and Chemistry of Water Contacting WP and WF
- Spatial and Temporal Distribution of Flow

U.S. Department of Energy Approach

Change in Emplacement-Drift Geometry

DOE is likely to rely on analyses documented in the *Drift Degradation Analysis* report (CRWMS M&O, 1999d) for the prediction of potential changes in emplacement-drift geometry. The AMR defined its objective as: (i) to provide a statistical description of block sizes formed by fractures around the emplacement drifts; (ii) to estimate changes in drift profiles resulting from progressive deterioration of the emplacement drifts both with and without backfill, and (iii) to provide an estimate of the time required for significant drift deterioration to occur.

The analyses reported in the AMR were conducted using a computer code DRKBA (Stone Mineral Ventures, Inc., 1998), which is based on a statistical analysis of fracture networks to determine the occurrence of key blocks (i.e., the rock blocks that would have to fall before their neighboring blocks can fall) and calculates the factor of safety against the fall of key blocks under their own weight. The only driving force in the code (i.e., the force that may cause a key block to fall) is gravity. Resistance against block fall is provided by the shear strength of the fracture surfaces that define the key block.

The DRKBA code has no mechanism for the analysis of distributed internal forces such as are associated with thermal and seismic loadings. The AMR stated that thermal and seismic loadings were incorporated in the analyses through reductions of the shear strength of fracture surfaces. The procedure of accounting for thermal and seismic loadings through fracture-strength reductions is, however, inadequate for the following reasons.

(i) A key characteristic of thermal and seismic loading is that they generate distributed internal forces with varying orientations and magnitudes, such that the geomechanical response of a rock mass to thermal or seismic loading depends partly on the stress-strain response of the rock blocks and partly on the response of fracture surfaces. A code such as DRKBA that is based on the kinematic modeling of rigid blocks separated by fractures is not able to account for the stress-strain response of rock blocks and, consequently, is not appropriate for modeling the geomechanical response of a rock mass to thermal or seismic loading.

(ii) Because the only driving force in the DRKBA code is vertical, the strength-reduction approach can only affect movement on vertical and near-vertical fracture planes. Block movements that may be caused by slip on subhorizontal fractures cannot be detected by the analysis procedure. Analyses conducted by other investigators using numerical codes based on stress analysis (e.g., Chen, et al., 2000; Ofoegbu, 2000) indicate that slip on subhorizontal fractures may be a predominant aspect of geomechanical response at YM because of the anticipated horizontal orientation of the maximum principal compressive stress during the thermal regime (e.g., Section 4.3.2).

Consequently, the analyses presented in the *Drift Degradation Analysis* report (CRWMS M&O, 1999d) are not capable of leading to any conclusion on the second and third objectives defined in the report. The first objective of the analysis, that is, providing a statistical description of block sizes formed by fractures around the emplacement drifts, can possibly be satisfied using the DRKBA code, depending on evaluations in Section 5.3.2, but the code is not appropriate for estimating potential changes in emplacement-drift geometry owing to thermal and seismic loading.

CRWMS M&O (CRWMS M&O, 2000e,f) proposed a procedure for incorporating drift-geometry changes in drift-seepage abstraction, but at the same time argued that only a small percentage of the emplacement drifts would be expected to experience significant changes in geometry. The conclusion regarding the percentage of drifts that may experience significant geometry changes was taken from the *Drift Degradation Analysis* report, which, as discussed earlier, is not capable of providing a technical basis for such a conclusion.

Change in Rock-Mass Hydrological Properties

The DOE approach to evaluating TM-induced hydrological-property changes is summarized in a statement, presented at the April 2000 DOE/NRC Technical Exchange, that "thermal loading will produce negligible changes in rock hydrologic properties."[5] This conclusion is based on an analysis by Blair (in Hardin, 1998) and numerical modeling by Berge et al. (1998, 1999), from which it was concluded that: (i) slip on a single vertical-fracture set can cause the permeability of the set to increase by a factor of two or less and (ii) if slip occurs simultaneously on two orthogonal sets of vertical fractures, the permeability of the sets can increase by a factor of four or less. As argued in Ofoegbu (2000), this suggested upperbound for thermally induced permeability increase is incorrect, having been calculated from an assumption that the magnitude of thermally induced slip on a given fracture is equal to the preexisting (i.e., before thermal loading) slip on the same fracture. No justification was offered for the assumption [Blair (in Hardin, 1998); Berge et al., 1998; 1999)]. In fact, there is no reason at all to expect a relationship between preexisting slip and thermally induced slip.

In contrast to the DOE position, information presented in Ofoegbu (2000) indicates that: (i) rock-mass permeabilities near the repository horizon can be expected to increase within laterally discontinuous zones centered at the emplacement drifts and in the middle of pillars, owing to fracture dilation associated with geomechanical response to thermal loading; (ii) the magnitude of permeability increase can be expected to greatly exceed the upper bound suggested by DOE and would be greater around the drift openings than in the pillars; (iii) the magnitudes would depend on thermal loading, rock-mass mechanical properties, and time-dependent mechanical degradation; (iv) altered zones characterized by horizontal-fracture dilation in areas of high rock-mass quality and vertical-fracture dilation in areas of low rock-mass quality can be expected, but fracture closure from thermally induced stresses is likely to be small and insignificant to rock-mass permeability; and (v) lateral flow of moisture can be expected in the altered zones and would result in elevated vertical percolation flux within and at the downstream end of the altered zones. In light of these findings, DOE will need to reexamine its position that the thermal loading will produce negligible changes in rock hydrologic properties and reassess its effects on repository performance.

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[5]Barr, D. *Thermal Effects on Flow. Presentation at DOE/NRC Technical Exchange on Yucca Mountain Pre-Licensing Issues.* Las Vegas, NV: U.S. Department of Energy, Yucca Mountain Site Characterization Office. April 2000.

Characterization of Repository Thermal Loading and Ventilation

This aspect of DOE's PA abstractions deals with thermal-load characterization of the emplaced nuclear waste, representation of thermal loading and ventilation in PA abstractions, and analysis to demonstrate that the ventilation design would remove the amount of heat assumed in PA abstractions.

A characterization of thermal loading for the proposed EDA-II design concept is documented in a calculation report (CRWMS M&O, 2000g) that is currently under review by NRC. The results of the review will be documented in future revisions.

Process level models that develop input information for TH abstractions (CRWMS M&O, 2000h) make an assumption that 70 percent of the waste-generated heat during the first 50 year would be removed by ventilation. The process level models implement this assumption by using only 30 percent of waste-generated heat as input thermal load during the first 50 years and 100 percent of the waste-generated heat thereafter (CRWMS M&O, 2000h). The procedure of using only 30 percent of the waste-generated heat (assuming that 70 percent of the heat is removed by ventilation) would satisfy the total energy balance of the repository control volume. The calculated temperatures within the repository volume are, however, likely to be incorrect, because the temperature gradients that drive heat transfer (by conduction, convection, and radiation) cannot be represented satisfactorily by using only 30 percent of the heat source. Heat transfer by radiation from the WP to the drift wall would be represented incorrectly using this procedure, possibly resulting in underestimation of the drift-wall and pillar temperatures.

Analyses to demonstrate that the proposed ventilation design would remove 70 percent of the waste-generated heat during the ventilation period are documented in the *Ventilation Model* report (CRWMS M&O, 1999c). The analyses are based on a combination of two-dimensional finite-element modeling for heat transfer in drift-normal planes, and spreadsheet calculations for heat transfer along the drift. The spreadsheet calculations use an explicit incrementation algorithm to advance the solution process in time and spatially along the drift. The conditions for numerical stability of the incrementation algorithm, which would define allowable limits for the time and drift-length increments, were not investigated. Furthermore, the algorithm did not use a predictor-corrector scheme to ensure consistency of corresponding estimates of drift-wall, air, and WP temperatures. These omissions from the algorithm raised a concern that the calculated drift-wall, air, and WP temperatures, and, consequently the predicted amounts of heat removal by ventilation, might not be correct. The concern was heightened by the results of calculations performed by CNWRA to check the consistency of the air and drift-wall temperatures given in the *Ventilation Model* report. The two sets of temperatures were found to be inconsistent; the drift-wall temperatures were not reproduced by analyses that used the air temperatures as input.

U.S. Nuclear Regulatory Commission Staff Evaluation

Degradation of Engineered Barriers

AC1 Important design features, physical phenomena and couplings, and consistent and appropriate assumptions have been identified and described sufficiently for incorporation into the abstraction of degradation of EBs and other related abstractions in the TSPA, and the technical bases are provided. The TSPA abstraction in the DOE LA identifies and describes design features of the EBS and aspects of the degradation of EBs that are important to waste isolation and includes the technical bases for these descriptions.

- DOE: (i) considers the effects of TM processes and thermohydrologic processes on the EB environment, taking into account heterogeneities such as joints and faults; (ii) bounds the range of thermally driven flux; and (iii) considers the possibility of water reflux during cool-down.

- DOE considers the effects of TM processes on ground movement (including rock fall, rock deformation, and alterations to porosity and existing fractures) and changes to the drift geometry that may affect the EB chemical environment.

- DOE's thermohydrologic models used to assess the effects of evaporation, thermally driven flow, and groundwater condensation on the EB environment include significant repository design features and evaluate the following potential thermohydrologic phenomena: (i) multidrift dry-out zone coalescence, (ii) lateral movement of condensate, (iii) cold-trap effect, (iv) repository edge effects, and (v) condensate drainage through fractures.

Status: Open.

Basis: Change in emplacement-drift geometry (from roof and side-wall collapse and floor heave) is screened out from the abstraction of degradation of EBs (CRWMS M&O, 2000l) based on conclusions from the *Drift Degradation Analysis* report (CRWMS M&O, 1999d). These conclusions is of limited use because thermal and seismic loadings are not considered satisfactorily in the analyses. Therefore, the conclusions from the report cannot be used as a basis to screen out TM processes from the abstraction of degradation of EBs.

TM-induced changes in hydrological properties are included in the abstraction of degradation of EBs through changes in the drift-seepage flux. Therefore, the treatment of TM effects on hydrological properties is evaluated as part of the abstraction of Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms (CRWMS M&O, 2000i).

The assessment of TH effects on the EB environment is documented in a CRWMS M&O report (CRWMS M&O, 1999e), which ignored the first 50 or 100 years of thermal loading in the calculations. This report did not explain how the distributions of temperature, saturation, and relative humidity at 50 or 100 years (i.e., the initial conditions used in the analyses) were obtained without considering thermal loading during the earlier period (of 50 or 100 year). The thermal-load characterization of the emplaced waste and ventilation are significant design features that need to be considered in the assessment of TH effects on the EB environment.

Quantity and Chemistry of Water Contacting WPs and WFs

AC1 Important design features, physical phenomena and couplings, and consistent and appropriate assumptions have been identified and described sufficiently for incorporation into the abstraction of the quantity and chemistry of water contacting WP and WF in the PA and other related abstractions in the TSPA, and the technical bases are provided. The features, phenomena and couplings, and assumptions used to abstract the quantity and chemistry of water contacting WP and WF have been provided. The TSPA abstraction is consistent with the identification and description of those aspects of the quantity and chemistry of water contacting WP and WF that are important to waste isolation. The TSPA abstraction is also consistent with the technical bases for these descriptions of barriers important to waste isolation. Specifically:

- DOE evaluates the potential for focusing of water flow into drifts caused by coupled THMC processes.
- DOE abstractions, including dimensionality of the abstractions, appropriately account for the various design features, site characteristics, and alternative conceptual approaches.
- DOE spatial and temporal abstractions appropriately address the physical couplings (thermal-hydrologic-mechanical-chemical).
- DOE provides the bases and justification for modeling assumptions and approximations where simplifications for modeling coupled THMC effects on seepage and flow and the WP chemical environment are used for PA.
- DOE provides adequate technical bases, including activities such as independent modeling, laboratory or field data, or sensitivity studies, for exclusion of any THMC couplings and FEPs.
- DOE uses important design features, including WP design and material selection, backfill, drip shield, ground support, cladding, thermal loading strategy, and degradation processes, to determine the initial and boundary conditions for calculations of the quantity and chemistry of water contacting WP and WF.

Status: Open.

Basis: CRWMS M&O (CRWMS M&O, 2000e,f) proposed an approach based on drift surface area for including drift-geometry changes in the abstraction of Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms. The long-term emplacement-drift geometry required as input to the abstraction needs to be estimated using a procedure that accounts for the rock-mass geomechanical response to thermal and seismic loading. The *Drift Degradation Analysis* report (CRWMS M&O, 1999d) is unable to provide this information because the analyses did not consider thermal and seismic loadings satisfactorily.

TM effects on hydrological properties are screened out of the abstraction of Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms for two reasons (CRWMS M&O, 2000h: First, TM effects on fracture permeability were considered to be small based on the Berge, et al. (1998) analyses (see *Change in Rock-Mass Hydrological Properties*, U.S. Department of Energy Approach of this section). The upper bound permeability increase suggested by Berge, et al., (1998) is, however, too small and can be exceeded as discussed in *Change in Rock-Mass Hydrological Properties*, U.S. Department of Energy Approach of this section. Second, analyses presented by CRWMS M&O (2000e) indicate that an increase in fracture permeability would result in decreased water flow into emplacement drifts. Alternative model calculations summarized in the *Change in*

Rock-Mass Hydrological Properties, U.S. Department of Energy Approach of this section (Ofoegbu, 2000; Ofoegbu et al., 2000), however, indicate that lateral flow of moisture can be expected within a TM-altered zone and would cause increased vertical percolation flux and, therefore, drift seepage, at the downstream end of the altered zone. One difference between the two studies that may explain the divergence in the findings relates to the change in capillarity associated with a change in fracture aperture. In the study conducted by CRWMS M&O (2000e), a two-fold increase in fracture aperture (ten-fold increase in fracture permeability) was combined with a ten-fold decrease in capillarity, which effectively caused the altered zone to function as a capillary barrier. On the other hand, a change in capillarity was not applied in the alternative study (Ofoegbu, 2000; Ofoegbu et al., 2000) in which an increase in fracture aperture by a factor of up to 10 was applied. DOE needs to provide the technical bases for the parameter values used to assess the effects of TM-altered hydrological properties on the abstraction of the Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms.

As discussed previously (in the *Characterization of Repository Thermal Loading and Ventilation*, U.S. Department of Energy Approach subsection of this section), process level models that develop input information for the abstraction of the Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms implement preclosure ventilation by using only 30 percent of waste-generated heat as input thermal load during the first 50 years after waste emplacement. Thereafter, the models use 100 percent of the waste-generated heat (CRWMS M&O, 2000h). To justify this representation of ventilation, DOE needs to demonstrate that: (i) the ventilation design would actually remove 70 percent of the waste-generated heat during the ventilation period, and (ii) the temperature distributions calculated using 30 percent of the heat source adequately represent the temperature distributions that would be calculated using 100 percent of the heat source with a proper representation of the ventilation design.

AC2 Sufficient data on design features (including drip shield, backfill, WP, cladding, other EB components, and thermal loading), geology, hydrology, geochemistry, and geomechanics of the unsaturated zone and drift environment (e.g., field, laboratory, and natural analog data) are available to adequately define relevant parameters and conceptual models necessary for developing the abstraction of the quantity and chemistry of water contacting WP and WF in the TSPA. The data are also sufficient to assess the degree to which FEPs related to the quantity and chemistry of water contacting WP and WF and which affect compliance with post-closure performance objectives have been characterized and to determine whether the technical bases provided for inclusion or exclusion of these FEPs are adequate. Where adequate data do not exist, other information sources such as expert elicitation have been appropriately incorporated into the abstraction process. Specifically:

- DOE demonstrates that sufficient data were collected on the characteristics of the natural system and engineered materials, such as the type, quantity, and reactivity of material, to establish initial and boundary conditions, including temporal and spatial variations in conditions, for conceptual models and simulations of thermal-hydrologic-mechanical-chemical coupled processes that affect seepage and flow and the WP chemical environment, as well as the chemical environment for radionuclide release.

Status: Open.

Basis: There are concerns regarding data used to define potential changes in: (i) emplacement-drift geometry; (ii) rock-mass hydrological properties owing to geomechanical response to thermal and seismic loading; and (iii) the characterization of repository thermal loading and ventilation. The information needed to address these concerns is discussed in Sections 4.3.2 and 5.3.1.

AC3 Parameter values, assumed ranges, probability distributions, and bounding assumptions used in the TSPA abstraction of quantity and chemistry of water contacting WP and WF, such as the pH, chloride concentration, and amount of water flowing in and out of the breached WP, are consistent with site characterization data, design data, laboratory experiments, field measurements, and natural analog data, are technically defensible, and reasonably account for uncertainties and variabilities. The technical bases for the parameter values used in the TSPA abstraction are provided. Specifically,

- DOE demonstrates that input values used in the quantity and chemistry of water contacting EBs (e.g., drip shield, WP, and cladding) calculations in TSPA are consistent with the initial and boundary conditions and the assumptions of the conceptual models and design concepts for the YM site, such as WP and EBS design (including backfill, drip shield, ground support, and cladding), WP degradation (corrosion and mechanical disruption), cladding degradation, deep percolation flux, important thermal-hydrologic-mechanical-chemical coupling effects, the thermal reflux model, the thermal loading strategy (including effects of ventilation), natural system masses and fluxes, and other design features that may affect performance.

- DOE establishes that reasonable or conservative ranges of parameters or functional relations are used to determine effects of coupled thermal-hydrologic-mechanical-chemical processes on seepage and flow and the WP chemical environment, as well as on the chemical environment for radionuclide release.

- DOE shows that the parameters used to define initial conditions, boundary conditions, and computational domain used in sensitivity analyses involving coupled THMC effects on seepage and flow and the WP chemical environment, as well as on the chemical environment for radionuclide release, are consistent with available data.

- DOE adequately considers the uncertainties in the characteristics of the natural system and engineered materials, such as the type, quantity, and reactivity of material, in establishing initial and boundary conditions for conceptual models and simulations of THMC coupled processes that affect seepage and flow and the WP chemical environment, as well as the chemical environment for radionuclide release.

Status: Open.

Basis: There are concerns regarding data used to define potential changes in: (i) emplacement-drift geometry; (ii) rock-mass hydrological properties owing to geomechanical response to thermal and seismic loading; and (iii) the characterization of repository thermal loading and ventilation. The information needed to address these concerns is discussed in Sections 4.3.2 and 5.3.1.

AC4 Alternative modeling approaches consistent with available data (e.g., design features, field, laboratory, and natural analog) and current scientific understanding are investigated and results and limitations are appropriately factored into the abstraction of quantity and chemistry of water contacting WP and WF. DOE has provided sufficient evidence that alternative conceptual models of FEPs have been considered, that the models are consistent with available data and current scientific understanding, and that the effect of these alternative conceptual models on TSPA has been evaluated. Specifically:

- DOE adequately considers the effects of THMC coupled processes that may occur in the natural setting or due to interactions with engineered materials or their alteration products in their assessment of alternative conceptual models. DOE considers: (i) thermohydrologic effects on gas and water chemistry; (ii) hydrothermally driven geochemical reactions such as zeolitization of volcanic glass, which could affect flow pathways, water chemistry and WP environmental conditions; (iii) dehydration of hydrous phases liberating moisture that may affect the WP chemical environment and the chemical environment for radionuclide release; (iv) effects of microbial processes on the WP chemical environment and the chemical environment for radionuclide release; (v) changes in water chemistry that may result from the release of corrosion products from the WP and interactions between engineered materials and groundwater, which, in turn, may affect flow and the WP chemical environment, as well as the chemical environment for radionuclide release; and (vi) changes in boundary conditions (e.g., drift shape and size) and hydrologic properties relating to the response of the geomechanical system to thermal loading, in their assessment of alternative conceptual models.

Status: Open.

Basis: DOE should provide adequate description of the alternative conceptual models used to assess the effects of change in: (i) emplacement-drift geometry; (ii) rock-mass hydrological properties owing to geomechanical response to thermal and seismic loadings; and (iii) ventilation on the abstraction of quantity and chemistry of water contacting WP and WF. For example, an alternative conceptual model for change in emplacement-drift geometry and hydrological properties may consist of two sets of abstractions, one set based on completely collapsed drifts and the other set based on the initial drift geometry with predictions from the two sets combined using a time-dependent weighting function. Similar alternative models may also be developed to explore the effects of ventilation, if it is determined that it is not practical to model ventilation explicitly.

AC5 Output from the TSPA abstraction of quantity and chemistry of water contacting WP and WF is justified through comparison with output from detailed process-level models and/or empirical observations (e.g., laboratory testing, field measurements, natural analogs).

- DOE demonstrates that abstracted models for coupled thermal-hydrologic-mechanical-chemical effects on seepage and flow and the WP chemical environment, as well as on the chemical environment for radionuclide release, are based on the same assumptions and approximations demonstrated to be appropriate for closely analogous natural or experimental systems.

- DOE clearly describes changes, if any, in hydrological properties (e.g., fracture porosity and permeability) due to thermally induced ground movements, and demonstrates that the magnitudes and distributions of the changes provided are consistent with the results of TM analyses of the underground facility.

Status: Open.

Basis: DOE needs to develop estimates of changes in hydrological properties and emplacement-drift geometry that account for the anticipated geomechanical response to the proposed thermal loading and potential seismic loading.

Spatial and Temporal Distribution of Flow

AC1 Important design features, site-specific physical phenomena and couplings, and consistent and appropriate assumptions have been incorporated into the spatial and temporal distribution of flow abstraction in the PA and the technical bases are provided. The TSPA abstraction in the DOE LA identifies and describes aspects of spatial and temporal distribution of flow that are important to waste isolation and includes the technical bases for these descriptions. Specifically:

- DOE temporal abstractions of the spatial and temporal distribution of flow appropriately incorporate the physical couplings (THMC) or sufficient justification is provided for exclusion of these couplings. The DOE abstraction incorporates or conservatively bounds coupled THMC processes based on, for example, independent models, laboratory and field analyses, literature reviews, natural analog data, and other available information.

- DOE estimates of performance are not over optimistic, given the excluded set of phenomena and the implementation of coupled THMC processes in the TSPA.

Status: Open.

Basis: TM effects on spatial and temporal distribution of flow are screened out of the DOE PA abstraction (CRWMS M&O, 2000j) using the assumptions that important TM effects would be reversible. These assumptions include that: (i) TM effects on hydrological properties would develop during the period of increasing temperature; (ii) drift seepage would not occur during this period because of hot and dry conditions at the repository level; and (iii) the TM effects would be reversed before moisture returns to the repository level. These assumptions are questions. Permanent TM-induced changes in hydrological properties and emplacement-drift geometry can be expected as discussed under the U.S. Department of Energy Approach subsection of this section (also, Ofoegbu, 2000; Ofoegbu et al., 2000). DOE needs to develop estimates of changes in hydrological properties and emplacement-drift geometry that account for the anticipated geomechanical response to the proposed thermal loading and potential seismic loading; and account for such changes in the abstraction of spatial and temporal distribution of flow.

AC3 Determine that parameter values, assumed ranges, probability distributions, and/or bounding assumptions used in the spatial and temporal distribution of flow abstraction are consistent with site characterization data, are technically defensible, and reasonably account for uncertainties and variabilities. The technical bases for the parameter values used in the PA have been provided. Specifically:

- Input values used in the abstraction are consistent with the initial and boundary conditions and the assumptions of the conceptual models for the YM site. For example, estimation of the deep percolation flux into the drift is based on the infiltration rate, structural control (for flow diversion via faults), thermal loading strategy (for reflux), and other design features that may affect spatial and temporal distribution of flow.

Status: Open.

Basis: The representation of repository thermal loading and ventilation in DOE's abstraction of the spatial and temporal distribution of flow is discussed under AC1 of *Quantity and Chemistry of Water Contacting Waste Packages and Waste Forms* under the U.S. Nuclear Regulatory Commission Staff Evaluation subsection of this section. There are concerns, and an approach to address these concerns is discussed in the same section.

5.3.4 Open Items from Site Characterization Plan/Site Characterization Analysis and Study Plans

Item ID: OSC0000001347C055 Comment 055 SCA
Title: Use of statistics in TM properties
Status: **Closed**
Basis: Overtaken by changes in testing program. Related concerns are being reviewed under a separate issue resolution report related to preclosure.

Item ID: OSC0000001346C056 Comment 056 SCA
Title: Validation of models/TM properties
Status: **Closed**
Basis: Subsumed under Acceptance Criterion 6 of Section 4.3.3.1 listed in Revision 2. For status, see Section 5.3.1.

Item ID: OSC0000001347Q042 Question 009 SCA
Title: Systematic drilling program implementation strategy
Status: **Closed**
Basis: Question not relevant under DOE's current strategy.

5.3.5 Other Related Items

To be determined.

5.4 DESIGN AND LONG-TERM CONTRIBUTION OF SEALS TO PERFORMANCE

Status: Closed.

Basis: The proposed 10 CFR Part 63 is a risk-informed and performance-based regulation. This regulation offers ample flexibility for DOE to demonstrate its case that the design of GROA meets preclosure and postclosure performance objectives. Since this regulation does not specifically provide requirements for design and performance of seals and DOE does not currently include seals in its PA, the staff determines that this subissue is closed. If DOE decides to take credit for seals in meeting postclosure performance objectives in the future, the status of this subissue may be reexamined.

5.4.1 Open Items from Site Characterization Plan/Site Characterization Analysis and Study Plans

Item ID: OSC0000001347Q042 Comment 074 SCA
Title: DOE's plan for *in-situ* testing of seal components
Status: **Closed**
Basis: The open item is related to seals. The design and long-term contribution of seals to performance subissue is closed since the proposed 10 CFR Part 63 does not specifically provide requirements for seals and DOE is not currently taking credit on seals for postclosure performance. Consequently, the open item is closed as well.

Item ID: OSC0000001347Q025 Question 025 SCA
Title: Sealing program/gaseous transport
Status: **Closed**
Basis: The open item is related to seals. The design and long-term contribution of seals to performance subissue is closed since the proposed 10 CFR Part 63 does not specifically provide requirements for seals and DOE is not currently taking credit on seals for postclosure performance. Consequently, the open item is closed as well.

Item ID: OSC0000001347Q028 Question 028 SCA
Title: Impacts on sealing program/calico hills penetration
Status: **Closed**
Basis: The current site characterization efforts have eliminated the need for penetrating the Calico Hills unit. Should DOE decide to revise its position to penetrate the Calico Hills unit, this concern may be reinstated.

Item ID: OSP0000831421Q001 Question 001 SP831421
Title: Status of borehole seal design
Status: **Closed**
Basis: The open item is related to seals. The design and long-term contribution of seals to performance subissue is closed since the proposed 10 CFR Part 63 does not specifically provide requirements for seals and DOE is not currently taking credit on seals for postclosure performance. Consequently, the open item is closed as well.

Item ID: OSP000831421Q002 Question 002 SP831421
Title: Specification for sealing boreholes
Status: **Closed**
Basis: The open item is related to seals. The design and long-term contribution of seals to performance subissue is closed since the proposed 10 CFR Part 63 does not specifically provide requirements for seals and DOE is not currently taking credit on seals for postclosure performance. Consequently, the open item is closed as well.

5.4.2 Other Related Items

To be determined.

5.5 OTHER OPEN ITEMS NOT INCLUDED UNDER THE FOUR SUBISSUES

5.5.1 Open Items from Site Characterization Plan/Site Characterization Analysis and Study Plans

Item ID: OSC0000001347C077 Comment 077 SCA
Title: Retrieval accidents/radiation exposure
Status: **Closed**
Basis: Related concerns will be reviewed under a separate activity that focuses on preclosure topics.

Item ID: OSC0000001347Q042 Comment 120 SCA
Title: Comprehensive, integrated and prioritized plan for model and code validation
Status: **Closed**
Basis: Transferred to TSPAI KTI IRSR Revision 2.

Item ID: OSC0000001347Q042 Comment 122 SCA
Title: Criteria for determining the acceptability of dry coring method
Status: **Closed**
Basis: Dry coring technology has been demonstrated.

Item ID: OSC0000001347Q042 Question 055 SCA
Title: Analysis of potential test interference from water storage facilities
Status: **Closed**
Basis: ESF construction completed. No evidence of test interference from surface water storage facilities.

5.5.2 Open Items from the Annotated Outline

Item ID: OAO030SEP1992C00 Comment 003 AO30SEP1992
Title: Planned area/controlled area
Status: **Closed**
Basis: DOE repository design is being revised.

Item ID: OAO030SEP1992C00 Comment 004 AO30SEP1992
Title: Legal definition of controlled area
Status: **Closed**
Basis: NRC has revised the definition of controlled area under DBE rule making.

Item ID: OAO030SEP1992Q00 Question 001 AO30SEP1992
Title: Figure reference/underground facility
Status: **Closed**
Basis: The underground facility design is being updated. The concern does not apply to the latest DOE design.

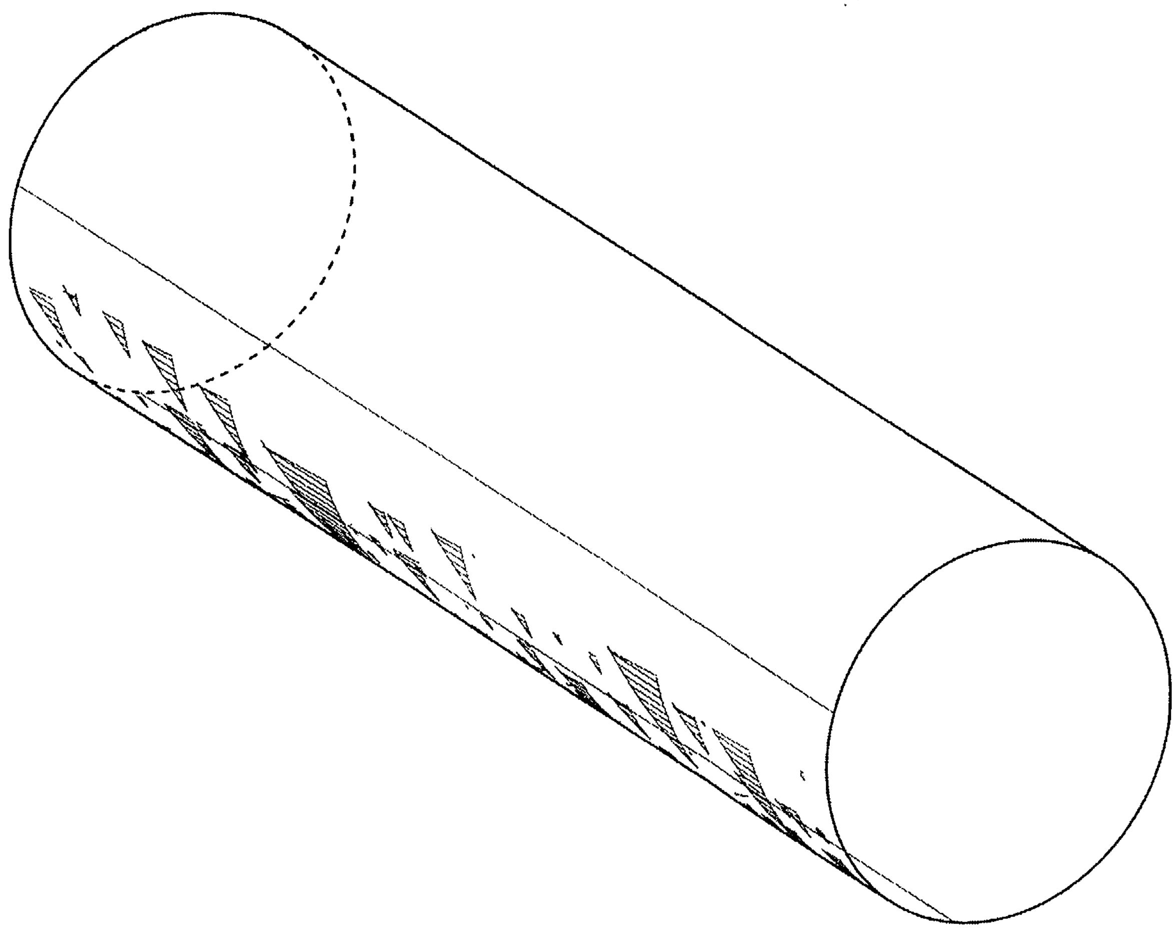

Figure 20. Traces of key blocks on emplacement surface for Topopah Spring Welded Tuff lower lithophysal unit

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APPENDIX

APPENDIX

This appendix lists important correspondences and interactions between the Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) related to the subissue of exploratory studies facility (ESF) design and design control process and briefly summarizes relevant details at the end of each item:

(1) U.S. Nuclear Regulatory Commission letter from R.M. Bernero to S. Rousso of U.S. Department of Energy, [cover letter to NRC's Site Characterization Analysis (SCA)] dated July 31, 1989.

[The letter and SCA raise two objections to DOE's continued deficiencies in its overall Quality Assurance Procedures (QAP) and inadequacy of its ESF design and design control process.]

(2) U.S. Nuclear Regulatory Commission letters from R.M. Bernero to J. Bartlett of U.S. Department of Energy, dated March 2, 1992, and November 2, 1992.

[The letters lift NRC's objections 1 and 2 based in part, on DOE's demonstration that it had revised its process of controlling ESF design and implementation of such a process.]

(3) U.S. Nuclear Regulatory Commission letters from J.J. Holonich to D. Shelor of U.S. Department of Energy, dated March 24, 1993, and May 5, 1993.

[The letters express renewed concerns related to ESF design and design control process.]

(4) U.S. Nuclear Regulatory Commission letter from B.J. Youngblood to D. Shelor of U.S. Department of Energy, dated August 20, 1993.

[The letter requests specific information from DOE including an action plan for implementing an acceptable design control process before proceeding with further design activities.]

(5) U.S. Department of Energy letter from D. Shelor to J.J. Holonich of U.S. Nuclear Regulatory Commission, dated November 1, 1993.

[This letter provides details related to the technical and regulatory design requirements and document hierarchy.]

(6) U.S. Department of Energy letter from D. Shelor to B.J. Youngblood of U.S. Nuclear Regulatory Commission, dated November 18, 1993.

[This letter provides response to specific NRC requests made in (4) above.]

(7) DOE–NRC interactions related to ESF design and design control process dated September 17, 1993, October 4–5, 1993, December 8, 1993, and January 5–7, 1994.

APPENDIX (cont'd)

[The discussions held during these interactions provide additional responses and clarifications to earlier staff requests.]

(8) U.S. Nuclear Regulatory Commission letter from B.J. Youngblood to D. Shelor of U.S. Department of Energy, dated March 30, 1994.

[This letter expresses limited satisfaction at the progress made by DOE and recommends further followup, such as quality assurance (QA) audits and surveillances for additional verification of DOE actions.]

(9) U.S. Nuclear Regulatory Commission from R.M. Bernero to D. Dreyfus of U.S. Department of Energy, dated October 13, 1994.

[This letter notifies DOE of staff continued concerns with DOE and its management and operating (M&O) Contractor QAP and transmits one major comment related to DOE and M&O QAP and three specific questions related to ESF design and its interface with geologic repository operations area (GROA) conceptual design.]

(10) U.S. Department of Energy letter from D. Dreyfus to R.M. Bernero of U.S. Nuclear Regulatory Commission, dated October 17, 1994.

[This letter provides a quick initial response to staff letter of October 13, 1994, and proposes a set of actions and commitments.]

(11) U.S. Department of Energy letter from D. Dreyfus to R.M. Bernero of U.S. Nuclear Regulatory Commission, dated November 14, 1994.

[This letter provides a detailed response to NRC's letter of October 13, 1994, and a series of actions and commitments. The staff uses this letter to develop a checklist of 51 items to be verified during an in-field verification.]

(12) U.S. Department of Energy letter from R.A. Milner to J.J. Holonich of U.S. Nuclear Regulatory Commission, dated January 27, 1995.

[This letter provides a list of DOE's commitments in response to staff recommendations.]

(13) U.S. Nuclear Regulatory Commission letter from J.J. Holonich to R.A. Milner of U.S. Department of Energy, dated March 9, 1995.

[This letter summarizes Phase-1 staff review of DOE's detailed response of November 14, 1994, and concludes that the responses provided by DOE are acceptable and presents a schedule for Phase-2 in-field verification.]

(14) U.S. Department of Energy letter from D. Dreyfus to R.M. Bernero of U.S. Nuclear Regulatory Commission, dated March 14, 1995.

APPENDIX (cont'd)

[This letter provides continued response to staff letter of October 13, 1994, and attaches the Regulatory Compliance Review Report (RCRR) showing the allocation and traceability of 10 CFR Part 60 requirements to the ESF.]

(15) U.S. Nuclear Regulatory Commission letter from J.J. Holonich to R.A. Milner of U.S. Department of Energy, dated March 16, 1995.

(This letter summarizes staff observations of DOE's QA audit of M&O.)

(16) U.S. Nuclear Regulatory Commission conducted in-field verification (phase-2) during April 3–6, 1995.

[See NRC (1995b), for in-field verification procedures and NRC (1995c), for the summary of findings from 6.0 List of References.]

(17) U.S. Department of Energy letter from R.A. Milner to J.J. Holonich of U.S. Nuclear Regulatory Commission, dated May 1, 1995.

[This letter informs NRC of DOE's decision to lift a self-imposed "hold" on tunnel boring machine (TBM) progress beyond upper Paintbrush Tuff nonwelded (Ptn) contact.]

(18) U.S. Nuclear Regulatory Commission letter from J.G. Greeves to R.A. Milner of U.S. Department of Energy, dated May 12, 1995.

[This letter concludes that an "objection" level concern does not exist with respect to the "pneumatic pathway" issue and documents that establishing or lifting "hold points" for TBM progress was a matter left to DOE's discretion.]

(19) U.S. Nuclear Regulatory Commission letter from J.J. Holonich to R.A. Milner of U.S. Department of Energy, dated June 16, 1995.

[This letter transmits staff in-field verification report, along with a commendation, closing several open items from the 51 items of the checklist and making three specific recommendations and proposals for followup.]

(20) U.S. Department of Energy letter from D. Dreyfus to C.J. Paperiello of U.S. Nuclear Regulatory Commission, dated August 3, 1995.

(This letter provides the balance of responses to NRC's letter of October 13, 1994, and provides the supplement to RCRR.)

(21) U.S. Department of Energy letter from S.J. Brocoum to J.J. Holonich of U.S. Nuclear Regulatory Commission, dated October 25, 1995.

APPENDIX (cont'd)

[This letter acknowledges the "cumbersome" nature of demonstrating regulatory flowdown and reports on two specific design process improvements: change to QAP–3–9 and modification to the structure and content of the Design Requirements Document.]

(22) U.S. Nuclear Regulatory Commission letter from M.J. Bell to S.J. Brocoum of U.S. Department of Energy, dated December 14, 1995.

[This letter transmits the staff review of DOE's RCRR and concludes that DOE made an acceptable demonstration of regulatory flowdown via the example of design package 2C and considered most of the applicable regulatory requirements from 10 CFR Part 60. In addition, the staff requests two specific items: a design example conducted under the new and improved design QA/design procedure and current versions of revised ESF Design Requirements Document along with DOE's latest description of "Document Hierarchy."]

(23) U.S. Department of Energy letter from S.J. Brocoum to M.J. Bell of U.S. Nuclear Regulatory Commission, dated September 1996.

[This letter responds to staff requests made in December 14, 1995, letter and provides clarifications sought by the staff.]

(24) U.S. Nuclear Regulatory Commission conducts an Appendix 7 meeting on June 12–13, 1997, at DOE/M&O Offices and at the YM site to gather data, conduct onsite reviews, and complete activities intended to be covered under phase-3 of the in-field verification, which had to be canceled because of personnel and budgetary reasons.

[The staff concludes that most of the checklist items that were not verified during phase-2 of the in-field verification conducted on April 3–6, 1995, could be closed out based on interviews with DOE/M&O staff and onsite reviews. The staff also concludes to keep two items open: (i) quality classification for the concrete inverts used for the ESF construction; and (ii) hierarchy of documents that control site characterization, design, construction, and operations activities at the YM site.]